Self-Organisation for Survival

Banerjee, I.

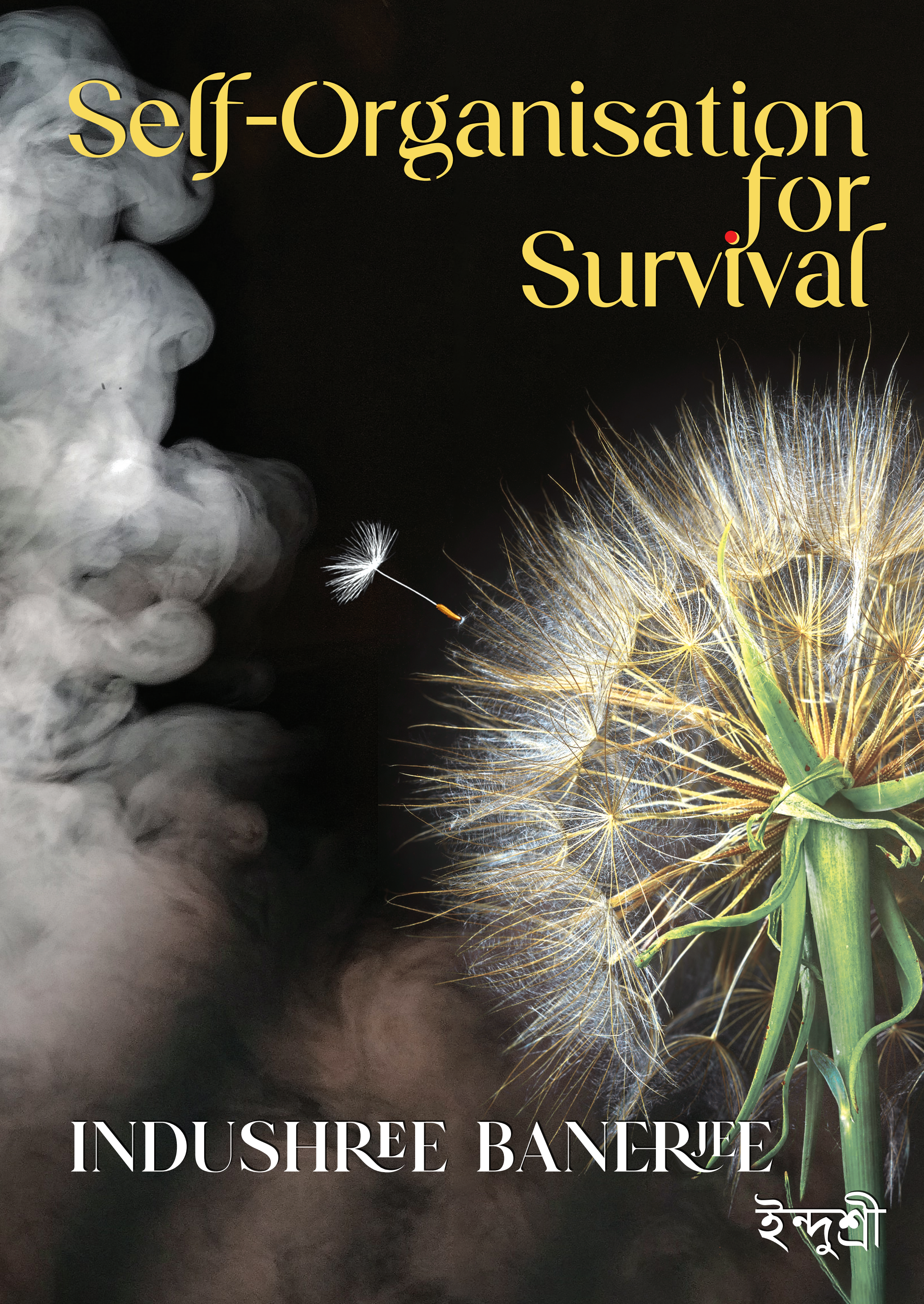
DOI
10.4233/uuid:300f7a64-53e6-4af7-b352-2805c551611c

Publication date
2022

Document Version
Final published version

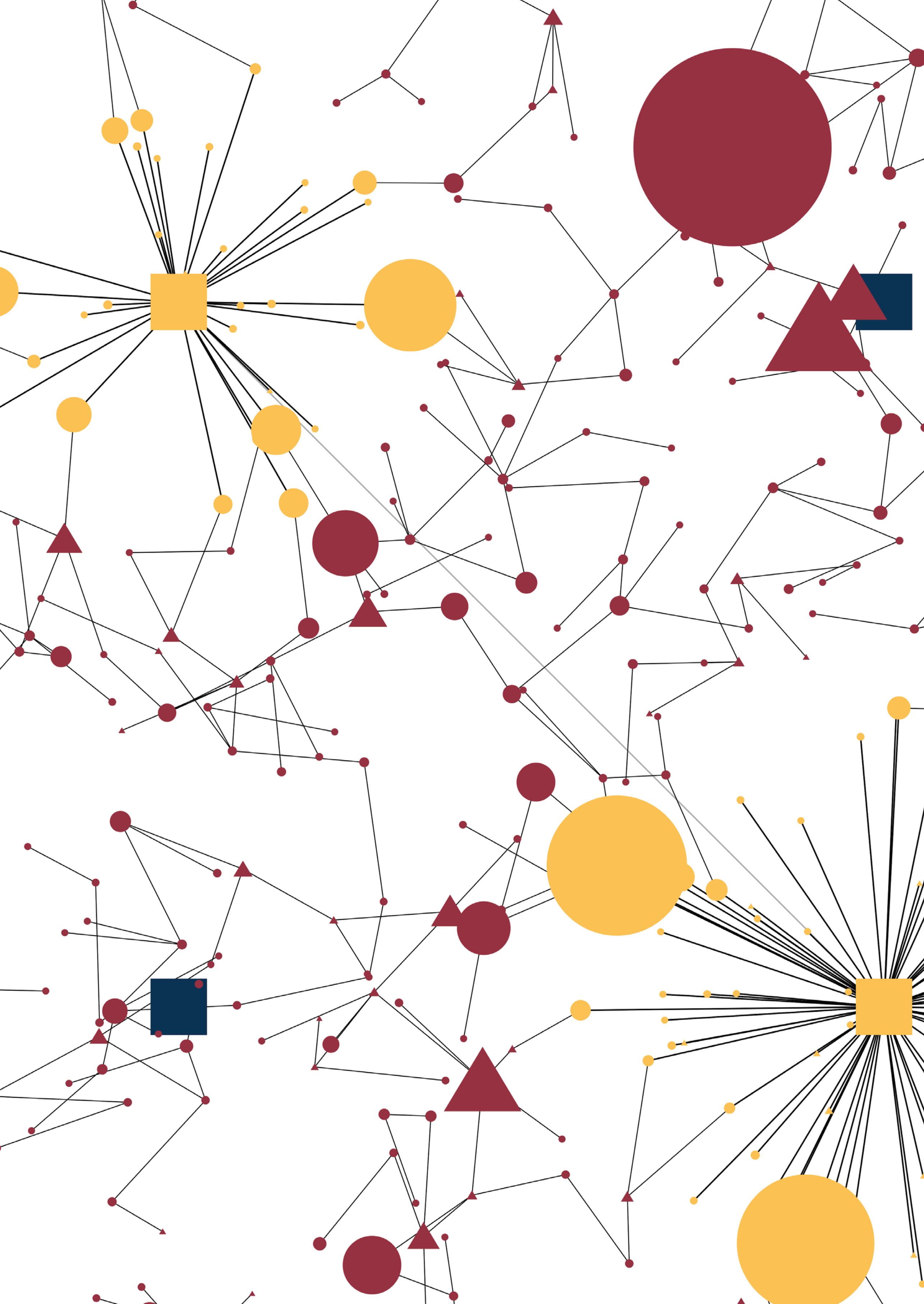
Citation (APA)
Banerjee, I. (2022). *Self-Organisation for Survival*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:300f7a64-53e6-4af7-b352-2805c551611c

Self-Organisation for Survival



INDUSHREE BANERJEE

ইন্দুশ্রী



Self-Organisation for Survival

Self-Organisation for Survival

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates to be defended publicly on
Wednesday 23rd, November 2022 at 12:00 o'clock

by

INDUSHREE BANERJEE
Master of Science in Networks and Distributed Systems,
University of St Andrews, Scotland
born on 21st January 1988 in Kolkata, India

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus	chairperson
Prof. dr. F. M. Brazier	Delft University of Technology, promotor
Prof. dr. M. Warnier	Delft University of Technology, promotor
Prof. dr. D. Helbing	TBM/ETH Zurich, promotor
Independent members:	
Prof. dr. M.J. van den Hoven	Delft University of Technology, Netherlands
Prof. dr. ir. R. Vingerhoeds	ISAE Toulouse, France
Prof. dr. S. Dobson	University of St Andrews, Scotland
Prof. dr. T.C. Comes	Delft University of Technology, Netherlands
Reserve member:	
Prof. dr. C.M. Jonker	Delft University of Technology, Netherlands

This research is funded by the research project

"Engineering Social Technologies for a Responsible Digital Future".

ISBN/EAN: 978-94-6366-618-3

This thesis is designed using Adobe InDesign and printed by Ridderprint.

Cover design by: Joost Agelink van Rentergem

Layout & Cover concept by: Indushree Banerjee

Dandelions can fly up to 100kms without any energy input to survive and extend their habitat. The parachute-like umbrella, made of hundred bristles, is called a pappus and holds the seed. Depending on humidity and wind velocity in the environment, the pappus decides to either widen the bristles or close them. A hinge structure at the core of the pappus is a unique tube-like structure that determines the movement of each bristle. During heavy rains, the core swells and absorbs water to change its cylindrical stem-like structure, which changes the angle of attachment for each bristle leading to a closing action. The process is entirely reversible when the wind is drier, leading to the widening of the bristles in the pappus, enhancing air drag if it aims to fly. This adaptive context-aware behaviour of the dandelions enhances their survival capacity. Similarly, the context-aware self-organising communication system designed and presented in this thesis aims to facilitate survival during disasters.
The fonts on the cover are a homage to Indushree's roots. As in Bengali, the fonts are round with ligatures. None of the letters closes into a circle, representing the loop-free nature of her network design. The red dot is a dedication to her mother and her Indian heritage. Indushree's name is written in Bengali script in the corner. Each chapter starts with a Sanskrit sloka she learnt as a child from her grandparents.

THE RIVER CANNOT GO BACK

It is said that before entering the sea
a river trembles with fear.
She looks back at the path she has traveled,
from the peaks of the mountains,
the long winding road crossing forests and villages.
And in front of her,
she sees an ocean so vast,
that to enter
there seems nothing more than to disappear forever.
But there is no other way.
The river can not go back.
Nobody can go back.
To go back is impossible in existence.
The river needs to take the risk
of entering the ocean
because only then will fear disappear,
because that's where the river will know
it's not about disappearing into the ocean,
but of becoming the ocean.

— KHALIL GIBRAN

॥ उत्तिष्ठत जाग्रत प्राप्य वरान्निबोधत ॥

ARISE ! AWAKE ! AND STOP NOT TILL THE GOAL IS REACHED

Preface

On April 25, 2015 at 11:56am in Nepal, Sajiya Gurung experiences a massive earthquake. Sajiya needs to enquire about her husband who is a Sherpa at the Everest base camp, make calls to her parents in a remote village of Nepal and collect her children from school. However, she finds no mobile services on her phone, as a 7.8 magnitude earthquake has destroyed all infrastructures.

Sajiya also needs to find a safe area to prevent getting under rubble of collapsing buildings. Her children are 20 km away at school and reaching them is impossible with split open roads and rubble. Outside her neighbour Tashi needs help to pull her child out of a toppled wall. The community collectively help her and Tashi out of the rubble and now need first aid for the child. The government hospital is far, but a retired nurse in the next community can be of help.

It is important to Sajiya and her community that they can communicate and send messages to other nearby communities to share resources such as medicine, water and safe space to help each other. As the next 72 hours are crucial to increase their chance of survival, it is crucial that there is an emergency mobile communication application running on their phones that works without physical infrastructure.

The community needs to be able to coordinate and collaborate with their phones in an autonomic and seamless manner without worrying about over-exploiting the depleting battery charges in their phones.

An easy to install mobile application, which works without any hardware modifications and offers fair communication opportunities for everyone despite the disparity of phones therefore becomes a necessity.

If governmental help arrives and infrastructure is restored, the emergency application running on the phones should be able to smoothly connect to this infrastructure to receive alert notifications regarding aid and making it possible for Sajiya to send messages to her parents and husband far away.

Sajiya represents citizens who are struck by sudden-onset disasters and need technologies that promote their autonomy to communicate, to enable situational altruism towards community, fair access to information, and inclusiveness and continuing communication with different sources of information. Such a mobile communication system when deployed in a disaster setting with various emergent needs is best categorised as a socio-technical system.

This thesis presents the design of an infrastructure-less ad hoc mobile emergency communication network system that facilitates automatic and seamless fair communication, and empowers citizens when they need it the most. Empowering citizens is important because they are often the first to respond, especially when sites are cut off and public rescue efforts start with a delay.

Part I: Setting the stage — **Contents**

Part 2: Identifying the knowledge gap *Contents*

Part 3: Design and Evaluation *Contents*

Part 4: Cognizance *Contents*

List of tables

List of figures

ABBREVIATIONS

MANET : Mobile Ad Hoc Network
SOS : Self-Organisation for Survival
MAPE: Monitoring, Analysing, Planning and Executing
BLE: Bluetooth low energy
APP : Application
DTN : Delay and disruption tolerant network
KPI : Key performance indicator
ECS: Emergency communication systems
P2P : Peer to peer

Part 1

Setting the stage

Contents

Chapter 1

॥ ॐ मणि पद्मे हूँ ॥

THROUGH THE UNCOMPROMISING PERSEVERANCE
OF USING METHODS AND WISDOM,
ONE CAN TRANSFORM THEIR MIND & BE ENLIGHTENED.

Part of this chapter is published as
Banerjee, Indushree, Martijn, Warnier, Frances M T Brazier, and Dirk Helbing. "*Introducing participatory fairness in emergency communication can support self-organization for survival.*" in Scientific reports 11, no. 1 (2021): 1-9.

INTRODUCTION

The frequency and severity of natural disasters – causing deaths and displacements – are steadily increasing [1]. The aftermath of Hurricane Katrina, the Nepal earthquake, and the Indian Ocean tsunami has shown that delays in rescue operations lead to the loss of human lives [2]. The first 72 hours following a disaster, called the "Golden Period" [3], are critical. However, mobilizing rescue operations and professional help for disaster recovery takes time [3, 4]. It is, therefore, crucial that citizens are provided with tools that enable participatory resilience and sustainability, allowing them to help themselves and support each other [3, 5, 6].

Emergency citizen-centric smartphone applications enable communication and collaboration during the aftermath of a disaster, thereby supporting community resilience. Simultaneously, reliable communication in an uncertain and dynamically changing environment is challenging [7, 8].

The challenge to stay connected during disasters is increased by

1. failure of damaged telecommunication infrastructures [9, 10], and
2. limited battery charge in phones due to power blackouts [11–14].

Power grids and mobile telecommunication are highly interdependent, so the failure of one has a cascading effect on the other [15, 16]. For example, 8000 mobile base stations immediately failed in Japan on March 11, 2011 after the tsunami. This number doubled by the following day, as backup power was exhausted, which led to 85% of mobile communication breaking down during this time [17]. Hurricane Katrina damaged three million telephone land-lines, disabling numerous 911 call centers. With approximately 2,000 cell sites uprooted and limited locations to charge phones due to power outages, many wireless phones were not reachable [11].

This has led to the development of various smartphone applications that are promoted as facilitators of emergency communication [18, 19]. In recent years, there has been a rise in the number of autonomous, self-organising mobile ad-hoc networks that use smartphones [20–23]. These applications utilize wireless capabilities of end-user devices such as Bluetooth and Wi-Fi to exchange messages peer-to-peer, forming an "ad hoc" communication network on-the-fly [24–26].

These applications typically rely on direct point-to-point connections between all phones that are in transmission range of each other. If sender and receiver are not within the transmission range, the message is relayed by other phones. This connection pattern is termed a mesh topology [25]. A mesh topology is the standard connection pattern for existing generic applications such as TeamPhone [27], RescueMe [28], FireChat, ServalMesh [29], BATMAN [30], Twimight [24] and Bluemergency [31]. The use of ad hoc networks for emergency communication has increased during the past 40 years. However, unavailability of charging facilities is still a major challenge, limiting communication options for a considerable fraction of affected citizens.

1.1 Challenges of citizen-centric communication

Using mobile phones to form infrastructure-less on-demand wireless mobile ad-hoc networks (MANET) presents certain challenges. These challenges are a result of either system design that limit deployment or limitations of the phones that form these networks. Some of these limitations and challenges are discussed in the following subsections:

1.1.1 System design impacts inclusion

Citizens in need of communication for survival and rescue often need emergency communication applications that are easy to install and use. Emergency communication applications refer to mobile applications used by citizens in a disaster area to exchange time-critical information to enhance their decision-making and survival process.

Recent surveys [32, 33] on usability of disaster applications found that an emergency communication application can both empower and hinder civilians in crisis mitigation. Users of emergency communication applications indicate that it is important for applications to be easy to deploy and not exhaustive of critical phone resources [32, 33].

Currently, the use of mobile applications is limited by the requirement of hardware changes or addition of extra equipment along with additional digital skills to deploy them. Additionally, the socio-economic disparity and the unpredictable digital literacy of citizens in a disaster situation may limit access to many sophisticated solutions [34].

1.1.2 Dynamic context impacts resilience

A resilient system has the capacity to bounce back to an acceptable level of services after any event [35]. How and to which extent a natural event might impact an area is not always known and can vary [36]. For disaster communication systems to be resilient they need to be adaptive to the dynamic context of a disaster site. The uncertain nature and dynamic context of a disaster site is characterised by:

- extent of damage to any infrastructure, which makes predicting the number of working infrastructures difficult,
- accessibility of the disaster site that determines how quickly help can arrive,
- number of people in an area, that can increase and decrease over time,
- access to resources required for forming and maintaining a mobile ad-hoc network.

Designing disaster communication applications that are adaptive to this changing context is a challenge.

For example, a disaster site has both mobile and immobile people that can form an infrastructure-less ad hoc network. Messages get relayed from one location to another as people walk or travel. The mobility of the people allows these phones to carry messages and deliver them to the next destination. The mobility of devices presents ample opportunity to connect and form new networks, it also brings the challenges of unstable connectivity.

The connection patterns or topology of these ad hoc networks are always dynamic and uncertain, as the mobility of phone owners and the density of phone owners in an area continuously change. These challenges make mobile ad hoc networks unreliable and difficult to deploy[37, 38].

1.1.3 Resource constraints impact participation

Disasters damage telecommunication infrastructure and cause electricity blackouts that prevent citizens from recharging their phones. Most current emergency communication applications drain energy without consideration of battery charge in phones. However, to work in an infrastructure-less mode phones need to relay messages. Sending, receiving and relaying messages increases the energy consumption of participating phones.

Not all phones in a disaster site have full batteries, and phones with limited battery charge cannot remain connected for a longer duration. Yet to support or deploy a large infrastructure-less mobile ad-hoc network for communication, mobile phones must participate in the relaying of messages.

The limited battery life of mobile phones is one of the most crucial challenges, that limits deployment of these communication networks. Lack of mechanisms to mitigate the disparity of battery in phones can lead to a communication network with certain phones having no communication at all and thus no longer participating in the network.

This sudden removal of phones can cause segmentation of the network and affects the robustness required to support connectivity for a larger area. This inevitably impacts the reliability of message delivery of the overall network.

1.1.4 Fragmentation impacts continuity

Participation and collaboration among various stakeholders such as governmental officials, rescue operators and citizens has been recognized as an important factor to minimize the impact of disasters on human lives. Communication applications help in this participation, however these applications often lack smooth and automatic transition to external Wi-Fi equipment such as Unmanned Aerial Vehicles (UAVs) [39], Wi-Fi access points [40], and high capacity radio relays [41] brought on site by rescue teams. Lack of automatic transition can lead to loss and non-continuous delivery of messages. Additionally, immobile citizens and citizens living in areas that do not fall in the coverage of deployed external equipment can be excluded from communicating their needs to rescue operations.

This thesis is motivated by the increasing need for autonomous modes of communication for citizens during disasters. To this end, this thesis :

1. investigates the properties that are essential to facilitate communication for survival and collective rescue efforts,
2. presents the design of a complex autonomous communication network with the essential properties,

3. proposes and evaluates metrics to quantitatively measure services delivered and,

4. provides guidelines based on evaluation to design and implement a mobile ad hoc system that can deliver communication autonomy and empowers local communities during sudden onset disasters.

So far, this introduction has outlined citizen-centric disaster communication and its challenges. The thesis further aims to understand:

How To Design A Value-Based Citizen-Centric Adaptive Mobile Communication System ?

The research road-map to investigate this question and fulfil this objective is specified in the next section in Research overview.

1.2 Research Overview

This section presents an overview of the research in this thesis. The research objectives introduce the overarching pursuits, the research questions highlight the specific knowledge required to address the research objective, and the research approach introduces an explanation of tools and means used in this thesis. The section ends with the main contributions of this thesis.

1.2.1 Research philosophy

Every researcher brings in "a basic set of beliefs that guide action" [42]. These beliefs are called paradigms or worldviews. They encompass the methodology and philosophy of research. The research conducted and presented in this thesis follows the post-positivist philosophy [43, 44]. A post-positivist philosophy posits that a researcher builds an approximation of the object of the research, and the theories, knowledge and values of the researcher can influence what is observed and designed [43].

In this thesis the objective is to design a value-sensitive communication system that will provide citizens with communication capability using their phones during disasters. This requires a definition of the values that are considered important and the conceptual design of the system encompassing these values. It is inevitable that the design is influenced by the knowledge of the researcher, her own belief systems and theories formed through observation and studies[45].

Research grounded in post-positivism takes a scientific approach to research [44]. John Creswell articulated and popularised this approach in his book [44]:

> *"In terms of practice, postpositivist researchers will likely view inquiry as a series of logically related steps, believe in multiple perspectives from participants rather than a single reality, and espouse rigorous methods of qualitative data collection and analysis. They will use multiple levels of data analysis for rigor, employ computer programs to assist in their analysis, encourage the use of validity approaches, and write their qualitative studies in the form of scientific reports, with a structure resembling quantitative approaches (e.g., problem, questions, data collection, results, conclusions)." - John W. Creswell [44]*

To have multiple perspectives [46], the research presented in this thesis has consulted multiple disciplines to gather requirements for the designed artifact. This research has used simulation and modeling to verify a conceptual model of the system designed and conducted numerous rigorous data analyses to evaluate results. The results of the research have been reported in journals that follow the structure of a quantitative approach (e.g., problem, questions, data collection, results, conclusions).

1.2.2 Research objectives

In a dynamic or disruptive situation, such as disasters, a fully mobile and decentralized infrastructure-less network seems to be a viable option for communication. Citizens however are confronted with challenges such as complicated deployment of these networks, resource-constrained mobile phones and mobility. This requires communication networks to adapt to these changing spatio-temporal-resource contexts. The main objective of this thesis is to design a value- based citizen-centric adaptive mobile communication system, that takes context and these aspects into account.

To design a value-based adaptive mobile communication system for citizens, the first step involves a thorough investigation of the current State of the Art. This investigation is followed by the identification of values that need to be part of the design process of an infrastructure-less citizen-centric communication network.

This thesis elaborates on key performance indicators (KPIs) that are important to design an adaptive and autonomous communication network for disasters. Once this objective is met, the thesis further investigates approaches to design a communication network based on these requirements.

The options "Autonomic Computing" provides are further investigated to design an adaptive and context-aware communication network. After the conceptual design of the network is finished, the next objective is to determine how to test the robustness of the design in a dynamic scenario, followed by an investigation whether the network can scale with changing population density without affecting reliability.

In this thesis the right to remain connected and communicate despite disparity in battery charge is considered the core value of the design process. To serve this purpose, the next part of the thesis focuses on investigating values deemed important for citizens that can be delivered with the design of a resilient communication network. This involves defining values of ”participatory fairness”, ”inclusion”, and ”continuity”. This thesis extends the current body of work on citizen-centric ad hoc networks for communication during crisis and disaster management.

The research question that follows the research objectives is given in the next section. This is further subdivided into sub-questions for further investigation.

1.2.3 Research questions

Main Research Question

How to design a value-based citizen-centric adaptive mobile communication system?

To fully grasp the research associated with answering the main question, the following sub-questions are addressed:

RQ1: *What is the current State of the Art in citizen-centric mobile communication systems for sudden-onset disasters, and how are questions of intended stakeholders, ease of use and implementation, deployment time, energy efficiency and context-reactivity approached?*

RQ2: *Can self-organization as an approach be used to design a citizen-centric communication system? And how?*

***RQ3**: Can a citizen-centric communication system fulfil the value of participatory fairness at the system level? And how?*

***RQ4**: Can a citizen-centric communication system be adapted such that it seamlessly and automatically integrates with other available infrastructure in a disaster context? And how?*

The remainder of this thesis addresses these research questions. Chapter 3 answers RQ1, followed by Chapter 4 that answers RQ2. Chapter 5 and 6 focus on RQ3 and RQ4 respectively.

1.2.4 Research approach

The focus of this thesis is to provide a solution to the given problem in a very specific context, given this objective, Research through Design has been chosen as the research approach. This approach guides scientific research to provide solutions for a scientific problem with emphasis on artifacts as the outcome of the research through iterative design. Artifacts can be models, concepts, methods or implemented/prototyped systems.

Alternatively, Research through Design has been advocated by designers [47, 48] to produce relevant conceptual frameworks that through rigorous refining can focus on knowledge gaps in current theories [49]. Finally Research through Design also produces artifacts/models that can be used to showcase a possible use of an artifact, promoting a meaningful invention [50].

1.2.5 Research instruments

The research instruments used in this research are:

- ***Literature review*** – Used for accumulating the background knowledge required to conduct research, identifying the knowledge gap and formulating the research questions and comparing the proposed solution with related work.
- ***Modeling and simulation*** – To understand the specification and design choices of the proposed artifact, modeling and simulation is performed in a controlled environment.
- ***Experimentation and evaluation*** – Performance evaluation using simulations allows for developing mechanisms to study the performance trade-off and show the effectiveness of the proposed system design. Additionally, experiments are conducted to evaluate if the developed system can fulfil all of the research objectives.

1.2.6 Research contributions

This thesis explores, for the first time, the effects of introducing a value-sensitive design approach for citizen-centric communication networks. The importance and originality of this research are that it explores Autonomic Computing [51–53] as an approach to the design of a decentralised context-aware communication system under stress while delivering values of participatory fairness, inclusion and continuity.

This study provides new insights into value characterisation and how values are translated into requirements to design emergency communication system for citizens. To be more specific, characterisation of values in regard to context is important for increased understanding of the design of complex socio-technical systems. This thesis contributes to this growing area of research [54–56] by introducing and quantifying values from a complex system design perspective. While the preferential attachment approach [57] has become a widespread descriptive model, for example, for the structure of the Internet, protein-protein networks, or scientific citation networks, this thesis demonstrates how it can be used as a design principle to improve the performance of damaged or unavailable communication networks. The contributions of the research are summarised as following:

C1: An in-depth literature review of disaster communication to investigate the State of the Art with respect to technologies designed in the last 20 years to facilitate communication between citizens during disasters. The review (Chapter 3) identifies the crucial knowledge gap related to the lack of value-based requirements and the need for metrics to quantify value delivery in communication systems catered towards citizens.

C2: Design of a decentralized context-adaptive communication system: Self-Organisation for Survival (SOS) (See Chapter 4). The system consists of a novel set of three self-organised context-aware distributed algorithms that form connections based on preferential attachment. This leads to the emergence of a loop-free, scale-free topology. An agent-based simulation model of an infrastructureless emergency communication network using SOS to evaluate the performance is also presented.

The model can be used to study communication disparity and examine the use of SOS for automatically and dynamically adapting the topology to changing battery charges, and self-organizing to remain robust and reliable when links fail or phones leave the network. (See Chapter 4).

C3: Design and evaluation of a metric that quantifies participatory fairness for a citizen-centric smartphone communication network used during sudden-onset disaster, incorporating the impact of disparity of battery charge and its effect in communication capacity in different population densities (See chapter 5).

A separate agent-based model of the de facto topology currently used in practice for disaster communication to perform comparative evaluation that can be used to see the basic difference in topology formations and performance differences. Establishing a connection between population density representative of various disaster prone cities and type of communication network suitable for communication deployment (See Chapter 5).

C4: Improve the design of SOS to SOS-Hybrid that allows for adaptive switching between different available communication networks through topology switching, based on decision criteria. This has two benefits. First, local self-organization can adapt to the local situation in a disaster area. Second, context-awareness can fill in the spatial gaps of coverage associated with top-down approaches. SOS-Hybrid allows phones to simultaneously provide the benefits of ad hoc mobile networking allowing hard-to-reach people to connect and the benefits of infrastructure-based communication allowing phones to more efficiently send messages over longer distances (see Chapter 6).

A separate agent-based model of a hybrid communication network using various infrastructures and SOS-hybrid is also presented to demonstrate effects of immobile citizens and out of coverage communication disparity.

This model is used to investigate a metric that quantifies continuity of communication capacity during disasters and inclusion for a citizen-centric smartphone communication network, incorporating the impact of disparity of infrastructure access and its effect in communication capacity in different population densities.

In conclusion, this research shows that it is possible to improve connectivity during the first 72 hours after disaster hits. With an ethically aligned, value-sensitive design process this thesis introduces a novel emergency communication system called “Self-Organisation for Survival” (“SOS”). SOS can provide affected communities extended and increased access to communication via a peer-to-peer communication network designed for fair participation. Extending the current body of work on citizen-centric ad hoc networks for crisis and disaster, this thesis provides a solution to one of the grand challenges of humanitarian aid [2].

1.2.7 Research scope and limitations

Security issues are not considered in this research. This thesis does not cater to the security limitations of wireless communication.

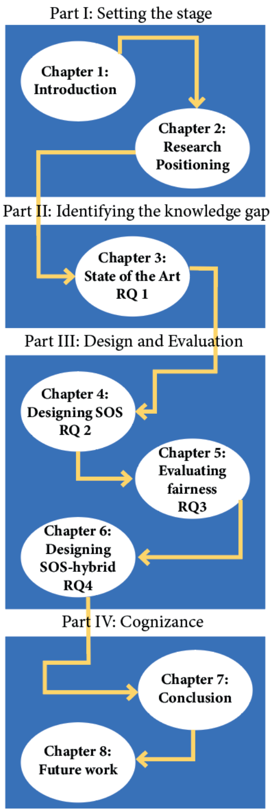


Figure 1: The navigation layout of the thesis

Therefore, values such as user privacy, identity management are out of the scope of this research. Additionally, as this thesis focuses on the application layer in which mobile phones form an overlay network, the physical layer of communication is not considered. Mechanisms are not catered towards VLSI chip design, or hardware/network interface configuration.

1.3 Chapter description & thesis layout

The structure of this thesis is given in figure 1 and described as follows: This thesis has 8 chapters and is subdivided into four parts.

- Part I: Setting the stage, with two chapters (1&2).
- Part II: Identifying the knowledge gap on the basis of chapter 3 on the State of the art.
- Part III: Design and analysis, with three chapters (4,5 & 6).
- Part IV: Cognizance, with two chapters (7 & 8)

1.3.1 Part I: Setting the stage

Part I contains chapter 1 and 2. Chapter 1: Introduction delves deeper into the first objective by stating the purpose of the current research, the challenge of citizen-centric communication, the approach towards the problem identified and the main research* question and sub-research questions are detailed.

** Main research question : How to design a value-based citizen-centric adaptive mobile communication system?*

Chapter 2 introduces basics of disaster management and communication needs of citizens, autonomic computing and self-organisation, mobile ad hoc networks and positions the research in this thesis. Additionally, to grasp the approach of this thesis and the multidisciplinary nature of the design, the application domain of the research, requirement specification tackling the questions and chosen methodology are addressed in chapter 2.

The chapter ends with set of functional and non-functional requirements for the design. This is followed by the part II of the thesis, that aims to investigate the current State of the Art in citizen-centric communication systems.

1.3.2 Part II: Identifying knowledge gap

The objective of this part of thesis is to identify the knowledge gap in current related work and is addressed in Chapter 3: State of the Art. Chapter 3 focuses on the first research question (RQ1) identified in the thesis. This includes a literature review of the State of the Art in emergency communication for sudden-onset disasters.

The chapter investigates (RQ1) the essential properties of a communication framework that facilitates and empowers local communities during sudden onset disasters focusing specifically on intended stakeholders, ease of use and implementation, deployment time, energy efficiency and context reactivity.

RQ1: What is the current State of the Art in citizen-centric mobile communication systems for sudden-onset disasters, and how are questions of intended stakeholders, ease of use and implementation, deployment time, energy efficiency and context-reactivity approached?

Chapter 3 presents an overview of the State of the Art in citizen-centric communication networks, identifies the knowledge gap and proposes an approach to address the knowledge gap. This chapter is based on "Revisiting citizen-centric disaster communication: A systematic review" Banerjee.I, Warnier, M., Brazier, F.M.T. (Under review). This is followed by the part III of the thesis.

1.3.3 Part III: Design and analysis

This part has three objectives, first using the approach discussed in Chapter 2 to design a communication network in Chapter 4. The second objective is to analyse if the designed communication network delivers the values of participatory fairness in the first 72 hours of a disaster for various densities in relation to traditional mesh networks, described in Chapter 5. Finally the design is enhanced to introduce inclusion and continuity as values related to participatory fairness to tackle "islands of inequity" to make the design resilient, as discussed in Chapter 6.

RQ2: Can self-organization as an approach be used to design a citizen-centric communication system? And how?

Chapter 4, SOS: Self-Organisation for Survival answers the second research question (RQ2). The chapter proposes the design of a decentralized context-adaptive topology control protocol.

The protocol consists of three algorithms and uses preferential attachment based on energy availability of devices to form a loop-free scale-free adaptive topology for an ad-hoc communication network without any changes in the hardware. The chapter also presents the evaluation of the protocol in a simulated environment to confirm the feasibility of creating and maintaining a self-adaptive ad-hoc communication network, consisting of multitudes of mobile devices for reliable communication in a dynamic context.

In addition this chapter presents a comparative analysis with other protocols proposed in the literature. The chapter performs evaluation using an agent-based model to verify if all the requirements specified are met. First, if it is adaptive to the environment, hence applicable in scenarios where the number of participating mobile devices and their availability of energy resources is always changing. Second, if it is energy-efficient through changes in the topology. This means it can be flexibly be combined with different routing protocols. This chapter uses research through design to design and evaluate the protocol.

This chapter is published as: "Self-organizing topology for energy-efficient ad-hoc communication networks of mobile devices.” Banerjee, Indushree, Martijn Warnier, and Frances MT Brazier in Complex Adaptive Systems Modeling 8.1 (2020): 1-21.

The second objective of part III is to determine fulfillment of values specified in the design of a citizen-centric communication network addressed in Chapter 5.

In Chapter 5 the focus is on values such as participatory resilience of disaster-struck communities. Chapter 5 addresses the third research question (RQ3). In Chapter 5 the novelty of the SOS protocol is demonstrated by agent-based simulations in comparing SOS with mesh communication networks.

RQ3 :Can a citizen-centric communication system fulfil the value of participatory fairness at the system level? And how?

A disaster area is simulated with blackouts preventing citizens from charging their phones, leading to disparity in battery charges and a digital divide in communication opportunities. The chapter then uses SOS to propose a value-based emergency communication system based on participatory fairness, ensuring equal communication opportunities for all, regardless of inequality in battery charge.

The chapter focuses on evaluation to demonstrate the pros and cons of a context-adaptive communication system in comparison to traditional Mesh. However, the main focus is on two vital factors: (i) impact of connection topology on node participation and (ii) energy efficiency on communication disparity in the 72 hours.

An evaluation using the Gini coefficient demonstrates that the network design of SOS results in fairer participation of all devices and a longer network lifetime, benefiting the community and its participants. This is repeated for various population densities representing cities prone to disasters. A phase diagram demonstrating the benefits of SOS and Mesh in regard to message frequency distribution and population distribution is presented. The chapter concludes with the benefits of value-sensitive design of a infrastructure-less emergency communication network that automatically and dynamically

• assigns high-battery phones as hubs,
• adapts the topology to changing battery charges, and
• self-organises to remain robust and reliable when links fail or phones leave the network.

This Chapter is based on publication "Introducing participatory fairness in emergency communication can support self-organization for survival." Banerjee, I., Warnier, M., Brazier, F.M.T., Helbing, D., in Scientific reports 11.1 (2021). 1-9. The last objective of Part III is to make the design of SOS a continuous resilient communication system, SOS-Hybrid is introduced in chapter 6.

RQ4: Can a citizen-centric communication system be adapted such that it seamlessly and automatically integrates with other available infrastructure in a disaster context? And how?

Chapter 6 addresses the challenge of establishing a resilient disaster communication system that transitions seamlessly from a phone-based ad hoc network to any portable infrastructure and back. This answers the last research question (RQ4).

For this purpose, this chapter presents a value-based design of an autonomous and self-organized protocol (SOS-Hybrid). This design ensures seamless integration between various communication networks taking local context into account to increase inclusion and continuity of connectivity.

SOS-Hybrid has two benefits. First, local self-organization can adapt to the local situation in a disaster area. Second, context-awareness can fill in the spatial gaps of coverage associated with top-down approaches ("islands of inequity"). An agent-based modelling approach was used to develop the simulation of the proposed communication network to evaluate the impact of introducing SOS-Hybrid in the aftermath of a disaster.

SOS-Hybrid allows phones to simultaneously provide the benefits of

- ad hoc mobile networking, allowing hard-to-reach people to connect, and
- infrastructure-based communication, allowing phones to more efficiently send messages over long distances.

Benefits include two-way communication between community and rescue operators, inclusion and continued connectivity for immobile citizens stuck in isolated out of coverage areas, and seamless transition without loss of messages. This chapter is based on publication "Designing inclusion and continuity for resilient communication during disasters." Banerjee, I., Warnier, M.& Brazier, F.M.T., in Sustainable and Resilient Infrastructures, (2022): 1-16.

1.3.4 Part IV: Cognizance

Chapter 7: Discussion and conclusion, focuses on summarising and looking back at the main research questions answered in the research. Finally the conclusion section provides a final overview of what is learned in this research in terms of results and approaches. Chapter 8: Future work, addresses the significance of the findings and recommendations for extending the current research.

Publications related to this thesis [and the corresponding chapters]

1. Banerjee, Indushree, Martijn Warnier,and Frances M T Brazier. "Revisiting citizen-centric disaster communication: A systematic review." (Under review) [Chapter 3]

2. Banerjee, Indushree, Martijn Warnier, and Frances M T Brazier. "Designing inclusion and continuity for resilient communication during disasters." Sustainable and Resilient Infrastructures, (2022): 1-16. [Chapter 6]

3. Banerjee, Indushree, Martijn Warnier, Frances M T Brazier, and Dirk Helbing. "Introducing participatory fairness in emergency communication can support self-organization for survival." Scientific Reports 11, no. 1 (2021): 1-9. [Chapter 5]

4. Banerjee, Indushree, Martijn Warnier, and Frances M T Brazier. "Self-organizing topology for energy-efficient ad-hoc communication networks of mobile devices." Complex Adaptive Systems Modeling 8, no. 1 (2020): 1-21. [Chapter 4]

5. Banerjee, Indushree, Martijn Warnier, and Frances M T Brazier. "Ad Hoc Communication Topology Switching during Disasters from Altruistic to Individualistic and Back." In COMPLEXIS, pp. 103-107. 2020. [Chapter 8]

Chapter 2

॥ सर्वं ज्ञानं मयि विद्यते ॥

ALL THAT I HAVE TO LEARN IS WITHIN ME.

RESEARCH POSITIONING

2.1 Introduction

This thesis presents self-organization as an approach to the design of a resilient value-centric mobile communication system for sudden-onset disasters. This chapter positions this research within the related fields and presents the key concepts, terminology, application domain, and approach to which the remainder of this thesis refers.

1. In detail presented in Chapter 3: State of the Art

The survey[1] on current citizen-centric mobile communication system reveals that vagueness in describing a disaster situation discounts many parameters for evaluation which would otherwise become important. It is noteworthy that requirements such as civilian inclusion and participation are, however, considered fundamental to community resilience [58, 59].

To facilitate civilian participation required for community resilience, developers and designers from engineering domains often focus more on advancing the operation of a communication device or a communication network [60]. Improvements in operation of a device refers to mechanisms designed to conserve battery power, or to include external battery sources [61]. Sophisticated mobile applications are becoming more popular without much emphasis being placed on usability of these applications [62].

This disconnect results in designs that discount the dynamic context of disasters despite being developed for citizen-centric communication during disasters [63].New requirements of citizen-centric properties requires the design of disaster communication systems to be seen through new lenses. A disaster communication system is a socio-technical system. This means that although the design of a communication system is technical in nature, its deployment is in a social setting. As a result this thesis claims that a multidisciplinary approach is required where:

• the application domain of the communication system is defined by the disaster context,
• requirements consist of both technical and societal values, and
• agent-based modeling and simulation are used to study behaviour in a controlled setting, to explore the potential of the design/solutions proposed.

This chapter describes the application domain of the proposed research, research approach and evaluation are detailed.

2.2 Application domain

The application domain of a designed artifact is defined by the context, i.e., the space and time of use, along with the users and their needs. Mobile ad hoc networks (MANETs) are deployed in dynamic hostile environments for communication without infrastructure. The requirements and the means to fulfil those requirements for MANET in disasters or crisis vary significantly than MANET deployed in other drastic environments. Such as MANETs used in wireless sensor networks for data collection in forests, grasslands, or for smart monitoring in urban cities.

The timeline of a disaster can be divided into “pre-disaster phase”, followed by “disaster response” and finally “post-disaster recovery” [64]. Communication challenges are the greatest in the ”disaster response phase” in the period right after a disaster has struck a community. This thesis focuses on the design of a citizen-centric MANET for the ”response phase” specifically for sudden-onset disasters.

A sudden or rapid onset disaster such as an earthquake or cyclone leaves many citizens injured under buildings and in need of rescue. However, traditional rescue is delayed as most roads are damaged and it takes time to move resources. The response phase can last from hours to days. During this phase the first 72 hours after a disaster has hit a community is defined as the ”golden period” [64]. The number of casualties could be reduced if interventions such as preliminary first aid and basic support are provided during this phase.

2.2.1 Communication needs during disasters

During large scale crisis, unavailability of resources and extreme dependence on governmental or traditional rescue support can cause devastating effects given the importance of being rescued during the “Golden period” [64].

For example the government struggled to reach and provide for people stuck on their roofs during Hurricane Katrina for the first 3 days. During this response period, citizens actively seek relevant information to facilitate rescue without being dependent on institutional support. Communities, in general, self-organize themselves into rescue teams and help people in need [5].

Contrary to popular belief, in general citizens react assertively, swiftly and automatically, as an intuitive reaction witnessed during the occurrence of a sudden and major natural catastrophe [19].

A key to empower these informal communities and networks is to provide them with a communication system that is self-organising and facilitates communication during the first 72 hours of disaster. However, the frequently changing spatio-temporal context with emerging needs, together with the values that need to be embraced, pose new types of requirements on the complex socio-technical system to be designed. The essential characteristics are described in the next subsection.

2.2.2 MANET as a socio-technical system

A socio-technical system constitutes use of technology by humans or in a society either to perform certain tasks or to make sense of situations when making decisions [65]. Communication services during disaster response can help citizens to form self-rescue groups and collectively make decisions. Factors that must be taken into consideration for designing citizen-centric communication networks during the immediate response phase are as follows:

- *First*, not all communities have high levels of digital literacy, which limits sophisticated system deployment and requires automatic communication systems.
- *Second*, people in a community may own phones with different battery and sensing capacity, which can lead to disparity in communication opportunity [66].
- *Third*, the number of mobile and immobile people that need communication services [37] will differ per area.
- *Fourth*, uncertainty on how long a communication network must work and how to charge the devices [67] will impact the network.
- *Finally fifth*, when and how to switch and connect to a traditional infrastructure as it becomes available in a different location needs to be considered [68].

The precise requirements are often emergent in nature and result from the use of technology in society by citizens in need [36, 59]. These requirements provide the grounds for conceptualisation of citizen-centric MANET systems as complex socio-technical systems.

2.2.3 MANET as a complex system

The human nervous system, Earth's changing climate, telecommunication infrastructures among others are examples of complex systems. Complex systems are characterized by non-linearity, feedback, self-organisation, emergence and decentralisation [69]. A decentralised self-organising disaster communication system that emerges without any order among various actors involved in disaster mitigation is considered a complex system [70, 71]. An ad hoc mobile disaster communication system is furthermore deployed in a dynamic context with multiple unknown factors such as the types of phones and their interfaces (for example Bluetooth or Wi-Fi interfaces), mobility of citizens owning these phones, resources to charge the phones, density of citizens in a given area. Interactions among citizens leads to new connections and relaying of messages leading to reliable delivery of messages despite lack of direct connections.

The emergence of an ad hoc network depends on these interactions, the longevity of the network depends on the resources available to keep these phones charged. Presence or absence of an infrastructure with Internet connectivity becoming available determines if an ad hoc network connects to the Internet or not. Transmission range of devices determine the number of visible possible connections. This number can grow exponentially. Together, these factors determine the performance and service of an ad-hoc network. For example, changes in the density of devices influences coverage and scalability, charging capacity determines reliability. All in all ad-hoc emergency communication networks are complex socio-technical systems.

2.3 Requirements

Prior to designing a system, requirements of the system need to be gathered through means such as extensive literature surveys, interviewing external stakeholders (citizens in this case) and from analysis of the environment. The environment in this thesis is a disaster context in dynamic settings. In this thesis the knowledge gap associated with current communication systems is presented in Chapter 3. The initial requirements related to this gap are summarised below. Current ad hoc communication systems (such as TeamPhone, RescueMe, HelpMe, ServalMesh, Firechat, LifeNet, SENSE-ME, StemNet [24, 27, 28, 38, 72–75]) meet the functional requirements of an infrastructure-less ad hoc communication system that allows people to connect.

These include:

*1. **Connectivity*** - All citizens should be able to connect using their phones to their neighboring phones to form an ad hoc network.

*2. **Reliability*** - All messages that are sent must be delivered to the intended receiver. In a disaster situation, every message can make the difference for a person's survival. It is useful to separate out the different parts of this requirement. First, no message should be lost indefinitely. Second, all messages that people want to send should be sent, regardless of their situation. Third, all messages that need to be received should be received, regardless of the sender's or the receiver's situation.

However, there are also certain non-functional requirements that need to be considered.

*1. **Scalability*** - The performance of a network must not be affected by density changes in the population.

*2. **Durability** -* All message exchange should be reliable for at least 72 hours (after the sudden onset of a disaster) for every individual.

*3. **Easy deployment and use** -* Technologies such as mobile applications that are being currently used need to be easy to use and implement without any requirement of technical know-how.

*4. **Context-awareness** -* The designed ad hoc communication network must be context-adaptive, i.e. it must be able to make adaptivity and energy trade-offs while maintaining scalability, durability and reliability according to the changing context or deployed environment.

Additionally, the citizen-centric focus of the design requires that certain values are considered that promotes inclusion and participation.

Every citizen, irrespective of diversity of phones, location of infrastructures and ability to move, must have fair participation opportunity, access to connectivity and reliable and continuous message delivery.

The values considered for design in this thesis are:

*1. **Participatory fairness*** - The system must enable and maintain the participation of practically all phones, i.e. it provides equal communication opportunities for all citizens regardless of the initial inequality in phone battery charges.

*2. **Inclusion and continuity*** - Impoverished, highly populated areas, so-called "islands of inequity"[76], need to be able to be reached by disaster response teams, i.e., continuous connectivity for all, despite 'islands of inequity'. The mobile application must ensure that regardless of where the government or rescue operators decide to put emergency communication equipment, as many people as possible should be able to access these resources using the application.

This thesis focuses on meeting the above value-based requirements along with the functional and non-functional requirements.

In this thesis, implementation of the protocols[2] leads to a value-based citizen-centric adaptive mobile communication system that provides durable and reliable message exchange and supports participatory fairness[3], inclusivity and continuity[4]. The design choices made are explained in the next section.

2. Presented in Chapter 4 and 6

3. Presented in Chapter 5

4. Presented in Chapter 6

2.3.1 Design choices

Design choices are a set of rules or specifications that are made to fulfill the requirements of a system. The choices made for this thesis most often involve trade-offs. These are explained below:

1. Spatial awareness and context adaptivity

The dynamic nature of a disaster area presents various challenges. For example, the number of people with phones and the battery charge in these phones change all the time. To address this, the choice was made to design a protocol based on local interaction given context information.

2. Autonomous Self-healing

Mobility of people and phones leaving the network can lead to dropped messages as routes can be lost. The choice was made to include autonomous event-driven reconfiguration to enable self-healing.

3. Minimising connections while maintaining functional and non-functional requirements

In all networks, energy is lost in connecting, sending, receiving and relaying messages through phones. Formation of an ad-hoc network using context-adaptive self-organisation is the design choice made to reduce these costs especially in densely populated areas. The trade-off between connection cost and relaying cost is discussed in detail in Chapter 4.

2.4 Approach

The main objective of this research is to design a value-based citizen-centric adaptive mobile communication system. The objective is divided into four parts. First, to investigate the missing values and requirements in citizen-centric communication system design through literature review. Second, to produce a new design that will fulfill the functional and non-functional requirements listed above. Third, to evaluate if the produced design fulfills the requirements, in particular the value-based non-functional requirements.

Finally fourth, to improve the design based on evaluation of system behaviour. This approach requires an amalgamation of two separate research methods: Research through Design (RtD) and Value-Sensitive Design (VSD). RtD is used for design and evaluation. VSD provides the base for definition and inclusion of ”values” in system design. In this section both approaches are detailed as following:

2.4.1 Research through Design

Research through Design (RtD); is a “research approach that employs methods and processes from design practice as a legitimate method of inquiry” [47].

The first advantage of RtD is the focus on developing design artifacts that combine theories from multiple disciplines to produce knowledge that can solve complex societal problems or ”wicked problems”. As described above the design of a value-based citizen-centric adaptive mobile communication system requires envisioning MANET as a complex socio-technical system.

RtD supports the use of knowledge from different domains and theories from multiple disciplines, and advocates an iterative design approach to find a workable solution distinct from traditional designs.

The second advantage of RtD is that it promotes iterative design cycles to understand the requirements and improve the design. For this RtD advocates the design of artifacts for evaluation, “where the knowledge gained can be implicit, residing almost entirely in within the resulting artefact” [77]. The communication system design prototype proposed in this thesis is modelled and simulated in this research to verify the delivery of functional and non-functional requirements such that with each verification improvements can be made. This iterative evaluation and design provides opportunities to explore possible system behaviour in various contexts.

The third advantage is that RtD promotes the use of prototypes for knowledge generation and transfer [48]. In this research the objective is to investigate fair participation and delivery of ”values” in the design of a communication system. The design artefact once prototyped as a model, the effects of multiple external parameters such as density, mobility and their combination on system behavior are explored during a design process. This allows other researchers, designers and policy makers to engage and observe how the system behaves during the design process.

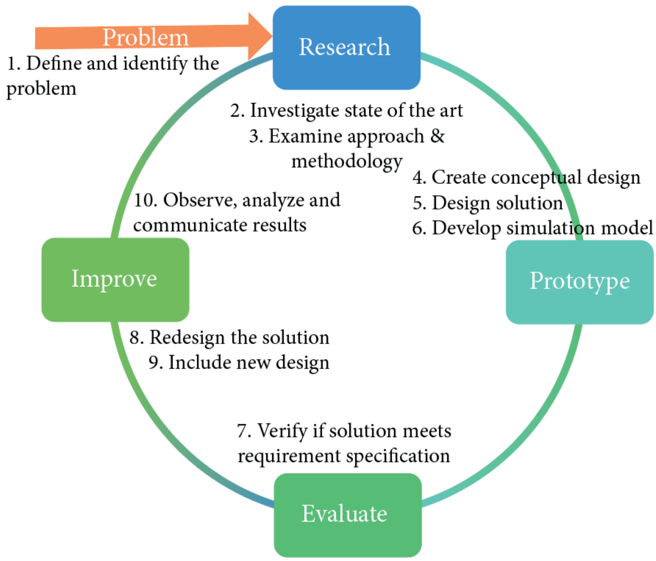


Figure 2 : Research through design cycle

Finally, RtD is capable of producing a set of guidelines and conceptual designs other than actual products enabling designers to rethink and approach the design process from a different perspective. As Zimmerman and Forlizzi [50] articulated:

> *"a type of research practice focused on improving the world by making new things that disrupt, complicate or transform the current state of the world. This research approach speculates on what the future could and should be based on an understanding of the stakeholders, a synthesis of behavioural theory, and the application of current and near current technology. The knowledge produced functions as a proposal, not a prediction."*

2.4.2 Value-sensitive design

Value-sensitive design advocates the design of systems that deliver values while in use [78, 79]. Values must be incorporated to increase the acceptance and utilization in the context of using these technologies, as human interaction with technology can change over time. For example, an ad hoc network can provide infrastructure-less connectivity for each individual allowing people to collaborate and facilitate autonomy.

However, suppose the design purpose is to provide collaboration and communication for a community during sudden-onset disasters. In that case, apart from communication failure, power blackout also needs to be considered. That consideration raises the question: Are these ad hoc networks energy-efficient? And how is energy efficiency defined?

As discussed earlier, emergency communication systems are often still derivative of tools designed from an engineering perspective with operational values. This perspective entails that a system's properties can be retroactively interpreted to match human values. However, to ensure that the design meets the value-based non-functional requirements, direct evaluation of these requirements in the context of use is required.

In value-sensitive design approach certain values have been formulated for system design [56]: autonomy [80], universal usability [81], human welfare [82] and freedom from technical bias [83].

The Required values of a citizen-centric MANET are described next.

Social Science research has continually promoted the significance of a citizen-centric mobile communication network with citizen-centric values such as autonomy, ease of use, democratic access [6, 19, 84–86].

Below follows a brief description of these values, their definition in context of disaster communication systems and their corresponding technical functional requirement are given:

a) Autonomy – This represents citizens' ability to make decisions and plans, and act as per their requirement and need independently. In disaster communication autonomy is damaged when infrastructure damage leads to out of service phones, preventing citizens from contacting conventional support systems such as hospitals and fire brigades in the early phase of disaster recovery. This situation highlights the need for a communication system that forms communication networks using available devices such as smartphones without the infrastructure in an ad-hoc manner. Autonomy in this thesis refers to allowing all citizens to connect, and communicate to plan and collaborate on the fly for collective action during disasters despite infrastructure failures.

b) Universal Usability – This value represents that all citizens are successful users of a designed system. In a disaster context therefore it is important that a designed system does not introduce technical complexity that prevents it from being equally accessible and usable by everyone. Therefore diversity of devices and types of digital literacy have to be considered. This disparity can result from socio-economic differences in a community hit by a disaster, thus the system should be easy to use with an automatic setup to reduce digital use inequality.

c) Freedom from bias – This value represents systematic unfairness experienced by citizens or a specific group, including pre-existing social bias, technical bias, and emergent social bias. In MANET deployed in a disaster scenario, there are many technical limitations that result from the mobility of smartphones, to a changing density of people that may lead to bias. During disasters, electricity failue, for example, can lead to a lack of phone charging options.

The disparity of charges in smartphones leads to the disparity of participation. A requirement that results from this consideration is that a communication system should consider the limitation of batteries in devices and must be energy-efficient to ensure connectivity for at least the first 72 hours.

The system must adapt to changes in population density, availability or unavailability of resources, and people leaving or joining the network. Context awareness is needed to be able to adapt to dynamic situations that are decentralized and self-organized to enable fair access to information.

d) Human Welfare – Response during disaster must support interaction between all stakeholders, government and citizens. The number and type of stakeholders (citizens, government, NGOs) can vary from hour to hour. A communication system must adapt to this situation in an automatic mode and be hybrid to allow multiple types of connectivity (supporting both top-down and bottom-up communication) to optimise communication.

Table 1 represents the values and their respective mapping onto norms and the initial design requirements. When designing a disaster communication system, these properties are critical to ensure a citizen-centric approach and inclusion of the human factor as a valuable resource.

2.5 Methodology

In this section the methodology used to address the requirements and evaluate the proposed design is presented in detail.

2.5.1 Autonomic computing

This thesis addresses the above requirements by the design of a self-organising emergency communication network using autonomic computing [51]. To develop self-organizing communication networks for phones owned by citizens that are spatially-aware and self-aware, autonomic computing [51] provides the means.

The goal of Autonomic Computing is to ensure that each of the smallest computing units self-configure and self-heal to maintain the desired behaviour of an overall system [51, 87]. Nodes monitor their own situation as they are spatially-aware of their system's state and self-aware of their own battery life and able to detect their own constraints [88]. Nodes can exchange information (such as node energy, number of connections, list of routes) in a distributed fashion and maintain a local view about the neighbours and their energy to plan and create a network topology.

In the present literature, phones are deployed as a mesh router, i.e. either actively participating in the process of packet forwarding towards a mesh gateway, or acting itself as a gateway toward the Internet [89].

Table 1 : Values, norms and example design requirements in the context of disaster communication systems and their corresponding technical functional requirements

Values	Norms	Example design requirements
Autonomy[80]	1. Independence from traditional infrastructure	Formed ad hoc
	2. Ability to coordinate with other survivors	Phones send messages without infrastructure to other citizen-owned phones within a disaster area of 1 square kilometer.
	3. Independence from organisations	No waiting for rescue operations, Not impacted by governmental decision-making
Universal Usability[81]	1. Usability regardless of digital literacy	Application runs automatically in the background after a disaster without user intervention
	2. Usability irrespective of the diversity of devices	Application runs on all mobile phones with Bluetooth or Wi-Fi interfaces
Freedom from bias[83]	1. Freedom from technical bias	Should provide reliable services despite mobility of people
	2. Freedom from emergent bias / equal opportunity for all phones to communicate	Functionality same between phones with high battery charge and low battery charge
Human Welfare[82]	1. Should promote survival	Functions within the 72 hours that are most important for survival
	2. Should promote receiving help	Allows exchange of needs and requirements
	3. Should promote giving help	Allows receiving of emergency information

Moreover recently mutating nodes that change their roles as per system configuration and environment has been proposed [88–90]. For example, in lack of infrastructures when cellular connectivity is not present, opportunistic networks that store and forward information are used to disseminate information. These ad-hoc networks are fundamentally human-centered and based on the density, mobility and proximity of nodes (or people carrying smartphones). Taking these recent advancements further, the research in this thesis explores and studies the potential of self-organization in developing a context-aware adaptive energy-efficient communication network to achieve the research objectives.

2.5.2 Agent-Based modeling and simulation

In this thesis, Agent-Based Modeling and Simulation (ABMS) is the deployed methodology for the exploration of the designed system and its behaviour. Agent-based modelling is often used to study complex socio-technical systems because of its ability to simulate heterogeneity observed in a social context, local interactions, and autonomous agents [91, 92]. This property makes ABMS a powerful tool to represent real-world problems, where there are multiple actors and dynamic context, such as climate change [93, 94].

There are many advantages of ABMS.
First, ABMS facilitates modelling systems comprised of interacting autonomous agents [95]. [96].

Second, in ABMS, it is possible to model individual behaviours and how behaviours affect others [97], which makes ABMS suitable for studying human groups or networks of people [98].

Third, ABMS provides effective visualization, which improves the comprehensive analysis of the researched system design and corresponding results [99].

Fourth, ABMS provides easy scripts to produce data for data analysis and can be combined with other programming languages such as Python and R for advanced data analysis.

Given these benefits, this research uses ABMS to explore and analyse system behaviour. In this thesis agents represent nodes that represent mobile devices that move freely over the grid and interact. NetLogo is the chosen platform for ABMS.

NetLogo executes the algorithms for each agent individually, and once all agents have completed their computations, the simulation time, denoted as a "tick", is incremented by one, and every node again executes the algorithms outlined in Chapter 4.

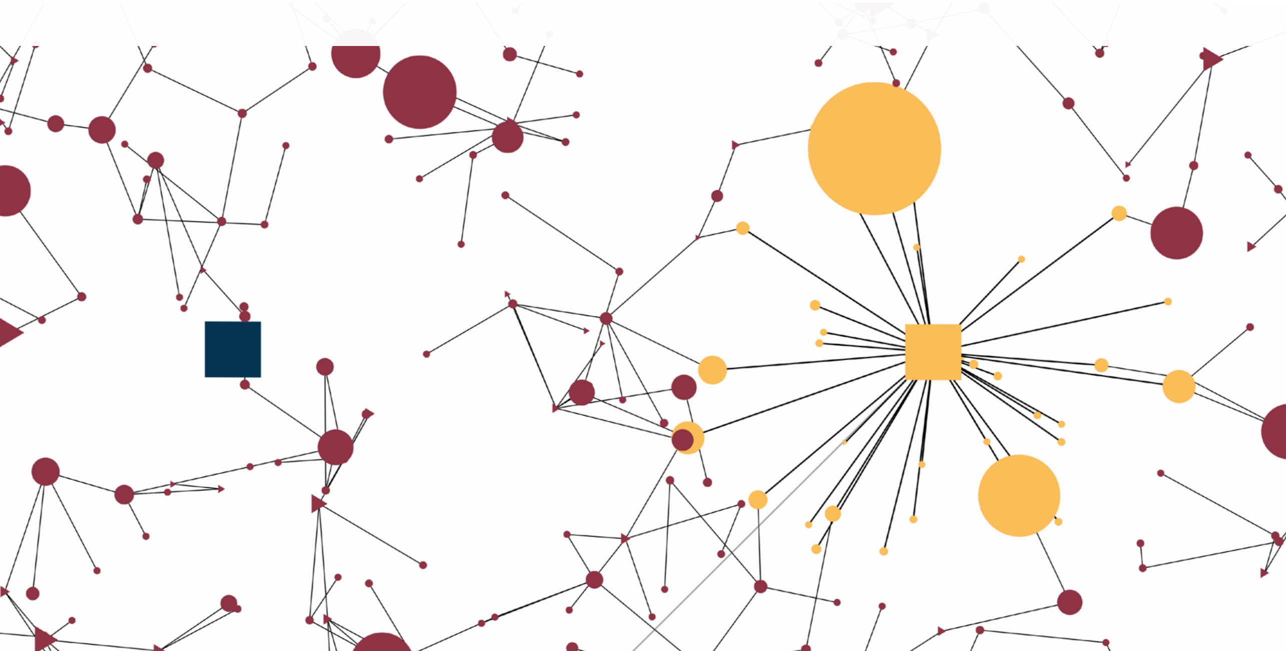
A comparison of the SOS protocol that defines the algorithms with existing work based on mesh topologies is performed in Chapter 5 and for this, a separate ABMS of mesh network is implemented. Chapter 6 presents the design of SOS-hybrid and two ABMS for evaluation: One with SOS-Hybrid and another with only infrastructure with mobile and immobile agents. In Chapter 6, the transmission range, coverage area, mobility and connection time of infrastructure are varied for comparison.

Part 2

Identifying the knowledge gap

Contents

Chapter 3 State of the Art



Chapter 3

॥ असतो मा सद्गमय ।
तमसो मा ज्योतिर्गमय ॥

FROM IGNORANCE, LEAD ME TO TRUTH,
FROM DARKNESS, LEAD ME TO LIGHT

This chapter is based on
Banerjee, Indushree, Martijn Warnier, and Frances M T Brazier. "*Revisiting citizen-centric disaster communication: A systematic review*." (Under review).

STATE OF THE ART

3.1 Introduction

In the past decade, many disrupting events such as earthquakes and cyclones have accentuated the vulnerability of infrastructure-based communication networks and drew attention towards the need to design infrastructure-less communication networks that provide connectivity to citizens in need[17, 100].

For example, in November 2012, as Hurricane Sandy made landfall in the United States, wireless communications coverage in the western half of the Rockaway Peninsula in New York became almost non-existent[101]. Communication providers such as AT&T and Verizon struggled for weeks, as more than 300 offices were flooded and around 25% of their wireless towers were either uprooted or severely damaged. As one-fourth of the infrastructure became unavailable, the sudden surge in traffic pressured the existing communication infrastructure and eventually made it crash.

Communication services during disasters are obviously a crucial resource for all actors involved in disaster mitigation. Disaster communication can start before a disaster hits a community and can last until normal communication channels are functional again [102]. Moreover, communication requirements in a disaster area are unpredictable, given that the type and extent of damage caused by a disaster is unknown and can vary. Uncertainties, for example, can involve (i) the time it takes for rescue operators to reach and establish an alternative means of communication, (ii) the extent of damage to traditional infrastructures, (iii) the number of victims and active rescuers that need to communicate, e.g., as defined by the population density of a disaster area. Communication services pre- and post-disaster fall under the Emergency Communication System (ECS) umbrella term in literature.

ECSs are computer-based systems, i.e., devices that enable information to be sent and received in numerous forms such as voice, text, maps, images, video, and live feed. Devices include radios, smartphones, but also private and public devices that broadcast information or distribute information in one-to-one or one-to-many communication. An ECS does not replace a regular communication infrastructure, but provides an expedited alternative communication channel to all actors involved in a disaster mitigation process [103].

In the early times of ECS designs [104], prompt notification and accurate public broadcasts were the most sought features, as information flow was top-down: from governmental and military organisations towards citizens [105]. Various technologies came into use, such as radios, walkie-talkie systems, satellite phones, and external devices with long-distance radio capacities [106]. Although disaster experts repeatedly showcased in field experiments [107] that citizen participation is a valuable resource for disaster mitigation, systems that facilitate citizen participation are mainly in the phase of conceptual designs [19]. With the advent of cheap mobile devices during the past 20 years, a new field of citizen-centric disaster communication has emerged [89].

These citizen-centric or smartphone-based communication systems are derivatives of ECSs with requirements such as reliable, accurate and timely delivery of information in a more horizontal flow, i.e. among citizens located in disaster areas [108]. However, mobile phones have their limitations.

Recent research has focused on operational limitations of devices in use and the communication services they can provide [109]. Direct two-way communication between affected persons and humanitarian agencies remains a fundamental challenge despite these advances. Such connectivity is essential to democratise access to information that has been recognized as one of the top ten grand challenges of humanitarian aid [2].

This review examines the current literature to investigate the State of the Art of technologies designed to facilitate communication between citizens during disasters. The goal of the review is to understand the essential properties of these communication systems and the requirements these disaster communication systems aim to fulfill.

3.2 Organisation of the paper

This paper is divided into four parts. Part I deals with background knowledge. This includes the definition of mobile ad hoc networks (MANET) and their use in a disaster context, followed by the origins of MANET, design factors that are currently considered essential for the deployment and the scope of the literature review. Part II discusses the process of conducting the literature review, detailing the methodology deployed and the resulting framework.

Part III reviews the current State of the Art in detail, using the framework presented in Part II. Part IV discusses the key learning points from the review and gives a detailed set of guidelines for designing future citizen-centric MANET to be used in a disaster context. The paper ends with a Conclusion.

3.3 Mobile ad-hoc networks (MANETs): Definitions and use in disaster context

Disasters often damage backbone infrastructures such as telecommunication and electricity grids that negatively influences availability of communication facilities [110]. Under such conditions, mobile ad hoc networks MANETs provide an alternative [111]. In a MANET, phones use their inbuilt network interfaces (such as Wi-Fi or Bluetooth) to connect to other phones [24, 89, 112–114]. When people carrying mobile phones are in each other's range, their devices can connect directly and communicate. Their devices can collect and relay messages to others. Intermediate phones are termed relays or hops. Infrastructure-less mobile ad hoc networks grow spontaneously without depending on existing infrastructure such as base stations or communication towers [115]. This on-the-fly utility of MANET makes it a perfect solution in situations with no infrastructures, such as during emergencies or disasters [116, 117].

Other factors that make MANET easy to deploy and popular are [118] (i)the increased penetration of mobile phones and their use around the globe, and (ii) their widespread reach in remote locations, that makes them a readily available solution for communication. MANETs are suited not only for situations such as disasters but also for many developing countries that always lack infrastructure and have region-specific pockets of zero network connectivity [119, 120].

These reasons make MANETs a practical choice for citizen communication during disasters. Collectively, MANET studies outline a critical role for providing some form of disaster mitigation for citizens. However, their deployment is entirely or partially dependent on government or professional aid workers. Additionally, such studies focus mainly on enhancing the technical and operational design of ad hoc networks in use. Historically, this has been the main evaluation criteria as ad hoc networks were mainly designed for governmental and military use.

3.3.1 The emergence of the Ad Hoc Network paradigm

The Defence Advanced Research Projects Agency (DARPA), first designed Ad Hoc Networking in 1972 within the packet radio networking project PRNET focussing on military application [105, 121]. Their objective was to connect every piece of equipment, such as tanks, walkie-talkies, aircraft, etc., to form an infrastructure-less network. The purpose of the network was to share information with soldiers and war operators in a remote and hostile setting through radio channels strictly for use during battlefield operations. The main contributions of this first generation of ad hoc networking were (i) creating digital byte streams from each terminal/source by partitioning them into packets (blocks) and sensing when to transmit them in a burst mode over a shared radio channel [122]; (ii) producing algorithms that prevented collision of data in these radio channels through collision avoidance algorithms (CSMA) [123], and (iii) the designing a basic distributed network layout or topology [124].

In the early 1980s, as radio devices became more affordable, compact and power thrift, ad hoc networks started to be commercialised outside of the military. Easy access to these devices led to the second generation of ad hoc networks. PRNET evolved into SURvivable and Adaptive radio Networks (SURAN) and mechanisms that allowed messages to be sent most efficiently, i.e., routing, came into use [125]. Networks became more self-organising, self-healing and scalable. To make these networks more scalable, the interface that transmits the signals utilised varying transmission ranges [126].

In the 1990s, as notebooks became more prevalent, the Internet Task Force developed software to use RFIDs that were built in these devices.. The term ”ad hoc networks” was coined in two seminal papers by IEEE 802.11 working group [127, 128]. Consecutively, DARPA initiated the Global Mobile Information Systems (Globo) and then the Near-Term Digital Radio (NTDR) to provide Ethernet-type multimedia connectivity anytime, anywhere, in hand-held devices [129, 130].

Globo and NTDR enabled the non-military commercial use of ad hoc networks, starting the third ad hoc generation of network design. Radio Frequency and Bluetooth interfaces in phones became more prevalent in commercial use, and routing protocols targeted design of ”on-the-fly” networks [128].

Public utilization became a fact. Since then, the design of Ad Hoc Networks has mainly focussed on technical and operational excellence. As detailed in the fundamental network design decisions by ARPA, which remain leading goals in the processing of data the main key performance indicators (KPIs) are:

1. low delay, i.e., delivery of every message within the minimum amount of waiting time,

2. high throughput, i.e., the total flow of data should be as large as possible,

3. reliability, i.e., all messages sent via the network should be delivered,

4. robustness, i.e., even when nodes fail, and the network must function,

5. cost-effectiveness, i.e., the cost of individual message services should be reasonable as measured in terms of utilisation of the network resources [131].

These operational KPIs have remained the same for all other paradigms that have evolved in the last 20 years of MANETs. Their use and context grew, from military to disaster to environmental monitoring, now ad hoc networks can be found ubiquitously. With the advent of cheap RFID technology and the growth of Web applications, Wireless Sensor Networks (WSN) have led to a vast body of work on information collection and dissemination.

3.3.2 Design factors of citizen-centric MANET for use in disaster contexts

Many new paradigms of ad hoc networks have shaped disaster communication, such as unmanned aerial vehicle (UAV), vehicular ad-hoc network (VANET), delay tolerant network (DTN), wireless sensor network (WSN) and wireless mesh networks. UAV such as drones or balloons provide connectivity over an area[132], where phones on-ground connect to these floating devices. VANET consist of vehicles that carry an access point to provide connectivity. WSN utilise sensors to collect information about impending floods or cyclones and provide alert information to citizens. Finally, wireless mesh networks allow all devices to connect and form ad hoc networks to send and receive information.

Figure 3: Focus areas for the review articles and attributes

This paper presents a review that only considers MANETs strictly designed for citizen communication during disasters. Attributes found in the literature are used to structure this review, namely [68, 111, 133, 134]:

• Designed artefact [111]: What is the purpose of the artefact designed–a mobile application, equipment or a framework etc?

• Stakeholders [36]: Who will use the designed artefact?

• Ease of use [66,133]:How easily can it be implemented? Automatically or manually?

• Time of deployment [133,135]: When will the designed artefact be used, before, immediately after the disaster, or at any point in time?

• Population density of deployment area [37,136]: How many users will use this system in relation to the area? Will it be used in a densely populated area or a sparsely populated area?

• Resource requirements [137,138]: What other resources such as battery or electricity are required for deployment?

• Communication topology: Is the proposed solution ad hoc (formed using citizens' phones), centralised (require extra equipment owned by government/organisations) or hybrid (both citizens' and government equipment work together)?

• Network adaptivity [68]: Is the communication network static (predefined) or adaptable to the highly dynamic disaster context (context-adaptive)?

The following section describes these attributes and their importance, along with the scope of the presented literature review.

3.3.3 Scope and attributes of the presented literature review

Compared to other surveys and reviews, the review presented in this paper focuses on the feasibility and usability of citizen- centric communication systems specifically for disasters. Fig.3 represents the attributes described above and used to structure this review. To provide a context for this review, Table 2 presents a summary comparison of all other surveys and reviews with their identified knowledge gap and future directions.

Most surveys and reviews [23, 24] focus on different paradigms for disaster communication such as MANETs, VANETs, DTN, except for Rawat et al., [139] who focus on new 5G technologies, and Maryam et al., [140], who focus on smart-phone applications. Each survey has noted a lack of energy in devices and a lack of automation as significant knowledge gaps in disaster communication. However, none of the surveys has looked into value quantification. They are only focused on citizen-centric attributes for disaster management.

This review will focus on the functional requirements while reviewing the literature. These functional requirements will be further categorised to understand the feasibility and design considerations of citizen-centric disaster communication systems. The relevant attributes are deployment time, ease of use, intended stakeholders, population density of deployment area, resource requirements, as well as context reactive and communication topology. The significance of each of these attributes is described below, and a schematic layout of these attributes is given in Fig.3.

3.3.3.1 Design Artifact, Stakeholders and ease of use

The first attribute considered is the deliverable presented, i.e., the design artefact. A design artefact can be a mobile application, a broadcast mechanism, a protocol (routing or topology), a framework, or a conceptual design. Stakeholders are the users of a design artefact. The users can be citizens or professionals, or sometimes both.. A citizen-centric design needs to address the needs of the citizen, a professional-centric design the specific needs of the professional. Ease of Use is an essential criterion for deployment. This attribute is subdivided into: Easy, representing automatic configuration requiring no skills, and Hard, requiring professional skills, not applicable if not discussed.

3.3.3.2 Time of Deployment

The design of a communication system for use in disasters must consider the first 24-72 hours (the Golden Period)[6, 141] after disaster hits. Citizens working as first responders need to be immediately provided with information such as the location of trapped citizens to be able to rescue them. Deployment time is recorded as Immediate in this review, if communication is provided during the Golden Period. If the time frame of deployment is not specified, it is recorded as Prolonged.

Year Survey	Identified knowledge gap	No. of articles
2011 Legendre et al.	· Interoperability between equipment. · Power supply of devices · Scaling issue · Intermittent coverage · Setup time limitation in hybrid systems. · Message transmission security and integrity.	5
2015 Rawat et al.	· Military SDR equipment expensive · SDR needs significant energy, computing resources · Computing limitation for handheld terminals. · Poor battery life of mobile phones affects QoS. · Reliability, scalability of the entire network. · Infrastructure damage limits Internet access.	45
2015 Reina et al.	· Lack of comparison of broadcasting schemes · Lack of energy efficiency, fairness · Scalability issues of using proactive routing. · Lack of automation and dependent on manual setup. · Lack of interoperability in interfaces used. · WSNs and MANETs i.e. Wi-Fi and Bluetooth.	30
2016 Maryam et al.	· Limited battery life of phones limiting their use · Multiple sensors lead to battery loss in phones. · Lack of automation limits usability · Phone charging is difficult due to power failures · Lack of citizen inclusion in governmental rescue.	15
2016 Salamanca et al.	· MANETs better in low mobility and high node density. · DTNs better in sparse networks with high node mobility. · Integrated schemes need to be adaptable to population density.	30
2017 Anjum et al.	· Limited battery capacity of devices needs energy efficiency. · Unstable and dynamic topology. · Security of wireless links. · Channel congestion in UAV communication networks. · Scalability	26
2019 Yasmin et al.	· Energy constraint of devices · Increased message frequency increases battery use · Topology and mobility are an important consideration	60

Table 2: Comparison of different surveys, identified knowledge gaps and future directions

Focus	Proposed future work
· Communication using MANET · DTN · Cellular networking	· Application named Twimight · Inclusion of social media platforms · Ease adoption and ease of use · Security of platforms · Integration of communication .
· 5G · Device-to-Device · 4G/LTE · Software-Defined Radio (SDR) · Cognitive radio · Mobile-based systems	· Methods for detailed analysis of gathered data · Mobile phones to measure vulnerability and resilience of community and individual · Energy efficiency mechanisms
Multihop Ad Hoc Networks for Disaster Response Scenarios Ad hoc paradigms: · MANET · VANET · DTN · WSN · Hybrid systems	· Interoperability between ad hoc paradigms · More real experimentation
Smartphones Systems for disasters · Android-based applications · Smartphone application (GPS) · Ad-hoc-Network (iPhone) WSN (Wireless Sensor Network)	· Management of energy use, especially in smartphones apps · No running tasks for phones with 20% battery · Inclusion of citizen-based mobile apps
· MANET DTN-based schemes, that employs the IEEE 802.11 standard · Integrated operation of MANET and DTN.	· Bluetooth instead of IEEE 802.11 interfaces. · Networks that adapt to population density · Realistic simulation model
· MANET based routing protocol for Search and Rescue Operations subdivided into system-based and mobile-based applications.	· Mobile Cloud Ad Hoc Technology for SAR · Explore impact of routing protocols · Evaluate reliability and feasibility metrics.
· Routing Protocols and Architecture of MANET	· Explore Artificial Intelligence · Adaptive solutions · Automation to replace manual · Maximize energy conservation

3.3.3.3 Population density of deployment area

The population density of an area is the number of people with mobile devices in a disaster area. This number denotes the number of phones that can form an ad hoc network for communication. When mobile nodes are in a transmission range, they can form direct links to exchange information. Messages are relayed by intermediary nodes if necessary. Visibility of a node to form direct connections depends upon its transmission range.

If the radius of transmission is high more nodes can connect directly, decreasing the number of intermediates and increasing reliability and robustness. On the contrary, only a few nodes can connect directly if the transmission range is small. More nodes need to participate and form a relay of multi-hop networks to circumvent this. If the number of nodes participating in its formation increases, the coverage area of the network increases. Thus scalability of the network depends on the number of mobile-nodes participation in relaying messages as hops.

Increasing the scalability by multi-hopping creates a trade-off between reliability and energy efficiency. Therefore, the number of nodes in an area or population density is essential when deploying a specific MANET.

3.3.3.4 Resource requirements

To enable mobile phones to participate and make MANET reliable, robust and scalable, each node must use its battery efficiently. Since multi-hopping is necessary and topology changes are frequent, mechanisms are needed to enable adaptive energy efficiency and/or energy resilience. The resource requirements considered in this review are energy efficiency mechanisms. They are subdivided into ”Self-sustained”, "External battery", or "Not considered". Self-sustained refers to a design that presents a solution for battery conservation. External battery refers to a design that introduces extra equipment or a power source. "Not considered" means that energy efficiency is either not considered at all or put into future work.

3.3.3.5 Communication topology and architecture

A communication network can either be entirely Ad hoc or Hybrid. An Ad hoc topology or architecture refers to a network without any traditional infrastructure.

An Ad hoc topology uses mobile devices in a disaster area, often termed ”left-over technology”. Hybrid technology requires civilian devices and external devices or equipment to be brought to the disaster site by government or professional rescue operators. An Ad hoc system is quicker to deploy and (nearly) instantaneous during disasters, hence more citizen-centric. A Hybrid topology or architecture is more suitable for prolonged use and offers more reliable connectivity for larger areas. Therefore, the review categorises artefacts based on architecture/topology.

3.3.3.6 Network adaptivity

Mobile ad hoc networks deployed in a disaster setting need to be adaptable to the dynamic circumstances of a disaster site. These circumstances include changing population density, resource availability, mobility of people, presence or absence of alternative connection and communication technology brought by rescue operators. The literature is examined for related work that considers these types of change and incorporates context in their design.

3.4 Methodology

This section describes the systematic review process used for the literature search. All papers are gathered using keywords in several databases. Several exclusion criteria are used to filter out irrelevant contributions in the next stage. The process, in brief, is explained as follows:

3.4.1 Literature search

This paper focuses on reviewing the last 20 years of wireless communication focused on citizen-centric peer-to-peer communication using smartphones. Three databases, IEEE, ACM and Web of Science, are selected for searching papers between the years 2000 and 2020. Each database required adjusting the search terms. The search terms are given below:

In the IEEE database, the following search syntax resulted in 306 papers:

> (("All Metadata":ad*hoc OR "All Metadata":*hop OR "All Metadata":P2P OR "All Metadata":peer-to-peer OR "All Metadata":self-organi* OR "All Metadata":mesh OR "All Metadata":MANET) AND "All Metadata":*phone* AND ("All Metadata":disaster* OR "All Metadata":crisis OR "All Metadata":emergency*))

For the ACM database, the following syntax resulted in 134 papers:

> Abstract:(hoc hop P2P peer-to-peer self-organization self-organisation mesh MANET) AND Abstract:(phone smartphone phones smartphones) AND Abstract:(disaster crisis emergency).

Finally to avoid missing journal papers that are neither IEEE nor ACM, Web of Science was used with the following search terms. This resulted in 90 papers.

> TS=(hoc OR hop OR P2P OR peer-to-peer OR self-organization OR self-organisation OR mesh OR MANET) AND TS=(phone OR smartphone OR phones OR smartphones) AND TS=(disaster OR crisis OR emergency)

The three search queries resulted in 531 papers in total. 36 duplicate entries were found and removed, resulting in 495 relevant papers for initial screening. Initially the abstracts of all 495 papers were read. In the next step several inclusion and exclusion criteria were used to filter papers out. At the end 75 papers were selected for thorough review. The attributes recorded in the research and the following synthesis table is given in table 3. The flow diagram of the entire process is given in figure 4.

3.4.2 Exclusion criteria

The following fields and topics were excluded from the re- view. Additionally, 11 literature reviews and 2 were used for confirming if any paper was missing. The following criteria were used to remove 404 papers:

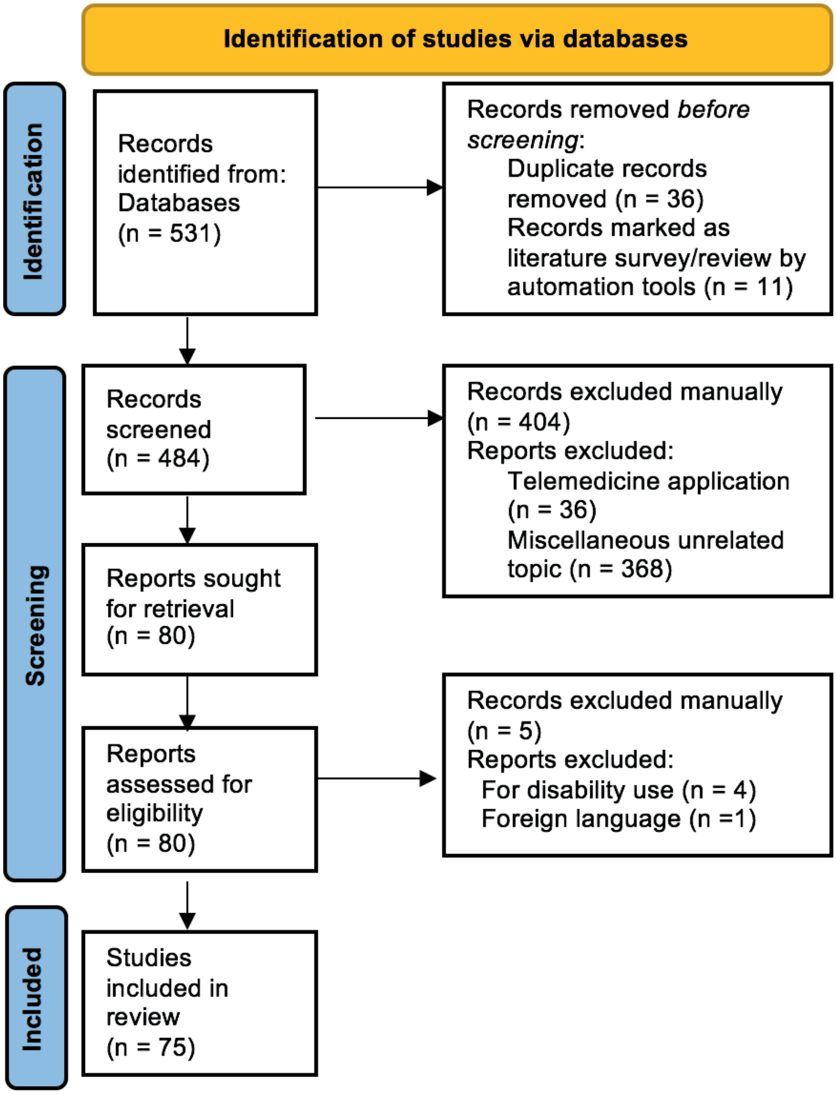


Figure 4: Flow diagram for identification and screening of literature for the review.

Table 3: Recording of the surveyed articles and classification into attributes

		design artifact	
		Mobile application	Broadcast mechanisms
Time of use and deployment after a disaster	Immediate	[152–155, 158, 161, 165, 26, 138, 156, 157, 163, 169]	[37, 17
	Prolonged	[27, 159, 160, 162, 164, 166, 167]	
Stakeholders	Citizen	[138, 152–154, 169]	[37]
	Professional	[157]	
	Both	[27, 155, 158, 161, 162, 165, 166, 26, 156, 159, 160, 163, 164, 167]	[171]
	NA		
Ease of usage and deployment	Hard (professional skill needed)	[27, 155, 165]	[171]
	Easy (automatic)	[152–154, 161, 163, 166, 167, 138, 157, 160, 162, 164, 169]	[37]
	NA	[26, 156, 158, 159]	
Population density of deployment area	Dense		[171]
	Sparse	[156, 158–160]	
	Both	[26, 155, 161]	[37]
	Not considered	[153, 154, 162, 163, 165–167] [27, 138, 152, 157, 164, 169]	
Resource requirement	External battery		
	Self-sustained	[26, 27, 154–156, 158, 163, 138, 164]	[37]
	Not considered	[152, 153, 157, 161, 165–167, 159, 160, 162, 169]	[171]
Communication Network topology / architecture	Centralized		
	Ad-hoc	[153, 154, 156, 157, 161, 163, 167, 169]	[37, 171
	Hybrid	[27, 152, 155, 158, 162, 165, 166, 26, 138, 159, 160, 164]	
Communication Network context reactive	Adaptive	[27, 153–155, 158, 162, 165, 26, 138, 159, 160]	[37, 171]
	Static	[152, 161, 166]	
	NA	[156, 157, 163, 164, 167]	

Routing	Topology	Framework	Conceptual design
[136, 172, 173]	[149, 211]	[38, 192, 208, 209, 189, 210]	[68, 191, 194–198, 67, 75, 193, 199, 200]
[137, 174–176] [177–179]	[185]	[190]	[22, 188, 201–204, 205–207]
[172–174]	[185]	[38, 189]	[67, 191]
[175, 177]			[22, 68, 188, 194, 197]
[136, 137, 176, 178, 179]	[149, 211]	[190, 192, 208, 209]	[195, 196, 199–203, 75, 193, 198, 204–207]
		[210]	
[136, 174, 175, 177, 178]	[149]	[189, 208, 209]	[22, 68, 188, 194–196, 201, 75, 193, 197, 204, 206]
[179]	[185, 211]	[38, 190, 192]	[67, 191, 198, 202, 203]
[137, 172, 173, 176]		[210]	[199, 200, 205, 207]
[175, 176, 178]		[208, 209]	[193]
[172]			[22, 204]
[136, 137]	[149, 211]	[210]	[75, 195, 200]
[173, 174, 177, 179]	[185]	[38, 189, 190, 192]	[68, 194, 196, 198, 199, 201, 202, 67, 188, 191, 197, 207]
			[67, 194, 205]
[136, 172, 173, 178, 179]	[149, 211]	[38, 209, 210]	[75, 193, 200]
[137, 174–177]	[185]	[189, 190, 192, 208]	[22, 68, 195, 196, 198, 199, 201, 202, 188, 191, 197, 203, 204, 206, 207]
	[185, 211]	[208, 210]	[196, 201, 202]
[137, 172, 174, 175, 176]			[68, 188, 195, 198, 200]
[136, 173, 177–179]	[149]	[38, 189, 192, 209, 190]	[22, 191, 194, 197, 199, 203, 204, 67, 75, 193, 205, 206]
[136, 137, 174, 175, 176, 178]	[211]	[38, 190, 208, 210]	[191, 194, 195, 197, 199, 203, 204, 75, 193, 200]
[172]		[189, 192, 209]	[22, 68, 196, 201, 205, 206]
[173, 179]	[149, 185]		[67, 198, 207]

• *Ad hoc networks for e-health and tele-medicine applications:* A vast body of research is available that caters to medical professionals to gather data on patients using ad hoc networks or from smartphones during disasters. These applications range from (i) enhancement of hospital response when infrastructures are unavailable [142] (ii) health monitoring of high-risk patients using their mobile phones in an ad hoc setting [143] and (iii) real-time and end-to-end patient monitoring networks and systems [144]

• *Security*: All papers contributing to tele-medicine applications were excluded from this review as their target audience are hospital managers, nurses, doctors, and rescue operators designated for medical support during disasters. Additionally, several other surveys that focus explicitly on tele-medicine and patient monitoring using wireless services on phones were excluded, see e.g. . [145–147].

• *Security mechanisms*: A large number of papers were targeted towards designing mechanisms to secure message transmission over wireless media. Papers that proposed design of mobile ad hoc networks with clear motivation towards security mechanisms were excluded from this review.

• *Wireless access for disabled people*: A substantial number of papers have used smartphones to design applications for wireless access for disabled people. These papers have been excluded.

3.4.3 Data recording

The review recorded attributes of 77 articles. It was found that the 77 articles, contained all articles cited by each article. The attributes recorded in the research and the following synthesis table is given in table 3. The flow diagram of the entire process is given in fig.4.

3.5 Design artifact

This section presents part III of the paper where each attribute is discussed in detail, starting with the design artifacts.

There is a growing body of literature that recognises the importance of communication during disasters [35, 100, 148]. Therefore researchers from Social Science [149], Computer Science [122], Disaster Science [66, 150] and System Engineering [24] contribute to designs deemed important for communication between citizens.

An ECS can be a mobile application that runs on the devices of citizens [151], or it can be a hybrid system where mobile phones access certain services from a centralised server and connect to external access points [111]. In this literature review the design artifact is subdivided into a :

1. *mobile application* - if the literature provides an Android or iPhone implementation,

2. *broadcast mechanism* - if the system or design is for spreading alert information,

3. *protocol* - if the literature presents an algorithm that facilitates either topology formation or routing of messages,

4. *framework* - that proposes procedures and mechanisms to make several systems work together to provide emergency communication

5. *conceptual design* - if the literature solely proposes the design of a prospective system

This classification is important because design considerations change as per the final artifact. For example, a mobile application needs to consider energy restrictions, while a framework can assume external energy sources. Below the State of the Art of design artifacts is presented:

3.5.1 Mobile applications

An objective of the review is to identify design artefacts purposefully built for citizens. As discussed in sections 2 and 2.1, factors that make MANET easy to deploy and popular are [118] (i) the increased penetration of mobile phones and their use around the globe, and (ii) their widespread reach in remote locations, which makes them a readily available solution for communication.

Further, these mechanisms can be beneficial in many developing countries that lack infrastructure and have region specific pockets of zero network connectivity [119, 120]. These factors make mobile applications easy to deploy and accessibly design artefacts, and the review found 19 mobile applications. The majority of proposed work in literature (14 mobile applications) consider the need to quickly deploy an application specifically in the first 72 hours of a disaster.

However, mobile applications specifically intended for citizen use are few. Citizen based applications are Lifeline[138], Bluemergency [152], SOSCast [153], and ProximAid [154].

All these applications consider the importance of the first 72 hours; however, only SOSCast [153] has checked the overall network's longevity in terms of hours. Additionally, none of these mobile applications have considered the impact of population density in their evaluation.

Since energy of mobile devices is a fundamental limiting factor there is a shift towards using Bluetooth over Wi-Fi by many mobile applications such as SOScast [153], Bluemergency [152], AEC(Android app for emergency communication) [155], and RescueMe [156].

Apart from choosing a different communication interface, energy efficiency has not gained much momentum in most application designs, neither the need of addressing diversity in battery devices. In the following these contributions are detailed:

Lifeline: Lifeline[138] is an ad hoc mobile application that is designed and implemented to provide efficient communication for densely populated residential areas such as schools, hospitals, sport centers, and shopping malls.

The design considers all devices present in an area such as laptops and routers but mainly focuses on mobile phones owned by citizens due to their ubiquitous nature and affordability. A citizen with Lifeline[138] installed on his/her phone during an emergency can connect with any other device with Lifeline[138] installed on it.

The importance of the first 72 hours and battery consumption in considered by Lifeline[138] and thus it works in two modes, one where an ad hoc network is formed only using mobile phones and another mode where battery-powered routers are introduced. For the phone only network: Lifeline App[138] in citizens' mobile phones provides features for sending emergency messages. In the app a specified range of IP addresses are reserved for emergency stations only, which are not used by the Lifeline Apps and battery-powered routers.

In the app mode, Lifeline[138] uses the Optimized Link State Routing Protocol (OSLR) [168] to forward emergency messages in a hop-by-hop fashion.

OSLR is an energy-efficient protocol that ensures that through repeated sleep and wake interval, phones with low battery power are excused from forwarding messaging, limiting their relaying cost battery loss.

The disadvantage to this mobile application is the lack of consideration of disparity of phones and their battery powers and lack of topology energy saving mechanism for the ad hoc network itself. In the other mode, to implement energy-saving mechanisms routers with pre-embedded Lifeline[138] program in routers are proposed.

Lifeline considers the presence of routers for the formation of ad hoc networks, and evaluates performance in terms of the number of routers and mobile phones, size and number of messages and the impact on the battery power consumption of Lifeline[138] ad hoc networks. However, population density is not considered: evaluations are conducted with only 1-4 routers and two mobile phones.

The proposed work evaluated the impact of message frequency and size on battery thoroughly. The purpose was to evaluate battery consumption with respect to the interval of emergency messages and the status of the mobile phones.

The evaluations of Lifeline[138] established that

(i) increased screen time reduces the battery of phones and dimming the brightness can elongate the battery life, and

(ii) mobile phones can last for about 7, 11, and 13 h for forwarding messages of fixed size 255 bytes in 10, 60 and 300 seconds interval.

Since this application is implemented in Android phones it is closer to being used and implemented.

SOScast: Citizen-oriented applications also focus on mobile and immobile victim localisation during disasters. SOScast [153] is one such mobile application that has a very specific application in a disaster scenario: facilitating victims to exchange SOS messages (including location information) automatically by communicating directly among smartphones with less mobility or stuck in specific places. The main goal of SOSCast is to be able to estimate the location of immobilized victims within the first 72 hours of a disaster.

In general, due to line of sight problems where debris and buildings can block the transmission of messages, SOSCast uses mobile citizens as mules to collect information about immobile citizens and their locations and carry it forward to rescue centers.

An Android application is presented and for evaluations real life field experiments with 5 phones are conducted to evaluate the feasibility of the proposed design. The messages when passed were received by the rescuers, but again many factors are yet to be evaluated such as population density, diversity of phone battery, longevity of network for the first 72 hours of a disaster.

Bluemergency: Bluemergency [152] is a mobile application that utilises Bluetooth similar to SOSCast, to form a mesh ad hoc network and evaluate its Android implementation. The Bluemergency app is implemented using sensor nodes and positioned to be used in smart cities and smart home environments where several sensors can connect with mobile phones to transmit messages across various floors. Bluemergency does acknowledge the low-power devices or smartphones and in its design topology proposes to reduce the relaying capacity of low power phones by putting them on the edges. For performance evaluation, packet loss and response time are considered.

In each experiment, the number of messages sent has been varied from 5 to 20 messages per minute. Similar to many other applications Bluemergency does not evaluate energy efficiency in its experimentation neither the longevity for the first 72 hours of the disaster.

ProximAid: ProximAid [154] is the only other mobile application that considers energy efficiency: in the design of the topology and in the mechanism for forwarding alert messages. The dynamic nature of the disaster area or network is considered in this mobile app. When building the communication topology the most connected nodes with a higher residual energy are prioritized for becoming cluster head and the recipient of alert messages. More than one cluster head is chosen as nodes only exchange information in their local vicinity. This ensures that messages remain in the network and are not dropped due to dying battery charge. The nodes with low energy are pushed to become leaf nodes to increase longevity. This mechanism increases energy efficiency.

Helpme: HelpMe [162] is an application used to build a content-based opportunistic network. The application mainly focuses on creating a content-based network specifically for disaster management so that skill-based mapping can be done.

Profiles are created prior to using the service indicating personal skills to be matched during deployment. The application can be used by both professionals and citizens for disaster mitigation. Deployment is specifically focused on iPhone users and uses considerable processing power in terms of energy and memory needed. The application suggests part rather than entire downloads of data to ensure judicial use of limited resources. Experiments validate the functionality of the app in terms of correct mapping, however many other factors such as an increased volume of information request and loss of information due to lack of battery power have not been considered in its design.

TeamPhone: TeamPhone[27] is the prototype of a system designed to include various modes of communication during disasters. TeamPhone[27] also includes a mobile application designed for self-rescue. The designers of TeamPhone[27] have considered energy efficiency and coverage issues by using cliques. When two nodes are in the radius of each other, they wake up periodically to conserve energy in each clique.

TeamPhone[27] also uses a scheduling mechanism to reduce energy loss of any particular node, possibly in multiple cliques. However, selection of which phone will wake up does not include energy disparity of different phones. To further investigate trade-offs, differences in battery charge, density of nodes, area and number of cliques possible must be analysed. Hence there is a very high possibility that despite being energy-efficient by design, the application will have disparity in their services when phones do not start with the same amount of battery charge, or if the number of connections made due to density increases.

Properties such as scalability of the network and reliability of messages are not evaluated. The focus is mainly on evaluating the routing protocol and the energy efficiency of choosing the best and optimal cliques and the specific scheduling algorithm used for message (re)routing. Only 4 phones are used for evaluating the mobile application.

In addition, these phones have a constant battery/power supply to evaluate the loss of energy for different network interface such as Wi-Fi direct, Bluetooth, hybrid and so forth.

Knowledge gap identified:

The current literature on mobile applications acknowledges the limitation of mobile phones in terms of battery capacity of phones. Lack of energy efficiency has led to mechanisms to tackle this energy issue; however, most applications steer away from evaluating trade-offs between other factors such as population density and message frequency on energy efficiency. A Classification of mobile applications based on stakeholders, resource constraints,and population density is presented in Table 4.

For example, SOSCast and Lifeline both do not check the impact of population density, making it difficult to know whether the proposed applications will have different performance levels when population size is varied. Apart from population density, energy disparity of mobile phones and impact of message frequency is not evaluated. For example, ProximAid focuses on alert message dissemination; however, message passing was homogeneous. There are exceptions such as TeamPhone that has presented mechanisms for energy efficiency. Their focus is on evaluating the routing protocol and the energy efficiency of choosing the best and optimal cliques and the scheduling algorithm. The application evaluation does not consider autonomous deployment, deployment time, and network longevity. Since the application is designed for deployment in disasters, the context is essential. Therefore mobility of nodes is of importance.

Apart from the earlier discussed smartphone applications that focus on citizens, the remainder of the analysed mobile ad hoc network applications target both citizens and professionals. The only exception to this is the HelpBeacon application that is specifically designed for professional rescue operators. HelpBeacon proposes and presents a functional mobile application that is easy to use and quick to deploy. For evaluation, the authors of HelpBeacon use interviews to evaluate its usefulness in a disaster context by actually simulating a crisis.

Table 4: Classification of mobile applications based on stakeholders, resource constraints, and population density

Citizen-centric			
	External battery	Self-sustained	Not considered
Dense			
Sparse			
Both			
Not considered		ProximAid[154], Lifeline[138]	Bluemergency[152]
Professional			
	External battery	Self-sustained	Not considered
Dense			
Sparse			
Both			
Not considered			Help Beacons[157]
Both			
	External battery	Self-sustained	Not considered
Dense			
Sparse		Nishiyama et al.[158] RescueMe[156]	Emergency Direct[159] NEED[160]
Both		AEC[155] WLAN-Opp[26]	SmartVL[161]
Not considered	HelpMe[162]	Wi-Fi Direct Locator[163]	LOCATE[165]
		TeamPhone[27, 164]	uRep[166]
			SOSCast[153]

3.5.2 Broadcast mechanisms

Broadcast mechanisms are used for SMS text messaging intended to alert first responders and to broadcast text messages in point-to-multi-point mode intended for public warning [170]. Three papers ([171],[165] and [37]) present broadcast mechanisms in a disaster context.

Pagliari et al. [37] present broadcast mechanisms specifically developed for citizens to guarantee (i) timely delivery and broadcast of information; (ii) longer periods of communication through energy efficiency.

To this purpose Pagliari et al. [37] presents an energy-efficient broadcast algorithm called Dynamic Fanout that adapts routing based on battery power of devices. This algorithm is based on classic gossip algorithms using BLE (Bluetooth Low Energy) devices that can adapt the relaying of messages among participating devices on the basis of their battery level, while guaranteeing information diffusion within a certain geographical area, all the while minimizing the over-all energy consumption. For this, Pagliari et al. [37] propose periodic transmission of messages based on the specific battery charge of a device and the number of neighbours the device can reach. If the battery reaches a certain low threshold the transmission is reduced and eventually stopped.

This paper also introduced a new metric Coverage Efficiency (CE). This metric expresses the effectiveness of the algorithm in terms of achieved coverage vs the required time to reach it. To evaluate the performance of the proposed mechanism, all devices simulated in their experiments have homogeneous battery charge. Uniquely, Pagliari et al. [37] consider some density from real cities to analyze actual scenarios. The experiments simulate several population densities representative of highly dense cities such as Rome and intermediary cities such as Milan.

However, the influence of node mobility on information diffusion was not evaluated. The other two broadcasting schemes, LOCATE [165] and [171], are specifically developed for sending emergency alert messages and are generic in their use and more focused on improving the operational performance of broadcast mechanisms during disasters.

The broadcast mechanism called ***LOCATE*** [165] consists of a mobile application connected to a LoRa (Long Range) transceiver via Bluetooth Low Energy (BLE); this application can be used to send emergency requests that are rebroadcasted by other users until reaching rescue personnel. This technology is constrained in terms of its use as additional equipment is required minimising opportunities for deployment immediately after a disaster.

Knowledge gap identified:

Most broadcast mechanisms, except those discussed above, are not specifically designed for citizen based communication in a disaster context. There are, however, more generic, applications that do address this context. For example ***Reina et al.***[171] propose a broadcasting scheme called DissBroadcast based on a similarity/dissimilarity coefficient designed for disaster response scenarios through a multi-objective optimization problem.

The presented work optimizes three widely used metrics: reachability, the number of re-transmissions and delay. Ease of use and deployment time are not explicitly discussed by others as well.

3.5.3 Protocols

A majority of literature (14 papers) addresses message routing and the network topology of an ad hoc network, thus a substantial number of design artifacts are protocols. A protocol can refer either to a routing protocol or to a topology protocol. The topology of a network refers to the layout of the network. It determines how nodes are connected to each other and how they will exchange information. A protocol that facilitates formation of an ad hoc network is called a topology protocol. A routing protocol refers to the mechanism of finding a route to transmit messages. In a mobile ad hoc network routes between sender and receiver are not static or stable, as people with devices move, connections (links) between them are removed as people move out of transmission range of other devices owned by other mobile citizens. A routing protocol ensures sending and receiving of messages via these dynamic routes in a mobile ad hoc network. Both protocols (routing and topology) work together to make MANET feasible. The topology or backbone topology determines the connection pattern of a network, and the routing mechanism determines the exact intermediate nodes (relays) to use for transferring messages.

Several published surveys focus on protocols for routing [180–182] and topology control [183, 184] for mobile ad hoc networks. Of these 14 protocols described only four [172– 174, 185] protocols were specifically designed for citizen communication. Protocol design is mostly done with operational performance in mind. Several possible application fields are suggested, including disaster communication.

Evaluation of disaster specific protocols mostly concerns comparing the disaster based protocol with more generic protocols. For example, ***Tasfe, Saha, and Chakrabarty*** [174] propose a novel social interest-based routing algorithm called “Gossip”. In this protocol the formation and forwarding of messages are based on two functions called decay and growth that are calculated based on a person’s interest. The design of the protocol is based on the assumption that *"The human tendency of keeping social relations with the people of similar interests opens up the way to distribute messages more effectively".* Tasfe, Saha, and Chakrabarty hypothesise that if it can be used for Pocket Switched Network (PSN), then it can be used in disasters. However, how to deploy this protocol, nor ease of use have been discussed. They also do not consider resource disparity or population density in their evaluation.

Mehendale, Paranjpe, and Vempala[137] propose a routing protocol called Lifenet and define a metric called reachability. Reachability(A, B, T, L) of node ***B*** from node A is defined as the expected number of packet copies received by B for every packet originated at ***A*** and diffused in the network for at most ***L*** hops in time interval ***T***.

Ito et al.[173] proposes a BLE-based ad hoc network and perform experiments to test the performance of the BLE routing protocol they propose: Examine packet reach rate with five BLE nodes to determine suitable times for transmitting a packet. They examine the packet reach rate in a building to know what percentage of packets can reach other nodes.

BLE is a relatively new standard that allows for energy-efficient connections. However, this connection type is not preferred due to the ”central-peripheral problem”. BLE is designed to connect gadgets such as music players to connect to peripherals such as smartphones. BLE does not allow connection between Central to Central or Peripheral. However, iPhone and a few Android smartphones can be a Peripheral.

Fujimoto et al. [185] proposes RecurChat RecurChat that can distribute itself to other noded that do not have RecurChat by using RecurShare. RecurShare is an inbuilt library that can replicate the application (apk) to other devices. The device with RecurChat uses its tethering function and serves as a router to relay the apk. It also becomes a web-server when another device needs to download the apk. This should makes it possible to use the RecurChat a mobile application in a disaster site. This separates RecurChat from other related work. However, the feasibility and use of this application is yet to be determined.

Knowledge gap identified:

The literature on protocols focuses on designing opportunistic networks as either MANETs (Mobile Ad-Hoc Networks) or as DTNs (Delay and Disruption Tolerant Network). For MANETs a full mesh topology is the de-facto standard, and for DTNs (Delay and Disruption Tolerant Network) either a mesh or a tree-based topology is used. Both relay information through other nodes and need the cooperation of nodes to support network longevity. But these protocols are not adaptive to changing parameters. With parameters determined by the environment such as node density and mobility MANETs can work in a stable environment of densely populated nodes whereas DTNs work better in a sparsely populated area.

Although there is a rise in proposing new metrics for evaluating quality of service, most work use the same operational values to determine performance evaluations: there is a need for new metrics such as coverage efficiency, participation of nodes etc. In section discussions, a detailed list of metrics are provided.

3.5.4 Frameworks and conceptual models

A conceptual design and framework is a design artifact that contributes [186, 187]: (i) a new definition of an evolving technology, (ii) the need for such technology and its impact and (iii) a theoretical example of how to design and implement new technology. An example of a conceptual design and framework is presented by ***Bahora et al.***[188] who propose a conceptual design of a p2p network mainly targeted at professionals, early responders that need to coordinate and exchange information among themselves for rescue and operations of civilians forming a mobile ad-hoc network.

The issues that were the focus in 2003 in this seminal work were (i) interoperability of devices, (ii) unavailability of situational awareness and (iii) the need of sharing more concrete data to avoid misinterpretation of voice messages by sharing information such as maps, images, text messages, video feeds and conferencing, statistical data, and location tracking. This work includes the initial design of a GUI: Graphical User Interface, an infant stage of a mobile application that supports group formation and peer-to-peer networks for sharing various forms of data/information.

The focus was not on using mobile phones for civilian use, or to promote collective intelligence and formation of autonomous ad hoc networks for and by citizens during disasters. This also resulted in less focus on the limited battery issues because professionals can own and have alternative charging facilities that are independent of the disabled infrastructure.

The majority of the other frameworks and conceptual designs found during consider the first 72 hours of a disaster as an important design criteria to consider . The initial methodology and search resulted in a total of 8 such frameworks and 20 conceptual designs. Only the designs proposed by ***Aloi et al.***[38], ***Utsunomiya and Minami***[189], ***Shahin and Younis***[190], ***and Minh et al.***[191] are citizen-centric in terms of their use.

Energy efficiency is not considered by the majority of these and is only included in 6 papers in which the only citizen-centric contribution is by Aloi et al.[38]. The same can be said for population density and ease of use. Not a single conceptual design or framework designed for use only by citizens has considered all of the factors discussed in earlier sections (energy, ease of use, population density, deployment time).

Most contributions are hybrid in design, and can be used by both citizens and professionals. For example, a conceptual model and testing framework for a crisis response communication system is proposed by ***Bradler et al.***[68]. The contribution is aimed at first responder teams and future designers of systems for group communication systems working without infrastructures.

The stakeholders addressed by this paper are professionals such as fire departments, law enforcement agencies, emergency medical services (EMS) and government agencies.

The problems identified by this paper are: diversity of devices used for information exchange, interoperability of devices, message prioritisation and frequency and validity of messages.

Bradler et al.[68] propose the following criteria as essential properties of a communication system used in a disaster context: (i) scalable, (ii) reliable, (iii) able to provide both horizontal connectivity but also vertical connectivity. However, a shift in perspective of design is made clear as Bradler et al.[68] propose to conceive the design of communication systems during disasters as more complex systems and as system of systems. Simulation is used to evaluate the design of their system and they propose three different mobility models for the disaster scenario.

The authors also propose certain requirements as essential for building and testing a distributed crisis response system. Since this is for early responders, specific limitations of phones such as battery capacity and charge are not addressed in the requirements, nor are deployment scenarios discussed. The lack of considering population density, diversity of resources, devices present and ease of use, limits determining the feasibility of such systems, is a limitation that is observed in most frameworks and conceptual models.

Most frameworks and conceptual models propose hybrid designs to deal with issues such as the changing density, coverage and resource limitations of a disaster area. Such hybrid designs, for example, combine a phone based ad hoc network with more centralized connectivity options such as using access points like Unmanned aerial vehicles, or equipment like radios owned by professional and governmental organisations.

For example **ARC** (Application framework for robust communications) as proposed by ***Santos et al.***[192] allows Wi-Fi direct and DTN to integrate for efficient mobile application development. ARC is an open source framework that supports users trapped in a collapsed building or disaster site without any infrastructure access to form their own groups for communication. The application also enables users to connect and send messages to people outside of the disaster site when any infrastructure access becomes available.

Hybrid technology has its own advantages as it combines the coverage range of professional devices and acquiring situational awareness from citizen-owned devices.

However, even in these conceptual designs where the best of both worlds meet, feasibility analysis of such applications does not replicate the reality of disasters.

For example for AEC, experiments only considered at most 3 nodes, with different file sizes and frequency of messages. The focus was to test reliability of messages while using either the DTN or the Wi-Fi direct modes. This limits its actual deployment in disaster sites where node density and mobility can be very dynamic. Energy efficiency is discussed where devices with high battery charge are declared as hubs, but energy distribution is still not considered. Thus, despite the experiments, the impact of parameters such as population density, mobility of nodes, resource distribution of devices participating on reliability of messages are not evaluated.

Other essential characteristics such as scalability, robustness and participation of devices and issues such as message loss while switching between various modes were not taken into consideration. This lack of a complete representation of the disaster context and a more extensive evaluation of the design artifact that takes this context into account is observed in most papers and is hence not included in detail in this review. Four works proposed by Banerjee, Warnier, and Brazier[63], Aloi et al.[38], Utsunomiya and Minami[189], Shahin and Younis[190], and Minh et al.[191] are citizen-centric in terms of use. These are discussed below.

Banerjee, Warnier, and Brazier[63] propose SOS(self-organisation for survival), a conceptual design of a citizen-centric communication system that uses context-awareness to design an energy-efficient adaptive communication system. The proposed system uses a protocol consisting of three distributed algorithms based on local self-organisation to create a MANET from phones available in the disaster site. The protocol leads to an adaptive topology. This is done to resolve the drawbacks of mesh topology that leads to an increased number of connections. Mesh is the de-facto topology of citizen-centric communication systems that caters to quick deployable P2P network of phones [89, 137].

Banerjee, Warnier, and Brazier[63] discusses the both the advantage and disadvantage of mesh topology. In mesh all nodes that are in transmission range are considered a possible connection. As phones connect to all possible connections this leads to a connected network.

Multiple connections leads to redundancy of routes and this makes mesh robust against link and node failure. However if energy efficiency is considered, this approach can lead to quick depletion as maximising connection can have higher cost in denser areas. For instance, the average node degree that is defined as the average number of connections maintained by each node will be very high for a full mesh topology.

In this situation the lack of consideration for the disparity of energy in the context can lead to a quick network segmentation as lower energy nodes will exhaust sooner. If these protocols are deployed in areas with no source of recharging batteries the longevity of the network will not last. In these scenarios if a scale-free network as proposed by Banerjee, Warnier, and Brazier[63] is deployed, energy efficiency will be higher as the number of connections will be very context dependent. However, the routing cost will be very high for the scale-free network as routes will constitute multiple hops due to limitation on the number of connections being made. This observation is clear from results as projected in the result section where density and population are varied for different frequency of message transmission.

The findings of Banerjee, Warnier, and Brazier[63] provide insights on the parameters such as density and frequency of message transmission, that impact scalability and longeivity. Despite its exploratory nature, this study offers insight into decentralized adaptive topology control mechanism without any modifications on the hardware level.

Utsunomiya and Minami[189] propose a grass-root information distribution system using mobile phones to dissipate information about impending disasters and early evacuations. There is specific equipment developed that is used for monitoring landslide data and then sends emergency messages. This dedicated equipment is, for example, installed in local household living rooms to collect data. The proposed technology uses BLE, and use a mesh topology to form an ad hoc network. They also use epidemic routing to send messages. Two different experiments are used to evaluate how quickly data is delivered through the network.

The two main limitations of the work are its lack of an energy efficiency component and a lack of early deployment due to the dependence on the specific equipment used. In addition, deployed equipment can also be destroyed during severe earthquakes, making the framework partially unavailable.

Shahin and Younis[190] propose a framework for group chatting in a p2p fashion. The authors propose the design of a generic protocol that ensures that despite topology changes, the network can provide connectivity and remain working. This framework can be used for any purpose and has not been designed specifically for a disaster context. The system is evaluated by looking at time to live and how quickly the messages are delivered despite topology changes. The framework does not discuss deployment time or focus on use in the first 72 hours of a disaster, neither is energy efficiency considered.

SENSE-ME[38] is the only presented framework that has specifically been designed for citizens, that considers deployment time, ease of use for citizens and the resource constraints of phones. Aloi et al. investigate the role that Commercial Off-The-Shelf (COTS) smartphones can play in emergency scenarios. Modern smartphones have a great potential for emergency monitoring and management: (i) they are truly pervasive, (ii) they can establish peer-to-peer wireless links using short-range communication technologies, thus guaranteeing coverage even when fixed infrastructures are unavailable, and finally (iii) they can sense the environment through several embedded sensors.

Knowledge gap identified:

Frameworks and conceptual designs are mainly designed for both citizens and professionals to use. However, how to implement these is typically not very concretely defined or explained for use. Many designs require introducing new equipment and changes on the hardware level, that can limit deployment and usability in under-developed or developing nations. Frameworks or conceptual models do not specifically define the requirements to promote further implementation and use .

3.6 Stakeholders, ease of use and time of deployment

Stakeholders are important in system design. In this literature review the intended users of a system are categorized as: citizens, professionals or both. Literature that focuses mainly on trapped citizens and that describe systems that only use smartphones are categorised in the citizen category. Literature that proposes the use of centralised services or that proposes the use of additional specialised equipment that is generally not owned by citizens are considered to belong to the professional category.

There are related works that propose frameworks that are hybrid in use, as they have mobile-based systems for citizens and a separate system for professionals that perform search-and-rescue operations. A generic system design can, for example, include both stakeholders as target users and these are thus placed in the "both" category. The next attribute considered is usability criteria. Systems that are designed with automatic configuration in mind and that require citizens to only download an application on their phones are grouped into the Easy category. System designs that can only be deployed with external equipment are grouped into the hard-to-use category. As described in the previous section, most mobile applications fall in the easy category, because they do not require any hardware modifications or other external devices.

Communication needs before and after a disaster are very different. Also designing systems in these two different time frames is challenging due to the different contexts. In this literature review, for time of deployment papers are divided into either immediate or prolonged deployment and use. Proposed systems or designs of systems that look into citizen communication post-disaster, specifically the first 72 hours are categorised in the immediate deployment category.

Any literature that does not mention any time frame or the importance of the first 72 hours are put in the prolonged category. This category is important to determine what services are considered significant in the current body of work and whether the proposed designs in literature include the availability of services for this period as evaluation criteria.

SOS(self-organisation for survival)[150] is the only work that was found to have conducted an comparative agent-based modeling approach to measure the node participation in the first 72 hours after a sudden-onset disaster. The authors compare the design of SOS [63] with a generic mesh network to evaluate the longevity of each node while varying the number of messages and population density.

A new metric "participatory fairness" is also proposed to show that SOS was able to deliver equal participation of phones/nodes despite disparity in charges.

Knowledge gap identified:

The number of papers that have specifically focussed on citizens are very less in comparison to papers that keep the stakeholders both citizen and professional. The ease of use is not very tested as most applications are not tested in field experiments.

3.7 Population density of the deployment area

The population density of an area is a metric that quantifies the number of people in a specific area. To ensure everyone in a disaster struck area can be connected to an ad hoc network, the proposed design has to consider population density.

In this literature review, four categories of population density are distinguished: Sparse, Dense, Both and None. It is important to verify properties such as network scaling using a variety of population densities. In this review, literature that has performed tests using a different number of devices or a varying population density are categorised as Both, the others are categorised on the basis of the number of devices used per square meter.

Evaluations irrespective of simulation or actual implementation that use less than 50 devices per square meter are categorised as Sparse. Evaluations with a higher number of devices are categorised as Dense. Lack of consideration of population density and its impact is categorised into the 'Not considered' category.

Most papers do not consider population density at all, but there are some exceptions in papers that have recognised the impact of population density on system performance and thus included population density in their analysis.

Banerjee, Warnier, and Brazier[63] propose SOS and evaluate the impact of changing population density on reliability, robustness, longevity and scalability. In the extension [150] to their first work, the authors take the density of top 10 disaster prone cities in an agent-based model to evaluate the impact on longevity of the network and its direct relation to population density. The experiments also varied the frequency of messages that were sent for each population density.

Pagliari et al. [37] have simulated the density of Rome, Milan and less dense cities to estimate (i) the impact of the number of nodes in a certain geographical area, i.e., the density of the peer-to-peer network; and (ii) the communication frequency, i.e., the Bluetooth transmission range on coverage. They show the impact of higher density and lower density. They show a decline in coverage area as density drops. However, as mentioned earlier they have kept the node density homogeneous, which is not representative of actual cities.

Node density was also considered in several protocols designed with energy efficiency and broadcast mechanisms in mind, such as the Adaptive Broadcast Protocol[136] as proposed by Durresi et al. that considered the effect of changing density on performance. This paper proposes a routing protocol called ABP, that is used for forming the best possible way of utilizing a specific density.

Similarly, ***Gorbil***[195] proposes a conceptual design for evacuation and urban search for civilians using ad hoc networks, called ESS (Emergency support system). They also vary population density and consider indoor and outdoor evacuation. This was the only paper that has considered the security aspect of emergency communication and the impact of wrong information on evacuation in a disaster context. Amongst others, they test if wrong information can impact the evacuation of disabled people.

Knowledge gap identified:

Population density, despite being a very vital factor to impact quality of service for each proposed design artefact, is not yet a standard evaluation factor. Additionally, replicating the population density of actual cities that are prone to disasters for testing in either simulation or field experiments has yet to be explored.

3.8 Resource requirements

During disasters, both the communication infrastructure and electricity grids can fail, preventing mobile phones from charging, leading to a resource-constrained environment. In this review, three categories are used to describe this attribute.

Designs that have explicitly acknowledged and presented a mechanism to deal with limited battery charge of device equipment for charging devices is usually done by government and non-governmental organisations. Literature that considers additional equipment such as generators and power backups are categorised as External source. Literature that does not consider resource constraints is categorised as Not considered.

In a MANET the sources of energy consumption are twofold [212]. Firstly, discovering a route consumes a fraction of energy and secondly, transmitting the intended message across various nodes consumes another fraction of energy. To discover a route, mobile nodes must exchange information such as their address with each other and neighbours in range using control packets. Control packets are exchanged to create a network topology. Once a topology is established, a message is transmitted. To transmit a message, several nodes must relay the message to the final point.

Reducing computational overhead to calculate a path for message routing can have an immediate impact on the overall energy consumption [212]. Sender, receiver and the participating routing nodes will reduce their energy consumption, if the number of exchanged control-packets is reduced. The total amount of energy consumed while transmitting the intended message or the actual information from its source to its destination is further sub-divided into sending, receiving and relaying the message. Sending information by the sender consumes the maximum amount of energy required in transmitting a message, followed by energy consumption while receiving a packet by the receiver. The amount of energy that is consumed while idle, which is equivalent to receive. The wireless interface consumes energy while being idle, as it keeps listening to the medium to discover new connections. To reduce this portion of energy loss, nodes are put to sleep. The technique of putting nodes or devices to sleep is a common technique that is used in wireless sensor networks. These techniques have also been deployed in ad hoc networks used in a disaster context, for example the Adaptive Broadcast Protocol.

Durresi et al.[136] propose a routing protocol called the Adaptive Broadcast Protocol(ABP), that is used for forming adaptive opportunistic ad hoc networks using mobile phones for communication among citizens and rescue operators based on a detailed discussion on the context of a disaster area.

The authors address: (i) heterogeneity of devices, (ii) changes in population density and its impact on scalability, (iii) a dynamic environment, needing an adaptive topology, (iv) various modes of communication such as multi-point and point-to-point, (v) energy of devices and need of energy efficiency.

The authors clearly elaborate their intuition behind the design principle of the protocol, indicating that not all nodes need to be involved in transmitting/retransmitting messages in order to broadcast a packet over a network. Instead, the authors propose that the goal can be achieved by allowing only a few nodes to retransmit the message, by trying to optimize the number of hops or intermediate phones that can relay the message. A major characteristic of ABP is to reduce overhead, i.e., the number of retransmissions, therefore, ABP saves both energy and bandwidth. Their fundamental goal is that since in an emergency situation everyone tries to communicate, it is important to save bandwidth. The authors propose the broadcast protocol ABP where they use a wireless sensor protocol for routing called Random Asynchronous Wakeup(RAW)[213]. RAW utilises a power-saving technique fundamentally designed for sensor networks that reduces energy consumption by putting certain devices to sleep. This decision is made in a distributed, randomized algorithm where devices make local decisions on whether to sleep, or to be active. Each node is awake for a randomly chosen fixed interval per time frame.

Mobile phones can be put to sleep mode, but re-awakening them can cost energy. As a result it is beneficial to utilize the maximum number of nodes for relaying messages rather than keeping them idle or putting them to sleep. Relaying an expensive functionality in terms of energy consumption and needs mechanisms or protocols to elongate the lifetime of nodes. Keeping this in consideration, various techniques have been proposed in the literature to enhance the longevity of mobile ad-hoc networks[135, 214–219].

Generally, these can be categorized into techniques that manipulate the transmission range to exert topology control or that selectively put nodes to sleep, and techniques that attempt to minimize energy consumption[215]. Adjusting the transmission power can allow the formation of a network with limited exchange of control packets, which can elongate the overall longevity of the MANET.

However because mobile phones cannot easily manipulate their transmission range this approach is not applicable without changes to the hardware of the phone. If two nodes have an overlapping transmission range they can communicate directly. Alternatively, intermediate nodes act as routers to relay the message and complete the communication [220]. A larger transmission range coverage increases the chances of direct communication and reduces the number of relaying nodes in between. On the contrary, a shorter coverage area needs more relaying nodes to create a connected network.

To reduce the number of participating nodes and conserve energy, in transmission power management, the transceiver of the radio is switched off[221]. Turning the transceiver off or putting it to sleep, ensure that the node does not participate in packet relaying. However, putting phones into sleep mode is also not a feasible technique for our a disaster scenario, because it is difficult to determine which phones are to be prioritized in an emergency setting.

The latter techniques can be further subdivided into techniques designed to minimize the overall cost of transmission, and techniques that try to minimize the transmission cost for individual nodes. The minimum total power transmission approach determines the route such that the smallest amount of power is required for end-to-end transmission. In this approach the minimum cost route in terms of the overall transmission of data is selected as optimal.

The disadvantage of this approach is that individual node battery is not taken into consideration. Thus energy consumption of an individual node is not considered as a performance metric. In this approach, specific mobile nodes eventually run out of battery charge leading to network segmentation.

The protocols that follow this approach include MTTPR, MBCR, and MMBCR [222]. The other category of protocols follow the approach of conserving individual nodes' battery charge. Based on the battery charge of nodes, routing algorithms consider nodes and try to enhance the battery lifetime of each node[223–226].

Wi-Fi-tethering is another approach proposed in the literature[179, 200, 227] to conserve battery life in a MANET. Wi-Fi-tethering is a technique where a smartphone is chosen to be a hotspot for connectivity based on its battery charge and proximity to other phones.

Wi-Fi-direct is used to discover and connect to hotspots. This approach is only available for devices with long term evolution advanced (LTEA) provided by 4G.

Raj, Kant and Das [200] propose a distributed coalition forming game E-Darwin [200] to design an ad hoc network based on residual battery charge and capabilities for capturing and distributing data based on Wi-Fi-tethering. They, however, assume the presence of gateway devices that are either satellite phones or access points with an active Internet connection, limiting its immediate deployment. Also, their performance evaluations show that the hotspotting state and switching to and from that state is highly energy intensive.

Knowledge gap identified:

There is an abundance of literature on energy efficiency mechanisms either for routing or topology control. However, these mechanisms are all derivatives of approaches used in wireless sensor networks. However, in a disaster context such mechanisms need to be evaluated for performance criteria that are relevant in such a context. Parameters such as the density of nodes, node mobility, available phones with their battery life, type of application (such as either the message is broadcasted or only sent to a specific group) all play a very vital role.
The current approaches are yet to investigate many of these issues, let alone all of them. In addition, mobile devices are power constrained devices i.e. they need to recharged after certain interval.

There is increase in their computational ability and amount of battery, however not every disaster prone country has the socio-economic capacity to own advanced sophisticated mobile phones. Therefore lack of applications that require limited computational ability and battery power presents the biggest bottleneck of using smartphones or mobile phones to create a communication network. But as described above, the existing energy approaches are rigid. They either conserve individual node energy i.e. certain phones have higher battery savings than others, or they focus on extending the entire lifetime of the network. Another approach taken is to manipulate the node transmission range or manipulate control of the topology. These mechanisms cannot be completely used in a phone if deployed as a node in MANET, such as putting the phone in a sleep mode.

Secondly, mobile devices come with a fixed network interface and have fixed ranges thus topology control by increasing or decreasing the transmission range can, using currently available phone models, not be implemented. Also pre-determining the network topology prior to a disrupting event is not possible.

To add to the existing challenges the type of application needs to play an important role in making these MANET successful. But as the number of mobile subscriptions worldwide increases [228], it is therefore important to consider applications that run on all kinds of phones and are less energy exhaustion. Lack of adaptivity in deployment and its effect on energy consumption may limit the deployment of phones as infrastructureless communication networks.

3.9 Network adaptivity

Information in a disaster area is highly dynamic. Properties such as the number of people, the availability of resources, node mobility and accessibility can all change over time. It is therefore important that a communication system that operates in such a context is capable of accommodating this change. Therefore, systems that consider this dynamic environment and that perform system evaluations that include parameters such as mobility, changing population density and variability in device resources such as battery charge, are all categorised as Reactive. If a proposed system does not consider this dynamic nature of a disaster context then it is categorised as Static.

There has been an increase in the number of disaster emergency communication systems that are context adaptive. Some of these papers include systems that are hybrid in nature, i.e., these systems can be used by both citizens and professionals. The literature review concludes that ad hoc networks are adaptable because they are formed using interactions. Therefore, their connection patterns adapt to mobility and availability of devices in an area. This property makes ad hoc networks self-organising in nature. However, as discussed in earlier sections on population density and resource constraints, not many related work consider the dynamic density or disparity of resources. Context awareness was found in a couple of selective works that are described in brief below.

One such work is proposed by ***Nishiyama, Ito, and Kato*** [158], where they use mobility, battery life, and density of nodes to determine which routing (MANET or DTN) to use. This paper presents the routing architecture of a protocol that combines and switches between MANET and DTN. They have also made a prototype of the system and evaluated it with real mobile phones. The main motivation of the work is to take advantage of population density and type of connection, in location with a sparse density the protocol switches to DTN, in denser populated areas the protocol switches to MANET. This ensures that the proposed work can be deployed irrespective of density and will scale well.

Pu and Zhou[156] propose a context adaptive network that dynamically adjusts the schedule of sending out distress signals according to a change in the network topology. Their paper introduces TeamPhone, a mobile app that consists of two components: a messaging system and a self-rescue system. The messaging system integrates cellular networking, ad hoc networking and opportunistic networking, and enables communication among rescue workers. The self-rescue system groups the smartphones of trapped survivors based on their energy efficiency and sends out emergency messages so as to assist rescue operations.

However, the self-rescue system does not consider that each smartphone of a trapped survivor may carry a different amount of residual energy, and the smartphone with less residual energy may turn off quickly because of frequently broadcasting emergency messages. Thus, the schedule of sending out emergency messages should be dynamically adjusted accordingly when the network topology changes because of the removal of a certain smartphone.

Utsunomiya and Minami[189] present a grass-root information distribution system using mobile phones to dissipate information about impending disasters and early evacuations. The system depends specific equipment that is developed for monitoring landslide data and then send emergency messages. This dedicated equipment is fixed in living rooms for example to collect data, however these can be destroyed. The devices use BLE configured in a Mesh network. They also use epidemic routing to send messages. Two experiments are done in order to evaluate how quickly data is delivered. Energy efficiency is not discussed.

Nishi et al.[203] propose the (conceptual) design of a system that helps in monitoring landslides in a Japan. Deep learning techniques are used to predict landslides. The system collects data using mobile phones that form an ad hoc network and collects the gathered data in a centralized database for processing. The system does not include properties such as node density, or node mobility in its evaluation criteria. However, message frequency is considered.

There are two very specific related works that have proposed an intricate design of a context-aware emergency communication system: StemNet[89] and SENSE-ME[38]. Both these works are from the same authors ***Aloi et al.*** [38, 89] who design and develop context-aware emergency communication systems for disasters, based on swarm intelligence.

In ***STEM-NET*** [89] they provide each mobile node with the capability to think and sense from their environment to facilitate self-* properties, namely self-organising, self-healing etc. STEM-NET consists of data gathering and processing algorithms that are based on hardware configurations of nodes, and thus can assume multiple network roles (i.e. gateway, relays, etc.). An end-user device with an active Internet connection can become a gateway, a end-user device with routing capacity can become a relay and a device which is not involved network management becomes the a stub.
Distributed algorithms that facilitated switching based on the battery charge of devices, congestion and hardware capacity are discussed in the paper. Their analysis of the proposed work is simulation based and focuses on operational parameters. However, the work also proposes some new metrics that are useful in evaluating disaster based services. These metrics are further detailed in the discussion section below.

Aloi et al.[38] also propose a context-aware framework named SelfEvolving Network and Services for Safe EnvironMents (SENSE-ME) for deploying available devices mainly smartphones into self-organising connected ad hoc network. This framework provides a platform to collect data from the disaster site to create situational awareness, and provide decision making capacity to citizens and professionals. For example, it uses all its sensor data to make decisions such as deciding which evacuation path to follow by facilitating distributed communication and coordination. It is a complete platform that works on all three layers, i.e.: a network layer, a sensing layer, and an information layer.

The advantage of this framework is that it does not require any additional specialized equipment for deployment. Since the framework is for communication and for situational awareness using sensor data, the performance evaluation consisted of operational metrics such as throughput, delay, scalability etc.

They conclude that for dissemination of high-frequency sensor data WiFi Direct is a suitable technology, despite the limited resources of mobile devices.

Lastly Banerjee, Warnier, and Brazier[63] propose a context-aware adaptive mobile communication system that uses information such as residual energy of neighbours to select and form a loop-free scale-free communication network. The context-awareness leads to an adaptive topology and a event-driven reconfiguration to tackle link breaks. SOS uses local self-organisation and context-awareness to produce a constantly energy adaptive system that leads to fairer participation of nodes and also reliable delivery of messages for various densities.

Knowledge gap identified:

The literature review identifies a shift towards context-aware designs for citizen based communication in a disaster context. The advantages of such approaches are recognised in the research community. However, most papers raise issues such as security aspects, inter-operability of devices and service fairness as major challenges that current research has only barely started to address.

3.10 Discussion: guidelines for designing citizen-centric communication systems in a disaster context

What stands out in reviewing the literature is the continuing increase of systems based on mobile applications that cater to citizens. There is a clear shift in the literature in acknowledging the need for more self-organising, automatic and energy resilient solutions. Additionally, a trend in proposing new metrics to measure the feasibility of proposed solutions is seen. In this section a summary of the main findings, together with identified knowledge gaps and recommendations is provided. The following subsections present the principal findings of this paper.

3.10.1 Define the stakeholders and the context of use explicitly

Two stakeholders are considered as the primary users of the proposed communication systems. These main stakeholders are professional aid workers (NGOs, governments, military etc.) and citizens in a disaster area. Some literature focuses solely on one of these stakeholders, where others can be used by both groups. Literature that focuses mainly on citizens always proposes some kind of mobile application, because that is the only way citizens can form an ad hoc communication network themselves. Papers that primarily focus on citizens [190, 191] typically have one of three overarching goals: they focus on helping citizens communicate with professional aid workers, or on helping citizens communicate among each other, or on helping citizens access information from a centralized source that is typically handled by a professional aid organization.

Other systems [68] focus more on professional aid workers, where they might use the mobile phones of citizens as intermediate nodes or relays, for example, human-centric mobile data networks that can provide information to rescue operators. Another potential use is for citizens' phones as a form of data capture devices, to gather information on, for example, seismic activity, or heat. Some of these systems use specialized equipment, like a UAV. Systems that are focused on both, citizens and professionals, are more collaborative to set up a hybrid network, which allows citizens to communicate and professionals to rescue. They typically involve a system that combines specialized equipment with mobile phones.

3.10.2 Include energy-efficient mechanisms in systems design

Energy efficiency is a dominant factor contributing to the feasibility of a mobile ad hoc network. Most presented work discusses the limitation of phones' battery charges and the need for energy-efficient mechanisms for the longevity of the proposed ad hoc networks. Some of the major trends noticed in the literature for energy efficiency are:

Use Bluetooth instead of WiFi:

Several authors advocate the use of Bluetooth over Wi-Fi as connecting, sending, receiving and relaying is more energy efficient with a Bluetooth connection.

Therefore, a shift is noticed in frameworks, conceptual designs and mobile applications to use BLE, for example, in the disaster communication systems: SOScast [153], Bluemergency [152], AEC (Android app for emergency communication) [155], and RescueMe [156]. Therefore it is recommended to choose Bluetooth Low Energy (BLE) over Wi-Fi for a better energy usage of phones.

Introduce adaptive topology reflective of disparity of residual battery of devices:

Alternatively, Pagliari et al. [37] as well as Banerjee, Warnier, and Brazier[63] propose an energy-efficient protocol that adapts its message routing based on the left-over battery charge of the devices. They use BLE for energy conservation and investigate, if smartphones can be used to distribute information as quickly as possible in a disaster scenario.

The aim of the adaptive nature of the design is to modify the behavior of each node over time in order to keep the best trade-off between the speed at which a piece of information reaches a large proportion of nodes in the network and the overall energy consumed by such large coverage. Hence to maximize the lifetime of a node and the overall longevity of the network can best be acquired by adapting traffic flow in order to ensure a scheduled and distributed energy loss among participating nodes.

3.10.3 Evaluate attributes representative of a disaster context

Almost all literature reviewed in this review acknowledged that the disaster context is characterised by a unique set of dynamic circumstances. These characteristics are, amongst others, a limited window of time to save lives, changing population density, diversity of devices, unavailability of resources and a lack of expertise to deploy a system. For example Lieser et al. consider different prioritisation of messages based on either size, utility and battery of sending nodes. In their analysis of what a disaster scenario needs are discussed and then a prioritisation of message is presented through an algorithm/framework. However, in most literature the evaluation process did not reflect the nature of disasters. Such as:

The Golden Period: Most work broadly recognises that deployment time is an essential characteristic of a disaster communication system. It is, therefore, frequently mentioned in the introduction section that the system has to be functional within the Golden Period of the first 72 hours after the start of a sudden onset disaster. However, tests to evaluate if the proposed solution delivers services for this time period during deployment are absent. Experiments need to be designed to evaluate if a proposed design artifact can be used for the full first 72 hours window.

One of the proposed ways of testing deployment time is evaluating the longevity of individual phones. For example, [138] has established in their evaluation of Lifeline [138] that dimming the screen of mobile phones result in saving phones' battery. Furthermore, for other factors that can impact the longevity they have experimented with forwarding different sized messages within several intervals respectively. The message interval can impact the battery life of phones.

Therefore it is advisable for future tests to keep the message size fixed and test the frequency of message passing in given time intervals to find the optimum number for a specific disaster scenario.

Population density: Until 2015, very few articles consider population density, even though this requirement is mentioned in the foundational articles [188] of this field. At most, sparsely populated areas are considered. In the last few years however, variations in population density are being considered and more researchers are starting to recognise its impact on the performance such as network reliability.

Context reactive: In a dynamic or disruptive situation, a fully mobile and decentralized infrastructure-less network seems to be a viable option for communication. Although challenges such as changing topology, unreliable nodes, intermittent connectivity and limited battery life of nodes require mechanisms (protocols) that adapt to these changing parameters.

However, this adaptiveness can cause overhead with respect to energy use of nodes, which ultimately affects the lifetime of the entire network. This is why most presented work consider the topology as de-facto ”mesh”, where all phones connect and lose an equal share of battery charge on routing messages. However, there is a need for more adaptive communication network topologies in order to adjust to dynamic factors such as changing density and resource availability.

3.10.4 Propose new metrics specific to disaster contexts

Key Performance Indicators (KPIs), are used to analyse and demonstrate performance improvement or deficit involved in a certain process [230]. On the other hand, metrics are used to indicate the quality of the products, to facilitate systems engineers in measuring effectiveness of a system that produces a product [231].

The field of Computer Science is very dominant in improving operational values of processes where KPIs are used to evaluate new conceptual designs in disaster management [232]. KPIs such as total throughput, bandwidth, end-to-end delay have become the norm to establish feasibility of a system. These default performance KPIs that focus on, for example, message throughput or network reliability, are, however, not sufficient.

In Table 2, an overview is provided of newly designed metrics that address other aspects that are of importance for communication networks in a disaster context.

1. ***Device Mobility and device mobility threshold***
   represent the frequency of messages. A device has a high mobility value if it has relayed a higher number of messages, based on the assumption that the more a person moves, the more messages he/she collects on their device. This metric is proposed by Franke et al. [149] focus on examining mobility and access points, human body temperature, line of sight etc to evaluate the feasibility of their proposed ad hoc system. Franke et al. [149] also propose the Last Seen and the Last seen threshold metrics.

2. ***Last Seen and the Last seen threshold***
   are used to measure how long a device has been connected or disconnected from a network. This metric is also used as a quality check. For example if the number of messages a node has exchanged is very low this means that it has not encountered anyone and is outside the coverage area.

3. ***Reachability***
   is used to measure the number of hops required to send the entirety of a message from sender to receiver. It is first proposed to evaluate a routing protocol called Lifenet [137].

4. ***Coverage Efficiency***
   expresses the effectiveness of a proposed algorithm in terms of achieved coverage vs the required time to reach it. This is proposed by Pagliari et al. [37] and is used specifically to evaluate the impact of changing population density and how quickly a message can be spread over a certain area. This metric can be very useful in estimating how quickly a disaster information can reach a community over time.
5. ***Consumption Threshold***
   proposed by Cheong,Lee,Si, et al. [67] is used to measure the remaining battery charge of a phone before it is triggered for a boot-up process.
6. ***The Energy Factor***
   is used to define the ratio of available battery charge to total battery capacity of a device. This is proposed by Aloi et al. [89] among other factors to determine the role of a device in a self-organising network.
7. ***The Congestion Factor***
   is another factor considered by Aloi et al. [89]. The Congestion factor is a measure of the network congestion. Aloi et al. [89] chose this formulation to reduce higher packet drop probability caused by higher queue occupation and because each message is equally important during disasters. Other advantages are the local computation of the metric value without introducing additional network overhead.
8. ***Participatory Fairness***
   proposed by Banerjee et al.[150] to measure distribution of energy loss for all phones when phones have disparity of battery charge. The participatory fairness of a phone battery charge distribution is calculated with the Gini coefficient. Participatory fairness in an ”Self-Organisation for Survival” (SOS) peer to peer communication network is used to show that initial inequality in phone battery charges is reduced over time leading to equal communication opportunities for all citizens. Participation is then calculated using Node Participation as described below.
9. ***Node Participation***
   proposed by Banerjee et al. [150] is used to calculate the number of phones that are able to send and receive messages over time. For the SOS approach the authors calculated the number of nodes that were able to send messages over a period of 72 hours.

3.11 Conclusion

This study reviews the current literature on technologies designed to facilitate communication between citizens during disasters. The essential properties of these communication systems are evaluated and the requirements these disaster communication systems have are identified. Despite the existence of a large number of mobile applications that are designed for citizen-centric communication during disasters, most of these mobile applications do not consider the dynamic context of disasters, thus limiting their deployment potential.

For example, population density, message frequency, and disparity between the battery charge in devices used, coverage efficiency etc. These properties were and currently only evaluated by select few papers. For better evaluation these properties need to be more actively considered.

One of the more significant findings from this study is that there is a shift towards using context-awareness to capture the dynamic requirements of a disaster communication system. Applications such as SENSE-ME [89] or STEMNET [193] have proposed the use of self-organisation and context-awareness to introduce adaptivity to tackle the dynamic disaster context.

The second major finding is the relevance of energy efficiency in the design for successful deployment of citizen-centric communication networks. The majority of literature acknowledges that a limited battery charge or other resource constraints of mobile phones deployed in ad hoc networks during disaster is a major challenge that can limit the successful deployment of disaster communication networks. However, energy efficiency is still not universally evaluated.

The very success of every design depends on whether the devices have enough resources to deliver the services designed. The past decade have utilised mechanisms that were designed for sensor networks for energy efficiency. There is however, a rise towards using BLE for energy saving.

As a recommendation, this paper proposes that developers focus more on systems that are reflective of a disaster situation and context of use. It is also important to know who is going to deploy the communication network, and who is going to own these systems.

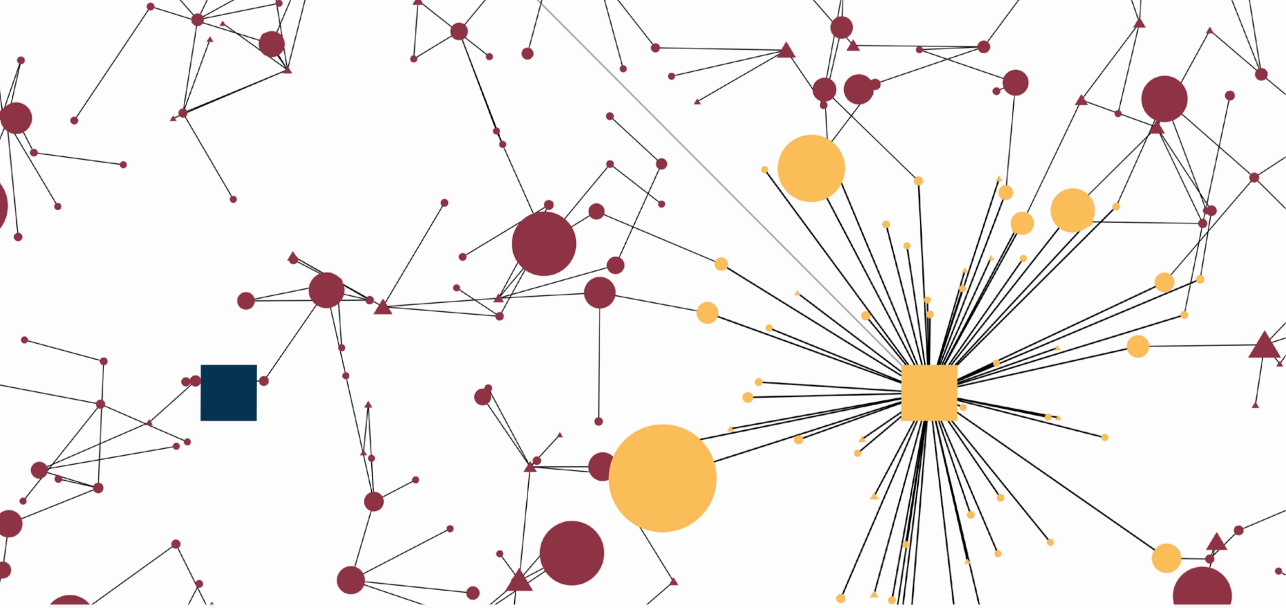
Additionally, cost and digital literacy plays an important role. In this review, the price of these systems was not considered, which is a limitation.

In regard to a communication service that is being deployed in a disaster context, thorough investigation of "citizen participation" is considered to be a crucial human value that emergency system must deliver [19, 233]. One possible way to proceed is to introduce value-based design or value-sensitive design as an approach to define and design these citizen-centric communication networks.

Value-based or value sensitive design (VSD) is an approach to the design of technology that accounts for human values in a principled and comprehensive way [78]. Values are important and hence it is important to make them explicit. That will help with new metrics that are very specific and more representative of values. Some of such metrics have been encountered in coverage efficiency, last-seen, energy factor etc.

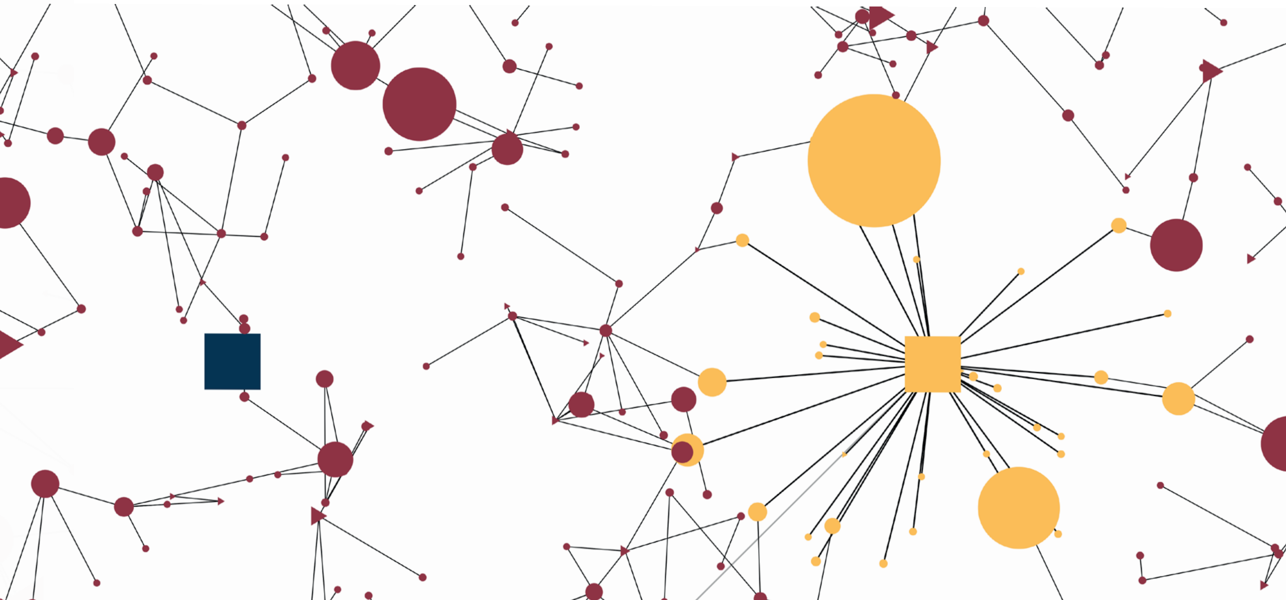
These metrics are different from operational metrics used for testing message throughput, delay and time to live. Disaster communication systems focused on providing communication and participation to citizens are deployed in a highly dynamic context and have multiple factors that impact use and design as discussed.

Part 3



Design & Evaluation

Contents



Chapter 4

कर्मण्येवाधिकारस्ते मा फलेषु कदाचन।
मा कर्मफलहेतुर्भूर्मा ते सङ्गोऽस्त्वकर्मणि॥

You have the right to work
without any entitlement to the fruits.
Let not the fruits be your motive,
nor let your attachment to the fruits lead to inaction.

This chapter is published as
Banerjee, Indushree, Martijn, Warnier, and Frances M T Brazier. "*Self-organizing topology for energy-efficient ad-hoc communication networks of mobile devices.*" in Complex Adaptive Systems Modeling 8, no. 1 (2020): 1-21.

DESIGNING SOS

SELF-ORGANISATION FOR SURVIVAL

4.1 Introduction

Connectivity is essential to today's society, and relies heavily on the availability and reliability of physical network infrastructures [11]. There are, however, periods of time when physical network infrastructures fail, for example due to cascading failures, extreme weather events, humanitarian crises or intentional shutdown of communication infrastructures [234, 235].

In these periods mobile ad-hoc networks (MANETs), i.e., infrastructure-less communication networks, can provide an alternative [236–239]. The performance of MANETs depend on its dynamic context characterized by the mobility of devices, changing density of devices, and depleting battery charge of nodes [89, 113, 240–242]. To ensure efficient MANET deployment, adaptive use of available energy resources is required within such dynamic contexts [243, 244].

To address this challenge this paper proposes a decentralized adaptive topology control protocol consisting of three algorithms. The algorithms use context information on the available energy of nodes as a basis for preferential attachment. This leads to the formation of a loop-free scale-free adaptive topology for an ad-hoc communication network. The novelty of the proposed protocol is that it allows for energy efficiency without any adaption on the hardware level as the adaptations are made at the level of topology. There is no manipulation on the physical layer or the link layer to mitigate limited battery charge of participating nodes [245, 246].

The protocol's performance is evaluated in terms of reliability, scalability and longevity of the network. Reliability is defined as the assurance that a message that is sent from one device to another will be delivered. Scalability is defined as the ability of the network to scale up or down with respect to the number of available devices without affecting its primary goal of reliable communication. Finally, longevity is defined as the lifetime of a MANET and depends upon efficient energy utilization. The rest of the chapter is structured as follows.

Section Background: Forms of energy consumption in ad hoc networks discusses energy consumption in mobile ad hoc networks, followed by a review of different approaches proposed in the literature for energy efficiency through topology creation and maintenance. The knowledge gap identified is that of context-adaptive topologies.

In Methodology: Protocol design and Pseudo-code of algorithms section, three algorithms that constitute the decentralized context-aware adaptive topology creation protocol are presented.

In Section Protocol evaluation and performance analysis, modeling and simulation used to evaluate the performance of the proposed protocol are presented. This is followed by the results section. The next section presents a comparative analysis with existing work. Finally the last section, concludes the article and proposes future work.

4.1.1 Energy efficiency approaches in ad-hoc networks

Current approaches on energy efficiency mainly focus on reducing energy associated with the routing procedure. A generic approach is to optimize the route by decreasing the number of hops to decrease relaying cost in order to increase performance and decrease delay in message delivery. Examples of protocols that follow this approach are Dynamic source routing (DSR), Ad-hoc on demand distance vector routing (AODV), Dynamic distance-vector routing (DSDV), Optimum link state routing (OLSR), Zone routing protocol (ZRP), and Location aware routing (LAR) [247–250].

These approaches either conserve individual node energy promoting opportunistic behaviour [223–225], or they focus on extending the entire lifetime of a network by minimizing total cost of transmitting a message from source to destination by choosing only high energy nodes depleting specific nodes faster [212, 222]. In short, some approaches have been shown to work relatively well in stable environments of densely populated areas whereas some approaches such as Delay tolerant networks (DTNs) work better in sparsely populated areas [251].

Energy efficiency however, requires not only efficient routing but also an effective and efficient topology. A topology determines the layout of connections between devices along which messages can be exchanged.

A route is defined by the nodes/hops [1] it follows and is very context-dependent. Both refer to a device that has a Wi-Fi or Bluetooth interface and can join other devices that are part of a network within its transmission range, such as a mobile phone.

1 Note that the terms nodes and devices are used interchangeably in this paper.

To maintain connectivity, a topology should ideally reflect this dynamic context to avoid high end-to-end delay and high energy consumption [215, 252]. To control the creation and maintenance of a topology various mechanisms are deployed.

4.1.2 Existing topology control mechanisms

Topology control mechanisms in the literature distinguishes function either by manipulating the transmission range (power control) or by allotting roles to nodes (topology management). Both have the capability of providing energy efficiency but are different in their approaches as explained below.

• **Topology control by Power Control:** A power control approach creates and maintains a topology by manipulating the transmission range [214, 217]. This option is considered beneficial in sensor networks where transmission ranges can be varied with a predetermined purpose [253]. However in most communication devices, the transmission range is fixed. Hence this approach is impractical for mobile phones. This paper focuses on mobile phones hence approaches for energy efficiency in wireless sensor networks are out of scope.

• **Topology control by Topology Management:** An alternative approach is to assign roles to nodes in a topology or clustering [254]. A topology is either flat, hierarchical or a hybrid of both. In a flat topology, all nodes have the same role in communication. In contrast, in a hierarchical topology leader roles are assigned based on, for example, a node's resources or number of connections to other nodes (node degree). Nodes with a high battery charge or a high number of connections are declared leaders. All other nodes communicate with each other via these leader nodes. This reduces transmission and routing energy cost by removing one-to-one links and building new links via these leader nodes.

There are two drawbacks to this type of approach during a power outage.

First, it is difficult to assign leader roles based on node resources, as these cannot be known in advance and change over time as the battery charge is used. Second, it is difficult to predict the density of participating devices in a given vicinity at any point in time [255].

To summarize, current approaches to the design of infrastructure-less communication networks are based on predetermined assumptions that (by definition) lack consideration of energy constraints of individual nodes or changing context. The context as defined by mobility and density of mobile phones, varies by a geographic area as does availability of charging facilities. Designing an adaptive distributed topology is a necessity to ensure reliability of message delivery and maximize the probability of finding new high energy nodes, especially given that nodes only have a local view. Thus, an energy-efficient decentralized approach for self-organization is needed with context-adaptive topology.

4.2 Protocol design and pseudo-code of algorithms

This section describes the design[2] of a decentralized adaptive topology control protocol. The protocol consists of three separate algorithms that work together to create and maintain a topology that allows message exchange over an ad hoc communication network, while maintaining reliability, scalability and longevity.

2. The initial design of SOS is given in this chapter. A further evolved design of algorithms and pseudo-codes are presented in Appendix.

The algorithms use spatio-temporal resource information of individual nodes and the nodes in their transmission range to determine their local context information. This information is used by each node for preferential attachment to form a loop-free scale-free adaptive topology for an ad-hoc communication network. Algorithm 1 creates the topology for a mobile ad-hoc network, followed by algorithm 2 that allows nodes to communicate and finally algorithm 3 that maintains the topology by reconfiguring to ensure reliability, longevity and scalability.

An ad-hoc network is conceptualized as a undirected graph with devices as nodes and connections as edges. Each node maintains its own context information tuple ***t*** as depicted in Table 1, and it consists of a unique identifier (U_{id}), a unique sub-tree identifier (S_{id}), the amount of battery charge left (e) and the view l_v.

Each node also maintains its local view of its neighbours (l_v) within its transmission range (r). This view contains spatio-temporal resource information and is updated as the node changes location.

Specifically, the view (l_v) is a list of

[i] a unique identifier of potential neighbours to which it can connect in its transmission range and

[ii] their energy or battery life left at that point in time.

The view is guaranteed to change and is updated continuously as neighbouring nodes move in and out of transmission range.

To form a connection, a node chooses to connect with only one other node from its local view (l_v): the node with the highest battery charge left. As each node follows this procedure independently, nodes with the highest residual energy will 'automatically' take a more critical central position in the network.

To prevent loops in the network (and thus redundant connections that need to be maintained and cost energy) each node compares the sub-tree ID in its individual view with that of the to-be-connected node before connecting to another node. If their sub-tree IDs do not match indicating they belong to separate networks they connect, otherwise the node tries to connect to the node with the second highest energy within its transmission range, etc.

Once this condition is fulfilled, the nodes exchange the context information an information tuple t given in Table 5. Control information is only exchanged between nodes that wish to connect.

3. An illustration of the entire process in given in Chapter 9

The procedure of getting connected and preventing loops is explained below in more detail[3].

Table 5: The information stored in ***t*** is exchanged with other nodes within a node's transmission range ***r***

t	Type
U_{id}	Unique Identification number of the node
S_{id}	The unique network number, where this node is connected. When disconnected set to its own unique identification number
e	Battery charge or residual energy of the node
l_v	View: List of potential nodes for connection and their residual energy in the transmission range, initially empty.

4.2.1 *Creation: The connection procedure*

The process starts with each node maintaining its own information tuple t. Initially a new node is not part of a network. In this case the sub-tree identifier S_{id} is set equal to its own unique identifier U_{id}. As nodes turn on their Bluetooth interface, they start discovering neighbouring nodes in their transmission range *r*. They receive information from neighbours in their transmission range on which they form their l_v.

Algorithm 1 Connection Procedure followed by each node in Transmission range ***r***

1: $t \leftarrow U_{id}, e, S_{id}, l_v$
2: Set $U_{id} = S_{id}$
3: Node A scans for neighbors in *r*
4: $l_v \leftarrow D_{Sid,e}, c_{Sid,e}, B_{Sid,e}$, ...
5: Sort lv neighbors with highest energy e first
6: $l_v \leftarrow B_e > D_e > C_e$, ...
7: **while** Node A not connected to a network **do**
8: Match the S_{id} of Node A with the S_{id} of Node B
9: **if** Node A' S_{id} != Node B' S_{id} then
10: Node A gets connected to Node B
11: Set Node AS_{id} = Node BS_{id}
12: Break
13: **else**
14: Node A does not connect to Node B
15: Repeats step 8 for next candidate in l_v
16: **EndIf**
17: **EndWhile**

From l_v, each node then considers the residual energy of all of the potential nodes in its view to which it can potentially connect and sorts them in order of neighbours with the highest residual battery charge first. The neighbour with the highest residual battery charge left is selected and the sub-tree IDs of both nodes are compared. This ensures that the new connection is part of a different sub-tree (representing a different, as of yet not connected, network).

If they have the same S_{id} this indicates that the nodes are connected through different nodes in the same network that might not be visible to the node, and if they connect they create a loop.

Hence they only connect if the S_{id} are different to ensure a loop-free network.

The node that initiates the connection changes its sub-tree identifier to match the network to which it wishes to connect. This procedure maintains uniformity among the network and additionally the uniqueness of each network. The pseudo-code for this procedure is shown below in Algorithm 1. Figure 5 shows the emergence of a connected network following Algorithm 1. The next section describes message delivery.

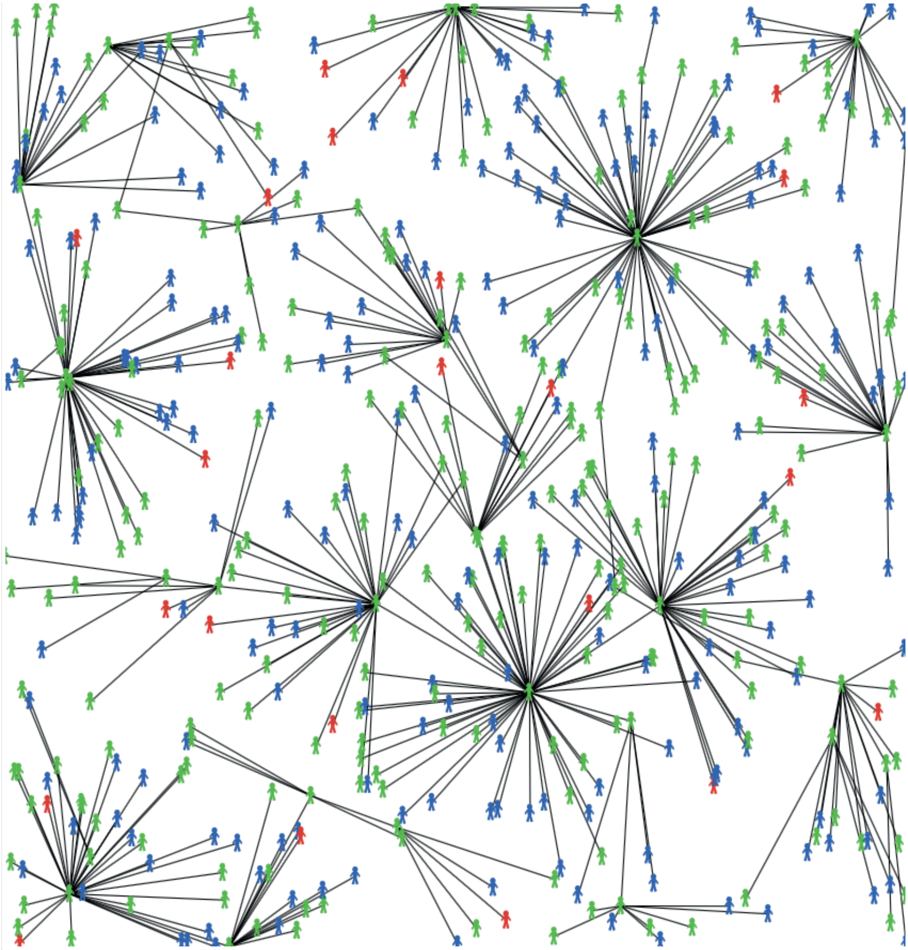


Figure 5: An example of an emerged network of 500 nodes spread over an area of 25x25 with a transmission range of 5. The picture shows the visualization of the network in the simulation environment NetLogo (see Protocol evaluation and performance analysis)

4.2.2 Communication: The message exchange procedure

As described above in the introduction, this paper focuses on the design and development of an self-adaptive topology and not on the design of a new routing protocol. Hence any routing protocol that works on the proposed topology to return a route enquiry based on shortest route between sender and receiver can be used. The algorithm described in this section works after Algorithm 1 has created a network and a node decides to communicate. Based on route enquiry, the node decides when to trigger a reconfiguration. It triggers reconfiguration of the topology (1) to maintain connectivity for reliably sending a message when no route is present and (2) to ensure that the loss of energy for relaying messages is distributed among various high energy nodes.

Algorithm 2 below determines the need for reconfiguration. Initially a Sender node sends a route inquiry using a routing protocol. This inquiry is to confirm if a route exists through which a message can be sent. Two results are pos- sible. First, the relay nodes confirm that they have energy left to relay the message and that they are still part of the network. In this case the Sender node forwards the actual message to the next hop or relay in the network. Second, the Sender node receives a response that no route is possible.

Algorithm 2 Sending and receiving information protocol followed by each node connected to a network

Sender sends a route inquiry
if No Route found **then**
    if Connected to a Network **then**
        Ask connected neighbours to Reconfigure
    else Not connected to any Network
        Self Reconfigure
else Route found
    Send information to next hop in the route
EndIf

The absence of a route can happen if the network has become temporarily fragmented. Network fragmentation can be due to relay nodes moving out of transmission range or one or more relay nodes leaving the network due to exhausted battery charge. In this case the Sender node stores the message as pending and triggers the reconfiguration algorithm. It confirms if it is part of a network. If the response is true, it triggers a reconfiguration only for the local neighbours connected to it.

In case the node is completely disconnected, it reconfigures itself to find new network or neighbouring nodes to connect with, in its transmission range. Reconfiguration allows nodes to adapt to the dynamic environment and change their connections thus providing new routing options. This reconfiguration Algorithm 3 is explained in the next section and addresses the challenge of creating dynamic self-adaptive self-organised topology.

4.2.3 Maintenance: The event-driven reconfiguration and relabeling procedure

Reconfiguration using Algorithm 3 is proposed to ensure reliable message communication despite network segmentation. While relaying a message a route can be unavailable due to mobility of devices or nodes leaving due to loss of energy. In this case the relaying node is informed to reconfigure. During reconfiguration, the relaying node looks for new connections in its transmission range to connect with the highest battery charge left belonging to a different network. Each node follows three steps during this adaptive reconfiguration process. Each step ensures that the network keeps updating the changing availability of high energy nodes while considering the mobility and density of the dynamic context. This ensures that nodes are connected with a new network and routes exist for the delivery of messages.

Algorithm 3 Adaptive reconfiguration and relabeling followed by a node A

$l_v \leftarrow t_B, t_C, t_D, t_E, t_M, t_N$
    ▷ list l_v is newly generated by exploring other nodes within transmission range
Remove links with nodes with low battery charge
$l_v \leftarrow t_B, t_D, t_M, t_N$
    ▷ list l_v is updated by removing nodes C and E
Remove links out of transmission range r
$l_v \leftarrow t_B, t_N$
    ▷ list l_v is updated by removing nodes D and M
Relabel node sub-tree id's using:
procedure Relabel (Node)
    if S_{id} != $u_{id}(A)$ then
        Set $S_{id} = u_{id}(A)$
        Relabel(connected nodes)
    else break
Connect to new nodes by following Algorithm 1

In the first step a node, let's call it A, disconnects from any node that either has no battery charge left or is running so low on charge that it will not be able to receive any more messages. In the second step nodes that are no longer within the transmission range are removed from the node's local view lv and their possible links are disconnected. If all connections were removed during the previous steps then the node also changes its own sub-tree identifier back to its own unique identifier and it recursively asks all still connected nodes to change their sub-tree identifier back to the caller's unique identifier i.e., to the unique identifier of node A. This ensures that all subnetworks that emerge from this step have unique identifiers, thereby maintaining consistency.

In the final step the node looks for possible new neighbours to which to connect. As nodes are mobile, they follow the same connection procedure described before in Algorithm 1 to prevent loops and still connect to new nodes with high energy. This results in a newly connected network with a different topology and new routes for message exchange. Once these three steps are completed the design goal of ensuring reliable message delivery, scalability and longevity of the network at different density and mobility is achieved.

4.3 Protocol evaluation and performance analysis

This section presents the implementation of the algorithms and simulations that were run to evaluate the performance. To focus on interaction of autonomous agents, needed for self-organisation and emergence NetLogo was chosen over alternatives such as ns-2, ns-3 and OMNeT++, as a level of abstraction for the changing spatio-temporal context of mobile devices [256–259] (rather than the simulators used in electronic engineering for studying hardware-level modifications).

4.3.1 Modelling an ad-hoc communication network

The model assumes a two-dimensional square world divided into a grid. Agents[4] move freely over the grid and interact. The size of the world can be changed so that the agent density can be controlled. NetLogo executes the algorithms for each agent individually and once all agents have completed their computations the simulation time, denoted as a tick, is incremented by one and every node again executes the algorithms outlined in the previous section, etc.

4 Formally, agents represent nodes which can be mobile devices. These terms are used interchangeably in this paper.

Agents represent devices/nodes, each with their own battery capacity. Different types of devices are modelled: a percentage of high-end phones such as Apple iPhones (with a maximum battery charge of 3000mAh) and a percentage of low-end budget phones, non-smartphones such as earlier versions of Nokia or Samsung (with maximum battery capacity of 2000mAh). The average assumed battery capacity is 2500mAh. To replicate a resource-constrained environment with sudden power loss, batteries are on average assumed to be 60% charged thus with an average charge of around 1500mAh. From a normal distribution with a mean of 1500mAh and a standard deviation of 275mAh values are drawn to initialize the battery charge of each agent.

Phones are assumed to use Bluetooth Low Energy (BLE) to make direct peer-to-peer connections to other agents within their transmission range (***r***). All agents are assumed to have the same transmission range. Agents can only directly send and receive messages with other agents within their transmission range. This paper assumes a transmission range of 5 units (in NetLogo) unless otherwise indicated. How this translates to actual values in more realistic environments is outside the scope of the paper. Furthermore, each agent is initialized at a random starting position in the grid, where agents can move independently at a fixed constant speed, turning randomly. Following connection procedure Algorithm 1 a scale-free network emerges with agents with high battery capacity at central locations in the network.

The algorithms from Section Methodology: Protocol design and Pseudo-code of algorithms are implemented in NetLogo agents, whereby each action, i.e., either getting connected, sending or receiving messages, or reconfiguring has an associated energy cost. At each iteration, sender agents are selected to send messages to other agents selected as receiver agents. Each sender agent enquires a route and if route is present relays the message to the next relay or hop in the route. The next relay node or hop relays the message in the next tick. If route is not present it triggers a reconfiguration.

The transmission range, residual battery capacity, the cost of sending, receiving, and relaying messages, and the cost of reconfiguration are all based on empirical results for BLE 5.0 [260] on mobile devices. Table 6 shows the cost associated with sending, receiving and relaying a single message over the network by a mobile device.

Table 6: Energy consumption associated with sending and receiving a single SMS over a BLE connection [260].

Activity	Power draw(mA)	Duration (mS)	Size bytes	Time*Current (mAmS)
Wakeup Preprocessing	5	1000		5000
Receiving (Rx)	22	1120	140	24620
Inter Frame Space (IFS)	15	150		2250
Transmission (Tx)	28	1120	140	31360
Post Processing	8	1400		11200
Total Time		4790		
Total Time * current				74450

To calculate the energy consumption of a node, each action is converted to same unit of milliAmpere per minute. Table 8 is used to calculate the battery cost of sending and receiving messages. Other actions and their associated energy cost involved such as wakeup preprocessing, Inter Frame Space (IFS) and post processing are also defined in the table for the Bluetooth connection procedure [261].

During the simulation set-up, each node loses battery charge based on these activities. When the node follows Algorithm 2 for communication, it loses energy based on the size of the message. Each message is assumed to be 140 bytes long.

The amount of lost battery charge is calculated as the product of the power drawn per byte (in milliWatts) and the duration associated with sending the message (in miliseconds). Using Ohm's law, the product is then converted to milliAmpere-minute, that represent the cost of sending or receiving per message.

Relaying is the sum of the cost associated with sending and receiving. Every node also has a specific cost associated with advertising its view multiplied by the number of neighbors in its view [261]. Once an agent connects to the network, the next step is to send or receive information. Algorithm 2 is executed by agents as explained above in the message exchange procedure.

To analyze the performance of the protocol (all the algorithms together) and validate the expected energy efficiency, a set of experiments have been designed to evaluate longevity, reliability and scalability of the proposed approach. Density, population (number of agents) and transmission range are varied to simulate the dynamic circumstances under which the protocol is envisioned to function.

4.3.2 Longevity evaluation

The first experiment is designed to evaluate the longevity of the network. The longevity of the network is measured as the lifetime of the network, where participating nodes are able to communicate. In this evaluation a 3x3 factorial experiment is used with varied density and transmission ranges. The number of nodes and repetition are kept constant. To vary the density area is changed. Therefore, 0.39 density equals 100 nodes in a area of 17 x 17, followed by 0.17 where the area is 25x25, and finally by 0.04 which equals area of 50x50.

For each density, the number of messages exchanged also varies from 1 message per node to 5 messages and finally to 10 messages per node.

The outcome is the amount of time in ticks it takes before there are only 10% nodes are left with battery capacity to communicate. Density is manipulated by varying the canvas size of the world in NetLogo 6.0.4, keeping the number of nodes constant. The parameter settings for this experiment are given in Table 7.

Table 7: Longevity evaluation parameters for varying density and message exchange.

Parameter	Value
Number of nodes	100
Density	0.39, 0.17, 0.04
Transmission range	5
Total messages sent and received per iteration	1, 5, 10 (per node)
Repetition	100

4.3.3 Scalability evaluation

To evaluate scalability, i.e., whether the network can scale and up and down with a changing population (number of nodes), the density is fixed and the population is varied. Density is again defined as the number of nodes per unit of area and calculated by dividing the population by the unit area. In this evaluation the simulation area varies according to the population that varies between 50, 100 and 200 to maintain the density.

For example for 50 nodes the area is fixed at 35x35 providing a density of 0.04. To keep the density fixed, the area changes as the population changes, therefore, for 100 nodes the area is 51x51, for 200 nodes the area is 71x71. For each population, the number of messages exchanged also varies from 1 message per node to 5 messages and finally to 10 messages per node.
Each simulation cycle the transmission range remains the same with 5 units.

The battery charge assumptions are similar to the earlier longevity evaluation. This experimental evaluation is again repeated with 100 runs for each population size and parameters given in Table 8.

In the last of the experiments, density is varied by varying the number of nodes between 50, 100 and 200, keeping the area constant at 25x25. This gives us a density of 0.08, 0.16 and 0.32. In each case nodes sent either 1, 5 or 10 messages. The settings are provided in Table 9.

Table 8: Scalability evaluation parameters. Population is varied for fixed density.

Parameter	Value
Number of nodes	50, 100, 200
Density	0.04
Transmission range	5
Total messages sent & received per iteration	1, 5, 10 (per node)
Repetition	100

Table 9: Scalability evaluation parameters. Density is varied for fixed area of 25x25.

Parameter	Value
Number of nodes	50, 100, 200
Density	0.08, 0.16, 0.32
Transmission range	5
Total messages sent & received per iteration	1, 5, 10 (per node)
Repetition	100

4.3.4 Reliability evaluation

To determine if messages are reliably sent and received this experiment is designed to determine the number of undelivered messages throughout the whole network lifetime the same experiment setting as scalability. The evaluation parameters are same as depicted in Table 8 and are similar to before.

4.4 Results and discussion

This section presents the results from the experiments discussed in the previous section. Three major performance outcomes are considered, as described above: longevity, scalability and reliability.

4.4.1 Longevity

The evaluation varies the density across three levels, and the number of messages sent range across three different levels, for a 3 by 3 design. As a test of statistical significance, Analyses of Variance (ANOVA) were performed[262]. The main effects of the density and number of messages, and the interaction effect of density and number of messages, on longevity, were examined, to test if longevity would be affected by differences in density and number of messages. Longevity was significantly different for different densities ($F(2, 891) = 52293.5$, $p < 0.001$). Longevity was different for different number of messages sent ($F(2, 891) = 64164.4$, $p < 0.001$). The effect of the number of messages sent on longevity was significantly different for different densities ($F(4, 891) = 7707.6$, $p < 0.001$).

Figure 6 shows that for the sparse density of 0.04, the simulation runs longer in comparison to higher densities of 0.17 and 0.39. This can be explained because when the density is very low the chances of getting connected and relaying reduce, hence the simulation runs longer. However, the nodes are disconnected with hardly any routes to relay. In a medium dense area represented with density 0.17, the longevity is lower than for a sparsely populated area because there are higher chances of being connected but longer relaying routes, thus increasing the number of relays and minimizing the lifetime.

In 0.39, the chances of a higher number of relays with higher energy is more than for other densities. Thus agents/nodes can stay connected longer than

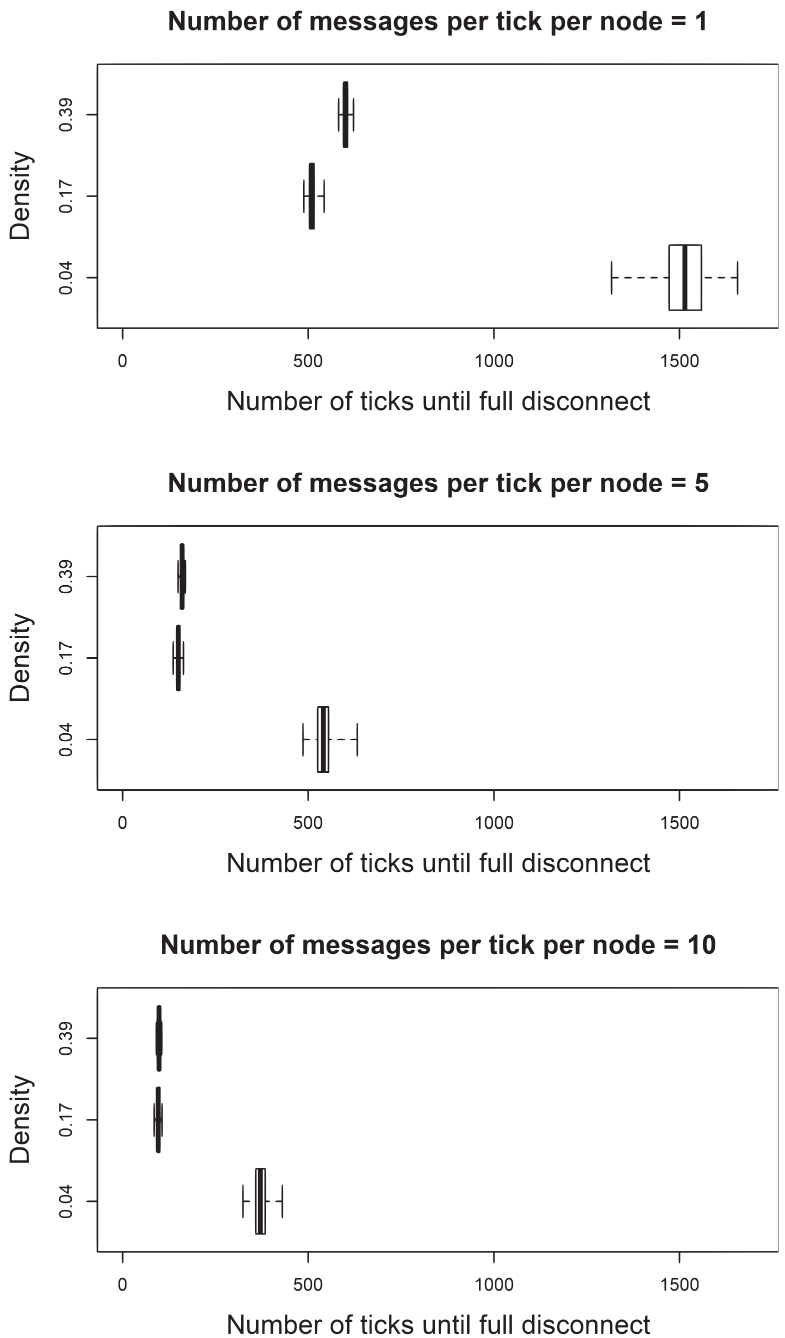


Figure 6: The longevity of the network for 100 nodes at different densities and transmission ranges

with density 0.17 but since it provides ample opportunity to form a network, it runs longer than 0.04. Similarly, the effect of number of messages can be easily seen on a lower density as sending a single message does not require too many reconfigurations. However when there are multiple messages to be sent, the nodes need to reconfigure a lot to find routes for pending messages.

This explains the declined longevity in sparsely populated areas for sending multiple messages. Whereas for densely populated areas, the number of messages does not cause many changes in their longevity due to the nodes being connected and relays being present. Higher density implies more connections being formed during the lifetime of the network. Note that run times of real networks will be highly dependent on specific circumstances such as actual battery charges and number of messages sent.

4.4.2 Scalability

To assess scalability, the effect of the number of nodes on the time it takes for the network to stop functioning is evaluated. The number of nodes is varied between 50,100 and 200, while the density is kept constant at 0.04 by changing the simulation area accordingly. The number of message exchanged is varied between 1, 5 and 10.

Scalability was significantly different for different numbers of nodes ($F(2, 891) = 1175.8$, $p < 0.001$). Scalability was different for different number of messages sent ($F(2, 891) = 30625.7$, $p < 0.001$). The effect of the number of messages sent on scalability was significantly different for different numbers of nodes ($F(4, 891) = 15.6$, $p < 0.001$). Figure 7 shows that the run time of the network extends as the population size increases. This can be explained as follows:

As the battery charges of the devices are assumed to be distributed as a normal distribution (see previous section), for higher population sizes, the total number of nodes with high battery charge is higher. With a higher total number of nodes there are significantly more high energy node outliers with a residual battery capacity that is higher than the rest. These nodes are crucial in the functioning of the network, because they use a relatively large amount of energy for routing purposes.

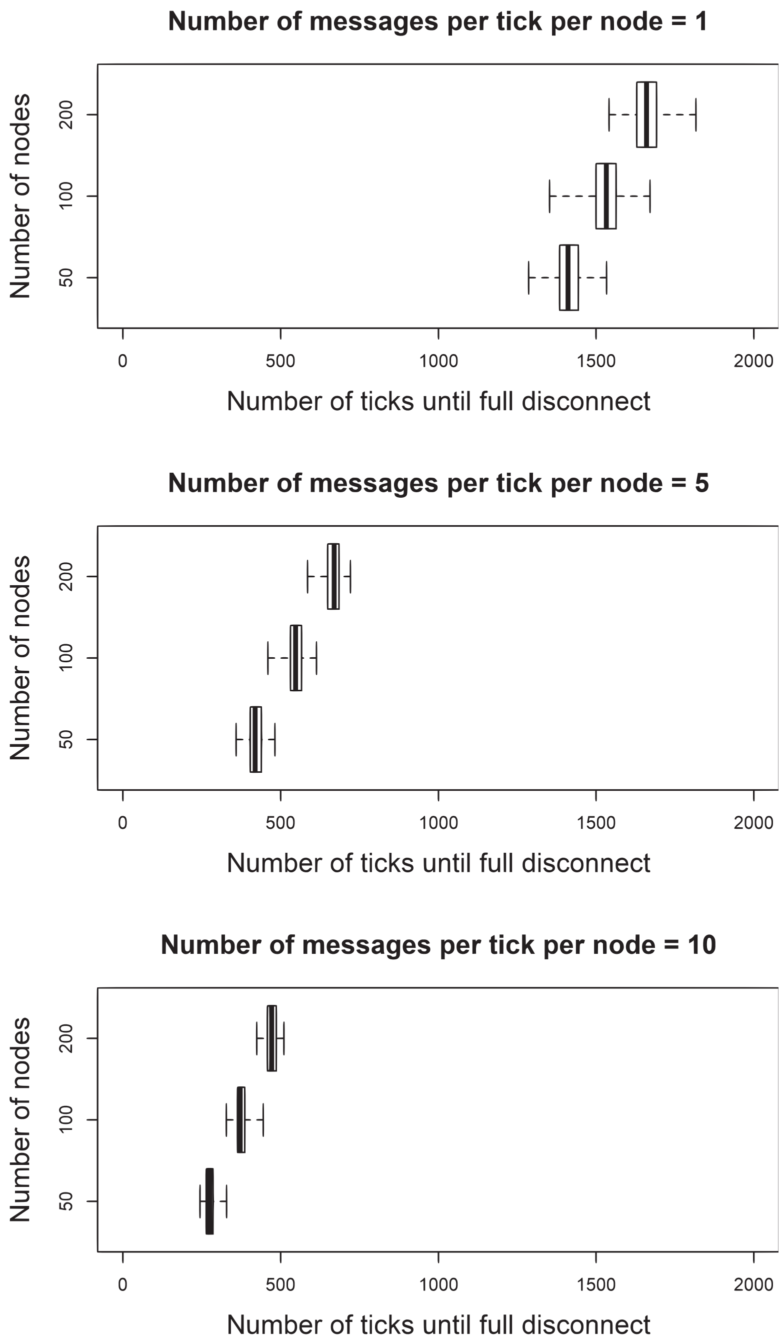


Figure 7: The scalability plot of the network for different population at fixed density = 0.04 and transmission range = 5.

While the average routing length in the network becomes higher, the larger number of high-energy nodes mitigates this effect and prolongs the lifetime of the network. On the contrary for smaller populations such as 50 nodes, the number of nodes with a high battery capacity is small due to the initialization using a normal distribution. This results in a few critical nodes and thus lower run times. With the assumption that battery charge in a population is normally distributed, the presented algorithm shows that it scales up for larger population sizes.

The effect of number of messages is same as longevity, higher frequency of messages results in more sending, receiving and relaying along with pending messages. Thus for lower frequency of just one message, the network runs longer. However, for higher frequency there is significant decrease in the run time. The assumption that the battery charge is normally distributed for a random population sample is unverifiable. Actual real life experiments are needed to evaluate this further, but the presented results show promise.

In the previous simulations, density was either kept constant, or the density was varied by keeping the number of nodes constant in a varying area. Density can also be varied by keeping the area constant, while the number of nodes is varied. This allows for the assessment of the effect of introducing more nodes. As the population increases, the number of connections and relays increase as well. As can be seen in figure 8, the simulation runs longer for a sparse population. However, the effect of relaying seems to be much smaller than the effect of the number of connections for denser populations: A higher message frequency has little impact.

4.4.3 Reliability

To evaluate the reliability of messages, the number of messages sent, received and failed were calculated for the same settings as when evaluating scalability. Reliability was significantly different for different numbers of nodes ($F(2, 891) = 853.8$, $p < 0.001$). Reliability was different for different number of messages sent ($F(2, 891) = 1204.7$, $p < 0.001$). The effect of the number of messages sent on reliability was significantly different for different numbers of nodes ($F(4, 891) = 8.5$, $p < 0.001$).

Figure 9 displays the boxplot with x-axis representing the percentage of messages delivered ranging from 0 to 100% and y-axis representing the increasing

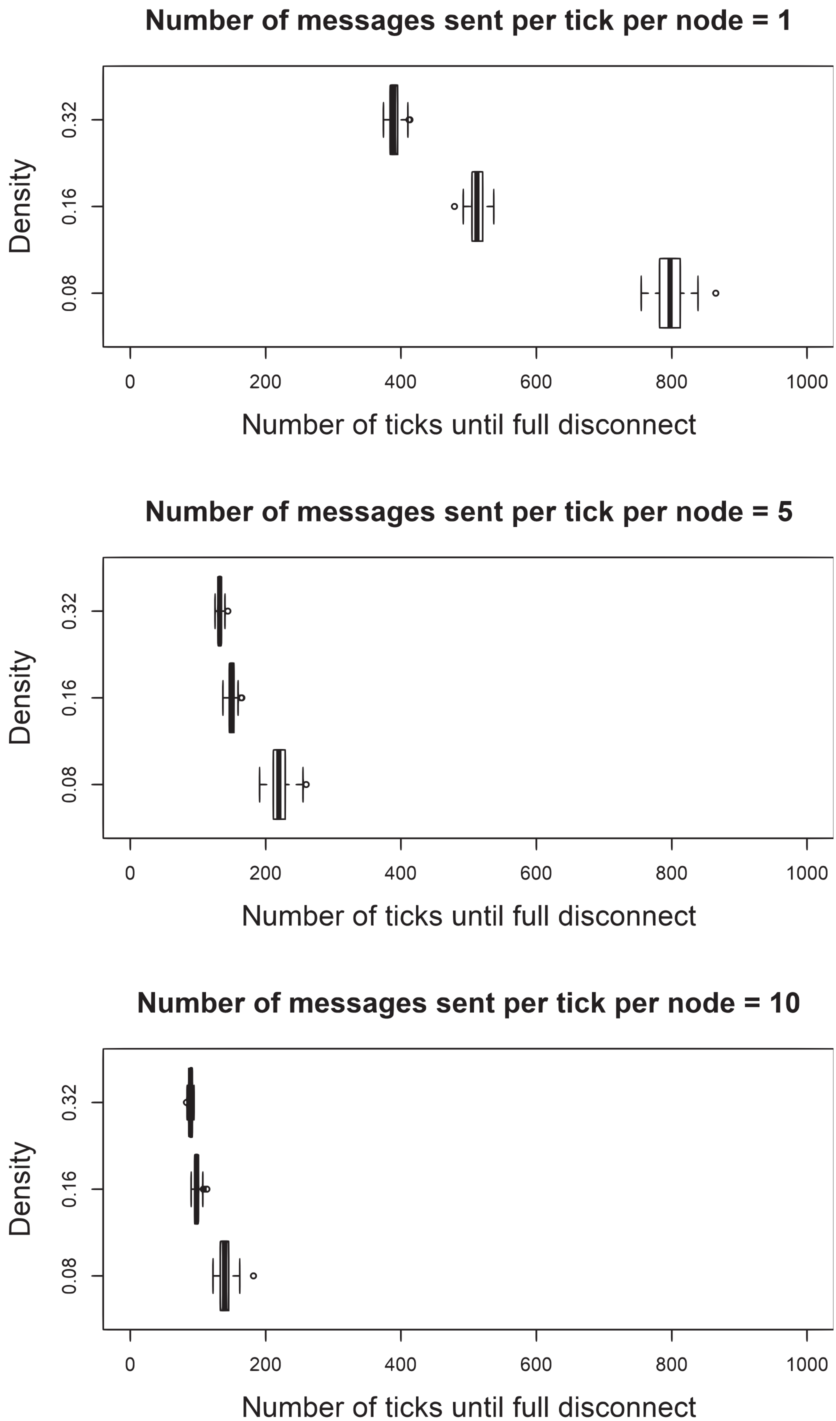


Figure 8: The scalability plot of the network for different densities at fixed area = 25x25 and transmission range = 5.

number of nodes. In all scenarios, the reliability is always observed above 80%. Thus in general most messages are delivered, unless the receiver dies before the message is relayed to it.

There is a difference observed while varying number of nodes. This is because a sparsely populated network runs longer than a densely populated network, thus giving nodes more time to stay alive and deliver messages when there is an encounter and a network forms.

Whereas in a densely populated area, the nodes quickly die as there is a network present and more relaying is done. If nodes die quickly, a central node when leaving the network can result in many messages being dropping. This explains the similar trend observed while frequency of mes- sages being sent is varied. However, the reliability remains above 80% in all densities and frequency of messages.

4.5 Comparative analysis: Similarities and differences with existing work

To the authors' knowledge there is no existing work that achieves energy efficiency through topology control for mobile ad hoc networks of mobile phones, with little preparation needed in advance. The proposed solution is positioned at the intersection of three research areas, each of which are described below in more depth:

- Hybrid ad-hoc networks: mobile ad hoc networks that focus primarily on restoration of existing infrastructure, centrally designing and maintaining a new topology positioning wireless access points (and UAVs) strategically with respect to stationary access points to acquire connectivity.
- Wireless sensor networks: mobile ad hoc networks that specifically cater to power-constrained sensors and focus on energy efficiency of these sensors with respect to the task at hand that mandates temporal connectivity through topology and power control.
- Peer-to-peer (P2P) phone-based applications: Peers form ad hoc networks for routing most often based on mesh topology. There are, however, P2P phone-based applications that deploy an adaptable topology that are, to some extent comparable, as discussed below.

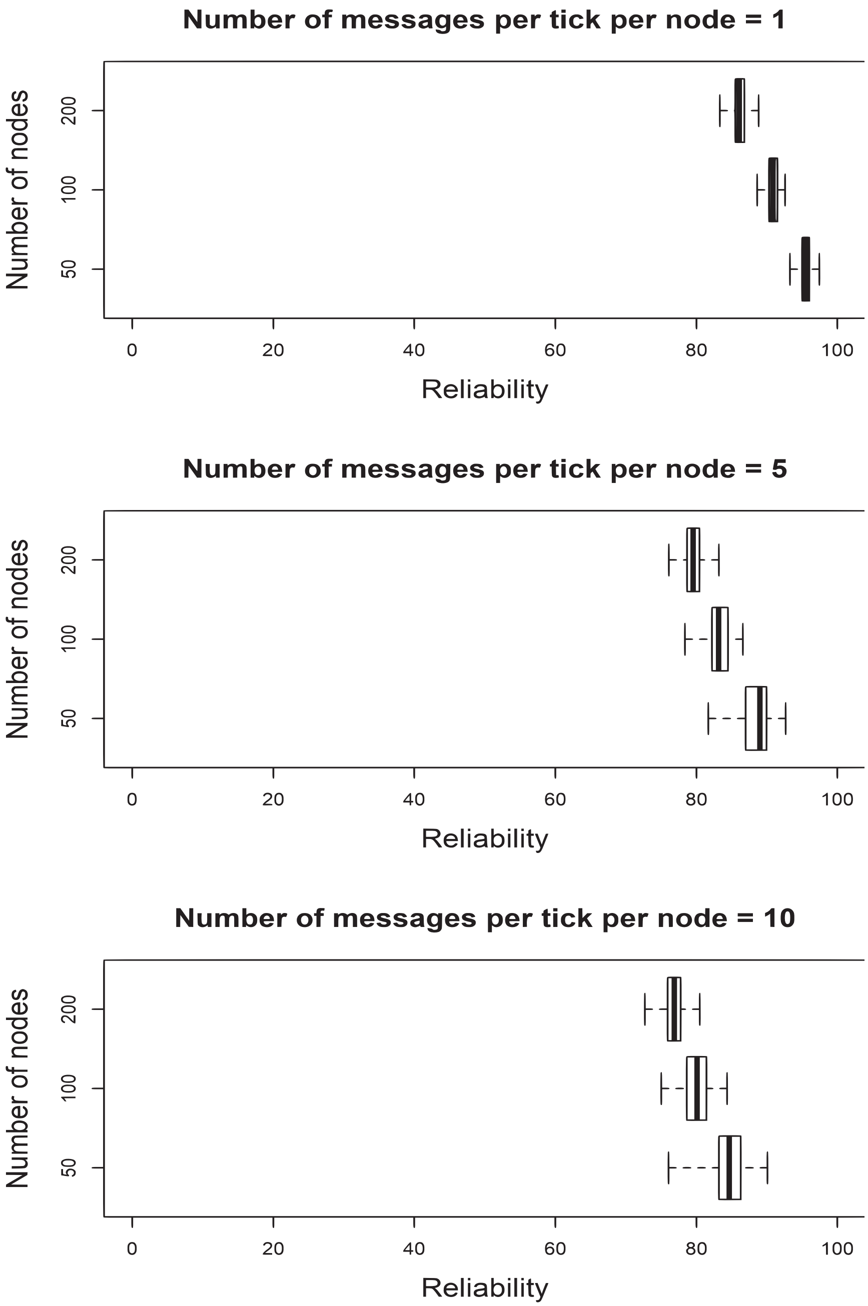


Figure 9: The reliability of the network for varying density and message exchange for a density of 0.04.

4.5.1 Hybrid ad-hoc networks

There is some overlap between this field and the proposed protocol, as the access points and high-energy nodes play a similar role, as they take over the burden of relaying messages and act as routers between phones [263, 264]. However, they are different because access points have their own power supply and are centrally managed, while the proposed protocol is distributed and works on local interaction, while still being immediately implementable. Therefore, the proposed protocol is preferred over hybrid ad hoc networks in situations where logistics issues prevent bringing in equipment, time is of the essence, or situations where centralized solutions are undesirable. Hybrid ad hoc networks may be preferred for situations where solutions are required for long periods of time as it easier to keep the access points charged.

4.5.2 Wireless sensor networks

The proposed protocol achieves energy efficiency through topology control. This is also common in the field of wireless sensor networks [265–268] within which battery-powered sensors are used primarily for long-term data collection. The algorithms developed for wireless sensor networks, however, make use of unique abilities of sensors, such as: their ability to sleep for long periods of time (as used in, for example, the SPAN protocol) [269]; their ability to manipulate their transmission range [270]; their ability to reduce the amount of information exchanged, e.g. using data reduction techniques [271]. These options are not available or feasible for mobile phones.

The primary similarity of the proposed protocol and such distributed topology protocols is that they are based on the fundamental design choice of local context awareness and distributed topology formation. Sensor networks often use local optimization or location-based topology control mechanisms such as LMSTs (Local Minimum Spanning Trees) [272]. LMSTs have also been shown to be used effectively for energy efficiency [273].

The protocol proposed in this paper extends this work by creating local minimum spanning trees on the fly, dynamically adapting the topology to the frequently-changing spatial-temporal-resource context without manipulating transmission range nor relying on knowledge of node connectivity [274–276].

4.5.3 Peer-to-peer phone-based applications

The proposed protocol is not that different from P2P networks of mobile devices that exploit their Wi-Fi or Bluetooth capacity to form direct connections. The difference lies in the topology, as current P2P networks employ a full mesh topology, in which all phones are assumed to be connected to all other phones within their range.

Current P2P protocols for energy efficiency focus primarily on improving routing [277–279] by minimizing the amount of information maintained by each peer and exchanged between peers. Routing and topology, however, are fundamentally different aspects of communication. Topology forms the backbone on which routing protocols can be run, while routing is a process of maintaining updated routes of mobile nodes to ensure reliable delivery of messages.

The topology control protocol proposed in this paper is compatible with most routing protocols, and possibly, synergistic energy efficiency increases can be achieved by combining the energy-efficient loop-free scale-free topology of the proposed protocol with the newest developments in energy-efficient routing [168, 276, 280, 281]. This is subject to future research.

4.6 Conclusion

When physical network infrastructures fail, infrastructureless communication networks such as mobile ad-hoc networks (MANET), can provide an alternative. This paper introduces a protocol that consists of three algorithms for creation, maintenance and message exchange for an infrastructureless ad-hoc communication network using mobile devices. In three evaluations in a simulated environment, this protocol was demonstrated to be scalable, long-lasting, and reliable, in a variety of contexts.

Energy efficiency was a primary design consideration for this protocol. Participating devices may vary in their battery charges, and recharging facilities are not guaranteed. Once nodes run out of battery charge and leave the network, nodes become disconnected and the network may become fragmented. It was vital in the new design to take spatio-temporal resource information into account.

The proposed protocol achieves this through preferential attachment to high resource nodes in the nodes' transmission range. In this manner, a loop-free, scale-free adaptive topology is formed, that avoids network fragmentation through the preservation of battery charge in low-energy nodes, and restores fragmented networks through flexible adaptation.

The proposed protocol has a number of advantages.

First, it is adaptive to the environment. This means it is applicable in scenarios that may vary in the density and mobility of devices, and in the availability of energy sources.

Second, it is energy-efficient through changes in topology. This means it can be flexibly be combined with different routing protocols.

Third, the protocol requires no changes on the hardware level. This means it can be implemented on all current phones, also in the Third World, without any recalls or investments in hardware changes.

The results of the evaluation confirm that the self-organizing context-adaptive protocol enables mobile devices to connect and communicate reliably and scale up despite changing energy availability and density of nodes.

Future work will necessarily focus on a number of factors. These include trade-offs between reliability and robustness. Furthermore, the effects of churn, and the costs of the reconfiguration step need to be studied further. Lastly, the performance of the self-adaptive ad-hoc communication network needs to be evaluated outside of lab conditions.

Chapter 5

॥ न कंचित् शाश्वतम् ॥

NOTHING IS PERMANENT, EVERYTHING IS TRANSIENT

This chapter is published as
Banerjee, Indushree, Martijn Warnier, Frances M T Brazier, and Dirk Helbing. *"Introducing participatory fairness in emergency communication can support self-organization for survival."* Scientific reports 11, no. 1 (2021): 1-9.

EVALUATING PARTICIPATORY FAIRNESS IN SOS

5.1 Introduction

In an unsustainable world, the frequency and severity of disasters is expected to increase. Disasters often damage telecommunication infrastructure and cause electricity blackouts that prevent citizens from recharging their phones. Most current emergency communication apps drain energy without consideration of battery charge in phones. This puts people at risk of losing their ability to communicate when they need it most. This chapter focus on these considerations and demonstrate how a value-sensitive design can make sure that a maximum number of people is able to communicate for an extended period of time: participatory resilience. Participatory resilience of disaster-struck communities requires reliable communication for self-organized rescue, which ensures equal communication opportunities for all, regardless of the inequality in battery charge. This chapter uses a comparative agent-based modeling approach to demonstrates that, compared to a conventional mesh communication network, SOS results in a fair participation of all devices and a longer network lifetime. Empowering citizens is important because they are often the first to respond, especially when sites are cut off and public rescue efforts start with a delay.

Participatory resilience of disaster-struck communities requires reliable communication for self-organized rescue, as conventional communication infrastructure is damaged. Disasters often lead to blackouts preventing citizens from charging their phones, leading to disparity in battery charges and a digital divide in communication opportunities. In this chapter the thesis focuses on defining and quantifying SOS as a value-based emergency communication system based on participatory fairness, ensuring equal communication opportunities for all, regardless of inequality in battery charge. SOS automatically and dynamically

(i) assigns high-battery phones as hubs,

(ii) adapts the topology to changing battery charges, and

(iii) self-organizes to remain robust and reliable when links fail or phones leave the network.

The novelty of SOS in comparison to mesh communication networks is demonstrated by comparative agent-based simulations.

An evaluation using the Gini coefficient demonstrates that SOS network design results in fairer participation of all devices and a longer network lifetime, benefiting the community and its participants.

5.2 Defining fairness

Our definition of "participatory fairness" is distinct from the fairness principles used in the areas of computer networks and resource scheduling [282–284]. The principle of fairness in computer science has been studied for the past 30 years with a fairness index [285]. This index measures the "equality" of user allocation of resources. Fairness as a concept has also been introduced in wireless networks related with fair channel allocation, bandwidth and throughput allocation [286, 287]. The goal has been to deliver fair end-to-end performance in wireless multi-hop networks [288]. These definitions, however, are not relevant for our work, as we are interested in social fairness and its individual and collective benefits.

Our system strives towards the creation of a collective public good and its fair use. In an emergency, the system design should not lead to a discriminatory bias against people with less battery charge and related communication resources. We, therefore, define fairness in the sense of equity and social justice.

This paper goes beyond the current state of the art in three ways: First, we introduce a value-sensitive design approach for communication networks. Second, we boost resilience by introducing participatory fairness into the operation of a peer-to-peer network based on context-adaptive self-organisation. Third, we improve the energy efficiency of communication under stress to benefit disaster-struck communities over extended periods of time, when they need communication most to help each other and survive. Overall, this creates massive individual and collective benefits.

In the following, we discuss the implementation and advantages of a value-sensitive design called "Self-Organization for Survival" ("SOS"), which is specifically made for disaster scenarios. It can benefit individuals and promote collective behavior based on local interactions [289]. Compared to a typical mesh network, the design of SOS ensures that phones with different battery charge have the opportunity to communicate for 72 hours without recharging. It does so by considering the additional value of "***participatory fairness***".

5.2.1 Design for values

"Design for values" is an approach to include values such as autonomy, fairness, usability, privacy, or democracy in the design and operation of technology [80, 290]. Existing applications establishing an infrastructure-less mesh network are implicitly or explicitly designed for citizen-based communication. They provide autonomy from a backbone infrastructure and reliability in communication.

To facilitate collaboration and communication of a community of people during an unexpected disaster, however, other factors must be considered as well. These include the unavailability of charging opportunities for participating devices, and the amount of time phones must be able to communicate, while the network needs to continuously adapt to a changing environment.

If an application is not designed with these factors in mind, biases may arise that could compromise the outcome in three ways [83]: through preexisting biases, technical biases, and/or emergent biases. Preexisting biases are rooted in the fabrics of society. Technical biases refer to technical constraints or issues. Emergent biases result from the usage, which may depend on the context. Today's ad hoc networks have technical biases due to technical limitations and emergent biases due to lack of consideration. Technical restrictions such as lack of charging facilities and limited resources of phones may also imply emergent biases such as the disparity of communication opportunities. We address the issue of participation disparity in the following.

Our paper pursues a design-for-values approach to reduce technical and emergent biases in a dynamically changing context. We have, therefore, designed a context-adaptive distributed protocol that uses local self-organisation to achieve participatory fairness in a peer-to-peer communication network.

SOS enables and maintains the participation of practically all phones, i.e. it provides equal communication opportunities for all citizens regardless of the initial inequality in phone battery charges. Overcoming inequality serves to keep the social fabric functional under stress, for example, during crisis and disasters.

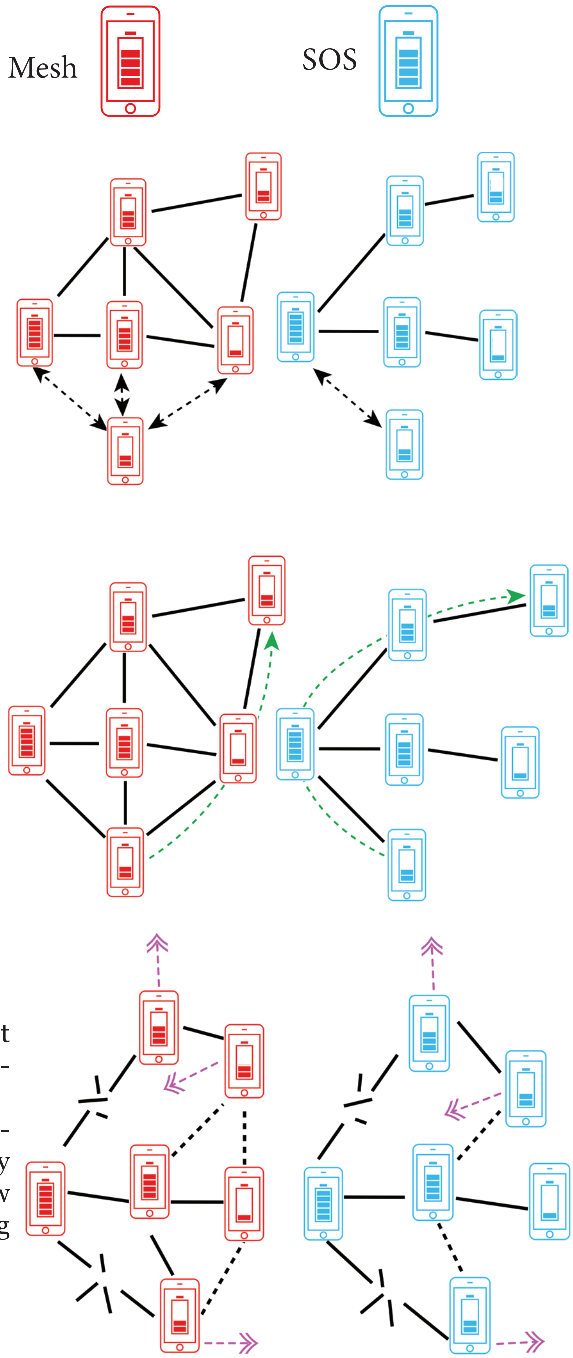
5.2.2 SOS: Designing for "participatory fairness"

A phone loses battery charge when connecting to another phone or when sending, receiving, or relaying a message (see the appendix; chapter 9 for realistic values). For simplicity, in our agent-based models and computer simulations, these costs are assumed to be the same for all phones participating in the formation of the peer-to-peer ("ad hoc") communication network. Note, however, that the battery charge is different, since some phones will have recently been charged, while others are about to run out of power. In addition, different phone models have different battery capacities. This disparity of phone battery charge would usually imply the loss of connectivity and communication opportunities over time for a quickly increasing number of phones. To ensure participatory fairness, we propose a communication protocol that avoids unnecessary connections and relays messages in a way that is, in a sense, proportional to battery charge.

In conventional mesh networks, every phone connects to every other phone in the transmission range (Fig. 10A; red phones). This results in direct peer-to-peer connections and few relays, but connection costs quickly increase with population density. Moreover, even low-battery phones may be used to relay messages (see Fig. 10B, red phones).

Using a minimal spanning tree for communication instead will reduce the number of links and, thereby, connection costs. However, it will increase relay costs to route all messages from the senders to the respective receivers. Both approaches will quickly discharge low battery phones, which will lose their communication opportunities quickly.

We overcome this problem by designing the "SOS" protocol for participatory fairness. For this, high-battery phones capable of maintaining a large number of connections are automatically assigned as hubs, leaving the low-energy phones with fewer connections and lower relay costs. As time progresses and high-battery hubs lose energy, they automatically change position within the peer-to-peer communication network, and nodes that then have higher battery charge become the new hubs (see Fig 12B).



A

Connection

SOS incurs fewer connection costs than generic full mesh, and connections are only made with phones that can afford it.

B

Communication

Generic full mesh relays through fewer phones.
SOS only relays through phones that can afford it.

C

Reconfiguration

Phones moving in and out of range leads to disconnection.
In mesh, everyone reconnects. In SOS, phones only reconfigure to find new routes if there are pending messages.

Figure 10: Differences in (A) connection, (B) communication and (C) reconfiguration patterns between a generic mesh protocol (red) and SOS (blue).

SOS uses (1) the principle of self-organization to maintain participatory fairness and (2) distributed local information exchange to learn about the spatio-temporal context and resources.

To be context-aware, every phone gathers local information about other phones in its transmission range (which consumes energy as well, as considered by our model). The local information consists of the battery charge of its neighbors as well as whether neighbors are part of an existing network. Once this information is exchanged, phones follow two rules before getting connected:
(i) select the phone with the highest battery charge in range for possible connection

(ii) connect only if the phone is part of a different network, i.e., do not connect to a phone, if intermediary connections already exist.

If there are messages to send and no route is present, the SOS protocol will reconfigure the local connections (see the Supplementary Information for details of the corresponding Algorithms). Overall, these rules lead to the emergence of a peer-to-peer network with the following characteristics:

• as a result of rule (i), phones with a high battery charge have a higher connectivity, while phones with a low battery charge automatically become edges with a single connection to the network (see Fig. 10A; blue phones).

• as a result of rule (ii), multiple connections and related costs are avoided.

• the topology is adaptive: It accounts for changes in the local context and updates the roles of participating nodes, if needed.

No manual intervention is required to adapt the topology, since the reconfiguration is event-driven (see Fig. 10C; blue phones). The distributed message exchange and context awareness make the network scalable and adaptable to changes of the density or mobility of people. Complementary, a detailed technical performance analysis of the SOS approach has been performed in a previous paper [63], evaluating the effects of varying density and message frequency on message reliability (and scalability and longevity).

There, it has been found that the reliability remained above 80% under a wide range of conditions. Further explanations of functional and non-functional requirements, subsequent design choices and their implications as well as the pseudo-code of the SOS protocol are presented in the appendix; chapter 9.

5.3 Methods

The performance of SOS was compared to a mesh communication topology through modeling and simulation in terms of longevity, traffic adaptivity, battery charge inequality, and phone participation (see the appendix; chapter 9 for details of the experimental setup).

5.3.1 Populating the model and simulating behavior

To examine the performance of both mesh and SOS communication networks, and to make comparative analyses, a mesh-based topology and a SOS-based topology were simulated in two separate agent-based models. The models assume a two-dimensional torus-shaped world and populates it randomly with nodes. Each node denotes a mobile phone that moves independently and in a random walk. Two nodes can communicate when there is a link between them. It is created when they are within transmission range of each other. If there is no direct link, nodes can communicate through intermediate nodes. Each node has a limited transmission range. When the nodes move out of transmission range they lose connection, i.e. the corresponding link breaks.

There is no limitation on the number of connections a node can form. Nodes have fixed battery charge that depletes once they start making connections and sending messages. Participating nodes are not assigned any roles as they join the network. As the network formation begins and the number of participating nodes increases, different roles are assigned to nodes automatically and dynamically to maintain connectivity and energy efficiency.

Nodes communicate directly or through multiple nodes/hops relaying messages. Algorithm 3 (see the appendix; chapter 9) is used for routing. In each model, all nodes send a message to a randomly selected node present in the model for receiving the message. The number of messages sent by each node is a model parameter and can vary from 1 to 10. In case no route is found, each node saves the message as "pending".

5.3.2 Model limitations

SOS could be implemented either as part of an operating system or simply as an application running on a smartphone, thereby putting an additional governance layer on top of the technical ad hoc network functionality.

Hence, the overlay network can be established and operated independently of service providers. The model also considers the loss of battery charge associated with other processes running on phones. Such processes would be restricted based on bandwidth needed. For example, text messages and similar low bandwidth communication would be prioritised, while pictures and videos would be restricted or sent with lower quality to spare bandwidth.

Communication devices have individual characteristics that might add further parameters for investigation. For example, under real circumstances, the diversity of phones implies different capabilities in-built in each of them, such as the amount of memory available for higher performance and traffic management. Our present model has not incorporated such traffic management and storage capacities. Including them might allow for additional refinements to the algorithms. However, these parameters are currently out of scope for this article.

5.4 Results: quantifying fairness

We use an agent-based modeling [93] approach to compare the SOS approach to a generic mesh network. For the results of Fig. 12-15, we simulate a torus-shaped world of 25x25 units with 500 people having phones, assuming normally distributed battery charges (see the appendix, chapter 9, for more details). In our model, people with phones perform a random walk moving at constant speed (which simplifies typically observed mobility patterns [291]). For simplicity, each phone sends one message every fifteen minutes to a randomly chosen other phone (even though the real message frequency is not this homogeneous [292]). The transmission range is assumed to be homogeneous at 5 units. The loss of battery charge associated with sending, receiving, relaying, connecting and reconfiguring is specified according to real Bluetooth Low Energy battery costs [293].

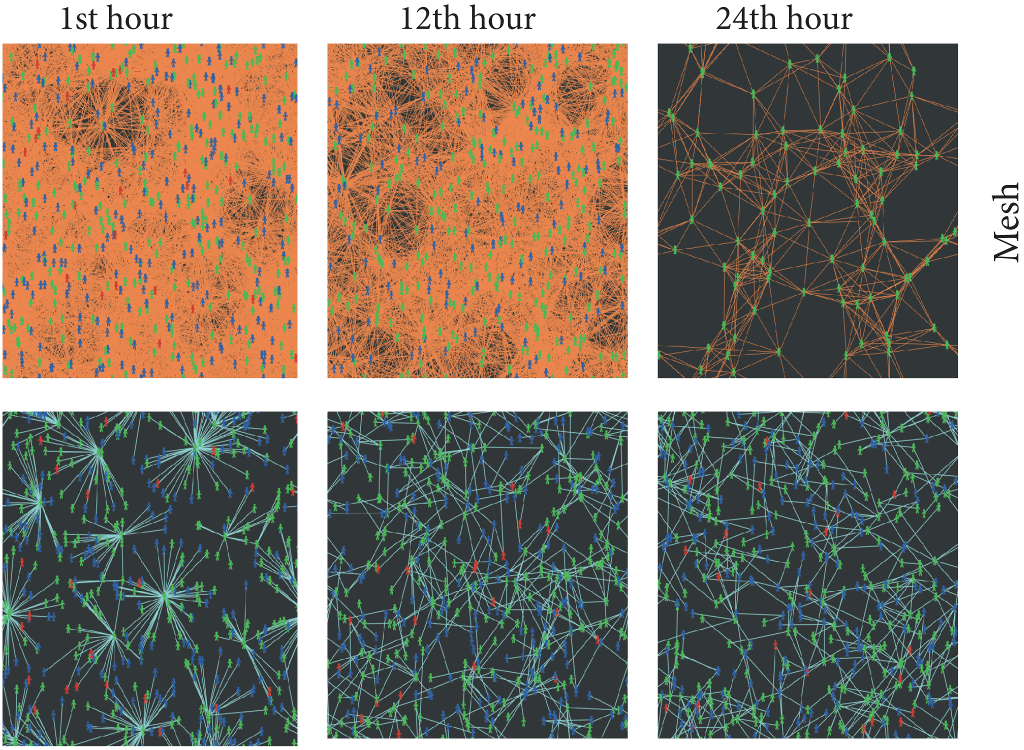
For the results of Fig. 16, settings were the same as above, with the exception of the number of people and message frequency. The number of people was systematically varied from 100 to 800 to estimate the effect of population density on longevity. Message frequency was varied between one and ten messages sent every fifteen minutes, to estimate the effect of the amount of data traffic on longevity.

5.4.1 Communicating for 72 hours: SOS lasts for 72 hours and considerably longer

Fig. 11 (and movie S1 in the appendix; chapter 9) shows the development of the topology over 72 hours for the mesh and SOS communication topologies. The mesh topology is tightly coupled with peer-to-peer connections between phones in each others' transmission range in the first hour. This continues and results in a crowded topology for 24 hours. Despite phones moving in and out of range, there is no noticeable change in topology. This is due to the "connect to all in range" characteristics of mesh.

The topology that emerges due to the SOS algorithm is context-adaptive and self-organised, with a few hubs and many low-degree nodes.

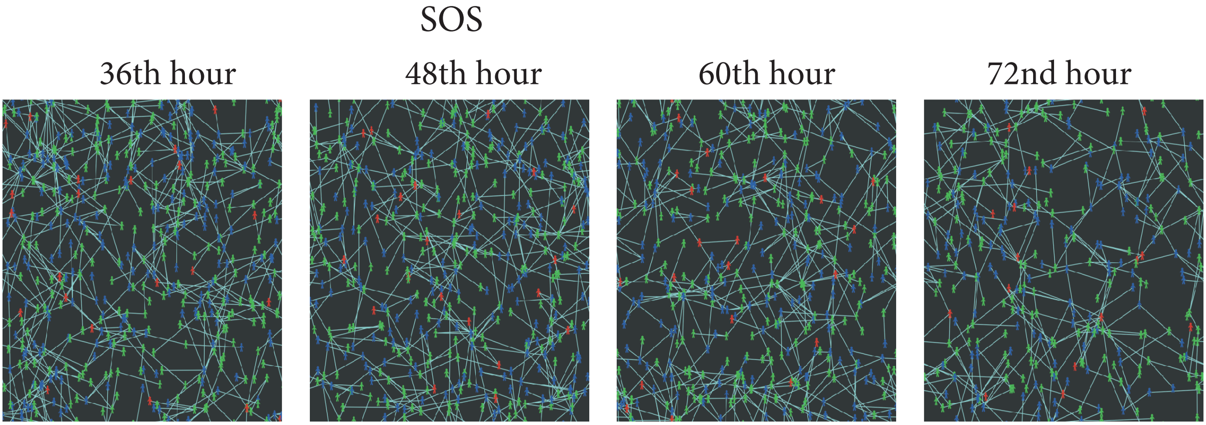
Network Topology evolution over 72 hours for both Mesh (top) & SOS (bottom)



This is most clearly visible in the 1st hour. Some phones (with a high battery charge) have many phones connected to them, acting as hubs.

Others (with a low battery charge) have one connection and lie on the edge of the network. Initial high battery charge phones later on take less central positions in the network, when other high battery charge phones take over as hubs. Over time, this results in a network with a more even energy distribution among phones.

Figure 11: Formation and evolution of the mesh (top) and SOS topology (bottom). The ad hoc mesh network runs just longer than a day. SOS runs for the entire duration of 72 hours. Results of simulations with 500 phones, sending and receiving 1 message per phone every 15 minutes for the
generic mesh and SOS protocols.



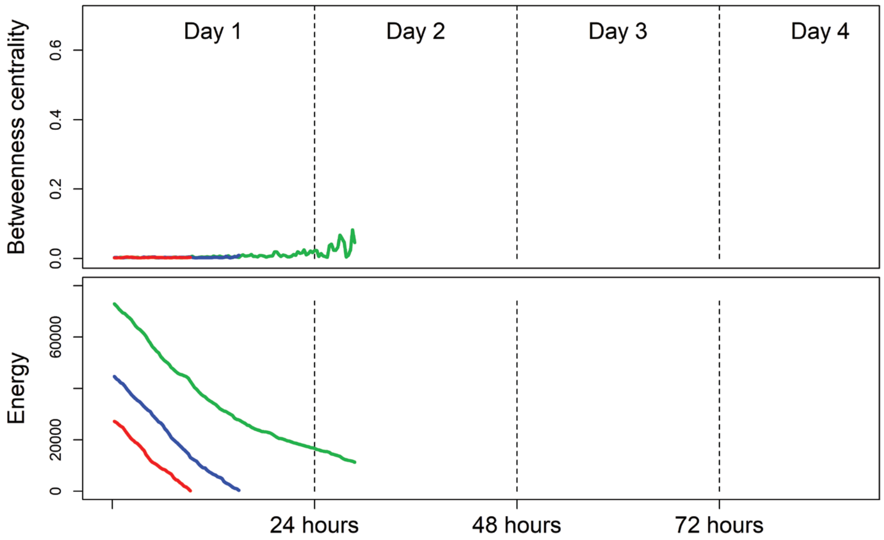


Figure 12A: Development of Battery charge (Energy) and Betweenness Centrality for a selection of three typical phones (red: low initial battery charge; blue: average initial battery charge; green: high initial battery charge) for mesh network. In the mesh network, every phone has the same Betweenness Centrality. Results of simulations with 500 phones, sending and receiving 1 message per phone every 15 minutes for the generic mesh (above) and SOS (top-right next page) protocols.

5.4.2 Cancelling load disparity: SOS adapts the traffic distribution to spare low-energy phones

Fig. 12A (and movie S2 and S3 in the appendix; chapter 9) shows how the adaptive mechanism of SOS affects the consumption of battery charge over time and the Betweenness Centrality. Betweenness Centrality measures the importance of a phone for passing information. Higher Betweenness Centrality shows that a particular phone is more centrally placed in the emerging network, which means maximum data traffic passes through this phone.

For mesh networks (see left of Fig. 13), the battery charge rank of phones is stable over time. All phones have almost the same Betweenness Centrality with a slight variation at the end towards 0.14, and all phones lose battery charge linearly over time. This creates a discriminatory bias against people with phones that happened to have a low initial battery charge (such as the red phone). They are disconnected earlier, limiting their communication opportunities in favour of people with a higher battery charge (green). SOS automatically assigns high-energy phones as hubs and monitors the spatio-temporal energy distribution to adapt the network topology.

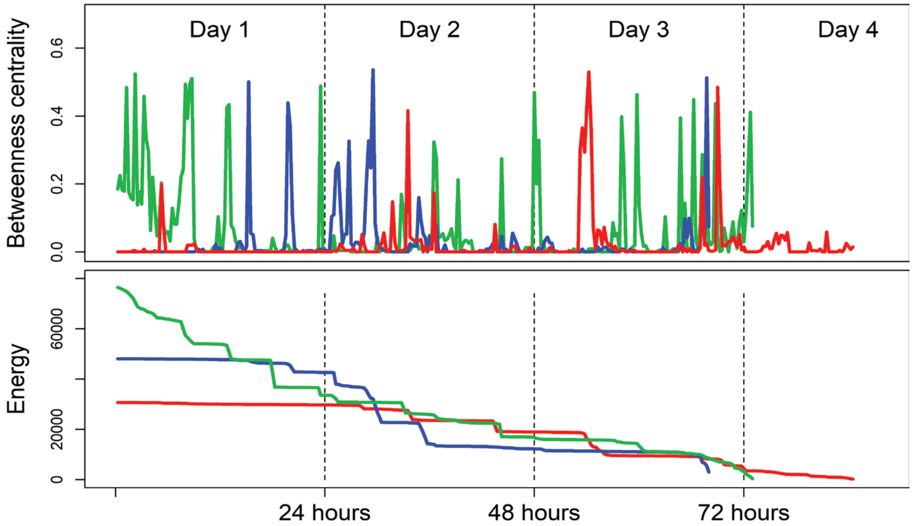


Figure 12 B : Development of Battery charge (Energy) and Betweenness Centrality for a selection of three typical phones (red: low initial battery charge; blue: average initial battery charge; green: high initial battery charge) In SOS, the Betweenness Centrality fluctuates, with green starting as a central hub; a role which is later taken over by blue and then red, as the relative battery charge changes. This ensures that all phones can equally participate in communication for an extended time period.

This mechanism prevents selfish behaviour and promotes altruism, which is reflected in the changing Betweenness Centrality.

For the SOS protocol, the Fig. 12B shows how the role of phones changes over time. The green phone initially plays a central role (with a Betweenness Centrality of 0.52 after two hours), because it has a high level of battery charge, while other phones are spared. After some time, the blue phone becomes a hub (with a Betweenness Centrality of 0.54, peaks between hours 25 and 38, and again towards the end). After that, there is a period where the red phone becomes a hub (with a Betweenness Centrality of 0.53). The red phone starts with the lowest battery charge and is the first to disconnect in the mesh network. In SOS, the red phone is spared from relaying messages, allowing it to stay connected for as long as the green phone with the highest initial battery charge. This illustrates how the topology adapts to the spatio-temporal situation of energy availability. The phones keep changing with regard to the load and traffic, to spare the lower battery charge phones, such that participatory fairness is achieved.

5.4.3 Balancing energy distribution disparity: SOS distributes energy more fairly over phones than traditional mesh

The participatory fairness of the phone battery charge distribution is calculated here with the Gini coefficient. Fig. 13 shows the Gini coefficient over time, for SOS (in blue) and mesh (in red). The Gini coefficient is typically used to study inequality, e.g. of income or resources [294]. Its value ranges from 0 to 1 with 0 signifying complete equality (all have the same battery charge) and 1 meaning extreme in- equality (one phone has all battery charge).

For the traditional mesh network, inequality increases quickly, with the Gini coefficient increasing from 0.13 to 0.39 within the first 14 hours, then stabilizing around 0.45. For SOS, in-equality decreases within the first 10 hours, with the Gini coefficient decreasing from 0.13 to 0.11. Then, within the next 62 hours, the Gini coefficient slowly increases to 0.27.

5.4.4 Participatory fairness: SOS allows more phones to participate for a longer period than mesh

Fig. 14 (and movie S1 in the appendix; chapter 9) shows phone participation over time. For mesh, phones almost immediately start to fail with the first phone dropping out after 3 hours. For SOS, the time period during which there are no failing phones is significantly extended, with the first phone dropping out of the network after 13 hours. Also, a significant improvement in longevity for SOS is immediately obvious, reflected by the considerable horizontal distance between the SOS and mesh curves. For the mesh topology, only 18% of phones remain connected after 24 hours, whereas for SOS, 99% of phones are still connected after 24 hours. For SOS, the phone participation is recorded to be 91% after 48 hours and 62% after 72 hours.

This illustrates a large difference in the energy efficiency between the two protocols. SOS has several advantages: The communication network lasts considerably longer, and the percentage of phones participating in the network is larger at every point in time. The large separation between the two participation curves demonstrates the success of SOS.

Battery inequality over 72 hours

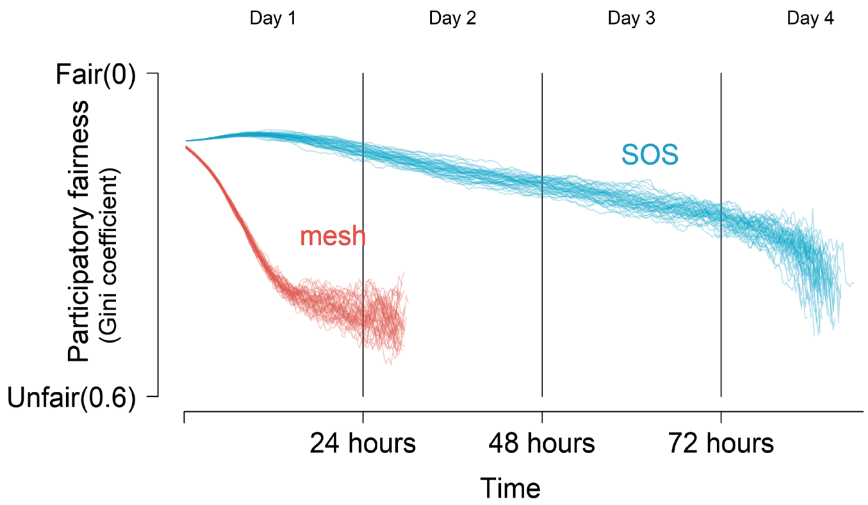


Figure 13: Development of battery charge inequality (Gini coefficient [294]) over 72 hours for the mesh network (red) and for SOS (blue). Results of simulations with 500 phones, sending and receiving 1 message per phone every 15 minutes for the generic mesh and SOS protocols

Phone participation over 72 hours

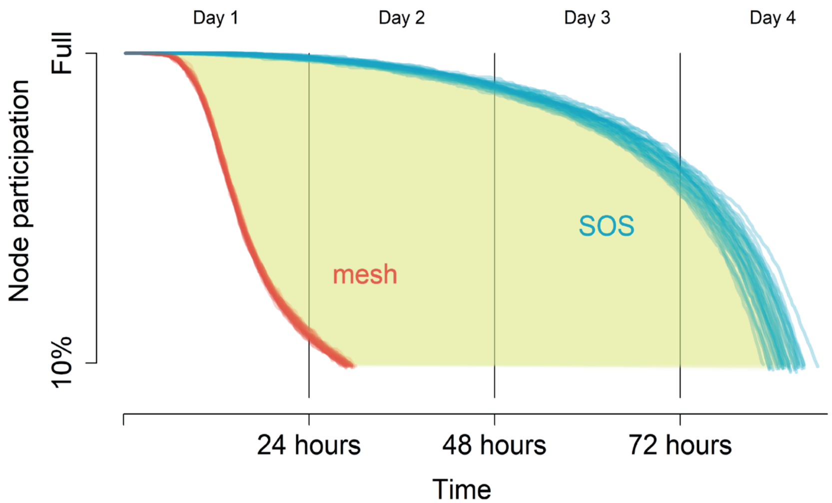
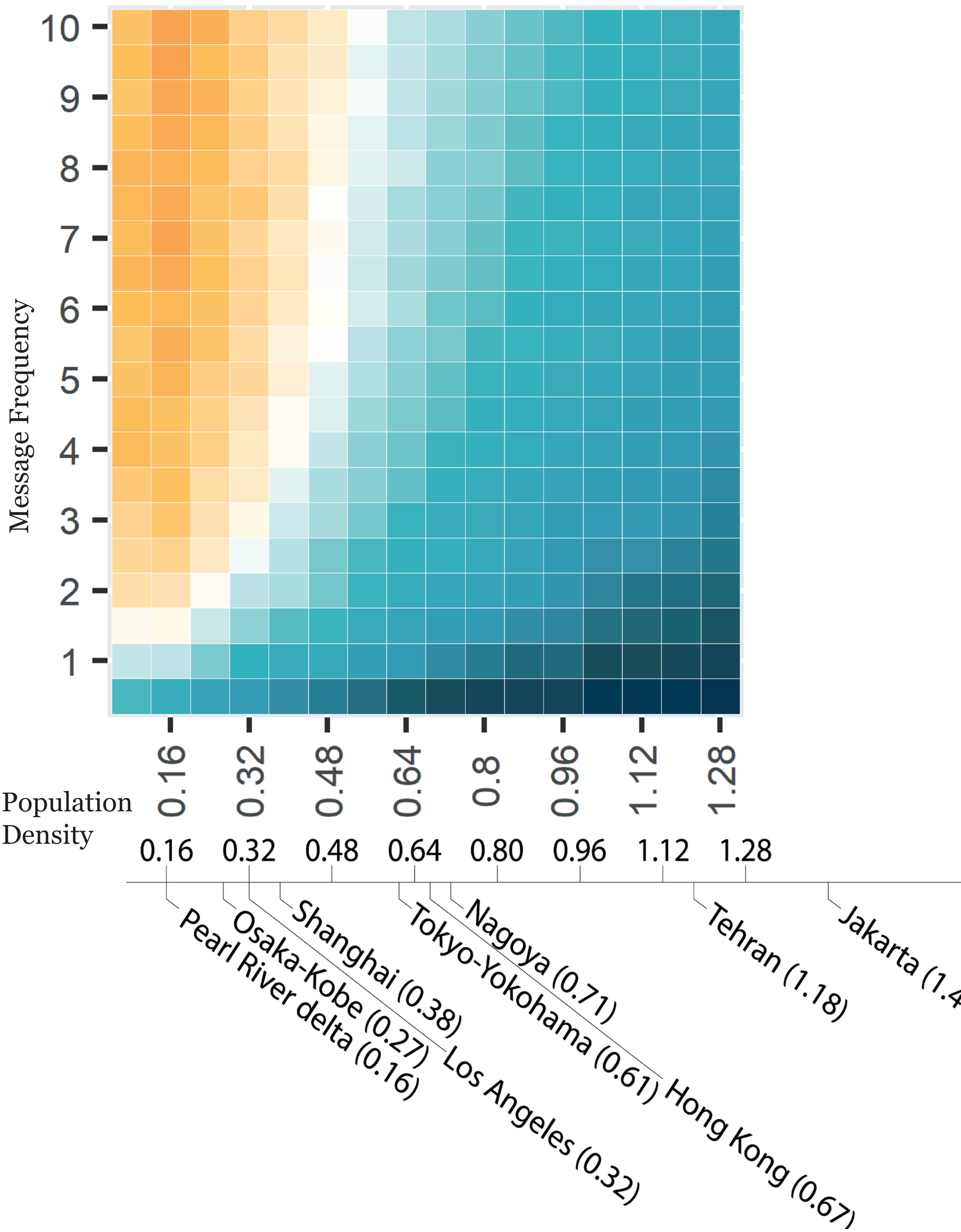


Figure 14: Phone participation over 72 hours for the mesh network (red) and for SOS (blue). Results of simulations with 500 phones, sending and receiving 1 message per phone every 15 minutes for the generic mesh and SOS protocols.


Message Frequency
10
9
8
7
6
5
4
3
2
1
0.16
0.32
0.48
0.64
0.8
0.96
1.12
1.28
Population Density
0.16
0.32
0.48
0.64
0.80
0.96
1.12
1.28
Pearl River delta (0.16)
Osaka-Kobe (0.27)
Los Angeles (0.32)
Shanghai (0.38)
Tokyo-Yokohama (0.61)
Hong Kong (0.67)
Nagoya (0.71)
Tehran (1.18)

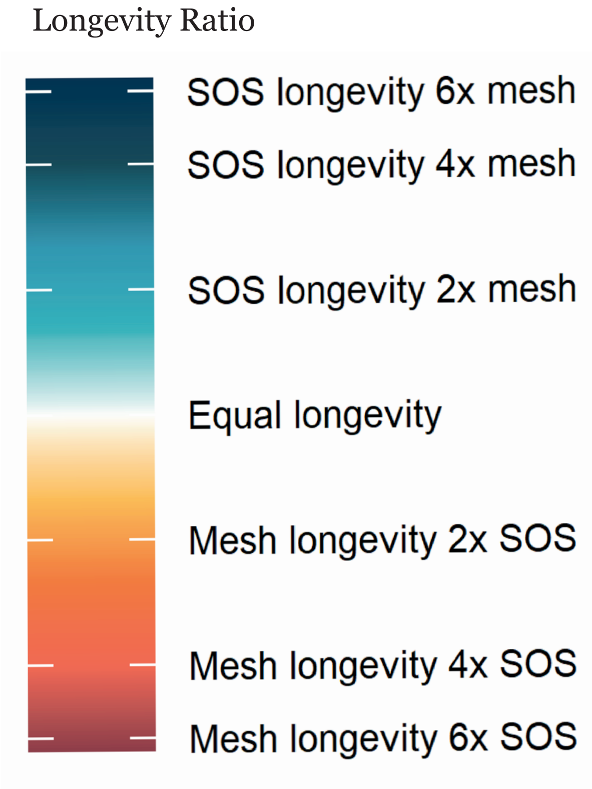


Figure 15: Phase diagram of the difference in longevity between mesh and SOS, for varying message frequency and population density. Light blue to deep blue indicates an increasing advantage for SOS over mesh. Orange to red indicates an increasing advantage for mesh over SOS (dark red not occurring). White indicates that longevity was equal between the two. SOS performs best when population densities are higher (towards the right) or message frequencies are lower (towards the bottom). Mesh performs best when population densities are low and message frequencies are high.

5.4.5 Performance comparison between Mesh v/s SOS: The relative advantage of SOS depends on the density and message frequency

Fig. 15 shows the difference in longevity between mesh and SOS as a function of message frequency and population density. The message frequency ranges from sending 1 to 10 messages per 15 minutes. The population density is varied by increasing the number of phones in a fixed area. Concretely, the population density is varied from 0.16, representing 100 phones, to 1.28, representing 800 phones.

The primary energy expenditure of mesh networks comes from connecting phones. Therefore, the right side of Fig. 15A – where there are more phones and thus more connections – shows larger advantages for SOS. The primary energy expenditure for SOS comes from relaying, as routes are longer. Therefore, the lower side of Fig. 15A – where fewer messages are sent and relayed – shows larger advantages for SOS. Conversely, the mesh topology performs better in scenarios with low densities and large numbers of messages. Note that the number of messages for scenarios where the mesh topology outperforms SOS is extreme, with every phone continuously sending multiple messages in each time step. For all other scenarios, SOS outperforms the mesh topology, with the best performance for high phone densities (as in disaster-struck cities) and reasonable volumes of information traffic (which can be technically ensured).

To interpret the densities and relate our simulated world to the real world, we need to make a few assumptions. The transmission range is 5 points, in a 25x25 world, while the transmission range in the real world would be around 50 meters. Therefore, the simulated world can be assumed to represent approximately an area of 250m2. This means that the simulated densities correspond to a range of densities observed, for example, in cities such as Sydney or Tehran. To have a general idea of where actual cities sit in terms of density, in Fig. 15B, example cities are provided for every density in the legend below.

The United Nations Department of Economic and Social Affairs/Population Division, World Urbanization Prospects in 2011 published a report on metropolitan urban cities in the world that are at highest risk of getting affected by natural calamities [295–297].

We show the top 10 cities in the world that have the highest risk of getting affected by five natural calamities: earthquake, tsunami, river flood, storm surge and tropical cyclones.

5.5 Discussion and conclusion

The increased penetration of mobile phones in remote parts of the world has opened avenues for their use to improve situational awareness during disasters [298, 299]. In this contribution, we developed a novel protocol for peer-to-peer communication using a "design for values" approach. The value of participatory fairness is particularly important in emergency situations. Our protocol achieves social fairness by self-organising and adapting its topology to the spatio-temporal context of a disaster situation. In the resulting peer-to-peer network, phones with high battery charge work as hubs, facilitating emergency communication for those citizens who are in immediate danger and have little battery charge to spare. This is in contrast with the generic mesh topology that underlies previously proposed emergency communication solutions. These solutions form so many connections that they do not provide the required functionality over a 72 hour period.

It seems that recent developments in emergency communication have focused more on introducing infrastructure to disaster-struck areas than on social innovation and better governance. For example, base stations with Wi-Fi capability may be brought to a disaster area, or unmanned aerial devices can provide connectivity [18, 300–303]. As mentioned above, however, the logistics of disaster response typical implies delays for such solutions, while delays are often deadly. That is why a solution such as SOS is needed, which works over an extended period of time even in the absence of recharging opportunities. Still, we think that every kind of emergency communication solution has its role to play. Generic mesh itself may transmit messages faster than SOS, because there are fewer hops in between. In situations where batteries can be recharged, generic mesh may therefore be preferable to SOS. Hence, it might be helpful if the communication protocol itself would adjust to the situation at hand. Dynamic decentralized switching between communication protocols is something we are currently looking into. However, the importance of the SOS approach is steadily increasing, as it works best in densely populated, urban areas.

Currently, over half of the world's population is living in cities, and this proportion is still growing. Also, the population density of cities is increasing, and so is the disparity of resources [304].

In the simulations that we used to illustrate differences between the SOS and mesh communication networks, battery charge was randomly distributed. For mesh, people with high battery charge phones will be able to send messages for longer than those with low battery charge phones. Low battery charge phones will quickly lose the ability to communicate, typically long before the crucial 72 hour period is over. With SOS, however, those people with high battery charge phones will increase the communication opportunities of those with low battery charge phones, thereby strengthening the social fabric and resilience [305].

Rerouting for energy efficiency is not new, as there have been many proposals to prolong battery life, also in ad hoc networks. However, we are not primarily interested in energy efficiency, here, but rather in a socially fair distribution of communication opportunities, which benefits individuals and social communities alike. If the energy required to maintain an inclusive communication network is shared, this produces a public good, where everyone can benefit from the increase in collective action and collective intelligence this enables.

Our definition of participatory fairness differs from game theoretical fairness definitions, and is more closely aligned with the literature on equity and justice. Rather than focusing on a competitive exchange, where parties can justly or unjustly gain advantages at the cost of others, we interpret fairness in the context of a redistribution of opportunities in times of need.

The requirement of participatory fairness has important implications for the design of peer-to-peer networks, and improves emergency communication in two ways:

(i) it enhances communication opportunities for a large number of people, &

(ii) it considerably extends the time period over which peer-to-peer communication can be maintained.

Finally, citizens are not interchangeable commodities, of course: Not all citizens will contribute in the same way. Different people have different requirements, but can also offer different skills and contributions [306].

Thus, it is important that everyone stays connected. Furthermore, abilities and requirements are not static, as they may change over time. By adapting to changing circumstances, and maximizing the strengths of each, one can empower individual citizens and community resilience, without forgetting those that are in need of support. Our communication protocol does just that.

Chapter 6

॥ तत्त्वमसि ॥

YOU ARE THE ONE YOU ARE SEEKING

This chapter is published as
Banerjee, Indushree, Martijn, Warnier, and Frances M T Brazier,"*Designing inclusion and continuity for resilient communication during disasters*" in
Sustainable and Resilient Infrastrctures, (2022) : 1-17.

INCORPORATING INCLUSION & CONTINUITY WITH SOS-HYBRID

6.1 Introducing inclusion and continuity as values

Communication is vital during disasters. Disaster response requires the involvement of and communication between non-governmental organisations, governments and affected citizens [2, 307]. However, damage to backbone telecommunications and electricity grids prevents traditional communication channels such as telephones, radios and televisions from exchanging and broadcasting information. Affected citizens are often no longer able to use their mobile phones to request help or coordinate rescue activities due to lack of connectivity. This paper presents the design of a hybrid communication system (SOS-hybrid) that ensures continued connectivity and communication during disasters to address this challenge.

Disasters are now occurring with an average of one disaster per week [1, 308, 309]. Rapid urbanisation, for example, entails that 2/3 of the world population (especially the poor) in the next decade will live in river deltas that are prone to massive natural calamities such as flooding due to sea level rise [310]. To ensure that a broader population has access to communication opportunities, availability of having affordable and easy to deploy solutions becomes a fundamental requirement for emergency communication systems. This holds in particular for the first 72 hours after a disaster, for which communication most often relies solely on the citizens' mobile phones.

Enabling communication between these phones without infrastructure using Mobile Ad hoc Network (MANET) has been shown to work, increasing community resilience [63, 311] until rescue arrives. Resilience here is defined as citizens being able to recover and adapt to the disrupted situation after a disaster. Notably, this does not necessarily mean the restoration of earlier infrastructures [312]. Once rescue teams are on-site, citizens can connect to external Wi-Fi equipment such as Unmanned Aerial Vehicles (UAVs) [39], Wi-Fi access points [40], and high capacity radio relays [41] brought on site by the rescue teams. These forms of equipment can provide connectivity over a larger area and provide Internet access over the disaster site. Such solutions, however, do not work for citizens who are outside the coverage of these infrastructures. Their rescue depends on the ability to communicate using an on-the-fly ad hoc mobile network that utilises Bluetooth or Wi-Fi capability of mobile phones to transmit messages.

Such ad hoc networks are the only possible way for those who are immobile (i.e. secluded) to communicate. This paper explores the potential of a new approach: a hybrid design, in which two types of solutions–ad hoc mobile MANET solutions and infrastructural WiFi solutions– work together. This paper makes this the primary goal and investigates whether a hybrid design can ensure reliable and continuous message delivery irrespective of the location and mobility of citizens.

6.2 Related work: Implications of the existing communication approaches

Traditionally, ad hoc mobile MANET solutions, i.e., bottom-up approaches, and infrastructural Wi-Fi solutions, i.e., top-down approaches, work independently from each other. A top-down approach directs communication towards the citizens and rescue operators. The equipment used for top-down communication is generally owned by the government, rescue operators and telecommunication providers. This equipment temporarily replaces traditional backbone telecommunication infrastructures during disasters and provide connectivity across a particular range.

In bottom-up approaches, a community can exploit available technologies such as phones to distribute information and use citizens' context-awareness to recover [313]. One of the benefits of such community-centered communication systems is that people know their community better than the authorities do. People know which houses have small children, elderly people, people in wheelchairs, etc., so they know where assistance is most urgent. People also know which of their neighbours with specific skill sets may help, such as medical doctors, firefighters and builders. Lastly, people know about local resources, such as tools, tractors, boats, medical supplies and food. This information can be shared with other citizens, utilized immediately after the disaster, and often does not reach authorities due to a lack of two-way communication. If locals are actively involved in rescuing themselves and others, this may greatly improve their survival chances. Both top-down and bottom-up approaches have their drawbacks. Top-down approaches require time to implement. The interplay between regulatory barriers such as socioeconomic status and government policy and technological and geographical limitations determines where broadband and telecommunication infrastructure is set up [314].

Most often, infrastructural coverage for communication and basic facilities does not equally extend to every part of a city or area. This is true for many countries such as Bangladesh [315], India [316], Nepal and Indonesia [317]. A disaster makes these 'islands of inequity' [318, 319] even more neglected.

Bottom-up approaches also have their drawbacks. Generic mobile ad hoc networks drain phone energy reducing communication opportunity and participation for phones with lower battery charges. Taking a systems perspective, Banerjee et al. [150] shows that forming all possible connections with nearby phones incurs such high battery costs that those who have low initial battery are quickly unable to participate. This is worsened by the possible unavailability of energy infrastructure, which means phones can also not be recharged.

Previous work [63, 150] proposes improvements to the bottom-up approach of mobile ad hoc networks that remedy the typical drawbacks of mobile ad hoc networks. The "Self-Organisation for Survival" (SOS) protocol self-organises to ensure that only phones with sufficient battery charge become central to reroute messages and that low battery charge phones only form necessary connections. This protocol is adaptive so that phones switch roles as the state of their relative battery charge changes over time. SOS enables all citizens with different phones, regardless of their battery charge, to form a communication network and participate in organising self-rescue operations during the immediate aftermath of a disaster. Notably, the SOS protocol is entirely decentralised. All operations are based on local knowledge and distributed.

Even though SOS can provide emergency communication to citizens, regular access to backbone communication infrastructures is often preferable. First, authorities use communication infrastructure to transmit trustworthy information to citizens, structure rescue operations, and communicate instructions for citizens to follow to improve their chance of survival.

Second, most communication infrastructures are more efficient in transferring messages than mobile ad hoc networks, especially over longer distances. Mobile ad hoc networks require many phones to reroute messages sent over longer distances, which incurs a small battery cost every time. The present article aims to combine the benefits of the bottom-up SOS with the benefits of top-down approaches: A hybrid approach.

A stylised resilient hybrid-communication system connectivity is shown in Fig.16, depicting the communication capacity of a community over time. Complete dependence on infrastructure results in discontinued communication, as shown in the graph (yellow line). Restoring communication requires either repairing infrastructure or replacing damaged parts with new equipment. While restoration can take days or even weeks, SOS and SOS-hybrid can fill in and reduce this impact through an autonomous and self-organised mobile ad hoc network. This ensures reduced disruption so that communication services can quickly resume when time is of the essence.

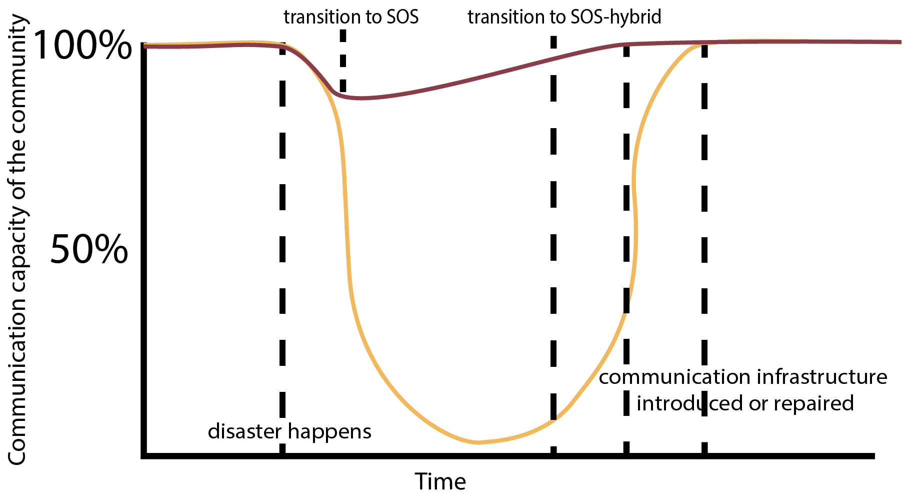


Figure 16: Stylised resilient communication graph. The yellow line represents the development of connectivity over time without the SOS-hybrid protocol. The brown line represents the same with the SOS-hybrid approach. Events occur at the dashed lines. The first dashed line denotes the beginning of infrastructure failure due to damage caused by disaster, where connectivity starts to drop due to cascading failures. At the last three dashed lines, more and more infrastructures become available again.

6.2.1 A hybrid approach: The missing systems perspective in existing research

Hybrid approaches have been proposed before. Researchers in Engineering and Computer Science have designed communication protocols and frameworks that allow multiple types of equipment to work together. Most studies propose frameworks [320] that are centrally controlled systems which improve either data latency or bandwidth optimization. These studies [160, 194, 196, 321] propose the use of global knowledge to control and design systems that ensure connectivity. For example, Madey, Szabo, and Barabási[320] propose the use of wireless call data triangulated from cellular towers to obtain and understand the movement and calling pattern of a population during an emergency in their WIPER (Wireless Phone-Based Emergency Response System). Bhatnagar et al. [321] propose an approach to designing a hybrid communication emergency network and use centralized control to gather and disseminate data. NerveNet [201] has been designed with central control and utilizes a mesh topology for increasing redundancy.

Hybrid systems that rely on centralized control can only work if power grids are not affected by disasters. Madey, Szabo, and Barabási [320] recognize that central control during extreme emergencies such as an earthquake is not possible as most infrastructures tends to be damaged. Additionally, extended power outages reduce the number of phones that can provide such services. A lack of consideration of energy efficiency and an over-reliance on centralized solutions have been common disadvantages in many technologies proposed over the years [24, 160, 196].

A second disadvantage is that many hybrid technologies require expensive equipment. NerveNet was developed in Japan. Many disaster-prone countries, however, are underdeveloped or still developing. Therefore, the proportion of tech-literate population is limited, and there is a limited budget available for maintaining sophisticated hybrid solutions. The top-down approach provides a stable means of communication for all people within the range of the available infrastructure. The SOS ad hoc mobile network is adaptive, forming and dropping ad hoc connections with phones that come into the transmission range or move out of this range, again. This adaptivity requires the costly formation of connections, but has its own merits.

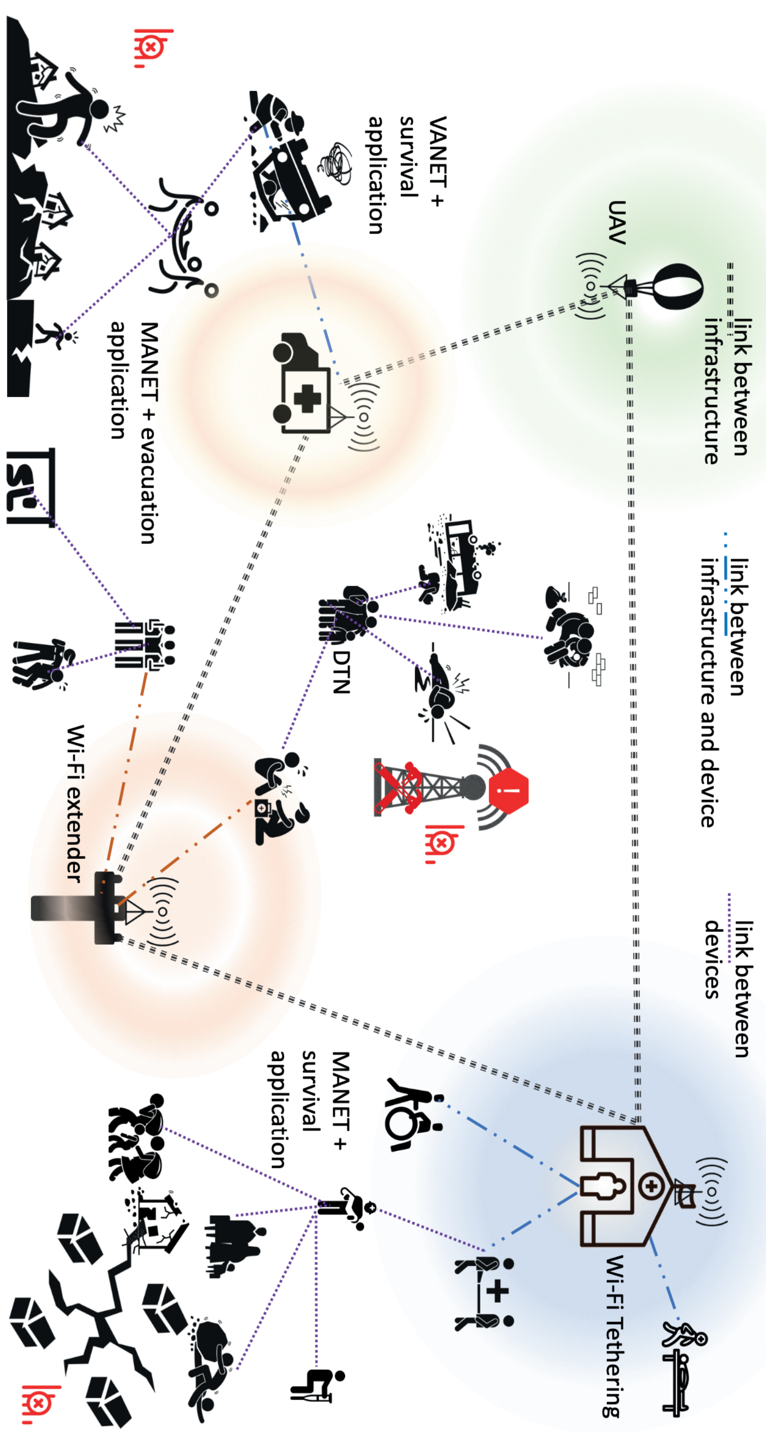


Figure 17: Illustration of a disaster site with various types of communication equipment used for connectivity and their corresponding possible network solutions. Four different bring-on-site types of infrastructure are shown, UAV, VANET, Wi-Fi Extenders, and a relief camp with Wi-Fi access. Each has its own coverage limitations. There are both mobile and immobile citizens and coverage areas corresponding to each type of equipment.

An adaptive network may not provide constant access to all people. However, as people move around, the network may also provide intermittent access to communication for those in remote locations. SOS fills in the spatial gaps, where infrastructure is unavailable.

Figure 17 illustrates a disaster site with various top-down communication equipment. It also shows that mobile and immobile citizens might not be in the coverage area. The citizens outside of the range of traditional equipment can utilize mobile ad hoc networks to communicate with others. A combined solution, in this case, allows a seamless and continued network consisting of both infrastructure-based communication and mobile ad hoc networks. A connection choice depends on what is available (optimum) at any given time.

6.3 Conceptual design requirements of the protocol: enhancing SOS to SOS-Hybrid

The primary goal of this paper is to design an easy-to-deploy hybrid communication system that can utilize the benefits of both top-down and bottom-up emergency communication approaches. To incorporate inclusion and continuity, SOS-Hybrid extends the design of "Self-Organization for survival" (SOS) system [63, 150]. SOS system uses a bottom-up self-organized communication approach to provide affected communities extended and increased access to communication via a peer-to-peer communication network designed for fair participation.

SOS [63] consists of a decentralized context-adaptive topology control protocol that utilizes Bluetooth low energy (BLE) interface of phones to connect with other phones in an area and form MANET. The SOS protocol combines three algorithms and uses preferential attachment based on the energy availability of devices to form a loop-free scale-free adaptive topology for an ad-hoc communication network. SOS aims at overcoming limitations generated by the uneven distribution of battery charge among mobile devices in emergency situations. The fundamental idea underlying SOS is compensating battery charge inequality with a non-homogeneous allocation of communication costs. SOS uses context-aware local self-organisation to deliver participatory fairness, where the topology adapts and no phone has a fixed role as message routing hub. As the battery charge changes over time their role also changes over time.

This makes sure that everyone has same amount of communication opportunity. The SOS system has a number of advantages. First, it is adaptive to the environment. This means it is applicable in scenarios that may vary in the density and mobility of devices, and in the availability of energy sources.

Second, it is energy-efficient through changes in topology. This means it can be flexibly combined with several routing protocols. Third, the protocol requires no changes on the hardware level as it uses BLE interface of phones. This means it can be implemented on all current phones, also in the global south, without any) recalls or investments in hardware changes[1].

1 The implementation details of SOS protocol and evaluation are available in previously published work. Readers are referred to [63, 150] for details.

This research presented in this paper differs from previous work as the design includes a protocol that accounts for switching between bottom-up and top-down communication approaches and delivers inclusive and continues communication services. The hybrid protocol utilizes local knowledge and context-awareness to find the most optimum network to connect depending on availability. This approach ensures that messages are delivered for both mobile and immobile citizens continuously and reliably for a more extended period if at all possible.

The design of the protocol adopts a socio-technical systems perspective for requirement specification. The system itself includes many entities, including the environment for which it is designed. Emergent behavior arises when all entities in the system: (mobile and immobile) citizens, physical infrastructure, and mobile phones (with or without access to energy resources) interact. Existing literature proposes solutions that focus on individual device level performance and do not account for the emergent behavior of the system as a whole.

Below, the scope of the research and design limitations are first introduced. Next are the requirements of this design, some of which are already met by SOS, and some of which are novel to this paper. The design approach itself is described as are the design choices. Last, the design itself is presented: a new protocol called SOS-Hybrid.

6.3.1 Research scope and design limitations

SOS-Hybrid is an advanced version of the preliminary design of SOS. The initial version of SOS has been proposed in previous work [63, 150] where it has been demonstrated that the relative advantage of SOS depends on the density of an area. In a densely populated area, more phones are in the range of each other, thus allowing more chances of transferring messages.

Therefore the successful deployment of SOS-Hybrid depends on the density of phones in an area. Additionally, each person must have the SOS-hybrid application installed on their phones to seamlessly transition back and forth between various communication networks.

6.3.2 Value-based system requirements: designing for continuity and inclusion

The design of the protocol is based on six main value-based system requirements: continuity, inclusion, participatory fairness, reliability, automatic and adaptive services, and distribution of tasks.

6.3.2.1 Continuous connectivity for all, despite 'islands of inequity'

The first requirement that SOS-Hybrid is designed to meet is "spatial justice". The requirement is to ensure that, regardless of where the government or rescue operators decide to put emergency communication equipment, as many people as possible should access these resources even if they are outside the coverage area of the equipment that rescue workers have brought. Impoverished, highly populated areas, so-called 'islands of inequity' [76], need to be able to be reached by disaster response teams.

Furthermore, those in impoverished areas especially need to be empowered to help themselves, because, if a system achieves resilience only through empowering the affluent citizens, the system may promote rather than reduce already existing injustices [59]. Hybrid solutions need to provide this functionality: to provide communication to these areas that may fall outside the range of current emergency communication infrastructures.

6.3.2.2 No new equipment

The second requirement is that no new equipment is needed or changes at the hardware level of phones. Other hybrid solutions that appear in the literature introduce new equipment [72], allow for Wi-Fi tethering [200], high-range radio relays [322], low power wide area network technology [323], or UAVs [39], and sometimes requires changes to be made to the hardware level of mobile phones as part of the solution.

Such solutions bring three disadvantages. First, they are often too expensive for citizens, especially as disaster-prone areas are often poorer than average. Second, not all governments have the budget or the foresight to invest in new equipment to help the mitigation of disasters. Third, the skilled professionals required to operate these systems are not always available.

6.3.2.3 Reliable message delivery for all

The third requirement is that all messages sent are to be received by the intended receiver within a reasonable period. Every message can make a difference in a person's survival in a disaster situation. It is helpful to separate the different parts of this requirement:

- No message should be lost indefinitely.
- All messages that people want to be sent should be sent, regardless of their situation.
- All messages that need to be received should be received, regardless of the sender's or the receiver's situation.

6.3.2.4 Automatic and adaptive services

The fourth requirement is that the system is autonomous and can automatically adapt to changing circumstances of a disaster [324]. The technical system should operate independently and automatically, without operators intervention. Citizens should not need to think about establishing a network or choosing the type of connection required to send a message. These operations should occur in the background seamlessly and automatically. This requirement ensures that the system is usable for a population with little technical education and know-how.

6.3.2.5 Distributed architecture

The fifth requirement is a distributed and decentralised system. Systems that rely on centrally organised communication are vulnerable to disruptions caused by disasters. There is always a central point of failure. Distributed systems are more resilient to adapt to changing conditions.

Centrally organised systems are often designed and optimised for a specific topology and disaster scenario. However, because no two disaster scenarios are the same, there is a risk of performing sub-optimally when the context is different from what was anticipated or when the context changes over time.

6.3.2.6 Participatory fairness

The sixth requirement, namely participatory fairness, was the primary requirement of the previous work published on SOS [63, 150]. Participatory fairness refers to equal opportunities for the participation of all citizens using their phones. As discussed in the introduction section, many ad hoc mobile communication solutions do not consider inequity in battery charges. They require significant battery power to form connections to neighbouring phones. SOS allows phones to switch roles, depending on battery availability.

High-battery phones carry the burden of forming connections and acting as hubs to relay. When they become depleted or the neighbouring phones have higher battery power they switch roles. The adaptive context-aware role switching allows low-battery phones to participate for a longer time period and higher-battery phones to remain connected. As participatory fairness was discussed at length in previous work[150] and is therefore not the primary focus of this paper. However, participatory fairness is a value that is still a requirement in the protocol design.

6.4 Approach: Context-awareness & self-organisation

Context-awareness and self-organisation as an approach can fulfil the central values formulated above in the requirements section. This paper proposes a context-adaptive protocol to enable autonomous self-organising and self-healing to ensure continued connectivity for communication in sudden onset disasters.

The protocol is based on the MAPE cycle proposed by [51]: a cycle of Monitoring contextual changes, Analyzing possible connections, Planning the network and then Executing the connection and message transmission, as described in this section. When a phone is not connected to any infrastructure and wants to send a message, it starts monitoring its context (i.e. its environment). It monitors if there is an alternative working infrastructure in the vicinity to connect. If not, it monitors if there are other phones nearby.

The protocol requires each phone or device to store an information tuple with contextual information. The contextual information stored on each phone consists of its unique identifier, an infrastructure-id that represents the infrastructure to which it is (possibly) connected, a subtree identifier and its residual battery charge.

The phone also maintains a list of possible connections with other phones in the vicinity. Initially, a disconnected phone has an empty list of connections. When the phone transitions to SOS or hybrid mode, it starts making connections, and this list grows. If the phone connects to infrastructure, it updates the information tuple: A phone that is connected to infrastructure maintains the identification of the infrastructure in its information tuple. Otherwise, the infrastructure identification number field in the information tuple remains null.

When this field is null, it triggers an event-driven reconfiguration process requiring the phone to find alternative ways to form a communication network. Phones either connect to other disconnected phones to form their own SOS ad hoc network, or connect with another phone with an infrastructure connection to being part of a the hybrid network. By analysing its context, each phone decides which connection to choose. The goal of the protocol is to facilitate a smooth transition between infrastructures and ad hoc mobile networks that travel back and forth between different communication choices. Choices range from:

- getting connected to newly available infrastructure, i.e., infrastructure mode,
- connecting to other phones to form a mobile ad-hoc network, e.g., SOS type,
- become part of a hybrid network by being indirectly connected to infrastructure through another phone.

Figure 19 depicts a flowchart representation of this process concerning the different types of connections. Since connecting to infrastructure is expensive, it does not look for more connections if a phone is already connected via another phone to infrastructure, limiting its scanning and connection energy loss. Suppose a message has to be sent and no routes are present. In that case, the protocol either looks for more phones to connect or asks its connected neighbours to update their connections by monitoring their context.

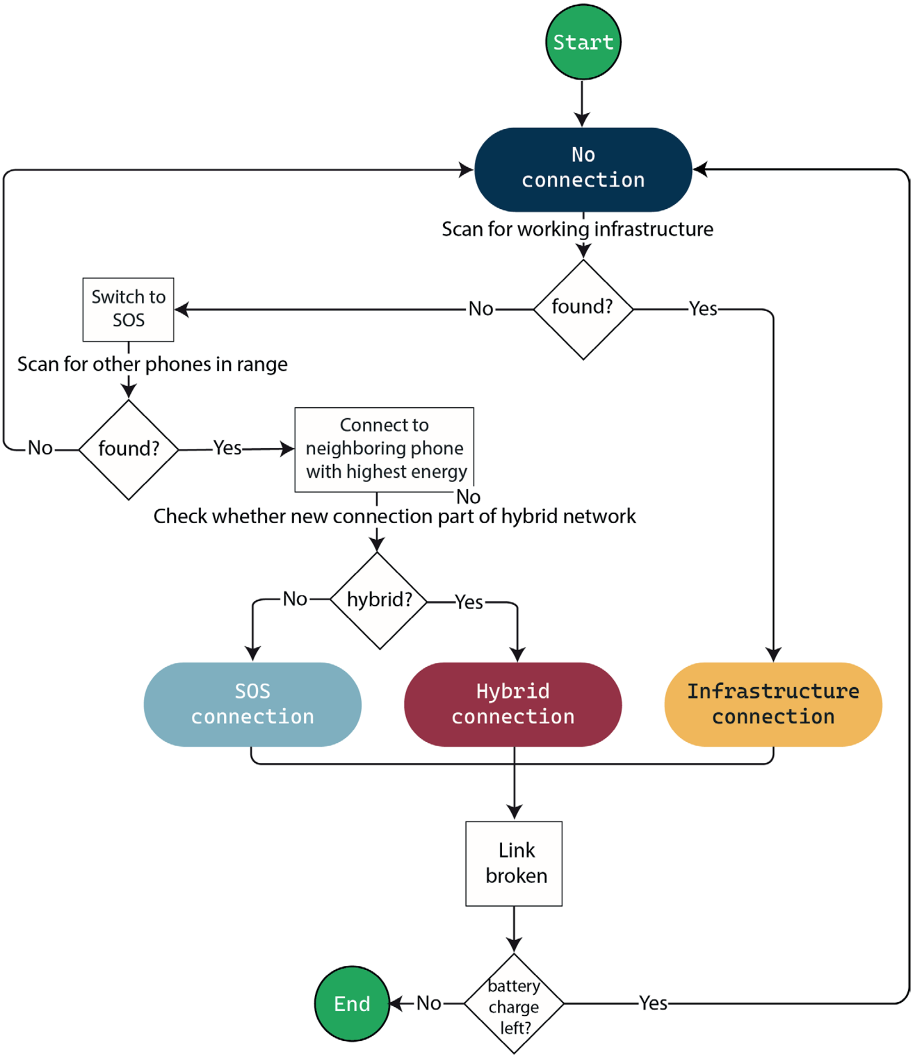


Figure 18: Flowchart representing the connection procedure. The connection procedure is followed by all phones. The goal of the protocol is a smooth transition that travels back and forth between different fragmented solutions or connections.
Choices include getting connected to a newly available infrastructure or a mobile ad hoc network. Each phone chooses between three types of connections. First, infrastructure mode, where a phone finds a working tower or any other equipment that allows a phone to get connected to the outside world (in yellow). Second, SOS mode, where phones outside of the range of infrastructure form a bottom-up self-organized mobile ad hoc network following the SOS protocol (in sky blue). Third, hybrid mode, where a phone is connected to infrastructure and has neighbouring phones that are indirectly connected to an infrastructure (in red). The process ends once the battery charge of a phone is exhausted.

Once monitoring is complete, the protocol determines a plan of action. This plan is based on choices derived from analysis of the context. If a phone finds other phones from a different subnetwork with a high battery charge, it connects to the other phone. All phones in the disaster area follow this procedure, leading to a self-organized mobile network in the absence of infrastructures.

Once Wi-Fi equipment is introduced, phones in the range of coverage connect to the infrastructure the Wi-Fi equipment provides. Phones that are not in the range of coverage, but were previously connected peers, become part of the hybrid network. Before sending a message, a route needs to be found: An enquiry is sent to all neighbours, and they respond positively if a route is available. The phone sends the message to the next connection if a route is available. If no route is available, the phone asks its locally connected neighbours to find more connections.

Upon the request to find more connections, each neighbour updates their connection list by checking if they are in range of working infrastructures and other phones. As citizens are mobile, and Wi-Fi equipment may not always be available, new connections may emerge (and older connections deleted). The connection pattern or topology of the network changes. If, despite this last effort no route is found, the message is saved as a pending message until it can be sent. The protocol specifies that the phone tries to send the messages each following cycle.

6.5 Methods

This paper demonstrates that context-awareness and self-organisation for transitioning can be used to seamlessly integrate various approaches for emergency communication. The focus of the study has been on the design of a hybrid communication system that supports inclusion and continuity through reliable delivery of messages for all.

An abstraction layer was necessary to support the interplay between connectivity of citizens, reliability of message delivery, continuity of connection and communication in terms of variable coverage and infrastructure availability. This required a mixed methodology design based on simulation and modelling following the MAPE cycle. The proposed protocol is designed to support community resilience during disasters.

The simulation using agent-based modelling was used to compare the proposed hybrid network system to an infrastructure-only communication system. Agent-based modelling is often used to study complex systems and social simulation, because of its ability to program heterogeneity in a social context, local interactions, and autonomous agents [91]. The hybrid network solution proposed in this paper is purposefully not compared to existing work that focuses on either centralised control or additional hardware, as these solutions do not satisfy the requirements proposed in this study. The comparison of the basic SOS protocol with existing work that uses mesh topology as their topology has been performed previously [150]. To the authors' knowledge, there are no other hybrid approaches that combine both centralised control and decentralised, self-organisation approaches, which are based on environmental context.

6.5.1 Populating the model and simulating behaviour

To examine the performance of both hybrid and infrastructure-only communication networks through comparative analysis, a hybrid topology and an infrastructure-only topology was simulated in two separate agent-based models. To this purpose, a two-dimensional torus-shaped world is populated randomly with two kinds of phones, mobile and immobile. 25% of the population of phones are defined as immobile, and the remaining 75% move around independently and randomly.

In addition to phones, four backbone communication infrastructures have been included in the simulation in four different locations in the world. Each has a different transmission range and thus a different coverage area. These infrastructures do not work initially but are activated one at a time. Every twelve hours, when infrastructure becomes active, phones in the coverage area of this infrastructure become connected to it. When all infrastructures are active, they provide coverage for 75% of the entire area.

In the infrastructure-only mode, phones in the range of infrastructure form a direct connection with the infrastructure and turn yellow as shown in fig. 19. If there is more than one infrastructure in range, a phone chooses the one to which it is closest. Each phone connects to only one infrastructure, and if they are out of range due to mobility, the connection is lost, and they turn dark blue.

In hybrid mode, i.e., in which SOS and infrastructure may both be available, a phone first attempts to connect to an active infrastructure, but in its absence connects to another phone in range, in a mobile ad hoc network.

Phones connected in SOS networks are shown all grey. When infrastructure becomes active, and is in range, they connect to the infrastructure and turn yellow. Neighbours are informed of the new connection, and they turn red, signifying that they are indirectly connected to infrastructure. Suppose a distant neighbour comes close to another working infrastructure. In that case, this neighbour connects to the infrastructure and leaves the hybrid network. All phones lose energy while connecting, sending and receiving data. Two phones can connect when they are in each other's transmission range, and once connected, they can communicate via this link. In the absence of a direct link, intermediate phones can relay messages for the sender and the receiver. Mobile phones that come in a range of immobile phones in hybrid mode connect and relay their messages.

In Infrastructure-only mode, if immobile phones are outside the coverage area of the infrastructure, they keep storing pending messages. The amount of information stored by a phone increases as per the pending messages. When a phone sends messages, the amount of information stored decreases. In the model, the buffers size is used to continually monitor the delivery of messages. The screenshots of the simulation are shown in Fig. 19. The simulation runs until only 10% of the phones (or less) have battery charge left.

6.5.2 Experimental setup

Experiments are designed to evaluate the delivery of mes- sages for mobile and immobile people in relation to the coverage area. Additionally, study reliable delivery of messages during the period of the first 72 hours after a disaster. The influence of different types of connections and the number of pending messages when no connections could be made are analysed.

To visualise the impact of these factors, mobile citizens are depicted by circles, and immobile citizens are represented by triangles in the agent-based model depicted in Fig. 19. Infrastructure equipment is represented by squares. Each phone grows in size when the number of pending messages grows and shrinks when they are delivered. A yellow square represents a working infrastructure.

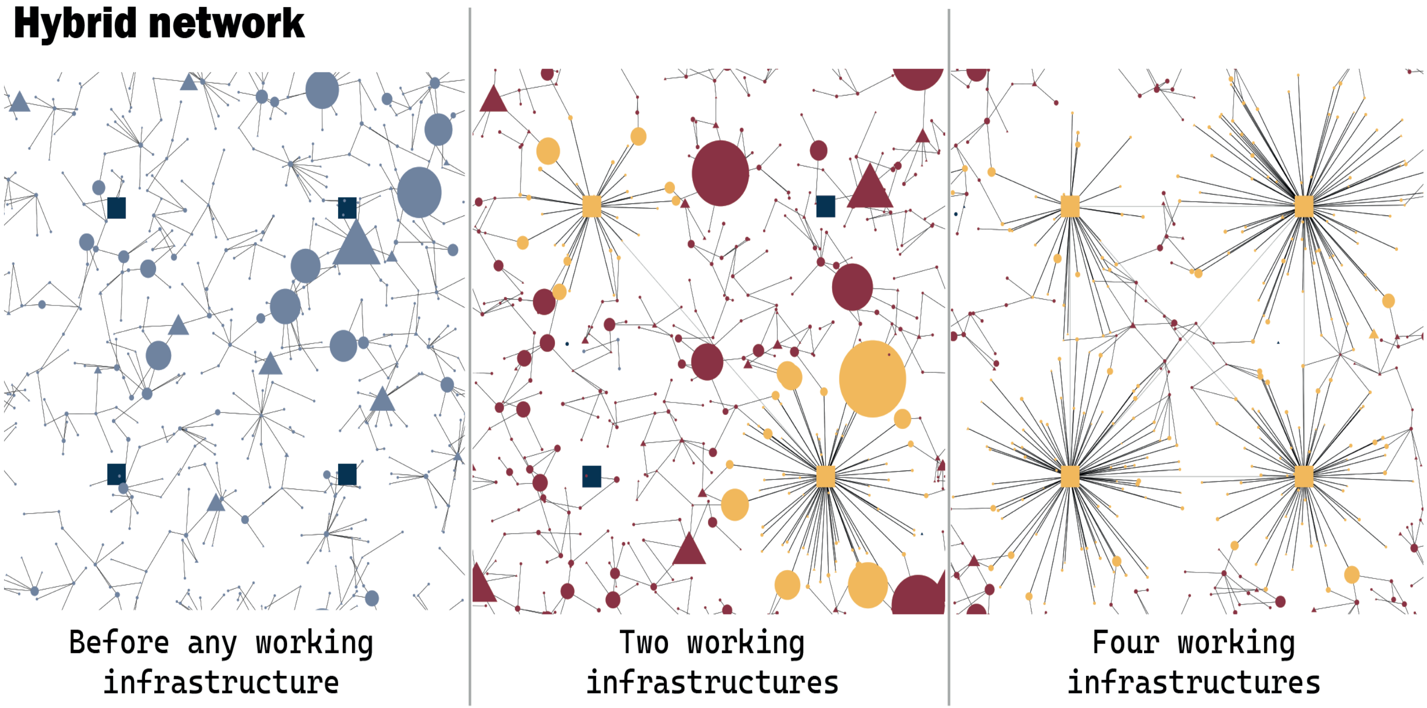
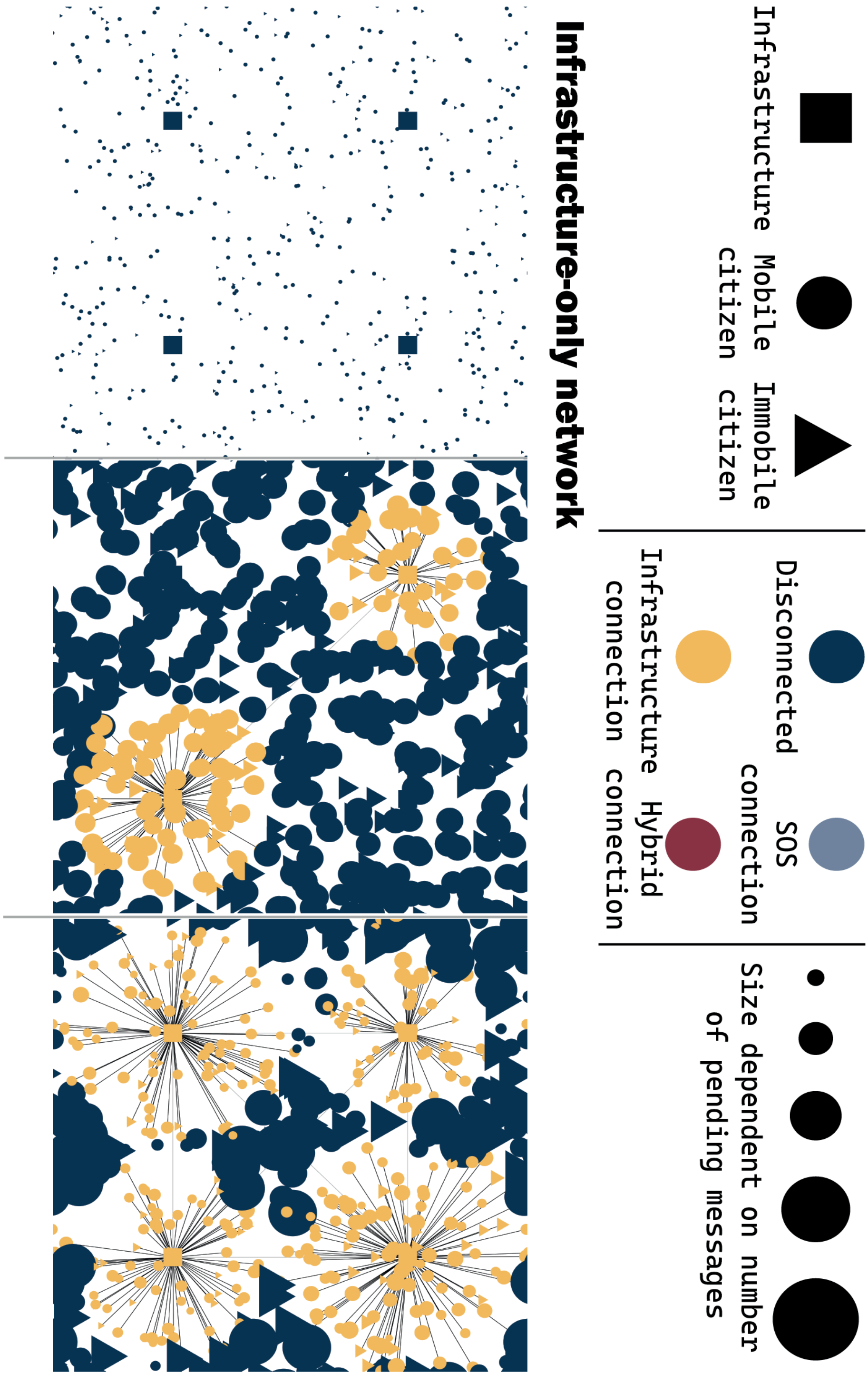


Figure 19: Screenshots of the infrastructure-only and hybrid network simulations are presented for three instances. Mobile citizens are represented by circles; triangles stand for immobile citizens. Infrastructure equipment is shown as squares. In the top rows, the infrastructure-only network is displayed. In the bottom row, the hybrid network simulation is displayed. In each row, screenshots corresponding to three different moments are shown. First, when no infrastructure is available, the hybrid network relies solely on the SOS ad hoc mobile network (in sky blue). In the second screenshot, two infrastructures are active. For infrastructure-only, phones in the coverage area of the two infrastructures are connected (in yellow). For the hybrid network, phones in the range of infrastructure are directly connected (in yellow). Other phones are indirectly linked to the infrastructure in hybrid mode (in red), and a few are in SOS mode in sky-blue). In the last screenshot, all four infrastructures are active.


Infrastructure
Mobile citizen
Immobile citizen
Disconnected
SOS connection
Infrastructure connection
Hybrid connection
Size dependent on number of pending messages
Infrastructure-only network

Once mobile phones start connecting, they turn yellow as well. In the absence of infrastructure, phones form SOS connections, denoted by sky-blue. To study the impact of coverage, each infrastructure becomes active and covers an area covering 75% of the area.

In each of the simulations, connectivity and/or message delivery of the hybrid network proposed is compared to infrastructure-only network over time. The simulation environment is a torus-shaped world of 100 x 100 units with 500 people carrying phones. Of 500 phones, 125 phones are used by immobile people. The transmission range of each phone is ten units. The four infrastructures with different transmission ranges, one of which starts working after every 12 hours. After 48 hours, all four infrastructures are working.

For those simulations, where message delivery is studied, messages are sent continuously: Each phone sends one message every 15 minutes, or five messages are sent in a single burst at the beginning of the simulation. The latter simulation is not a realistic scenario. However, it allows for an evaluation how long it takes for messages to be delivered and how many of the five messages reach the correct location. Battery charge in phones was normally distributed at initialisation.

Different metrics are examined that are aimed at avoiding the pitfall of examining the resilience of the system as a whole while forgetting to assess whether functionality for individual citizens is achieved [325]. Therefore, metrics are computed for different groups of citizens, and the percent age of citizens who achieve a certain functionality is calculated.

6.6 Results

This sections elaborates the results of the evaluation con- ducted in two simulations models to compare the performance of SOS-Hybrid and Infrastructure only communication and is given below:

6.6.1 A hybrid network is more inclusive compared to infrastructure-only network

In Fig. 19, the last three screenshots of the bottom rows are the hybrid network, and the first row screenshots are the infrastructure-only network.

The hybrid network has more red phones than yellow phones, signifying that a significant number of people can access the infrastructure despite a limited coverage area. The last two screenshots of the top row show that in the infrastructure-only network, as more infrastructure becomes active, phones in range become yellow, and their size shrinks.

However, immobile people (triangles) outside of the coverage remain blue (disconnected), and their size keeps growing, signifying that they can never send or receive messages. In contrast, the hybrid network allows immobile people outside of coverage to communicate through phones connected in the SOS network with the infrastructure within range.

6.6.2 A hybrid network has continuous messages delivery, infrastructure-only has intermittent burst delivery

Figure 20 shows the message delivery of 500 phones sending 1 message each. In total, 500 messages are being sent over both the hybrid network and the infrastructure-only network. Again, 25% of phones are immobile. In fig. 20, it is clear that for hybrid network message, delivery is continuous. Even if immobile phones are not in range of active infrastructure, their messages are relayed through the mobile ad hoc network keeping the overall message delivery at 90%.

In the infrastructure-only mode, delivery of messages is very dependent on the coverage area and availability of infrastructures. Therefore, a large number of pending messages are not necessarily being delivered as some phones move in and out of the coverage area. Whenever they are (re-)connected, messages are being delivered in a burst, resulting in the visible peaks.

For mobile phones, this still provides a way to have messages delivered despite the delay. However, message delivery is not possible for immobile phones if they are outside coverage.

6.6.3 No difference in the delivery of messages for mobile and immobile people for the hybrid network

In Figure 21, the yellow line representing infrastructure-based message delivery for mobile phones starts working as soon as the first infrastructure becomes available. It takes all infrastructure to be available to deliver all messages for 80% of the phones, i.e., 400 phones that are mobile can walk around and get connected to various infrastructures.

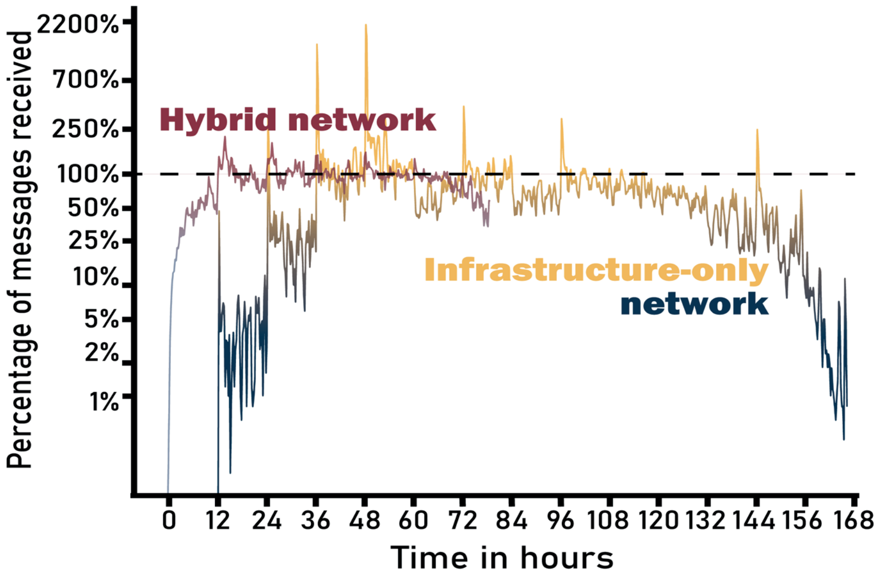


Figure 20: The results for a scenario in which all received messages are tallied to estimate the distribution of message delivery over time. For the infrastructure-only situation, the delivery of messages is very uneven, with as many as 11000 messages being delivered in a single moment and many moments where very few messages are being delivered. To visualize the data from the infrastructure-only data with all its peaks and troughs alongside the more stable data from the hybrid network, the y-axis is displayed on a logarithmic 2 scale. The x-axis displays the time in hours

Of all immobile phones, only around 50% experience full delivery of messages once the infrastructure near them becomes available. Approximately 60-65 phones can send and receive all messages. However, around 7%-10% of phones can never communicate as the coverage area of the infrastructure is only 75% of the entire area.

This means many phones can neither send nor receive any messages at all. So, suppose an immobile phone is in coverage. In that case, this does not necessarily mean that it will receive all of the messages that have been sent from other locations. If a sender is also immobile and outside coverage, message passing between these two phones is not possible.

However, there is no difference in the delivery of messages for mobile and immobile people in the hybrid network. Within the first few hours, many phones have received all of the messages that have been sent even before infrastructure has become available.

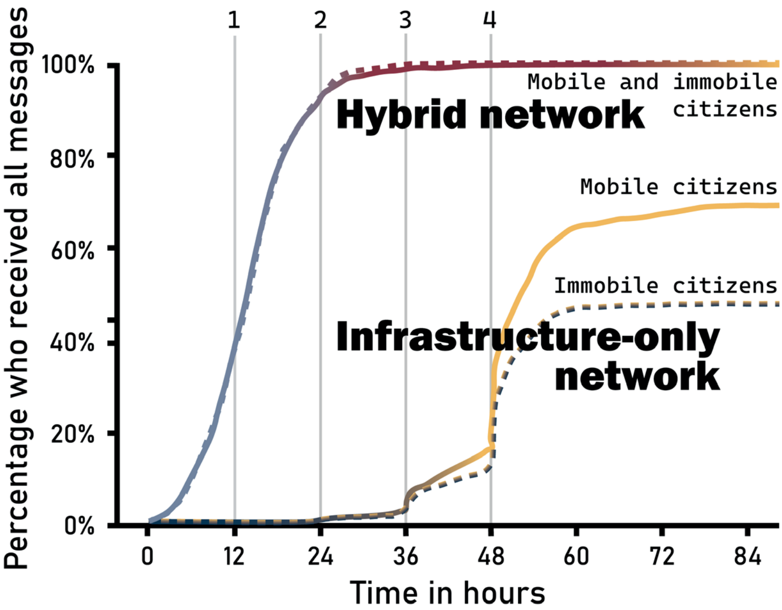


Figure 21: Development of the percentage of phones that have received all of their messages for a specific scenario, in which all phones send just five messages at the start of the simulation. This is not a realistic scenario, but allows for quantification of the time it takes for messages to reach their destination. The y-axis depicts the percentage of phones that have received all of their messages. The x-axis displays the time in hours, and is truncated to zoom in on whether the messages sent at the start are delivered in time.

This is because the presented hybrid network utilizes the SOS protocol and only transitions to infrastructure when available. SOS ensures that, before the infrastructure comes up, even low battery phones can stay connected. With the ad hoc mobile connection, immobile people can connect with nearby phones. This ensures that, despite energy, mobility and coverage differences, all phones have equal participation and continuous message delivery, irrespective of infrastructure presence or absence if other phones are within range.

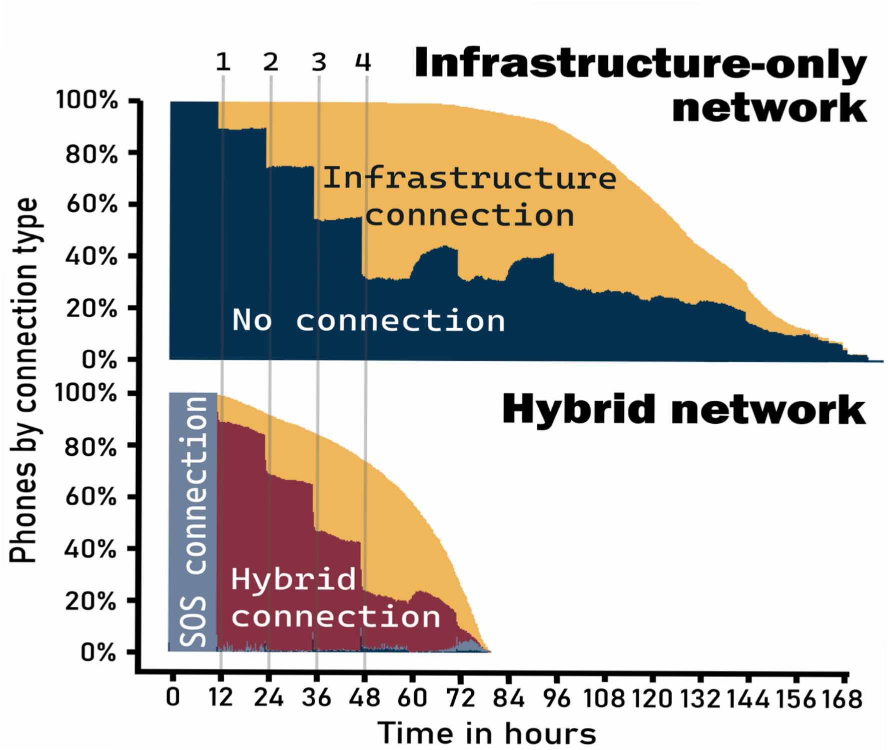


Figure 22: Development of the percentage of phones that belong to one of four categories of connection types (on the y-axis). The x-axis displays the time in hours. Yellow represents phones with connection to infrastructure, dark blue represents no connectivity, red represents hybrid connection and grey represents phones with SOS connection. Every 12 hour an infrastructure is made available such as UAV, Wi-Fi extenders etc, by rescue operators.

6.6.4 Hybrid network provides full connectivity for the 72 hours, Infrastructure-only network runs longer than the hybrid SOS network

In Figure 22, the connectivity of the hybrid network is compared to the infrastructure-only network. The hybrid network runs only for the first 72 hours. In the hybrid network, each phone fulfils tasks that are not required for the infrastructure-only network, i.e., forming connections to other phones and relaying messages. These tasks are costly in terms of battery. By default, the infrastructure-only network runs longer than the hybrid network.

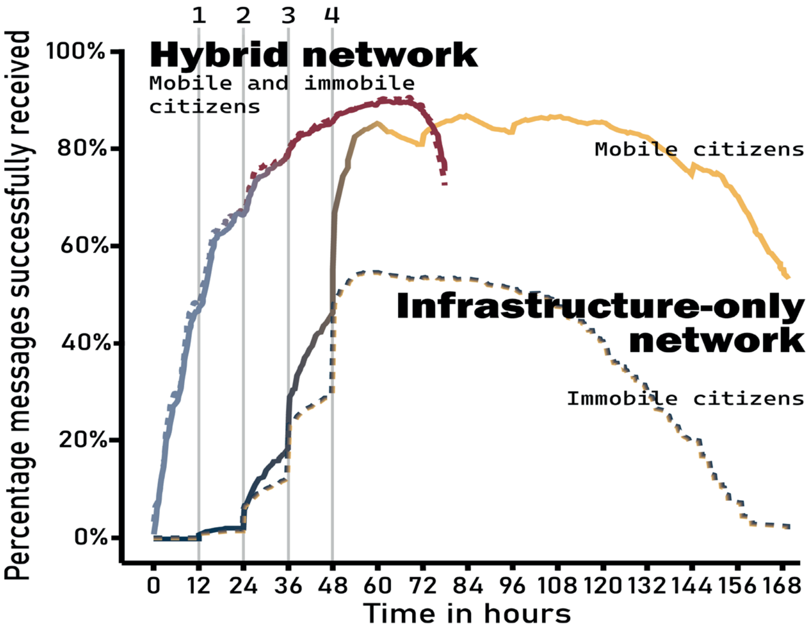


Figure 23: Development of the percentage of messages that have been delivered to their intended receiver for a scenario in which all phones are continuously sending messages. Hence, the number of existing messages keeps growing. The x-axis displays the time in hour. At the left of the x-axis, data is removed from participants that do not have messages intended for them yet, to avoid divide-by-0 error

However, as shown in fig. 22, this also means that for an extended period, when timely delivery of messages is crucial, there is no communication at all. Also, despite the network providing almost 75% coverage, immobile people with phones remain disconnected and are not included in the network.

The last experiment is the extension of the previous experiment in which every phone sends one message continuously. The x-axis in figure 24 represents time in hours, and the y-axis represents the percentage of messages received in relation to the total number of messages that could be received. This is never 100%, because messages are continuously being sent, so there are always new messages that have not been delivered, yet. The dotted lines represent immobile phones, and continuous lines represent mobile phones. Red represents message delivery over an infrastructure-only network, and blue represents message delivery over the hybrid network.

In Figure 23, message delivery over the hybrid network is continuous and inclusive for both mobile and immobile phones. From the very beginning, message delivery shoots up and nears 80% before infrastructure becomes available. As soon as the infrastructure starts to function, message delivery reaches a plateau at around 95% of all messages for all phones delivered.

There is no message delivery for the infrastructure-only network unless the infrastructure is active and functional. Additionally, a clear difference between mobile and immobile phones is visible once infrastructure becomes avail- able. For mobile phones, as the number of infrastructures increases, the coverage area increases and hence it reaches 95% delivery for 375 phones.

However, for 125 immobile phones, some are inside the coverage area and some outside, which results in only 40% of messages being delivered to the intended receiver. This is the highest that immobile phones can achieve despite all infrastructures working.

However, the infrastructure-only network runs longer. The hybrid network runs shorter than the infrastructure-only network as the transition between different connectivity patterns, sending, receiving and relaying messages for other phones and maintaining the network through self-organization is energy-intensive, and battery power is limited.

6.7 Discussion

This paper presents a new perspective on inclusion: ensuring coverage is available to all. Coverage is a standard indicator to maximize to achieve a maximum number of people with access to mobile communication, which makes sense from a utilitarian perspective. However, when it is accepted that coverage will not be 100% for all people all the time, but perhaps only 90% on average, one needs to consider how to allocate lack of coverage.

In this sense, coverage is a resource that needs to be fairly distributed. Lack of coverage and communication opportunities should not always fall on the shoulders of the immobile (i.e. secluded), or those with low battery. Many algorithms introduce unintended biases towards particular segments of society. If these biases are unavoidable, different algorithms' bias should affect different segments, rather than always disadvantaging the same group [326–328].

Continuity was formulated as a requirement for communication. Technically, whether continuity is vital depends on the type of communication. It may be acceptable for some forms of communication if messages are not delivered for some time and then delivered in batches. This delivery pattern was observed in this paper when SOS was not available. This may be acceptable if messages are not time critical but rather form of logging of reports, e.g., about the number of casualties. For other forms of communication, where time critical information exchange such as location of people trapped under rubble needing immediate rescue is required, SOS-hybrid approach is essential for faster delivery times and more continuous communication.

The results were not all positive for SOS-hybrid. The connecting and relaying costs that come with ad hoc mobile networking meant that the SOS-hybrid solution's longevity was much reduced compared to waiting for infrastructure. This shows that, if the goal is to preserve the battery in setting where recharging is impossible, the SOS-hybrid protocol is unsuitable.

However, SOS-hybrid maybe is favourable if the goal is to send time-critical information right after a disaster, but there is a fundamental decision to make: For some disasters, the emergency may be significantly prolonged with little opportunity for emergency action. In this case, preserving the battery and waiting for infrastructure may be the best strategy. SOS-hybrid may be preferred for other disasters, where the crisis is immediate, and time-critical information requesting help or offering help needs to be exchanged immediately.

6.8 Conclusion

The results demonstrate that, with the large number of communication solutions available for disasters, there are clear benefits of combining these isolated solutions. There is a growing body of literature [329] that recognises the importance of transitioning from top-down or military-style 'command & control' approaches to more 'community-centric' or 'people-centered' participatory approaches, to ensure effective communication of risks and requirements among all actors [330]. Rescue operations are impeded by disasters affecting communication, energy and transportation infrastructure [331].

This paper extends [63, 150] by showing how an ad hoc mobile network can synergise with emergency infrastructure solutions to fill in contextual and temporal gaps in infrastructure availability.

These gaps are not necessarily a result of disasters and may have existed already prior to it, in which case, the ad hoc solution transforms rather than restores communication to reduce prior inequalities [332]. This value-based design is extended to include marginalised victims. It ensures continuity of seamless communication during disasters to deliver a resilient solution for all.

To fulfil these value-based requirements, SOS-hybrid is presented in this paper. SOS-hybrid is a protocol that enables transitioning between infrastructure-based communication and ad-hoc mobile communication. A hybrid protocol is described that achieves this while being fully distributed: There is no central authority deciding which of the systems is used by a particular phone.

In agent-based modelling simulations, the efficiency of message delivery is compared for scenarios with and without SOS. Scenarios are evaluated in which infrastructure covers various portions of the simulated world, with mobile and immobile phones. Results show that SOS-hybrid can fill the temporal gaps when infrastructure becomes temporarily unavailable. In a real disaster, messages will have different priorities and hence there should be a mechanism by which the protocol based on the message content registers the priority of each message. SOS-hybrid does not look at the message content or label any message based on priority. Including these mechanisms in an extended design could ensure that emergency response teams reach affected people who need immediate attention quicker.

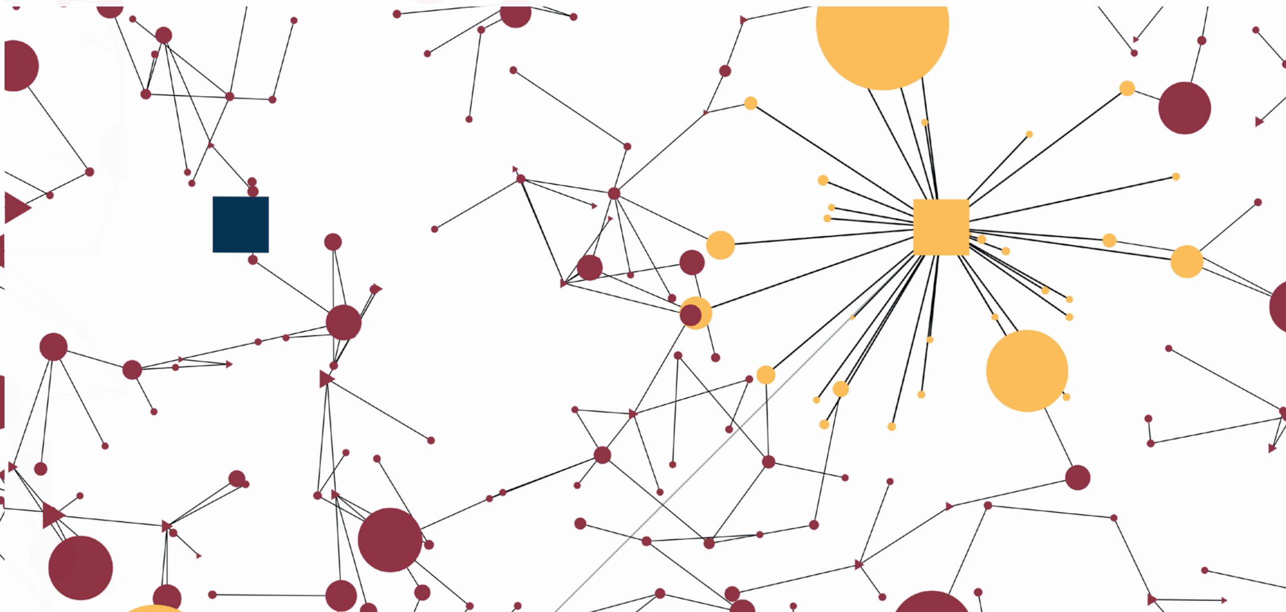
The issue of inclusion and continuity are essential for a resilient society. As climate change will continue to increase, the severity and frequency of disasters with the accompanying civilian deaths and displacements [1]. It thus becomes imperative to design communication systems that enable citizen autonomy to seek rescue during disasters. The design of an autonomous and self-organised protocol that ensures seamless integration between various communication networks based on the respective context can maximise the participation people using their phones, which allows reliable and continuous message delivery, is the first step in this direction.

These findings have significant implications for understanding how the benefits of ad hoc mobile networking allowing hard-to-reach people to connect and the benefits of infrastructure-based communication allowing phones to more efficiently send messages over long distances can be achieved simultaneously.

Part 4

Cognizance

Contents



Chapter 7

॥ कोऽहम् | सोऽहम् ॥

WHO AM I? I AM (EMERGENCE).

CONCLUSION

This thesis presented the design of a resilient citizen-centric communication network and evaluated the delivery of functional and non-functional requirements and fulfilling values that arise at the system level during sudden-onset disasters. This answers the overarching research question:

Main Research Question

How to design a value-based citizen-centric adaptive mobile communication system?

In this chapter the research questions are revisited, and perspectives gained from the entire investigation and the conclusions of the study are provided.

7.1 Research questions revisited

The main research question was further sub-divided into four sub-research questions. The first step into the research was to understand whether current mobile communication systems facilitate and empower local communities for resilient communication during sudden-onset disasters, and a literature survey was conducted. This answers the first sub-research question RQ1.

Sub-Research Question: RQ1

What is the current state of the art in citizen-centric communication systems for sudden-onset disasters, and how are questions of intended stakeholders, ease of use and implementation, deployment time, energy-efficiency and context-reactivity approached?

In the literature survey presented in Chapter 3, citizen-centric design artifacts were reviewed to learn about essential properties that are considered to improve communication and empower citizens. These design artifacts are mobile applications, broadcast mechanisms, protocols, frameworks and conceptual models. The survey found that it is important that developers focus more on systems that are reflective of a disaster situation and context of use. One of the more significant findings from this study is that there is a shift towards using context-awareness to capture the dynamic requirements of a disaster communication system.

With regard to a communication service that is being deployed in a disaster context, "citizen participation" is considered to be a crucial value that an emergency system must fulfil. Additionally, it was proposed to define and use new metrics to measure and represent values that need to be fulfilled in citizen-centric communication systems.

To fulfil the knowledge gaps identified in Chapter 3 and following the guidelines, a new approach was considered for designing a value-based adaptive mobile communication system for citizens. This answers the second research question RQ2.

Sub-Research Question: RQ2

Can self-organization as an approach be used to design a citizen-centric communication system? And how?

To answer RQ2, chapter 4 presents the design of SOS (Self-Organisation for Survival). SOS uses self-organization and autonomic computing to deliver a context-adaptive distributed mobile communication system. In this chapter, functional requirements such as scalability, reliability, robustness, and longevity with a dynamic setting are evaluated. An agent-based model is used to evaluate the design. The evaluations demonstrate that self-organization as an approach is capable of producing a citizen-centered communication systems at par with current systems used in disaster context.

The proposed system has a number of advantages. First, it is adaptive to the environment. This means it is applicable in scenarios that may vary in the density and mobility of devices, and in the availability of energy sources.

Second, it is energy-efficient through changes in topology. This means it can be flexibly combined with several routing protocols. Third, the protocol requires no changes on the hardware level. This means it can be implemented on all current phones, also in the Third World, without any recalls or investments in hardware changes. The results of the evaluation confirm that the self-organizing context-adaptive system enables mobile devices to connect and communicate reliably and scale up despite changing energy availability and density of nodes.

The next step in the research project was to evaluate if SOS can fulfil the value of participatory fairness at the system level. For this purpose two separate agent-based models were created and evaluated. The evaluations and results are presented in Chapter 5, answering the next research question RQ3.

Sub-Research Question: RQ3

Can a citizen-centric communication system fulfil the value of participatory fairness at the system level? And how?

A set of evaluations were conducted in Chapter 5 to answer RQ3 and the simulation shows that the citizen-centric communication system can be designed in such a way that the interaction between individual nodes can lead to the delivery of system level value of participatory fairness.

It is observed that SOS lasts for 72 hours and considerably longer in comparison to mesh. Due to the ”connect to all in range” characteristics of mesh, this results in a crowded topology for 24 hours. The mesh topology is tightly coupled with peer-to-peer connections between phones in each others’ transmission range in the first hour. The increased number of connections and lack of consideration of disparity of energy quickly drains low energy phones, leading to segmentation and eventual disintegration of the network.

On the contrary, since the SOS algorithm is context-adaptive and self-organised, the topology that emerges has few hubs and many low-degree nodes. This is visible in the 1st hour itself (see Appendix for movies). Phones with a high battery charge have many phones connected to them, acting as hubs. Phones with a low battery charge have one connection and lie on the edge of the network.

This is a result of the loop-free nature that was designed in the algorithms (for algorithms and pseudo-code refer to the Appendix). Over time as the battery of initial high battery charge phones reduces, their role changes to leaf node. Over time, this results in a network with a more even energy distribution among phones.

Finally, the thesis presents Chapter 6 with the design of SOS-Hybrid that answers the last research question RQ4.

Sub-Research Question: RQ4

Can a citizen-centric communication system be adapted such that it seamlessly and automatically integrates with other available infrastructure in a disaster context? And how?

To answer RQ4, further evaluations are conducted in Chapter 6. The simulations demonstrate that the system can be designed in such a way that it can function in a larger dynamic context, where it can seamlessly switch between providing a complete ad hoc network when required, using the backbone infrastructure when it becomes available, and functioning in a hybrid mode combining the two. The hybrid design ensures reliable and continuous message delivery irrespective of the location and mobility of citizens. Chapter 6 presents the hybrid design SOS-Hybrid in which the two types of solutions ad hoc mobile MANET solutions and infrastructural Wi-Fi solutions work together.

SOS-Hybrid is designed to meet spatial justice. Spatial justice in SOS-Hybrid is defined as a fundamental requirement to ensure that regardless of where the emergency communication equipment is put by the government or rescue operators, a maximum number of people should be able to access these resources despite being outside the coverage area of the equipment.

Disaster response teams need to be able to reach impoverished, highly populated areas, so-called 'islands of inequity', [76]. Furthermore, those in impoverished areas especially need to be empowered to help themselves, because, if a system achieves resilience only through empowering the affluent citizens, the system may promote rather than reduce already existing injustices [59].

To evaluate the performance of the SOS-Hybrid two agent-based models are presented in Chapter 6. One is with SOS-Hybrid, one is just using equipment owned by the government, or rescue operators called

Infrastructure-only. In the hybrid network, a significant number of people can access the infrastructure despite a limited coverage area. The hybrid network also allows immobile people outside of coverage to communicate through phones connected in the SOS network with the infrastructure within range. Without SOS-Hybrid, immobile people outside of coverage had large numbers of pending messages, signaling that they had no way of communicating.

Second, for hybrid network message delivery is continuous. Messages of immobile phones outside of range of active infrastructure are relayed through the mobile ad hoc network keeping the overall message delivery at 90%. Whereas for infrastructure-only mode, delivery of messages is very dependent on the coverage area and availability of infrastructures.

Third, for phones with SOS-Hybrid there was no difference in the delivery of messages for mobile and immobile people. There is no difference in the delivery of messages for mobile and immobile people for the hybrid network. Within the first few hours even before infrastructure has become available, many phones have received all of the messages that have been sent. This is the result of switching between connection patterns where the hybrid network utilizes the SOS protocol and only transitions to infrastructure when available.

Before the infrastructure comes up, SOS ensures that even low battery phones can stay connected. This results in all phones having the opportunity to connect to infrastructure. With the ad hoc mobile connection, immobile people can connect with nearby phones. SOS-Hybrid ensures that despite energy, mobility and coverage differences, all phones have equal participation and continuous message delivery, irrespective of infrastructure presence or absence if other phones are within range.

7.2 Conclusions

In conclusion, one way of empowering civilians during disasters is to design technologies that civilians can use for decision making, for collecting and distributing resources, or to come together and collectively perform tasks [333]. These technologies, such as applications running on smartphones are becoming easier to deploy as smartphones are ubiquitous and cheap. In order to utilise these mobile smartphones as tools of empowerment, be it in sensemaking and situational awareness [334], decision making, or communicating, certain limitations need to be considered.

These limitations can be built in the device, or in-built in the environment or context. If these limitations are not considered, this can create more disparities than empowerment. In Chapter 3, these limitations are discussed at length, as the state of the art on citizen-centric communication systems is reviewed.

To address these limitations, there is a need to change the way technologies are being designed and evaluated and used. Therefore in this thesis, self-organisation was used to design a context-aware adaptive communication system. The design of the SOS system was validated in an agent-based model. A disaster is a dynamic setting, which consists of many uncertainties such as population density, resource availability, and sudden presence or absence of infrastructure.

The agent-based models used in this thesis represent this dynamic setting, allowing for evaluation of all functional requirements. It is concluded from Chapter 4 that self-organisation as an approach can be used to design an adaptive citizen-centric communication system.

In disaster settings, citizens using a communication system have certain expectations from these systems such as that it is easy to use and deploy them without the need of any extra equipment. They also expect being able to communicate despite the lack of resources, being able to communicate in the first 72 hours until rescue arrives and seamless integration into infrastructure when available. These expectations arise from values such as participation, inclusion and fair access to communication opportunities. These values result in the design of SOS and SOS-Hybrid as emergent properties, as shown in Chapter 5 and 6.

To Conclude

Self-organization can be used as an approach to design a value-based adaptive mobile communication system for citizens that

(i) is robust, reliable and scalable; delivering all functional requirements;

(ii) fulfils the value of participatory fairness at the system level, and

(iii) seamlessly and automatically integrates with other available infrastructure for inclusive and continuous message delivery for all phones, despite energy disparities and varied population densities of a disaster area.

Chapter 8

॥ अंतः अस्ति प्रारंभः ॥

THE END IS THE BEGINNING

Part of this chapter is published in :
1. Banerjee, Indushree, Martijn Warnier, and Frances M T Brazier. "Designing inclusion and continuity for resilient communication during disasters." Sustainable and Resilient Infrastructures, (2022): 1-16.

2. Banerjee, Indushree, Martijn Warnier, Frances M T Brazier, and Dirk Helbing. "Introducing participatory fairness in emergency communication can support self-organization for survival." Scientific reports 11, no. 1 (2021): 1-9.

3. Banerjee, Indushree, Martijn Warnier, and Frances M T Brazier. "Self-organizing topology for energy-efficient ad-hoc communication networks of mobile devices." Complex Adaptive Systems Modeling 8, no. 1 (2020): 1-21.

4. Banerjee, Indushree, Martijn Warnier, and Frances M T Brazier. "Ad Hoc Communication Topology Switching during Disasters from Altruistic to Individualistic and Back." In COMPLEXIS, pp. 103-107. 2020.

FUTURE WORK

8.1 Field studies with an actual application

8.2 Integration and standardisation

8.3 Investigate if SOS is scale-free or not

Participation and collaboration among various stakeholders such as government, rescue operators and citizens has been recognized [335] as important criteria to minimize the impact of disasters. This thesis focused on this requirement and designed a communication network to tackle the issue of participatory fairness and inclusion in citizen-centric communication during disasters.

The thesis presented a prototype using agent-based modeling and used it for verification to test requirements. In future work, the performance of the self-adaptive ad-hoc communication network needs to be evaluated outside of lab conditions. The findings of this study have a number of important implications for future practice as described in this chapter.

8.1 Field studies with an actual application

Although more work is needed, the current prototype has demonstrated that SOS can be implemented on multitudes of phones, without further requirements on the hardware. In this way, implementation requires the development of a new mobile application, and the improvements in energy efficiency can have an immediate positive impact. A natural progression of this work is to perform controlled trials to verify the suitability and practical implications of the use of both SOS and SOS-Hybrid [336] and to analyse the impact on communication between different actors involved in disaster recovery. Therefore, research using a real-life study is an essential next step.

Additionally, how phones connect depends on the willingness of citizens and their want to participate. SOS works with the assumption that high-energy nodes are willing to bear the load for the entire network. Further research needs to examine more closely the links between different incentive mechanisms that can be used to mitigate selfish behaviour of nodes to promote more co-operative behaviour.

8.2 Integration and standardisation

Further research could usefully explore the integration of various applications including SOS, along with other applications discussed in related work, to develop a standardised integrated system for field trials. Investigation and experimentation into delivery of an easy-to-use and deploy system in different geographic regions with diverse urban settings is strongly recommended.

Further work needs to be done to establish the extent of technology adoption that can be achieved based on existing digital literacy, present in disaster-prone cities. Research should focus on determining factors that prevent mass usage and develop workshops to learn about how to ease the usage of emergency mobile applications.

8.3 Investigate if SOS is scale-free or not

As future investigation, the property of scale-free can be investigated on SOS. There are multiple similarities between SOS and a scale-free network. Just as in a scale-free network, hubs are formed, and the node degree distribution is similar to a power-law distribution. Connections are not formed randomly but are formed based on a preference for some nodes, which entails that these nodes will automatically gain larger numbers of connections. However, there are several notable differences. The two mechanisms that lead to a scale-free network —preferential attachment and growth— are different in SOS.

First, the attachment is not based on node degree but available battery charge, so connections themselves do not affect the probability of forming connections. This has implications for who is selected as a hub initially: high-battery phones in SOS and random phones in scale-free networks. Second, in scale-free networks, the probability of choosing a connection is proportional to the degree, while SOS selects the maximum battery charge in range, to keep distributed computations simple. Third, SOS is constrained to be loop-free to simplify paths between nodes, while most scale-free networks do not have this property. Therefore, SOS has no redundant paths, which has advantages and disadvantages.

Fourth, reconfiguration in SOS means that nodes can switch roles over time, starting as hubs, while later moving to the edge of the network, while the hubs in scale-free networks become ever more central due to preferential attachment. Fifth, there is no growth in the number of connections over time in the SOS simulation that was implemented in this article.

In real life, new phones will of course join the network over time, but expired phones will also leave, so there is no continuous growth as in a scale-free network.

Sixth, finite transmission range prevents phones from reaching all other phones in SOS, while scale-free networks are typically found in networks without a spatial component (like the WWW).

In conclusion, whether a network is scale-free is contentious. The mechanisms behind the formation of the network in SOS is context-adaptivity and self-organization based on local rules followed by phones. In preferential attachment in a strict sense, energy consideration and participatory fairness would be lost if phones only connect with phones with high node degrees. Therefore, SOS uses a different type of preference for preferential attachment, where we change the rules of the attachment.

While the mechanism of preferential attachment is known to produce scale-free networks, if based on node degrees [337], it remains to be investigated whether scale-free property also emerges when preferential attachment is based on battery charge. Furthermore, the embeddedness in two-dimensional space and limited transmission range may lead to changes in the distribution. Note, however, that scale-free is not a functional requirement/prerequisite for the SOS system to work that is also, why the question was not further investigated in this thesis.

A scale-free network could still emerge from this rule, and indeed, the node degree distribution seems to follow a power-law distribution. However, other distributions might fit equally well or better. Therefore, more investigation is required.

Appendix

Supplementary material
of Chapter 5

9.1 QR Code of movies

All Supplementary Movies are available at

https://www.nature.com/articles/s41598-021-86635-y#Sec50

Figure 24: QR code of SI

9.1.1 Illustration of both SOS and mesh topology evolving network.

Supplementary Movie S1 is a simulation of 500 phones sending and receiving messages. We demonstrate the energy loss and node participation.

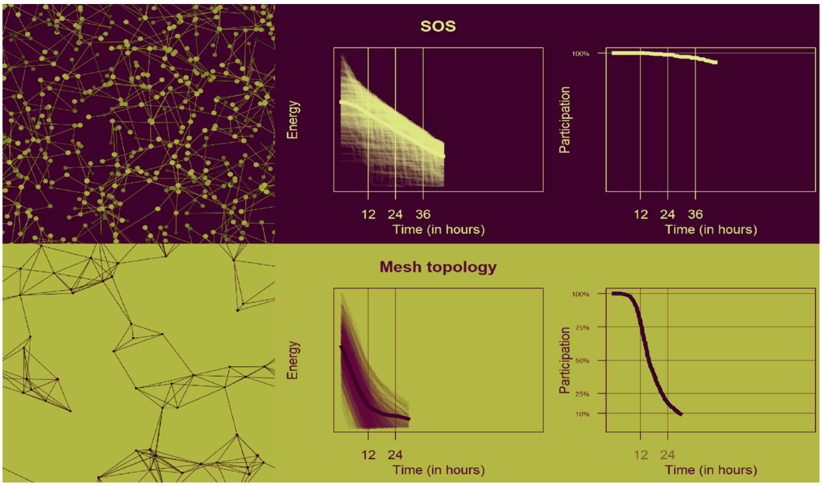


Figure 25: Screenshot of movie S1

9.1.2 SOS: Illustration of the SOS evolving network.

Supplementary Movie S2 is a simulation of 500 phones sending and receiving messages. We demonstrate the energy loss and betweenness centrality of three phones. These are phones with high (green), medium (yellow) and low (red) initial battery charge.

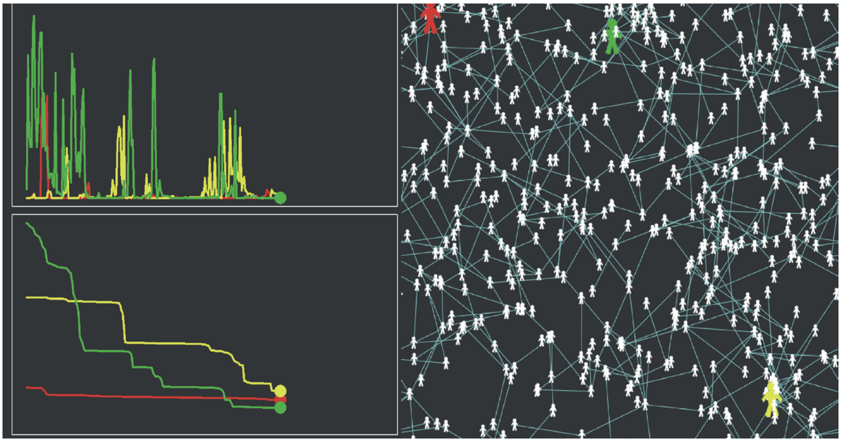


Figure 26: Screenshot of movie S2

9.1.3 Mesh: Illustration of a mesh topology evolving network.

Supplementary Movie S3 is a simulation of 500 phones sending and receiving messages. We demonstrate the energy loss and betweenness centrality of three phones. These are phones with high (green), medium (yellow) and low (red) initial battery charge.

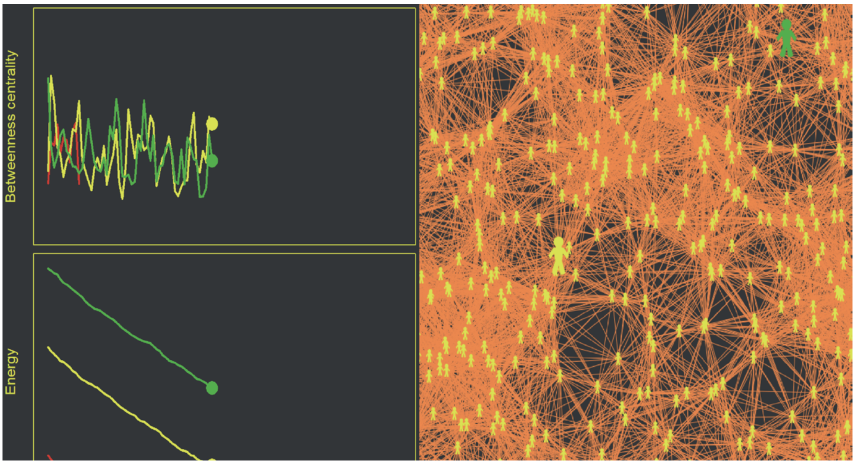
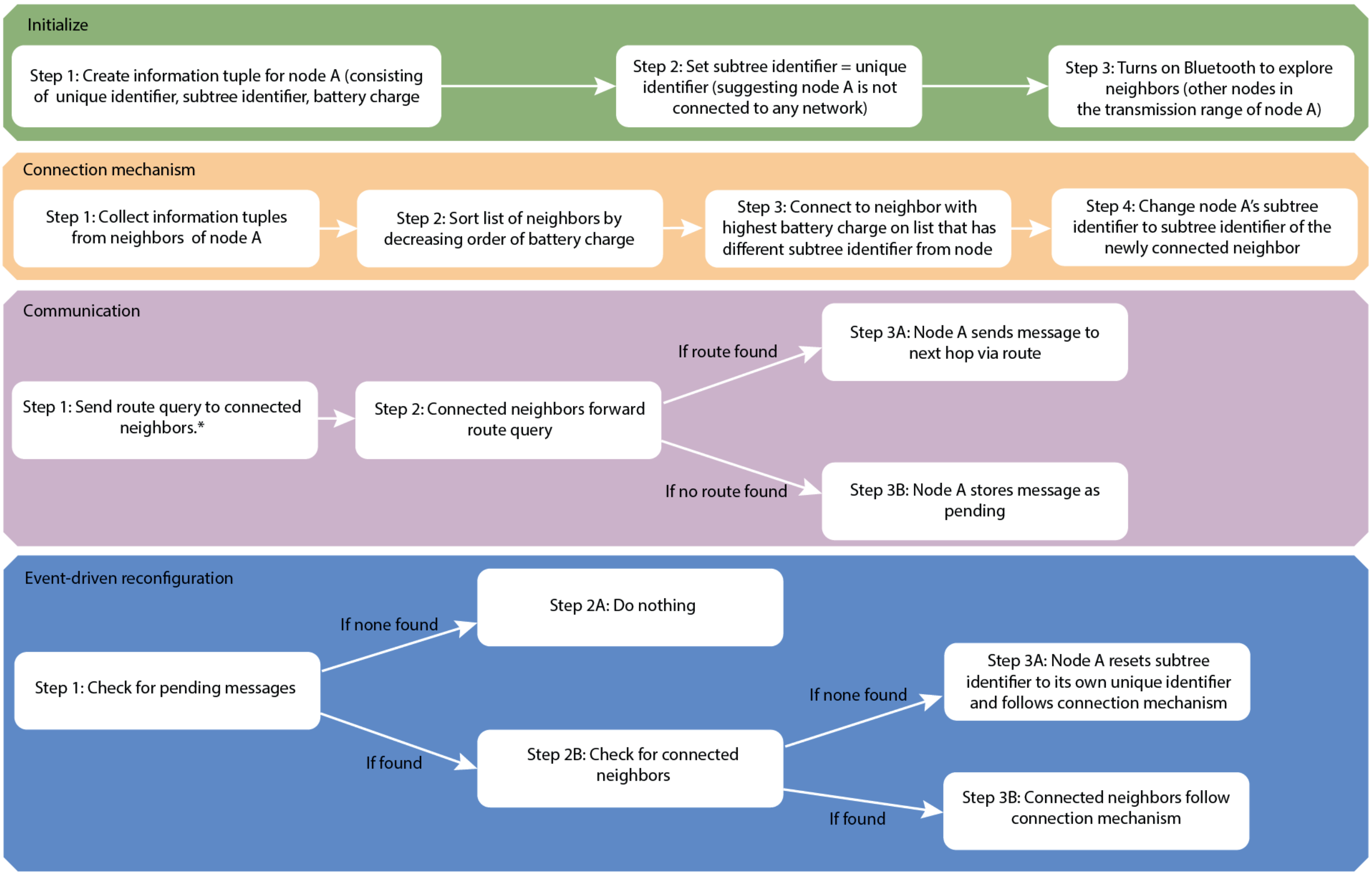


Figure 27: Screenshot of movie S3

Figure 28: The figure represents the detailed working of the algorithm 1 (green and orange), algorithm 2 (purple) and algorithm 3 (blue). Note that this is done by an independent routing protocol (outside scope of the paper)



9.2 Algorithms and pseudo-codes

There are two algorithms that are part of this protocol. Algorithm 4 defines the connection procedure by forming connections based on contextual information. Algorithm 5 determines the event-driven reconfiguration to maintain autonomous self-organisation. As each phone follows these two algorithms, they follow a cycle of monitoring spatial changes, analyzing context, planning next steps, and executing decisions based on this information. Monitoring, analyzing, planning and executing are the four fundamental steps of MAPE cycle [51]. Following a MAPE cycle is critical for designing autonomous systems and in this case leads to the emergence of a context-adaptive self-organised network. Algorithm 4 and algorithm 5 are used to create, and adapt the topology of the network as the context (spatial-temporal and resource) changes in their environment. To model and simulate the communication part of the network we design algorithm 2. Algorithm 2 is for message routing and the pseudocode is presented in the modeling section separately as it is not part of the main protocol and utilizes a gradient-based routing protocol [338]. Algorithm 4 and 5 are explained in detail in the following section. The illustration of algorithm 4,5 and 2 for simulation and modeling is presented in Fig. 28.

Table 10: The spatial information stored in *t*

Information	Type
U_{id}	Unique identifier of the phone
S_{id}	Subtree identifier = connected network number
e	Battery charge left

9.2.1 Connection mechanism

The process starts with each phone on its own, which is not connected to any other phone in its transmission range. As each phone turns on their Bluetooth, they start discovering phones in their transmission range *r*. Each phone then collects information of its surrounding by creating an information tuple *t*.

The spatial information stored in *t* is presented in Table 10 . The tuple t consists of their own unique identifier (U_{id}), subtree identifier (S_{id}) and battery charge left (e). The phone also maintains a list of its connections (l_v).

Initially l_v is empty as a phone is not connected to anyone. As the phones start making connections this list grows. Initially the subtree identifier is set to the unique identifier of the phone to represent that the phone is disconnected from any network. As a phone informs its presence and starts to explore possible connections, it also starts receiving the *t* from other phones in its transmission range. Based on this spatial information, the phone then decides a favourable or preferred choice of connection. This connection is based on the battery charge of other phones. The phone considers the energy of all the potential phones in the range and sorts them in decreasing order of battery charge. The potential phone with the highest energy is selected and the connection-initiating phone compares their subtree identifier. If they do not match, it confirms that both these phones belong to different networks and then these phones connect and change their subtree identifier to match. Once connection is established, both phone populate their l_v with the connection they made. This procedure ensures that there are no redundant routes between nodes. Different subtree identifiers indicate that phones belong to different networks. If the subtree identifiers match it indicates that the nodes are connected through different phones in the same network. By matching subtree identifiers, redundant routes between nodes are prevented.

Let's assume citizen A is disconnected from communication infrastructures and would like to form a network or get connected to an ad hoc network. A switches on its Bluetooth and starts to explore other phones around in its transmission range. The phone of A finds other citizens (B, D) also trying to form a network or get connected. These phones exchange their information tuple that consists of their own U_{id}, their S_{id} (which at this point will be set to their unique identifier, since they are all disconnected), and their own battery charge (*e*). They also have a empty list of connected neighbors (l_v), which they will populate once they start forming connections.

Imagine the battery charge in phones of the citizens is in order A >D >B. Thus A has the highest energy of all of them. The phones B and D select A to connect since it can afford multiple connections. Now phones B and D change their subtree identifier to the subtree identifier of A, representing that they are now part of the same network. Between B and D there is no direct connection since they are connected via A. They know this as they both have the same subtree identifier. This prevents the formation of redundant routes reducing connection cost and ensuring low node degree for less battery charge phones. Since there is local information exchange in a distributed manner, a context-adaptive self-organised network emerges. These connection patterns and the topology keep changing as phones move in and out of the transmission range. Suppose citizen M comes in the range of this network and has higher battery charge than A. Then M becomes central as other phones switch to phone M. This way the traffic is diverted through a separate set of phones and prevents the exploitation of certain specific phones. Local information exchange ensures that the energy lost in this exchange is limited and maintains the trade-off between adaptivity and energy consumption.

Algorithm 4 Connection Procedure followed by each node in Transmission range *r*

1: $t \leftarrow U_{id}, e, S_{id}, l_v$
2: $U_{id} = S_{id}$ ▷ Node A sets its unique identifier to its subtree identifier signifying it is not connected to any network
3: ▷ Node A turns on its Bluetooth and scans for neighbors within *r*
4: ▷ list O_l is a temporary list generated to store information of other phones within r
5: **if** O_l != *null* **then** ▷ Other phones found within r
6: $O_l \leftarrow t_D, t_C, t_B, \ldots$ ▷ Put the information tuple of neighboring phones
7: $O_l \leftarrow t_{B_e} > t_{D_e} > t_{C_e}, \ldots$ ▷ Sort O_l in decreasing battery charge
8: **EndIf**
9: **while** O_l != *null* **do** ▷ Select neighbor to connect from the list
10: **if** $S_{id}(A)$!= $S_{id}(\underline{B})$ **then** ▷ Compare the S_{id} of Node A with the S_{id} of Node B
11: $S_{id}(A) = S_{id}(B)$ ▷ Connect and equalize subtree identifier
12: $l_v \leftarrow B$ ▷ Include the new connection in list l_v, initially empty.
13: **Break**
14: **EndIf**
15: **EndWhile**
16: $O_l \leftarrow null$ ▷ Empty O_l

This connection procedure results in a fully connected network with a dynamic topology that ensures participatory fairness and energy efficiency. A network structure emerges with central phones being high in energy and pushing low energy nodes to the edge of the network. To improve the performance, phones remove connected phones with exhausted battery and connect to new phones whenever the network is unable to send or receive information. Thus this self-organizing adaptive protocol allows mobile phones to interact with their neighbors in a distributed mechanism to collaboratively achieve connectivity, robustness, scalability and reliability as emergent properties of the entire system.

9.2.2 Event-driven reconfiguration: Adaptive reconfiguration and relabeling

The purpose of the protocol is to maintain reliability and robustness despite link failures and phones leaving due to loss of battery charge. Additionally the topology must adapt to ensure that the loss of energy for relaying messages is distributed among various high energy nodes. This is achieved by event-driven reconfiguration. Let's assume citizen A has a set of pending messages in his phone that it needs to forward/relay to the next hop. The algorithm then triggers an event-driven reconfiguration. This results in A following algorithm 5.

The phone first looks into its list of connected phones, l_v. Let's say A is connected to citizen B, C, D, E, M and N. Since citizens are walking around and are not static it is quite possible that some of them are out of range. Additionally, they are losing battery charge, meaning that some of them may now be below the acceptable level for getting connected. Therefore A updates its l_v by removing links with citizens that are out of its transmission range (D and M) and removing links with citizens with phones that have almost negligible battery left (C and E).

If all connections were removed during the previous steps then the phone of A also changes its own subtree identifier back to its own unique identifier and it recursively asks all still connected phones to change their subtree identifier back to the caller's unique identifier i.e., to the unique identifier of node A. This ensures that all subnetworks that emerge from this step have unique identifiers, thereby maintaining consistency.

However, to utilize mobility and maintain connections, node A looks for possible new neighbors or phones with high energy. If new citizens with higher-battery-charge phones come into transmission range, A follows the same connection procedure described before in Algorithm 1 to prevent redundant routes while still getting connected and forming new connections or become part of a network.

This leads to the emergence of a new topology every time there is an event-driven reconfiguration, which is not only optimized for finding new routes for sending and receiving messages but also more energy efficient as different high energy phones act as hubs. As every phone follows these three algorithms autonomously with distributed information exchange, the network remains robust, scalable and reliable for changing density and energy availability.

9.3 Method: Modeling and simulation of both mesh network and SOS

As described in chapter 5, both mesh and SOS were modelled in NetLogo. Below, more detail is provided on the implementation.

9.3.1 Populating the model and simulating behavior

To examine the performance and do comparative analysis of both mesh and SOS, both topologies were simulated in two separate agent-based models. The model takes a two-dimensional torus-shaped world and populates it randomly with nodes. Each node denotes a mobile phone that moves independently and in a random walk. Two nodes can communicate when there is a link between them, which gets created when they are in the transmission range of each other. If there is no direct link, nodes can communicate through intermediate nodes. Each node has a transmission range. When the nodes moves out of transmission range they lose the connection link. This helps in investigating the effect of mobility on performance, scalability and robustness of the network.

There is no limitation on the number of connections a node can form. Nodes have fixed battery charge that depletes once they start making connections and sending messages. As the simulation starts, every node follows algorithm 4 that lead to the emergence of an ad hoc network. Participating nodes are not assigned any roles as they join the network.

Algorithm 5 Event driven Adaptive reconfiguration and relabeling followed by a node A

$l_v \leftarrow t_B, t_C, t_D, t_E, t_M, t_N$
    ▷ list l_v is newly generated by exploring other nodes within transmission range
Remove links with nodes with low battery charge
$l_v \leftarrow t_B, t_D, t_M, t_N$
    ▷ list l_v is updated by removing nodes C and E
Remove links out of transmission range r
$l_v \leftarrow t_B, t_N$
    ▷ list l_v is updated by removing nodes D and M
Relabel node sub-tree id's using:
procedure RELABEL (Node)
    if $S_{id} \mathrel{!}= u_{id}(A)$ **then**
        Set $S_{id} = u_{id}(A)$
        RELABEL(connected nodes)
    else break
Connect to new nodes by following **Algorithm 1**

As the network formation begins and the number of nodes participating increases, different roles are assigned to them automatically and dynamically to maintain connectivity and energy efficiency. Nodes communicate directly or through multiple nodes/hops relaying messages. To maintain participatory fairness, the traffic keep flowing through different nodes.

9.3.2 Routing of messages

In each model, all nodes send a message to a randomly selected node present in the model for receiving the message. The number of messages sent by each node is a model parameter and can vary from 1 to 10. Assume citizen A wants to send a message to citizen Z. If citizen A is not connected to Z directly, A sends a route enquiry to all its connected phones using algorithm ??.

If there are no direct connections, relaying phones then forward this enquiry to their own connections. This route enquiry can have two results. First if there is a route, A is notified and A forwards it to the next hop or relay. If at some point during relaying one of the relaying phones does not find a route, it stores the message as a pending message.

Once it gets a route, it forwards the message to the receiver Z.

This is true for mesh topology and is thus implemented in the simulation as such. However, for SOS the model follows algorithm 6. When there are no routes A saves the message as pending. Next A checks if it is disconnected or if it has connections. In case it is disconnected, A reconfigures following algorithm 5. If A has connections, A triggers algorithm 5 for its connections. The communication algorithm pseudocode is presented in algorithm 6. A gradient-based routing protocol [338] is assumed for routing.

Algorithm 6 Sending and receiving information protocol followed by each node connected to a network

```
Sender sends a route inquiry
if No Route found then
    if Connected to a Network then
        Ask connected neighbours to Reconfigure
    else Not connected to any Network
        Self Reconfigure
else Route found
    Send information to next hop in the route
EndIf
```

9.3.3 Modeling changes in battery charge

To ensure that energy efficiency is achieved, it is important to consider each factor associated with losing battery charge while participating in a network. The first consideration was to choose between available interfaces for communication i.e. either Bluetooth low energy (BLE) or Wi-Fi. Research suggests that BLE was 30% more energy efficient than Wi-Fi. Moreover, BLE is a standard interface that is available in every phone making our approach more easy to deploy in countries where the population cannot afford smartphones.

The battery costs associated with sending, receiving, relaying and forming connections were taken from the literature [293], and are presented in Table 13. A variety of phones is modeled: We simulated a combination of high-end phones such as Apple iPhones (with full battery charge capacity of 3000mAh) and low-end budget phones, non-smartphones (with full battery charge capacity of 2000mAh).

For both the models, phones can form a direct connection with other phones if they are in transmission range. In mesh all phones connect that are in range, without consideration of the battery charge of phones. For mesh, if phones move out of range, they remove links and if phones no longer have energy they leave the network.

For simulating SOS, algorithm 4 and algorithm 5 are followed. The sending and relaying is same in both the topologies and hence kept the same across models. The real difference lies in the event-driven reconfiguration that is only implemented in SOS by following algorithm 6. Apart from this, both simulations perform the same tasks and are initiated with an equal number of nodes and equal battery charges of the phones for the sake of comparison. For SOS, the cost associated with event-driven reconfiguration is taken into consideration and calculated as per Table 11.

Table 11: Energy consumption associated with sending and receiving a single SMS over a BLE connection [293, 339]

Activity	Power draw(mA)	Duration (mS)	Size bytes	Time*Current (mAmS)
Wakeup Preprocessing	5	1000		5000
Receiving (Rx)	22	1120	140	24620
Inter Frame Space (IFS)	15	150		2250
Transmission (Tx)	28	1120	140	31360
Post Processing	8	1400		11200
Total Time		4790		
Total Time * current				74450

9.4 Evaluation

Impact of transmission range variability : Additionally, we have performed experiments with variable transmission ranges (specifically, a uniform distribution ranging from 5 to 8 units). In its present form, the algorithm also works given such heterogeneity, as the decision whether to connect or not, is on the basis of battery availability around a node. The transmission range impacts the number of possible connections a node can choose from.

Nodes with higher transmission range see a larger selection pool increasing their chances to getting connected to higher battery charge phones. This increases the overall network lifetime, as shown in the Fig. 29. For nodes with smaller transmission range the pool of possible connections to choose is smaller; However, the rules remain the same, i.e., connect to the highest battery phone in the vicinity. Given the context-adaptive nature of our approach, which automatically self-heals and self-organises the network, fairness is not impacted as an emergent global property (see Fig. 30).

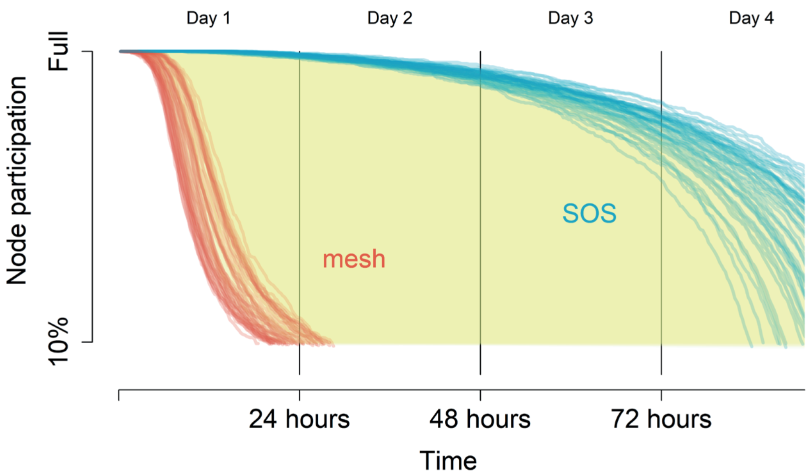


Figure 29: Node participation over 72 hours for the mesh network (red) and for SOS (blue) for varying transmission range

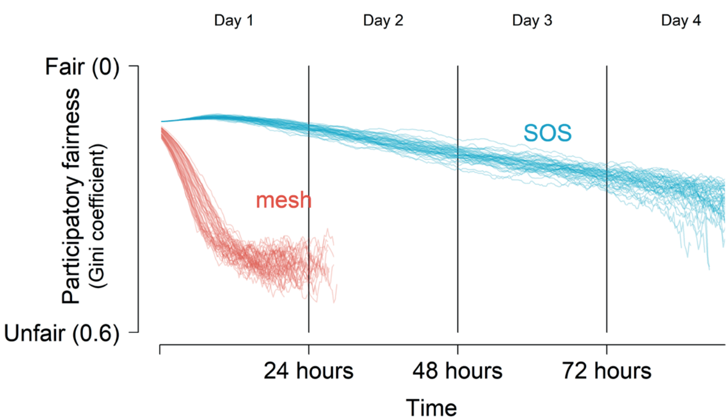


Figure 30: Development of battery charge inequality (Gini coefficient [51]) over 72 hours for the mesh network (red) and for SOS (blue) for varying transmission range

Phase diagram : In the phase diagram in chapter 5, Fig. 15, the ratio of the longevity is plotted for a single run of both SOS and mesh, for 8x10 combinations of node density and message frequency. To get an estimate of the sampling variability, five combinations of node density and message frequency were repeated 100 times. Density plots and histograms for these 100 runs are displayed in Figs 32-36. In each density plot, a vertical line is provided to show the SOS and mesh longevities that were used to create the phase diagram. Although the inter-run variability is different for different combinations of factors, the inter-run variability is small compared to the difference between the two protocols.

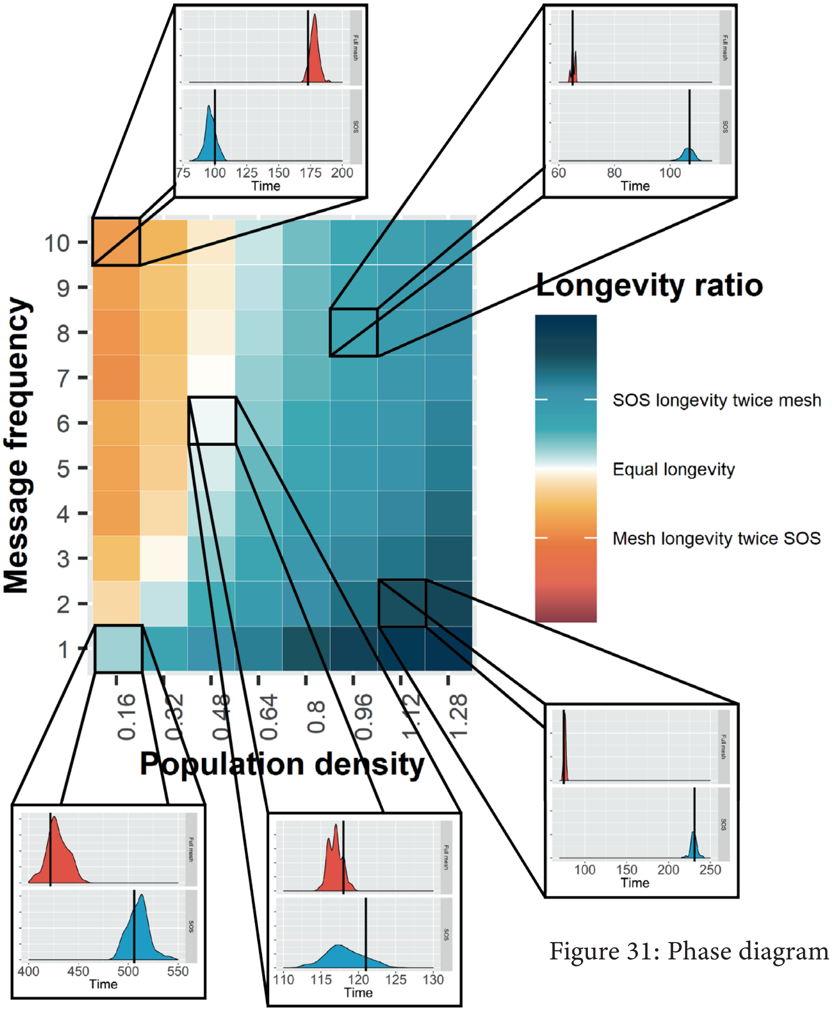


Figure 31: Phase diagram

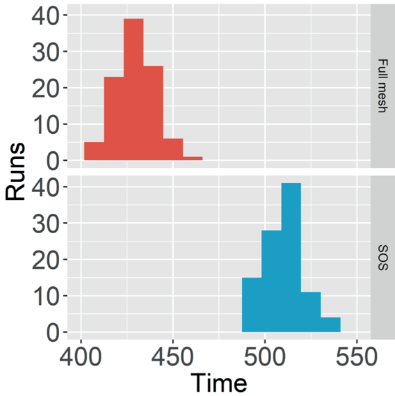


Figure 32: Histogram of longevity across a 100 runs for mesh (red) and SOS (blue), 100 nodes sending 1 message

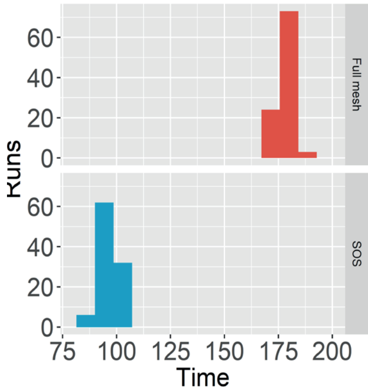


Figure 33: Histogram of longevity across a 100 runs for mesh (red) and SOS (blue), 100 nodes sending 10 messages

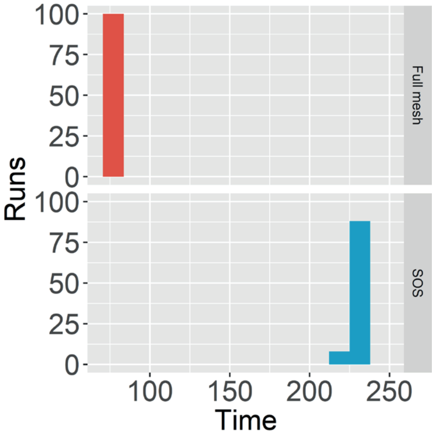


Figure 34: Histogram of longevity across a 100 runs for mesh (red) and SOS (blue), 700 nodes sending 2 messages

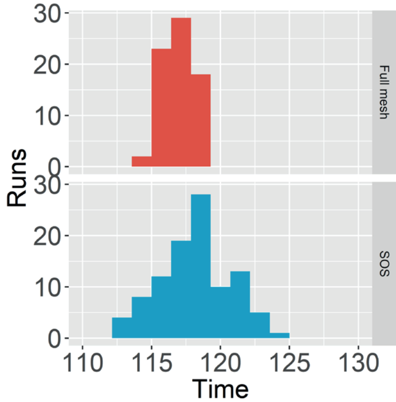


Figure 35: Histogram of longevity across a 100 runs for mesh (red) and SOS (blue), 300 nodes sending 6 messages

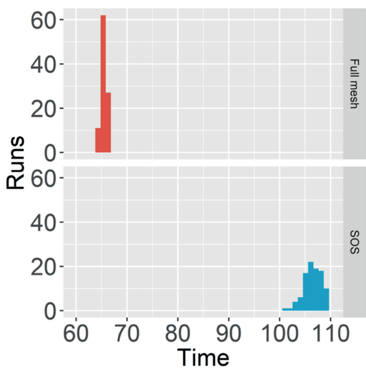


Figure 36: Histogram of longevity across a 100 runs for mesh (red) and SOS (blue), 600 nodes sending 8 messages

BIBLIOGRAPHY

[1] Adam Yeeles. "Unequal exposure." In: Nature Climate Change 8.5 (2018), pp. 359–359.

[2] Abdallah S Daar, Trillium Chang, Angela Salomon, and Peter A Singer. "Grand challenges in humanitarian aid." In: Nature 559 (2018), pp. 169–173.

[3] Sivan Kohn, Jennifer Lipkowitz Eaton, Saad Feroz, Andrea A Bainbridge, Jordan Hoolachan, and Daniel J Barnett. "Personal disaster preparedness: an integrative review of the literature." In: Disaster Medicine and Public Health Preparedness 6.3 (2012), pp. 217– 231.

[4] Lubos Buzna, Karsten Peters, Hendrik Ammoser, Christian Kühnert, and Dirk Helbing. "Efficient response to cascading disaster spreading." In: Physical ReviewE 75.5 (2007), p. 056107.

[5] W D Stephenson and E Bonabeau. "Expecting the Unexpected : The Need for a Networked Terrorism and Disaster Response Strategy." In: Homeland Security Affairs 3 (2007), pp. 1–9. ISSN: 1558643X.

[6] Daniel P Aldrich. "The power of people: Social capital's role in recovery from the 1995 Kobe earthquake." In: Natural Hazards 56.3 (2011), pp. 595–611. ISSN: 0921030X. DOI: 10.1007/s11069-010-9577-7.

[7] Lea Winerman. "Crisis communication." In: Nature 457.7228 (2009), pp. 376–379.

[8] Balakrishan S Manoj and Alexandra Hubenko Baker. "Communication challenges in emergency response." In: Communications of the ACM 50.3 (2007), pp. 51– 53.

[9] Jaime De La Ree, Yilu Liu, Lamine Mili, Arun G Phadke, and Luiz Dasilva. "Catastrophic failures in power systems: causes, analyses, and countermeasures." In: Proceedings of the IEEE 93.5 (2005), pp. 956– 964.

[10] Eli M Noam and Harumasa Sato. "Kobe's lesson: dial 711 for "open" emergency communications." In: Science 274.5288 (1996), pp. 739–740.

[11] James PG Sterbenz, David Hutchison, Egemen K Çetinkaya, Abdul Jabbar, Justin P Rohrer, Marcus Schöller, and Paul Smith. "Resilience and survivability in communication networks: Strategies, principles, and survey of disciplines." In: Computer Networks 54.8 (2010), pp. 1245–1265.

[12] Richard G Little. “Controlling cascading failure: Understanding the vulnerabilities of interconnected infrastructures.” In: Journal of Urban Technology 9.1 (2002), pp. 109–123.

[13] Amir Bashan, Yehiel Berezin, Sergey V Buldyrev, and Shlomo Havlin. “The extreme vulnerability of interdependent spatially embedded networks.” In: Nature Physics 9 (2013), p. 667.

[14] Stephanie E. Chang, Timothy L. McDaniels, Joey Mikawoz, and Krista Peterson. “Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm.” In: Natural Hazards 41.2 (2007), pp. 337–358. ISSN: 0921-030X. DOI: 10.1007/s11069-006-9039-4.

[15] Dirk Helbing. “Globally networked risks and how to respond.” In: Nature 497.7447 (2013), pp. 51–59.

[16] Alessandro Vespignani. “The fragility of interdependency.” In: Nature 464.7291 (2010), pp. 984–985.

[17] Mitsuyoshi Kobayashi. “Experience of infrastructure damage caused by the Great East Japan Earthquake and countermeasures against future disasters.” In: IEEE Communications Magazine 52.3 (2014), pp. 23– 29.

[18] Dario Floreano and Robert J Wood. “Science, technology and the future of small autonomous drones.” In: Nature 521.7553 (2015), pp. 460–466. DOI: 10.1038/ nature14542.

[19] Ira Helsloot and Arnout Ruitenberg. “Citizen response to disasters: a survey of literature and some practical implications.” In: Journal of contingencies and crisis management 12.3 (2004), pp. 98–111.

[20] K. Miranda, A. Molinaro, and T. Razafindralambo. “A survey on rapidly deployable solutions for postdisaster networks.” In: IEEE Communications Magazine 54.4 (2016), pp. 117–123.

[21] J. Wang, Y. Wu, N. Yen, S. Guo, and Z. Cheng. “Big data analytics for emergency communication networks: a survey.” In: IEEE Communications Surveys Tutorials 18.3 (2016), pp. 1758–1778.

[22] Sujoy Saha, Subrata Nandi, Partha Sarathi Paul, Vijay K Shah, Akash Roy, and Sajal K Das. “Designing delay constrained hybrid ad hoc network infrastructure for post-disaster communication.” In: Ad Hoc Networks 25 (2015), pp. 406–429.

[23] DG Reina, Mohamed Askalani, SL Toral, Federico Barrero, Eleana Asimakopoulou, and Nik Bessis. “A survey on multihop ad hoc networks for disaster response scenarios.” In: International Journal of Distributed Sensor Networks 11.10 (2015), p. 647037.

[24] Franck Legendre, Theus Hossmann, Felix Sutton, and Bernhard Plattner. “30 years of wireless Ad Hoc networking research: what about humanitarian and disaster relief solutions? What are we still missing?” In: Proceedings of the 1st International Conference on Wireless Technologies for Humanitarian Relief (ACWR), Amritapuri, Kollam, Kerala, India. 2011, pp. 217–217.

[25] Raffaele Bruno, Marco Conti, and Enrico Gregori. “Mesh networks: commodity multihop ad hoc networks.” In: IEEE Communications Magazine 43.3 (2005), pp. 123–131.

[26] Sacha Trifunovic, Maciej Kurant, Karin Anna Hummel, and Franck Legendre. “WLAN-Opp: ad-hocless opportunistic networking on smartphones.” In: Ad Hoc Networks 25 (2015), pp. 346–358.

[27] Zongqing Lu, Guohong Cao, and Thomas La Porta. “Teamphone: Networking smartphones for disaster recovery.” In: IEEE Transactions on Mobile Computing 16.12 (2017), pp. 3554–3567.

[28] Jinyuan Sun, Xiaoyan Zhu, Chi Zhang, and Yuguang Fang. “RescueMe: Location-based secure and dependable VANETs for disaster rescue.” In: IEEE Journal on Selected Areas in Communications 29.3 (2011), pp. 659– 669.

[29] Paul Gardner-Stephen, Andrew Bettison, Romana Challans, and Jeremy Lakeman. “The rational behind the serval network layer for resilient communications.” In: Journal of Computer Science 9.12 (2013), pp. 1680–1685.

[30] D Johnson, N Ntlatlapa, and C Aichele. “Simple pragmatic approach to mesh routing using BATMAN.” In: 2nd IFIP International Symposium on Wireless Communications and Information Technology in Developing Countries, CSIR. 2008, pp. 6–7.

[31] F. Álvarez, L. Almon, H. Radtki, and M. Hollick. “Bluemergency: Mediating Post-disaster Communication Systems using the Internet of Things and Bluetooth Mesh.” In: 2019 IEEE Global Humanitarian Technology Conference (GHTC). 2019, pp. 1–8.

[32] Marion Lara Tan, Raj Prasanna, Kristin Stock, Emma EH Doyle, Graham Leonard, and David Johnston. "Modified usability framework for disaster apps: a qualitative thematic analysis of user reviews." In: International Journal of Disaster Risk Science 11.5 (2020), pp. 615–629.

[33] Esteban Bopp, Johnny Douvinet, and Damien Serre. "Sorting the good from the bad smartphone applications to alert residents facing disasters-Experiments in France." In: 16th International Conference on Information Systems for Crisis Response and Management. 2019.

[34] Marion Lara Tan, Raj Prasanna, Kristin Stock, Emma Hudson-Doyle, Graham Leonard, and David Johnston. "Mobile applications in crisis informatics literature: A systematic review." In: International journal of disaster risk reduction 24 (2017), pp. 297–311.

[35] Tina Comes and Bartel A Van de Walle. "Measuring disaster resilience: The impact of hurricane sandy on critical infrastructure systems." In: ISCRAM 11.May (2014), pp. 195–204.

[36] Nitesh Bharosa, JinKyu Lee, and Marijn Janssen. "Challenges and obstacles in sharing and coordinating information during multi-agency disaster response: Propositions from field exercises." In: Information Systems Frontiers 12.1 (2010), pp. 49–65.

[37] Lorenzo Pagliari, Raffaela Mirandola, Diego PerezPalacin, and Catia Trubiani. "Energy-aware adaptive techniques for information diffusion in ungoverned peer-to-peer networks." In: 2016 12th International ACM SIGSOFT Conference on Quality of Software Architectures (QoSA). IEEE. 2016, pp. 96–105.

[38] Gianluca Aloi, Orazio Briante, Marco Di Felice, Giuseppe Ruggeri, and Stefano Savazzi. "The SENSE-ME platform: Infrastructure-less smartphone connectivity and decentralized sensing for emergency management." In: Pervasive and Mobile Computing 42 (2017), pp. 187– 208.

[39] Gurkan Tuna, Bilel Nefzi, and Gianpaolo Conte. "Unmanned aerial vehicle-aided communications system for disaster recovery." In: Journal of Network and Computer Applications 41 (2014), pp. 27–36.

[40] Toshikazu Sakano, Satoshi Kotabe, Tetsuro Komukai, Tomoaki Kumagai, Yoshitaka Shimizu, Atsushi Takahara, Thuan Ngo, Zubair Md Fadlullah,

Hiroki Nishiyama, and Nei Kato. “Bringing movable and deployable networks to disaster areas: development and field test of MDRU.” In: IEEE Network 30.1 (2016), pp. 86–91.

[41] Akram Al-Hourani and Sithamparanathan Kandeepan. “Cognitive relay nodes for airborne LTE emergency networks.” In: 2013, 7th International Conference on Signal Processing and Communication Systems (ICSPCS). IEEE. 2013, pp. 1–9.

[42] Egon G Guba, Yvonna S Lincoln, et al. “Competing paradigms in qualitative research.” In: Handbook of qualitative research 2.163-194 (1994), p. 105.

[43] Colin Robson. Real world research: A resource for social scientists and practitioner-researchers. Wiley-Blackwell, 2002.

[44] John W Creswell and Cheryl N Poth. Qualitative inquiry and research design: Choosing among five approaches. Sage publications, 2016.

[45] Katherine Miller. “Communication theories.” In: USA: Macgraw-Hill (2005).

[46] Dirk Helbing. “Pluralistic modeling of complex systems.” In: arXiv preprint arXiv:1007.2818 (2010).

[47] John Zimmerman, Erik Stolterman, and Jodi Forlizzi. “An Analysis and Critique of Research through Design: Towards a Formalization of a Research Approach.” In: Proceedings of the 8th ACM Conference on Designing Interactive Systems. DIS ’10. New York, NY, USA: Association for Computing Machinery, 2010,pp. 310–319. ISBN: 9781450301039. DOI: 10.1145/1858171. 1858228. URL: https://doi.org/10.1145/1858171. 1858228.

[48] William Gaver. “What Should We Expect from Research through Design?” In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. CHI ’12. New York, NY, USA: Association for Computing Machinery, 2012, pp. 937–946. ISBN: 9781450310154. DOI: 10.1145/2207676.2208538. URL: https://doi. org/10.1145/2207676.2208538.

[49] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. “Research through design as a method for interaction design research in HCI.” In: Proceedings of the SIGCHI conference on Human factors in computing systems. 2007, pp. 493–502.

[50] John Zimmerman and Jodi Forlizzi. "Research through design in HCI." In: Ways of Knowing in HCI. Springer, 2014, pp. 167–189.

[51] Jeffrey O Kephart and David M Chess. "The vision of autonomic computing." In: Computer 36.1 (2003), pp. 41–50.

[52] Simon Dobson, Roy Sterritt, Paddy Nixon, and Mike Hinchey. "Fulfilling the vision of autonomic computing." In: Computer 43.1 (2010), pp. 35–41.

[53] Simon Dobson, Spyros Denazis, Antonio Fernández, Dominique Gaïti, Erol Gelenbe, Fabio Massacci, Paddy Nixon, Fabrice Saffre, Nikita Schmidt, and Franco Zambonelli. "A survey of autonomic communications." In: ACM Transactions on Autonomous and Adaptive Systems (TAAS) 1.2 (2006), pp. 223–259.

[54] Gordon Baxter and Ian Sommerville. "Socio-technical systems: From design methods to systems engineering." In: Interacting with computers 23.1 (2011), pp. 4– 17.

[55] Noëmi Manders-Huits and Jeroen van den Hoven. "The need for a value-sensitive design of communication infrastructures." In: Evaluating New Technologies. Springer, 2009, pp. 51–60.

[56] Batya Friedman, Peter H Kahn, Alan Borning, and Alina Huldtgren. "Value sensitive design and information systems." In: Early engagement and new technologies: Opening up the laboratory. Springer, 2013, pp. 55– 95.

[57] Eli Eisenberg and Erez Y Levanon. "Preferential attachment in the protein network evolution." In: Physical review letters 91.13 (2003), p. 138701.

[58] Louise K Comfort, Namkyung Oh, Gunes Ertan, and Steve Scheinert. "Designing adaptive systems for disaster mitigation and response." In: Designing resilience: Preparing for extreme events (2010), pp. 33–62.

[59] Tina Comes, Kenny Meesters, and Stina Torjesen. "Making sense of crises: the implications of information asymmetries for resilience and social justice in disasterridden communities." In: Sustainable and Resilient Infrastructure 4.3 (2019), pp. 124–136.

[60] Heejae Jung and Hyunggu Jung. "Evaluation of mobile applications for disaster responses through personas and scenarios." In: Proceedings of Asian CHI Symposium 2019: Emerging HCI Research Collection. 2019, pp. 121–127.

[61] Hsiu-Ju Chen. “A conceptual model of mobile disaster relief system combining social apps.” In: Proceedings of the International Conference on Advanced Information Science and System. 2019, pp. 1–5.

[62] Christoph Kotthaus, Thomas Ludwig, and Volkmar Pipek. “Persuasive System Design Analysis of Mobile Warning Apps for Citizens.” In: ECSW@ PERSUASIVE. 2016.

[63] Indushree Banerjee, Martijn Warnier, and Frances MT Brazier. “Self-organizing topology for energyefficient ad-hoc communication networks of mobile devices.” In: Complex Adaptive Systems Modeling 8.1 (2020), pp. 1–21.

[64] Ira Helsloot and Arnout Ruitenberg. “Citizen response to disasters: a survey of literature and some practical implications.” In: Journal of contingencies and crisis management 12.3 (2004), pp. 98–111.

[65] Fabiano Dalpiaz, Paolo Giorgini, and John Mylopoulos. “Adaptive socio-technical systems: a requirementsbased approach.” In: Requirements engineering 18.1 (2013), pp. 1–24.

[66] Murray Turoff. “The Design of a Dynamic Emergency Response Management.” In: Annual Review of Network Management and Security (2006), p. 101.

[67] Se-Hang Cheong, Kai-Ip Lee, Yain-Whar Si, et al. “Lifeline: emergency ad hoc network.” In: 2011 Seventh International Conference on Computational Intelligence and Security. IEEE. 2011, pp. 283–289.

[68] Dirk Bradler, Benjamin Schiller, Erwin Aitenbichler, and Nicolas Liebau. “Towards a distributed crisis response communication system.” In: Proceedings of ISCRAM 9 (2009), pp. 10–13.

[69] James Ladyman, James Lambert, and Karoline Wiesner. “What is a complex system?” In: European Journal for Philosophy of Science 3.1 (2013), pp. 33–67.

[70] Louise K Comfort, Mark Dunn, David Johnson, Robert Skertich, and Adam Zagorecki. “Coordination in complex systems: increasing efficiency in disaster mitigation and response.” In: International Journal of Emergency Management 2.1-2 (2004), pp. 62–80.

[71] Gregory A Bigley and Karlene H Roberts. “The incident command system: High-reliability organizing for complex and volatile task environments.” In: Academy of Management Journal 44.6 (2001), pp. 1281– 1299.

[72] Karen Miranda, Antonella Molinaro, and Tahiry Razafindralambo. “A survey on rapidly deployable solutions for post-disaster networks.” In: IEEE Communications magazine 54.4 (2016), pp. 117–123.

[73] Gianluca Aloi, Luca Bedogni, Luciano Bononi, Orazio Briante, Marco Di Felice, Valeria Loscrì, Pasquale Pace, Fabio Panzieri, Giuseppe Ruggeri, and Angelo Trotta. “Stem-net: How to deploy a self-organizing network of mobile end-user devices for emergency communication.” In: Computer Communications 60 (2015), pp. 12–27.

[74] Hrushikesh Mehendale, Ashwin Paranjpe, and Santosh Vempala. “LifeNet: A Flexible Ad Hoc Networking Solution for Transient Environments.” In: Proceedings of the ACM SIGCOMM 2011 Conference. SIGCOMM ’11. 2011, pp. 446–447. DOI: 10.1145/2018436. 2018513.

[75] Paul Gardner-Stephen, Romana Challans, Jeremy Lakeman, Andrew Bettison, Dione Gardner-Stephen, and Matthew Lloyd. “The serval mesh: A platform for resilient communications in disaster & crisis.” In: 2013 IEEE Global Humanitarian Technology Conference(GHTC). IEEE. 2013, pp. 162–166.

[76] Tony H Grubesic. “Efficiency in broadband service provision: A spatial analysis.” In: Telecommunications Policy 34.3 (2010), pp. 117–131.

[77] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. “Research Through Design as a Method for Interaction Design Research in HCI.” In: Proceedings of the SIGCHI (2007).

[78] Batya Friedman. “Value-sensitive design.” In: interactions 3.6 (1996), pp. 16–23.

[79] Jaana Leikas, Raija Koivisto, and Nadezhda Gotcheva. “Ethical framework for designing autonomous intelligent systems.” In: Journal of Open Innovation: Technology, Market, and Complexity 5.1 (2019), p. 18.

[80] Batya Friedman and Helen Nissenbaum. “Software Agents and User Autonomy.” In: Proceedings of the First International Conference on Autonomous Agents. AGENTS ’97. New York, NY, USA: Association for Computing Machinery, 1997, pp. 466–469. DOI: 10. 1145/267658.267772.

[81] Constantine Stephanidis. User interfaces for all: concepts, methods, and tools. CRC Press, 2000.

[82] Nancy G Leveson. “Software safety in embedded computer systems.” In: Communications of the ACM 34.2 (1991), pp. 34–46.

[83] Batya Friedman and Helen Nissenbaum. “Bias in computer systems.” In: ACM Transactions on Information Systems (TOIS) 14.3 (1996), pp. 330–347.

[84] Kathleen J Tierney and James D Gotlz. “Emergency Response: Lessons Learned from the Kobe earthquake.” In: University of Delaware Disaster Research Center Preliminary Papers 260 (1997). DOI: http://dspace. udel. edu:8080/dspace/handle/19716/202.

[85] Eric K Noji, Gabor D Kelen, Haroutune K. Armenian, Ashot Oganessian, Nicholas P Jones, and Keith T Sivertson. “The 1988 earthquake in Soviet Armenia: A case study.” In: Annals of Emergency Medicine 19.8 (1990), pp. 891–897. ISSN: 01960644. DOI: 10.1016/ S0196-0644(05)81563-X.

[86] Russell R Dynes, Thomas E Drabek, and Gary Kreps. “Community Emergency Planning : False assumptions and inappropriate analogies.” In: International Journal of Mass Emergencies and Disasters 12.2 (1990).

[87] Falko Dressler and Autonomic Networking Group. “Self-Organization in Ad Hoc Networks: Overview and Classification.” In: (2006), pp. 1–12.

[88] Qingzhi Liu, Stefan Dulman, and Martijn Warnier. “AREA: an Automatic Runtime Evolutionary Adaptation mechanism for Creating Self-Adaptation Algorithms in Wireless Networks.” In: Proceedings of the Spatial Computing Workshop (2013).

[89] Gianluca Aloi, Luca Bedogni, Marco Di Felice, Valeria Loscri, Antonella Molinaro, Enrico Natalizio, Pasquale Pace, Giuseppe Ruggeri, Angelo Trotta, and Nicola Roberto Zema. “STEM-Net: an evolutionary network architecture for smart and sustainable cities.” In: Transactions on Emerging Telecommunications Technologies 25.1 (2014), pp. 21–40.

[90] Chenyu Zheng. “Self-Organizing Hybrid CellularMANETs.” In: (2014).

[91] Andrew Crooks, Christian Castle, and Michael Batty. “Key challenges in agent-based modelling for geospatial simulation.” In: Computers, Environment and Urban Systems 32.6 (2008), pp. 417–430.

[92] Uri Wilensky and William Rand. An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo. Mit Press, 2015.

[93] Eric Bonabeau. “Agent-based modeling: methods and techniques for simulating human systems.” In: Proceedings of the National Academy of Sciences 99.suppl 3 (2002), pp. 7280–7287.

[94] Anthony Patt and Bernd Siebenhüner. “Agent based modeling and adaption to climate change.” In: Vierteljahrshefte zur Wirtschaftsforschung 74.2 (2005), pp. 310– 320.

[95] Charles M Macal and Michael J North. “Tutorial on agent-based modeling and simulation.” In: Proceedings of the Winter Simulation Conference, 2005. IEEE. 2005, 14–pp.

[96] Steven F Railsback and Volker Grimm. Agent-based and individual-based modeling: a practical introduction. Princeton university press, 2019.

[97] Charles Macal and Michael North. “Introductory tutorial: Agent-based modeling and simulation.” In: Proceedings of the winter simulation conference 2014. IEEE. 2014, pp. 6–20.

[98] Nigel Gilbert. Agent-based models. Vol. 153. Sage Publications, 2019.

[99] Daniel Kornhauser, Uri Wilensky, and William Rand. “Design guidelines for agent based model visualization.” In: Journal of Artificial Societies and Social Simulation 12.2 (2009), p. 1.

[100] M Farhan Habib, Massimo Tornatore, Ferhat Dikbiyik, and Biswanath Mukherjee. “Disaster survivability in optical communication networks.” In: Computer Communications 36.6 (2013), pp. 630–644.

[101] Alexis Kwasinski. “Hurricane sandy effects on communication systems.” In: The University of Texas at Austin, Tech. Rep. PR-AK-0112-2012 (2012).

[102] Teresa Gomes, János Tapolcai, Christian Esposito, David Hutchison, Fernando Kuipers, Jacek Rak, Amaro De Sousa, Athanasios Iossifides, Rui Travanca, Joao André, et al. “A survey of strategies for communication networks to protect against large-scale natural disasters.” In: 2016 8th international workshop on resilient networks design and modeling (RNDM). IEEE. 2016, pp. 11–22.

[103] Harit Sharma, Ravi Kanth Reddy, and Archana Karthik. "S-CarCrash: Real-time crash detection analysis and emergency alert using smartphone." In: 2016 International Conference on Connected Vehicles and Expo (ICCVE). IEEE. 2016, pp. 36–42.

[104] John W Farnham. "Disaster and emergency communications prior to computers/Internet: a review." In: Critical Care 10.1 (2005), pp. 1–4.

[105] John Jubin and Janet D Tornow. "The DARPA packet radio network protocols." In: Proceedings of the IEEE 75.1 (1987), pp. 21–32.

[106] Ram Ramanathan and Jason Redi. "A brief overview of ad hoc networks: challenges and directions." In: IEEE communications Magazine 40.5 (2002), pp. 20– 22.

[107] Robert Dourandish, Nina Zumel, and Michael Manno. Command and control during the first 72 hours of a joint military-civilian disaster response. Tech. rep. Quimba Software Inc San Mateo Ca, 2007.

[108] Wladimir J Alonso, Cynthia Schuck-Paim, and Ghassem R Asrar. "Global health and natural disaster alerts: preparing mobile phones to endure the unthinkable." In: Earth Perspectives 1.1 (2014), pp. 1–6.

[109] Watcharachai Kongsiriwattana and Paul Gardner-Stephen. "Smartphone battery-life short-fall in disaster response: Quantifying the gap." In: 2016 IEEE Global Humanitarian Technology Conference (GHTC). IEEE. 2016, pp. 220– 225.

[110] Toni Sebastian, Kasper Lendering, Baukje Kothuis, Nikki Brand, Bas Jonkman, Pieter van Gelder, Maartje Godfroij, Bas Kolen, Tina Comes, Stef Lhermitte, et al. "Hurricane Harvey Report: A fact-finding effort in the direct aftermath of Hurricane Harvey in the Greater Houston Region." In: (2017).

[111] Leysia Palen and Sophia B Liu. "Citizen communications in crisis: anticipating a future of ICT-supported public participation." In: Proceedings of the SIGCHI conference on Human factors in computing systems. 2007, pp. 727–736.

[112] Xian Wu, Maciej Mazurowski, Zhen Chen, and Nirvana Meratnia. "Emergency message dissemination system for smartphones during natural disasters." In: 2011 11th International Conference on ITS Telecommunications. IEEE. 2011, pp. 258–263.

[113] Pramita Mitra and Christian Poellabauer. “Emergency response in smartphone-based mobile ad-hoc networks.” In: 2012 IEEE International Conference on Communications (ICC). IEEE. 2012, pp. 6091–6095.

[114] Suman Bhattacharjee, Siuli Roy, and Somprakash Bandyopadhyay. “Exploring an energy-efficient DTN framework supporting disaster management services in post disaster relief operation.” In: Wireless Networks 21.3 (2015), pp. 1033–1046. ISSN: 15728196. DOI: 10.1007/s11276-014-0836-5.

[115] Ian F Akyildiz, Xudong Wang, and Weilin Wang. “Wireless mesh networks: a survey.” In: Computer Networks 47 (2005), pp. 445–487. DOI: 10.1016/j. comnet.2004.12.001.

[116] Mikio Aoyama and Hiroshi Takeichi. “Adaptive SelfOrganizing Overlay Network for Car-to-Car Communications.” In: 2008 Ninth ACIS International Conference on Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing. IEEE, 2008, pp. 605–610. ISBN: 978-0-7695-3263-9. DOI: 10. 1109/SNPD.2008.75.

[117] M. Frodigh, P. Johansson, and P. Larsson. “Wireless ad hoc networking: the art of networking without a network.” In: Ericsson Review No.4 (2000), pp. 248– 263.

[118] Can Aydin, Cigdem Tarhan, Ahmet Selcuk Ozgur, and Vahap Tecim. “Improving disaster resilience using mobile based disaster management system.” In: Procedia Technology 22 (2016), pp. 382–390.

[119] Anna Bon, Victor de Boer, Pieter De Leenheer, Chris van Aart, Nana Baah Gyan, Max Froumentin, Stephane Boyera, Mary Allen, and Hans Akkermans. “The Web of Radios Introducing African Community Radio as an Interface to the Web of Data.” In: The Semantic Web: ESWC 2012 Satellite Events: ESWC 2012 Satellite Events, Heraklion, Crete, Greece, May 27-31, 2012. Revised Selected Papers. Ed. by Elena Simperl, Barry Norton, Dunja Mladenic, Emanuele Della Valle, Irini Fundulaki, Alexandre Passant, and Raphaël Troncy. Berlin, Heidelberg: Springer Berlin Heidelberg, 2015, pp. 219–232. ISBN: 978-3-662-46641-4. DOI: 10.1007/ 978-3-662-46641-4_16.

[120] Dong Hee Shin, Won Yong Kim, and Dong Hoon Lee. “Future public information infrastructure: lessons from four US case studies.” In: info 8.3 (2006), pp. 47– 59. DOI: 10.1108/14636690610664651.

[121] Chai K Toh. Ad hoc mobile wireless networks: protocols and systems. Pearson Education, 2001.

[122] Leonard Kleinrock and Fouad Tobagi. "Packet switching in radio channels: Part I-carrier sense multipleaccess modes and their throughput-delay characteristics." In: IEEE transactions on Communications 23.12 (1975), pp. 1400–1416.

[123] Fouad Tobagi and Leonard Kleinrock. "Packet switching in radio channels: Part II-The hidden terminal problem in carrier sense multiple-access and the busytone solution." In: IEEE Transactions on communications 23.12 (1975), pp. 1417–1433.

[124] Mario Gerla and Leonard Kleinrock. "On the topological design of distributed computer networks." In: IEEE Transactions on communications 25.1 (1977), pp. 48–60.

[125] Jil Westcott and John Jubin. "A distributed routing design for a broadcast environment." In: MILCOM 1982-IEEE Military Communications Conference-Progress in Spread Spectrum Communications. Vol. 3. IEEE. 1982, pp. 10–4.

[126] Ting-Chao Hou and Victor Li. "Transmission range control in multihop packet radio networks." In: IEEE Transactions on Communications 34.1 (1986), pp. 38– 44.

[127] Charles E Perkins and Pravin Bhagwat. "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers." In: ACM SIGCOMM computer communication review 24.4 (1994), pp. 234–244.

[128] David B Johnson. "Routing in ad hoc networks of mobile hosts." In: 1994 First Workshop on Mobile Computing Systems and Applications. IEEE. 1994, pp. 158– 163.

[129] Russell Ruppe, Stan Griswald, Pat Walsh, and Robert Martin. "Near term digital radio (NTDR) system." In: MILCOM 97 MILCOM 97 Proceedings. Vol. 3. IEEE. 1997, pp. 1282–1287.

[130] Barry M Leiner, RJ Ruther, and Ambatipudi R Sastry. "Goals and challenges of the DARPA GloMo program [global mobile information systems]." In: IEEE Personal communications 3.6 (1996), pp. 34–43.

[131] John M McQuillan and David C Walden. “The ARPA network design decisions.” In: Computer Networks (1976) 1.5 (1977), pp. 243–289.

[132] Paul Bupe, Rami Haddad, and Fernando Rios-Gutierrez. “Relief and emergency communication network based on an autonomous decentralized UAV clustering network.” In: SoutheastCon 2015. IEEE. 2015, pp. 1–8.

[133] Yao-Nan Lien, Hung-Chin Jang, and Tzu-Chieh Tsai. “A MANET based emergency communication and information system for catastrophic natural disasters.” In: 2009 29th IEEE international conference on distributed computing systems workshops. IEEE. 2009, pp. 412–417.

[134] Neerai Kumar, Alka Agrawal, and Raees Ahmad Khan. “Emergency alert networks for disaster management: applications perspective.” In: 2018 International Con ference on Research in Intelligent and Computing in Engineering (RICE). IEEE. 2018, pp. 1–5.

[135] Miguel A Labrador and Pedro M Wightman. Topology Control in Wireless Sensor Networks: with a companion simulation tool for teaching and research. Springer Science & Business Media, 2009.

[136] Arjan Durresi, Mimoza Durresi, Vamsi Paruchuri, and Leonard Barolli. “Ad hoc communications for emergency conditions.” In: 2011 IEEE International Conference on Advanced Information Networking and Applications. IEEE. 2011, pp. 787–794.

[137] Hrushikesh Mehendale, Ashwin Paranjpe, and Santosh Vempala. “Lifenet: a flexible ad hoc networking solution for transient environments.” In: ACM SIGCOMM Computer Communication Review 41.4 (2011), pp. 446–447.

[138] Se-Hang Cheong, Yain-Whar Si, and U Leong-Hou. “Saving lives: design and implementation of lifeline emergency ad hoc network.” In: International Journal of Pervasive Computing and Communications (2018).

[139] Priyanka Rawat, Majed Haddad, and Eitan Altman. “Towards efficient disaster management: 5G and Device to Device communication.” In: 2015 2nd International Conference on Information and Communication Technologies for Disaster Management (ICT-DM). IEEE. 2015, pp. 79–87.

[140] Hafsa Maryam, Munam Ali Shah, Qaisar Javaid, and Muhammad Kamran. “A survey on smartphones systems for emergency management

(SPSEM).” In: International Journal of Advanced Computer Science and Applications 7.6 (2016), pp. 301–311.

[141] Gerald Lewis. Organizational Crisis Management: The Human Factor. Auerbach Publications, 2006.

[142] Victoria Garshnek and Frederick M Burkle Jr. “Telecommunications systems in support of disaster medicine: applications of basic information pathways.” In: Annals of emergency medicine 34.2 (1999), pp. 213–218.

[143] Urs Anliker, Jamie A Ward, Paul Lukowicz, Gerhard Troster, Francois Dolveck, Michel Baer, Fatou Keita, Eran B Schenker, Fabrizio Catarsi, Luca Coluccini, et al. “AMON: a wearable multiparameter medical monitoring and alert system.” In: IEEE Transactions on information technology in Biomedicine 8.4 (2004), pp. 415–427.

[144] Mars Lan, Lauren Samy, Nabil Alshurafa, MyungKyung Suh, Hassan Ghasemzadeh, Aurelia MacabascoO’Connell, and Majid Sarrafzadeh. “Wanda: An endto-end remote health monitoring and analytics system for heart failure patients.” In: Proceedings of the conference on Wireless Health. 2012, pp. 1–8.

[145] Alexandros Pantelopoulos and Nikolaos G Bourbakis. “A survey on wearable sensor-based systems for health monitoring and prognosis.” In: IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews) 40.1 (2009), pp. 1–12.

[146] Giovanni Acampora, Diane J Cook, Parisa Rashidi, and Athanasios V Vasilakos. “A survey on ambient intelligence in healthcare.” In: Proceedings of the IEEE 101.12 (2013), pp. 2470–2494.

[147] NM Napi, AA Zaidan, BB Zaidan, OS Albahri, MA Alsalem, and AS Albahri. “Medical emergency triage and patient prioritisation in a telemedicine environment: a systematic review.” In: Health and Technology 9.5 (2019), pp. 679–700.

[148] Mirca Madianou, Liezel Longboan, and Jonathan Corpus Ong. “Finding a voice through humanitarian technologies? Communication technologies and participation in disaster recovery.” In: International Journal of Communication 9 (2015), p. 19.

[149] Tobias Franke, Sascha Negele, George Kampis, and Paul Lukowicz. “Leveraging human mobility in smartphone based ad-hoc information distribution in crowd management scenarios.” In: 2015 2nd International Conference on Information and Communication Technologies for Disaster Management (ICT-DM). IEEE. 2015, pp. 27–34.

[150] Indushree Banerjee, Martijn Warnier, Frances MT Brazier, and Dirk Helbing. “Introducing participatory fairness in emergency communication can support self-organization for survival.” In: Scientific reports 11.1 (2021), pp. 1–9.

[151] Theus Hossmann, Franck Legendre, Paolo Carta, Per Gunningberg, and Christian Rohner. “Twitter in disaster mode: Opportunistic communication and distribution of sensor data in emergencies.” In: Proceedings of the 3rd Extreme Conference on Communication: The Amazon Expedition. 2011, pp. 1–6.

[152] Flor Álvarez, Lars Almon, Hauke Radtki, and Matthias Hollick. “Bluemergency: mediating post-disaster communication systems using the internet of things and bluetooth mesh.” In: 2019 IEEE Global Humanitarian Technology Conference (GHTC). IEEE. 2019, pp. 1–8.

[153] Jane Louie Fresco Zamora, Noriyuki Suzuki, and Shigeru Kashihara. “SOS Message Distribution for Searching Disaster Victims.” In: Smartphones from an Applied Research Perspective (2017), p. 57.

[154] Konstandinos Koumidis, Panayiotis Kolios, Christos Panayiotou, and Georgios Ellinas. “ProximAid: Proximal adhoc networking to aid emergency response.” In: 2015 2nd international conference on information and communication Technologies for Disaster Management (ICT-DM). IEEE. 2015, pp. 20–26.

[155] Maneesha V Ramesh, Anoop Jacob, and RD Aryadevi. “Participatory sensing for emergency communication via MANET.” In: 2012 International Conference on Data Science & Engineering (ICDSE). IEEE. 2012, pp. 181–186.

[156] Cong Pu and Xitong Zhou. “RescueMe: Smartphonebased self rescue system for disaster rescue.” In: 2019 IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC). IEEE. 2019, pp. 0832– 0837.

[157] Amro Al-Akkad, Leonardo Ramirez, Alexander Boden, Dave Randall, and Andreas Zimmermann. "Help beacons: Design and evaluation of an ad-hoc lightweight sos system for smartphones." In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. 2014, pp. 1485–1494.

[158] Hiroki Nishiyama, Masaya Ito, and Nei Kato. "Relayby-smartphone: realizing multihop device-to-device communications." In: IEEE Communications Magazine 52.4 (2014), pp. 56–65.

[159] Marco Di Felice, Luca Bedogni, and Luciano Bononi. "The emergency direct mobile app: Safety message dissemination over a multi-group network of smartphones using wi-fi direct." In: Proceedings of the 14th ACM International Symposium on Mobility Management and Wireless Access. 2016, pp. 99–106.

[160] Arul Mathi Maran Chandran, Maciej Zawodniok, and Aaron Phillips. "Convergence Communication over Heterogeneous Mesh Network for Disaster and Underserved Areas." In: 2020 IEEE 17th Annual Consumer Communications & Networking Conference (CCNC). IEEE. 2020, pp. 1–4.

[161] Akbar Hossain, Sayan Kumar Ray, and Roopak Sinha. "A smartphone-assisted post-disaster victim localization method." In: 2016 IEEE 18th International Conference on High Performance Computing and Communications; IEEE 14th International Conference on Smart City; IEEE 2nd International Conference on Data Science and Systems (HPCC/SmartCity/DSS). IEEE. 2016, pp. 1173–1179.

[162] Osnat Mokryn, Dror Karmi, Akiva Elkayam, and Tomer Teller. "Help Me: Opportunistic smart rescue application and system." In: 2012 The 11th Annual Mediterranean Ad Hoc Networking Workshop (Med-HocNet). IEEE. 2012, pp. 98–105.

[163] Iván Santos-González, Pino Caballero-Gil, Alexandra Rivero-García, and Candelaria Hernández-Goya. "Distributed communication system for emergencies." In: 2016 24th Euromicro International Conference on Parallel, Distributed, and Network-Based Processing (PDP). IEEE. 2016, pp. 309–312.

[164] Zongqing Lu, Guohong Cao, and Thomas La Porta. "Networking smartphones for disaster recovery." In: 2016 IEEE International Conference on Pervasive Computing and Communications (PerCom). IEEE. 2016, pp. 1– 9.

[165] Luca Sciullo, Federico Fossemo, Angelo Trotta, and Marco Di Felice. "Locate: a lora-based mobile emergency management system." In: 2018 IEEE Global Communications Conference (GLOBECOM). IEEE. 2018, pp. 1–7.

[166] Allan Goncalves, Carlos Silva, and Patricia Morreale. "Design of a mobile ad hoc network communication app for disaster recovery." In: 2014 28th International Conference on Advanced Information Networking and Applications Workshops. IEEE. 2014, pp. 121–126.

[167] Noriyuki Suzuki, Jane Louie Fresco Zamora, Shigeru Kashihara, and Suguru Yamaguchi. "Soscast: Location estimation of immobilized persons through sos message propagation." In: 2012 Fourth International Conference on Intelligent Networking and Collaborative Systems. IEEE. 2012, pp. 428–435.

[168] Floriano De Rango, Marco Fotino, and Salvatore Marano. "EE-OLSR: Energy Efficient OLSR routing protocol for Mobile ad-hoc Networks." In: MILCOM 2008-2008 IEEE Military Communications Conference. IEEE. 2008, pp. 1–7.

[169] Tina Sachdeva, Neha Garg, Shivani Digari, Himani Kaira, Shivani Tiwary, Neerajpreet Kaur, Bhavna Goel, Priya Naib, Chhavi Jain, Shivani Jain, et al. "Designing of an application for group based coordination for information exchange in Ad-hoc networks." In: 2017 International Conference on Computing and Communication Technologies for Smart Nation (IC3TSN). IEEE. 2017, pp. 66–70.

[170] Rohan Samarajiva and Nuwan Waidyanatha. "Two complementary mobile technologies for disaster warning." In: info (2009).

[171] DG Reina, Jose Maria León-Coca, SL Toral, Eleana Asimakopoulou, Federico Barrero, Peter Norrington, and Nik Bessis. "Multi-objective performance optimization of a probabilistic similarity/dissimilaritybased broadcasting scheme for mobile ad hoc networks in disaster response scenarios." In: Soft Computing 18.9 (2014), pp. 1745–1756.

[172] J ane Louie Fresco Zamora, Noriyuki Suzuki, Hiroaki Takemoto, Shigeru Kashihara, Yuzo Taenaka, and Suguru Yamaguchi. "Battery-saving message collection method for disrupted communication service areas." In: 2014 IEEE 11th Consumer Communications and Networking Conference (CCNC). IEEE. 2014, pp. 113– 118.

[173] Atsushi Ito, Takuya Kato, Hiroyuki Hatano, Mie Sato, Yu Watanabe, Eiji Utsunomiya, Yuko Hiramatsu, and Fumihiro Sato. "A study on designing ad hoc network protocol using Bluetooth low energy." In: 2016 7th IEEE International Conference on Cognitive Infocommunications (CogInfoCom). IEEE. 2016, pp. 000109– 000114.

[174] Mahrin Tasfe, Binita Saha, and Amitabha Chakrabarty. "Social interest based pocket switched network communication." In: 2017 IEEE Region 10 Humanitarian Technology Conference (R10-HTC). IEEE. 2017, pp. 59– 62.

[175] Satoru Inazu, Omuwa Oyakhiire, and Koichi Gyoda. "Evaluation of MANET Protocol FORP-SOS for Disaster Relief Communication Considering Received Signal Strength." In: 2019 34th International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC). IEEE. 2019, pp. 1–4.

[176] Xian Wu, Maciej Mazurowski, Zhen Chen, and Nirvana Meratnia. "Emergency message dissemination system for smartphones during natural disasters." In: 2011 11th International Conference on ITS Telecommunications. IEEE. 2011, pp. 258–263.

[177] Michael Lescisin and Qusay H Mahmoud. "Ad-hoc messaging infrastructure for P2P communication in disaster management." In: 2017 IEEE Canada International Humanitarian Technology Conference (IHTC). IEEE. 2017, pp. 172–176.

[178] Amitangshu Pal, Mayank Raj, Krishna Kant, and Sajal K Das. "A smartphone-based network architecture for post-disaster operations using WiFi tethering." In: ACM Transactions on Internet Technology (TOIT) 20.1 (2020), pp. 1–27.

[179] Amitangshu Pal and Krishna Kant. "E-Darwin2: A smartphone based disaster recovery network using WiFi tethering." In: 2018 15th IEEE Annual Consumer Communications & Networking Conference (CCNC). IEEE. 2018, pp. 1–5.

[180] Changling Liu and Jörg Kaiser. "Survey of mobile ad hoc network routing protocols." In: (2005).

[181] Azzedine Boukerche, Begumhan Turgut, Nevin Aydin, Mohammad Z Ahmad, Ladislau Bölöni, and Damla Turgut. "Routing protocols in ad hoc networks: A survey." In: Computer networks 55.13 (2011), pp. 3032– 3080.

[182] Sunil Taneja and Ashwani Kush. “A survey of routing protocols in mobile ad hoc networks.” In: International Journal of innovation, Management and technology 1.3 (2010), p. 279.

[183] Rajmohan Rajaraman. “Topology control and routing in ad hoc networks: A survey.” In: ACM SIGACT News 33.2 (2002), pp. 60–73.

[184] Azzedine Boukerche. Algorithms and protocols for wireless and mobile ad hoc networks. John Wiley & Sons, 2008.

[185] Manato Fujimoto, Seigi Matsumoto, Yutaka Arakawa, and Keiichi Yasumoto. “RecurChat: BLE-based message forwarding system with on-site application distribution.” In: 2016 Ninth International Conference on Mobile Computing and Ubiquitous Networking (ICMU). IEEE. 2016, pp. 1–6.

[186] Sebastian Macmillan, John Steele, Simon Austin, Paul Kirby, and Robin Spence. “Development and verification of a generic framework for conceptual design.” In: Design studies 22.2 (2001), pp. 169–191.

[187] Sreenivasa R Gorti and Ram D Sriram. “From symbol to form: a framework for conceptual design.” In: Computer-aided design 28.11 (1996), pp. 853–870.

[188] Altaf S Bahora, Tyler Collins, Steven Davis, Sinem Goknur, Jason Kearns, Trinh Lieu, Thinh Nguyen, Jim Zeng, Barry M Horowitz, and Stephen D Patek. “Integrated peer-to-peer applications for advanced emergency response systems. Part II. Technical feasibility.” In: IEEE Systems and Information Engineering Design Symposium, 2003. IEEE. 2003, pp. 261–268.

[189] Eiji Utsunomiya and Yuya Minami. “Consideration on Propagation of Disaster Information Among Different Types of Terminals for Grass-Roots Information Distribution System Using MANET.” In: 2018 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI). IEEE. 2018, pp. 1571–1576.

[190] Ahmed A Shahin and Mohamed Younis. “A framework for P2P networking of smart devices using WiFi direct.” In: 2014 IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC). IEEE. 2014, pp. 2082–2087.

[191] Quang Tran Minh, Kien Nguyen, Eiji Kamioka, and Shigeki Yamada. "Tree-based disaster recovery multihop access network." In: 2013 19th Asia-Pacific Conference on Communications (APCC). IEEE. 2013, pp. 409– 414.

[192] Jan Vincent Santos, Danah Veronica Torres, Monica Kathrina Villanoy, Cedric Angelo Festin, John Norman Doctor, and Roel Ocampo. "Rapid mobile development with ARC: Application framework for robust communications for disaster risk reduction and management." In: 2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob). IEEE. 2016, pp. 1– 6.

[193] Gianluca Aloi, Marco Di Felice, Giuseppe Ruggeri, and Stefano Savazzi. "A mobile phone-sensing system for emergency management: The SENSE-ME platform." In: 2016 IEEE 2nd International Forum on Research and Technologies for Society and Industry Leveraging a better tomorrow (RTSI). IEEE. 2016, pp. 1–6.

[194] Sergio F Ochoa and Rodrigo Santos. "Human-centric wireless sensor networks to improve information availability during urban search and rescue activities." In: Information Fusion 22 (2015), pp. 71–84.

[195] Gokce Gorbil. "No way out: Emergency evacuation with no internet access." In: 2015 IEEE International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops). IEEE. 2015, pp. 505– 511.

[196] Yoshitaka Shibata, Hiroaki Yuze, Tsuyoshi Hoshikawa, Kazuo Takahata, and Nobuhiro Sawano. "Large Scale Distributed disaster information system based on MANET and overlay network." In: 27th International Conference on Distributed Computing Systems Workshops (ICDCSW'07). IEEE. 2007, pp. 33–33.

[197] Seokhoon Kim and Jinweon Suk. "Efficient peer-topeer context awareness data forwarding scheme in emergency situations." In: Peer-to-Peer Networking and Applications 9.3 (2016), pp. 477–486.

[198] Archana Rajeshirke, Jugal Shah, Rushabh Sheth, and Vaishali Gaikwad. "Communication in a self-reliant ad hoc network." In: International Conference & Workshop on Electronics & Telecommunication Engineering (ICWET 2016). IET. 2016, pp. 21–26.

[199] Ahmad Hasan Afridi and Muhammad Ali. “Towards swarming mobile devices.” In: 2010 3rd International Conference on Advanced Computer Theory and Engineering (ICACTE). Vol. 6. IEEE. 2010, pp. V6–242.

[200] Mayank Raj, Krishna Kant, and Sajal K Das. “E-DARWIN: energy aware disaster recovery network using wifi tethering.” In: 2014 23rd International Conference on Computer Communication and Networks (ICCCN). IEEE. 2014, pp. 1–8.

[201] Masugi Inoue, Yasunori Owada, Kiyoshi Hamaguti, and Ryu Miura. “Nerve net: A regional-area network for resilient local information sharing and communications.” In: 2014 Second International Symposium on Computing and Networking. IEEE. 2014, pp. 3–6.

[202] Kanchana Kanchanasut, Thirapon Wongsaardsakul, Manutsiri Chansutthirangkool, Anis Laouiti, Hajime Tazaki, and Khandakar Rashedul Arefin. “Dumbo ii: a v-2-i emergency network.” In: Proceedings of the 4th Asian Conference on internet Engineering. 2008, pp. 37– 38.

[203] Masahiro Nishi, Haruki Kozato, Yusuke Ota, and Koichi Shin. “Development of disaster monitoring techniques in the grass-root information distribution system for detecting landslide dangers.” In: 2018 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/S-CALCOM/UIC/ATC/CBDCom/IOP/SCI). IEEE. 2018, pp. 1599–1604.

[204] Yuya Kitaura, Yuya Minami, Eitaro Kohno, and Yoshiaki Kakuda. “A self-organized approach for the communication method to adapt connectivity of terminals in Bluetooth MANETs.” In: 2014 IEEE 17th International Symposium on Object/Component/ServiceOriented Real-Time Distributed Computing. IEEE. 2014, pp. 342–347.

[205] Jingwen Tian, Shiru Zhou, and Meijuan Gao. “City crisis response system based on mesh wireless selforganization network.” In: 2008 Chinese Control and Decision Conference. IEEE. 2008, pp. 4691–4695.

[206] GTC Gunaratna, PVNM Jayarathna, SSP Sandamini, and DS De Silva. “Implementing wireless Adhoc networks for disaster relief communication.” In: 2015 8th International Conference on Ubi-Media Computing (UMEDIA).

IEEE. 2015, pp. 66–71.

[207] Wen Yen Lin, Kuang-Po Hsueh, and Pai-Shan Pa. “The development of emergency communication app using ad hoc network with ipv6.” In: 2015 International Conference on Intelligent Information Hiding and Multimedia Signal Processing (IIH-MSP). IEEE. 2015, pp. 41–44.

[208] Angela Sara Cacciapuoti, Francesco Calabrese, Marcello Caleffi, Giusy Di Lorenzo, and Luigi Paura. “Humanmobility enabled wireless networks for emergency communications during special events.” In: Pervasive and Mobile Computing 9.4 (2013), pp. 472–483.

[209] Leszek Lilien, Ajay Gupta, and Zijiang Yang. “Opportunistic networks for emergency applications and their standard implementation framework.” In: 2007 IEEE International Performance, Computing, and Communications Conference. IEEE. 2007, pp. 588–593.

[210] Marco Di Felice, Luca Bedogni, Angelo Trotta, Luciano Bononi, Fabio Panzieri, Giuseppe Ruggeri, Gianluca Aloi, Valeria Loscri, and Pasquale Pace. “Smartphones like stem cells: cooperation and evolution for emergency communication in post-disaster scenarios.” In: 2013 first international Black Sea conference on communications and networking (BlackSeaCom). IEEE. 2013, pp. 28–33.

[211] Vijay K Shah, Satyaki Roy, Simone Silvestri, and Sajal K Das. “Ctr: Cluster based topological routing for disaster response networks.” In: 2017 IEEE International Conference on Communications (ICC). IEEE. 2017, pp. 1–6.

[212] Santashil PalChaudhuri and David B Johnson. “Power mode scheduling for ad hoc networks.” In: 10th IEEE International Conference on Network Protocols, 2002. Proceedings. IEEE. 2002, pp. 192–193.

[213] Vamsi Paruchuri, Shivakumar Basavaraju, Arjan Durresi, Rajgopal Kannan, and S Sitharama Iyengar. “Random asynchronous wakeup protocol for sensor networks.” In: First International Conference on Broadband Networks. IEEE. 2004, pp. 710–717.

[214] Paolo Santi. “Topology control in wireless ad hoc and sensor networks.” In: ACM computing surveys (CSUR) 37.2 (2005), pp. 164–194.

[215] Martin Burkhart, Pascal Von Rickenbach, Rogert Wattenhofer, and

Aaron Zollinger. "Does topology control reduce interference?" In: Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing. ACM. 2004, pp. 9–19.

[216] Ning Li, Jennifer C Hou, and Lui Sha. "Design and analysis of an MST-based topology control algorithm." In: IEEE Transactions on Wireless Communications 4.3 (2005), pp. 1195–1206.

[217] Swetha Narayanaswamy, Vikas Kawadia, Ramavarapu S Sreenivas, and PRe Kumar. "Power control in adhoc networks: Theory, architecture, algorithm and implementation of the COMPOW protocol." In: European wireless conference. Vol. 2002. Florence, Italy. 2002, p. 156162.

[218] Hiroki Nishiyama, Thuan Ngo, Nirwan Ansari, and Nei Kato. "On minimizing the impact of mobility on topology control in mobile ad hoc networks." In: IEEE Transactions on Wireless Communications 11.3 (2012), pp. 1158–1166.

[219] Nishant Gupta and Samir R. Das. "Energy-Aware On-Demand Routing for Mobile Ad Hoc Networks." In: Distributed Computing: Mobile and Wireless Computing 4th International Workshop, IWDC 2002 Calcutta, India, December 28–31, 2002 Proceedings. Ed. by Swapan Das Sajal K.and Bhattacharya. Berlin, Heidelberg: Springer Berlin Heidelberg, 2002, pp. 164–173. ISBN: 978-3-540-36385-9". DOI: 10.1007/3-540-363858_17.

[220] M. N. Jambli, H. Lenando, K. Zen, S. M. Suhaili, and A. Tully. "Transmission power control in mobile wireless sensor networks: Simulation-based approach." In: IET International Conference on Wireless Communications and Applications (ICWCA 2012). 2012, pp. 1– 6. DOI: 10.1049/cp.2012.2109.

[221] Aman Kansal, Jason Hsu, Sadaf Zahedi, and Mani B. Srivastava. "Power Management in Energy Harvesting Sensor Networks." In: ACM Trans. Embed. Comput. Syst. 6.4 (Sept. 2007). ISSN: 1539-9087. DOI: 10.1145/1274858.1274870. URL: http://doi.acm.org/ 10.1145/1274858.1274870.

[222] Suresh Singh, Mike Woo, and C. S. Raghavendra. "Power-aware Routing in Mobile Ad Hoc Networks." In: Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking. MobiCom '98. Dallas, Texas, USA: ACM, 1998, pp. 181–190. ISBN: 1-58113-035-X. DOI: 10.1145/288235. 288286.

[223] C-K Toh. “Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks.” In: IEEE communications Magazine 39.6 (2001), pp. 138–147.

[224] Suresh Singh and Cauligi S Raghavendra. “PAMAS— power aware multi-access protocol with signalling for ad hoc networks.” In: ACM SIGCOMM Computer Communication Review 28.3 (1998), pp. 5–26.

[225] A Rajaram and J Sugesh. “Power aware routing for MANET using on-demand multipath routing pro- tocol.” In: International Journal of Computer Science Is- sues (IJCSI) 8.4 (2011), p. 517.

[226] S. K. Dhurandher, S. Misra, M. S. Obaidat, P. Gupta, K. Verma, and P. Narula. “An Energy-Aware Routing Protocol for Ad-Hoc Networks Based on the Foraging Behavior in Ant Swarms.” In: 2009 IEEE International Conference on Communications. 2009, pp. 1–5. DOI: 10.1109/ICC.2009.5198728.

[227] Sayan Kumar Ray, Ruopak Sinha, and Swapan Kumar Ray. “A smartphone-based post-disaster management mechanism using WiFi tethering.” In: 2015 IEEE 10th conference on industrial electronics and applications (ICIEA). IEEE. 2015, pp. 966–971.

[228] Ericsson. “ON THE PULSE OF THE NETWORKED SOCIETY Ericsson Mobility Report.” In: (2016). URL: https://www.ericsson.com/res/docs/2016/ ericsson-mobility-report-2016.pdf.

[229] Patrick Lieser, Flor Alvarez, Paul Gardner-Stephen, Matthias Hollick, and Doreen Boehnstedt. “Architecture for responsive emergency communications networks.” In: 2017 IEEE Global Humanitarian Technology Conference (GHTC). IEEE. 2017, pp. 1–9.

[230] Niklas Kattner, Tianyi Wang, and Udo Lindemann. “Performance metrics in engineering change management-Key Performance Indicators and engineering change performance levels.” In: 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). IEEE. 2016, pp. 1180–1184.

[231] Joe Kasser and Robin Schermerhorn. “Determining metrics for systems engineering.” In: INCOSE International Symposium. Vol. 4. 1. Wiley Online Library. 1994, pp. 740–745.

[232] Michael Wade and John Hulland. “The resource-based view and

information systems research: Review, extension, and suggestions for future research." In: MIS quarterly (2004), pp. 107–142.

[233] Peng Lu, Hou Yang, Hao Li, Mengdi Li, and Zhuo Zhang. "Swarm intelligence, social force and multiagent modeling of heroic altruism behaviors under collective risks." In: Knowledge-Based Systems 214 (2021), p. 106725.

[234] Philip N Howard, Sheetal D Agarwal, and Muzammil M Hussain. "When do states disconnect their digital networks? Regime responses to the political uses of social media." In: The Communication Review 14.3 (2011), pp. 216–232.

[235] Helen Pidd. "India blackouts leave 700 million without power." In: The guardian 31 (2012).

[236] Md Forhad Rabbi and Md Ahsan Arefin. "ELearning using wireless ad-hoc network to support people of rural areas." In: 2006 International Conference on Communication Technology. IEEE. 2006, pp. 1–4.

[237] Vinoth Gunasekaran and Fotios C Harmantzis. "Emerging wireless technologies for developing countries." In: Technology in Society 29.1 (2007), pp. 23–42.

[238] S. M. George, W. Zhou, H. Chenji, M. Won, Y. O. Lee, A. Pazarloglou, R. Stoleru, and P. Barooah. "DistressNet: a wireless ad hoc and sensor network architecture for situation management in disaster response." In: IEEE Communications Magazine 48.3 (2010), pp. 128–136. ISSN: 1558-1896. DOI: 10.1109/MCOM. 2010.5434384.

[239] Z. Lu, G. Cao, and T. La Porta. "TeamPhone: Networking SmartPhones for Disaster Recovery." In: IEEE Transactions on Mobile Computing 16.12 (2017), pp. 3554– 3567. ISSN: 2161-9875. DOI: 10.1109/TMC.2017.2695452.

[240] H. Nishiyama, T. Ngo, N. Ansari, and N. Kato. "On Minimizing the Impact of Mobility on Topology Control in Mobile Ad Hoc Networks." In: IEEE Transactions on Wireless Communications 11.3 (2012), pp. 1158– 1166. ISSN: 1558-2248. DOI: 10.1109/TWC.2012.010312. 110783.

[241] F. Maan and N. Mazhar. "MANET routing protocols vs mobility models: A performance evaluation." In: 2011 Third International Conference on Ubiquitous and Future Networks (ICUFN). 2011, pp. 179–184. DOI: 10.1109/ ICUFN.2011.5949158.

[242] Radhika Ranjan Roy. Handbook of mobile ad hoc networks for mobility models. Vol. 170. Springer, 2011.

[243] M. Vanjale, J. S. Chitode, and S. Gaikwad. "Residual Battery Capacity Based Routing Protocol for Extending Lifetime of Mobile Ad Hoc Network." In: 2018 International Conference On Advances in Communication and Computing Technology (ICACCT). 2018, pp. 445–450. DOI: 10.1109/ICACCT.2018.8529412.

[244] Marco Conti and Silvia Giordano. "Mobile ad hoc networking: milestones, challenges, and new research directions." In: IEEE Communications Magazine 52.1 (2014), pp. 85–96.

[245] Vasileios Miliotis, Luis Alonso, and Christos Verikoukis. "CooPNC: A cooperative multicast protocol exploiting physical layer network coding." In: Ad hoc networks 14 (2014), pp. 35–50.

[246] P. Mekikis, A. S. Lalos, A. Antonopoulos, L. Alonso, and C. Verikoukis. "Wireless Energy Harvesting in Two-Way Network Coded Cooperative Communications: A Stochastic Approach for Large Scale Networks." In: IEEE Communications Letters 18.6 (2014), pp. 1011–1014. ISSN: 2373-7891. DOI: 10.1109/LCOMM. 2014.2320926.

[247] Thomas Clausen and Philippe Jacquet. RFC3626: Optimized link state routing protocol (OLSR). 2003.

[248] David B. Johnson and David A. Maltz. "Dynamic source routing in ad hoc wireless networks." In: Mobile Computing. Kluwer Academic Publishers, 1996, pp. 153–181.

[249] Charles E Perkins and Pravin Bhagwat. "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers." In: ACM SIGCOMM computer communication review 24.4 (1994), pp. 234–244.

[250] Young-Bae Ko and Nitin H Vaidya. "Location-Aided Routing (LAR) in mobile ad hoc networks." In: Wireless networks 6.4 (2000), pp. 307–321.

[251] Wenrui Zhao, Mostafa Ammar, and Ellen Zegura. "A message ferrying approach for data delivery in sparse mobile ad hoc networks." In: Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing. ACM. 2004, pp. 187–198.

[252] Brent Ishibashi and Raouf Boutaba. “Topology and mobility considerations in mobile ad hoc networks.” In: Ad hoc networks 3.6 (2005), pp. 762–776.

[253] Fatih Deniz, Hakki Bagci, Ibrahim Korpeoglu, and Adnan Yazıcı. “An adaptive, energy-aware and distributed fault-tolerant topology-control algorithm for heterogeneous wireless sensor networks.” In: Ad Hoc Networks 44 (2016), pp. 104–117.

[254] Ossama Younis and Sonia Fahmy. “HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks.” In: IEEE Transactions on mobile computing 3.4 (2004), pp. 366–379.

[255]Lichun Bao and JJ Garcia-Luna-Aceves. “Stable energyaware topology management in ad hoc networks.” In: Ad Hoc Networks 8.3 (2010), pp. 313–327.

[256] Matt Duckham. Decentralized spatial computing: foundations of geosensor networks. Springer Science & Business Media, 2012.

[257] Seth Tisue and Uri Wilensky. “Netlogo: A simple environment for modeling complexity.” In: International conference on complex systems. Vol. 21. Boston, MA. 2004, pp. 16–21.

[258] Iván García-Magariño, Raquel Lacuesta, Muttukrishnan Rajarajan, and Jaime Lloret. “Security in networks of unmanned aerial vehicles for surveillance with an agent-based approach inspired by the principles of blockchain.” In: Ad Hoc Networks 86 (2019), pp. 72–82.

[259] Wolfgang Kiess and Martin Mauve. “A survey on real-world implementations of mobile ad-hoc networks.” In: Ad Hoc Networks 5.3 (2007), pp. 324–339.

[260] Texas Instruments. Bluetooth Power Calculator Tool. http: //www.ti.com/tool/BT-POWER-CALC, Accessed: 2018-11-22. 2018.

[261] Joakim Lindh, Christin Lee, and Marie Hernes. “Measuring bluetooth low energy power consumption.” In: Application Note AN092 (2017).

[262] Chris Franklin and Alan Agresti. Statistics: The art and science of learning from data. Upper Saddle River, New Jersey: Pearson Prentice Hall, 2007.

[263] Naeem Raza, Muhammad Umar Aftab, Muhammad Qasim Akbar, Omair Ashraf, and Muhammad Irfan. “Mobile ad-hoc networks applications

and its challenges.” In: Communications and Network 8.3 (2016), pp. 131–136.

[264] RA Santos, Apolinar González-Potes, Miguel A GarciaRuiz, A Edwards-Block, V Rangel-Licea, and LA VillaseñorGonzález. “Hybrid Routing Algorithm for Emergency and RuralWireless.” In: Elektronika ir Elektrotechnika 89.1 (2009), pp. 3–8.

[265] Tifenn Rault, Abdelmadjid Bouabdallah, and Yacine Challal. “Energy efficiency in wireless sensor networks: A top-down survey.” In: Computer Networks 67 (2014), pp. 104–122.

[266] Farzad Kiani, Ehsan Amiri, Mazdak Zamani, Touraj Khodadadi, and Azizah Abdul Manaf. “Efficient intelligent energy routing protocol in wireless sensor networks.” In: International Journal of Distributed Sensor Networks 11.3 (2015), p. 618072.

[267] Maciej Piechowiak and Piotr Zwierzykowski. “Topology Properties of Ad-Hoc Networks with Topology Control.” In: International Conference on Computer Networks. Springer. 2014, pp. 89–98.

[268] A. A. Aziz, Y. A. Sekercioglu, P. Fitzpatrick, and M. Ivanovich. “A Survey on Distributed Topology Control Techniques for Extending the Lifetime of Battery Powered Wireless Sensor Networks.” In: IEEE Communications Surveys & Tutorials 15.1 (2013), pp. 121– 144.

[269] Benjie Chen, Kyle Jamieson, Hari Balakrishnan, and Robert Morris. “Span: An energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks.” In: Wireless networks 8.5 (2002), pp. 481–494.

[270] Priscilla Chen, Bob O’Dea, and Ed Callaway. “Energy efficient system design with optimum transmission range for wireless ad hoc networks.” In: 2002 IEEE International Conference on Communications. Conference Proceedings. ICC 2002 (Cat. No. 02CH37333). Vol. 2. IEEE. 2002, pp. 945–952.

[271] Muhammad Naeem, Kandasamy Illanko, Ashok Karmokar, Alagan Anpalagan, and Muhammad Jaseemuddin. “Energy-efficient cognitive radio sensor networks: Parametric and convex transformations.” In: Sensors 13.8 (2013), pp. 11032–11050.

[272] Paolo Santi. “Topology control in wireless ad hoc and sensor networks.” In: ACM computing surveys (CSUR) 37.2 (2005), pp. 164–194.

[273] Ning Li, Jennifer C Hou, and Lui Sha. “Design and analysis of an MST-based topology control algorithm.” In: IEEE Transactions on Wireless Communications 4.3 (2005), pp. 1195–1206.

[274] F. Ingelrest, D. Simplot-Ryl, and I. Stojmenovic. “Target transmission radius over LMST for energy-efficient broadcast protocol in ad hoc networks.” In: 2004 IEEE International Conference on Communications (IEEE Cat. No.04CH37577). Vol. 7. 2004, 4044–4049 Vol.7.

[275] Julien Cartigny, Francois Ingelrest, David SimplotRyl, and Ivan Stojmenović. “Localized LMST and RNG based minimum-energy broadcast protocols in ad hoc networks.” In: Ad Hoc Networks 3.1 (2005), pp. 1–16.

[276] L. B. Abiuzi, C. D. A. C. Cesar, and C. H. C. Ribeiro. “A-LMST: An Adaptive LMST Local Topology Control Algorithm for Mobile Ad Hoc Networks.” In: 2016 IEEE 41st Conference on Local Computer Networks (LCN). 2016, pp. 168–171.

[277] Tzu-Chieh Tsai, Ting-Shen Liu, and Chien-Chun Han. “Waterchat: A group chat application based on opportunistic mobile social networks.” In: J. Commun12.7 (2017), pp. 405–411.

[278] C.Chou,D.S.l.Wei,C..J.Kuo,andK.Naik.“Anefficient anonymous communication protocol for peerto-peer applications over mobile ad-hoc networks.” In: IEEE Journal on Selected Areas in Communications 25.1 (2007), pp. 192–203.

[279] O. Mokryn, D. Karmi, A. Elkayam, and T. Teller. “Help Me: Opportunistic smart rescue application and system.” In: 2012 The 11th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net). 2012, pp. 98–105.

[280] Tipu Arvind Ramrekha, Vahid Nazari Talooki, Jonathan Rodriguez, and Christos Politis. “Energy efficient and scalable routing protocol for extreme emergency ad hoc communications.” In: Mobile Networks and Applications 17.2 (2012), pp. 312–324.

[281] D. K. Anand and S. Prakash. “A Short Survey of Energy-Efficient Routing Protocols for Mobile AdHoc Networks.” In: 2010 International Conference on Advances in Recent Technologies in Communication and Computing. 2010, pp. 327–329.

[282] Chunyi Peng, Haitao Zheng, and Ben Y Zhao. “Utilization and fairness in spectrum assignment for opportunistic spectrum access.” In: Mobile Networks and Applications 11.4 (2006), pp. 555–576.

[283] Michael Isard, Vijayan Prabhakaran, Jon Currey, Udi Wieder, Kunal Talwar, and Andrew Goldberg. “Quincy: fair scheduling for distributed computing clusters.” In: Proceedings of the ACM SIGOPS 22nd Symposium on Operating Systems Principles. 2009, pp. 261–276.

[284] Ali Ghodsi, Matei Zaharia, Benjamin Hindman, Andy Konwinski, Scott Shenker, and Ion Stoica. “Dominant Resource Fairness: Fair Allocation of Multiple Resource Types.” In: Networked Systems Design and Implementation (NSDI). Vol. 11. 2011, pp. 323–326.

[285] Rajendra K Jain, Dah-Ming W Chiu, William R Hawe, et al. “A quantitative measure of fairness and discrimination.” In: Eastern Research Laboratory, Digital Equipment Corporation, Hudson, MA (1984).

[286] B. Bensaou, Yu Wang, and Chi Chung Ko. “Fair medium access in 802.11 based wireless ad-hoc networks.” In: 2000 First Annual Workshop on Mobile and Ad Hoc Networking and Computing. MobiHOC (Cat. No.00EX444). 2000, pp. 99–106.

[287] Xin Wang and K. Kar. “Throughput modelling and fairness issues in CSMA/CA based ad-hoc networks.” In: Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Vol. 1. 2005, 23–34 vol. 1.

[288] Violeta Gambiroza, Bahareh Sadeghi, and Edward W. Knightly. “End-to-End Performance and Fairness in Multihop Wireless Backhaul Networks.” In: Proceedings of the 10th Annual International Conference on Mobile Computing and Networking. MobiCom ’04. New York, NY, USA: Association for Computing Machinery, 2004, pp. 287–301. ISBN: 1581138687. DOI: 10.1145/1023720.1023749.

[289] Michele Ballerini, Nicola Cabibbo, Raphael Candelier, Andrea Cavagna, Evaristo Cisbani, Irene Giardina, Vivien Lecomte, Alberto Orlandi, Giorgio Parisi, Andrea Procaccini, et al. “Interaction ruling animal collective behavior depends on topological rather than metric distance: Evidence from a field study.” In: Proceedings of the National Academy of Sciences 105.4 (2008), pp.

1232–1237.

[290] Jeroen Van den Hoven. “ICT and Value Sensitive Design.” In: The Information Society: Innovation, Legitimacy, Ethics and Democracy in Honor of Professor Jacques Berleur SJ. Springer, 2007, pp. 67–72.

[291] Pierre Deville, Chaoming Song, Nathan Eagle, Vincent D Blondel, Albert-László Barabási, and Dashun Wang. “Scaling identity connects human mobility and social interactions.” In: Proceedings of the National Academy of Sciences 113.26 (2016), pp. 7047–7052.

[292] Ye Wu, Changsong Zhou, Jinghua Xiao, Jürgen Kurths, and Hans Joachim Schellnhuber. “Evidence for a bimodal distribution in human communication.” In: Proceedings of the National Academy of Sciences 107.44 (2010), pp. 18803–18808.

[293] Joakim Lindh, Christin Lee, and Marie Hermes. Measuring Bluetooth low energy power consumption. Tech. rep. Texas Instruments, 2017.

[294] A Druckman and Thomas Jackson. “Measuring resource inequalities: The concepts and methodology for an area-based Gini coefficient.” In: Ecological economics 65.2 (2008), pp. 242–252.

[295] Stephane Hallegatte, Colin Green, Robert J Nicholls, and Jan Corfee-Morlot. “Future flood losses in major coastal cities.” In: Nature climate change 3.9 (2013), pp. 802–806.

[296] Re Swiss. “Mind the risk: a global ranking of cities under threat from natural disasters.” In: (2013).

[297] “Population density by city, 2011-2014.” In: Our World in Data (2014).

[298] Pierre Deville, Catherine Linard, Samuel Martin, Marius Gilbert, Forrest R Stevens, Andrea E Gaughan, Vincent D Blondel, and Andrew J Tatem. “Dynamic population mapping using mobile phone data.” In: Proceedings of the National Academy of Sciences 111.45 (2014), pp. 15888–15893.

[299] Yury Kryvasheyeu, Haohui Chen, Nick Obradovich, Esteban Moro, Pascal Van Hentenryck, James Fowler, and Manuel Cebrian. “Rapid assessment of disaster damage using social media activity.” In: Science Advances 2.3 (2016), e1500779.

[300] H. Y. Yatbaz, B. Çinar, A. Gökdemir, E. Ever, F. AlTurjman, H. X.

Nguyen, and A. Yazici. “Hybrid Approach for Disaster Recovery using P2P Communications in Android.” In: 2018 IEEE 43rd Conference on Local Computer Networks Workshops (LCN Workshops). 2018, pp. 46–52.

[301] F. Mezghani and N. Mitton. “The potential of cooperative communications to speed up disaster relief operations.” In: 2019 International Conference on Information and Communication Technologies for Disaster Management (ICT-DM). 2019, pp. 1–6.

[302] Shivsubramani Krishnamoorthy and Ashok Agrawala. “M-Urgency: a next generation, context-aware public safety application.” In: Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services. 2011, pp. 647–652.

[303] Ali Masood, Navuday Sharma, M Mahtab Alam, Yannick Le Moullec, Davide Scazzoli, Luca Reggiani, Maurizio Magarini, and Rizwan Ahmad. “Deviceto-device discovery and localization assisted by UAVs in pervasive public safety networks.” In: Proceedings of the ACM MobiHoc Workshop on Innovative Aerial Communication Solutions for First Responders Network in Emergency Scenarios. 2019, pp. 6–11.

[304] Alison P Galvani, Chris T Bauch, Madhur Anand, Burton H Singer, and Simon A Levin. “Human–environment interactions in population and ecosystem health.” In: Proceedings of the National Academy of Sciences 113.51 (2016), pp. 14502–14506.

[305] Hirokazu Shirado, George Iosifidis, and Nicholas A Christakis. “Assortative mixing and resource inequality enhance collective welfare in sharing networks.” In: Proceedings of the National Academy of Sciences 116.45 (2019), pp. 22442–22444.

[306] Jacob Freeman, Jacopo A Baggio, and Thomas R Coyle. “Social and general intelligence improves collective action in a common pool resource system.” In: Proceedings of the National Academy of Sciences 117.14 (2020), pp. 7712–7718.

[307] Susan Spierre Clark, Mikhail V Chester, Thomas P Seager, and Daniel A Eisenberg. “The vulnerability of interdependent urban infrastructure systems to climate change: Could Phoenix experience a Katrina of extreme heat?” In: Sustainable and Resilient Infrastructure 4.1 (2019), pp. 21–35.

[308] Mo Hamza. World Disasters Report, Focus on local actors, the key to humanitarian effectiveness. 2015.

[309] Michael Berlemann and Max Friedrich Steinhardt. “Climate change, natural disasters, and migration— a survey of the empirical evidence.” In: CESifo Economic Studies 63.4 (2017), pp. 353–385.

[310] Susan L Cutter and Christina Finch. “Temporal and spatial changes in social vulnerability to natural hazards.” In: Proceedings of the national academy of sciences 105.7 (2008), pp. 2301–2306.

[311] Laura Petersen, Laure Fallou, Paul Reilly, and Elisa Serafinelli. “Public expectations of critical infrastructure operators in times of crisis.” In: Sustainable and Resilient Infrastructure 5.1-2 (2020), pp. 62–77.

[312] Maria Koliou, John W van de Lindt, Therese P McAllister, Bruce R Ellingwood, Maria Dillard, and Harvey Cutler. “State of the research in community resilience: Progress and challenges.” In: Sustainable and resilient infrastructure 5.3 (2020), pp. 131–151.

[313] Amanda Howard, Kylie Agllias, Miriam Bevis, and Tamara Blakemore. “They’ll tell us when to evacuate”: The experiences and expectations of disasterrelated communication in vulnerable groups.” In: International journal of disaster risk reduction 22 (2017), pp. 139–146.

[314] Tony H Grubesic, Timothy C Matisziw, and Alan T Murray. “Market coverage and service quality in digital subscriber lines infrastructure planning.” In: International Regional Science Review 34.3 (2011), pp. 368– 390.

[315] Yogesh Kumar Dwivedi, Naureen Khan, and Anastasia Papazafeiropoulou. “Consumer adoption and usage of broadband in Bangladesh.” In: Electronic Government, an International Journal 4.3 (2007), pp. 299– 313.

[316] Kallol Bagchi. “Factors contributing to global digital divide: Some empirical results.” In: Journal of Global Information Technology Management 8.3 (2005), pp. 47–65.

[317] Muhammad Ghulam Quibria, Shamsun N Ahmed, Ted Tschang, and Mari-Len Reyes-Macasaquit. “Digital divide: determinants and policies with special reference to Asia.” In: Journal of Asian Economics 13.6 (2003), pp. 811–825.

[318] Tooran Alizadeh. “Planning Deficiencies and Telecommunication Infrastructure: A Multi-level Investigation of the National Broadband Network in Australia.” In: disP-The Planning Review 53.3 (2017), pp. 43–57.

[319] Tony H Grubesic. “The broadband provision tensor.” In: Growth and Change 46.1 (2015), pp. 58–80.

[320] Gregory R Madey, Gabor Szabo, and Albert-László Barabási. “WIPER: The integrated wireless phone based emergency response system.” In: International conference on computational science. Springer. 2006, pp. 417– 424.

[321] A Bhatnagar, A Kumar, RK Ghosh, and RK Shyamasundar. “A framework of community inspired distributed message dissemination and emergency alert response system over smart phones.” In: 2016 8th International Conference on Communication Systems and Networks (COMSNETS). IEEE. 2016, pp. 1–8.

[322] David Soldani and Sudhir Dixit. “Wireless relays for broadband access [radio communications series].” In: IEEE communications Magazine 46.3 (2008), pp. 58– 66.

[323] Kamran Ali, Huan X Nguyen, Purav Shah, QuocTuan Vien, and Enver Ever. “D2D multi-hop relaying services towards disaster communication system.” In: 2017 24th international conference on telecommunications (ICT). IEEE. 2017, pp. 1–5.

[324] Erica J Gilrein, Thomaz M Carvalhaes, Samuel A Markolf, Mikhail V Chester, Braden R Allenby, and Margaret Garcia. “Concepts and practices for transforming infrastructure from rigid to adaptable.” In: Sustainable and Resilient Infrastructure 6.3-4 (2021), pp. 213–234.

[325] Neelke Doorn, Paolo Gardoni, and Colleen Murphy. “A multidisciplinary definition and evaluation of resilience: The role of social justice in defining resilience.” In: Sustainable and Resilient Infrastructure 4.3 (2019), pp. 112–123.

[326] Megan Garcia. “Racist in the machine: The disturbing implications of algorithmic bias.” In: World Policy Journal 33.4 (2016), pp. 111–117.

[327] Keith Kirkpatrick. “Battling algorithmic bias: how do we ensure algorithms treat us fairly?” In: Communications of the ACM 59.10 (2016), pp. 16–17.

[328] David Danks and Alex John London. “Algorithmic Bias in Autonomous Systems.” In: IJCAI. Vol. 17. 2017, pp. 4691–4697.

[329] Marie-Ange Baudoin, Sarah Henly-Shepard, Nishara Fernando, Asha Sitati, and Zinta Zommers. “From top-down to “community-centric” approaches to early warning systems: exploring pathways to improve disaster risk reduction through community participation.” In: International Journal of Disaster Risk Science 7.2 (2016), pp. 163–174.

[330] Anna Scolobig, Tim Prior, Dagmar Schröter, Jonas Jörin, and Anthony Patt. “Towards people-centred approaches for effective disaster risk management: Balancing rhetoric with reality.” In: International Journal of Disaster Risk Reduction 12 (2015), pp. 202–212.

[331] Roberto Guidotti, Hana Chmielewski, Vipin Unnikrishnan, Paolo Gardoni, Therese McAllister, and John van de Lindt. “Modeling the resilience of critical infrastructure: The role of network dependencies.” In: Sustainable and resilient infrastructure 1.3-4 (2016), pp. 153– 168.

[332] Michael Nagenborg. “Urban resilience and distributive justice.” In: Sustainable and resilient infrastructure 4.3 (2019), pp. 103–111.

[333] Bartel Van de Walle and Tina Comes. “On the nature of information management in complex and natural disasters.” In: Procedia Engineering 107 (2015), pp. 403–411.

[334] David Paulus, Ramian Fathi, Frank Fiedrich, Bartel Van de Walle, and Tina Comes. “On the interplay of data and cognitive bias in crisis information management– An exploratory study on epidemic response.” In: arXiv preprint arXiv:2201.03508 (2022).

[335] Soon Chun, Stuart Shulman, Rodrigo Sandoval, and Eduard Hovy. “Government 2.0: Making connections between citizens, data and government.” In: Information Polity 15.1, 2 (2010), pp. 1–9.

[336] Mikko VJ Heikkinen, Jukka K Nurminen, Timo Smura, and Heikki Hämmäinen. “Energy efficiency of mobile handsets: Measuring user attitudes

and behavior.” In: Telematics and Informatics 29.4 (2012), pp. 387– 399.

[337] Albert-László Barabási and Eric Bonabeau. “Scalefree networks.” In: Scientific american 288.5 (2003), pp. 60–69.

[338] Sangho Yi, Junyoung Heo, Yookun Cho, and Jiman Hong. “PEACH: Power-efficient and adaptive clustering hierarchy protocol for wireless sensor networks.” In: Computer communications 30.14-15 (2007), pp. 2842– 2852.

[339] Sandeep Kamath and Joakim Lindh. Measuring Bluetooth® Low Energy Power Consumption. Tech. rep. Application Note-AN092. Texas Instruments, 2010.

[340] Seale, M., Kiss, A., Bovio, S., Viola, I.M., Mastropaolo, E., Boudaoud, A. and Nakayama, N., 2022. "Dandelion pappus morphing is actuated by radially patterned material swelling. In: Nature communications, 13(1), pp.1-14.

Summary

In 2018 the United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA) reported that 140 million people in 37 countries were directly affected by humanitarian crises such as disasters. The re-port suggested that apart from monetary aid, all these displaced people also needed innovative technical solutions that could empower these communities. Increasing the digital connectivity of these communities and providing them with communication facilities to connect with aid providers are currently two (out of ten) grand challenges faced by UN OCHA.

Communication facilities during disasters are a crucial resource that is a fundamental need for rescue and a resource that every individual or organization involved in the disaster mitigation process requires. Therefore, disaster communication can start before a disaster hits a community and can last until normal communication channels are functional again. Moreover, the communication requirements in a disaster area can be unpredictable, given that the damage caused by each disaster on infrastructure can vary. Uncertainties, for example, can involve (i) the time it takes for rescue operators to reach and establish alternative means of communication, (ii) the extent of damage to traditional infrastructures limiting their recovery and reuse, (iii) the number of victims and active rescuers that need to communicate, i.e., the population density of a disaster area. This complexity leads to various systems providing communication services during disasters among all stakeholders pre and post-disaster.

This thesis starts with reviewing recently proposed disaster communication solutions from the literature. Mobile Ad hoc Networks (or MANETs) are discussed, that make use of peer-to-peer communication. In these MANETs, messages are exchanged directly between phones that are near each other. If phones are not that close to each other, a path is formed of intermediate phones, that relay messages over longer distances. The reviewed solutions make use of different kinds of protocols and mechanisms to improve an operational aspect of disaster communication, such as the reliability of message delivery, and throughput among others. However, using mobile phones to form an infrastructure-less on-demand wireless mobile ad-hoc network (MANET) presents certain challenges of its own. These challenges result from complicated system designs that limit deployment or the limitations possessed by phones that form these networks. Limited battery charge in phones and the inability to charge them due to power blackouts increases the challenge to

remain connected. Therefore, there is an abundance of literature on energy efficiency mechanisms either for routing or topolo-gy control. However, these mechanisms are all derivatives of approaches used in wireless sensor networks. However, in a disaster context, such mechanisms need to be evaluated for performance criteria that are rel-evant in such a context. Parameters such as the population density of nodes, mobility of people owning these phones, available phones with their battery life, and type of application (such as whether the message is broadcasted or only sent to a specific group) all play a very vital role. The current approaches are yet to investigate many of these issues, let alone all of them. Additionally, mobile and immobile citizens stuck in impoverished, highly populated areas, so-called 'islands of inequity' where often initial infrastructure is missing need to be able to connect with disaster response teams requiring hybrid communication ap-proaches.

To serve this purpose this thesis presents the design of a resilient communication network. In this thesis, the right to communicate and remain connected is considered the core requirement for the design process. To fulfil this goal the thesis investigates the values that are fundamental in the resilient communication net-work. Participatory fairness, inclusion and continuity are considered the three main non-functional values that are included in the design of the communication system presented in this thesis.

This thesis makes use of a self-organization as an approach to create a context-aware adaptive communica-tion system. This design, termed "Self-Organization for Survival" (SOS), makes use of algorithms that allows the network to adapt to the changes in the spatial-temporal-resource context of a disaster area. The thesis further explores the value-sensitive design process to quantify and evaluate the delivery of values in SOS. SOS enables and maintains the participation of practically all phones, i.e., it provides equal communica-tion opportunities for all citizens regardless of the initial inequality in phone battery charges. To achieve this goal SOS automatically and dynamically (i) assigns high-battery phones as hubs, (ii) adapts the communication topology to changing battery charges, and (iii) self-organizes to remain robust and reli-able when links fail, or phones leave the network. The proposed protocol has several advantages. In ABM models it is demonstrated through experiments that SOS is adaptive to the environment. This means it is applicable in scenarios that may vary in the density and mobility of devices, and in the availability of energy sources. Second, SOS is energy-efficient through changes in topology. This means SOS can flexibly be combined with different routing protocols. Third, SOS requires no changes on the hardware level. This means SOS can be implemented on all current phones, also in the global south without any recalls or in-vestments in hardware changes. To test if the proposed design delivers all functional and non-functional requirements, simulation and modeling were performed. First, it was important to investigate whether the longevity of the network, reliability of message delivery, and scalability of the approach were satisfactory. This was established using an Agent-Based Modeling (ABM) approach that simulated the behaviour of actors moving around in the disaster area, with phones with different battery charges.

The previously mentioned conditions serve as baseline conditions, as these are typical conditions for these types of emergency communication solutions. In this thesis, the goal was to achieve additional system-level properties, in a design that is based on the values that should be included. Specifically, this thesis identifies participatory fairness as a core value to be achieved in the value-sensitive design. Participatory fairness in this context is defined as optimizing the opportunity for all participants in the network to be able to communicate for the longest possible time, regardless of the amount of battery charge that they start with. The phones that have high battery charge become responsible for performing the energy-consuming task of relaying messages, while phones with low battery charge no longer relay messages. This allows all participants to participate for the longest time, thus achieving participatory fairness. This was again demonstrated using an ABM approach.

Other values under investigation in this thesis were inclusion and continuity. By inclusion, the value is meant that the approach should provide connectivity to those citizens in areas that are outside of the range of traditional infrastructures that are introduced by rescue operators. Some of these citizens outside of this range may not be mobile, so they are stuck in these areas without being able to communicate. To alleviate this problem, the SOS approach is extended to also include communication with newly introduced back-bone infrastructures. Those outside the backbone infrastructure range make use of ad hoc communication to communicate with each other, and with those inside the backbone infrastructure range. In this way, messages can be delivered, increasing inclusivity towards citizens in these areas as well. The sudden introduction of a backbone infrastructure could introduce problems for the SOS design, because it may interrupt connectivity because phones must dynamically switch from one protocol to another. Continuity of service was also established in this thesis with an ABM approach. Through these demonstrations, this dissertation shows one potential solution to the question of how to design a value-based citizen-centric adaptive mobile communication system.

Samenvatting

In 2018 meldde het Bureau voor de Coördinatie van Humanitaire Zaken van de Verenigde Naties (OCHA) dat 140 miljoen mensen in 37 landen rechtstreeks werden getroffen door humanitaire crises zoals rampen. Het rapport geeft aan dat al deze ontheemden naast monetaire hulp ook innovatieve technische oplossingen nodig hebben die deze gemeenschappen onafhankelijker kunnen maken. Het vergroten van de digitale connectiviteit van deze gemeenschappen en hen voorzien van communicatievoorzieningen om in contact te komen met hulpverleners zijn momenteel twee (van de tien) grote uitdagingen voor OCHA.

Communicatievoorzieningen tijdens rampen zijn een essentiële hulpbron en een middel dat elk individu of elke organisatie die betrokken is bij de bestrijding van rampen nodig heeft. Daarom kan de communicatie bij rampen beginnen voordat een ramp een gemeenschap treft en duren tot de normale communicatiekanalen weer functioneel zijn. Bovendien kunnen de communicatiebehoeften in een rampgebied onvoorspelbaar zijn, aangezien de schade die elke ramp aan de infrastructuur toebrengt, kan variëren. Onzekerheden kunnen bijvoorbeeld betrekking hebben op (i) de tijd die reddingswerkers nodig hebben om het gebied te bereiken en alternatieve communicatiemiddelen tot stand te brengen, (ii) de omvang van de schade aan traditionele infrastructuren die het herstel en hergebruik ervan beperken, (iii) het aantal slachtoffers en actieve reddingswerkers die moeten communiceren, d.w.z. de bevolkingsdichtheid van een rampgebied. Deze complexiteit leidt tot verschillende systemen die tijdens rampen communicatiediensten leveren tussen alle belanghebbenden vóór en na de ramp.

Dit proefschrift begint met een overzicht van recent voorgestelde oplossingen voor rampencommunicatie uit de literatuur. Mobiele Ad hoc Netwerken (of MANETs) worden besproken, die gebruik maken van peer-to-peer communicatie. In deze MANETs worden berichten rechtstreeks uitgewisseld tussen telefoons die zich dicht bij elkaar bevinden. Als telefoons zich niet zo dicht bij elkaar bevinden wordt een pad gevormd van tussenliggende telefoons, die de berichten over langere afstanden doorgeven. De besproken oplossingen maken gebruik van verschillende soorten protocollen en mechanismen om een operationeel aspect van rampencommunicatie te verbeteren, zoals de betrouwbaarheid van de berichtaflevering en de doorvoer.

Het gebruik van mobiele telefoons om een infrastructuurloos draadloos on-demand mobiel ad hoc netwerk (MANET) te vormen brengt echter bepaal-

de eigen uitdagingen met zich mee. Deze uitdagingen vloeien voort uit ingewikkelde systeemontwerpen die het gebruik beperken of uit de beperkingen van de telefoons die deze netwerken vormen. De beperkte batterijcapaciteit van telefoons en het onvermogen om ze op te laden als gevolg van stroomuitval vergroten de uitdaging om verbonden te blijven.

Er is een overvloed aan literatuur over energie-efficiënte mechanismen voor routering of topologiecontrole. Deze mechanismen zijn echter allemaal afgeleiden van benaderingen die in draadloze sensornetwerken worden gebruikt. In een rampencontext moeten dergelijke mechanismen echter worden geëvalueerd op basis van prestatiecriteria die in een dergelijke context relevant zijn. Parameters zoals de bevolkingsdichtheid, de mobiliteit van mensen die deze telefoons bezitten, de beschikbare telefoons met hun batterijduur, en het type toepassing (zoals of het bericht wordt uitgezonden of alleen naar een specifieke groep wordt gestuurd) spelen allemaal een zeer vitale rol. De huidige benaderingen moeten veel van deze kwesties nog onderzoeken, zo niet allemaal. Bovendien moeten mobiele en immobiele burgers die vastzitten in verarmde, dichtbevolkte gebieden, zogenaamde "eilanden van ongelijkheid" waar vaak de eerste infrastructuur ontbreekt, verbinding kunnen maken met rampenteams waarvoor hybride communicatiebenaderingen nodig zijn.

Om dit doel te bereiken presenteert dit proefschrift het ontwerp van een veerkrachtig communicatienetwerk. In dit proefschrift wordt het recht om te communiceren en verbonden te blijven beschouwd als de kernvereiste voor het ontwerpproces. Om dit doel te bereiken onderzoekt dit proefschrift de waarden die fundamenteel zijn in het veerkrachtige communicatienetwerk. Participatieve eerlijkheid, inclusie en continuïteit worden beschouwd als de drie belangrijkste niet-functionele waarden die zijn opgenomen in het ontwerp van het in dit proefschrift gepresenteerde communicatiesysteem.

Dit proefschrift maakt gebruik van zelforganisatie als benadering om een contextbewust adaptief communicatiesysteem te creëren. Dit ontwerp, "Self-Organization for Survival" (SOS) genaamd, maakt gebruik van algoritmen die het netwerk in staat stellen zich aan te passen aan de veranderingen in de ruimtelijk-temporele-bronnencontext van een rampgebied.

Het proefschrift onderzoekt verder het waardenbewuste ontwerpproces om de levering van waarden in SOS te kwantificeren en te evalueren. SOS maakt de deelname van vrijwel alle telefoons mogelijk en handhaaft deze, d.w.z. het biedt gelijke communicatiemogelijkheden voor alle burgers, ongeacht de aanvankelijke ongelijkheid in batterijlading van de telefoons.

SOS richt zich automatisch en dynamisch op het (i) aanwijzen van telefoons met een hoge batterijlading als hubs, (ii) aanpassen van de communicatietopologie op veranderende batterijladingen, en (iii) zelf-organiseren om robuust en betrouwbaar te blijven wanneer verbindingen uitvallen. Het voorgestelde protocol heeft verschillende voordelen. Met ABM-modellen (Agent-Based Modeling) wordt via experimenten aangetoond dat SOS zich aanpast aan de omgeving. Dit betekent dat het toepasbaar is in scenario's die kunnen variëren in dichtheid en mobiliteit van apparaten, en in de beschikbaarheid van energiebronnen. Ten tweede is SOS energie-effciënt door middel van veranderingen in de topologie. Dit betekent dat SOS flexibel kan worden gecombineerd met verschillende routeringsprotocollen. Ten derde vereist SOS geen veranderingen op hardwareniveau. Dit betekent dat SOS kan worden toegepast op alle huidige telefoons, ook in ontwikkelingslanden, zonder terugroepingen of investeringen in hardwareveranderingen.

Om te testen of het voorgestelde ontwerp aan alle functionele en niet-functionele eisen voldoet, werden simulatie en modellering uitgevoerd. Eerst moest worden onderzocht of de levensduur van het netwerk, de betrouwbaarheid van de berichtaflevering en de schaalbaarheid van de aanpak bevredigend waren. Dit werd vastgesteld met behulp van een ABM-benadering die het gedrag simuleerde van actoren die zich in het rampgebied verplaatsen, met telefoons met verschillende batterijlading.

De eerder genoemde eisen dienen als basisvoorwaarden, aangezien dit typische eisen zijn voor dit soort noodcommunicatieoplossingen. In dit proefschrift was het doel om aanvullende eigenschappen op systeemniveau te bereiken, in een ontwerp dat is gebaseerd op de waarden die moeten worden opgenomen. Meer bepaald identificeert dit proefschrift participatieve eerlijkheid als een kernwaarde die moet worden bereikt in het waardenbewuste ontwerp. Participatieve eerlijkheid wordt in deze context gedefinieerd als het optimaliseren van de mogelijkheid voor alle deelnemers in het netwerk om zo lang mogelijk te kunnen blijven communiceren, ongeacht de hoeveelheid batterijlading waarmee ze beginnen. De telefoons met een hoge batterijlading worden verantwoordelijk voor het uitvoeren van de energievretende taak van het doorgeven van berichten, terwijl telefoons met een lage batterijlading geen berichten meer doorgeven. Hierdoor kunnen alle deelnemers het langst deelnemen, waardoor participatieve eerlijkheid wordt bereikt. Dit werd opnieuw aangetoond met behulp van een ABM-benadering.

Andere waarden die in dit proefschrift werden onderzocht waren inclusie en continuïteit. Met inclusie wordt bedoeld dat de aanpak connectiviteit moet bieden aan die burgers in gebieden die buiten het bereik liggen van traditionele infrastructuren die door reddingswerkers worden ingevoerd. Sommige van deze burgers buiten dit bereik zijn wellicht niet mobiel, zodat zij in deze gebieden vastzitten zonder te kunnen communiceren. Om dit probleem te verlichten, wordt de SOS-benadering uitgebreid tot communicatie met nieuw geïntroduceerde backbone-infrastructuren. Degenen die zich buiten het bereik van de backbone-infrastructuur bevinden, maken gebruik van ad hoc-communicatie om met elkaar en met degenen binnen het bereik van de backbone-infrastructuur te communiceren. Op deze manier kunnen berichten worden overgebracht, waardoor ook in deze gebieden de inclusiviteit voor de burgers toeneemt. De plotselinge invoering van een backbone-infrastructuur kan problemen opleveren voor het SOS-ontwerp, omdat het de connectiviteit kan onderbreken omdat de telefoons dynamisch van het ene protocol naar het andere moeten overschakelen. Continuïteit van dienstverlening werd in dit proefschrift ook vastgesteld met een ABM-benadering.

Door deze demonstraties toont dit proefschrift één potentiële oplossing voor de vraag hoe een op waarden gebaseerd burger-centrisch adaptief mobiel communicatiesysteem kan worden ontworpen.

सारांश

2018 में मानवता के एजेंडे पर काम करने वाला संयुक्त राष्ट्र सचिवालय (यूएन ओसीएचए) ने बताया कि 37 देशों में 140 मिलियन लोग आपदाओं जैसे मानवीय संकटों से सीधे प्रभावित हुए थे। रिपोर्ट ने सुझाव दिया कि इन सभी विस्थापित लोगों को आर्थिक रूप से मदद करने के अलावा, ऐसे नवीन तकनीकी समाधानों की भी आवश्यकता है जो इन समुदायों को सशक्त बना सकें। इन समुदायों की डिजिटल कनेक्टिविटी को बढ़ाना और उन्हें राहत प्रदाताओं से जुड़ने के लिए संचार सुविधाएं प्रदान करना वर्तमान में संयुक्त राष्ट्र के सामने दो (दस में से) बड़ी चुनौतियां हैं।

आपदाओं के दौरान संचार सुविधाएं एक महत्वपूर्ण संसाधन हैं। संचार बचाव और संसाधन के लिए एक मूलभूत आवश्यकता है जिसकी प्रत्येक व्यक्ति या संगठन को आवश्यकता होती है। इसलिए, आपदा संचार किसी समुदाय में आपदा आने से पहले शुरू हो सकता है और तब तक चल सकता है जब तक कि सामान्य संचार चैनल फिर से काम नहीं कर लेते। इसके अलावा, आपदा क्षेत्र में संचार आवश्यकताओं का अनुमान लगाना मुश्किल हो सकता है। ऐसा इसलिए है क्योंकि बुनियादी ढांचे पर प्रत्येक आपदा से होने वाली क्षति अलग-अलग हो सकती है। उदाहरण के लिए, अनिश्चितताओं में शामिल हो सकते हैं :

(1) बचाव ऑपरेटरों द्वारा संचार के वैकल्पिक साधनों तक पहुंचने और स्थापित करने में लगने वाला समय, (2) पारंपरिक बुनियादी ढांचे द्वारा अनुभव की गई क्षति की मात्रा, जो उनकी कार्यक्षमता और उपयोग को नष्ट कर सकती है, (3) पीड़ितों और सक्रिय बचाव दल की संख्या जिन्हें संवाद करने की आवश्यकता है, अर्थात, आपदा क्षेत्र की जनसंख्या घनत्व।

कई वैज्ञानिकों द्वारा इस जटिलता की जांच की जा रही है, जो आपदाओं के दौरान संचार सेवाएं प्रदान करने की कोशिश कर रहे विभिन्न प्रणालियों के डिजाइन पर ध्यान केंद्रित करते हैं। यह शोध वैज्ञानिक साहित्य से हाल ही में प्रस्तावित आपदा संचार समाधानों की समीक्षा के साथ शुरू होता है। इसका उद्देश्य यह समझना है कि आपदाओं के दौरान संवाद करने के मौजूदा अभिनव तरीके कितने प्रभावी हैं? अन्य कौन सी नई प्रौद्योगिकियां मौजूद हैं? थीसिस मोबाइल तदर्थ नेटवर्क (या MANET) पर चर्चा करती है, और बताती है कि बुनियादी ढांचे के अभाव में संचार के लिए मोबाइल फोन का उपयोग कैसे किया जाता है। इन MANETs में, WiFi-Direct का उपयोग करके फोन के बीच सीधे संदेशों का आदान-प्रदान किया जाता है जो एक दूसरे के पास होते हैं। यदि फोन एक-दूसरे के करीब नहीं हैं, तो अन्य फोन का उपयोग मध्यवर्ती फोन के रूप में लंबी दूरी पर संदेशों को रिले करने के लिए किया जाता है।

शोध में पाया गया कि वर्तमान समाधान संचार के केवल परिचालन पहलू को बेहतर बनाने के लिए विभिन्न प्रकार के प्रोटोकॉल और तकनीकों का उपयोग करते हैं, जैसे कि कोई संदेश कितनी जल्दी वितरित होता है या यदि सही उपयोगकर्ता को संदेश मिलता है। हालांकि, एक बुनियादी ढांचा-रहित ऑन-डिमांड वायरलेस मोबाइल एड-हॉक नेटवर्क (एमएनेट) बनाने के लिए मोबाइल फोन का उपयोग करना कुछ चुनौतियां प्रस्तुत करता है। ये चुनौतियां हैं:

(1) यदि कोई प्रणाली जटिल है, तो कम डिजिटल रूप से शिक्षित आबादी को इसका उपयोग करना बहुत मुश्किल हो सकता है। (2) सिस्टम का उपयोग करने वाले लोगों के पास सीमित बैटरी चार्ज वाले बहुत ही बुनियादी फोन हो सकते हैं। (3) पावर ब्लैकआउट के कारण फोन चार्ज करने में असमर्थता वाईफाई-डायरेक्ट को कनेक्टेड रहने की चुनौती को बढ़ा देती है।

इन चुनौतियों को देखते हुए शोध में पाया गया कि संदेश भेजने या नेटवर्क बनाने के लिए ऊर्जा दक्षता तंत्र में

सुधार पर प्रचुर मात्रा में वैज्ञानिक साहित्य है। हालाँकि, ये सभी तंत्र वायरलेस सेंसर नेटवर्क में उपयोग किए जाने वाले दृष्टिकोणों से प्रभावित हैं। वायरलेस सेंसर नेटवर्क का उपयोग सेंसर से डेटा एकत्र करने के लिए किया जाता है, न कि आपदाओं के दौरान संचार के लिए, इसलिए आपदाओं के लिए अनुकूलित ऊर्जा-कुशल तकनीकों को डिजाइन करना महत्वपूर्ण है। एक आपदा एक बहुत ही अलग परिवेश है इसलिए आपदाओं के लिए विशिष्ट मापदंडों पर विचार किया जाना चाहिए।

आपदाओं में जिन महत्वपूर्ण कारकों पर विचार किया जाना चाहिए, वे हैं:
(1) कितने लोगों को संवाद करने की आवश्यकता है यानी, एक क्षेत्र में फंसे लोगों की जनसंख्या घनत्व,
(2) कितने लोग जो बचाव के लिए चलने में असमर्थ हैं, उन्हें संवाद करने की आवश्यकता है
(3) क्या वे लोग जिनके पास पर्याप्त बैटरी चार्ज नहीं है वे बचाव के लिए जुड़े रह सकते हैं।

ये सभी महत्वपूर्ण कारक हैं जो एक बहुत ही मौलिक भूमिका निभाते हैं। विकासशील या अविकसित देशों में बड़ी संख्या में आपदा प्रवण क्षेत्र अत्यधिक आबादी वाले हैं और प्रारंभिक अवसंरचना गायब हैं। इन क्षेत्रों में बड़ी संख्या में नागरिक गरीब, अत्यधिक आबादी वाले क्षेत्रों, तथाकथित 'असमानता के द्वीप' में फंस गए हैं। वर्तमान दृष्टिकोण जांच और परीक्षण नहीं करते हैं कि क्या उनका समाधान इन आबादी की संचार आवश्यकताओं को पूरा कर सकता है। इसलिए इन क्षेत्रों को आपदा प्रतिक्रिया टीमों के साथ जोड़ने में सक्षम होने की आवश्यकता है | इस उद्देश्य की पूर्ति के लिए, यह थीसिस एक स्व-संगठित मजबूत संचार नेटवर्क का डिज़ाइन प्रस्तुत करता है। इस शोध और थीसिस में निष्पक्ष संचार अधिकार और निरंतर संपर्क को सबसे महत्वपूर्ण आवश्यकता माना जाता है। इस लक्ष्य को पूरा करने के लिए, थीसिस डिजाइन प्रक्रिया में मूलभूत आवश्यकताओं की जांच करती है। सहभागी निष्पक्षता, समावेश और निरंतरता को तीन मुख्य गैर-कार्यात्मक आवश्यकताएं माना जाता है जो इस थीसिस में प्रस्तुत संचार प्रणाली के डिजाइन में शामिल हैं।

यह थीसिस स्वचालित स्वायत्त कंप्यूटिंग को एक दृष्टिकोण का उपयोग करता है। थीसिस एक नेटवर्क का डिज़ाइन प्रस्तुत करता है जो एक आपदा क्षेत्र में उपलब्ध फोन के जनसंख्या घनत्व और बैटरी चार्ज में बदलाव के बावजूद काम करता रहता है। यह डिज़ाइन, जिसे "सर्वाइवल के लिए स्व-संगठन" (एसओएस) कहा जाता है, चार एल्गोरिदम से बना है जो एक गतिशील आपदा क्षेत्र के अनुकूल होने के लिए एक बुनियादी ढांचा-रहित संचार नेटवर्क की आवश्यकताओं को पूरा करता है। थीसिस एसओएस में सभी मौलिक मूल्यों के वितरण को मापने और मूल्यांकन करने के लिए मूल्य-संवेदनशील डिजाइन प्रक्रिया का और शोध करती है। एसओएस व्यावहारिक रूप से सभी फोन की भागीदारी को सक्षम और बनाए रखता है, यानी फोन बैटरी शुल्क में प्रारंभिक असमानता की परवाह किए बिना, यह सभी नागरिकों के लिए समान संचार अवसर प्रदान करता है। SOS स्वचालित रूप से

(1) हाई-बैटरी फोन को हब के रूप में असाइन करता है,
(2) बदलते बैटरी चार्ज के अनुसार टोपोलॉजी को अपनाता है और बदलता है, और
(3) जब लिंक विफल हो जाते हैं या फोन नेटवर्क छोड़ देते हैं, तो स्वचालित रूप से मजबूत और विश्वसनीय बने रहने के लिए व्यवस्थित हो जाते हैं। प्रस्तावित प्रोटोकॉल के कई फायदे हैं।

सिमुलेशन मॉडल में, प्रयोगों के माध्यम से यह प्रदर्शित किया जाता है कि एसओएस बदलते परिवेश के अनुकूल है। इसका मतलब यह है कि यह बदलती परिस्थितियों में लागू होता है जहां उपकरणों के घनत्व और गतिशीलता और ऊर्जा स्रोतों की उपलब्धता में भिन्नता हो सकती है। दूसरा, कनेक्टिविटी पैटर्न में बदलाव के माध्यम से एसओएस ऊर्जा-कुशल है।

इसका मतलब है कि एसओएस को विभिन्न रूटिंग प्रोटोकॉल के साथ जोड़ा जा सकता है। तीसरा, SOS को हार्डवेयर स्तर पर किसी परिवर्तन की आवश्यकता नहीं है। इसका मतलब है कि एसओएस सभी मौजूदा फोनों पर लागू किया जा सकता है, विकासशील और अविकसित देशों में भी, बिना किसी फोन के रिकॉल या नए फोन के लिए हार्डवेयर परिवर्तन में निवेश के बिना। आगे इस शोध में, यह परीक्षण करने के लिए कि क्या प्रस्तावित डिज़ाइन सभी कार्यात्मक और गैर-कार्यात्मक आवश्यकताओं को पूरा करता है, सिमुलेशन और मॉडलिंग का उपयोग किया गया था। सबसे पहले, यह जांचना महत्वपूर्ण था कि फोन चार्ज करने का कोई तरीका नहीं होने के बावजूद संचार नेटवर्क लंबे समय तक चलेगा या नहीं। दूसरा संचार नेटवर्क सुरक्षित रूप से संदेश पहुंचा सकता है। तीसरा अगर बहुत सारे लोग इस नेटवर्क का उपयोग कर सकते हैं। यह एक एजेंट-आधारित मॉडलिंग (एबीएम) दृष्टिकोण का उपयोग करके स्थापित किया गया है। सिमुलेशन में विभिन्न क्षेत्रों में लोगों की अलग-अलग आबादी का अनुकरण किया गया। सिमुलेशन में विभिन्न बैटरी चार्ज वाले फोन के साथ आपदा क्षेत्रों में घूमने वाले लोगों का व्यवहार भी शामिल था।

पहले उल्लिखित कार्यात्मकताओं को पूरा करने के बाद, थीसिस ने मूल्यों की पूर्ति का परीक्षण किया। विशेष रूप से, मूल्य-संवेदनशील डिजाइन में भागीदारी निष्पक्षता हासिल की जानी चाहिए। एक आपदा वातावरण में भागीदारी निष्पक्षता को नेटवर्क में सभी लोगों के लिए सबसे लंबे समय तक संवाद करने में सक्षम होने के अवसर के रूप में परिभाषित किया गया है।

सहभागी निष्पक्षता का उद्देश्य यह सुनिश्चित करना है कि बैटरी चार्ज की मात्रा में असमानता के बावजूद सभी की संचार अवधि समान हो। उच्च बैटरी चार्ज वाले फ़ोन संदेशों को रिले करने के ऊर्जा-खपत कार्य को करने के लिए ज़िम्मेदार हो जाते हैं, जबकि कम बैटरी चार्ज वाले फ़ोन अब संदेशों को रिले नहीं करते हैं। यह सभी को सबसे लंबे समय तक भाग लेने की अनुमति देता है, इस प्रकार भागीदारी निष्पक्षता प्राप्त करता है। यह फिर से परीक्षण किया गया और एबीएम दृष्टिकोण का उपयोग करके साबित हुआ। इस थीसिस में जांच के तहत अन्य आवश्यकताएं समावेश और निरंतरता थीं। समावेशन से, मूल्य का अर्थ है कि नेटवर्क को उन नागरिकों को उन क्षेत्रों में कनेक्टिविटी प्रदान करनी चाहिए जो बचाव ऑपरेटरों द्वारा पेश किए जाने वाले पारंपरिक बुनियादी ढांचे की सीमा से बाहर हैं। इनमें से कुछ नागरिक चलने में सक्षम नहीं हो सकते हैं और जो नेटवर्क की सीमा से बाहर हैं वे संदेश भेजने में सक्षम हुए बिना क्षेत्रों में फंस गए हैं। इस समस्या को कम करने के लिए SOS को SOS-हाइब्रिड में सुधारा गया है।

एसओएस-हाइब्रिड बुनियादी ढांचे के बिना और नए पेश किए गए बुनियादी ढांचे के साथ काम पर स्विच कर सकता है। इंफ्रास्ट्रक्चर रेंज से बाहर के लोग एसओएस का इस्तेमाल करते हैं और इंफ्रास्ट्रक्चर रेंज के अंदर के लोग एसओएस-हाइब्रिड का इस्तेमाल करते हैं। इस तरह, संदेश वितरित किए जा सकते हैं, लगातार लोगों के बीच और बाहर के लोगों के बीच इसे समावेशी बनाते हुए। बुनियादी ढांचे की अचानक शुरूआत एसओएस डिजाइन के लिए समस्याएं पेश कर सकती है क्योंकि यह कनेक्टिविटी को बाधित कर सकती है। आखिरकार, फोन को गतिशील रूप से एक प्रोटोकॉल से दूसरे प्रोटोकॉल में स्विच करना चाहिए। एबीएम दृष्टिकोण के साथ इस थीसिस में सेवा की निरंतरता का भी परीक्षण किया गया और साबित किया गया।

इन प्रदर्शनों के माध्यम से, यह शोध प्रबंध इस सवाल का एक संभावित समाधान दिखाता है कि एक आवश्यकता आधारित नागरिक-केंद्रित मजबूत मोबाइल संचार प्रणाली को कैसे डिजाइन किया जाए जो पर्यावरण की जरूरतों के अनुसार बदलती है|

PUBLICATIONS

1. Banerjee, Indushree, MartijnWarnier,and Frances M T Brazier. "***Revisiting citizen-centric disaster communication: A systematic review.***" (Under review)

2. Banerjee, Indushree, Martijn Warnier, and Frances M T Brazier. "***Designing inclusion and continuity for resilient communication during disasters.***" Sustainable and Resilient Infrastructures, (2022): 1-16.

3. Banerjee, Indushree, Martijn Warnier, Frances M T Brazier, and Dirk Helbing. "***Introducing participatory fairness in emergency communication can support self-organization for survival.***" Scientific reports 11, no. 1 (2021): 1-9.

4. Banerjee, Indushree, Martijn Warnier, and Frances M T Brazier. "***Self-organizing topology for energy-efficient ad-hoc communication networks of mobile devices.***" Complex Adaptive Systems Modeling 8, no. 1 (2020): 1-21.

5. Banerjee, Indushree, Martijn Warnier, and Frances M T Brazier. "***Ad Hoc Communication Topology Switching during Disasters from Altruistic to Individualistic and Back.***" In COMPLEXIS, pp. 103-107. 2020.

6. Perera, I., Choudhury, J., and Banerjee, I., "***Educating users for disaster management: An exploratory study on using immersive training for disaster management.***" 2013 IEEE International Conference in MOOC, Innovation and Technology in Education (MITE). IEEE, 2013

7. Banerjee, I., Perera, I., and Choudhury, J., "***Introducing immersive technologies for learning: A study evaluating the readiness for using virtual worlds for learning and teaching in an Indian University.***" 2013 Sixth International Conference on Contemporary Computing (IC3). IEEE, 2013.

8. Choudhury, J., and Banerjee, I., "***Progressing the security landscape of cloud by incorporating security service level agreement (Sec-SLA).***" Proceedings of the First International Conference on Intelligent Computing and Communication. Springer, Singapore, 2017

9. Banerjee, I., Perera, I., Nag, A. and Choudhury, J., "***Incorporating smart software-defined networks to enhance resilience and survivability in the cloud: survey of current challenges and future research scopes.***" Smart Computing Review, 5(4), 2015,. pp.308-317.

10. Choudhury, J, and Banerjee, I., "***Programming in virtual worlds for educational requirements: LSL scripting and environment development challenges.***" International Journal of Computer Science Research and Application 2.3 (2012): 30-41.

Acknowledgements

Often one is questioned about what matters the most, the journey or the destination. In my opinion, it's the company.

In 2016, I got accepted to TU Delft to do a PhD under the supervision of Prof Frances Brazier, Prof Martijn Warnier and Prof Dirk Helbing. I remember seeing the position and reading about it one day before the deadline. I was very intimidated by the entire set of requirements. My father encouraged me to apply, jokingly saying, "at most, it will end up in the rejection pile, but you don't fear rejection, do you?". So, I applied, and here I am. When I was informed that it was Martijn, Frances and Dirk as my supervisory team, I knew I was going to work with the best in the field.

Martijn, being my daily supervisor, had the most impact on me and my work, as I got to spent the maximum amount of time with him brainstorming ideas and concepts. This PhD in every form results from his faith in giving me space. From the very beginning, Martijn insisted that I create my niche, that I talked back, that I argued and questioned and debated. Martijn, you also ensured that I took my holidays, was happy, and felt safe and comfortable. You nurtured every idea that I threw your way. You made it clear that I was the boss of my efforts and failures. So, you neither took credit for any success nor judged me harshly for my failures. Martijn, over the years, you have become my mentor, friend, and support. I will never forget that you forced me to take a six months' leave of absence after falling sick. You were always available and still are to this date. I do not think using the words thank you sums up my admiration and gratitude. It has been a privilege to learn from you and to be your PhD candidate.

Prof Brazier is the first woman scientist I know personally. Prof Brazier taught me the art of framing and the power of saying "I do not understand". I am amazed how she effortlessly, without any inhibition, can ask to explain the most complex designs and concepts. Prof Brazier, you have taught me that we understand science ourselves only when we can explain science in the most elementary manner. I have learnt that the power of asking "I do not understand" is not a sign of limited knowledge but a tool to exercise our right to gain access to expertise objectively. With you I have learned to be assertive and engaging. You reached out to me even when you were on a holiday to ensure I was doing well, you were protective, affectionate and patient. You inspire me every day.

Prof Helbing, without you, this PhD position would not have happened. You had a fantastic vision, and the idea of a digitally responsible society led not just me but the 6 other PhDs to TU Delft. Thank you for selecting me and putting me in this eclectic group of PhDs. I had the opportunity to work with you on my second paper, and it is undoubtedly currently my favorite paper. I enjoyed my time in the summer schools discussing my ideas with you and receiving your in-depth feedback; thank you for pushing me to aim higher. Through countless unfiltered, unbiased, critical assessment of my work, all three of you have trained me to be scientifically meticulous, analytical and perceptive. Every individual meeting has significantly improved my scientific acumen and made me a better scientist.

I also had the privilege of having a group of excellent independent committee members assess my work for the obtainment of this PhD. I would like to express my gratitude to Prof Tina Comes, Prof Simon Dobson, Prof Rob Vingerhoed and Prof Jeroen van de Hoven.

Most PhD journeys are presented as very isolated. They are in many ways; however, in my case, I was fortunate to be surrounded by tremendously inclusive people. Liberal, generous, funny and kind are common traits of my friends and colleagues that I made in TU Delft. Starting with Selma, with whom I shared my office. Selma and I shared a space that was safe to discuss everything that went through our minds as we delved through paper rejections, marriage, family and grief while doing a PhD. I also shared my room later with Supriya. Supriya brought her beautiful flare for the Indian culture that I only knew I was missing when I shared the room with her. I thank you both for being so open and always being so accommodating.

I also had the pleasure of knowing and sharing everyday lunch with Yilin, Iulia, Angelo, Geertje, Isabella, Vasiliki, Stefan, Igor, and Natalie. You all made me feel like I was home as you accepted my eccentricities graciously. Thank you for making me an integral part of this big systems engineering family. My working late partners Nina, Xavier, Rado, Vittorio, and Kusnander, you all motivated me to keep going. You are all very dedicated scientists, and you all shared your paper rejections, debugging irritations and coding failures to make sure I felt comfortable. Thank you for being vulnerable.

Esther, Wendela, and Everdine, our outstanding secretaries, always ensured that I felt I was in a place of positivity. I am one of the few lucky people who hardly had to wait for appointments. I am amazed by how much you made my life easy and smooth. Thank you. Apart from System engineering, the graduate school made sure I met a lot of exciting PhD candidates who started with me. I am happy I met Anna, Alexia, Amir, Rijk, Annabeth, Filip, Rishab, Grace, Ionna, Moolud, Javanshir, Weronika, Diego, Shantanu, Chirag, Kees, Wenting Ma, Bijan, Qasim, Sharzad and Wenhua. You introduced me to many cultures and made me a better person through your conversations and shared experiences, thank you. Janine, who heads the graduate school, has always been available for the numerous emails that I have sent her way, thank you for being patient and always finding solutions.

TPM in general also ensured that I got enough opportunity to shine, and for that I would like to thank Tanja Emonts our communication expert who made sure that my work was featured and covered. Thank you for seeing such value and for teaching how to present myself. A special shout out to Soren Johnson for teaching the art of writing science for a general audience.

More than research experience and training as a scientist, I have received the gift of friendship in these years. Amit, Vittorio, Fernando, Francesco, Niranjan & Sahil, Sergei, Sameer, Pritish & Sai, Rado; you have reinstated my faith in dependable men who listen. I think it has been innumerable occasions where you have rescued me from a situation. Sai, you stayed outside the building when I got locked inside TPM on a weekend until I was out and I know that you are simply a call away.

Niranjan and Sahil, you made me laugh on days when life felt unlivable. Pritish and Sameer, you fed me on days when all I could do was complain about my models not working. Amit, Vittorio, Fernando and Sergei, you were always available to listen to me. Francesco, you are one of my very few dear friends who always makes sure to reach out and have always ensured that I knew that I was important. Rado, the number of walks, coffees and bear hugs that I have received from you have been a major source of positive energy in the last years of finishing the thesis. Thank you all for being dependable friends, I am very grateful for your generosity and encouragement. Your presence made my time in Delft memorable.

Marina, Clara and Christine are the three girlfriends that I think I have gained permanently for life. Marina, you are the purest person I know. You are my ethical soundboard. You protected me and showed me the mirror whenever I needed it. You are the person who visited the library for me on weekends and introduced me to the joys of cycling in the Netherlands. You held me accountable and reminded me of my strengths when I doubted myself. You taught me the power of surrender and prayers. I am forever indebted to you for your guidance and compassion. Thank you.

Clara, in the early days of making Delft my home, you played a very significant role. With you I learnt the similarities of our culture and with you I shared the pain of missing family. Thank you for being generous with your time and empathy whenever I was homesick.

Christine, you introduced me to the carnival of life. I was amazed that you became my tango partner so that I could learn to dance. You took me to jazz festivals, we celebrated new years and we cooked and ate. You and Michael took me in when I needed your company. With you I learned to relax and take life slow and learnt to celebrate each milestone. We travelled together, and on many ups and downs of life, I found you next to me, comforting and ensuring my well being. I will forever be indebted for your friendship. You are my confidante, my dear friend for life.

I believe a PhD journey requires both mental and academic preparation, and usually, the prerequisites are developed way before one embarks on the journey. After all trees that grow the tallest have the deepest roots. My PhD has been one of the most challenging and fulfilling works that I have ventured till date. I had the privilege of being born to two very stubborn, passionate, kind and hopeful people. Maa, Baba you instilled in me from an early age the drive, dedication and determination to adapt, which I needed the most for this PhD. My parents are value-oriented people who made me believe in the power of dedication. Context-awareness and self-organisation are two approaches used in this thesis. In my life however these approaches have been instigated from an early age. Maa, Baba, thank you for being my parents and teaching me the beauty of being mindful and adaptive self-reliance for flourishing in life.

During my PhD. I experienced both love and loss. I lost my grandparents, whom I dearly miss and will always be thankful for making me know that I was special.
My childhood consisted of a lot of time spent with my grandparents, Dida & Dadu.

Dida taught me to be brave. I am the first person in my family to get a Master's and PhD degrees abroad. So, I did not have any members as such to encourage or lead me the way. Dida used the word bravery and loyalty interchangeably. She was the first in her family to leave at 16 to become a teacher. As a kid, I used to accompany her to these government schools that used to be flooded each monsoon. In her very neatly pleated saree, she would sit at a desk and give lessons while I doodled. I hated paddling through the murkier waters to reach her school with her, where she taught the poorest kids in the community. I often complained and questioned why she bothered, why not skip the days when my tiny boots were wet and stinking. She used to tell me the kids needed her loyalty, so she needs to be brave. The kids needed to know the importance of education, so she needed to be committed. I learned loyalty from her, which was a massive help in the Netherlands' cold, dark rainy days. It pulled me through my neck hernia, as I remembered that I need to be loyal to my PhD, irrespective of how difficult things get. So even though she left us a few months ago forever, she will always remain my guiding post. Thank you, you taught me when we love things and do them against all odds, we become loyal and that on many occasion is brave.

Dadu, I am sure you would have been proud to see me finish this thesis. I am very sad that you passed away before it was finished. I grow to appreciate your wisdom more and more with every passing year, and I would love to speak with you once more. I was very happy to include your teachings as epigraphs starting each chapter.

I am happy both Dida and Dadu met Joost, Louis and Liesbeth. From opening your home to driving to Delft, Louis and Liesbeth ensured that I was comfortable. Thank you for your generosity.

A special thank you to Arya Vaidyashala in Kottakal, that healed my hernia with their holistic approach without surgery and to Vera, my therapist. Vera, you helped with my emotional state that led me to do research while experiencing joy, love, success and desires. With you I have realized that kindness and acceptance of self is the only way forward towards loving others. Thank you.

Lastly, in 2020 when the world went into isolation, I found my sister and my soulmate living with me. Sritama, you are and always will be my one true advocate. You made sure that I went back to work effortlessly. While doing your Master's, you took charge of my food, mood, and whims. We quickly became the three musketeers, and I will forever be grateful for your devotion towards the stretch of this PhD where I finished the thesis. You are my champion, my blessing, my privilege.

As I compile this journey, I look at you, Joost, my north star. You are my constant companion towards home that does not always represent a known location filled with childhood memories, but a constant journey that facilitates growth and acceptance of one's current self. Thank you for belonging to me and for letting me belong to you. With you I have experienced the joys of *dolce far niente*, with you every day is a festival. You are the highlight of my life.

Indushree

Indushree Banerjee is a postdoctoral researcher at the Department of Water Resource Management in Civil Engineering and Geosciences, TU Delft, where she studies the impact of climate change in the Terai region of Nepal and the inter relationships between river dynamics, groundwater, land cover and land use, and tigers.

In 2016 Indushree was selected to do her PhD in Complex Systems Engineering at TU Delft within the "Engineering Social Technologies for a Responsible Digital Future" programme. Her work was featured in the New Scientist and Computer World Magazine. Her designed system was nominated for the Best tech Idea of 2021 by KijK and was awarded the second prize.

Indushree did her Bachelor's in Computer Science and Engineering at the West Bengal University of Technology, India, and her Master's in Networks and Distributed Systems at the University of St Andrews, Scotland, where she was invited with a full scholarship.

Indushree was born in Kolkata (1988) and grew up in the rural parts of Bihar and Jharkhand, India, travelling with her family. She currently lives in Amsterdam with her husband and two cats.


TU Delft