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DOI
10.23919/URSI-EMTS.2019.8931469

Publication date
2019

Document Version
Final published version

Published in
2019 URSI International Symposium on Electromagnetic Theory, EMTS 2019

Citation (APA)
Roederer, A. G., & Yarovoy, A. G. (2019). Semi-active multiple beam arrays. In *2019 URSI International Symposium on Electromagnetic Theory, EMTS 2019* Article 8931469 (2019 URSI International Symposium on Electromagnetic Theory, EMTS 2019). IEEE. https://doi.org/10.23919/URSI-EMTS.2019.8931469

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URSI EM Theory Symposium, EMTS 2019, San Diego, CA, 27– 31 May 2019

Semi-Active Multiple Beam Arrays

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Abstract

The low power efficiency (5-15%) of solid state power amplifiers, working in back-off to guarantee a good linearity, could become the show stopper for some future space and terrestrial communication ventures at Ka-band and above. Semi-active reflector and conformal antennas, using Butler-like matrices between the power amplifiers and the feed elements, were first introduced to directly generate flexible multiple beams most efficiently.
For linear and planar arrays, such phase-only control at power amplifier inputs can provide beam zooming or amplitude tapering, but no proper beam steering. The paper discusses and analyses the extension of the semi-active principle to linear and planar arrays, by use of multiport amplifiers with amplitude and phase input control to power the elements most efficiently.
Performances and limitations of such systems are analyzed and demonstrated for a few examples.

1. Introduction

Efficient spectrum re-use requires multiple beams with low side lobes and power-to-beam flexibility. They can be generated by reflectors or by arrays. Low power efficiency of linear amplifiers with tapered amplitudes is the key problem and has serious thermal control implications.
The semi-active concept, with Butler-like matrices inserted between the power amplifiers (PA's) and the feed elements, was introduced by ESA in the 80's to help improve efficiency and flexibility for array fed reflector antennas The RF power of each beam is moved in the focal plane of a reflector [1] or similarly around a conformal array [2], to create multiple shaped beams. Flexible power to beam allocation and side lobe control are provided with all equally powered amplifiers and thus optimum power efficiency.

For semi-active reflector or conformal antennas, RF power is directed by the matrices to the part of the radiating elements generating each beam. This is done by proper phase-only control of signals at the inputs of the PA's preceding the matrices. If a large number of uncorrelated simultaneous channels is transmitted, all PA's, fed with a superposition of signals, all with the same uniform amplitudes, can be loaded close to their nominal power.

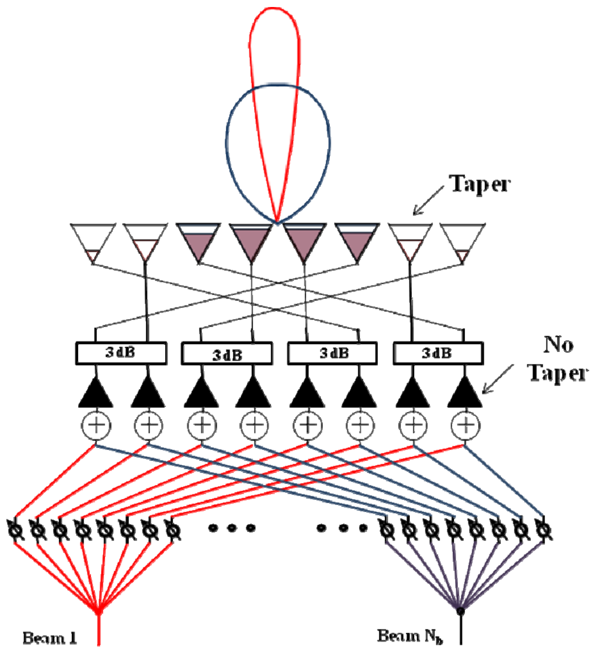

Figure 1. Semi-active array with phase only control.

This concept has been used world-wide for multiple beam reflector antennas of communication satellites, starting with INMARSAT III [3] and also for some conformal arrays, such as the electronically de-spun data transmission phased array antenna presently onboard the ESA GAIA spacecraft [4].
In [2], mostly focusing on conformal arrays, semi-active linear and planar arrays are also mentioned and the configuration in Figure 1 (here with 3 dB hybrids) is described.
A key difference with reflector feed arrays or with conformal arrays is that, here, all or most of the radiating elements, rather than a few, typically contribute to each beam.
The phase-only control at the PA inputs essentially translates into amplitude control at the elements, with the constraint that the total power out of every matrix to the elements it feeds should be the same.

The concept is applicable to beam zooming, as proposed in [5] for satellites with highly elliptical orbits and where the zooming is achieved by progressively extending the power distribution over the array using 4x4 Butler-like matrices. Contoured beams can also be generated but not scanned beams.
In [6], the authors also notice this limitation. They propose to use the properties of an equiangular triangular lattice and semi active feeding with 3 dB couplers connected to elements with a specific separation to generate a grid of multiple fixed beams with low side lobes in frequency re-use areas.

With the availability of compact RF, digital or hybrid beam forming IC technology, it becomes possible to implement, at low level, amplitude and phase rather than phase-only control. Then, in order to keep all the PA powers equal for best efficiency, additional Butler-like matrices (or 3dB hybrids in the case of Figure 1) need to be added before the PA's, making up "Multiport Amplifiers" (MPA's).

2. Semi-Active arrays with amplitude and phase control

An MPA, here with two amplifiers, is shown in Figure 2.

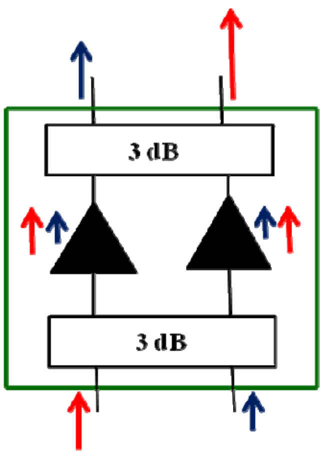

Figure 2. 2x2 Multiport amplifier

It has the property that a signal fed at its left input port is split in 2 signals with equal powers and comes out amplified and intact at the top right port. The same applies at the right input port.
When a number of uncorrelated signals are applied at the input ports, each will come out amplified of one output port. All PA's will have similar average loadings, with, as a result, optimum power efficiency. The MPA fed semi-active configuration is shown in Figure 3.
Unlike in Figure 1, it is clear that radiating elements could be provided for each beam with the desired signals in amplitude and phase, as with a tapered active array.
As in the phase-only configuration, the constraint remains that the total power out of every matrix to its elements should be the same. This will be shown to be tolerable in the examples of the next section.

Performance will be close to that of a multi-beam active array, but with all amplifiers operating close to nominal conditions and thus with optimum power efficiency.

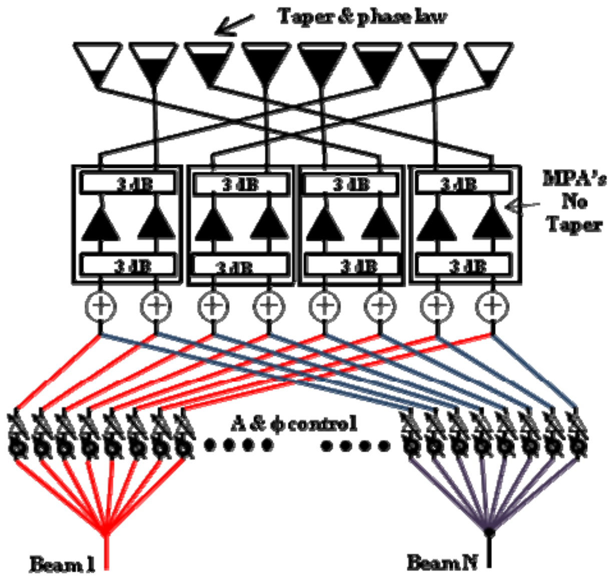

Figure 3. Semi-active array fed by multiport amplifiers

3. Semi-Active linear array example

The configuration of Figure 3 has been analyzed and optimized for an array of 24 elements with 2λ spacing which must be capable of scanning independently 24 low side lobe beams over a field of view of +/- 10^0, typical in space telecommunications.
Wider fields of view could equally be served using smaller antenna element.
A modified Taylor distribution, with 25 dB as the first side lobe level, is taken as reference and will be approximated using the multiport amplifier based configuration of Figure 3.
Figure 4 shows the reference modified Taylor distribution in blue and the achieved one in green taking the constraint of equal total powers to paired elements into account.

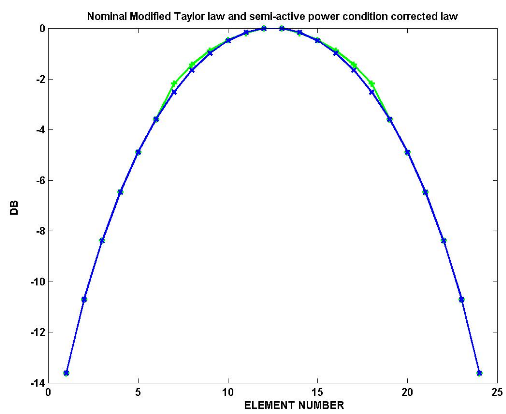

Figure 4. Array nominal modified Taylor law (blue) v.s. semi-active power condition corrected law (green)

The resulting beams, scanned towards 24 randomly located uncorrelated users, are shown in Figure 5. The 25 dB target for side lobes is met and could be lowered further.

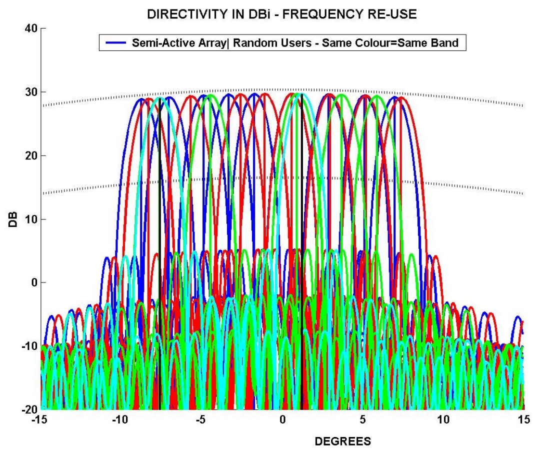

Figure 5. Beams from the multi-matrix array scanned towards 24 users randomly located in the field of view

Figure 6 shows, for the 24 uncorrelated users, the average power levels for the 24 amplifiers of the semi-active array (green) and for the reference modified Taylor distribution (blue) for the active array. The semi-active design reduces the range of powers to around 1 dB with a large impact on the efficiency of the amplifiers.

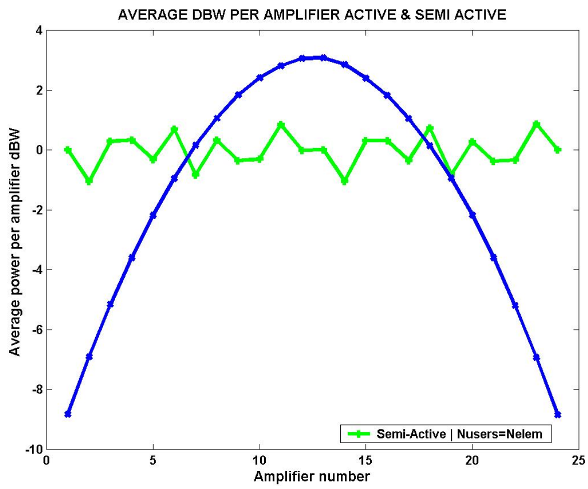

Figure 6. Semi-active array: average power levels for the 24 PA's (green) and reference modified Taylor law (blue) for the active array.

4. Semi-active planar array example

As indicated in the previous section, creating an amplitude taper using 3 dB couplers in a linear array is achievable by pairing elements as shown in Figures 1 and 3. In the case of a planar array, there are not enough elements in the center to pair with the more numerous elements at the periphery. Use of higher order Butler-like matrices would help, but at the cost of additional hardware and losses.

What is proposed here is an array with some space tapering in the center part and a combination of space and semi-active tapering for outer elements.
The optimization aims at matching the resulting equivalent taper to the ideal Taylor-like law for 25 dB side lobes over the field of view.
The elements are arranged on rings to enhance circular symmetry of the beams, with the outer ones grouped in a large number of radial linear sub-arrays (spikes) of 4 or 6 elements in pairs, each connected to a 3 dB coupler or a 2x2 multiport amplifier. Spike sub-arrays are identical and modular. For low frequencies (L or S band) they could be hinged and folded to limit the array diameter during launch.
A drawing of such an array is shown in Figure 7 with highlighted a typical spike sub-array detailed in Figure 8.

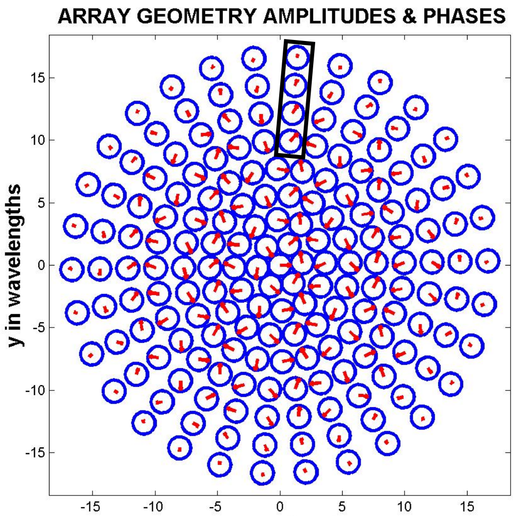

Figure 7. Configuration of a 181 element array with space and semi-active tapering

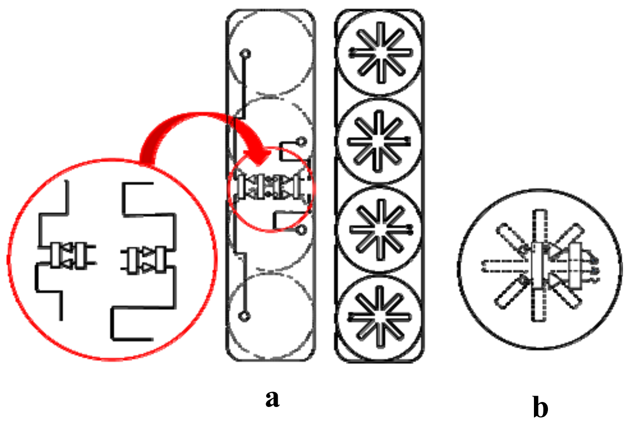

Figure 8. a) Panel of four 1.8λ dual and two MPA's (Figure7)
b) Single central element with 1 MPA

For a field of view of +/- 9° and at L or S band frequencies in circular polarization, 1.8λ dual CP cross elements [7] could be an element candidate, possibly with some sequential rotation applied.

A pattern cut through the peak of a beam scanned to 9º from bore sight is shown in Figure 9. Side lobes in the +/- 9º cut are below 25 dB. Peak directivity at 9º is 35.7 dB for 181 elements.

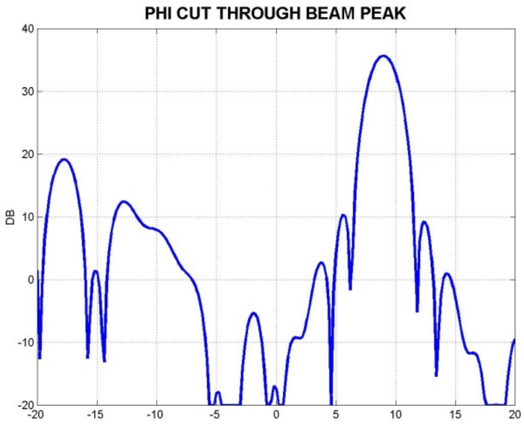

Figure 9. Pattern cut for a most scanned beam

Figure 10 shows an iso-directivity contour plot for the same beam pointed to the edge of the Earth coverage from a geostationary orbit.
The goal side lobe level of 25 dB is not exceeded, with over 30 dB level in most of field of view.

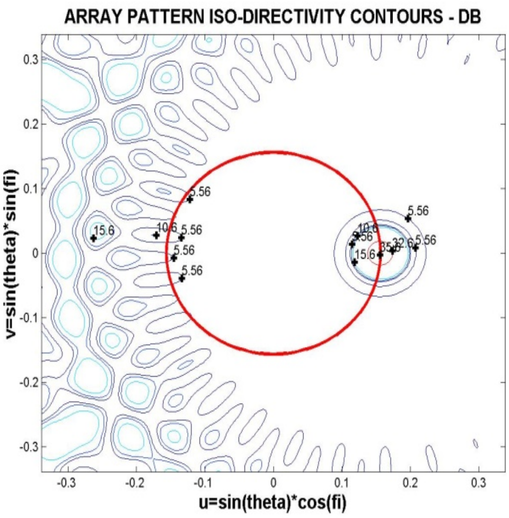

Figure 10. Contour plot for a most scanned beam

As for the linear array, when a sufficiently large number of simultaneous uncorrelated channels is transmitted by the array, all amplifiers will operate at approximately the same average power level, thus with the best efficiency. This is illustrated in Figure 11, for 32 uncorrelated channels transmitted in 8 sub bands by the array of Figure 7.
In Figure 11, average PA powers across a diameter of the array are shown in green and compared to the active array tapered law in blue.
In the semi-active case, the range for the power loadings of all power amplifiers is reduced to around 1 dB with, as a result, a dramatic increase of their power efficiency.

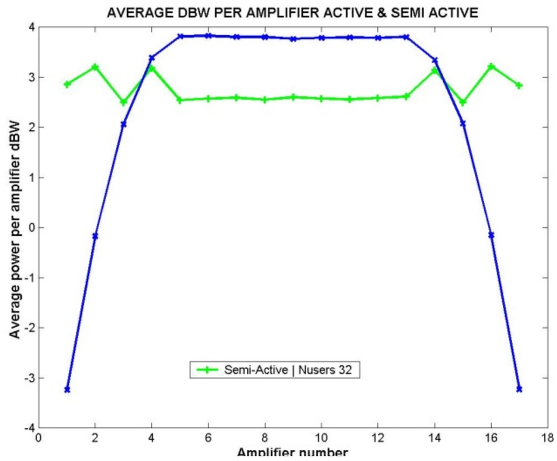

Figure 11. Average amplifier powers across the planar array of Figure 7 with semi-active (green) and with reference law for the active array (blue)

5. Acknowledgements

The authors are grateful to Giovanni Toso, Peter de Maagt, Piero Angelletti, and Marco Lisi of ESA, for their support.

6. Conclusions.

Semi-active or multi-matrix feeding can help with the realization and improvement of illumination tapering for multiple beam linear or planar arrays to control their side lobes and with close to uniformly powered power amplifiers level for best efficiency. This can be done using 3 dB hybrids between the PA's and the radiating elements, without or with input hybrids (MPA's). Amplitude and phase input control is required to generate steerable beams, preferably using digital beam forming.

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