# A P4 Data Plane for the Quantum Internet

Kozlowski, W.; Kuipers, F.A.; Wehner, S.D.C.

**DOI**
10.1145/3426744.3431321

**Publication date**
2020

**Document Version**
Final published version

**Published in**
EuroP4 2020 - Proceedings of the 3rd P4 Workshop in Europe, Part of CoNEXT 2020

# A P4 Data Plane for the Quantum Internet

Wojciech Kozlowski[1,2], Fernando Kuipers[3], and Stephanie Wehner[1,2]
[1]QuTech, Delft University of Technology, Delft, The Netherlands
[2]Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands
[3]Delft University of Technology, Delft, The Netherlands
{w.kozlowski,f.a.kuipers,s.d.c.wehner}@tudelft.nl

## ABSTRACT

The quantum technology revolution brings with it the promise of a quantum internet. A new — quantum — network stack will be needed to account for the fundamentally new properties of quantum entanglement. The first realisations of quantum networks are imminent and research interest in quantum network protocols has started growing. In the non-quantum world, programmable data planes have broken the pattern of ossification of the protocol stack and enabled a new — software-defined — network software architecture. Similarly, a programmable quantum data plane could pave the way for a software-defined quantum network architecture. In this paper, we demonstrate how we use $P4_{16}$ to explore abstractions and device architectures for quantum networks.

## CCS CONCEPTS

• **Networks → Programmable networks**; **Programming interfaces**; • **Hardware → Quantum communication and cryptography**.

## KEYWORDS

quantum internet, quantum networks, quantum communication, quantum data plane, P4, programmable networks

**ACM Reference Format:**
Wojciech Kozlowski, Fernando Kuipers, and Stephanie Wehner. 2020. A P4 Data Plane for the Quantum Internet. In *3rd P4 Workshop in Europe (EuroP4'20), December 1, 2020, Barcelona, Spain.* ACM, New York, NY, USA, 3 pages. https://doi.org/10.1145/3426744.3431321

## 1 INTRODUCTION

The idea of a quantum internet has been around for some time [3, 10] and in the last few years physicists have made significant progress towards building the first long-range quantum networks [5, 11, 12]. As the hardware grows in maturity, research interest in software and network architectures for a quantum internet has also been growing [4, 6, 8]. Software-defined networking (SDN) concepts have even already been applied to quantum key distribution (QKD) networks [2]. However, these networks are single-purpose and are not designed for applications beyond QKD. SDNs for more general quantum networks based on quantum repeaters [10] have not yet been considered. Recent advances in non-quantum (classical) networking have shown that programmable data planes offer a powerful foundation for SDNs [7]. A programmable quantum data plane could similarly provide the building blocks for a software-defined quantum network (SDQN) architecture.



*EuroP4'20, December 1, 2020, Barcelona, Spain*

ACM ISBN 978-1-4503-8181-9/20/12.
https://doi.org/10.1145/3426744.3431321

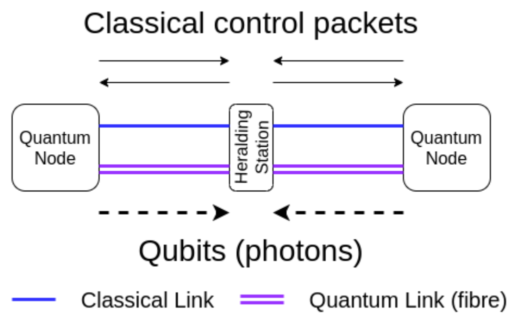


**Figure 1: The heralding station upon simultaneous receipt of photons "heralds" the success or failure of an attempt.**

In this paper, we present a software package [1], developed for NetSquid [9], to run P4 programs on a simulated quantum network. NetSquid is one of the most realistic quantum network simulators and has already been used to validate new quantum protocols [4]. NetSquid's accurate results and rich library of hardware models mean that P4 programs validated in simulation can later be ported to real quantum hardware by making the device P4 programmable. We demonstrate how we use this package to explore quantum data plane abstractions by implementing a recent quantum protocol [4] in P4. Quantum networks are complex and generally require advanced knowledge of quantum mechanics. With our P4 package, we start abstracting these low-level details behind quantum device architectures. In addition to laying the foundation for SDQNs, this could also make quantum protocol design more accessible.

## 2 DOMAIN-SPECIFIC LANGUAGE

Classical networks deliver packets from a source to a destination. Quantum networks distribute quantum entanglement between two or more nodes. Entanglement is a special state of two or more quantum bits (qubits) in which the individual qubits cannot be described independently of the others across, in principle, arbitrary distances. It is the key ingredient for long-distance quantum communication, because an entangled pair of qubits can be used to teleport (transmit) arbitrary quantum data.

An entanglement based programmable data plane will most likely need its own domain-specific language (DSL), just like P4 was created as a DSL for packet data planes. However, whilst entangled qubits are the fundamental unit of quantum networks, all protocol control information (i.e. headers) is transmitted in classical packets [4], which could be easily processed by a P4 program. Thus, the P4 language offers a convenient starting point for programmable quantum data planes. The $P4_{16}$ language has two additional features that make this a practical approach. First, $P4_{16}$ allows the vendor to provide a custom architecture-specific API, which allows us to define a new architecture that can support a quantum network stack. Second, P4 has a sizeable ecosystem of open-source software, such as P4Runtime and ONOS, that will facilitate the deployment of the first experimental SDQNs.

## 3 ARCHITECTURE OF A QUANTUM NETWORK PROTOCOL

For our demonstration, we have implemented the Midpoint Heralding Protocol (MHP) [4]. The architecture of the link is shown in Fig. 1. The MHP is responsible for the individual attempts to generate entangled pairs of qubits between two neighbouring nodes. It is a lightweight protocol that, together with quantum hardware, constitutes the lowest (i.e. physical) layer of a quantum network. The next layer in the quantum protocol stack (the link layer) uses the physical-layer protocol to keep making attempts until entanglement generation succeeds to provide a robust entanglement generation service for the end-to-end quantum network layer service. End-to-end entanglement between two hosts connected to a quantum network is generated by combining many such link-pairs using a process called entanglement swapping [3], but end-to-end connectivity is beyond the scope of this demonstration.

On each attempt (synchronised between the nodes using a hardware clock and protocol), the two nodes each emit a photon towards a midpoint station that is placed in between the two nodes. This midpoint, also called the heralding station, stochastically succeeds or fails in the entanglement attempt and "heralds" the result back to the nodes. If the attempt was successful the two nodes now each have a qubit that is entangled with its counterpart at the other node. The MHP will also send a classical message along with the photon towards the midpoint carrying control information about the photon. The heralding station responds to this message with a success or failure or an error notification if the control information from the two nodes was found to be inconsistent.

## 4 ENTANGLEMENT GENERATION IN P4

To implement the MHP in $P4_{16}$, we wrote two programs: one for the two nodes on either side of the link and one for the heralding station. We also defined a new architecture by extending the *v1model* with extern functions for sending qubits (photons) and multicasting the heralding response from the midpoint. The P4 pipelines are illustrated in Fig. 2. The MHP protocol triggers based on a hardware timer that injects a pseudo-packet on port 0 at regular intervals. These packets carry a cycle number that is incremented with every attempt. The P4 program then performs a table lookup to determine the parameters of the request for this cycle. If the lookup results in a hit, a photon is emitted on the quantum interface indicated in the request using one of the new extern functions. Additionally, the program appends the request information to the timer packet

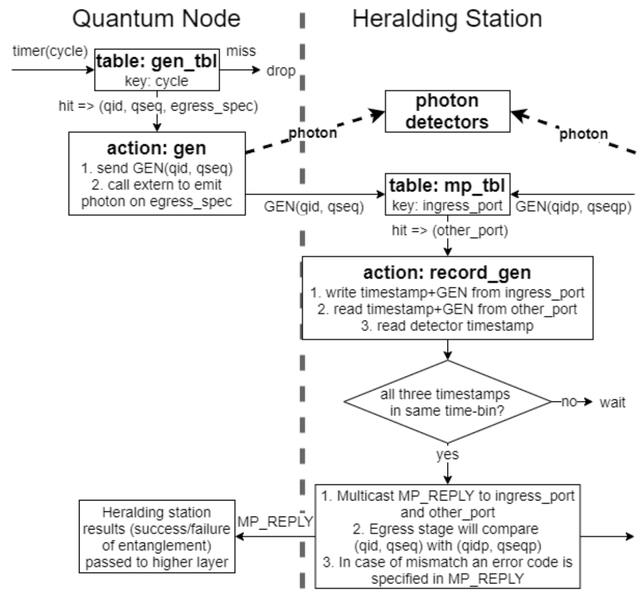


**Figure 2: The node upon receipt of the timer pseudo-packet looks up its `gen_tbl`. A hit yields the parameters for the attempt and the node sends a photon and a GEN packet. The heralding station must wait for a GEN packet from both sides before it can send an `MP_REPLY`. The `mp_tbl` provides the `other_port` value as one heralding station can serve more than two nodes. For clarity not all pathways are shown.**

and forwards it via the classical interface paired with the quantum interface on which the photon was emitted.

The heralding station program is more complicated as it must correlate three messages. First, the photons will trigger a success/failure notification from the hardware detectors. Second, the two MHP packets will arrive on either side with control information that must be processed by the midpoint. The P4 program achieves this by saving the packet content and the arrival time into P4 registers. Once recorded, it uses the timestamps to check if the other two messages were received in the same time bin. If so, it multicasts a response to the two nodes with an indication of success/failure.

## 5 CONCLUSIONS

We have presented a software package [1] for running P4 programs on a simulated quantum network and we have given an example of an implementation of a recent quantum network protocol. We plan to use this framework to explore quantum device architectures and quantum network abstractions with the intention of developing a software-defined architecture for quantum networks.

## ACKNOWLEDGMENTS

We would like to thank Belma Turkovic for helpful discussions. We are also grateful to Bruno Rijsman for technical discussions and contributions to the source code of the package.

This work was supported by the EU Flagship on Quantum Technologies, Quantum Internet Alliance (No. 820445) (WK, SW), an ERC Starting Grant (SW), and an NWO VIDI Grant (SW).

# REFERENCES


[1] 2020. Quantum P4 Snippet for NetSquid. https://gitlab.com/softwarequtech/netsquid-snippets/netsquid-qp4

[2] Alejandro Aguado, Victor López, Juan Pedro Brito, Antonio Pastor, Diego R. López, and Vicente Martin. 2020. Enabling Quantum Key Distribution Networks via Software-Defined Networking. In *2020 International Conference on Optical Network Design and Modeling (ONDM)*. 1–5. https://doi.org/10.23919/ONDM48393.2020.9133024

[3] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller. 1998. Quantum Repeaters: The Role of Imperfect Local Operations in Quantum Communication. *Physical Review Letters* 81, 26 (Dec. 1998), 5932–5935. https://doi.org/10.1103/PhysRevLett.81.5932

[4] Axel Dahlberg, Matthew Skrzypczyk, Tim Coopmans, Leon Wubben, Filip Rozpędek, Matteo Pompili, Arian Stolk, Przemysław Pawełczak, Robert Knegjens, Julio de Oliveira Filho, Ronald Hanson, and Stephanie Wehner. 2019. A link layer protocol for quantum networks. In *Proceedings of the ACM Special Interest Group on Data Communication (SIGCOMM '19)*. Association for Computing Machinery, New York, NY, USA, 159–173. https://doi.org/10.1145/3341302.3342070

[5] Peter C. Humphreys, Norbert Kalb, Jaco P. J. Morits, Raymond N. Schouten, Raymond F. L. Vermeulen, Daniel J. Twitchen, Matthew Markham, and Ronald Hanson. 2018. Deterministic delivery of remote entanglement on a quantum network. *Nature* 558, 7709 (June 2018), 268–273. https://doi.org/10.1038/s41586-018-0200-5 arXiv: 1712.07567.

[6] Takaaki Matsuo, Clément Durand, and Rodney Van Meter. 2019. Quantum link bootstrapping using a RuleSet-based communication protocol. *Physical Review A* 100, 5 (Nov. 2019), 052320. https://doi.org/10.1103/PhysRevA.100.052320 Publisher: American Physical Society.

[7] Larry Peterson, Carmelo Cascone, Brian O'Connor, and Thomas Vachuska. 2020. Software-Defined Networks: A Systems Approach — Software-Defined Networks: A Systems Approach Version. https://sdn.systemsapproach.org/

[8] A. Pirker and W. Dür. 2019. A quantum network stack and protocols for reliable entanglement-based networks. *New J. Phys.* 21, 3 (March 2019), 033003. https://doi.org/10.1088/1367-2630/ab05f7 Publisher: IOP Publishing.

[9] QuTech. 2020. NetSquid. https://netsquid.org/

[10] Rodney Van Meter. 2014. *Quantum Networking*. ISTE Ltd/John Wiley and Sons Inc, Hoboken, NJ.

[11] Juan Yin, Yuan Cao, Yu-Huai Li, Sheng-Kai Liao, Liang Zhang, Ji-Gang Ren, Wen-Qi Cai, Wei-Yue Liu, Bo Li, Hui Dai, Guang-Bing Li, Qi-Ming Lu, Yun-Hong Gong, Yu Xu, Shuang-Lin Li, Feng-Zhi Li, Ya-Yun Yin, Zi-Qing Jiang, Ming Li, Jian-Jun Jia, Ge Ren, Dong He, Yi-Lin Zhou, Xiao-Xiang Zhang, Na Wang, Xiang Chang, Zhen-Cai Zhu, Nai-Le Liu, Yu-Ao Chen, Chao-Yang Lu, Rong Shu, Cheng-Zhi Peng, Jian-Yu Wang, and Jian-Wei Pan. 2017. Satellite-based entanglement distribution over 1200 kilometers. *Science* 356, 6343 (June 2017), 1140–1144. https://doi.org/10.1126/science.aan3211 Publisher: American Association for the Advancement of Science Section: Research Articles.

[12] Yong Yu, Fei Ma, Xi-Yu Luo, Bo Jing, Peng-Fei Sun, Ren-Zhou Fang, Chao-Wei Yang, Hui Liu, Ming-Yang Zheng, Xiu-Ping Xie, Wei-Jun Zhang, Li-Xing You, Zhen Wang, Teng-Yun Chen, Qiang Zhang, Xiao-Hui Bao, and Jian-Wei Pan. 2020. Entanglement of two quantum memories via fibres over dozens of kilometres. *Nature* 578, 7794 (Feb. 2020), 240–245. https://doi.org/10.1038/s41586-020-1976-7 Number: 7794 Publisher: Nature Publishing Group.