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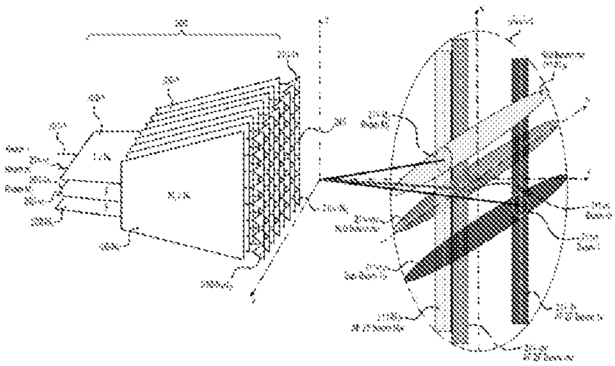
(54) **Multiple beamforming networks for array antennas with interference mitigation functionality**

(57) Beamforming network for array antenna producing reconfigurable multiple beams with simplified co-channel interference mitigation by zero forcing, sidelobe control, MMSE weighting or other. Array antenna elements are arranged in identical sub-arrays. Beamforrning network includes:

- array factor sub-beamformers, each with one array beam port, connected to its subarray ports with signal weightings optimised for each beam
- sub-array sub-beamformers, with sub-array beam ports, each connected, with optimised signal weightings, to all its sub-array element ports
- Sub-array ports of the same array factor sub-beamformer connect to the same sub-array beam port of the sub-array sub-beamformers
- Optimisation is for fan pencil/shaped beams, with/without interference mitigation, with array factor and sub-array fan beams at 90º

Pattern multiplication of one array factor by one sub-array pattern applies for each antenna beam, allowing to create zeros in only one set of sub-beamformers and reduce processing and hardware complexity.



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# Multiple beamforming networks for array antennas with interference mitigation functionality

## FIELD OF THE INVENTION

The invention relates to beamforming networks with interference mitigation functionality for use with arrays of antenna elements and to reconfigurable multibeam array antennas with interference mitigation functionality, comprising such beamforming networks.

## BACKGROUND OF THE INVENTION

A single (or multiple) antenna beam, with a beam port, is normally formed towards a given user having a communication terminal or a sensing target to maximize the power transmitted to or received from the wanted terminal(s) or sensing target(s) via this (these) port(s).

An Interference Mitigation (IM) beam has the additional requirement that its power transmitted to or received from other terminals, targets (acting as interferers) in other directions using the same frequency is minimized.

The aim is thus to minimize co-channel interference and maximise quality of service and spectrum efficiency, for example in wireless terrestrial or satellite communications or for remote sensing systems operating in the microwave part of the spectrum between 300 Megahertz (MHz) and 300 Gigahertz (GHz). The interference minimization process can also take into account additional noise sources (e.g. receiver thermal noise) in the beam optimization.

IM beamforming can be close to optimum when the selection of co-channel terminals or targets served at each time is optimised, taking into account their angular separation and the antenna resolution, as shown in "On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming", by Taesang Yoo and A. Goldsmith, in the IEEE Journal on Selected Areas in Communications, vol. 24, no. 3, pp. 528-541, March 2006 and in “Heuristic radio resource management for massive MIMO in satellite broadband communication networks,” by P. Angeletti and R. de Gaudenzi, in IEEE Access, vol. 9, pp. 147164-147190, 2021.

However, for serving mobile terminals or targets via such IM techniques, even with pre-determined directions, the processing load, the complexity, the cost, the losses, and the power consumption of multiple-beam beamformers must be dramatically reduced.

"Multibeam Antenna Technologies for 5G Wireless Communications", by Wei Hong et al., in IEEE Transactions on Antennas and Propagation, Vol. 65, No. 12, December 2017, provides a review of the relevant background art on multiple beam array antennas.

A conventional array antenna beamforming network in accordance with the prior art for the generation of multiple pencil or spot beams in the transmitting or receiving mode is schematically illustrated in Fig.1A.

The beamforming network has M beam ports 101-1 to 101-M, and the array antenna has N radiating elements 110-1 to 110-N. In a fully connected beamforming network, a total of M x N signal paths connect each of the M beam ports 101-1 to 101-M to each of the N amplification modules 109-1 to 109-N and corresponding radiating elements 101-1 to 110-M. In the transmitting mode, The radiating elements are configured to radiate beams 111-1 to 111-M towards targets or terminals 112-1 to 112-M. The signal entering a beam port 101-m is radiated by the array antenna in a beam 111-m in a line of sight or non-line of sight direction of a terminal or target 112-m, with ideally zero radiation towards line of sight or non line of sight directions of other terminals or targets 112-q with $q \neq m$.

In the receiving mode, all the incoming signal power from a terminal or target 112-m entering the radiating elements 110-1 to 110-N is ideally focused into the beam port 101-m with no power reaching the other beam ports 101-q with $q \neq m$.

For each beam, the corresponding beam shape and/or the directions of peaks and zeros of the beam can be controlled by proper weighting in amplitude and phase and/or time delay of the N signals travelling on these paths. Some of these weights can be zero if not all N radiating elements are involved in some beams.

The beamforming network can be analogue, with signal weighting at radio frequency (RF) or at intermediate frequency (IF), or digital, with weighting coefficients applied in the digital domain at baseband, or hybrid with a mix of analogue and digital weighting.

A digital processor and control unit 105, is configured to compute and refresh as required the beam-channel signal weight values. The digital processor and control unit 105 is also configured to control the calculation and updating of the pointing directions and weights as well as calibration corrections if required.

In the transmitting mode, the signal entering a beam port 101-m is divided by a 1:N signal divider 103-m and the beam former, using inputs from the processor and control unit 105, applies the N computed weights 104-m1 to 104-mN relevant to this beam m to each of these N signals.

The signals weighted by the 104-1n to 104-Mn weights and destined for each element chains n are combined by the M:1 signal combiner 107-n.

Depending on the beamforming approach (analogue or digital), modulation, data formatting and/or frequency translations are applied to the composite signals by converters 108-1 to 108-N before (or after) connection to the amplification modules at ports 109-1 to 109-N.

For analogue beamforming at the radiation RF frequency, with combination of M weighted signals by conventional M:1 signal combiners 107, only 1/Mth of the power is actually kept for power amplification and radiation. This loss has to be compensated by extra and costly (linear) power amplifier gain.

After amplification and filtering, the composite signals are directed to the N associated antenna radiating elements 110-1 to 110-N.

A signal initially applied to a particular beam port 101-m will be radiated in the corresponding IM (e.g. typically Zero-Forcing or ZF) beam 111-m.

In the receiving mode, combined signals incoming from M terminals or targets 112-1 to 112-M into each radiating element 110-1 to 110-N are then filtered and amplified in the modules connected through ports 109-1 to 109-N.

Depending on the beamforming approach (analogue or digital), the required modulation, data formatting and/or frequency translations are applied to the composite signals by converters 108-1 to 108-N after (or before) connection to the beamforming network.

Each of the composite signals incoming from an element chain 109-n (or converter 108-n) is divided by an M:1 divider

Using inputs from the processor and control unit 105, the beamformer applies the M computed weights 104-m1 to 104-mN relevant to each beam 112-m to each of these M signals. Signals with 104-m1 to 104-mN weights and destined for receiving beam m are combined by the M: 1 combiner 103-m and directed to port 101-m.

In conventional systems, such as those depicted in Fig. 1A, N element weights must be computed and refreshed for each of the M beams. Well separated beams typically re-use the same frequency sub-bands.

Even for simple pencil/spot beams this implies a large computational burden, as discussed for satellite applications in “A Pragmatic Approach to Massive MIMO for Broadband Communication Satellites”, by P. Angeletti and R. De Gaudenzi in IEEE Access, vol. 8, pp. 132212- 132236, 2020.

For IM beams with more constraints, and as evidenced e.g. in "Overview of Precoding Techniques for Massive MIMO," by M. A. Albreem et al., in IEEE Access, vol. 9, pp. 60764-60801, 2021, the precoding/beamforming and refreshing of agile IM beams for a high number of antenna elements requires accurate channel state information and very extensive computations. The synthesis of element weights typically requires repetitive evaluation of large Moore-Penrose pseudo-inverse matrices, with potentially prohibitive computational implications. Also, the high number N of frequency and data conversion channels (also called "RF Channels") leads to excessive cost and power consumption, with, for analogue beamforming, high RF losses from M:1 combiners 107-1 to 107-N.

The patent by J. Noh, T. Kim & C. Lee, "Hybrid zero-forcing beamforming method and apparatus ", U.S. Patent 9712296, Jul. 18, 2017, discloses a hybrid zero-forcing beamforming approach with precoding of a fully connected RF beamformer as in Fig. 1A, coordinated with zero-forcing precoding at baseband and aided by user feedback on per user information including ray gain. This system can serve a relatively high number of co-channel users in a multipath environment and advantageously only includes one frequency and data conversion channel per user beam port. For M beams and N elements, it requires the computation and RF implementation of the MxN RF weights.

However, the system does not make use of multiplication of linear sub-arrays and linear array factor patterns, which greatly simplifies the baseband and the RF precoding, admittedly of fewer beams. It also suffers the full signal combiner/divider losses at RF, requiring undesirable gain compensation from element amplifiers, not shown in the figures.

The patent by Seol, Ji-Yun, et al. "Communication method and apparatus using analogue and digital hybrid beamforming," U.S. Patent No. 9,362,994, 7 June 2016, discloses partially relevant work on two basic hybrid beamforming designs and their derivatives for MIMO communications:

1) A fully connected multiple beam array hybrid beamformer, with each beam port connected to all the radiating elements of one array.
2) A partially-connected array hybrid beamformer, with each beam port only connected to the radiating elements of one sub-array, each equipped with one beam port only.

The first design, similar to that in Fig.1A below, has maximum complexity, combining losses at element chains level. The second partially-connected design also has high complexity and interference problems.

Hybrid beamforming having multiple linear sub-arrays and separating analog/digital in elevation/azimuth is discussed in a publication by Y. Hu and W. Hong: "A Novel Hybrid Analogue-Digital Multibeam Antenna Array for Massive MIMO Applications," 2018 IEEE Asia-Pacific Conference on Antennas and Propagation (APCAP), 2018, pp. 42-45, 2018. This approach is also complex.

A similar hybrid analogue/digital beamforming architecture using simple quasi-optical lenses is disclosed in the patent by Hervé Legay: ”Active antenna architecture with reconfigurable hybrid beamforming”, U.S. Patent No. 10236589B2, 4 Dec. 2015. Such a design has less complexity than beamforming networks of similar size, but suffers from interference issues.

Another relevant two stage beamforming architecture, also using quasi-optical lenses fed by orthogonal reconfigurable analogue beamformers, is disclosed in the patent by Jean François Fraysse *et al.*, “Two-dimensional analogue multibeam beamformer of reduced complexity for reconfigurable active array antennas,” U.S. patent No. 2020411971A1, 31 Dec. 2020. These sub-arrays generate fixed beams which are not agile in elevation and the design does not include any interference mitigation functionality.

Solutions by which the N radiating elements are arranged in an array of $N_1$ (identical or not) sub-arrays with $N_2$ radiating elements and $N_s < N_2$ ports each, have been proposed and implemented. This typically reduces from $N = N_1 \times N_2$ to $N_1 \times N_s$ the number of such RF chains where true time delays can improve bandwidth, for example in hybrid digital/analogue beamforming configurations. One or several co-channel terminals or targets with sufficient angular separation can use each one of the sub-array beams. RF amplification at radiating element level might be avoided in the case of single port/beam sub-arrays but becomes mandatory to compensate for combining losses at elements for conventional “multiport” sub-arrays, where each sub-array has multiple sub-array beams. This type of solution is further elaborated in the patent by P. Angeletti, G. Toso, “Network for forming multiple beams from a planar array.” US Patent Application No. US 20210249782Al, Aug. 12, 2021. There, arrangements of planar arrays into linear sub-arrays parallel to a certain direction and each with several sub-array beam ports are proposed. These aim at simplifying the flexible generation of multiple circular or shaped pencil or spot beams that can be selected/switched or reconfigured using one multiport sub-beamformer for each of the $N_1$ linear sub-arrays.

An example of such a beamforming network with vertical sub-arrays is schematically shown in Fig. 1B. Ports of these (e.g. vertical in Fig 1B) sub-array sub-beamformers 106 each generate a fan-like beam laying perpendicular to the plane including the normal to the array and the sub-array axis and containing the direction of the terminal(s) or target(s) to be served.

Corresponding ports of the $N_1$ (e.g. vertical in Fig 1B) sub-array sub-beamformers 106 are each connectable to an (e.g. horizontal in Fig 1B) array sub-beamformer 102 which generates fan-like beam typically parallel to the plane including the normal to the array and the sub-array axis and containing the directions of terminals or targets to be served. A beam port of an array sub-beamformer connected with the corresponding beam ports of the sub-array sub-beamformers will generate a pencil/spot beam resulting from the product in the beam space of the two corresponding fan beams (e.g. typically perpendicular to each other in Fig 1B). To maximize the power transmitted to or received from wanted terminal(s) using multiple beam arrays, the approach in this patent reduces the system computational load and the complexity compared to the conventional design in Fig. 1A. However, directions of maximum gain for beams generated by each array sub-beamformer are restricted to be in or close to one sub-array fan beam plane

Patent US 20210249782Al addresses normal pencil/spot/shaped beams without an intrinsic and dynamic multiple interference reducing function of IM beams, for which ensuring low beam sidelobe levels and/or by orthogonal coding of same beam signals is mentioned. Moreover flexibility of signal to beam assignments can be enhanced by selective switching rather than by accurate real time weight elaboration and adjustments.

Designs based on this grid-of-beams approach are also disclosed in the patent by Locke, John Wesley. "Apparatus and method for beamforming in a triangular grid pattern" U.S. Patent No. 5,812,089. 22 Sep. 1998. A grid-of-beams is also used for the SPACEWAY satellite multiple beam arrays, as described by R.F.J. Fangin the publication "Broadband IP transmission over SPACEWAY satellite with on board processing and switching", Global Telecommunications Conference (GLOBECOM), 2011.

It would be advantageous to implement a more efficient architecture for providing agile beams at low complexity and minimized interference.

## SUMMARY OF THE INVENTION

An object of the invention is to provide beamforming networks as disclosed in the claims, for use with antenna arrays of radiating elements, organised in identical, typically linear and parallel multiport sub-arrays of several antenna elements each, with each sub-array beam port corresponding to a different, possibly agile, sub-array beam.

This provides a novel approach for multiple reconfigurable beamforming in array antennas with Interference Mitigation (IM) functionality with low complexity and interference, and very directive or shaped fixed or reconfigurable beams.

To generate ($M_1$) such beams, all the ($N_1$) typically linear and vertical identical multiport sub-arrays, each comprising ($N_2$) radiating elements, are provided with identical sub-array sub-beamformers. Each sub-array sub-beamformer comprises ($M_1$) beam ports, with $M_1<N_2$, each connected to all of its ($N_2$) sub-array antenna element ports, each with optimal weighting of each beam ($N_2$) sub-signals. To each of the ($M_1$) sub-array beam ports of the sub-array sub-beamformer then corresponds a sub-array beam, identical for all sub-arrays, dedicated to and configured for each of the ($M_1$) wanted agile or fixed antenna beams.

In the typical case of linear vertical sub-arrays, each of these ($M_1$) sub-array beams will be fan beams with directive pencil or shaped lobes towards selected elevation direction(s) in the vertical plane, with or without Interference Mitigation added. These beams will have low directivity in their other dimension.

To achieve conditions for advantageous array pattern multiplication for each antenna beam, a typically linear horizontal array of the ($N_1$) multiport sub-arrays is configured with optimum sub-signal weightings for each desired fixed or agile antenna beam (m of $M_1$), each only involving the corresponding same sub-array beam port (m) of each of the $N_1$ multiport sub-arrays. Such sub-signals, if associated to a (nominally horizontal) linear array of $N_1$ isotropic radiating elements with the same separation as the $N_1$ (nominally vertical) sub-arrays of the array (240), result in the m-th "array factor" beam pattern, dedicated to and configured as required for the antenna beam (m) concerned.

This is achieved by providing as many different array factor sub-beamformers as fixed or agile beams, wherein each array sub-beamformer (m of $M_1$) will have one array beam port connected to all of its ($N_1$) sub-array ports, each with optimal weighting of the ($N_1$) sub-signals so that the resulting array factor beam (m) is formed in the required direction or shape and with or without interference mitigation added, for the antenna beam (m) concerned.

In the typical case of a linear horizontal array (m) of sub-arrays, each of these ($M_1$) array factor beams will be fan beams with directive pencil or shaped lobes towards selected horizontal direction(s) in the horizontal plane containing the array, with or without interference mitigation added. These beams will have low directivity in their other (vertical) dimension.

In the transmitting mode, the sub-array output port (n) of an array factor sub-beamformer (m) is connected to the right sub-array beam input port (m) of the corresponding sub-array sub-beamformer (n) as described above,

for an array beam (m), the weighting for the sub-signal path from the multibeam antenna beam port (m) to a radiating element (k) of a particular sub-array (n) will be the product of the relevant array factor weight by the relevant sub-array weight and thus pattern multiplication will be applicable.

Accordingly, following basic array theory, the final agile antenna beam (m) pattern will be, in each direction, the product of the array factor fixed agile beam (m) pattern by the sub-array fixed or agile beam (m) pattern.

Antennabeam(m) = ArrayFactorbeam(m) x Sub-Arraybeam(m)

So both the array factor and the sub-array beams will need to be maximum or shaped in directions where optimum beam directivity is required, but only one of the two will have to be zero or very low in directions where zero or very low interference is required.

The product of a narrow array factor fan beam, typically parallel to one plane, by a sub-array pattern fan beam, typically parallel to another plane making an angle (typically but not necessarily of 90° ) with the plane of the array factor beam, will typically produce a highly directive elliptical beam in the target direction(s) where both fan beams have optimum directivity, and with zero or reduced directivity in other co-channel directions, enforced in at least one of the two fan beams, or possibly in both for enhanced interference mitigation.

The beam forming network for a conventional fully connected $M_1$ beam array antenna of $N_1xN_2$ radiating elements, requires the computation and implementation of $M_1xN_1xN_2$ analogue and/or digital signal weights, particularly heavy with interference mitigation.

Also, the conventional fully connected $M_1$ beam array antenna requires one converter chain per antenna element i.e. $N_1xN_2$ chains.

The beam forming network for an array antenna of $N_1xN_2$ radiating elements according to the invention producing the same $M_1$ beams, only requires the computation of $M_1x(N_1+N_2)$ signal weights, with only $M_1xN_1$ or $M_1xN_2$ of them requiring heavy processing with interference mitigation. Also, since it is identical for all $N_1$ multiport sub-arrays, the digital and/or analogue implementation of the signal weights is also greatly simplified.

Moreover, the beam forming network according to the invention only requires $M_1 x N_1$ converter chains in case of a digital + analogue configuration and only $M_1$ converter chains in case of a fully analogue configuration.

As said, this allows to generate, with reduced complexity, cost and power consumption, multiple agile IM array antennas beams. Each IM beam must optimize or maximize the signal power transmitted to or received from one wanted terminal or sensing target T and at the same time ensure that its power transmitted to or received from other terminals, targets or interferers in other directions and using the same frequency is zero or below a given adjustable level. Additionally, the optimisation of the array factor weights and of the sub-array weights can aim at an optimal trade-off between interference and noise. This minimizes co-channel interference and maximises quality of service and spectrum efficiency.

Each of the $N_2$ sub-array beam port outputs of each of the $N_1$ sub-array sub-beamformers may be configured to generate and provide a plurality of sub-array weighted sub-signals to one of the radiating elements.

Each of the $N_1$ sub-array ports of each of the $M_1$ array sub-beamformers may be configured to provide a plurality of array beams, sharing the same sub-array beam.

The beamforming network may further be associated to amplification modules and filtering modules, between its element ports and the array radiating elements.

The interference mitigation functionality may be implemented using Zero-Forcing (ZF), Minimum Mean-Square Error (MMSE) weighting, which may provide improved performance taking into account the receiver noise power, or sidelobe control array synthesis.

The $N_1$ sub-array sub-beamformers may be analogue beamformers at a radiating frequency and the $M_1$ array sub-beamformers may be digital beam formers at baseband and may be configured to provide the interference mitigation functionality.

The $N_1$ sub-array sub-beamformers may be analogue beamformers at a radiating frequency and the $M_1$ array sub-beamformers may be analogue beam formers at baseband and may be configured to provide the interference mitigation functionality.

The $N_1$ sub-array sub-beamformers are also configured to provide the interference mitigation functionality.

The $N_1$ sub-array sub-beamformers may be conventional analogue beamformers comprising combiner modules with combining losses. This increases the losses of the beamforming network.

The $N_1$ sub-array sub-beamformers may be analogue orthogonal beamformers at a radiating frequency and may be configured to provide zero-forcing interference mitigation functionality. This reduces the losses of the beamforming network.

The $M_1$ array sub-beamformers may also be configured to provide partial or full zero-forcing interference mitigation functionality .

To generate losslessly multiple orthogonal sub-array beams with partial zero-forcing functionality, the $N_1$ analogue sub-array sub-beamformers 329 with $M_1$ sub-array beam ports and $N_2$ element ports , may comprise:

- Cascaded fixed coupler four port modules 321 and variable four port coupler modules 324, each including a phase or time shifter 323 and respectively an isolated and matched fixed coupler 322 or a variable coupler 325. These could also be replaced by equivalent four port IC components with variable gain amplification.
- $N_2$-1 such modules each set and cascaded as to optimize directivity as desired for a first selected beam (port) 1, and therefore leaving no interference power from that beam direction in other beam ports.
- $N_2$-2 such modules, collecting or transmitting signals from or to unused ports of the previous $N_2$-1 four port modules, and set and cascaded as to optimize directivity as desired for a second selected beam (port) 2, and therefore leaving no interference power to or from that beam direction in other beam ports.
- $N_2$-3 such modules, collecting or transmitting signals from or to unused ports of the previous $N_2$-2 four port modules, and set and cascaded as to optimize directivity as desired for a third selected beam (port) 3, and therefore leaving no interference power to or from that beam direction in other beam ports.
- $N_2$-$M_1$ such modules, collecting or transmitting signals from or to unused ports of the previous $N_2$- $M_1$+1 four port modules, and set and cascaded as to optimize directivity as desired for the last beam (port) $M_1$, with no interference power left from beam directions of other beam ports. This last beam $M_1$ is therefore zero-forcing from or towards the other $M_1$-1 beam directions.

This avoids that the combining losses associated with the generation of each beam are combined, thereby is providing a very efficient implementation.

To generate losslessly multiple orthogonal sub-array beams with full zero-forcing, the $N_1$ analogue sub-array sub-beamformer with $M_1$ sub-array beam ports and a total of $N_2 + (M_1\text{-}1)^2$ element ports may comprise:

- A first sub-network 329, the analogue sub-array beamformer 329 of the embodiment described in the previous section, with $M_1$ orthogonal beam ports, each connected to $N_2$ core elements used for all beams
- A second sub-network 330, added to cancel interferences received from or transmitted towards the directions of the 1 to $M_1$-1 orthogonal but not fully zero-forcing beam ports of the first sub-network 329. This sub-network 330 comprises, for each of these $M_1$-1 ports, an interference nulling circuit, connected to $M_1$-1 dedicated radiating elements, added to $N_2$ core elements connected to the first sub-network 329. Each interference nulling circuit uses cascaded variable four port coupler modules 324, set to extract in an iterative manner.

ZF weighting can be applied for cancellation of signals from one more very strong line of sight interferer(s) from which low sidelobe protection is not sufficient.

A multibeam antenna comprising anyone one of the beamforming networks 200 disclosed above, further associated to the array antenna 240 by connection of the respective element ports of the beamforming network 200 to the respective antenna elements of the array antenna 240 also constitutes part of this invention.

Such a multibeam antenna wherein the array antenna 240 comprises an array of $N_1$ identical multiport sub-arrays of $N_2$ radiating elements each, all sub-arrays being translated from each other and non-overlapping, and all having identical sub-array beam patterns also constitutes part of this invention.

The main problems solved by the invention when generating multiple agile IM beams are:

1. Reduction of required information on co-channel terminal/target directions and levels (or channel state information)
2. Reduction of the number of weights to be computed and applied for each IM beam
3. Reduction of cost and power consumption by lowering the number of data format and frequency conversion chains (“so called RF chains”),
4. Reduction or elimination of pre-amplification combining RF losses, otherwise requiring gain compensation

The invention reduces significantly the complexity of the beamforming function in planar arrays with interference mitigation/cancellation functionality and can be implemented both with analogue and digital technology.

It also reduces losses in analogue beamforming networks having multiple beams when using orthogonal matrices.

Furthermore, sidelobe control/reduction by array weight synthesis and/or by optimised non-regular array spacings can also benefit from the orthogonal beamforming and/or from the key pattern multiplication in this disclosure.

Minimum Mean-Square Error (MMSE) weighting, which generates more gain than Zero-Forcing but without nulling interference, can improve the signal to noise ratio in the presence of Gaussian noise. This IM technique can also benefit from the key pattern multiplication in this disclosure.

The person skilled in the art will understand that the features described above may be combined in any way deemed useful. Moreover, modifications and variations described in respect of the system may likewise be applied to a method.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the following, aspects of the invention will be elucidated by means of examples, with reference to the drawings. The drawings are diagrammatic and are not drawn to scale.

Fig. 1A shows a schematic drawing of a conventional fully connected array multiple beamformer, in accordance with the prior art.

Fig. 1B shows a schematic drawing of an example of an array multiple beamformer in accordance with the prior art.

Fig. 2A shows a schematic diagram of a beamforming network in accordance with an embodiment of the invention.

Fig. 2B shows an example of an antenna array configuration with a linear array of vertical sub-arrays.

Fig. 2C shows an example of another antenna array configuration with a linear array of the same sub-arrays of Fig. 2B rotated to achieve a more compact triangular lattice for the radiating elements and for the beams.

Fig. 2D shows a schematic diagram of an implementations of a beamforming network according to an embodiment of the invention with a linear horizontal array of linear vertical multiport sub-arrays.

Figs. 2D-bis and 2D-ter show additional details of embodiments according to the invention.

Fig. 2E shows a schematic diagram of a beamforming network using conventional analogue sub-beamformers with high combining losses according to an embodiment of the invention.

Fig. 3A shows a schematic diagram of the modules with fixed and with variable couplers used in the analogue sub-array sub-beamformer of Fig. 3B.

Fig. 3B shows a schematic diagram of an analogue multiple beam sub-array beamformer for the theoretically lossless generation of agile orthogonal sub-array beams with partial zero-forcing interference mitigation according to an embodiment of the invention.

Fig. 3C shows a schematic diagram of an analogue lossless multiple beam sub-array beamformer where the agile beams of Fig. 3A are all made fully zero-forcing, by adding dedicated radiating elements and interference cancelling circuits for each beam.

Fig. 4 shows a schematic diagram of a beamforming network according to an embodiment of the invention using digital array sub-beamformers with interference mitigation associated with an analogue multiple beam sub-array beamformer for the theoretically lossless generation of agile orthogonal sub-array beams as depicted in Fig. 3B.

Fig. 5A shows a linear horizontal antenna array comprising eight linear vertical 3-port sub-arrays of eight radiating elements each using the beamforming network of Fig. 4 and Fig.5B, with variable power divider settings of Fig. 5C, generating the directivity contour plots shown in Fig. 5D, demonstrating perfect interference mitigation for three co-channel beams, obtained by pattern multiplication of orthogonal sub-array patterns with partial zero forcing by array factor patterns with full zero forcing.

## DETAILED DESCRIPTION OF EMBODIMENTS

In accordance with the present invention, there is provided an interference mitigation (which might be a zero-forcing or other interference mitigation) beamforming network for an array antenna. Each beam has a beam port and its functions are:

1) To maximize or adaptively set the signal power transmitted to or received from wanted directions
2) To cancel or adaptively reduce co-channel transmission to or reception from other unwanted directions.

The invention takes advantage of the principle of array pattern multiplication which has long been known as part of array antenna theory and described for example in the book by John D. Kraus, “Antennas” - McGraw-Hill,1950, pp. 66-74. As explained in the book by C. A. Balanis, “Antenna Theory: Analysis and Design”, John Wiley & Sons, 2016, p 287, the principle of array pattern multiplication states that for an array antenna of identical elements:

$\text{Field}_{total}$ = [Field of element at a reference point] x [Array factor]

Wherein the reference point is usually the origin of the coordinate system used to describe the antenna array, which typically lies in the plane of the antenna array and is located in a central position of the antenna array, and the array factor (AF) is derived from amplitudes, phases and positions of ideal elements assumed to have isotropic individual radiation patterns.

By extension, this principle is also valid if the “elements” are groups or sub-arrays of several radiating elements, as long as, for each beam, the sub-arrays used are identical and have identical sub-array radiation patterns. It also applies if the array and sub-arrays have multiple ports (each for a sub-array beam), as long as, for each beam, the same port with the same sub-array pattern of each participating sub-array is used. With arrays of $N_1$ identical sub-arrays (with $N_2$ radiating element each), for which pattern multiplication applies, directivity has to be optimized in both the array factor and the sub-array patterns which are multiplied by each other in directions of terminals or targets where optimum directivity is required. The invention exploits the following particularity of ZF beamforming with arrays of sub-arrays for which pattern multiplication applies: zero radiation, and thus zero interference, in one direction only requires that one zero be created in that direction either in the sub-array radiation pattern or in the array factor pattern, but not necessarily in both. This principle of decomposition which is described for ZF can be extended to a broader class of IM techniques such as MMSE beamforming.

As a result, for each IM beam, computation-intensive weight elaboration and more complex implementation can be limited to $N_1$ array factor weights or $N_2$ sub-array beam weights (identical for all $N_1$ identical sub-arrays).

According to the publication by C. -S. Park, Y. -S. Byun, A. M. Bokiye and Y. -H. Lee, "Complexity reduced zero-forcing beamforming in massive MIMO systems," 2014 Information Theory and Applications Workshop (ITA), pp. 1-5, 2014, the computation and implementation complexity of adding the IM function increases with the square of the number of antennas and the fourth power of the number of nulls.

The above simplification can help benefit from otherwise too complex zero-forcing beam forming. Hybrid configurations with IC based analogue sub-array sub-beamformers and digital array sub-beamformers for accurate zero-forcing are preferred ways of carrying out the invention, but other combinations are possible.

The above disclosure is applicable to all arrays of identical sub-arrays for which pattern multiplication applies, thus not necessarily linear arrays nor sub-arrays. In practice, planar arrays formed as linear arrays of linear sub-arrays seem to offer better angular resolution and ease of manufacturing, with good modularity potential.

They result for each beam in the multiplication of one fan beam type array factor by one specific fan beam type sub-array pattern at 90 ° or some other angle, preferably both with optimum directivity in the target direction(s), and with zero or reduced directivity in other co-channel directions used for at least one of the two fan beams.

Fig. 2A shows a schematic diagram of a beamforming network 200 for the generation of two or more agile beams from an array antenna 240 in accordance with an embodiment of the invention. The array antenna 240 shown in Fig. 2A comprises a number $N_1 \times N_2$ of radiating elements 210-1, …, 210-$N_1$x$N_2$. The $N_1 \times N_2$ of radiating elements 210-1, …, 210-$N_1$x$N_2$. The beamforming network 200 shown in Fig.2A is described below in the transmitting mode from array beam ports to sub-array element ports but is also usable in the receiving mode from sub-array element ports. It comprises $N_1$ identical, and identically configured, sub-array sub-beamformers 206-1, …, 206-$N_1$ and $M_1$ array sub-beamformers 202-1,…, 202-m,…, 202-$M_1$.

Each of the M1 array factor sub-beamformers 202-1,…, 202-m,…, 202-M1 of Fig. 2A comprises respectively a beam port input 201-1,…, 201-m,…, 201-$M_1$ wherein each of the $M_1$ beam port inputs 201-1,…, 201-m,…, 201-$M_1$ is configured to receive respectively a beam signal 1,…, m,…, $M_1$ to be respectively transmitted to a terminal or target. Each of the $M_1$ array factor sub-beamformers 202-1,…, 202-m,…, 202-$M_1$ of Fig. 2A forms a 1x$N_1$ connection matrix such that each array beam port input of an array sub-beamformer is connected to the $N_1$ sub-array port outputs of said sub-array sub-beamformer.

Furthermore, each of the $N_1$ sub-array sub-beamformers 206-1,…, 206-m,…, 206-$M_1$ of Fig. 2A forms a $M_1$x$N_2$ connection matrix connected to the $M_1$ array factor sub-beamformers 202-1,…, 202-m,…, 202-$M_1$ and configured to provide $N_2$ outputs to $N_2$ radiating elements.

The $M_1$ array factor sub-beamformers 202-1,…, 202-m,…, 202-$M_1$ of Fig. 2A are configured to generate the vertical array factor beams 211-1v, …, 211-mv,…, 211-$M_1$v and the

$N_1$ sub-array sub-beamformers 206-1,…, 206-m,…, 206-$M_1$ are configured to generate the horizontal sub-array beams 211-1u, …, 211-mu,…, 211-$M_1$u such that the antenna array, based on the multiplication of both beam patterns, is configured to generate the agile beams 1,…, m,…, $M_1$ in the targeted direction or shape, with or without interference mitigation in other co-channel directions.

A schematic example of such a horizontal linear array of vertical linear sub-arrays illustrating the principle of zero-forcing pattern multiplication of fan beams is shown in Fig. 2A and Fig. 2B, together with the coordinate systems used.

The array antenna 240 shown in Fig. 2A comprises a linear array of $N_1$ identical linear sub-arrays of $N_2$ radiating elements each. These linear sub-arrays are translated from each other and non-overlapping with each other.

The $N_1$ identical and identically set sub-array sub-beamformers 206-1, …, 206-$N_1$, one per each linear sub-array of the array antenna 240, each comprise $M_1$ sub-array beam ports. Each of these $M_1$ sub-array beam ports is connected to the $N_2$ radiating elements of a specific linear sub-array of the array antenna 240 with optimised signal weightings corresponding to a sub-array beam in a targeted direction or shape with or without interference mitigation. The $N_1$ sub-array sub-beamformers 206-1, …, 206-$N_1$ may be analogue or may be digital. The $M_1$ array sub-beamformers 202-1,…, 202-m,…, 202-$M_1$ may also be analogue or digital.

Each array factor sub-beamformer beam port is connected with proper adjustable weights to the $N_1$ sub-array ports of the sub-array beamformers corresponding to the wanted sub-array beam. As a result, pattern multiplication of the optimised array factor pattern by the optimised sub-array beam pattern, but only one of them with interference mitigation applied, provides full interference mitigation and optimum gain for each of the M1 antenna beams The resulting processing and hardware complexity as well as the losses involved are minimized.

Furthermore, more than one beam can be generated by each array factor sub-beamformer 202-1,…, 202-m,…, 202-$M_1$, if required, to serve directions within (or close to) the same sub-array beam and with somewhat reduced gains and higher interference levels.

In Fig. 2A, the sub-array sub-beamformers 206-1, …, 206-$N_1$ generate the horizontal fan beams 211-mu. The array sub-beamformers 202-1,…, 202-m,…, 202-$M_1$ generate the vertical fan array factor beams 211-mv, typically with zero-forcing towards other co-channel directions of beams 211-1v to 211- $M_1$v.

The product of fan beams 211-mu and 211-mv results in the spot beam 211-m corresponding to the array beam input port 201-m with maximum peak gain and with a vertical column of zero radiation through the other co-channel directions.

Furthermore, the pattern multiplication principle above is also applicable with array antennas having the radiating elements arranged in sub-arrays which are not orthogonal nor linear.

Fig. 2B shows an example of a a preferred array antenna configuration wherein the radiating elements are arranged in a linear array of $N_1$ linear sub-arrays of $N_2$ radiating elements each, where the alignment of the linear array and that of the sub-arrays are at a 90° angle.

Fig. 2C shows an example of another antenna array configuration with a linear array of the same sub-arrays of Fig. 2B rotated to achieve a more compact triangular lattice for the radiating elements and for the beams. The only necessary conditions are that the array factors are derived assuming isotropic elements and that all the sub-array ports used for each beam have identical radiation patterns. In a practical implementation, some characteristics of the antenna array, such as mutual coupling between radiating elements, may degrade the IM function. However, these limitations are not specific to the invention and are generally acceptable as the impact is often marginal.

Figs. 2A, 2D 2D-bis and 2D-ter show schematic diagrams of an implementation of a beamforming network according to an embodiment of the invention. Figs. 2A, 2D 2D-bis and 2D-ter show a hybrid configuration of the beamforming network 200 wherein one set of sub-beamformers comprises a number $N_1$ of identical, and identically configured sub-array sub-beamformers 206-1, ..., 206-$N_1$, with $N_1 > 1$, which are analogue, at Radio Frequency (RF) or Intermediate Frequency (IF), and the other set of sub-beamformers comprises a number $M_1$ of array factor sub-beamformers 202-1,..., 202-$M_1$, with $M_1 > 1$, and that are digital at baseband.

In the transmit mode, a signal entering an array beam input port 201-m, is divided by the 1:$N_1$ digital or analogue signal divider 203-m. Computed digital weights are applied at baseband, or analogue ones at IF or RF, and the signals are converted in data format and /or translated in frequency as required. Then each signal enters the appropriate sub-array sub-beamformer and is divided by the 1:$N_2$ analogue signal divider and appropriately weighted before recombination with the signals from other beams through one of the $N_2$ signal combiner 208 into the amplifier module via port 209 and the radiating element.

The signal will then be radiated into beam 211-m and terminal or target direction 211-m with zero radiation in the other $M_1$-1 co-channel directions.

The same is applicable in the receiving mode with the appropriate changes from signal dividers to combiners as well as in data format and frequency translations etc...

It is to be noted that, when they only generate a single beam, the array factor sub-beamformers 202-1 to 202-$M_1$ imply a much reduced processing burden and, if they are analogue, they can each form an IM beam theoretically without losses and without adding extra elements unlike multiple beam sub-beamformers.

However, the beamforming network 200 of Figs. 2A, 2D 2D-bis and 2D-ter may be further generalized assuming multiple beams in both the array sub-beamformers 202-1,..., 202-$M_1$ and the sub-array sub-beamformers 206-1, ..., 206-$N_1$, thus more than one beam can be generated by each array sub-beamformers 202-1,..., 202-$M_1$ for each sub-array sub-beamformers 206-1, ..., 206-$N_1$, if required, to serve directions within (or close to) the same sub-array beam, which could also be shaped, reconfigurable or fixed. This allows the array antenna to generate more than $M_1$ or $N_2$ beams.

Fully analogue or hybrid digital-analogue implementations of the beamforming networks shown in Figs. 2A, 2D 2D-bis and 2D-ter are possible, as well as a fully digital implementation.

Fig. 2E shows a schematic diagram of a beamforming network with high combining losses according to an embodiment of the invention.

The beamforming network shown in Fig. 2E comprises $M_1$ analogue array sub-beamformers 202-1,..., 202-m,..., 202-$M_1$ (only the analogue array sub-beamformer 202-m is shown in Fig. 2E but the other analogue array sub-beamformers are similar) and $N_1$ analogue sub-array sub-beamformers 206-1,..., 206-m,..., 206-$N_1$ (again only the analogue sub-array sub-beamformer 206-m is shown in Fig. 2E but the other analogue sub-array sub-beamformers are similar) wherein the analogue sub-array sub-beamformer 206-m comprises an array beam input port 201-m, a signal divider 203-m configured to receive a beam signal from the array beam input port 201-m and to divide the received beam signal into $N_1$ signals. The analogue sub-array sub-beamformer 206-m comprises further $N_1$ weighting devices configured to apply respectively weights Wm1,..., Wm$N_1$ each one connected to the signal divider 203-m to receive the divided signal and output the received divided signal weighted by the corresponding weight among the weights Wm1,..., Wm$N_1$.

To resolve the major problem of high combining losses in analogue multiple beamforming which greatly limits the achievable number of beams, the invention also includes the related disclosures of novel analogue sub-array agile multiple beamforming designs to reduce the pre-amplification RF losses of conventional microwave combiner solutions.

"Orthogonal versus zero-forced beamforming in multibeam antenna systems: review and challenges for future wireless networks," by Y. Alan et al., in IEEE Journal of Microwaves, vol. 1, no. 4, pp. 879-901, Oct. 2021) describes the generation of zero forcing beams.

Fig. 3A shows a schematic diagram of the modules with fixed and with variable couplers of Fig. 3B.

Fig. 3B shows a schematic diagram of an analogue multiple beam sub-array sub-beamformer for the generation of agile orthogonal beams according to an embodiment of the invention.

Fig. 3C shows a schematic diagram of an analogue multiple beam sub-array sub-beamformer where the agile beams of Fig. 3B are made zero-forcing, by adding dedicated radiating elements and interference cancelling circuits for each beam.

In Fig. 3B, $M_1$ is equal to three such that an array antenna comprising linear sub-arrays, wherein each linear sub-arrays comprises eight radiating elements is configured to produce three gain optimised orthogonal beams A, B and C but non zero-forcing (excepted the last one beam C and particular configurations of beams B and A), and then to transform the three beams A, B and C into zero-forcing beams. The sub-array sub-beamformer of Fig. 3B can be extended to more than three beams and comprises twelve fixed couplers modules 322 as the one shown in Fig. 3A and six variable couplers modules 325 as the one shown in Fig. 3A.

The sub-array sub-beamformer of Fig. 3B is configured to perform low loss synthesis of $M_1 = 3$ orthogonal non zero-forcing beams A, B and C from the linear (or planar) sub-array of $N_2 = 8$ radiating elements and the twelve fixed couplers modules 322 and six variable couplers modules 325 within the dotted area 329. The fixed couplers modules 322 and the variable couplers modules 325 within the dotted area 329 are isolated and matched couplers comprising each one a variable phase or time shifters 323, two inputs and two outputs.

The variable couplers modules 325 may be made using two fixed 3 decibels (dBs) hybrid couplers separated by one or two variable phase-shifters. Alternatively, the variable couplers modules 325 may be made using four port active Integrated Circuits (ICs) with variable gain amplification or with tuneable coupling functionality.

The functioning of the sub-array sub-beamformer of Fig, 3B will be explained now. When three incoming plane waves or beams A, B and C arrived to the eight radiating elements of the linear sub-array from the 3 different terminal or target directions, the radiating elements 310-1,..., 310-$N_2$ of the linear sub-array are each assumed to receive a power equal to $a^2 + b^2 + c^2$ from the plane waves A, B and C wherein a is the amplitude of the wave A, b is the amplitude of the wave B and c is the amplitude of the wave C.

A preferred orthogonal beam synthesis approach is derived from Gram Schmidt orthogonalization in vector spaces, and will provide maximum beam gain in one of the beam directions of the beams A, B and C (in Fig, 3B, maximum beam gain is provided in the direction of beam A). The solution is therefore not unique and maximum beam gain may be provided in other beam directions.

The sub-array sub-beamformer of Fig. 3B will concentrate at port 309-1 all the power received from wave A. This is only feasible when the angular spacings of the beams are multiple of the angular resolution of the sub-array, as is the case for Butler matrix beams.

The sub-array sub-beamformer of Fig. 3B is configured to, by proper adjustment of phase at all the seven ($N_2$-1) fixed couplers modules A, collect all the power of wave A arriving to the eight radiating elements, in this case said power is equal to $N_2 \times a^2$ , at port 309-1, but still with some co-channel interfering power from the received power of waves B and C.

The sub-array sub-beamformer of Fig. 3B is further configured, by proper adjustment of phase (and also amplitude for two of them) at the six ($N_2$-1) variable and fixed couplers modules B, to collect in port 309-2 all the received power from wave B not lost in port 309-1, but with some interfering power received from wave C.

Finally, sub-array sub-beamformer of Fig. 3B is configured, by proper adjustment of phase (and also amplitude for four of them) at the five ($N_2$-1) variable and fixed couplers modules C, to collect in port 309-3 all the received power from wave C not lost in port 309-1 and port 309-2 with no interfering power from waves A and B.

Beams A, B and C are orthogonal.

An equivalent design of the one shown and explained with relation to Fig. 3B may be used as a receiver and, in this case, all the intercepted power incoming from the arrival direction of beam A is focused to port 309-1. Thus beam A has optimum gain, potentially allowing optimal received signal power S from the arrival direction of beam A. However interference will be received in port 309-1 from the power received from the arrival directions of beams B and C. Once again, no power from the arrival direction of beam A will interfere in any of other ports 309-2 and 309-3. Thus, if the incoming power from the arrival direction of beam A is not desired (interference, jammer…), terminating port 309-1 on a load will allow interference free operation of all other (agile…) beams B and C.

Some incoming power from the arrival direction of beam B will interfere in beam port 309-1 reducing the gain of beam B, but none is left for potentially interfering in the other beams. Thus, like port 309-1, port 309-2 can be used, or terminated to block all interference from power coming from the arrival direction of beam B to port 309-3.

The last port 309-3 receives zero interference from the arrival directions of beams A and B, but its gain is reduced with respect to the optimum by the loss of received power from its direction interfering in the other ports 309-1 and 309-2.

This can be advantageous in the case of two beams, for example for seamless satellite hand-over.

The Gram Schmidt orthogonalization inspired synthesis is preferred here because it allows to minimize the number of required variable power dividers, thus reducing complexity, while providing selective interference mitigation.

Other modifications to the above synthesis technique aimed at spreading the gain loss and the interference at lower level to all beams may be used. These require more variable power dividers with added complexity.

Fig. 3C shows an extension of the sub-array sub-beamformer of Fig. 3B wherein an interference cancelling circuit 330 has been added to Fig. 3B. The non zero-forcing orthogonal beams A and B can be made zero-forcing at ports 307-1 and 307-2. For each of the other $M_1$ - 1 (two) beams, $M_1$ -1 (two) extra fixed or variable couplers modules must be added to provide and apply interference nulling signals towards or from the other selected directions.

In Fig. 3C, an interference of amplitude c coming from the arrival direction of beam C, is coupled out from the main signal path of beam B, by inserting on said path a variable coupler module at its other input port, with signals from waves B and C, extracted from the extra elements dedicated to beam B. The operation has to be repeated straightforwardly for coupling out the next of remaining interferences, as shown in Fig. 3-C for beam A between port A and ZF port A' 307-1.

The orthogonal and zero-forcing low loss analogue sub-array sub-beamformers, disclosed in Fig. 3B and Fig. 3C, can also be used for non-linear sub-arrays, for example for planar sub-arrays of radiating elements in square or triangular lattices. Provided all sub-array ports used for a beam have identical sub-array patterns pattern multiplication can be used as is in this invention with the orthogonal or ZF function provided by the array sub-beamformers, the sub-array sub-beamformers or both if extra null depths or suppression of array factor grating lobe(s) are required.

These analogue sub-array sub-beamformers, avoiding combiner/divider losses and disclosed in Fig. 3B and Fig. 3C, can be used instead of the conventional analogue ones.

Complexity increases rapidly with the number of beams, particularly for zero-forcing beam generation, which requires extra elements and circuits.

Fig. 4 shows a schematic diagram of the preferred embodiment of the invention with the above low loss sub-array but simpler orthogonal beam formers. The IM function can be provided by the (e.g. horizontal) array sub-beamformers.

This hybrid multiple beam array uses baseband digital IM beamforming for the (e.g. horizontal) array beamforming 402 and this disclosure for the low loss analogue generation in 406 sub-array sub-beamformers of sub-array orthogonal beams.

Directivity contour plots for 3 beams generated with 8 vertical sub-arrays of 8 elements each (Fig. 5A), using the beamforming configuration of the invention as depicted in Fig. 4 and Fig. 5B, are shown in Fig. 5D.

The simulation confirms that the low-loss orthogonal beamformers 506, as well as the simplification benefits of IM (zero-forcing in the reported example) by pattern multiplication, performed as disclosed.

Using standard zero-forcing techniques, this particular case would require the inversion of a matrix of size 3x64. The proposed approach reduces the zero-forcing technique to a matrix of size 3x8. This leads to a significant reduction in computational effort and hardware complexity.

Both the concepts of simplified agile IM beamforming by using multiport sub-arrays and pattern multiplication and the low-loss analogue orthogonal beamforming do limit the number of usable agile beams.

This makes this approach best suited for applications with 2, 3 or 4 beams such as satellite or mobile user terminals or for active remote sensing applications, such as single or multiple beam radar systems, where power from single or multiple fixed or mobile jammers can be fully absorbed and thus suppressed from the radar beam(s).

Hybrid designs are also potentially applicable to 5G or 6G communications with a few (shaped-reconfigurable) sector beams in elevation produced by the disclosed low loss analogue orthogonal beam formers and multiple zero forcing or MMSE digitally formed array-factor beams in azimuth.

Independently of the beamforming design used, the gain at users or targets of IM beams is much affected by their angular distance to the closest co-channel user or target, which should not be less than the (sub-) array resolution. This is often ignored in signal processing statistical analysis and can lead to misinterpreting achievable beamforming performance.

Those skilled in the art will be able to implement various arrangements and combinations that embody the principles of these disclosures and are included within their spirit and scope.

For instance, and as already said, the array sub-beamformers can be analogue at RF or at an IF frequency, for example using IC technology, and generate orthogonal sub-array beams, the IM function being provided by the array sub-beamformers, that can be analogue or digital.

For IM beamforming, a fully digital implementation with $N_1 x N_2$ data format and frequency conversion (RF) chains would also benefit from the much reduced computational and processing load associated with the pattern multiplication approach.

The beamforming networks disclosed in the above-described embodiments have the following advantages:

1) They provide analogue beamforming networks for generation from an array antenna of multiple agile beams, with or without zero-forcing, sidelobe control, with elimination of combining RF losses
2) They provide, with reduction of complexity, multiple agile beamforming with interference mitigation (in analogue and/or digital domains), by use of pattern multiplication
3) They provide beamforming with beams generated by the product of one or more fixed or reconfigurable sub-array shaped beams, each by one or several reconfigurable array factor beams formed with zero forcing, Minimum Mean-Square Error weighting or sidelobe control synthesis, for interference mitigation.

The examples and embodiments described herein serve to illustrate rather than limit the invention. The person skilled in the art will be able to design alternative embodiments without departing from the scope of the claims. Reference signs placed in parentheses in the claims shall not be interpreted to limit the scope of the claims. Items described as separate entities in the claims or the description may be implemented as a single hardware or software item combining the features of the items described.

Although the document mostly describes the present invention with respect to a transmitting system, the invention can be equally applied to a receiving or to a transmitting and receiving antenna system.

**Conclusies**

1. Een beamforming netwerk (200) voor het genereren van twee of meer beweeglijke stralen van een arrayantenne (240), waarbij de arrayantenne (240) een aantal van N1 x $N_2$ stralingselementen (210-1,..., 210-$N_1$ x $N_2$) bevat, opgesteld in een lineaire array van $N_1$ identieke lineaire subarrays, waarbij elke lineaire subarray een reeks van $N_2$ stralingselementen onder de $N_1 \times N_2$ stralingselementen (210-1,..., 210-$N_1$x$N_2$) bevat, waarbij de $N_1$ lineaire subarrays onder een hoek van 90° of een andere hoek ten opzichte van de lineaire array zijn gedraaid,

waarbij het beamforming netwerk (200) twee reeksen sub-beamformers bevat, waarbij:

- de ene reeks subbeamformers een aantal $M_1$ subbeamformers met matrixfactor (202-1,..., 202-$M_1$) bevat, waarbij $M_1 > 1$;

- de andere reeks sub-beamformers bevat een aantal $N_1$ identieke en identiek geconfigureerde subarray sub-beamformers (206-1, ..., 206-$N_1$), waarbij $N_1 > 1$;

waarbij, voor m = 1,..., $M_1$, elke m-de array factor sub-beamformer (202-m) een arraystraalpoort (201-m) bevat voor straal (m) signaal, en een aantal $N_1$ sub-beamformers (205-$m_1$,...,205-m$N_1$), waarbij elke arraystraalpoort (201-m) is aangesloten op alle $N_1$ sub-beamformers (205-$m_1$, ..., 205-m$N_1$) met, voor elk sub-signaalpad van de arraystraalpoort (201-m) naar een subarraypoort (205-mn), een variabele weging van het sub-signaal wmn, geoptimaliseerd zodat, als de $N_1$ uitgangssubarraypoorten (205-$m_1$,..., 205-m$N_1$) zijn aangesloten op een lineaire array van $N_1$ isotrope stralingselementen met dezelfde afstand als de $N_1$ subarrays van de array (240), het resulterende m-de "arrayfactor" stralingspatroon een waaierstraal is in een vereiste richting of een gevormde waaierstraal, met of zonder toegevoegde interferentievermindering, waarbij de toegevoegde interferentievermindering kan bestaan uit nulling/zero-forcing, sidelobe-controle of weging van de minimale gemiddelde kwadratenfout in de richting van andere stralen die dezelfde frequenties opnieuw gebruiken,

waarbij, voor n = 1,..., $N_1$, elke n-de sub-beamformer (206-n) een aantal $M_1$ van subarraystraalpoorten (207-$n_1$,...,207-n$M_1$) en een aantal $N_2$ van subarrayelementpoorten (209-$n_1$,...,209-n$N_2$) bevat, waarbij $N_2 > M_1$, waarbij voor een bepaalde reeks $M_1$ arraystralen alle $N_1$ sub-beamformers (206-1,...., 206- $N_1$) identiek geconfigureerd zijn zodat:

- voor n = 1,..., $N_1$, elke n-de sub-beamformer (206-n) zijn subarraystraalpoort (207-nm) aangesloten heeft op alle $N_2$ subarrayelementpoorten (209-$n_1$,..., 209-n$N_2$) met, voor elk subsignaalpad van de arraystraalpoort (207-nm) naar een subarrayelementpoort (209-nk), een variabel subsignaalpad wnk, waarbij het variabele subsignaalpad wnk zo is geoptimaliseerd dat, als de $N_2$ uitgangspoorten voor subarray-elementen (209-$n_1$,..., 209-n$N_2$) waren aangesloten op de corresponderende $N_2$ stralingselementen van subarray n van de array (240), het resulterende m-de subarraystraalpatroon een waaierstraal is in een vereiste richting of een gevormde waaierstraal, met of zonder toegevoegde storingsbeperking, gedraaid onder een hoek van 90° of een andere hoek ten opzichte van het corresponderende m-de "arrayfactor" waaierstraalpatroon, waarbij de toegevoegde storingsbeperking door subarraystralen kan worden uitgevoerd door nulling/zero forcing, sidelobe controle of weging van de minimale gemiddelde kwadratenfout in de richting van andere waaierstralen die dezelfde frequenties hergebruiken,

- en
- voor iedere k=1,...,$N_2$:

de m-de subsignalen voor m=1 tot $M_1$ door de k-de aansluiting van het element van de subarray gaan;

de associatie van de lineaire subarray met een dergelijke sub-beamformer met meerdere straalpoorten een multiport subarray wordt genoemd;

waarbij de n-de subarraypoort (205-mn) van de m-de arrayfactor sub-beamformer is aangesloten op de m-de subarraystraalpoort (207-nm) van de n-de subarray sub-beamformer voor n = 1,..., $N_1$ en m = 1,..., $M_1$;

waarbij, als gevolg van de bovengenoemde verbindingen van de sub-beamformers van de arrayfactor met de sub-beamformers van de subarraystraalpoorten, de algemene straalpatronen voor stralen m = 1,..., $M_1$, in associatie met de arrayantenne (240), de producten zullen zijn van het straalpatroon m van de arrayfactor door het bijbehorende straalpatroon m van de subarray;

waardoor, als resultaat, voor stralen m = 1,..., $M_1$, de straling in één richting wordt gemaximaliseerd door maximalisatie van zowel het straalpatroon m van de arrayfactor als het bijbehorende subarraystraalpatroon m in die richting, terwijl de interferentie wordt gemitigeerd door nulling/zero-forcing, sidelobe-controle, weging van de minimale gemiddelde kwadratenfout of andere middelen beperkt kan worden tot de arrayfactor sub-beamformers of de subarray sub-beamformers, wat resulteert in een belangrijke vereenvoudiging van de verwerking en hardware voor de mitigatie van interferentie, waarbij opgemerkt wordt dat het op beide typen sub-beamformers tegelijk toegepast kan worden voor stralen die extra mitigatie van interferentie nodig hebben.

2. Het beamforming netwerk (200) volgens een van de voorgaande conclusies waarin meer dan één straal kan worden gegenereerd door elke sub-beamformer (202) voor elke subarraystraal, indien nodig, om richtingen binnen (of sluitend bij) dezelfde subarraystraal te bedienen, die ook vormbaar, herconfigureerbaar of vast kan zijn, zodat het array-systeem meer dan $M_1$ of $N_2$ stralen kan genereren.

3. Het beamforming netwerk (200) volgens een van de voorgaande conclusies, waarin de $N_1$ subarray sub-beamformers analoge beamformers op een stralingsfrequentie zijn en de $M_1$ array factor sub-beamformers digitale beamformers op basisband zijn en geconfigureerd zijn om de functie voor interferentie mitigatie te verschaffen.

4. Het beamforming netwerk (200) volgens een van de voorgaande conclusies, waarbij de $N_1$ subarray sub-beamformers analoge straalvormers zijn bij een stralingsfrequentie en de $M_1$ array sub-beamformers analoge straalvormers zijn en geconfigureerd zijn om de functionaliteit voor interferentie mitigatie te verschaffen.

5. Het beamforming netwerk (200) volgens conclusies 3 of 4, waarbij de $N_1$ sub-beamformers ook geconfigureerd zijn om de interferentie te mitigeren.

6. Het beamforming netwerk (200) volgens een van de bovenstaande conclusies, waarin de $N_1$ subarray sub-beamformers geconfigureerd zijn als de sub-beamformers (329) om, nominaal verliesvrij, meerdere orthogonale subarraystralen te genereren, waarin elke subarray sub-beamformer een meervoud van vierpoorts IC-componenten met variabele aanwinstversterking of een meervoud van microgolfkoppelmodules met vier poorten van het vaste (321) en/of variabele (324) type bevat, elk met een fase- of

tijdverschuiver (323) en respectievelijk een geïsoleerde en gekoppelde vaste koppeling (322) of een variabele koppeling (325), waarbij de vierpoorts IC-componenten met variabele versterkingsfactor of de meervoudige vierpoorts modules met microgolfkoppeling iteratief geconfigureerd zijn om signalen die door de uitstralende elementen uit verschillende richtingen worden ontvangen, te verzwaren en te focussen op een andere straalpoort; waarin een eerste reeks $N_2$-1 fase/amplitude variabele modules van de meervoudige fase/amplitude variabele modules elk geconfigureerd zijn om de optimalisatie van de richtingsgevoeligheid uit te voeren voor een eerste geselecteerde straal die wordt ontvangen op een eerste subarraystraalpoort van de $M_1$ subarraystraalpoorten, zodat geen richtingsgevoeligheid uit een richting van aankomst van de geselecteerde straal wordt ontvangen op andere subarraystraalpoorten van de $M_1$ subarraystraalpoorten; waarin een tweede reeks $N_2$-2 fase/amplitude variabele modules van de meervoudige reeks fase/amplitude variabele modules geconfigureerd is om signalen te ontvangen van andere subarraystraalpoorten van de $M_1$ subarraystraalpoorten dan de subarraystraalpoorten die op de eerste reeks fase/amplitude variabele modules aangesloten zijn, om de richtingsgevoeligheid te optimaliseren voor een tweede geselecteerde straal die op een tweede subarraystraalpoort ontvangen wordt, zodat geen interferentievermogen uit een richting van aankomst van de tweede geselecteerde straal op andere subarraystraalpoorten van de $M_1$ subarraystraalpoorten ontvangen wordt; waarin een derde reeks $N_2$-3 fase/amplitude variabele modules van de meervoudige reeks fase/amplitude variabele modules geconfigureerd is om signalen te ontvangen van andere subarraystraalpoorten van de $M_1$ subarraystraalpoorten dan de subarraystraalpoorten die op de eerste en tweede reeks fase/amplitude variabele modules aangesloten zijn, om de richtingsgevoeligheid te optimaliseren voor een derde geselecteerde straal die op een derde subarraystraalpoort ontvangen wordt, zodat geen interferentievermogen uit een richting van aankomst van de derde geselecteerde straal op andere subarraystraalpoorten van de $M_1$ subarraystraalpoorten ontvangen wordt; waarbij een $M_1$e reeks van $N_2$-$M_1$ fase/amplitude variabele modules onder de meervoudige fase/amplitude variabele modules geconfigureerd is om signalen te ontvangen van andere subarraystraalpoorten onder de $M_1$ subarraystraalpoorten dan de subarraystraalpoorten die aangesloten zijn op de eerste, tweede en derde reeks fase/amplitude variabele modules, om de richtingsgevoeligheid te optimaliseren voor een vierde geselecteerde straal die wordt ontvangen op een vierde subarraystraalpoort, zodat geen interferentievermogen uit de richting van aankomst van de eerste, tweede en derde geselecteerde straal wordt ontvangen op de vierde subarraystraalpoort, zodat de vierde geselecteerde straal zero-forcing is van of naar de richting van aankomst van de eerste, tweede en derde geselecteerde straal,

waarbij dergelijke theoretisch verliesloze sub-beamformers (329) beweeglijke stralen met gedeeltelijke zero-forcing verschaffen.

7. Het beamforming netwerk (200) volgens een van de bovenstaande conclusies 1 tot en met 5, waarbij elke analoge sub-beamformer, met $M_1$ subbeamformers en in totaal $N_2 + (M_1\text{-}1)^2$ elementpoorten, nominaal verliesvrij is en bevat:

het subnetwerk (329) van conclusie 6 met $M_1$ (maximaal $N_2$) orthogonale stralingspoorten, elk aangesloten op $N_2$ kernelementen die voor alle stralen worden gebruikt; een tweede subnetwerk (330), toegevoegd om storingen te annuleren die ontvangen worden van of verzonden worden naar de richtingen van de 1 tot $M_1$-1 orthogonale maar niet volledig nul-forcerende stralingspoorten van het subnetwerk (329), het tweede subnetwerk (330) bevat, voor elk van deze $M_1$-1 poorten, een circuit voor het opheffen van storingen, aangesloten op $M_1$-1 specifieke stralingselementen, toegevoegd aan $N_2$ kernelementen die verbonden zijn met het subnetwerk (329), waarin elk circuit voor het opheffen van storingen gebruik maakt van in cascade geschakelde variabele modules met vier poortkoppelingen (324), geconfigureerd om uit elke toegevoegde straal specifieke stralingselementen gewenste en storingsonderdrukkende signalen te extraheren die op een iteratieve manier worden gewogen en respectievelijk worden toegevoegd aan en afgetrokken van de signalen op elk van de uitgangspoorten van de stralen van het subnetwerk (329), waardoor de aanwinst voor gewenste stralingssignalen wordt verhoogd en de resterende storende signalen worden geannuleerd, zodat behendige subarraystralen met volledige zero-forcing interferentie mitigatie worden gegenereerd.

8. Het beamforming netwerk (200) volgens conclusie 1, waarbij de $N_1$ sub-beamformers conventionele analoge beamformers met combinatieverliezen zijn.

9. Het beamforming netwerk (200) volgens conclusie 1, waarbij de $M_1$ array factor sub-beamformers conventionele analoge beamformers met combinatieverliezen zijn.

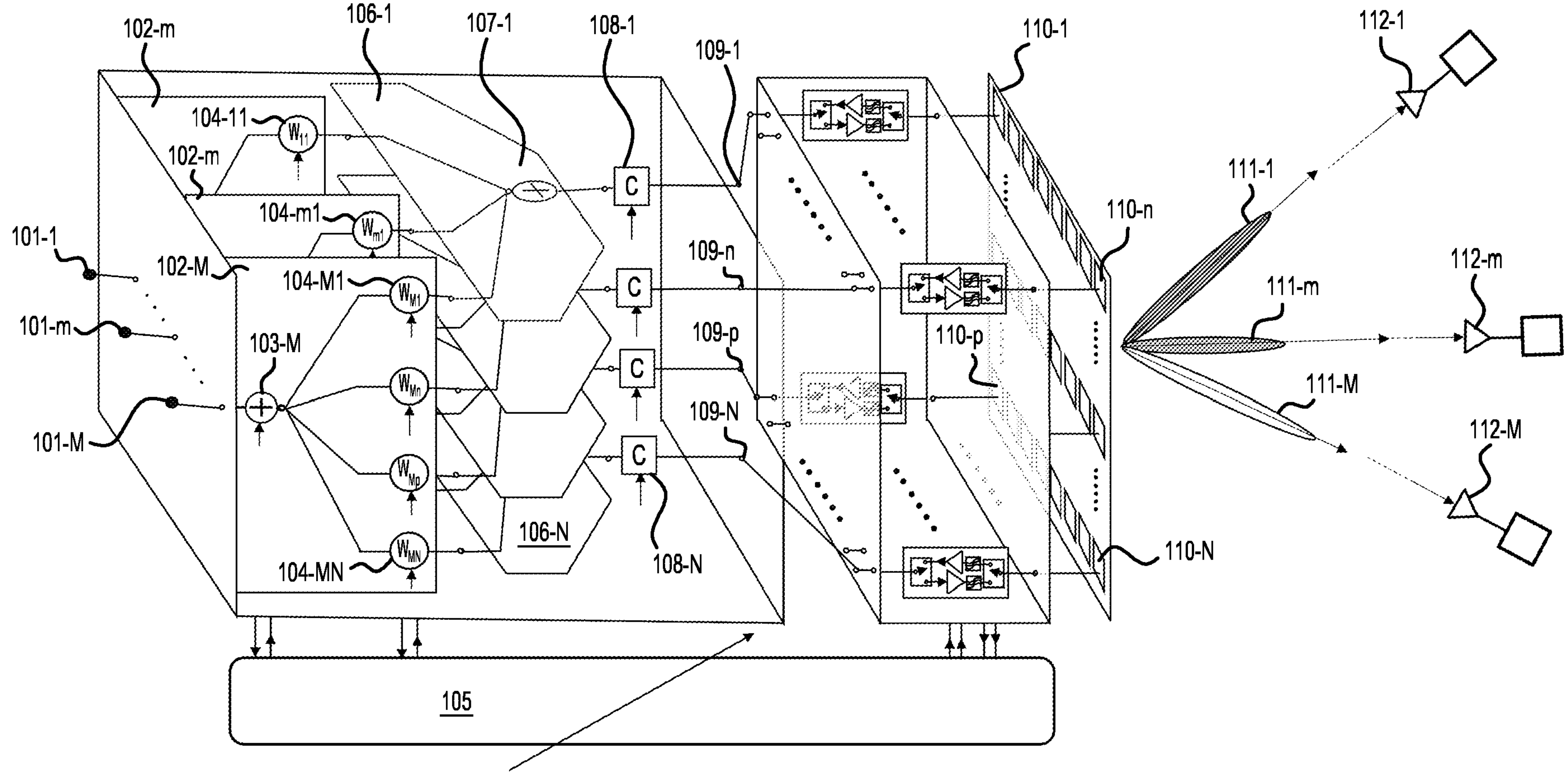
10. Een multibeam-antenne bevattende het beamforming netwerk (200) volgens een van de voorgaande conclusies, verder verbonden met de arrayantenne (240) door verbinding van de respectievelijke elementaansluitingen van het beamforming netwerk (200) met de respectievelijke antenne-elementen van de arrayantenne (240).

11. Een multibeam-antenne volgens conclusie 10 waarbij de arrayantenne (240) een array van $N_1$ identieke multiport subarrays van elk $N_2$ stralingselementen bevat, alle subarrays ten opzichte van elkaar zijn vertaald en alle worden gebruikt met een identieke reeks van subarray straalpatronen.

12. Het beamforming netwerk (200) volgens conclusie 1, dat verder volledig analoog is en $N_1$ analoge subarray sub-beamformers en $M_1$ analoge array factor sub-beamformers bevat, of dat verder volledig digitaal is en $N_1$ digitale subarray sub-beamformers en $M_1$ digitale array factor sub-beamformers bevat, of dat verder hybride is en $N_1$ analoge subarray sub-beamformers en $M_1$ digitale array factor sub-beamformers bevat.

13. Het beamforming netwerk (200) volgens conclusie 1, dat verder is verbonden met versterkingsmodules en filtermodules tussen de aansluitingen van de sub-beamformers en de stralingselementen.

Fig. 1A - Prior art -



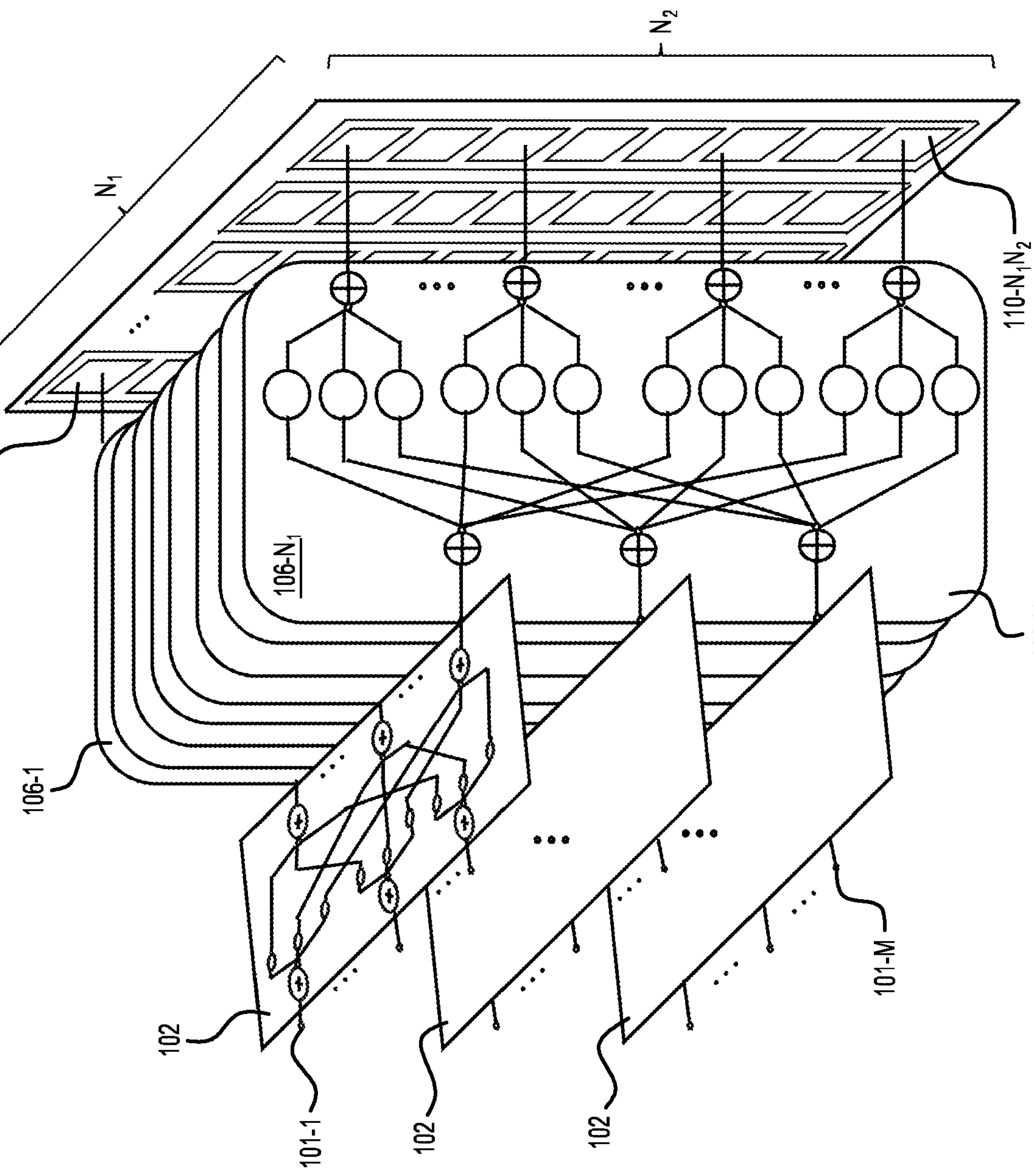



Fig. 1B - Prior art -

Fig. 2A

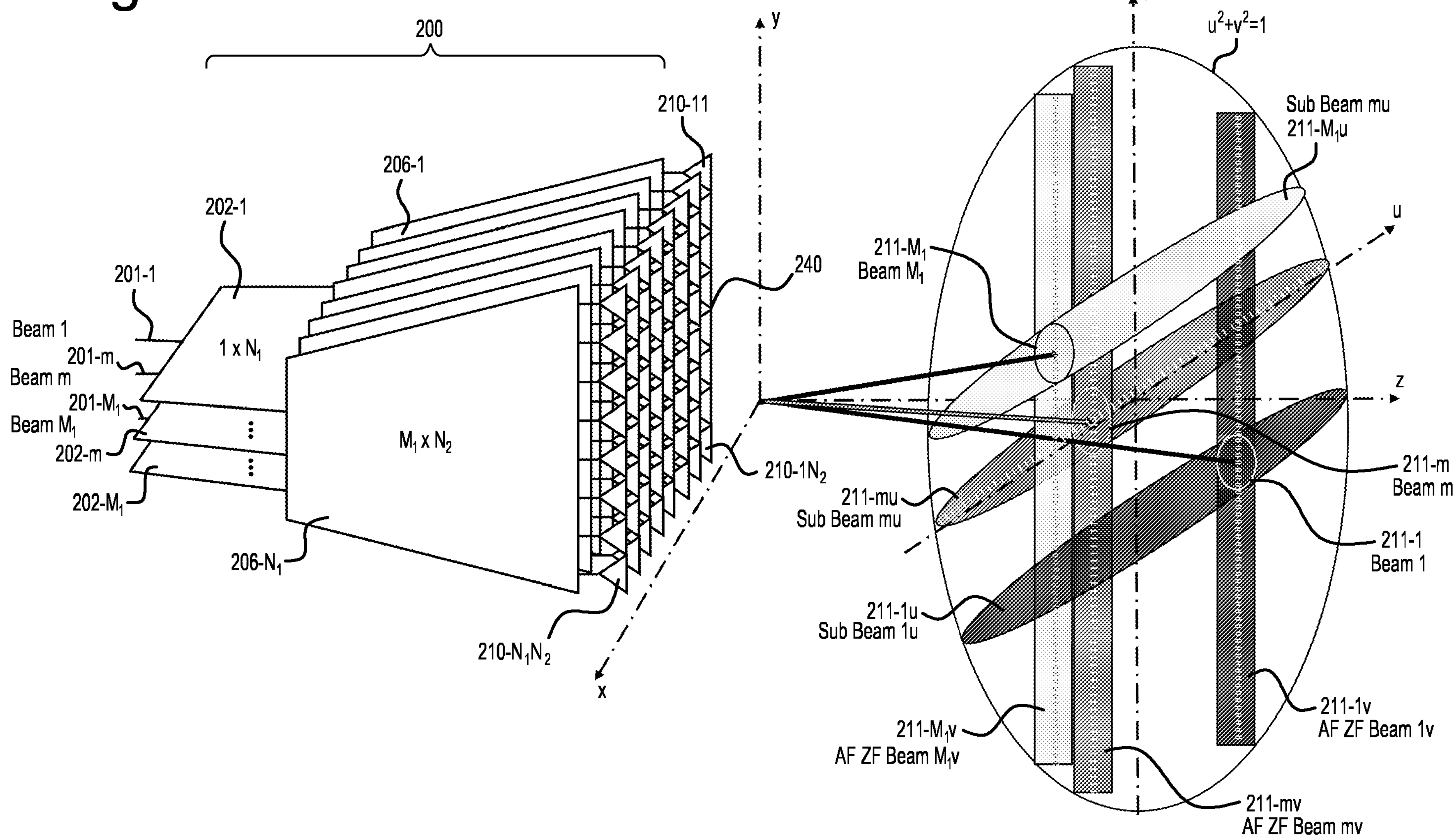

200
Beam 1
201-1
Beam m
201-m
Beam $M_1$
201-$M_1$
202-1
202-m
202-$M_1$
1 x $N_1$
$M_1$ x $N_2$
206-1
206-$N_1$
210-11
210-$1N_2$
210-$N_1N_2$
240
x
y
z
u
v
$u^2+v^2=1$
Sub Beam mu
211-$M_1$u
211-$M_1$
Beam $M_1$
211-mu
Sub Beam mu
211-1u
Sub Beam 1u
211-m
Beam m
211-1
Beam 1
211-1v
AF ZF Beam 1v
211-$M_1$v
AF ZF Beam $M_1$v
211-mv
AF ZF Beam mv

Fig. 2B

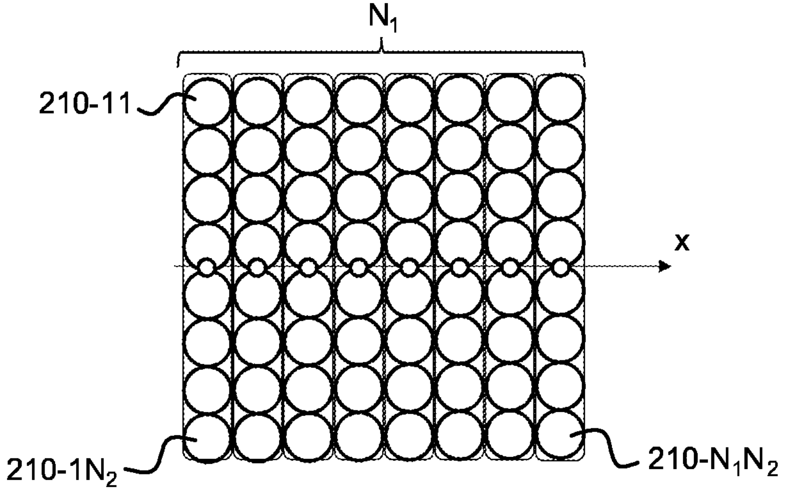



Fig. 2C

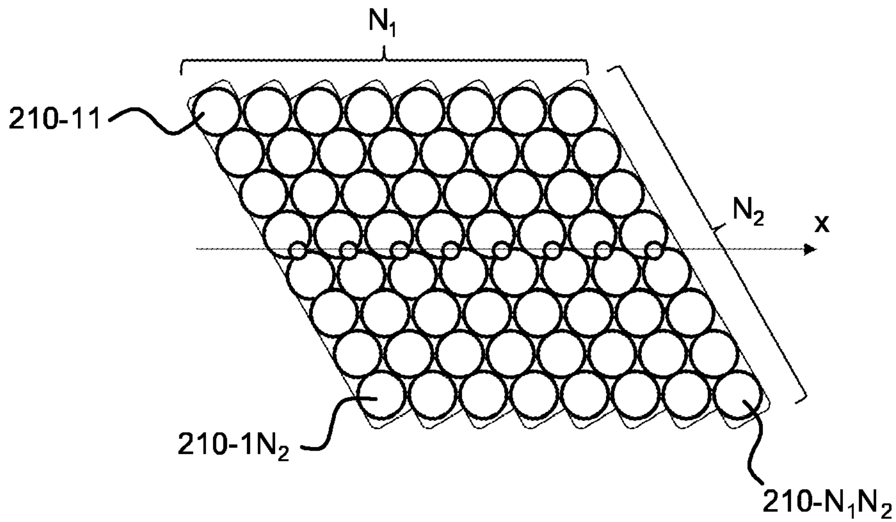


Fig. 2D

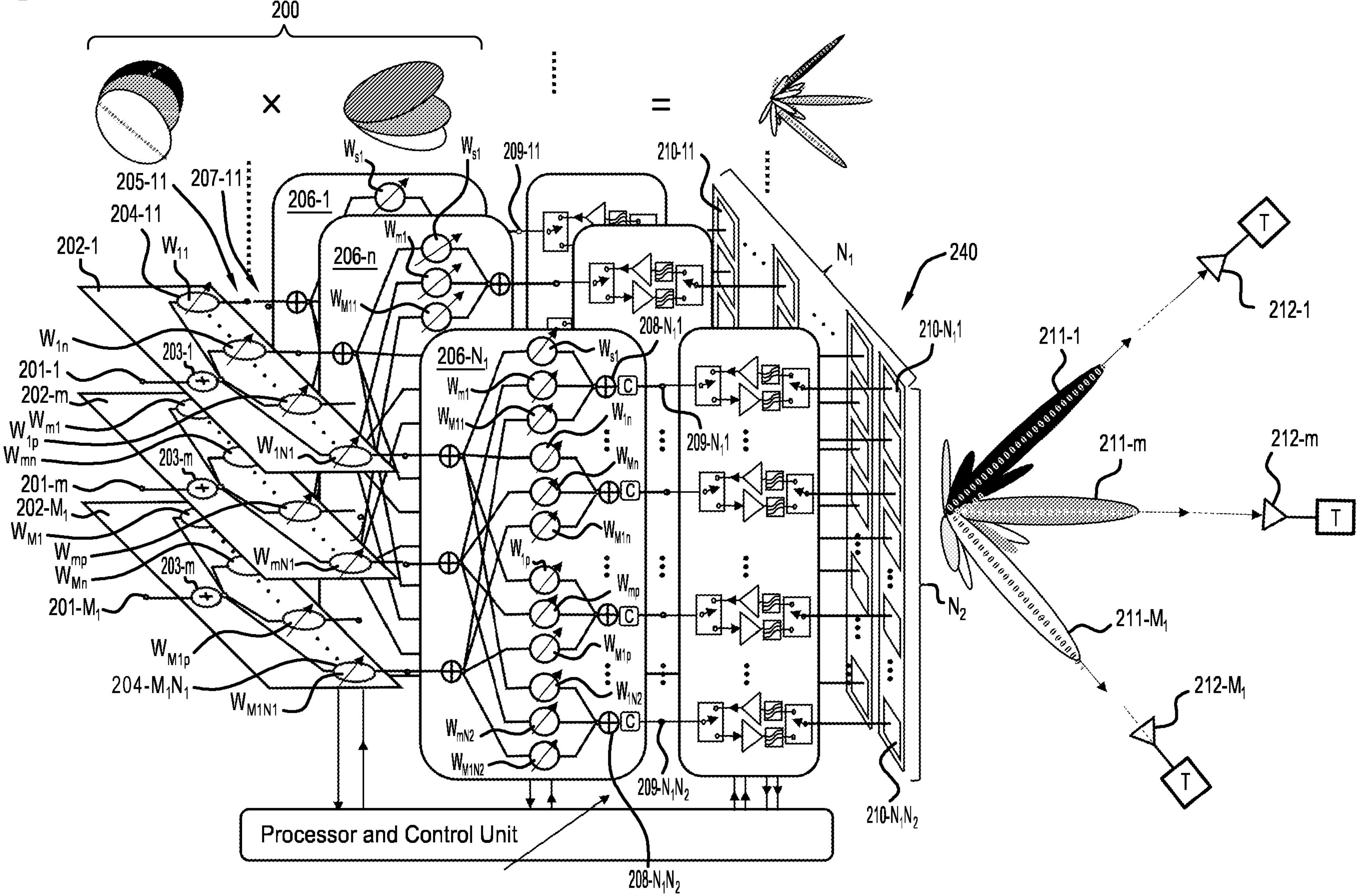

200
205-11
207-11
204-11
202-1
W11
206-1
206-n
206-N1
Ws1
Wm1
WM11
209-11
210-11
N1
240
208-N11
209-N11
210-N11
211-1
212-1
211-m
212-m
211-M1
212-M1
T
W1n
201-1
202-m
Wm1
W1p
Wmn
203-1
203-m
W1N1
201-m
202-M1
WM1
Wmp
WMn
WmN1
201-M1
WM1p
204-M1N1
WM1N1
W1n
WMn
WM1n
W1p
Wmp
WM1p
W1N2
WmN2
WM1N2
C
N2
209-N1N2
210-N1N2
208-N1N2
Processor and Control Unit

Fig. 2D - bis

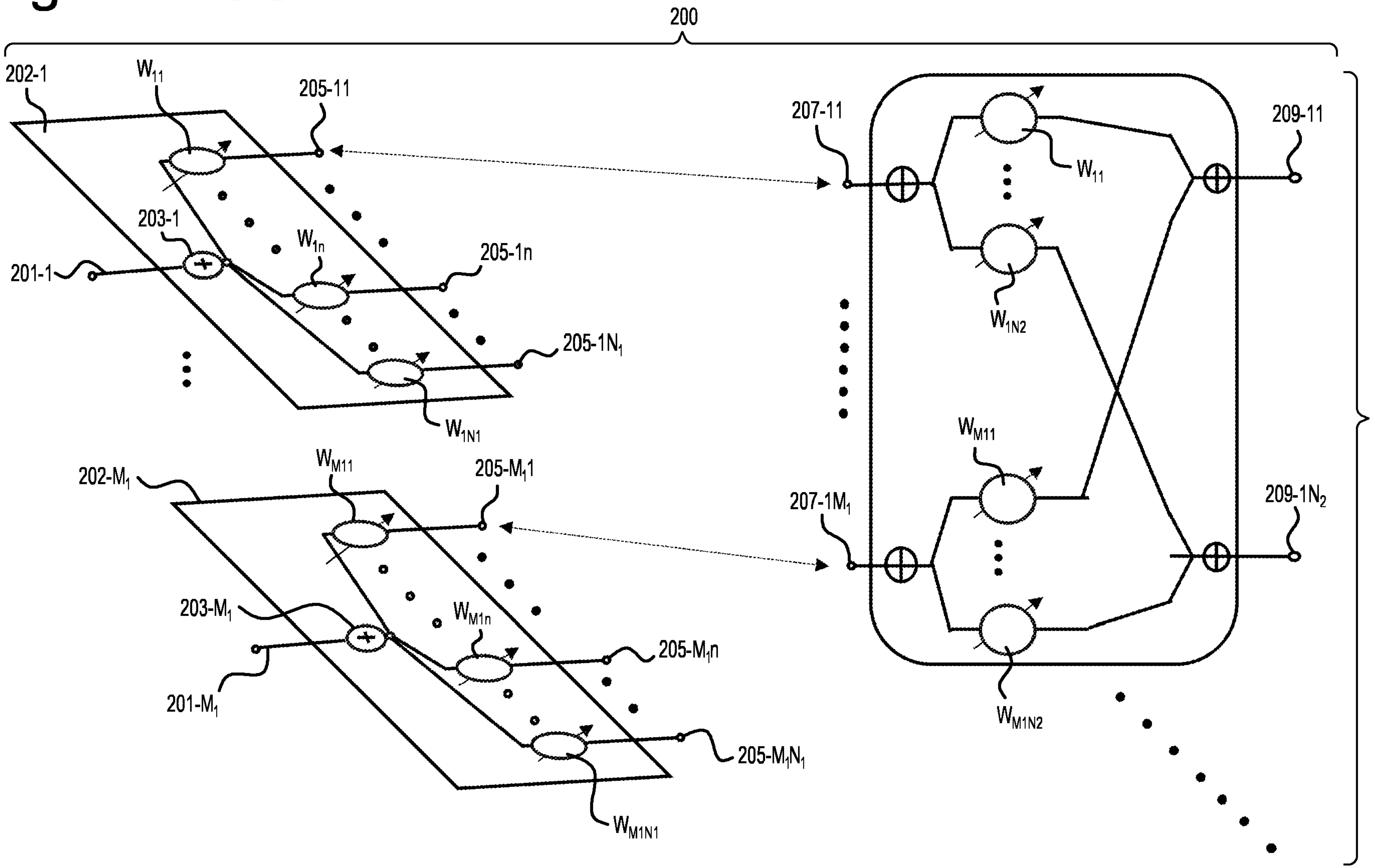
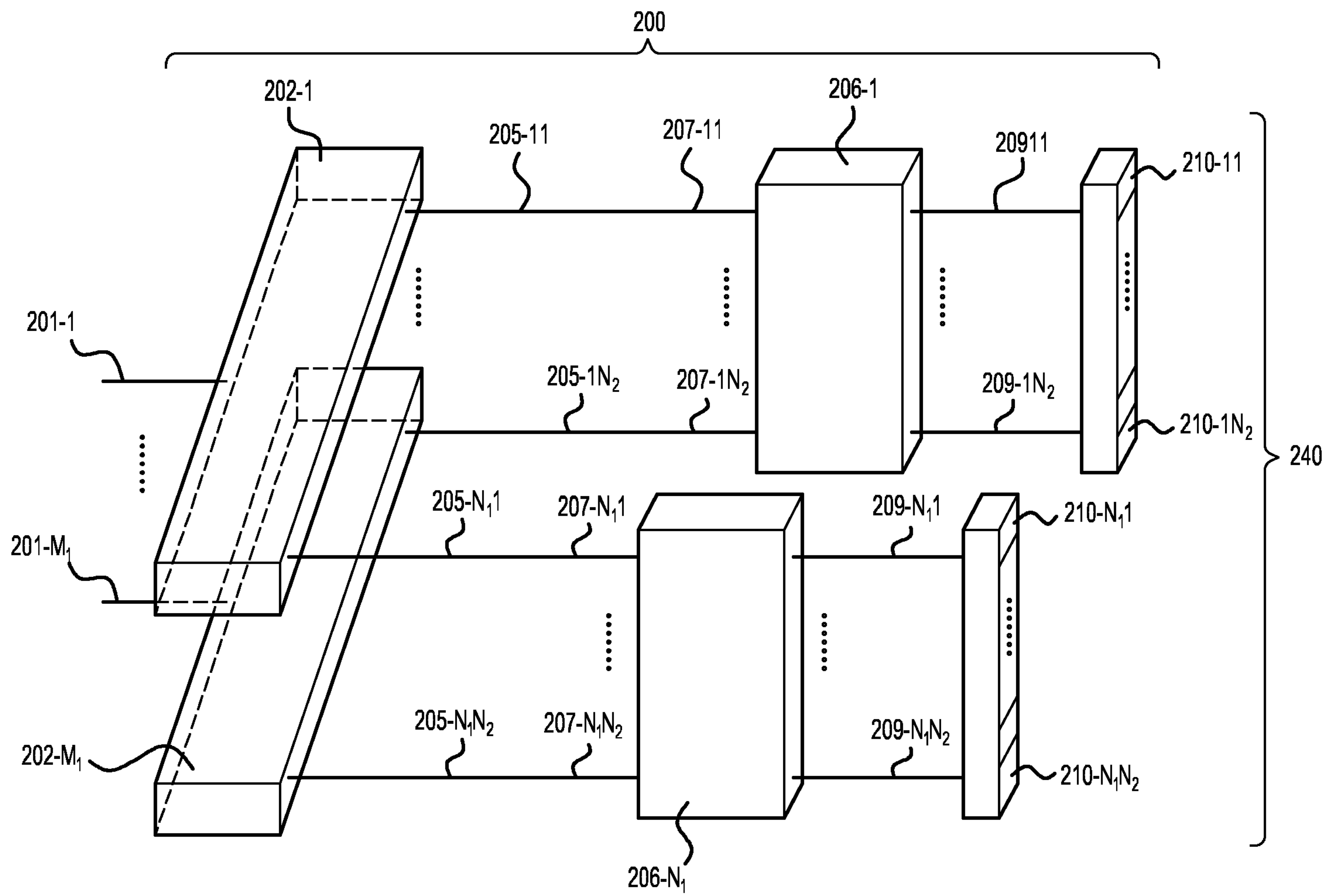

200
202-1
W11
205-11
203-1
W1n
201-1
205-1n
205-1N1
W1N1
202-M1
WM11
205-M11
203-M1
WM1n
201-M1
205-M1n
205-M1N1
WM1N1
207-11
W11
W1N2
WM11
207-1M1
WM1N2
209-11
209-1N2
240

Fig. 2D - ter


200
202-1
205-11
207-11
206-1
20911
210-11
201-1
205-1N2
207-1N2
209-1N2
210-1N2
240
205-N11
207-N11
209-N11
210-N11
201-M1
202-M1
205-N1N2
207-N1N2
209-N1N2
210-N1N2
206-N1

# Fig. 2E

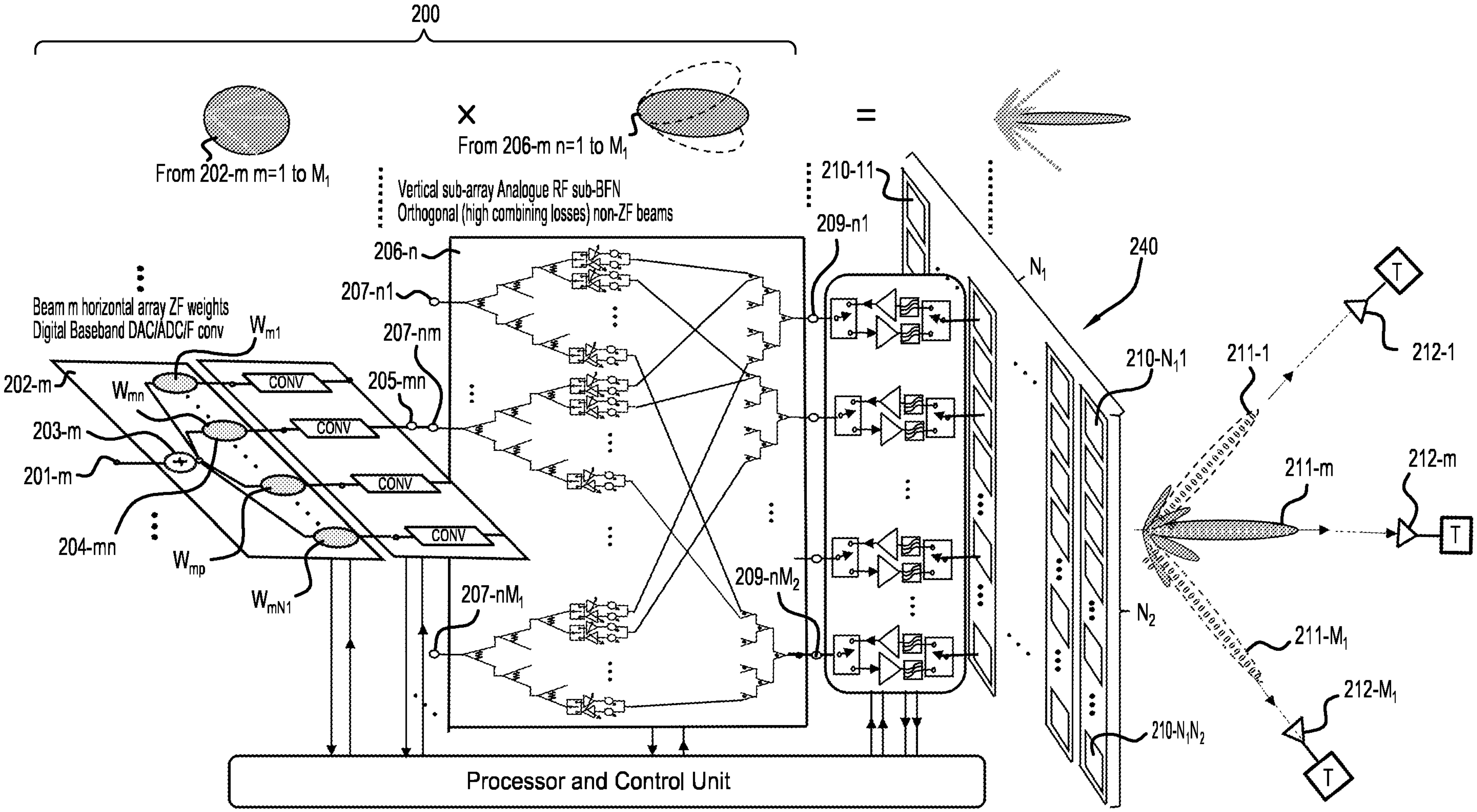

200
From 202-m m=1 to $M_1$
×
From 206-m n=1 to $M_1$
=
Vertical sub-array Analogue RF sub-BFN
Orthogonal (high combining losses) non-ZF beams
Beam m horizontal array ZF weights
Digital Baseband DAC/ADC/F conv
$W_{m1}$
$W_{mn}$
$W_{mp}$
$W_{mN1}$
202-m
203-m
201-m
204-mn
205-mn
206-n
207-n1
207-nm
$207\text{-}nM_1$
CONV
CONV
CONV
CONV
209-n1
$209\text{-}nM_2$
210-11
$210\text{-}N_11$
$210\text{-}N_1N_2$
$N_1$
$N_2$
240
211-1
211-m
$211\text{-}M_1$
212-1
212-m
$212\text{-}M_1$
T
T
T
Processor and Control Unit

Fig. 3A

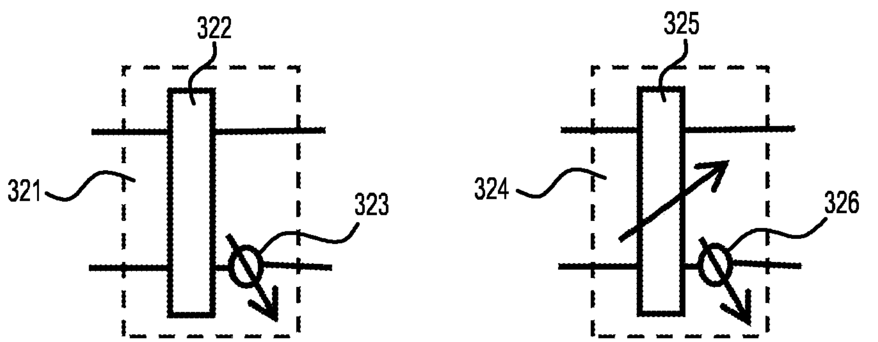

322
321
323
325
324
326

Fig. 3B

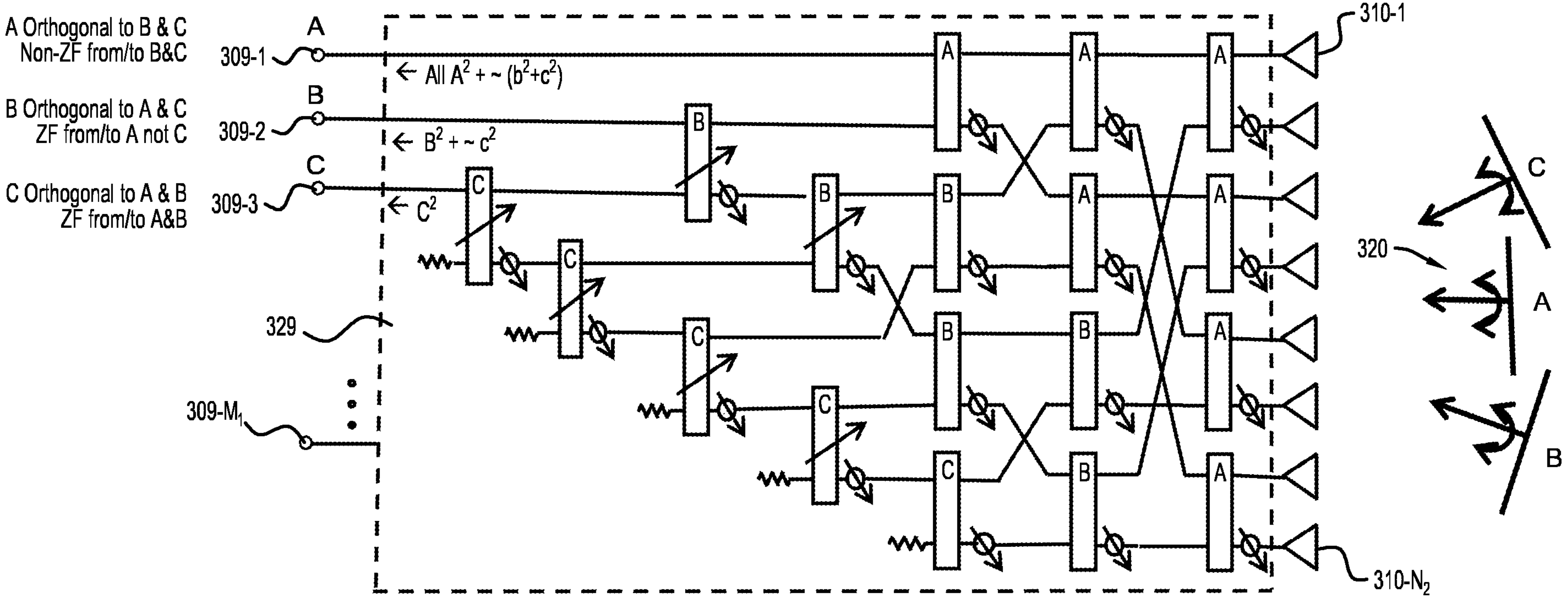
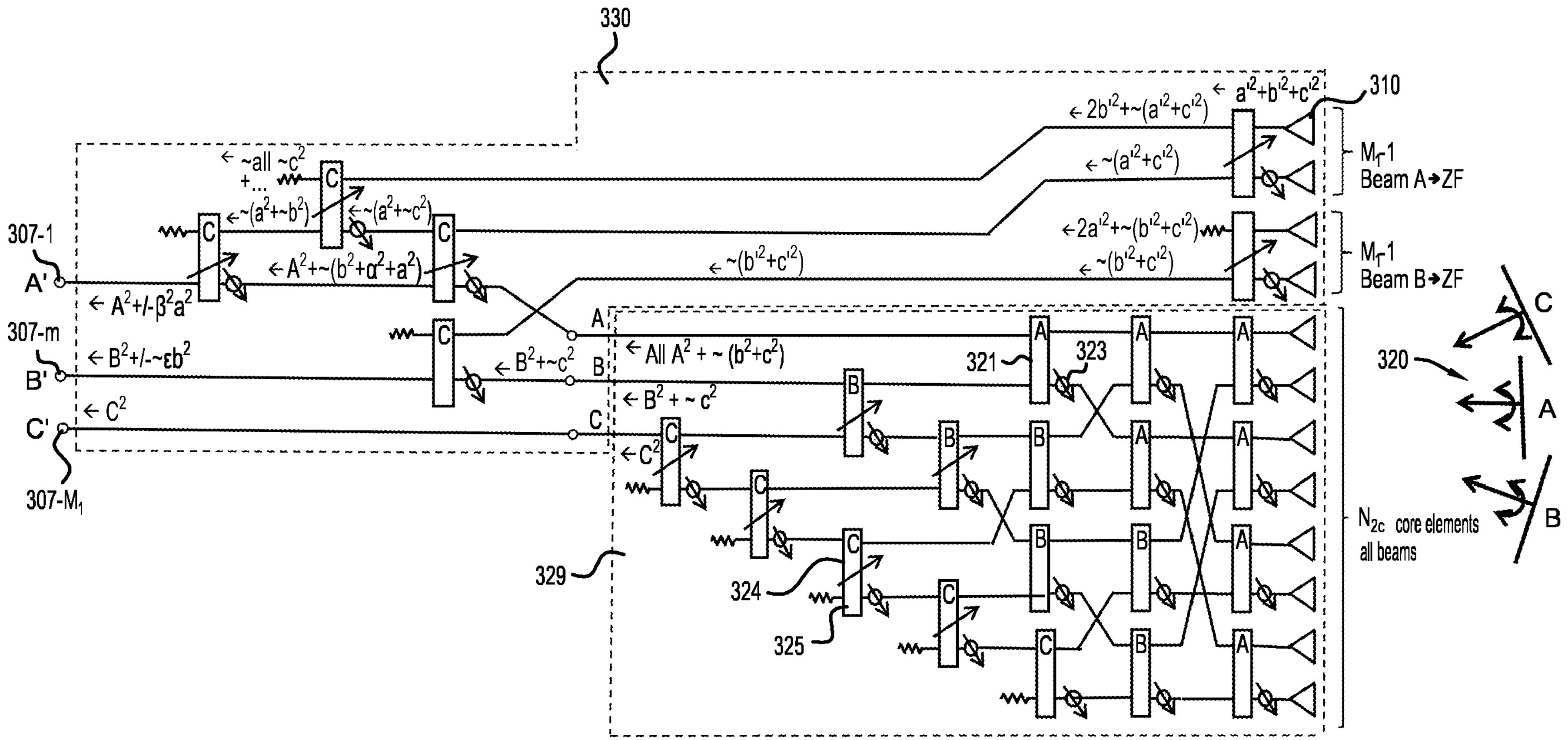

A Orthogonal to B & C
Non-ZF from/to B&C
B Orthogonal to A & C
ZF from/to A not C
C Orthogonal to A & B
ZF from/to A&B
309-1
309-2
309-3
309-M1
329
A
B
C
← All A2 + ~ (b2+c2)
← B2 + ~ c2
← C2
310-1
310-N2
320
A
B
C

Fig. 3C



330
310
307-1
A'
307-m
B'
C'
307-M1
← ~all ~c2
+...
←~(a2+~b2)
←~(a2+~c2)
← A2+~(b2+α2+a2)
← A2+/-β2a2
← B2+/-~εb2
← C2
← B2+~c2
A
B
C
← All A2 + ~ (b2+c2)
← B2 + ~ c2
← C2
← 2b'2+~(a'2+c'2)
← a'2+b'2+c'2
← ~(a'2+c'2)
←2a'2+~(b'2+c'2)
← ~(b'2+c'2)
← ~(b'2+c'2)
MT-1
Beam A→ZF
MT-1
Beam B→ZF
N2c core elements
all beams
320
321
323
324
325
329

Fig. 4

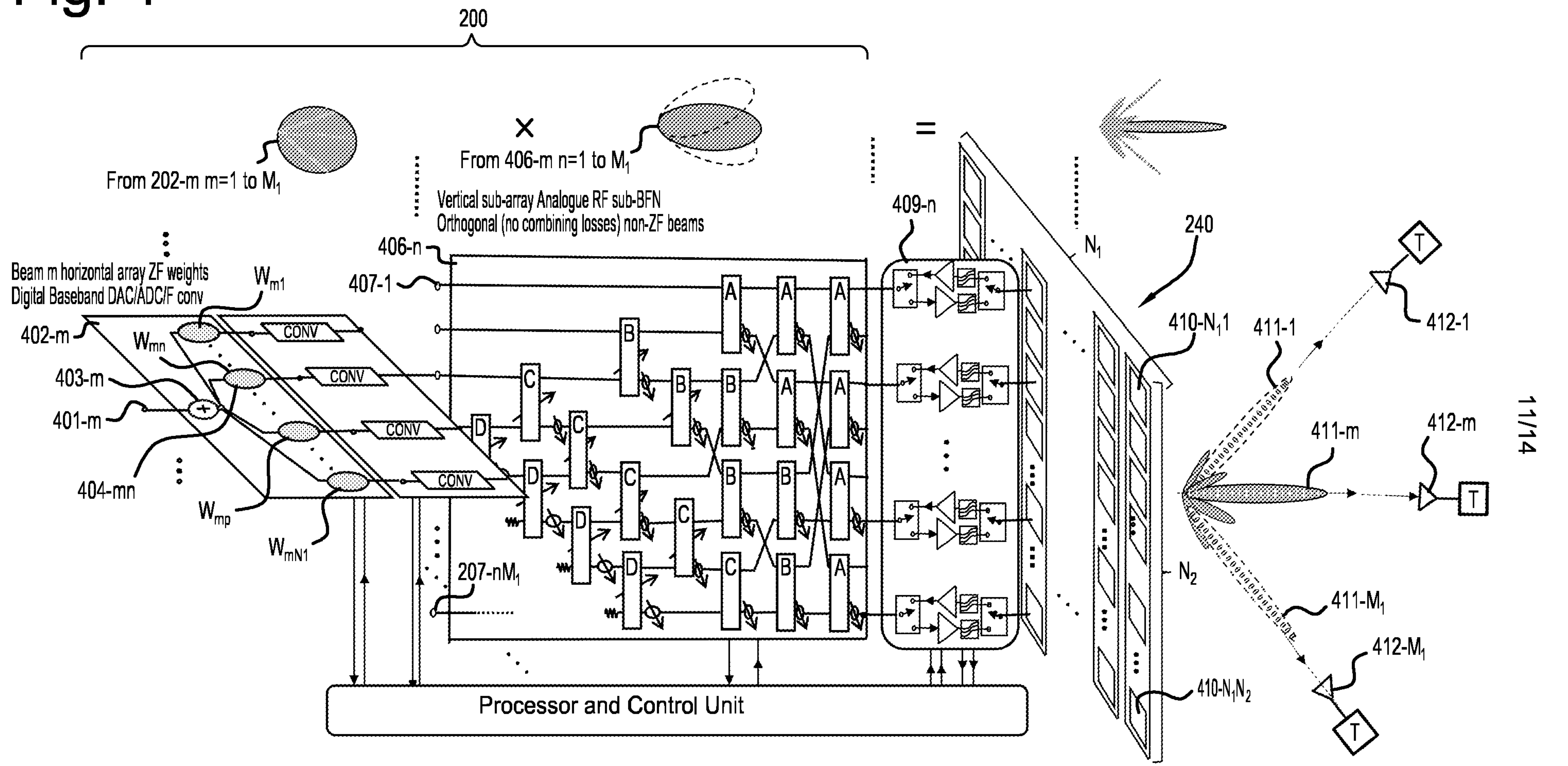
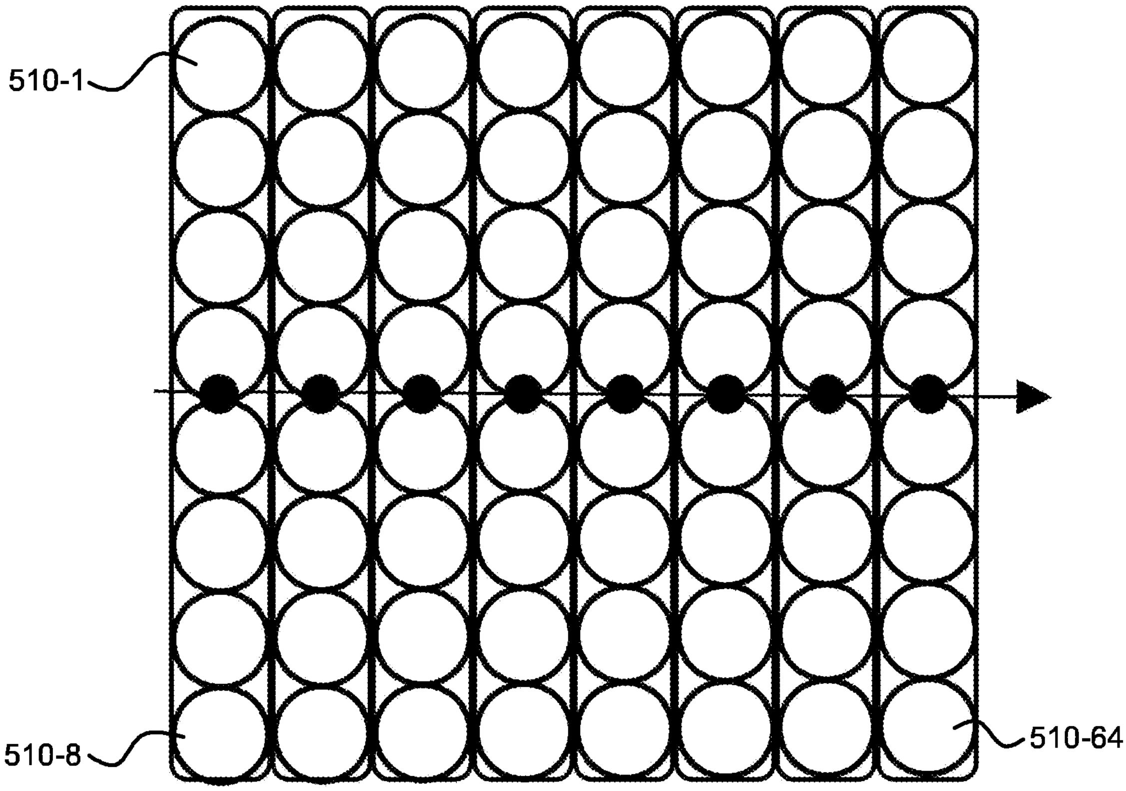
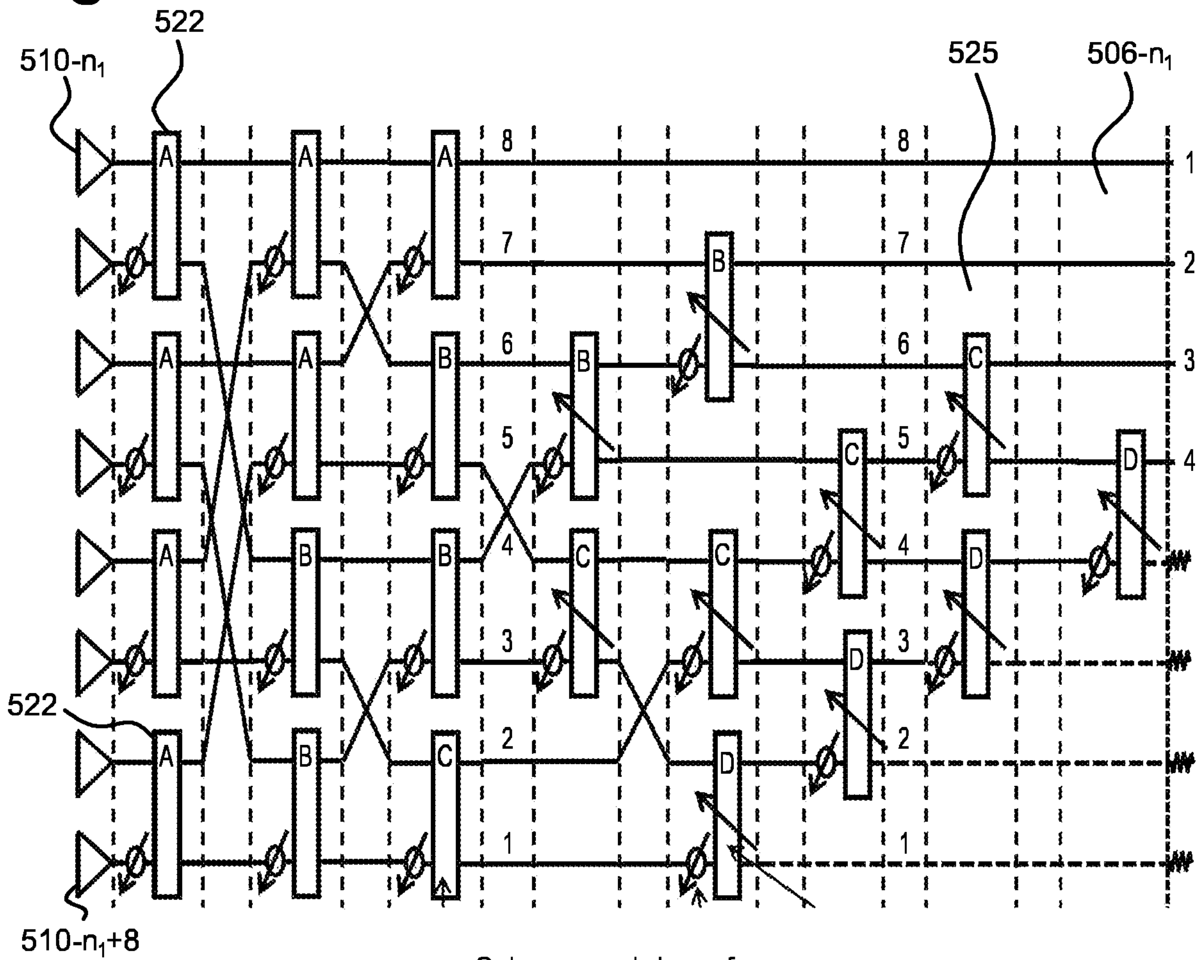

200
From 202-m m=1 to $M_1$
×
From 406-m n=1 to $M_1$
=
Vertical sub-array Analogue RF sub-BFN
Orthogonal (no combining losses) non-ZF beams
Beam m horizontal array ZF weights
Digital Baseband DAC/ADC/F conv
402-m
403-m
401-m
404-mn
$W_{m1}$
$W_{mn}$
$W_{mp}$
$W_{mN1}$
CONV
406-n
407-1
207-$nM_1$
A
B
C
D
409-n
Processor and Control Unit
240
$N_1$
$N_2$
410-$N_1$1
410-$N_1N_2$
411-1
411-m
411-$M_1$
412-1
412-m
412-$M_1$
T

Fig. 5A



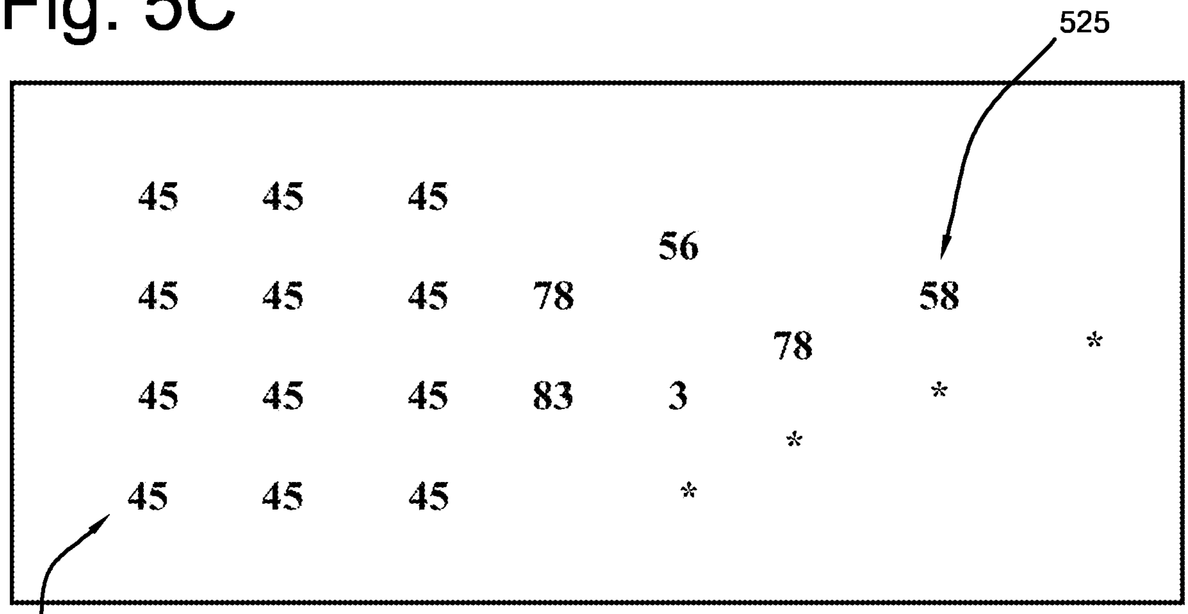

Array of 8 Sub-arrays of 8 elements

# Fig. 5B



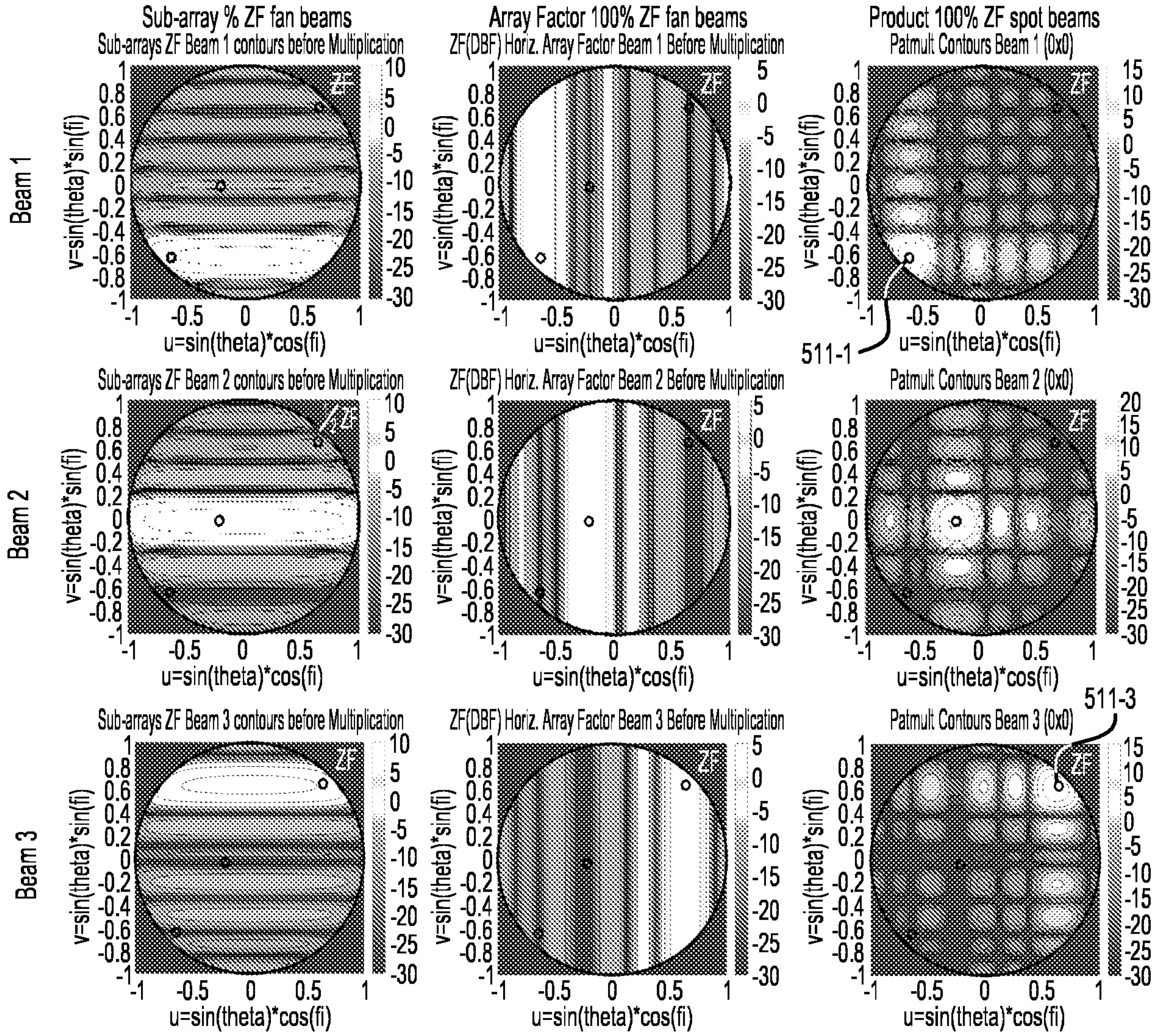

Sub-array sub-beamformer:
4 Non-ZF ortho beams x 8 elements

# Fig. 5C




Beamformer VPD angles deg. (45° - 3dB Hybrid)
For 3 top beam ports (* beam 4 not used)

# Fig. 5D




Beam 1 Patmult Peak directivity dB efficiency w.r.t. uniform array: -1.3129 dB
Beam 2 Patmult Peak directivity dB efficiency w.r.t. uniform array: -0.2810 dB
Beam 3 Patmult Peak directivity dB efficiency w.r.t. uniform array: -1.6407 dB

# SAMENWERKINGSVERDRAG (PCT)

## RAPPORT BETREFFENDE NIEUWHEIDSONDERZOEK VAN INTERNATIONAAL TYPE

| | |
|---|---|
| **IDENTIFICATIE VAN DE NATIONALE AANVRAGE** | **KENMERK VAN DE AANVRAGER OF VAN DE GEMACHTIGDE** |
| Nederlands aanvraag nr.<br>**2035700** | Indieningsdatum<br>**29-08-2023** |
| | Ingeroepen voorrangsdatum |
| Aanvrager (Naam)<br>**Technische Universiteit Delft** | |
| Datum van het verzoek voor een onderzoek van internationaal type<br>**24-10-2023** | Door de Instantie voor Internationaal Onderzoek aan het verzoek voor een onderzoek van internationaal type toegekend nr.<br>**SN84961** |
| **I. CLASSIFICATIE VAN HET ONDERWERP** (bij toepassing van verschillende classificaties, alle classificatiesymbolen opgeven) | |
| Volgens de internationale classificatie (IPC)<br>**Zie onderzoeksrapport** | |
| **II. ONDERZOCHTE GEBIEDEN VAN DE TECHNIEK** | |
| | Onderzochte minimumdocumentatie |
| Classificatiesysteem | Classificatiesymbolen |
| **IPC** | **Zie onderzoeksrapport** |
| Onderzochte andere documentatie dan de minimum documentatie, voor zover dergelijke documenten in de onderzochte gebieden zijn opgenomen | |
| | |
| **III.** ☐ **GEEN ONDERZOEK MOGELIJK VOOR BEPAALDE CONCLUSIES** | (opmerkingen op aanvullingsblad) |
| **IV.** ☐ **GEBREK AAN EENHEID VAN UITVINDING** | (opmerkingen op aanvullingsblad) |

Form PCT/ISA 201 A (11/2000)

# ONDERZOEKSRAPPORT BETREFFENDE HET RESULTAAT VAN HET ONDERZOEK NAAR DE STAND VAN DE TECHNIEK VAN HET INTERNATIONALE TYPE

Nummer van het verzoek om een onderzoek naar de stand van de techniek
NL 2035700

A. CLASSIFICATIE VAN HET ONDERWERP
INV. H04B7/06 H01Q3/26
ADD.

Volgens de Internationale Classificatie van octrooien (IPC) of zowel volgens de nationale classificatie als volgens de IPC.

B. ONDERZOCHTE GEBIEDEN VAN DE TECHNIEK

Onderzochte miminum documentatie (classificatie gevolgd door classificatiesymbolen)
H04B H01Q

Onderzochte andere documentatie dan de mimimum documentatie, voor dergelijke documenten, voor zover dergelijke documenten in de onderzochte gebieden zijn opgenomen

Tijdens het onderzoek geraadpleegde elektronische gegevensbestanden (naam van de gegevensbestanden en, waar uitvoerbaar, gebruikte trefwoorden)

EPO-Internal

C. VAN BELANG GEACHTE DOCUMENTEN

| Categorie ° | Geciteerde documenten, eventueel met aanduiding van speciaal van belang zijnde passages | Van belang voor conclusie nr. |
|---|---|---|
| X,D | HU YUN ET AL: "A Novel Hybrid Analog-Digital Multibeam Antenna Array for Massive MIMO Applications", 2018 IEEE ASIA-PACIFIC CONFERENCE ON ANTENNAS AND PROPAGATION (APCAP), IEEE, 5 augustus 2018 (2018-08-05), bladzijden 42-45, XP033448401, DOI: 10.1109/APCAP.2018.8538310 [gevonden op 2018-11-15] in de aanvraag genoemd | 1-4,8-13 |
| Y | * het gehele document * | 5 |
| A | | 6,7 |
| | ----- | |
| | -/-- | |

[X] Verdere documenten worden vermeld in het vervolg van vak C.

[ ] Leden van dezelfde octrooifamilie zijn vermeld in een bijlage

° Speciale categorieën van aangehaalde documenten

"A" niet tot de categorie X of Y behorende literatuur die de stand van de techniek beschrijft

"D" in de octrooiaanvrage vermeld

"E" eerdere octrooi(aanvrage), gepubliceerd op of na de indieningsdatum, waarin dezelfde uitvinding wordt beschreven

"L" om andere redenen vermelde literatuur

"O" niet-schriftelijke stand van de techniek

"P" tussen de voorrangsdatum en de indieningsdatum gepubliceerde literatuur

"T" na de indieningsdatum of de voorrangsdatum gepubliceerde literatuur die niet bezwarend is voor de octrooiaanvrage, maar wordt vermeld ter verheldering van de theorie of het principe dat ten grondslag ligt aan de uitvinding

"X" de conclusie wordt als niet nieuw of niet inventief beschouwd ten opzichte van deze literatuur

"Y" de conclusie wordt als niet inventief beschouwd ten opzichte van de combinatie van deze literatuur met andere geciteerde literatuur van dezelfde categorie, waarbij de combinatie voor de vakman voor de hand liggend wordt geacht

"&" lid van dezelfde octrooifamilie of overeenkomstige octrooipublicatie

Datum waarop het onderzoek naar de stand van de techniek van internationaal type werd voltooid

21 februari 2024

Verzenddatum van het rapport van het onderzoek naar de stand van de techniek van internationaal type

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## ONDERZOEKSRAPPORT BETREFFENDE HET RESULTAAT VAN HET ONDERZOEK NAAR DE STAND VAN DE TECHNIEK VAN HET INTERNATIONALE TYPE

Nummer van het verzoek om een onderzoek naar de stand van de techniek
**NL 2035700**

C.(Vervolg). VAN BELANG GEACHTE DOCUMENTEN

| Categorie ° | Geciteerde documenten, eventueel met aanduiding van speciaal van belang zijnde passages | Van belang voor conclusie nr. |
|---|---|---|
| Y,D | ASLAN YANKI ET AL: "Orthogonal Versus Zero-Forced Beamforming in Multibeam Antenna Systems: Review and Challenges for Future Wireless Networks", IEEE JOURNAL OF MICROWAVES, IEEE, deel 1, nr. 4, 27 september 2021 (2021-09-27), bladzijden 879-901, XP011881858, DOI: 10.1109/JMW.2021.3109244 [gevonden op 2021-10-05] in de aanvraag genoemd | 5 |
| A | * samenvatting * * bladzijde 892, linker kolom, alinea 2; figuren 2,17,22, 25,32 * | 1-4,6-13 |

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Formulier PCT/ISA/201 (vervolg tweede blad) (Januari 2004)

# WRITTEN OPINION

| File No.<br>SN84961 | Filing date *(day/month/year)*<br>29.08.2023 | Priority date *(day/month/year)* | Application No.<br>NL2035700 |
|---|---|---|---|
| International Patent Classification (IPC)<br>INV. H04B7/06 H01Q3/26 | | | |
| Applicant<br>Technische Universiteit Delft | | | |

This opinion contains indications relating to the following items:

- ☒ Box No. I — Basis of the opinion
- ☐ Box No. II — Priority
- ☐ Box No. III — Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
- ☐ Box No. IV — Lack of unity of invention
- ☒ Box No. V — Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
- ☐ Box No. VI — Certain documents cited
- ☐ Box No. VII — Certain defects in the application
- ☒ Box No. VIII — Certain observations on the application

| | Examiner<br>Sieben, Stefan |
|---|---|

# WRITTEN OPINION

**Box No. I Basis of this opinion**

1. This opinion has been established on the basis of the latest set of claims filed before the start of the search.
2. With regard to any **nucleotide and/or amino acid sequence** disclosed in the application, this opinion has been established on the basis of a sequence listing:

   a. ☐ forming part of the application as filed.

   b. ☐ furnished subsequent to the filing date for the purposes of search,

   ☐ accompanied by a statement to the effect that the sequence listing does not go beyond the disclosure in the application as filed.

3. ☐ With regard to any nucleotide and/or amino acid sequence disclosed in the application, this opinion has been established to the extent that a meaningful opinion could be formed without a WIPO Standard ST.26 compliant sequence listing.
4. Additional comments:

**Box No. V Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

1. Statement

| | | | |
|---|---|---|---|
| Novelty | Yes: | Claims | 1-13 |
| | No: | Claims | |
| Inventive step | Yes: | Claims | 6, 7 |
| | No: | Claims | 1-5, 8-13 |
| Industrial applicability | Yes: | Claims | 1-13 |
| | No: | Claims | |

2. Citations and explanations

   **see separate sheet**

**Box No. VIII Certain observations on the application**

**see separate sheet**

## Re Item V

**Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

Reference is made to the following documents:

D1 HU YUN ET AL: "A Novel Hybrid Analog-Digital Multibeam Antenna Array for Massive MIMO Applications", 2018 IEEE ASIA-PACIFIC CONFERENCE ON ANTENNAS AND PROPAGATION (APCAP), IEEE, 5 augustus 2018 (2018-08-05), bladzijden 42-45

D2 ASLAN YANKI ET AL: "Orthogonal Versus Zero-Forced Beamforming in Multibeam Antenna Systems: Review and Challenges for Future Wireless Networks", IEEE JOURNAL OF MICROWAVES, IEEE, deel 1, nr. 4, 27 september 2021 (2021-09-27), bladzijden 879-901

1 The lack of clarity mentioned in item VIII below notwithstanding, the present application does not meet the criteria of patentability, because the subject-matter of claim 1 does not involve an inventive step.

1.1 The document D1 is regarded as being the prior art closest to the subject-matter of claim 1, and discloses (the references in parentheses applying to this document) een beamforming netwerk voor het genereren van twee of meer beweeglijke stralen van een arrayantenne (fig. 1: "*multibeam array*"), waarbij de arrayantenne een aantal van $N_1$ x $N_2$ stralingselementen bevat, opgesteld in een lineaire array van $N_1$ identieke lineaire subarrays, waarbij elke lineaire subarray een reeks van $N_2$ stralingselementen onder de $N_1 \times N_2$ stralingselementen bevat, waarbij de $N_1$ lineaire subarrays onder een hoek van 90° of een andere hoek ten opzichte van de lineaire array zijn gedraaid (fig. 1), waarbij het beamforming netwerk twee reeksen sub-beamformers bevat, waarbij:

- de ene reeks subbeamformers een aantal $M_1$ subbeamformers met matrixfactor bevat, waarbij $M_1 > 1$ (fig. 1: Digital Beamformer);

- de andere reeks sub-beamformers bevat een aantal $N_1$ identieke en identiek geconfigureerde subarray sub-beamformers, waarbij $N_1 > 1$ (fig. 1: Passive Beamforming Network);

waarbij, voor m = 1,..., $M_1$, elke m-de array factor sub-beamformer een arraystraalpoort bevat voor straal (m) signaal, en een aantal $N_1$ sub-beamformers, waarbij elke arraystraalpoort is aangesloten op alle $N_1$ sub-beamformers (fig. 1: e.g. the red signal paths) met, voor elk subsignaalpad van de arraystraalpoort naar een subarraypoort, een faste weging van het sub-signaal wmn, geoptimaliseerd zodat, als de $N_1$ uitgangssubarraypoorten zijn aangesloten op een lineaire array van $N_1$ isotrope stralingselementen met dezelfde afstand als de $N_1$ subarrays van de array, het resulterende m-de "arrayfactor" stralingspatroon een waaierstraal is in een vereiste richting of een gevormde waaierstraal (fig. 1),

met of zonder toegevoegde interferentievermindering, waarbij de toegevoegde interferentievermindering kan bestaan uit nulling/zero-forcing, sidelobe-controle of weging van de minimale gemiddelde kwadratenfout in de richting van andere stralen die dezelfde frequenties opnieuw gebruiken (This feature is optional.),

waarbij, voor n = 1,..., $N_1$, elke n-de sub-beamformer een aantal $M_1$ van subarraystraalpoorten en een aantal $N_2$ van subarrayelementpoorten bevat, waarbij $N_2 > M_1$ , waarbij voor een bepaalde reeks $M_1$ arraystralen alle $N_1$ sub-beamformers identiek geconfigureerd zijn (fig. 1) zodat:

- voor n = 1,..., $N_1$, elke n-de sub-beamformer zijn subarraystraalpoort aangesloten heeft op alle $N_2$ subarrayelementpoorten met, voor elk subsignaalpad van de arraystraalpoort naar een subarrayelementpoort, een faste subsignaalpad wnk, waarbij het faste subsignaalpad wnk zo is geoptimaliseerd dat, als de $N_2$ uitgangspoorten voor subarray-elementen waren aangesloten op de corresponderende $N_2$ stralingselementen van subarray n van de array, het resulterende m-de subarraystraalpatroon een waaierstraal is in een vereiste richting of een gevormde waaierstraal (page 42, right-hand column, 2nd paragraph: "*The pointing angles of the radiation beams in the elevation plane are fixed by exciting the corresponding port arrays of a passive beamforming networks*"),

met of zonder toegevoegde storingsbeperking, gedraaid onder een hoek van 90° of een andere hoek ten opzichte van het corresponderende m-de "arrayfactor" waaierstraalpatroon, waarbij de toegevoegde storingsbeperking door subarraystralen kan worden uitgevoerd door nulling/zero forcing, sidelobe controle of weging van de minimale gemiddelde kwadratenfout in de richting van andere waaierstralen die dezelfde frequenties hergebruiken (This feature is optional.),
- en
- voor iedere k=1,...,$N_2$:

de m-de subsignalen voor m=1 tot $M_1$ door de k-de aansluiting van het element van de subarray gaan;

de associatie van de lineaire subarray met een dergelijke sub-beamformer met meerdere straalpoorten een multiport subarray wordt genoemd;

waarbij de n-de subarraypoort van de m-de arrayfactor sub-beamformer is aangesloten op de m-de subarraystraalpoort van de n-de subarray sub-beamformer voor n = 1,..., $N_1$ en m = 1,..., $M_1$ (fig. 1);

waarbij, als gevolg van de bovengenoemde verbindingen van de sub-beamformers van de arrayfactor met de sub-beamformers van de subarraystraalpoorten, de algemene straalpatronen voor stralen m = 1,..., $M_1$ , in associatie met de arrayantenne, de producten zullen zijn van het straalpatroon m van de arrayfactor door het bijbehorende straalpatroon m van de subarray (implicit feature of the beamforming netwerk of fig. 1);

waardoor, als resultaat, voor stralen m = 1,..., $M_1$, de straling in één richting wordt gemaximaliseerd door maximalisatie van zowel het straalpatroon m van de arrayfactor als het bijbehorende subarraystraalpatroon m in die richting (implicit feature of the beamforming netwerk of fig. 1),

terwijl de interferentie wordt gemitigeerd door nulling/zero-forcing, sidelobe-controle, weging van de minimale gemiddelde kwadratenfout of andere middelen beperkt kan worden tot de arrayfactor sub-beamformers of de subarray sub-beamformers, wat resulteert in een belangrijke vereenvoudiging van de verwerking en hardware voor de mitigatie van interferentie, waarbij opgemerkt wordt dat het op beide typen sub-beamformers tegelijk toegepast kan worden voor stralen die extra mitigatie van interferentie nodig hebben (This feature is optional as the interference mitigation/limitation in the two beamformers is defined as being optional.).

1.2 The subject-matter of claim 1 therefore differs from this known network in that in the beamforming network of claim 1

a) the weighting of the sub-signal wmn in the M1 subbeamformers is variable (een <u>variabele</u> weging van het sub-signaal wmn); and

b) the subsignal path wnk in each of the N1 sub-beamformers is variable (een <u>variabel</u> subsignaalpad wnk).

Claim 1 is therefore new.

1.3 The problem to be solved by the present invention may therefore be regarded as how to simplify the beamforming network.

1.4 The solution proposed in claim 1 of the present application cannot be considered as involving an inventive step for the following reasons:

Concerning feature a), fig. 1 of D1 shows a hybrid beamformer with the azimuth of the beams being steered by a digital beamformer. The realization of the digital beamformer with variable weights as defined in claim 1 is however obvious for the skilled person.
Concerning feature b), also analogue beamforming has been realized in the prior art with flexible weights, so that variable signal paths result; see e.g. the document D2, fig. 32 and page 892, left-hand column, 2nd full paragraph: "*flexibly programmable analog beamforming by exploiting a vector modulator*". Also the realization of the analogue beamformers with flexible weights must therefore be considered an obvious design choice for the skilled person according to the circumstances.

2 Dependent claims 2-5 and 8-13 do not contain any features which, in combination with the features of any claim to which they refer, meet the requirements of inventive step, see the documents D1 and D2, and the corresponding passages cited in the search report. In particular:

2.1 The additional features of claims 2, 10, 11 and 13 are at least rendered obvious by D1 (fig. 1).

2.2 The additional features of claims 3, 4, 8, 9 and 12 are either rendered obvious by D1 disclosing a hybrid beamforming network or obvious design choices for the skilled person.

2.3 The subject-matter of claim 5 is rendered obvious by the combined teachings of D1 as cited above and D2 (e.g. abstract and fig. 2).

3 The lack of clarity mentioned in item VIII below notwithstanding, the combination of the features of dependent claim 6 (an consequently also claim 7, as indicated in item VIII-3 below) is neither known from, nor rendered obvious by, the available prior art. The reasons are as follows:

3.1 The subject-matter of claim 6 differs from the beamforming network known from D1 in addition by the additional features of claim 6.

3.2 The problem to be solved by these features may be regarded as how to realize an analogue zero-forcing beamformer.

3.3 The solution to this problem proposed in claim 6 of the present application is considered as involving an inventive step because neither D1 nor D2, nor any other available prior art document suggests or hints at the implementation of the beamformer using the specific combination of phase/amplitude modules in order to solve the problem posed.

3.4 Claim 7 is considered dependent on claim 6 (see item VIII-3 below) and is therefore also considered new and inventive.

**Re Item VIII**

**Certain observations on the application**

Claims 1, 6 and 7 are not clear.

1 Claim 1 defines for the $N_1$ "subarray sub-beamformers" interference mitigation ("met of zonder toegevoegde interferentievermindering") as being optional, and for the $M_1$ subbeamformers interference limitation ("met of zonder toegevoegde storingsbeperking") as being optional. However, later in the claim reference is made to the interference mitigation ("terwijl de interferentie wordt gemitigeerd door nulling/zero-forcing, sidelobe-controle, weging van de minimale gemiddelde kwadratenfout of andere middelen beperkt kan worden"). Therefore a lack of clarity arises.

2 Claim 6 is not supported by the description, as its scope is broader than justified by the description and drawings. Figures 3B and 3C and the accompanying text passage disclose the coupler modules "A" to be fixed coupler modules as shown in fig. 3A and the coupler modules "B" to be fixed and variable coupler modules. In contrast, claim 6 defines the "eerste reeks $N_2$-1" coupler modules corresponding to the coupler modules "A" as variable coupler modules ("fase/ amplitude variabele modules") and the "tweede reeks $N_2$-2" coupler modules corresponding to the coupler modules "B" as variable coupler modules ("fase/

amplitude variabele modules"). Only the "derde reeks $N_2$-3 fase/amplitude variabele modules" corresponds to the disclosure of figures 3B and 3C.

3 Claim 7 lacks clarity as it makes reference to "het subnetwerk (329) van conclusie 6". It is however not completely clear which features of claim 6 are comprised as claim 6 does not define a "subnetwerk". For the assessment of claim 7 in item V above, it is assumed that claim 7 comprises all the features of claim 6.