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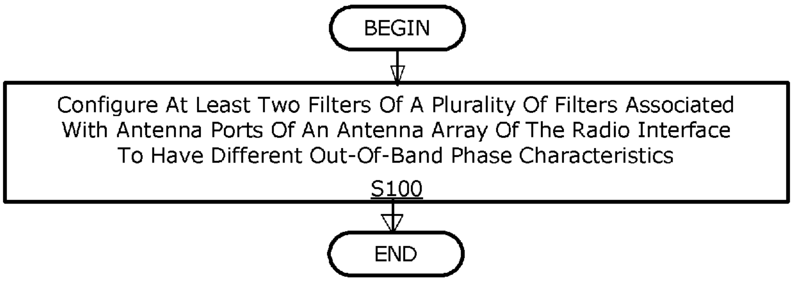

FIG. 4

(57) **Abstract:** A method and radio interface for multiple input-multiple output (MIMO) radio out of band (OOB) unwanted emission (OBUE) phase decorrelation are disclosed. According to one aspect, a radio interface includes a plurality of antenna ports, each antenna port being associated with at least one antenna element of an array of antennas elements. The radio interface also includes a plurality of filters associated with the plurality of antenna ports, at least two of the plurality of filters having different out-of-band phase characteristics from one another, a difference in out-of-band phase characteristics between the at least two filters of the plurality of filters being configured to provide an out-of-band beam forming gain that does not increase as much as an in-band beam forming gain when the in-band beam forming gain is increased.

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MULTIPLE INPUT-MULTIPLE OUTPUT (MIMO) RADIO OUT OF BAND UNWANTED EMISSION (OBUE) PHASE DECORRELATION

TECHNICAL FIELD

The present disclosure relates to wireless communications, and in particular, to multiple input-multiple output (MIMO) radio out of band (OOB) unwanted emission (OBUE) phase decorrelation.

BACKGROUND

The Third Generation Partnership Project (3GPP) has developed and is developing standards for Fourth Generation (4G) (also referred to as Long Term Evolution (LTE)), Fifth Generation (5G) (also referred to as New Radio (NR)) and Sixth Generation (6G) wireless communication systems. Such systems provide, among other features, broadband communication between network nodes, such as base stations, and mobile wireless devices (WD), as well as communication between network nodes and between WDs.

In addition to these standards, the Institute of Electrical and Electronic Engineers (IEEE) has developed and continues to develop standards for other types of wireless communication networks, including Wireless Local Area Networks (WLANs), including Wireless Fidelity (Wi-Fi) networks and Bluetooth networks. WLANS include wireless communication between access points (APs) and WDs (non-AP STAs. Such IEEE standards include IEEE 802.11a/b/g/n/ac/ax and IEEE 802.15.

The mobile cellular communications network is a driving force of economic prosperity, providing increasing levels of wireless connectivity to billions of people with WD devices. Each evolution of network technology has been accompanied with the allocation of new frequency bands allocated by governments and international agencies to enable new services and capabilities. Current and new frequency mobile cellular bands are often noncontiguous and interleaved with existing incumbent services such as fixed microwave services, fixed or mobile satellite services, weather or military radar, radio astronomy, radio altimeters, etc.

Government and international agencies create regulations to protect incumbent operators of these services including in-band on cellular equivalent isotropic radiated power (EIRP) and out-of-band (OOB) unwanted emissions (OBUE). As an example, in the United States of America, EIRP is limited to 3280 W/MHz and out-of-band emissions are limited to -13 dBm/MHz. However, in some cases, regulations specify significant further restriction on OBUE. U.S. Federal Communications Commission (FCC) regulations Part 27.53(n) is an example, where for base station operations in the 3450-3550 MHz band, the conducted power of any emission below 3440 MHz or above 3560 MHz shall not exceed −25 dBm/MHz, and the conducted power of emissions below 3430 MHz or above 3570 MHz shall not exceed −40 dBm/MHz. These OBUE regulations represent a significant drop in EIRP, in the above case, where permitted in-band power levels are 3280W/MHz equivalent to 65 dBm/MHz, and the difference between in-band and OBUE is 125 dB. Recent requests by the aviation industry for 4.2-4.4 GHz OBUE levels of -48 dBm/MHz EIRP, represent 133 dB of in-band to OBUE. These are impossible specifications to achieve with filters without wide guard bands.

Some governments and agencies require exclusion zones, such as surrounding radio astronomy sites, often located in high mountainous areas. Other governments, in protecting civilian and military radar applications have specified LBT or listen-before-talk protocols required to dynamically detect the presence of an incumbent.

Significant technology has been developed to ensure non-interfering coexistence of adjacent bands. The primary technology has always been and continues to be intermediate frequency (IF) and radio frequency (RF) filters employed to attenuate out-of-band radio frequency energy before it is radiated by antenna elements. These filters often provide attenuations of 70 dB or more and may achieve significant reductions in out-of-band total radiated power (TRP) to meet stringent regulations such as -30 dBm/MHz. Legacy radio base stations (RBS) such as 2G, 3G and 4G generally used external sector antennas to provide “cellular” coverage, and these antennas had typical gains in the range of 15 dBi so that spurious out-of-band radiated emissions in protected bands may see EIRP levels of -15 dBm/MHz.

The introduction of fifth generation (5G) radios has brought advanced antenna systems (AAS), also known as beamforming antennas, with typical gains of 25 dBi, but with 10 dB higher gains expected within a few years as sixth generation (6G) radios systems start to be released. AAS radios therefore have increased out-of-band radiated emissions which may be 20 dB higher than legacy 3G and 4G network nodes. This increased EIRP has not been accompanied with a corresponding improvement in filter technology. In fact, the opposite is true, as larger antenna arrays result in physical limitation on available space for filters, reducing achievable attenuation.

Innovations unique to AAS network nodes such as precoder matrix indicator (PMI) restrictions provide the means to spatially manage potential antenna patterns and have found utility in avoiding or correcting interference cases for in-band fixed incumbents such as weather radar or satellite communications systems. However, these features do not address the generalized problem of out-of-band radiated emissions EIRP since in-band antenna patterns do not have good alignment with out-of-band antenna patterns.

Therefore, the dominant means to mitigate out-of-band radiated emissions remains the use of filters. To achieve greater attenuation levels, network nodes resort to employing cascaded filters, adding cost to the radio design. Additional costs are incurred in the power amplification, often performed at the final stage in advance of a single low loss filter before the antenna element. Power amplifiers introduce a broadband noise floor as well as “side band” emissions cause by unmanaged non-linearities in the signal amplification process. If not attenuated sufficiently, all of these unwanted emissions may result in the network nodes not meeting government mandated out-of-band emissions levels.

Finally, current technology has been unable to develop an “ideal” brick wall filter. This is to say that all filters have a pass band, to allow the intended signals to be transmitted, and a reject band where signals are blocked. An ideal brick wall filter would have no in-band attenuation, and infinite out-of-band attenuation, but this is not possible. In-band attenuation is often in the 0.5 dB range for high powered “macro” network node radios and reach a level of 60-70 dB of attenuation after a typical guard band of 40-100 MHz. Unfortunately, it is this transition zone between the pass and rejection bands of reduced attenuation, that the highest levels of non-linear amplifier side band emissions exist and are fed into the AAS elements. These antennas have wide operational ranges, and often transmit adjacent channel band out-of-band signals with the same beamforming gain as in-band signals.

As there are no known technologies to address this concern, operators often use a portion of their spectrum as a guard-band. Operators request network node products with filters that attenuate the top 20 or 40 MHz of their spectrum to meet regulatory out-of-band radiated emissions into incumbent bands.

Existing technology used to reduce out-of-band emissions in the adjacent channel region consists of two main tools – filter technology and power amplifier linearization algorithms, referred to as DPD or digital predistortion. 3GPP defines Adjacent Channel Leakage Ratio (ACLR) as the ratio of ratio of the transmitted power to the power in the adjacent radio channel, and it is a well-known and documented concern. The ACLR is measured after the transmitter filter, as a point where test equipment may assess these two powers before the signals are fed into the antennas. The term ACLR1 refers to the first adjacent channel, where the highest levels of unwanted out-of-band emissions occur. The ACLR1 region spans the edge of the passband into the rejection band of the filter where filter attenuation is increasing rapidly, typically reaching maximum attenuation after 40-100 MHz from the passband edge.

Filter and DPD technologies are used to reduce spurious emissions in the ACLR1 region. As discussed, filter technology may achieve significant out-of-band attenuation in this region in the range of 70 dB and has been the dominant means to suppress unwanted emissions. Digital predistortion is predominantly employed to linearize power amplifier operation to meet in-band transmitter error vector magnitude (EVM) requirements so that transmitted high order quadrature amplitude modulated (QAM) signals may be received by user equipment (UEs). Sidelobes are caused by transmitter non-linearities generating intermodulation products and are therefore improved by linearizing the transmitter.

While existing filter and DPD technology has been sufficient to minimize out-of-band emissions and meet 3GPP ACLR1 specification for 3G and 4G products that use sector antennas with typical gains in the range of 15 dBi, this issue has become more difficult with 5G AAS radio base stations (RBS) where beamforming antenna gains today achieve 26 dBi and are expected to move to 36 dBi in the near future.

Existing DPD and filter technologies are well understood and mature and have evolved over decades to achieve the current high performance seen in 3G, 4G and 5G radios. While DPD improvements are possible, current technology has reached a level of performance which is not readily improved. DPD is not only employed to linearize existing power amplifier designs, but it is used to achieve the maximum power performance possible with the technology, pushing devices to operate into highly non-linear regions. The key focus of existing DPD technologies is therefore to achieve necessary transmitter error vector magnitude specifications while operating in these non-linear regions. The dynamic range of the feedback paths has been optimized for the high transmitted signal levels.

Algorithms have been proposed to reduce intermodulation products within the carrier band to further improve ACLR distortion. Non-linear algorithms are common tools in the reduction of ACLR minimizing detectable non-linear products to such an extent that the remaining leakage power has minimal correlation with intermodulation

(IM) products. This leakage power is often 40 - 50 dB reduced from in-band signals and approaching measurable quantization levels and appears as random noise, yet still contains correlated components. In short, while the use of DPD has made significant advancements in ACLR reduction, correlated components still exist, possibly due to clipping noise, or transmitter reverse intermodulation, or possibly but less likely, transmitter spatial reverse intermodulation. While this area still has potential gains, it is unknown if algorithm improvements will further reduce out-of-band correlation components.

Existing filter technology is also well understood and has reached its performance limits.

Cellular communications have approached performance limits for transmitted power, made possible with precision cavity filters, characterized by their physically large size, and visible tuning screws. Cavity filters have a key advantage of low insertion losses, minimizing power loss in this final stage between power amplification and antenna transmission. The myriad of adjustment screws enables manufacturers to precision tune these filters, compensating for manufacturing variations, ensuring that the final product achieves tightly specified customer defined attenuation masks. While improved specifications and tighter masks are possible, they come at the cost of higher insertion loss and increased size as more poles and zeros are added to the filter, and these larger sizes often cannot fit into the allocated space of an AAS radio with hundreds of filters.

As AAS radios evolve from hundreds of antenna elements to thousands, the space and performance of the filters used with each port is further limited. Metal cavity filter technology is being replaced by ceramic waveguides, sheet metal waveguides, and 3D printed filters, to achieve lower costs and higher densities. These new technologies do not achieve improvements in specifications, rather more often result in performance reductions such as higher insertion loss and less stringent masks.

Fortunately, the evolution to larger numbers of antenna elements and higher beamforming gain reduces the required transmitted power per antenna element, enabling filter designs with higher insertion loss. The smaller, non-tuned filters achieve similar rejection band performance, but suffer from reduced precision in the ACLR1 region which this disclosure addresses. While the evolved miniaturized filters, regardless of the technology, may include some form of manufacturing tuning, these devices will still see similar or reduced performance in the ACLR1 region. Bulk acoustic wave (BAW) filters at 3.7 GHz or commercial parts all require 40 – 100 MHz of guard band between the pass and rejection bands, where ACLR1 emissions are attenuated far below the 50-70 dB typical in the rejection band.

It is noteworthy that, in the design of RF filters, higher selectivity requires increased size.

Filter resonant sections, each with specified physical dimensions and corresponding impedances, cascade to determine the transfer function defining the input to output characteristics. Larger filters with more sections enable higher numbers of poles and zeros and the possibility of steeper roll offs for reduced guard bands. The example of FIG. 1 shows a typical filter with pass band, and a roll-off of approximately 100 MHz to the rejection band starting at 4500 MHz.

Current filter technologies are designed with the goal of improving transmitter emissions or receiver rejection, and not to address issues unique to high gain beamforming systems, in that they provide no management or specification of out-of-band phase variations which are taught in this disclosure.

The inability to control the out-of-band phase variations in the ACLR1 region is a lost opportunity for improved spectrum use - not only for high power transmitter systems, such as 5G and 6G advanced antenna systems to achieve low beamforming gain in this critical region, but also for MIMO receiver systems to reduce out-of-band beamforming gain which impacts blocking performance.

SUMMARY

Some embodiments advantageously provide methods and radio interfaces for multiple input-multiple output (MIMO) radio out of band (OOB) unwanted emission (OBUE) phase decorrelation.

Some embodiments may be applied to transmission and reception, for a RBS and/or a WD or any similar arrangement where massive antenna wireless functions are required to exist in adjacent bands.

Some embodiments employ circuitry to modify the out-of-band phase of the filtered signal. The solution may be static or dynamic but is designed to predominantly affect the out-of-band phase.

Some embodiments impact only the out-of-band signal phase and not both out-of-band and in-band phase. Algorithms are used in MIMO system to phase align in-band signals, compensating for filter group delay variations across the band which are often quite significant nearing the band edge. If out-of-band phase variations impact both the in-band and out-of-band signals, these algorithms are configured to compensate for these variations, nullifying them in some embodiments.

Under the conditions where the out-of-band phase variations may be modified and uncompensated by algorithms used to correct the in-band signals, large beamforming gain reductions are possible.

In some embodiments, only the out-of-band phase response of the filter is modified without impacting the in-band phase response.

Some embodiments are applicable to high powered advanced antenna systems to reduce out-of-band antenna array gain and therefore transmitted out-of-band EIRP in the stopband or ACLR1 region. Some embodiments are applicable to advanced antenna systems to reduce out-of-band array gain for received signals in this same stop-band region, thereby improving rejection of potential adjacent band interference sources. Some embodiments are applicable to devices with a plurality of antennas. achieving out-of-band array gain reduction through filter design.

In high powered advanced antenna systems, high performance filters designed with specified pole and zero locations may shift poles or zeros directly affecting the phase of the out-of-band region.

Implementations are realizable for various technologies with a generalized filter schematic.

Some embodiments may employ staggering of the frequencies of the band edge poles or zeros by small amounts, possibly by 1.0 MHz so that for an 8 antenna MIMO system, for example, the zeros would be at 4172 MHz to 4179 MHz. The filter design may ensure that the selected staggering achieves out-of-band phase responses with the necessary degrees of variation to achieve design targets.

Current multiple antenna systems employ identical filters on each of the transmit/receive antenna ports, thereby having consistent performance of key parameters such as filter bandwidth, insertion loss, amplitude variation, voltage standing wave ratio (VSWR), in-band and out-of-band attenuation curves, in-band group delay, and second and third harmonic performance, etc. Some embodiments match these parameters and augments them with an additional parameter of in-band to out-of-band relative group delay. In some embodiments, filters of general capability are defined. In some embodiments, MIMO antenna systems employing filters with different in-band to out-of-band relative group delays are defined.

Some embodiments differ from traditional MIMO radios which employ the same filter element for all port branches in the antenna array. The filters typically have similar in-band and out-of-band phase delays with respect to each other. Therefore, when a traditional MIMO radio is configured to align the phase of the transmitted in-band signal to achieve beamforming gain, this configuration also results in out-of-band beamforming gain. This solution uses a plurality (i.e., two or more) filters with unique in-band to out-of-band phase delays.

Some embodiments may include one or more of the following:

1. filters with out-of-band phase delays that vary between 0° to ±180° with respect to the in-band phase at the center frequency of the filter passband, where the phase delay variations are either fixed (as in an orderable delay) or controllable; and/or
2. systems which arrange a plurality of these filters in a MIMO radio antenna, where filters are employed on transmit paths, or receive paths, or on common receive and transmit paths as may be the case for time division duplex (TDD) MIMO radios.

According to one aspect, a radio interface includes a plurality of antenna ports, each antenna port being associated with at least one antenna element of an array of antennas elements. The radio interface also includes a plurality of filters associated with the plurality of antenna ports, at least two of the plurality of filters having different out-of-band phase characteristics.

According to this aspect, in some embodiments, a phase difference between at least two out-of-band phase characteristics is one of 180 degrees and an integer multiple of 360 degrees plus 180 degrees. In some embodiments, a phase difference between at least two out-of-band phase characteristics exceeds one of 90 degrees and an integer multiple of 360 degrees plus 90 degrees. In some embodiments, a phase difference between out-of-band phase characteristics of filters for every pair of two adjacent antenna ports is substantially a same amount. In some embodiments, the same amount is one of at least 45 degrees and at least an integer multiple of 360 degrees plus 45 degrees. In some embodiments, a phase difference between out-of-band phase characteristics for every pair of two adjacent antenna ports differs from the phase difference between out-of-band phase characteristics of at least one other pair of two adjacent antenna ports. In some embodiments, each of the different phase differences is one of at least 45 degrees and at least an integer multiple of 360 degrees plus 45 degrees. In some embodiments, phase differences between out-of-band phase characteristics for different sets of adjacent antenna ports differ by random amounts. In some embodiments, the array of antenna elements is a two-dimensional array and phase differences between out-of-band phase characteristics for antenna ports in an azimuth direction are different from phase differences between out-of-band phase characteristics for antenna ports in an elevation direction. In some embodiments, an out-of-band phase characteristic of a filter is determined relative to an in-band phase at a center frequency of a passband of the filter. In some embodiments, out-of-band phase characteristics of different filters are programmable. In some embodiments, out-of-band phase characteristics of a set of filters for the antenna ports are configured to have a fixed set of delays over a frequency bandwidth that is a subset of a frequency bandwidth of operation of the radio interface. In some embodiments, first filters of a first filter block have substantially a same first out-of-band phase characteristic and second filters of a second filter block have substantially a same second out-of-band phase characteristic different from the first out-of-band phase characteristic. In some embodiments, a plurality of the filters have substantially a same in-band phase characteristic. In some embodiments, the radio interface is configured to operate within one of a network node, a satellite and a wireless device.

According to another aspect, a method in a radio interface includes configuring at least two filters of a plurality of filters associated with antenna ports of an antenna array of the radio interface to have different out-of-band phase characteristics.

According to this aspect, in some embodiments, the method includes configuring a phase difference between at least two out-of-band phase characteristics to be one of 180 degrees and an integer multiple of 360 degrees plus 180 degrees. In some embodiments, the method includes configuring a phase difference between at least two out-of-band phase characteristics to exceed one of 90 degrees and at least an integer multiple of 360 degrees plus 90 degrees. In some embodiments, the method includes configuring a phase difference between out-of-band phase characteristics of filters for every pair of two adjacent antenna ports to be substantially a same amount. In some embodiments, the same amount is one of at least 45 degrees and at least an integer multiple of 360 degrees plus 45 degrees. In some embodiments, the method includes configuring a phase difference between out-of-band phase characteristics for every pair of two adjacent antenna ports to differ from a phase difference between out-of-band phase characteristics of at least one other pair of two adjacent antenna ports. In some embodiments, each of the different phase differences is one of at least 45 degrees and at least an integer multiple of 360 degrees plus 45 degrees. In some embodiments, the method includes configuring phase differences between out-of-band phase characteristics for different sets of adjacent antenna ports to differ by random amounts. In some embodiments, the antenna array is a two-dimensional array and the method further includes configuring phase differences between out-of-band phase characteristics for antenna ports in an azimuth direction to be different from phase differences between out-of-band phase characteristics for antenna ports in an elevation direction. In some embodiments, an out-of-band phase characteristic of a filter is determined relative to an in-band phase at a center frequency of a passband of the filter. In some embodiments, out-of-band phase characteristics of different filters are programmable and the method includes programming at least one filter to obtain a desired out-of-band phase characteristic for the at least one filter. In some embodiments, the method also includes configuring out-of-band phase characteristics of a set of the filters for the antenna ports to have a fixed set of delays over a frequency bandwidth that is a subset of a frequency bandwidth of operation of the radio interface. In some embodiments, the method also includes configuring first filters of a first filter block to have substantially a same first out-of-band phase characteristic and configuring second filters of a second filter block to have substantially a same second out-of-band phase characteristic different from the first out-of-band phase characteristic. In some embodiments, the method also includes configuring a plurality of the filters to have substantially a same in-band phase characteristic. In some embodiments, the method includes configuring the radio interface to operate within one of a network node, a satellite and a wireless device.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present embodiments, and the attendant advantages and features thereof, will be more readily understood by reference to the following detailed description when considered in conjunction with the accompanying drawings wherein:

FIG. 1 illustrates a filter function of a bandpass filter;

FIG. 2 is a schematic diagram of an example network architecture illustrating a communication system according to principles disclosed herein;

FIG. 3 is a block diagram of a network node in communication with a wireless device over a wireless connection according to some embodiments of the present disclosure;

FIG. 4 is a flowchart of an example process in a radio interface of one of a network node and a WD for multiple input-multiple output (MIMO) radio out of band (OOB) unwanted emission (OBUE) phase decorrelation;

FIG. 5 is a graph of empirical cumulative distribution functions (CDFs) for gain reduction;

FIG. 6 is a plot of out-of-band (OOB) phase variations for 8 cavity filters used in an advanced antenna system (AAS);

FIG. 7 is a first example filter phase characteristic;

FIG. 8 is a second example filter phase characteristic;

FIG. 9 is a third example filter phase characteristic; and

FIG. 10 is a plot showing poles and zeros for an example filter.

DETAILED DESCRIPTION

Before describing in detail example embodiments, it is noted that the embodiments reside primarily in combinations of apparatus components and processing steps related to multiple input-multiple output (MIMO) radio out of band (OOB) unwanted emission (OBUE) phase decorrelation. Accordingly, components have been represented where appropriate by conventional symbols in the drawings, showing only those specific details that are pertinent to understanding the embodiments so as not to obscure the disclosure with details that will be readily apparent to those of ordinary skill in the art having the benefit of the description herein.

As used herein, relational terms, such as “first” and “second,” “top” and “bottom,” and the like, may be used solely to distinguish one entity or element from another entity or element without necessarily requiring or implying any physical or logical relationship or order between such entities or elements. The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the concepts described herein. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises,” “comprising,” “includes” and/or “including” when used herein, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

In embodiments described herein, the joining term, “in communication with” and the like, may be used to indicate electrical or data communication, which may be accomplished by physical contact, induction, electromagnetic radiation, radio signaling, infrared signaling or optical signaling, for example. One having ordinary skill in the art will appreciate that multiple components may interoperate and modifications and variations are possible of achieving the electrical and data communication.

In some embodiments described herein, the term “coupled,” “connected,” and the like, may be used herein to indicate a connection, although not necessarily directly, and may include wired and/or wireless connections.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the concepts described herein. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises,” “comprising,” “includes” and/or “including” when used herein, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

The term “network node” used herein may be any kind of network node comprised in a radio network which may further comprise any of base station (BS), radio base station, base transceiver station (BTS), base station controller (BSC), radio network controller (RNC), g Node B (gNB), evolved Node B (eNB or eNodeB), Node B, multi-standard radio (MSR) radio node such as MSR BS, multi-cell/multicast coordination entity (MCE), relay node, donor node controlling relay, radio access point (AP), transmission points, transmission nodes, Remote Radio Unit (RRU) Remote Radio Head (RRH), a core network node (e.g., mobile management entity (MME), self-organizing network (SON) node, a coordinating node, positioning node, MDT node, etc.), an external node (e.g., 3rd party node, a node external to the current network), nodes in distributed antenna system (DAS), a spectrum access system (SAS) node, an element management system (EMS), etc. The network node may also comprise test equipment. The term “radio node” used herein may be used to also denote a wireless device (WD) such as a wireless device (WD) or a radio network node.

In some embodiments, the non-limiting terms wireless device (WD) or a user equipment (UE) are used interchangeably. The WD herein may be any type of wireless device capable of communicating with a network node or another WD over radio signals, such as wireless device (WD). The WD may also be a radio communication device, target device, device to device (D2D) WD, machine type WD or WD capable of machine to machine communication (M2M), low-cost and/or low-complexity WD, a sensor equipped with WD, Tablet, mobile terminals, smart phone, laptop embedded equipped (LEE), laptop mounted equipment (LME), USB dongles, Customer Premises Equipment (CPE), an Internet of Things (IoT) device, or a Narrowband IoT (NB-IOT) device etc.

Also, in some embodiments the generic term “radio network node” is used. It may be any kind of a radio network node which may comprise any of base station, radio base station, base transceiver station, base station controller, network controller, RNC, evolved Node B (eNB), Node B, gNB, Multi-cell/multicast Coordination Entity (MCE), relay node, access point, radio access point, Remote Radio Unit (RRU) Remote Radio Head (RRH).

Note that although terminology from one particular wireless system, such as, for example, 3GPP LTE and/or New Radio (NR), may be used in this disclosure, this should not be seen as limiting the scope of the disclosure to only the aforementioned system. Other wireless systems, including without limitation Wide Band Code Division Multiple Access (WCDMA), Worldwide Interoperability for Microwave Access (WiMax), Ultra Mobile Broadband (UMB) and Global System for Mobile Communications (GSM), may also benefit from exploiting the ideas covered within this disclosure.

Note further, that functions described herein as being performed by a wireless device or a network node may be distributed over a plurality of wireless devices and/or network nodes. In other words, it is contemplated that the functions of the network node and wireless device described herein are not limited to performance by a single physical device and, in fact, may be distributed among several physical devices.

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having a meaning that is consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

Some embodiments are directed to multiple input-multiple output (MIMO) radio out of band (OOB) unwanted emission (OBUE) phase decorrelation.

Returning to the drawing figures, in which like elements are referred to by like reference numerals, there is shown in FIG. 2 a schematic diagram of a communication system 10, according to an embodiment, such as a 3GPP-type cellular network that may support standards such as LTE, NR (5G) and/or 6G, which comprises an access network 12, such as a radio access network, and a core network 14. The access network 12 comprises a plurality of network nodes 16a, 16b, 16c (referred to collectively as network nodes 16), such as NBs, eNBs, gNBs or other types of wireless access points, each defining a corresponding coverage area 18a, 18b, 18c (referred to collectively as coverage areas 18). Each network node 16a, 16b, 16c is connectable to the core network 14 over a wired or wireless connection 20. A first wireless device (WD) 22a located in coverage area 18a is configured to wirelessly connect to, or be paged by, the corresponding network node 16a. A second WD 22b in coverage area 18b is wirelessly connectable to the corresponding network node 16b. While a plurality of WDs 22a, 22b (collectively referred to as wireless devices 22) are illustrated in this example, the disclosed embodiments are equally applicable to a situation where a sole WD is in the coverage area or where a sole WD is connecting to the corresponding network node 16. Note that although only two WDs 22 and three network nodes 16 are shown for convenience, the communication system may include many more WDs 22 and network nodes 16.

Also, it is contemplated that a WD 22 may be in simultaneous communication and/or configured to separately communicate with more than one network node 16 and more than one type of network node 16. For example, a WD 22 may have dual connectivity with a network node 16 that supports LTE and the same or a different network node 16 that supports NR. As an example, WD 22 may be in communication with an eNB for LTE/E-UTRAN and a gNB for NR/NG-RAN. Also, the network nodes 16 and/or WDs 22 may be in wireless communication with communication satellites 36.

Example implementations, in accordance with an embodiment, of the WD 22 and network node 16 discussed in the preceding paragraphs will now be described with reference to FIG. 3.

The communication system 10 includes a network node 16 provided in a communication system 10 and including hardware 28 enabling it to communicate with the WD 22. The hardware 28 may include a radio interface 30 for setting up and maintaining at least a wireless connection 32 with a WD 22 located in a coverage area 18 served by the network node 16. The radio interface 30 may be formed as or may include, for example, one or more RF transmitters, one or more RF receivers, and/or one or more RF transceivers. The radio interface 30 includes an array of antennas 34 to radiate and receive signal(s) carrying electromagnetic waves. The radio interface 30 may be configured to include filters 94 and antenna ports 96 configured according to principles set forth herein.

In the embodiment shown, the hardware 28 of the network node 16 further includes processing circuitry 36. The processing circuitry 36 may include a processor 38 and a memory 40. In particular, in addition to or instead of a processor, such as a central processing unit, and memory, the processing circuitry 36 may comprise integrated circuitry for processing and/or control, e.g., one or more processors and/or processor cores and/or FPGAs (Field Programmable Gate Array) and/or ASICs (Application Specific Integrated Circuitry) adapted to execute instructions. The processor 38 may be configured to access (e.g., write to and/or read from) the memory 40, which may comprise any kind of volatile and/or nonvolatile memory, e.g., cache and/or buffer memory and/or RAM (Random Access Memory) and/or ROM (Read-Only Memory) and/or optical memory and/or EPROM (Erasable Programmable Read-Only Memory).

Thus, the network node 16 further has software 42 stored internally in, for example, memory 40, or stored in external memory (e.g., database, storage array, network storage device, etc.) accessible by the network node 16 via an external connection. The software 42 may be executable by the processing circuitry 36. The processing circuitry 36 may be configured to control any of the methods and/or processes described herein and/or to cause such methods, and/or processes to be performed, e.g., by network node 16. Processor 38 corresponds to one or more processors 38 for performing network node 16 functions described herein. The memory 40 is configured to store data, programmatic software code and/or other information described herein. In some embodiments, the software 42 may include instructions that, when executed by the processor 38 and/or processing circuitry 36, causes the processor 38 and/or processing circuitry 36 to perform the processes described herein with respect to network node 16.

The communication system 10 further includes the WD 22 already referred to. The WD 22 may have hardware 44 that may include a radio interface 46 configured to set up and maintain a wireless connection 32 with a network node 16 serving a coverage area 18 in which the WD 22 is currently located. The radio interface 46 may be formed as or may include, for example, one or more RF transmitters, one or more RF receivers, and/or one or more RF transceivers. The radio interface 46 includes an array of antennas 48 to radiate and receive signal(s) carrying electromagnetic waves. In some embodiments, the radio interface 46 may be configured to include filters 98 and antenna ports 100.

The hardware 44 of the WD 22 further includes processing circuitry 50. The processing circuitry 50 may include a processor 52 and memory 54. In particular, in addition to or instead of a processor, such as a central processing unit, and memory, the processing circuitry 50 may comprise integrated circuitry for processing and/or control, e.g., one or more processors and/or processor cores and/or FPGAs (Field Programmable

Gate Array) and/or ASICs (Application Specific Integrated Circuitry) adapted to execute instructions. The processor 52 may be configured to access (e.g., write to and/or read from) memory 54, which may comprise any kind of volatile and/or nonvolatile memory, e.g., cache and/or buffer memory and/or RAM (Random Access Memory) and/or ROM (Read-Only Memory) and/or optical memory and/or EPROM (Erasable Programmable Read-Only Memory).

Thus, the WD 22 may further comprise software 56, which is stored in, for example, memory 54 at the WD 22, or stored in external memory (e.g., database, storage array, network storage device, etc.) accessible by the WD 22. The software 56 may be executable by the processing circuitry 50. The software 56 may include a client application 58. The client application 58 may be operable to provide a service to a human or non-human user via the WD 22.

The processing circuitry 50 may be configured to control any of the methods and/or processes described herein and/or to cause such methods, and/or processes to be performed, e.g., by WD 22. The processor 52 corresponds to one or more processors 52 for performing WD 22 functions described herein. The WD 22 includes memory 54 that is configured to store data, programmatic software code and/or other information described herein. In some embodiments, the software 56 and/or the client application 58 may include instructions that, when executed by the processor 52 and/or processing circuitry 50, causes the processor 52 and/or processing circuitry 50 to perform the processes described herein with respect to WD 22.

In some embodiments, a communication satellite radio interface 35 of a communication satellite 36 includes filters 102 and antenna ports 104, configured according to principles disclosed herein.

In some embodiments, the inner workings of the network node 16 and WD 22 may be as shown in FIG. 3 and independently, the surrounding network topology may be that of FIG. 2.

The wireless connection 32 between the WD 22 and the network node 16 is in accordance with the teachings of the embodiments described throughout this disclosure. More precisely, the teachings of some of these embodiments may improve the data rate, latency, and/or power consumption and thereby provide benefits such as reduced user waiting time, relaxed restriction on file size, better responsiveness, extended battery lifetime, etc. In some embodiments, a measurement procedure may be provided for the purpose of monitoring data rate, latency and other factors on which the one or more embodiments improve.

FIG. 4 is a flowchart of an example process in a radio interface 32, 34, 35 for multiple input-multiple output (MIMO) radio out of band (OOB) unwanted emission (OBUE) phase decorrelation. One or more blocks described herein may be performed by one or more elements of the network node 16, WD 22, network node radio interface 32, WD radio interface 34, and communications satellite radio interface 36, which are individually and/or collectively configured to configure at least two filters 94, 98, 102 of a plurality of filters 94, 98, 102 associated with antenna ports 96, 100, 104 of an antenna array of the radio interface to have different out-of-band phase characteristics (S100).

In some embodiments, the method includes configuring a phase difference between at least two out-of-band phase characteristics to be one of 180 degrees and an integer multiple of 360 degrees plus 180 degrees. In some embodiments, the method includes configuring a phase difference between at least two out-of-band phase characteristics to exceed one of 90 degrees and an integer multiple of 360 degrees plus 89 degrees. In some embodiments, the method includes configuring a phase difference between out-of-band phase characteristics of filters 94, 98, 102 for every pair of two adjacent antenna ports 96, 100, 104 to be substantially a same amount. It is noted that, as used herein, the term “substantially a same” is not intended to imply or mean that there must be some difference. Rather, the interpretation of “substantially a same” can include “the same” as used herein. In some embodiments, the same amount is one of at least 45 degrees and at least an integer multiple of 360 degrees plus 45 degrees. In some embodiments, the method includes configuring a phase difference between out-of-band phase characteristics for every pair of two adjacent antenna ports 96, 100, 104 to differ from a phase difference between out-of-band phase characteristics of at least one other pair of two adjacent antenna ports 96, 100, 104, respectively. In some embodiments, each of the different phase differences is one of at least 45 degrees and at least an integer multiple of 360 degrees plus 45 degrees. In some embodiments, the method includes configuring phase differences between out-of-band phase characteristics for different sets of adjacent antenna ports to differ by random amounts. In some embodiments, the antenna array is a two-dimensional array and the method further includes configuring phase differences between out-of-band phase characteristics for antenna ports 96, 100, 104 in an azimuth direction to be different from phase differences between out-of-band phase characteristics for antenna ports 96, 100, 104 in an elevation direction, respectively. In some embodiments, an out-of-band phase characteristic of a filter is determined relative to an in-band phase at a center frequency of a passband of the filter. In some embodiments, out-of-band phase characteristics of different filters 94, 98, 102 are programmable and the method includes programming at least one filter to obtain a desired out-of-band phase characteristic for the at least one filter. In some embodiments, the method also includes configuring out-of-band phase characteristics of a set of the filters 94, 98, 102 for the antenna ports 96, 100, 104 to have a fixed set of delays over a frequency bandwidth that is a subset of a frequency bandwidth of operation of the radio interface. In some embodiments, the method also includes configuring first filters 94, 98, 102 of a first filter block to have substantially a same first out-of-band phase characteristic and configuring second filters 94, 98, 102, respectively, of a second filter block to have substantially a same second out-of-band phase characteristic different from the first out-of-band phase characteristic. In some embodiments, the method also includes configuring a plurality of the filters 94, 98, 102 to have substantially a same in-band phase characteristic. In some embodiments, the method includes configuring the radio interface to operate within one of a network node 16, a satellite and a wireless device 22.

Having described the general process flow of arrangements of the disclosure and having provided examples of hardware and software arrangements for implementing the processes and functions of the disclosure, the sections below provide details and examples of arrangements for multiple input-multiple output (MIMO) radio out of band (OOB) unwanted emission (OBUE) phase decorrelation.

FIG. 5 illustrates empirical cumulative distribution functions (CDFs) arising from computer simulations of a 32-branch system where the maximum phase difference of the out-of-band random signal is adjusted by different amounts. No beamforming gain reductions are observed if out-of-band phases are the same for all branches – shown as “0” in FIG. 5

As out-of-band phase offsets are introduced between branches, the beamforming gains reduce. Out-of-band phase variations up to 90 degrees due to component variations and manufacturing tolerances yield negligible < 2 dB reductions in out-of-band gain. It is not until the out-of-band phase variations exceed 180 degrees that useful gain reductions are achieved.

These simulations show 50% percentile gain reductions of 17 dB are possible when the out-of-band phase variations are designed to cover a full 360-degree range. The out-of-band gain reduction for systems employing this technology may be on the order of 10*log(N) where in this case N = 32 elements, yielding approximately 15 dB of gain reductions. 5G and 6G antenna systems with 256 to 1024 antennas may have gain reductions of 24 to 30 dB.

FIG. 6 shows an example of out-of-band phase variations for 8 different filters 94, 98, 102 used in an advanced antenna system. These out-of-band signal phase variations are less than 30 degrees and will result in no gain reductions in the stopband or ACLR1 region shown below from 3.98 GHz to 4.1 GHz.

These plots are for cavity filters 94, 98, 102, which are manufactured to achieve high performance operation; however, similar results may occur in all technologies such as BAW, surface acoustic wave (SAW) and film bulk acoustic resonator (FBAR) technologies which may be mass produced with consistent in-band and out-of-band phase performance.

Current multiple antenna systems employ identical filters 94, 98, 102 on each of the transmit/receive antenna ports, thereby having consistent performance of key parameters such as filter bandwidth, insertion loss, amplitude variation, VSWR, in-band and out-of-band attenuation curves, in-band group delay, and second and third harmonic performance, etc. Some embodiments match these parameters and augments them with an additional parameter of in-band to out-of-band relative group delay. In some embodiments, filters 94, 98, 102 with this general capability are defined. In some embodiments, MIMO antenna systems employing filters 94, 98, 102 with different in-band to out-of-band relative group delays are defined.

The solution differs from traditional MIMO radios which employ the same filter element for all port branches in the antenna array. In known systems, the filters 94, 98, 102 typically have similar in-band and out-of-band phase delays with respect to each other. Therefore, when a traditional MIMO radio is configured to align the phase of the transmitted in-band signal to achieve beamforming gain, this configuration also results in out-of-band beamforming gain. In contrast, some embodiments disclosed herein employ a plurality of filters 94, 98, 102 with unique in-band to out-of-band phase delays.

Some embodiments include filters 94, 98, 102 with out-of-band phase delays that vary between 0° to ±180° with respect to the in-band phase at the center frequency of the filter passband, where the phase delay variations are either fixed (as in an orderable delay) or controllable. Some embodiments include systems which arrange a plurality of these filters 94, 98, 102 in a MIMO radio antenna, where filters 94, 98, 102 are employed on transmit paths, or receive paths, or on common receive and transmit paths as may be the case for TDD MIMO radios.

In some embodiments, an advanced antenna system employs filters 94, 98, 102 with different relative phase delays between the in-band or passband and the out-of-band or rejection band(s). These relative phase delays may be from one frequency point (such as the center of the band) to another frequency point, such as 20 MHz from the edge of the passband of the filter. Relative delays may be presented graphically as a plot. Relative delays may be specified only over a range of operation, such as in a restricted band. Relative delays may be presented as a range of delays over one frequency or a range of frequencies. Some embodiments include filter blocks with one or more filter circuits, such as an octal filter block used in advanced antenna systems with large antenna arrays. In this case, filter blocks may be identical, but the filters within a block may have one or more different relative phase delays between in-band and out-of-band.

Embodiments may include fixed, non-programmable filters 94, 98, 102 that are preconfigured with offsets for in-band and out-of-band phases. This may be advantageously employed for current MIMO radios that employ cavity filters 94, 98, 102. These products with 64 antenna branches contain 8 filter units, each of which contains 8 cavity filters 94, 98, 102. Some embodiments are applicable to and/or include a MIMO radio system where two or more of the individual cavity filters 94, 98, 102 have measurable differences between the in-band and out-of-band relative phases. In some embodiments, a system with 8 filter blocks, each with 8 filters 94, 98, 102, where each of the filters 94, 98, 102 in a filter block has a different in-band and out-of-band relative delay. In some embodiments, each of the filter blocks have different in-band and out-of-band relative delays, but the filters 94, 98, 102 in each filter block all have the same relative delays.

Some embodiments may include programmable or configurable filters 94, 98, 102. This disclosure teaches an advanced antenna system or MIMO radio system leveraging filters 94, 98, 102 with different in-band and out-of-band relative phase delays.

Some embodiments include two MIMO antennas and two filters 94, 98, 102. The two filters 94, 98, 102 have similar in-band phase and delay characteristics, and a different out-of-band phase compared to the in-band phase. These embodiments ensure that in-band beamforming gains resulting from controlling the phase fed to the two antennas will not yield similar out-of-band beamforming gains. These two-antenna embodiment may be configured to ensure that the 3 dB of in-band beamforming gain applicable to the conducted power of the transmitted carrier will not be realized in the out-of-band signals, including in the adjacent channel region where undesired leakage power, called ACLR (adjacent channel leakage ratio) exists and is significant. Some embodiments ensure that beamforming gain is achieved only in the passband and not in the rejection band or out-of-band. In some embodiments, it may be likely that the out-of-band filter phase should be offset by ±180° as shown in FIG. 7, effectively transmitting out-of-band signals so that they completely cancel. While in this embodiment, ±180° would be an optimal out-of-band phase difference between these two filters 94, 98, 102, any phase difference greater than ±90° would have beneficial effects, shown as. Moreover, given that most filters 94, 98, 102 would be expected to have out-of-band filter delay variations less than ±45°. Note that other offsets may be configured, such as ±270° or ±360°. Note also that the difference of the in-band and out-of-band phase (or group delay) of two filters 94, 98, 102 is discussed, this difference may be realized as different poles and/or zero locations of the two filters 94, 98, 102.

In some embodiments, an azimuthal array of MIMO antennas is configured according to principles disclosed herein. A MIMO antenna array with N elements is capable of azimuthal beam steering with an array gain of 10log(N). As an example, an array with eight antenna elements arranged horizontally, each with a gain of ***G*** dBi would generate a beamforming gain of G + 10*log(N) dBi. Applying typical parameters of G = 12 dBi and N = 8, the MIMO antenna would have a beamforming gain of 21 dBi. This gain would be realized both in-band and out-of-band since antennas have minimal frequency discrimination, and the filters 94, 98, 102 used after each of the power amplifiers driving the 8 antennas are identical.

However, in some embodiments, the filters 94, 98, 102 may be configured to have phase offsets across the band ranging over a range of 360 degrees. An optimal arrangement with 8 elements may have equal phase offsets across the filters 94, 98, 102 feeding the antenna, so that the filters 94, 98, 102 have increasing phase differences between in-band and out-of-band of 360/8 = 45 degrees. The filter elements would then have phase offsets relative to Θ of 0, 45, 90, …, 315 degrees. An example of this is shown in FIG. 8.

Of course, the phase offsets may have different arrangements or values, but it is sufficient to note that the in-band versus out-of-band phase delays is visibly modified for at least a significant portion of the antenna elements.

The amount of phase difference between in-band and out-of-band frequencies may depend on the antenna element beamwidth and the beamformed beamwidth.

Assuming a standard sector antenna, with an azimuth 3 dB beamwidth of 120°, the beamformed beamwidth is approximately 120/8 = 45°. It is therefore sufficient to offset the various out-of-band phases by at least 45° to ensure that a beamformed in-band carrier will not see any out-of-band beamforming gain.

In some embodiments, a two-dimensional array of MIMO antennas, with R-rows and C-columns and with (RC) elements is capable azimuth and elevation beam steering with an array gain of G + 10log(RC) where Gi is the element gain. As an example, if G = 9 dBi and R = 8, C = 4, the MIMO antenna would have a beamforming gain of 24 dBi, and this gain may be realized both in-band and out-of-band since antennas have minimal frequency discrimination, and the filters 94, 98, 102 used after each of the power amplifiers driving the 64 antennas are identical.

Before showing a potential arrangement, it is important to note that the element gain in a sector radio would have an azimuth 3 dB beamwidth of 120° and an elevation beamwidth of 30° which is quite typical of advanced antenna systems. The azimuth beamformed beamwidth be 45°, the elevation beamwidth would be a minimum of 30/4 = 7.5° and no more the azimuth beamformed gain/C/R = 11.25 degrees. The example of FIG. 9 shows azimuth rows separated by offsets of 11.25° to avoid elevation beamforming gains. This is one example of arrangements of the relative phase of in-band to out-of-band phase, Other arrangements may be implemented according to the principles set forth herein. FIG. 10 illustrates an example filter characteristic indicating locations of poles and zeros.

The phase offsets may be greater than 360° as filters 94, 98, 102 often have quite large group delays of tens of nanoseconds, representing delays of many wavelengths. Regardless, the wavelength phase difference seen at the antenna port that is relevant for beamforming. In short, integer offsets of delay may be considered identical, where Θ + 60° is considered the same as Θ + (N*360° + 60°).

Arrangements may employ random phases. While the example of FIG. 9 shows well defined fixed phase offsets between branches, an arrangement of random phases may achieve improved performance over known filtering techniques.

In some embodiments, not all branches have different phase offsets. It may be that the MIMO antenna design only requires 3 dB of reduction in the beamforming gain, which may be achieved with a reduced set of in-band to out-of-band phase relative phase delays in some embodiments.

Filters may have dynamically time varying phase offsets between in-band and out-of-band delays. Such an arrangement may enable filters 94, 98, 102 to form beams with random out-of-band phases, achieved with control of the phase offsets in time.

Some embodiments include a multiple antenna system in a MIMO radio that employs a plurality of antenna ports, with at least one port employing a filter with a first relative phase between in-band and out-of-band, and one or more other ports employing a filter with a second relative phase between in-band and out-of-band.

Some embodiments include a multiple antenna system in a MIMO radio that employs a plurality of antenna ports, with at least one port employing a filter configured via a control means to a first relative phase between in-band and out-of-band, and one or more other ports employing a filter configured via a control means, to a different relative phase between in-band and out-of-band.

The above multiple antenna systems embodiments may employ a plurality of filter elements, with a plurality of relative phases between in-band and out-of-band phase delays

For transmission, some embodiments may mitigate all beamforming gain in the out-of-band regions, enabling products to meet tight EIRP specifications when operating adjacent to sensitive bands such as used for radio altimeters (4200-4400 MHz) or sensitive satellite bands such as 23.6-24.0 GHz. Many bands exist with sensitive ground-based equipment which would benefit from the application of principles disclosed herein. Many more bands exist with sensitive satellite equipment operating in adjacent bands where beamformed adjacent channel leakage may cause significant interference.

For reception, some embodiments may enable the RBS to mitigate out-of-band signal levels by mitigates beamforming in these regions. This is especially important for systems with significant beamforming gains, and high power out-of-band radiating sources, such as radar transmitters.

With respect WDs, some embodiments may mitigate out-of-band signal reception during beamforming. While these WDs do not have large antenna arrays, they may still benefit by 6-9 dB for 4-8 antenna designs.

Some embodiments minimize guard bands between bands. 3GPP Specifications typically assume 50-100 MHz guard bands and have been pushing tighter guard bands of 40 MHz, which is fully born in filter requirements. The goal of 3GPP is for very small guard bands, improving spectrum utilization. Some embodiments provide may become standardized on new bands such as the 7.125 - 8.400 GHz band currently under investigation with the U.S. National Telecommunications and Information Administration (NTIA).

Some embodiments are applicable to VLA (very large arrays) with 1000+ antenna elements and beamforming array gains of 30 dB or more. Some embodiments mitigate the beamforming gain of these solutions in the guard band, enabling a path for such large arrays without a subsequent increase in filter performance needed to meet out-of-band emissions requirements.

Some embodiments enable radio design cost reductions. With the elimination of beamforming array gain from transmitter adjacent channel leakage, filter performance may be reduced, yielding an effective cost reduction. Increasingly complex digital predistortion circuitry may be simplified and cost reduced, as out-of-band beamforming gains are rendered of reduced concern.

As will be appreciated by one of skill in the art, the concepts described herein may be embodied as a method, data processing system, computer program product and/or computer storage media storing an executable computer program. Accordingly, the concepts described herein may take the form of an entirely hardware embodiment, an entirely software embodiment or an embodiment combining software and hardware aspects all generally referred to herein as a “circuit” or “module.” Any process, step, action and/or functionality described herein may be performed by, and/or associated to, a corresponding module, which may be implemented in software and/or firmware and/or hardware. Furthermore, the disclosure may take the form of a computer program product on a tangible computer usable storage medium having computer program code embodied in the medium that may be executed by a computer. Any suitable tangible computer readable medium may be utilized including hard disks, CD-ROMs, electronic storage devices, optical storage devices, or magnetic storage devices.

Some embodiments are described herein with reference to flowchart illustrations and/or block diagrams of methods, systems and computer program products. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, may be implemented by computer program instructions. These computer program instructions may be provided to a processor of a general purpose computer (to thereby create a special purpose computer), special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

These computer program instructions may also be stored in a computer readable memory or storage medium that may direct a computer or other programmable data processing apparatus to function in a particular manner, such that the instructions stored in the computer readable memory produce an article of manufacture including instruction means which implement the function/act specified in the flowchart and/or block diagram block or blocks.

The computer program instructions may also be loaded onto a computer or other programmable data processing apparatus to cause a series of operational steps to be performed on the computer or other programmable apparatus to produce a computer implemented process such that the instructions which execute on the computer or other programmable apparatus provide steps for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

It is to be understood that the functions/acts noted in the blocks may occur out of the order noted in the operational illustrations. For example, two blocks shown in succession may in fact be executed substantially concurrently or the blocks may sometimes be executed in the reverse order, depending upon the functionality/acts involved. Although some of the diagrams include arrows on communication paths to show a primary direction of communication, it is to be understood that communication may occur in the opposite direction to the depicted arrows.

Computer program code for carrying out operations of the concepts described herein may be written in an object oriented programming language such as Python, Java® or C++. However, the computer program code for carrying out operations of the disclosure may also be written in conventional procedural programming languages, such as the "C" programming language. The program code may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer. In the latter scenario, the remote computer may be connected to the user's computer through a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

Many different embodiments have been disclosed herein, in connection with the above description and the drawings. It will be understood that it would be unduly repetitious and obfuscating to literally describe and illustrate every combination and subcombination of these embodiments. Accordingly, all embodiments may be combined in any way and/or combination, and the present specification, including the drawings, shall be construed to constitute a complete written description of all combinations and subcombinations of the embodiments described herein, and of the manner and process of making and using them, and shall support claims to any such combination or subcombination.

It will be appreciated by persons skilled in the art that the embodiments described herein are not limited to what has been particularly shown and described herein above. In addition, unless mention was made above to the contrary, it should be noted that all of the accompanying drawings are not to scale. A variety of modifications and variations are possible in light of the above teachings without departing from the scope of the following claims.

What is claimed is:

1. A radio interface (32, 34, 36), comprising:

a plurality of antenna ports (96, 100, 104), each antenna port (96, 100, 104) being associated with at least one antenna element of an array of antennas elements; and

a plurality of filters (94, 98, 102) associated with the plurality of antenna ports (96, 100, 104), at least two of the plurality of filters (94, 98, 102) having different out-of-band phase characteristics.

2. The radio interface (32, 34, 35) of Claim 1, wherein a phase difference between at least two out-of-band phase characteristics is one of 180 degrees and an integer multiple of 360 degrees plus 180 degrees.

3. The radio interface (32, 34, 35) of Claim 1, wherein a phase difference between at least two out-of-band phase characteristics exceeds one of 90 degrees and an integer multiple of 360 degrees plus 90 degrees.

4. The radio interface (32, 34, 35) of Claim 1, wherein a phase difference between out-of-band phase characteristics of filters (94, 98, 102) for every pair of two adjacent antenna ports (96, 100, 104) is substantially a same amount.

5. The radio interface (32, 34, 35) of Claim 4, wherein the same amount is one of at least 45 degrees and at least an integer multiple of 360 degrees plus 45 degrees.

6. The radio interface (32, 34, 35) of Claim 1, wherein a phase difference between out-of-band phase characteristics for every pair of two adjacent antenna ports (96, 100, 104) differs from the phase difference between out-of-band phase characteristics of at least one other pair of two adjacent antenna ports (96, 100, 104).

7. The radio interface (32, 34, 35) of Claim 6, wherein each of the different phase differences is one of at least 45 degrees and at least an integer multiple of 360 degrees plus 45 degrees.

8. The radio interface (32, 34, 35) of Claim 1, wherein phase differences between out-of-band phase characteristics for different sets of adjacent antenna ports (96, 100, 104) differ by random amounts.

9. The radio interface (32, 34, 35) of any of Claims 1-8, wherein the array of antenna elements is a two-dimensional array and phase differences between out-of-band phase characteristics for antenna ports (96, 100, 104) in an azimuth direction are different from phase differences between out-of-band phase characteristics for antenna ports (96, 100, 104) in an elevation direction.

10. The radio interface (32, 34, 35) of any of Claims 1-9, wherein an out-of-band phase characteristic of a filter (94, 98, 102) is determined relative to an in-band phase at a center frequency of a passband of the filter (94, 98, 102).

11. The radio interface (32, 34, 35) of any of Claims 1-10, wherein out-of-band phase characteristics of different filters (94, 98, 102) are programmable.

12. The radio interface (32, 34, 35) of any of Claims 1-11, wherein out-of-band phase characteristics of a set of filters (94, 98, 102) for the antenna ports (96, 100, 104) are configured to have a fixed set of delays over a frequency bandwidth that is a subset of a frequency bandwidth of operation of the radio interface (32, 34, 36).

13. The radio interface (32, 34, 35) of any of Claims 1-12, wherein first filters (94, 98, 102) of a first filter block have substantially a same first out-of-band phase characteristic and second filters (94, 98, 102) of a second filter block have substantially a same second out-of-band phase characteristic different from the first out-of-band phase characteristic.

14. The radio interface (32, 34, 35) of any of Claims 1-13, wherein a plurality of the filters (94, 98, 102) have substantially a same in-band phase characteristic.

15. The radio interface (32, 34, 35) of any of Claims 1-14, wherein the radio interface (32, 34, 35) is configured to operate within one of a network node (16), a satellite (36) and a wireless device (22).

16. A method in a radio interface (32, 34, 36), the method comprising:

configuring (S100) at least two filters (94, 98, 102) of a plurality of filters (94, 98, 102) associated with antenna ports (96, 100, 104) of an antenna array of the radio interface (32, 34, 35) to have different out-of-band phase characteristics.

17. The method of Claim 16, further comprising configuring a phase difference between at least two out-of-band phase characteristics to be one of 180 degrees and at least an integer multiple of 360 degrees plus 180 degrees.

18. The method of Claim 16, further comprising configuring a phase difference between at least two out-of-band phase characteristics to exceed one of 90 degrees and at an integer multiple of 360 degrees plus 90 degrees.

19. The method of Claim 16, further comprising configuring a phase difference between out-of-band phase characteristics of filters (94, 98, 102) for every pair of two adjacent antenna ports (96, 100, 104) to be substantially a same amount.

20. The method of Claim 19, wherein the same amount is one of at least 45 degrees and at least an integer multiple of 360 degrees plus 45 degrees.

21. The method of Claim 16, further comprising configuring a phase difference between out-of-band phase characteristics for every pair of two adjacent antenna ports (96, 100, 104) to differ from a phase difference between out-of-band phase characteristics of at least one other pair of two adjacent antenna ports (96, 100, 104).

22. The method of Claim 21, wherein each of the different phase differences is one of at least 45 degrees and at least an integer multiple of 360 degrees plus 45 degrees.

23. The method of Claim 16, further comprising configuring phase differences between out-of-band phase characteristics for different sets of adjacent antenna ports (96, 100, 104) to differ by random amounts.

24. The method of any of Claims 16-23, wherein the antenna array is a two-

dimensional array and the method further includes configuring phase differences between out-of-band phase characteristics for antenna ports (96, 100, 104) in an azimuth direction to be different from phase differences between out-of-band phase characteristics for antenna ports (96, 100, 104) in an elevation direction.

25. The method of any of Claims 16-24, wherein an out-of-band phase characteristic of a filter (94, 98, 102) is determined relative to an in-band phase at a center frequency of a passband of the filter (94, 98, 102).

26. The method of any of Claims 16-25, wherein out-of-band phase characteristics of different filters (94, 98, 102) are programmable and the method includes programming at least one filter (94, 98, 102) to obtain a desired out-of-band phase characteristic for the at least one filter (94, 98, 102).

27. The method of any of Claims 16-26, further comprising configuring out-of-band phase characteristics of a set of the filters (94, 98, 102) for the antenna ports (96, 100, 104) to have a fixed set of delays over a frequency bandwidth that is a subset of a frequency bandwidth of operation of the radio interface (32, 34, 36).

28. The method of any of Claims 16-27, further comprising configuring first filters (94, 98, 102) of a first filter block to have substantially a same first out-of-band phase characteristic and configuring second filters (94, 98, 102) of a second filter block to have substantially a same second out-of-band phase characteristic different from the first out-of-band phase characteristic.

29. The method of any of Claims 16-28, further comprising configuring a plurality of the filters (94, 98, 102) to have substantially a same in-band phase characteristic.

30. The method of any of Claims 16-29, further comprising configuring the radio interface (32, 34, 35) to operate within one of a network node (16), a satellite (36) and a wireless device (22).

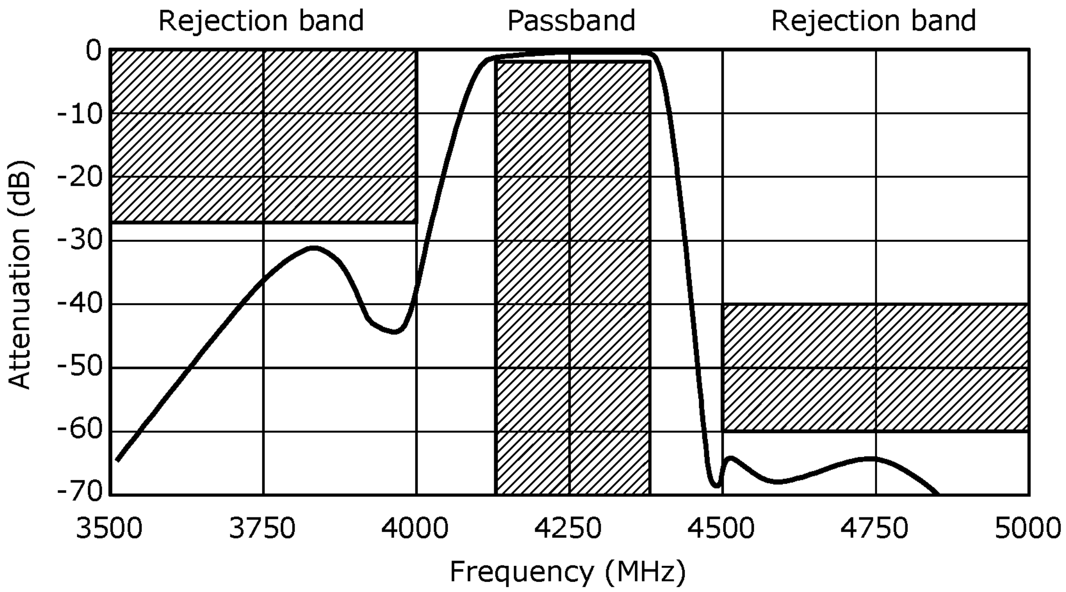
Rejection band
Passband
Rejection band
Attenuation (dB)
0
-10
-20
-30
-40
-50
-60
-70
3500
3750
4000
4250
4500
4750
5000
Frequency (MHz)

FIG. 1

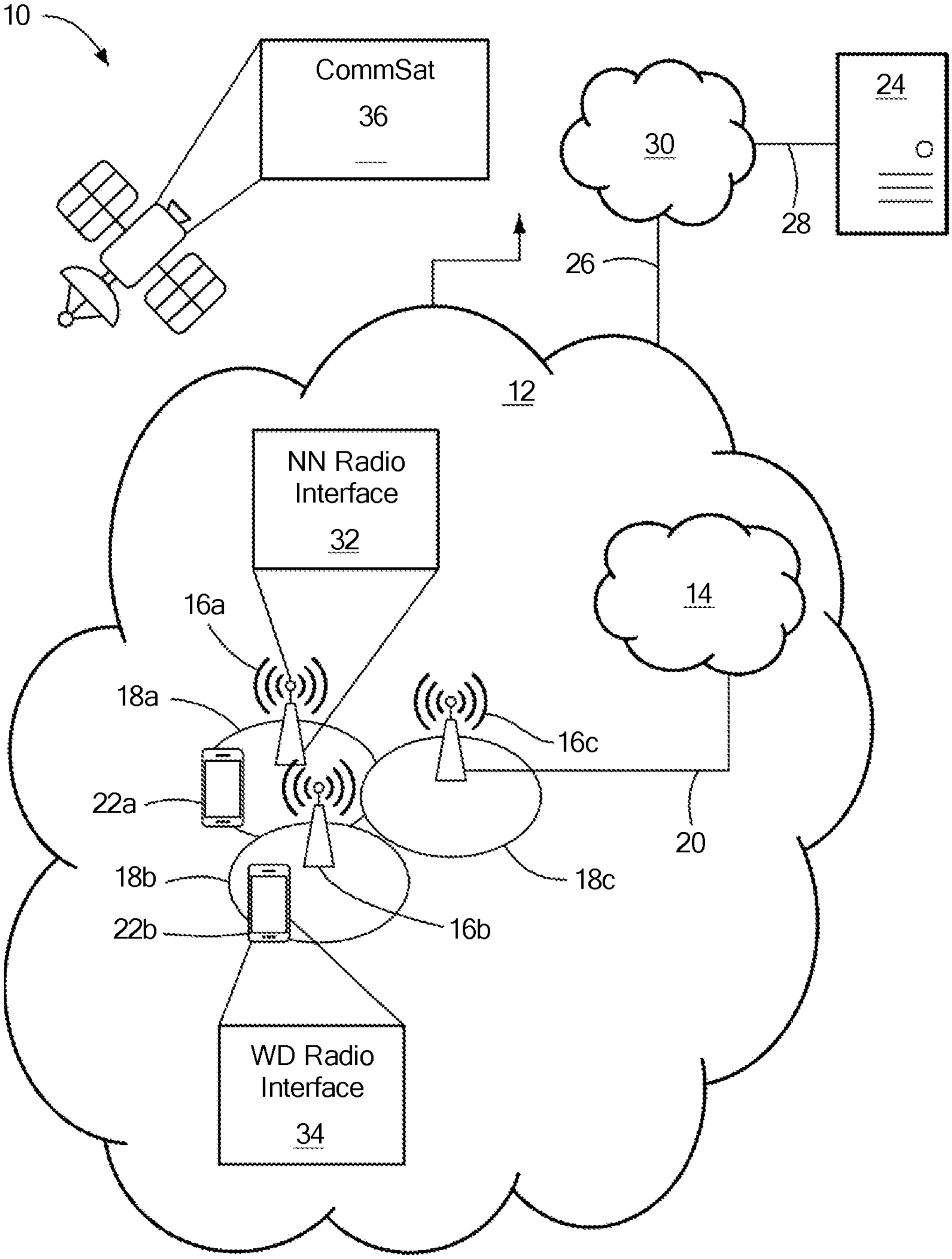
10
CommSat
36
24
30
28
26
12
NN Radio
Interface
32
14
16a
18a
16c
22a
20
18c
18b
16b
22b
WD Radio
Interface
34

FIG. 2

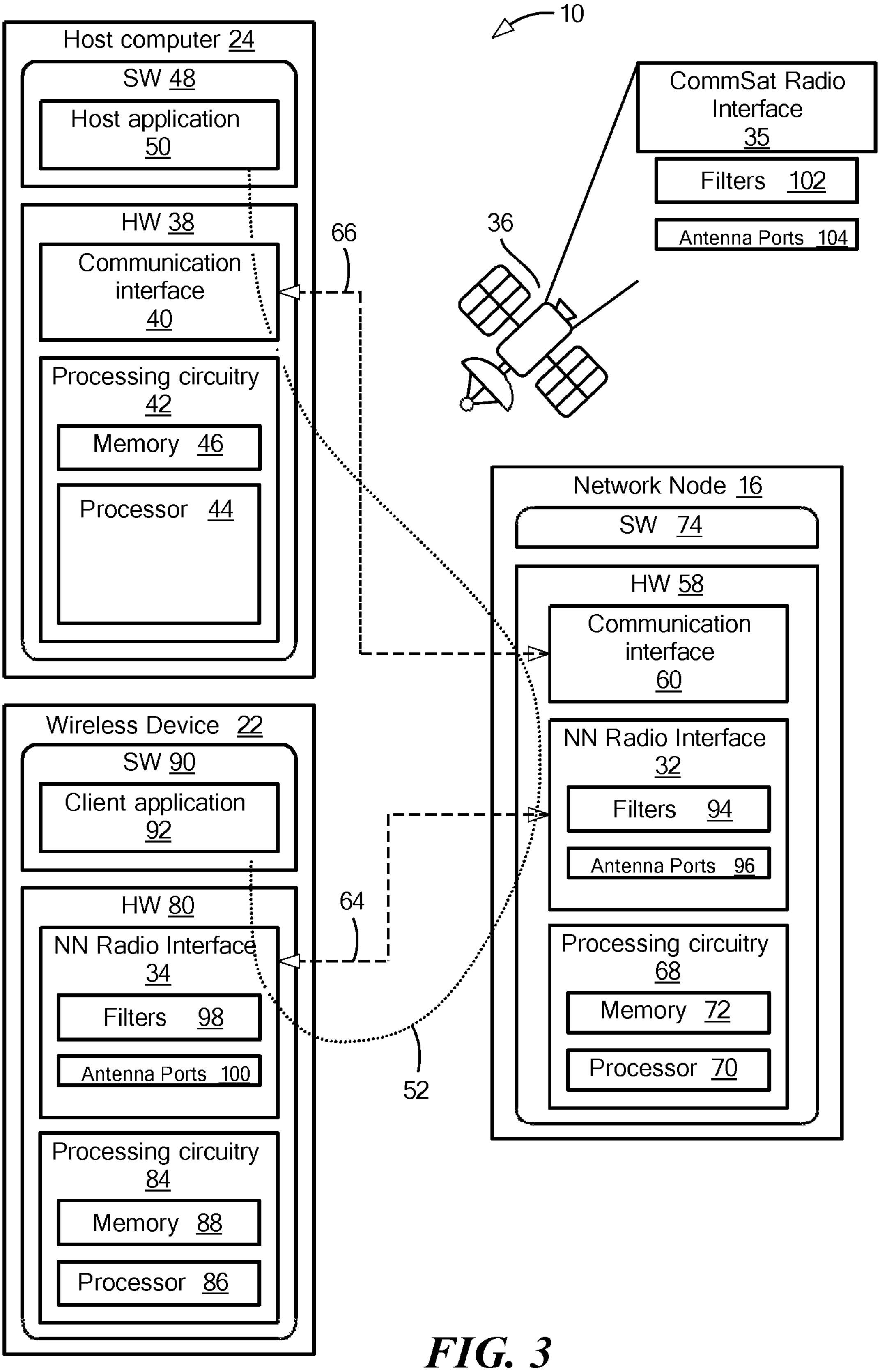
10
Host computer 24
SW 48
Host application 50
HW 38
Communication interface 40
Processing circuitry 42
Memory 46
Processor 44
66
36
CommSat Radio Interface 35
Filters 102
Antenna Ports 104
Network Node 16
SW 74
HW 58
Communication interface 60
NN Radio Interface 32
Filters 94
Antenna Ports 96
Processing circuitry 68
Memory 72
Processor 70
Wireless Device 22
SW 90
Client application 92
HW 80
NN Radio Interface 34
Filters 98
Antenna Ports 100
Processing circuitry 84
Memory 88
Processor 86
64
52

FIG. 3

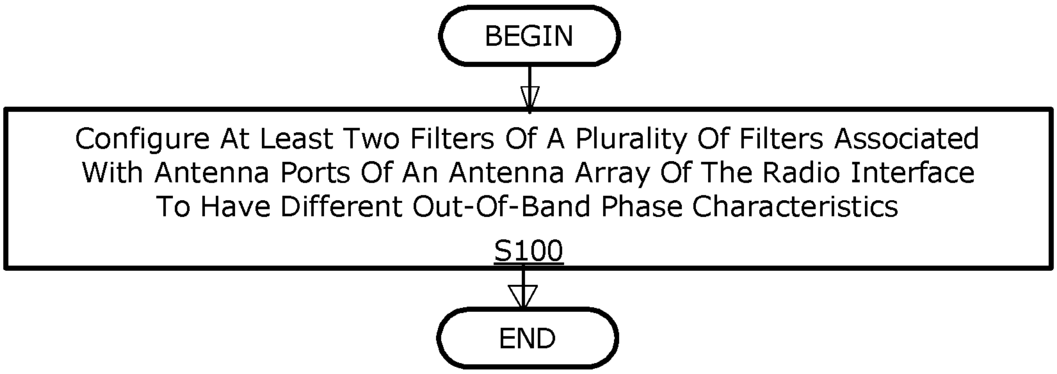
BEGIN
Configure At Least Two Filters Of A Plurality Of Filters Associated With Antenna Ports Of An Antenna Array Of The Radio Interface To Have Different Out-Of-Band Phase Characteristics
S100
END

FIG. 4

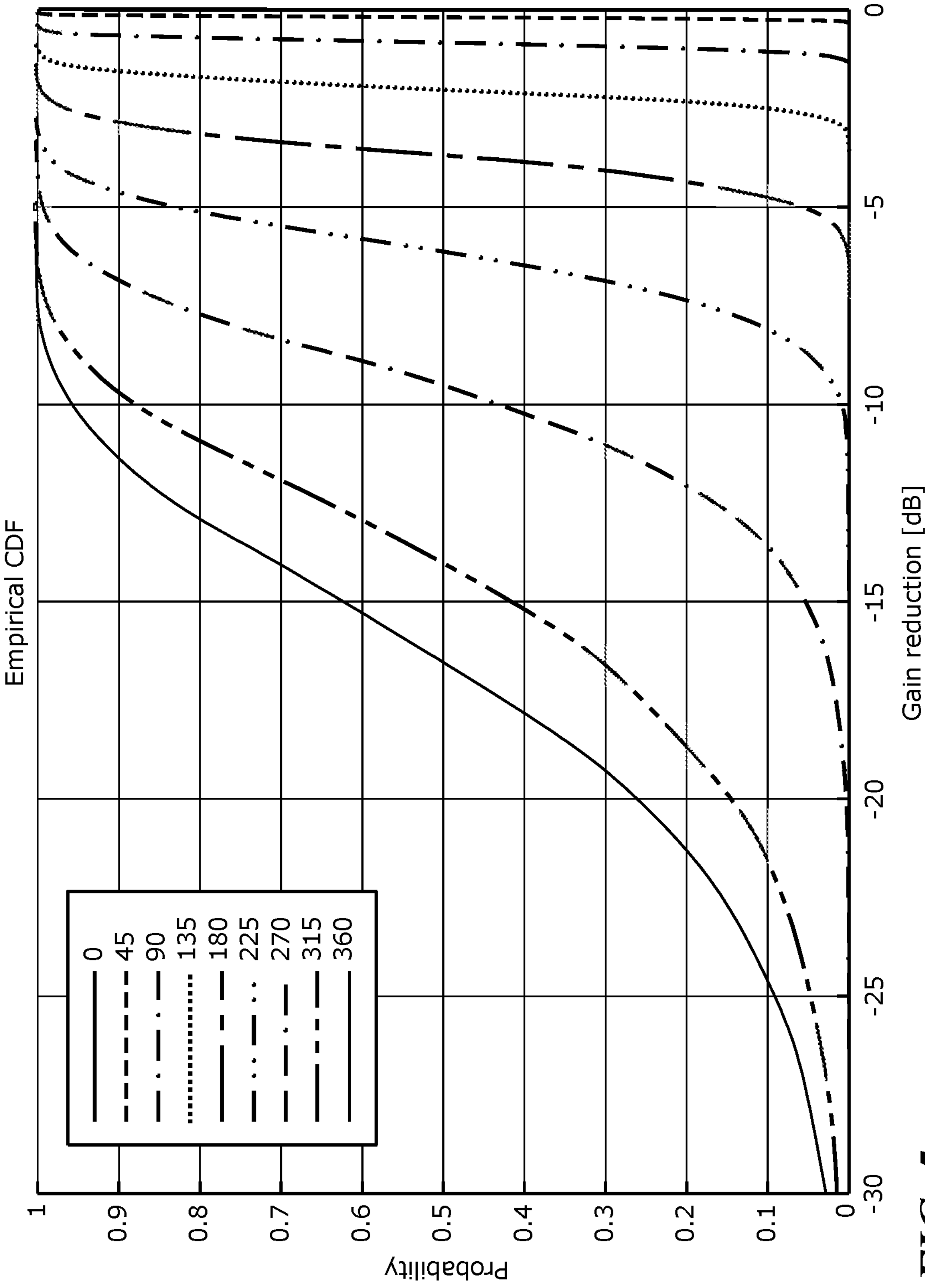
Empirical CDF
Probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-30
-25
-20
-15
-10
-5
0
Gain reduction [dB]
0
45
90
135
180
225
270
315
360

FIG. 5

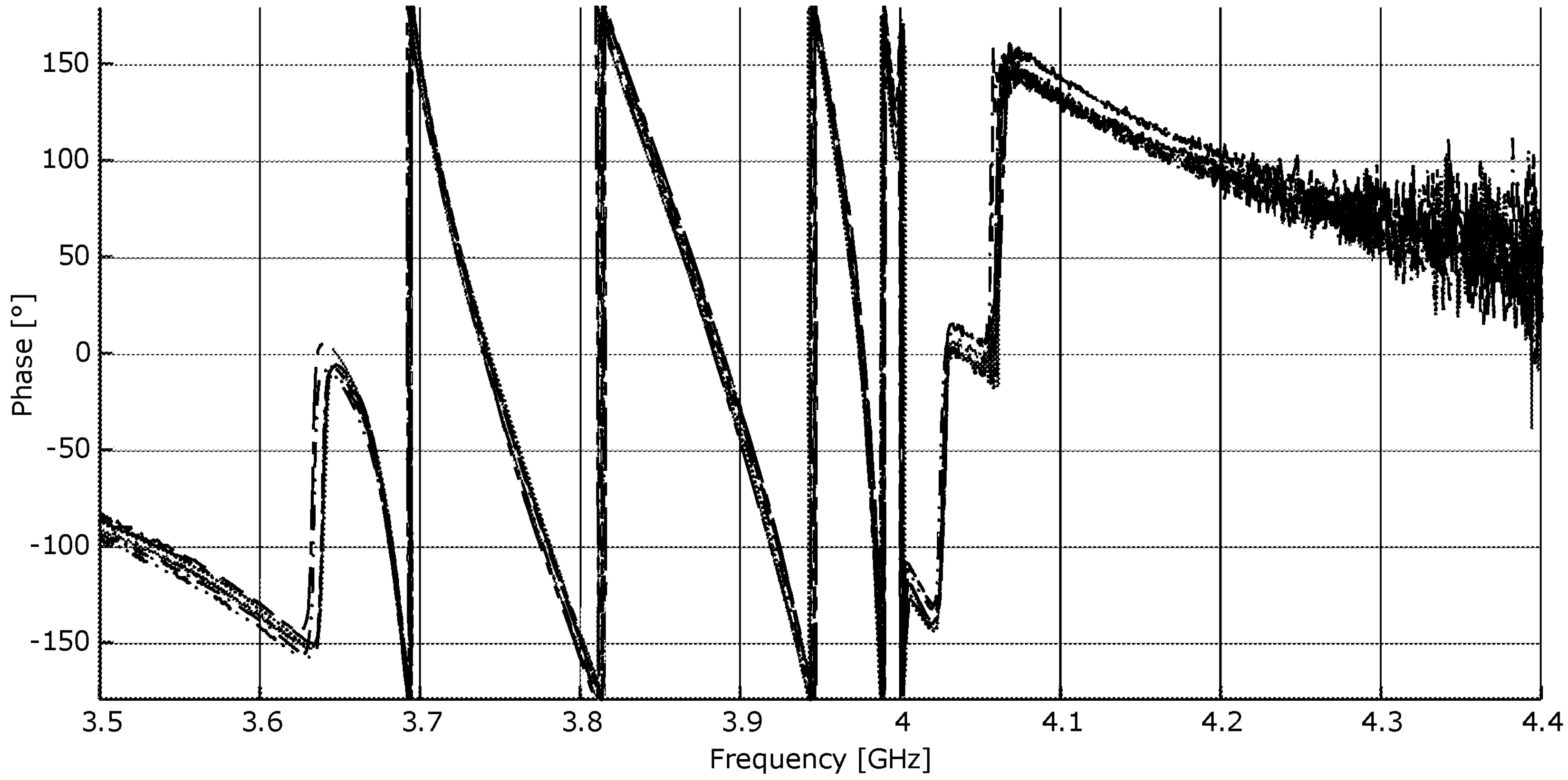
150
100
50
0
-50
-100
-150
Phase [°]
3.5
3.6
3.7
3.8
3.9
4
4.1
4.2
4.3
4.4
Frequency [GHz]

FIG. 6

Θ	Θ± 180°

FIG. 7

Θ+0	Θ+45°	Θ+90°	Θ+135°	Θ+180°	Θ+225°	Θ+270°	Θ+315°

FIG. 8

Θ +00.00°	Θ +45.00°	Θ +90.00°	Θ +135.00°	Θ +180.00°	Θ +225.00°	Θ +270.00°	Θ +315.00°
Θ +11.25°	Θ +56.25°	Θ +101.25°	Θ +146.25°	Θ +191.25°	Θ +236.25°	Θ +281.25°	Θ +326.25°
Θ +23.50°	Θ +67.5°	Θ +112.5°	Θ +157.50°	Θ +202.50°	Θ +247.50°	Θ +292.50°	Θ +337.50°
Θ +33.75°	Θ +78.25°	Θ +123.75°	Θ +168.75°	Θ +213.75°	Θ +258.75°	Θ +303.75°	Θ +348.75°

FIG. 9

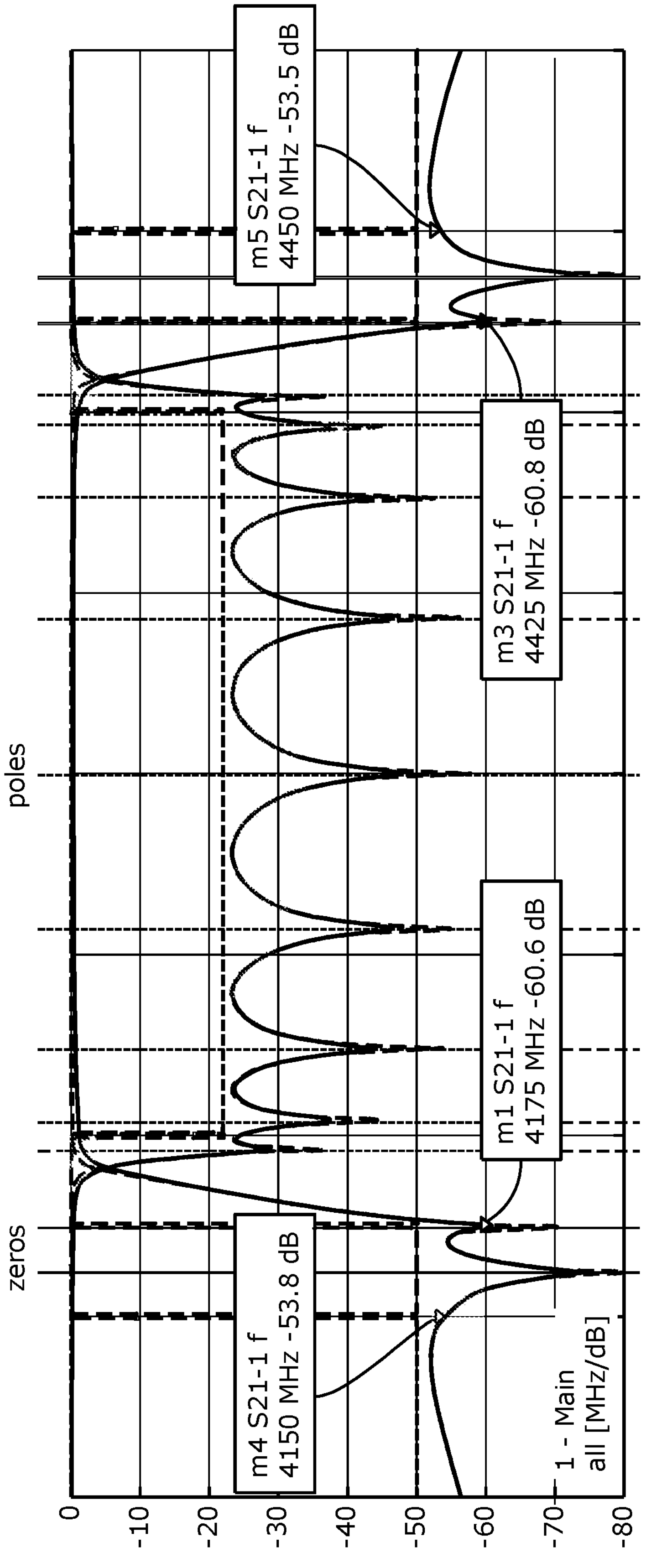
zeros
poles
m4 S21-1 f
4150 MHz -53.8 dB
m1 S21-1 f
4175 MHz -60.6 dB
m3 S21-1 f
4425 MHz -60.8 dB
m5 S21-1 f
4450 MHz -53.5 dB
1 - Main
all [MHz/dB]
0
-10
-20
-30
-40
-50
-60
-70
-80
4100
4150
4200
4250
4300
4350
4400
4450
4500

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2023/056286

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B1/04 H04B7/06
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2023/031648 A1 (ERICSSON TELEFON AB L M [SE]) 9 March 2023 (2023-03-09) figures 4, 5,6, 11 page 3, line 3 - line 25 -----	1-30
A	ANTTILA LAURI ET AL: "On Antenna Array Out-of-Band Emissions", IEEE WIRELESS COMMUNICATIONS LETTERS, IEEE, PISCATAWAY, NJ, USA, vol. 8, no. 6, 1 December 2019 (2019-12-01), pages 1653-1656, XP011758917, ISSN: 2162-2337, DOI: 10.1109/LWC.2019.2934442 [retrieved on 2019-12-06] abstract Conclusion figure 1 -----	1-30

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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 20 December 2023	Date of mailing of the international search report 15/01/2024
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Avilés Martínez, L

2

International application No
PCT/IB2023/056286

C(Continuation). **DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	MAHMOUD ABDELAZIZ ET AL: "Digital Predistortion for Hybrid MIMO Transmitters", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 6 April 2018 (2018-04-06), XP080868198, page 1, right-hand column abstract figure 1 -----	1-30
A	WO 2022/262991 A1 (ERICSSON TELEFON AB L M [SE]) 22 December 2022 (2022-12-22) paragraph [0013] figures 4, 9A-9C -----	1-30

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2023/056286

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2023031648 A1	09-03-2023	NONE	
WO 2022262991 A1	22-12-2022	NONE	