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SYSTEM AND METHOD FOR SCALABLE ON-ARRAY PROCESSING AND INTERFERENCE MITIGATION USING ADAPTIVE BEAMFORMING

Abstract

Methods and systems are described herein for adaptive beamforming and interference mitigation using a time synchronized scalable cohered on-array processing system ("system"). The system may be a phased array implementing a software-defined radio using multi-input-multi-output antenna elements. The system includes multiple subarray elements which are configured into a tiered array of scalable subarrays that performs intermediary collation, coherence, noise reduction, and adaptive beamforming operations through processor nodes disposed between tiers. The intermediary collation operations process discrete portions of node excitation data to enable the phased array to generate an adaptive beam profile that directs high-directionality beams toward desired targets while adaptively partitioning interference sources between subarray elements. Further, the system makes use of a scalable multidimensional array to provide telecommunication and electromagnetic wave manipulation operations for applications of varying scale.

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Background/Summary

BACKGROUND

[0001] Phased array antennas and beamforming technologies have been pivotal in advancing radar systems, satellite communications, and the burgeoning field of 5G networks. These technologies enable the steering of the antenna beam electronically, providing flexibility and precision in targeting and communications. However, despite their advantages, the currently used technologies come with significant shortcomings.

[0002] One of the primary challenges is their complexity and associated cost. The intricate design and need for precision alignment of numerous array elements make production and maintenance both challenging and expensive. This complexity limits their accessibility and application, particularly in cost-sensitive domains. Traditional phased arrays are often bulky and heavy. This is a substantial drawback for mobile platforms and space applications where weight and space are at a premium. The physical size of these systems can also limit their field of view and scanning range, affecting performance in critical applications.

[0003] Traditional phased arrays generally have high power requirements, which poses a challenge for mobile applications. Additionally, increasing array complexity leads to increased thermal management requirements which frequently call for additional power consuming cooling equipment.

[0004] Finally, the adaptability and scalability of traditional phased arrays are limited. Tailoring these systems for different applications or frequency ranges can be an arduous task, often requiring a complete redesign. While traditional phased arrays and beamforming technologies have been instrumental in advancing modern communication and radar systems, their complexity, cost, size, power consumption, and limited adaptability pose significant challenges. There is therefore a need to address the above-cited issues.

SUMMARY

[0005] In general, the method(s) described herein may facilitate and/or otherwise include calibrating, via an arbitrary processor node, a plurality of aggregated weight vectors for a plurality of subarray elements within a phased array, where the arbitrary processor node is from a plurality of processor nodes. The method(s) may include determining, via a corresponding processor node, if a covariance matrix is full rank in relation to each of the plurality of aggregated weight vectors, where each of the plurality of subarray elements is associated with the corresponding processor node from the plurality of processor nodes. The method(s) may include generating, via the corresponding processor node, an interference mitigation protocol for each of the plurality of subarray elements based on at least one of the aggregated weight vector and the covariance matrix. The method(s) may include outputting, via the plurality of subarray elements, an adaptive beam pattern in accordance with the interference mitigation protocol, where the adaptive beam pattern includes an at least one high-directionality beam generated by at least one first subarray element and at least one mitigation signal modulated by at least one second subarray element. Other embodiments include corresponding computer systems, apparatus, and computer programs recorded on one or more computer storage devices, each configured to perform one or more of the actions of the method(s).

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1**A shows a block diagram of a tiered phased array system, consistent with various embodiments.

[0007] FIG. **1**B shows a block diagram of a subarray element within the tiered phased array of FIG. **1**A, consistent with various embodiments.

[0008] FIG. **2** is a block diagram of a subarray element of the system of FIG. **1**A, consistent with various embodiments.

[0009] FIG. **3**A shows an example of synchronizing the phased arrays using a calibration signal from a subarray element of the system of FIG. **1**A, consistent with various embodiments.

[0010] FIG. **3**B shows a block diagram of the system of FIG. **1**A configured to function as a scalable multidimensional array of subarray elements and antenna elements, consistent with various embodiments.

[0011] FIG. **4** shows a flowchart of a method for generating at least one adaptive beam directed toward the at least one target and at least one mitigation signal directed toward an interference source, consistent with various embodiments.

[0012] FIG. **5**A is a first block diagram illustrating the system generating an adaptive beam pattern to direct spatial nulls toward interference sources and track targets with high-directionality beams, consistent with various embodiments.

[0013] FIG. **5**B is a block diagram illustrating the system partitioning interference sources between subarray elements, consistent with various embodiments.

[0014] FIG. **6** shows a flowchart of a method for generating the adaptive beam pattern by cohering time aligned data signals from subarray elements of the system of FIG. **1**B, consistent with various embodiments.

[0015] FIG. **7**A shows a simulation of a typical antenna pattern, consistent with various embodiments.

[0016] FIG. **7**B shows a demonstration of the system performing adaptive antenna nulling at spatial angles of interferers, consistent with various embodiments.

[0017] FIG. **8** is a block diagram of a radar system implemented using the system of FIG. **1**A, consistent with various embodiments.

DETAILED DESCRIPTION

[0018] In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the embodiments of the invention. It will be appreciated, however, by those having skill in the art, that the embodiments of the invention may be practiced without these specific details or with an equivalent arrangement. In other cases, well-known structures and devices are shown in block diagram form to avoid unnecessarily obscuring the embodiments of the invention.

[0019] The disclosed concept relates to a system that leverages an adaptive phased array transceiver that may implement a plurality of transmit and receiver operations (e.g., analog RC chain communication, or a software-defined radio (SDR) system) and comprises a number of time aligned antenna nodes within a phased array to provide a flexible multi-function radio frequency (RF) solution. For example, the system may use modular (or tile) and scalable units that contain multiple antenna elements and digital processors. This reduces the number of printed circuit boards and connectors in the array, which lowers the cost and complexity of the system. Further, this modular processing architecture reduces the overall power requirements and thermal management constraints for operation. The system may provide communications, radar, and electronic intelligence (ELINT) capabilities in a rapidly deployable software-defined architecture. In some embodiments, the system leverages machine learning algorithms to enable a phased array of SDR antenna elements to mitigate, respond to, and potentially implement RF interference and jamming techniques (e.g., frequency hopping jamming, spread spectrum jamming, powerful pulse jamming, smart or adaptive jamming, low probability of intercept (LPI) techniques). For example, the system may implement or respond to jamming operations where the jamming devices rapidly switch frequencies, making it difficult for traditional static-frequency countermeasures to adapt. The system may implement or respond to jamming operations where jammers spread their energy across a wide range of frequencies, effectively diluting the power of the jamming signal but impacting a broader set of frequencies. The system may employ or respond to synchronized short bursts of high-power signals capable of overwhelming receivers (e.g., systems relying on sensitive detection equipment). The system may employ or respond to jamming operations that analyze the target's signal and adapt the jamming strategy accordingly. The system may employ or respond to jamming operations that mimic legitimate signals to create confusion or use selective jamming techniques to target specific communications while leaving others unscathed. The system may employ or respond to jamming operations that use signals with low power levels to remain undetected while still effectively disrupting communications. The system is designed to adapt with continuous advancement in both jamming techniques and beamforming countermeasures used in electronic warfare. The system's ability to rapidly adapt to the changing electronic warfare landscape is designed to both leverage and counteract the integration of advanced technologies such as artificial intelligence (AI) and machine learning. The system may leverage adaptive beamforming techniques to point high-gain directional beams toward satellites of interest while simultaneously creating null beams to cancel 5G and/or multispectral interference. These beams can be arbitrarily steered in real time to track the satellite's transition across the sky based on orbital parameters known a priori and/or gathered in real time. Further, being able to synchronize multiple antenna nodes provides a technical discriminator enabling the system to implement a scalable processing architecture where the computational overhead of signal processing and adaptive beamforming required to cohere groups of subarray elements within the phased array is distributed across a number of processor nodes. In some embodiments the system employs a method for deploying a phased array to generate interference-signal attenuation of any desired signal (e.g., an in-name interferer or an electronic warfare/intentional jamming signals). The system may implement sidelobe cancellation and nulling to bolster interference mitigation operations. In some embodiments, the system may operate in a range from 5 Hz to 10 THz.

[0020] FIG. **1**A shows a scalable cohered on-array processing (SCOAP) system **100**, consistent with various embodiments. For example, the system **100** may include a phased array **101** that has been partitioned into a plurality of subarrays **102***a*-**102***n*, at least one reference node **106**, and a plurality of processor nodes **108***a*-**108***n*, and an array processing interface **122**. In some embodiments, each of the plurality of subarrays **102***a*-**102***n* comprises a plurality of SDR antenna elements that are computationally and/or physically grouped. For example, the phased array **101** may include **256** SDR antenna elements arranged into a 16×16 grid. The entire collection of SDR antenna elements may then be partitioned into 16 subarrays that each contain a four-by-four array of SDR antenna elements. In some embodiments, the plurality of antenna elements is configured to operate using analog RF chain components **210** (FIG. **2**). In some embodiments, the system **100** may implement all of the beamforming, steering, filtering, and analysis operations via SDR or analog RF chain configurations so that, except as stated otherwise, the terms “SDR” and “analog RF chain” can be used interchangeably herein to refer to electromagnetic transceivers. In further embodiments, the system **100** may include both SDR and analog RF chain antenna elements within the same phased array **101**. For example, the system **100** may partition the plurality of subarrays **102***a*-**102***n* such that a first subgroup contains SDR antenna elements, a second subgroup contains analog RF antenna elements, and/or a third group contains a mix of the various antenna element types. The system **100** may generate unique adaptive beam protocols that direct each of the subgroups to generate a desired output. Further, the system **100** may determine the appropriate antenna element type to include in the subgroups based on the desired implementation.

[0021] In some embodiments, the SDR antenna elements may be selected for inclusion in an arbitrary subarray (e.g., **102***a*) based on at least one of a signal's angle of arrival (AOA), the characteristics of at least one spatial interference source, a desired adaptive beam pattern, a current position and/or path of travel of a target, operational capacity (e.g. functioning properly or malfunctioning), and algorithmic analysis (e.g., machine learning and/or AI models for determining an optimized configuration of SDR antenna elements in response to interference sources and/or the output of additional subarrays (e.g., **102***n* in the phased array **101**). In some embodiments, each of the plurality of subarrays **102***a*-**102***n* can be envisioned as a sensor node that facilitates the transmission of waveforms as beams in at least one desired direction.

[0022] In some embodiments, the system **100** synchronizes each of the plurality subarrays **102***a*-**102***n* with a reference node **106** of the system **100** by computing a time offset between a timestamp of an occurrence of the event at a reference node **106** of the system **100** and a timestamp of an occurrence of the event at the corresponding subarray **102***n*. The reference node **106** may be a single SDR antenna element in the phased array **101** that is designated as the reference node. For example, in the event the plurality subarrays **102***a*-**102***n* are implemented using factory-calibrated atomic clocks, the designated reference node **106** of the system **100** (e.g., a processor node **108***a*-**108***n*) sends a request to each of the plurality subarrays **102***a*-**102***n*, including a reference node **106** of the system **100**, for a local timestamp of the corresponding subarray **102***n* and obtains a response including the local timestamp (e.g., a time at which the request is received at the corresponding subarray **102***n*).

[0023] In some embodiments, the plurality of processor nodes **108***a*-**108***n* may be virtualized processors designed to execute tasks in a cloud computing environment. In further embodiments, the plurality of processor nodes **108***a*-**108***n* may refer to a plurality of physical processing cores in a processing device that may further implement a series of virtualized processor nodes. In further embodiments the plurality of processor nodes **108***a*-**108***n* is implemented by a Field Programmable Gate Array (FPGA) capable of being reconfigured based on processing requirements. In some embodiments, the array processing interface **122** may refer to a communications architecture or framework through which the plurality of processor nodes **108***a*-**108***n*, the plurality of subarrays **102***a*-**102***n*, and the reference node **106** communicate. For example, where the plurality of processor nodes **108***a*-**108***n* is a plurality of virtualized processors, the array processing interface **122** may refer to a data structuring algorithm or a transfer control protocol that facilitates scalable communication between the plurality of processor nodes **108***a*-**108***n*, the reference node **106**, and the plurality of subarrays **102***a*-**102***n*.

[0024] In an alternative embodiment, the array processing interface **122** may enable the plurality of physical processor nodes **108***a*-**108***n* to be algorithmically coupled to a corresponding subarray from the plurality of subarrays **102***a*-**102***n*. For example, a central processing node in the plurality of processor nodes **108***a*-**108***n* may dynamically determine if at least one arbitrary processor node **108***a* should be assigned to direct adaptive beamforming operations performed by at least one corresponding subarray **102***a*-**102***n* based on at least one node selection criteria (e.g., processor node availability, physical proximity to the at least one corresponding subarray **102***a*-**102***n*, type of processing task, user preference). The phased array **101** includes pluralities of both physical and virtualized processor nodes **108***a*-**108***n* that communicate with the plurality of subarrays **102***a*-**102***n* through both physical and virtualized components of the array processing interface **122**.

[0025] The array processing interface **122** architecture may enable the plurality of processor nodes **108***a*-**108***n* to perform intermediary collation operations to analyze, filter, equalize, cohere, and adaptively modify the excitation data for the plurality of SDR antenna elements in discrete subarray-specific packets rather than in an array-wide raw data stream, as will be described in greater detail hereinbelow. The discrete packets from each of the plurality of subarrays **102***a*-**102***n* can be further aggregated in a recursive series of operations that requires less computational overhead than analyzing an unsegmented array-wide raw data stream. For example, by removing noise and cohering excitation data at the subarray level, the system **100** may generate an adaptive beam profile that attenuates a newly instantiated interference source by directing a subset of subarrays **102***a*-**102***n* to perform spatial nulling without recomputing new steering vectors and/or beam weights for the remaining subarrays **102***a*-**102***n* in the phased array **101**.

[0026] FIG. **1**B is a block diagram representative of each of the plurality of subarrays **102***a*-**102***n* according to an embodiment of the system **100**. In some embodiments, the phased array **101** includes a plurality of subarray elements **104***a*-**104***n* that function as SDR antenna elements configured to operate in a wide range of radio frequencies (e.g., 1 Hz to 300 GHz). The system **100** may be implemented for various applications. For example, the system **100** may be implemented for surveillance as a radar system, a sonar system, in oil and gas industry for finding energy resources, in mining industry for finding metals, etc. The following paragraphs describe the system **100** configured for transmission and reception of radio frequency (RF) waveforms, but the system **100** is not limited to working with RF waveforms and may be configured to work with other waveforms as well (e.g., acoustic waves, seismic waves, etc.). In some embodiments, the array processing interface **122** architecture is implemented for intra-subarray communication. Accordingly, each of the plurality of subarray elements **104***a*-**104***n* may be algorithmically coupled to at least one of the plurality of processor nodes **108***a*-**108***n* and the reference node **106**. In some embodiments, the plurality of subarray elements **104***a*-**104***n* within the subarray **102** may be divided into subgroups that are each associated with at least one of the plurality of processor nodes **108***a*-**108***n*. Thus configured, each of the subgroups functions as a nested subarray of the subarray **102** that can be coupled (e.g., algorithmically, physically, communicably, or any combination thereof) to the plurality of processor nodes **108***a*-**108***n* to enable granular control over each element of the phased array **101**, and thereby decrease the processing overhead and power requirements of beamforming operations performed by the system **100**. Further, by implementing the array processing interface **122** architecture, phased arrays **101** can be sectored into a tiered operational structure that can be seen as a tiered array of scalable subarrays **102***a*-**102***n* (FIG. **3**B) where excitation data derived from a lower tier of the scalable architecture is used as input for a subsequent tier of the scalable architecture. This configuration enables the phased array **101** to generate adaptive beam patterns that include multiple high-directionality beams and/or spatial nulls of tunable resolution. For example: the entire phased array **101** may be configured to generate a single high-directionality beam; each of the plurality of subarrays **102***a*-**102***n* may a generate high-directionality beam and/or spatial null that is/are oriented using independent steering vectors; a first subset of the plurality of subarrays **102***a*-**102***n* may a generate first high-directionality beam and/or spatial null based on a first steering vector, a first adaptive beam weight and a first covariance matrix representation of interference sources, while at least one second subset of the plurality of subarrays **102***a*-**102***n* may a generate at least one second high-directionality beam and/or spatial null that is based on a second steering vector, a second adaptive beam weight and a second covariance matrix representation of interference sources. Further, a tiered array of scalable subarrays **102***a*-**102***n* may partition the interference sources contained in the covariance matrix between the plurality of subarray elements **104***a*-**104***n* such that each interference source within the covariance matrix is spatially nulled by at least one subarray element **104***a*-**104***n* such that the covariance matrix is fully ranked and signal transmission and reception is optimized relative to steady-state interference and transient noise

[0027] A subarray element **104***a*-**104***n* may be configured to be one of (a) a transmit only subarray element in which case it may transmit waveforms but not receive waveforms, (b) a receive only subarray element in which case it may receive waveforms but not transmit waveforms, or (c) both transmit and receive subarray element in which case it may transmit or receive waveforms. Unless stated otherwise, a subarray element may be both a transmit and receive subarray element. Each of the subarray elements **104***a*-**104***n* may be configured to transmit an outgoing waveform (e.g., referred to as a “probe signal”) that may all combine together to form a beam in a particular direction. Each of the subarray elements **104***a*-**104***n* may receive a response to the probe signal (e.g., referred to as a “data signal”) that may be “time aligned” and cohered by the system **100** for further processing (e.g., by a third-party system) for one or more applications.

[0028] The system **100** time synchronizes the subarray elements **104***a*-**104***n* to time align the transmitted probe signals or the data signals received by the subarray elements. In some embodiments, time aligning the data signals includes applying at least one of a time offset, phase, or amplitude to the data signals such that the data signals of all subarray elements **104***a*-**104***n* have the same time offset, phase and amplitude. The system **100** may synchronize the subarray elements **104***a*-**104***n* in several ways. In one example, each subarray element may have a corresponding local clock (e.g., a quartz oscillator) and the local clock may be synchronized with a phase lock loop, which is synchronized with an external signal such as (a) an external clock signal that is wired to each receiver, or (b) a wireless external signal such as a GPS signal, an astrological signal (e.g., a quasar signal, the cosmic microwave background signals or other signals from radio astronomy), waveforms from television towers, acoustic waveform, or a calibration signal from a transmitter node **302** (FIG. **3**) in the system **100**. In another example, each subarray element's local clock may be made up of an atomic clock with a low drift (e.g., that may not drift more than a microsecond over the period of days or even months), where the atomic clock for each subarray element may be synchronized and aligned at the factory before the subarray elements are deployed.

[0029] In some embodiments, each of the subarray elements **104***a*-**104***n* shares status information with the system **100** (e.g., one or more other subarray elements **104***a*-**104***n*) such that any received signals or signals transmitted by the subarray elements **104***a*-**104***n* are calibrated and synchronized with each other to synchronize data collection across the system **100**. The status information may include tier; subarray, relative position on the phased array **101**, location of interference sources and targets, terrain data, temperature in an environment of the subarray element; location (such as determined by GPS) of the subarray element; calibration metrics such as phase and amplitude offsets of the RF components (or optical components in the case of optics); or a timestamp of an occurrence of an event such as (a) a receipt of a signal (e.g., calibration signal, GPS signal, or any other known waveform) or (b) a receipt of a request for local timestamp of the subarray element. subarray element. The system **100** synchronizes a first subarray element **104***a* with the reference node **106** by computing a time offset between a reference timestamp of the reference node **106** and a first timestamp of the first sensor node **104***a*.

[0030] In another example where the system **100** is configured to synchronize the subarray elements **104***a*-**104***n* using a calibration signal, the system **100** synchronizes each of the subarray elements **104***a*-**104***n* with a reference node **106** of the system **100** by computing a time offset between a timestamp of a receipt of a calibration signal at a reference node **106** of the system **100** and a timestamp of receipt of the calibration signal at the corresponding subarray element. For example, the system **100** synchronizes a first subarray element **104***a* with the reference node **106** by computing a time offset between a timestamp of a receipt of a calibration signal at the reference node **106** and a first timestamp of receipt of the calibration signal at the first subarray element **104***a*.

[0031] When a probe signal is transmitted or a data signal is received by the subarray elements **104***a*-**104***n*, the system **100** (e.g., a processor node **108***a*-**108***n*) may apply the corresponding time offsets to the probe signals or the data signals of the subarray elements **104***a*-**104***n* to generate time aligned data signals for each of the subarray elements **104***a*-**104***n*.

[0032] After the data signals are time aligned, the system **100** coheres the time aligned data signals to generate a combined data signal with a coherent gain such that power level of the combined signal may be a function of the individual time aligned signals being combined. For example, the power level of the cohered signal for a subarray a is a sum of the power levels of the individual time aligned signals of the different subarray elements **104***a*-**104***n* contained therein. In another example, the power level of the cohered signal is greater than the power levels of any of the individual time aligned signals of the different subarray elements. In some embodiments, the data signals are cohered by adding the time domain signals together from the different subarray elements **104***a*-**104***n* such that the data signals are time aligned and coherently added together. The cohered signal may then be intelligently signal processed by the system **100**, or provided to a third-party system, for one or more applications. One such application may include a surveillance application, such as a radar system to determine one or more parameters of an object (e.g., speed and distance of an aircraft) in an environment of the system **100**. Another application may include detection of radar pulses. Another application may include digital receive beamforming.

[0033] In some embodiments, one of the subarray elements **104***a*-**104***n* is designated as a reference node **106**, whose clock acts as a reference clock for synchronizing the clocks of the other subarray elements **104***a*-**104***n*. In some embodiments, a central processing node **108***a*-**108***n* is one of the subarray elements **104***a*-**104***n* that is configured to perform various types of processing, such as computing time offsets, partitioning the phased array **101** into a tiered structure of scalable subarrays **102***a*-**102***n*, algorithmically selecting couplings between processor nodes **108***a*-**108***n* and subarray elements **104***a*-**104***n*, calibrating matrices of subarray weight vectors with respect to each other, generating time aligned data signals, cohering time aligned data signals, etc. In some embodiments, the central processing node **108***a*-**108***n* and the reference node **106** are the same subarray element. In further embodiments, each individual subarray element is able to perform the requisite processing and coordination operations of the central processing node **108***a*-**108***n*. Accordingly, each subarray element **104***a*-**104***n* may operate independently without losing the capability to perform adaptive beamforming and interference mitigation operations. Further, while descriptions included herein reference the operations (e.g., time synchronization) being performed by a single subarray element, such as the central processing node **108***a*-**108***n*, the operations may be performed by another subarray element, such as the reference node **106**, or by more than one subarray element. For example, any number of subarray elements may perform the time synchronization or time alignment of data signals in the case where processing is done in a distributed way. Furthermore, time synchronization operations can be performed on a scheduled basis, prior to transmitting a probe signal, or prior to receiving the data signal.

[0034] The subarray elements **104***a*-**104***n*, including the reference node **106** and the central processing node **108***a*-**108***n*, may be co-located (e.g., located within a specified number of wavelengths of the operating frequency) or may be remotely located (e.g., located beyond the specified number of wavelengths of the operating frequency). For example, the first subarray element **104***a* and the second subarray element **104***n* may be co-located, while the reference node **106** may be remotely located. In another example, the first subarray element **104***a* and the second subarray element **104***n* may be co-located, while a third subarray element may be remotely located. Regardless of how the subarray elements **104***a*-**104***n* are located, the subarray elements **104***a*-**104***n* may be synchronized as long as the location information of the subarray elements **104***a*-**104***n* within a tier of the array processing interface **122** architecture, the reference node **106**, or the central processing node **108***a*-**108***n* is available. For example, as mentioned above, the subarray elements **104***a*-**104***n* may have the capability to self-organize (e.g., share location information such as tier, subarray, and relative position on the phased array **101**, via the status information) or self-calibrate (e.g., synchronize themselves to the reference node **106**). The system **100** may have location information of the reference node **106** and subarray elements **104***a*-**104***n* that may be used in determining a time difference in arrival of the calibration signal at the subarray elements **104***a*-**104***n* with respect to the reference node **106**, which may be further used in determining the time offset between the subarray elements **104***a*-**104***n* and the reference node **106**. The subarray elements **104***a*-**104***n* may self-calibrate using the factory-calibrated atomic clocks, the calibration signal **304** (FIG. **3**A), or other known waveforms on a scheduled basis, prior to transmitting a probe signal, or prior to receiving a response to the probe signal.

[0035] The subarrays **102***a*-**102***n* of the system **100** may be easily scaled up or scaled down by adding or removing subarray elements **104***a*-**104***n*, respectively. Furthermore, since each subarray element **104**_a_-**104**_n_ may communicate with the reference node **106** or the central processing node **108**_a_-**108**_n_ directly, all the subarray elements **104**_a_-**104**_n_ are a single hop away from the reference node **106** or the central processing node **108**_a_-**108**_n_, and any scaling of the system **100** may not result in degradation of the time synchronization accuracy. In some embodiments, by having the subarray elements **104**_a_-**104**_n_ dynamically organized into tiered groups of subarrays coupled to corresponding processor nodes the system **100** is able to produce multiple simultaneous high-directionality beams at full gain and resolution, direct spatial nulls toward interference sources **110**.

[0036] While FIG. **1**A shows a single cluster of subarray elements **104**_a_-**104**_n_, the system **100** may have several clusters in which each cluster may have several subarray elements. Different clusters may have different number of subarray elements or the same number of subarray elements. In some embodiments, such a configuration enables detection of a moving object at ultra-long range and hypersonic speeds; better angle resolution than available with a single cluster. Also, some clusters may remain completely passive making the location of the cluster difficult to impossible to ascertain without active transmissions. Yet another advantage of having multiple clusters may be that one cluster could be significantly closer in distance to the received signal and suffer much less free space path loss of the signal and thus, get a much stronger signal to share between nodes. In some embodiments, the clusters may be spread over a few hundred meters or distributed throughout a massive geographic region. Each cluster may generate a cohered signal from the time aligned signals of its constituent subarray elements and the cohered signal from all the clusters may be further cohered to generate a master cohered signal with a coherent gain such that the power level of the master cohered signal is a function of the power levels of the constituent cohered signals of the different clusters. For example, the power level of the master cohered signal is a sum of the power levels of the constituent cohered signals of the different clusters. In another example, the power level of the master cohered signal is greater than the power levels of any of the constituent cohered signals of the different clusters.

[0037] FIG. **2** is a block diagram of a subarray element of a system of FIG. **1**A, and FIG. **1**B, consistent with various embodiments. A subarray element (e.g., first subarray element **104**_a_) includes an antenna **202** that facilitates radiation or reception of waveforms when connected to a transmitter or receiver (not illustrated). The antenna **202** may be configured to transmit or receive waveforms of a wide range of frequencies. The first subarray element **104**_a_ may include a clock **204** that generates a clock signal for use in synchronizing the operations (e.g., coordinate sequence of actions) of the first subarray element **104**_a_. The clock **204** may be a quartz clock, an atomic clock, or another type of clock.

[0038] The first subarray element **104**_a_ may include a time synchronization component **208** that synchronizes the clock **204** of the first subarray element **104**_a_ in any of a number of ways mentioned above. For example, the time synchronization component **208** synchronizes the clock **204** with an external signal such as an external clock signal that is wired to the first subarray element **104**_a_ or a wireless external signal such as a GPS signal or an astrological signal. In another example, the time synchronization component **208** synchronizes the clock **204** to a clock of the reference node **106** using a calibration signal from a transmitter node (additional details of which are described at least with reference to FIGS. **3-7** below).

[0039] The first subarray element **104**_a_ includes a digital signal processor (DSP) **206** that is configured to perform various signal processing operations including generating time aligned signals, match filtering received calibration signals or data signals, setting a frequency range of the first subarray element **104**_a_, radar signal processing, etc.

[0040] The first subarray element **104**_a_ includes an RF chain **210**. In some embodiments, the RF chain **210** may be a cascade of electronic components and sub-units which may include any of amplifiers, filters, mixers, attenuators, and detectors. All these components may be combined to serve a specific application (e.g., a radar system for detection of moving objects). One or more of the components (e.g., the DSP **206** and time synchronization component **208**) may be implemented using an SDR. The SDR facilitates various functionalities. For example, the SDR may facilitate obtaining of location information of the subarray elements **104***a***-104***n*, the reference node **106**, or the central processing node **108***a***-108***n* relative to each other on the phased array. In another example, the SDR may facilitate in the generation of time aligned data signals.

[0041] Note that one or more components of the first subarray element **104***a* may be communicatively coupled to another device of the system **100** via a communication module to coordinate its operations. Some or all of the components of the first subarray element **104***a* may be combined as one component. A single component may also be divided into sub-components, each sub-component performing a separate method step or method steps of the single component. Any one or more of the components described herein may be implemented using hardware (e.g., a processor of a machine) or a combination of hardware and software. For example, any component described herein may configure a processor **206** to perform the operations described herein for that component. Note that as used herein, processor, plurality of processor nodes **108***a***-108***n*, and central processing node are used interchangeably to indicate the same processing portions of system **100**.

[0042] FIG. **3**A shows an example of synchronizing a plurality of phased arrays **101** using a calibration signal **304** from a transmitter node **302** of the system **100**. The calibration signal **304** may be any of a wide range of frequencies (e.g., 50 MHz, 144 MHz, 30 GHz, etc.). Because the time synchronization is not limited to being performed using a calibration signal, it can be performed in a number of ways as mentioned above at least with reference to FIG. **1**A and FIG. **1**B. For example, the plurality of phased arrays **101** may be time synchronized using an external wireless signal such as a calibration signal **304** that is of a known waveform, such as a GPS signal, an astrological signal, seismic signal, acoustic signal, a signal transmitted from a transmitter (e.g., signal from television towers), or a signal transmitted from a transmitter node of the system **100**. In another example, time synchronization may be achieved by using factory-calibrated atomic clocks in the subarray elements **104***a***-104***n*.

[0043] FIG. **3**A is a block diagram of time synchronization of the plurality of phased arrays **101** in an embodiment where multiple systems of FIG. **1**A, FIG. **1**B are configured into a distributed array, consistent with various embodiments. The transmitter node **302** may be co-located with the plurality of phased arrays **101** or may be remotely located. In some embodiments, the transmitter node **302** is considered to be co-located with the plurality of phased arrays **101** if the transmitter node **302** is within a specified proximity (e.g., a specified number of wavelengths of the calibration signal **304**) of the plurality of phased arrays **101**. For example, if the transmitter node **302** frequency of transmission is 144 MHz, then the transmitter node **302** is considered to co-located with the plurality of phased arrays **101** if it is within “20”-“50” meters of any of the plurality of phased arrays **101**. If the transmitter node **302** is beyond the specified proximity (e.g., beyond 50 m for 144 MHz frequency) of the plurality of phased arrays **101**, then the transmitter node **302** is considered to be remotely located. In some embodiments, the transmitter node **302** can even be located beyond the horizon in the case where the transmitter is quite powerful (e.g., hundreds or thousands of watts per transmit power amp with multiple transmit antennas that create a transmit phased array, and where the transmit frequency is at 50 MHz). Further yet, the transmitter node **302** may also be configured to be mobile, in motion or moving. In some embodiments, by having the transmitter node **302** being remotely located with respect to the plurality of phased arrays **101**, and being in motion, a “no probability of detection” sensor system may be established (e.g., because the transmitter node **302** is not co-located with the receiver phased arrays **101**, an adversary may not geo-locate the receiver sensor nodes by using the transmitter signal).

[0044] Regardless of whether the transmitter node **302** is co-located or remotely located, the transmitter node **302** is located in a known location relative to the sensor nodes **104***a***-104***n*, and the calibration signal **304** may be “seen” (e.g., calibration signal **304** is above the noise) or received by the plurality of phased arrays **101** without the need for signal processing. For example, the system

100 may know the location information (e.g., tier, subarray, relative position on the phased array **101**, latitude, longitude information) of the transmitter node **302**. Such a configuration provides the flexibility of having the transmitter node **302** at any of various locations.

[0045] Each of the plurality of phased arrays **101**, including the reference node **106**, receives the calibration signal **304** and determines a timestamp of the receipt of the calibration signal **304**. The system **100** computes the time offsets of the plurality of phased arrays **101** based on the timestamps of the plurality of phased arrays **101** and the timestamp of the reference node **106** to synchronize the plurality of phased arrays **101** with respect to the reference node **106**.

[0046] FIG. **3**B is a block diagram of an embodiment of the system **100** (FIG. **1**A) where the phased array **101** is configured as a tiered array of scalable subarrays **102***a*-**102***n* that utilizes the array processing interface **122** to enable a processing architecture where each of the plurality of subarray elements **104***a*-**104***n* in an arbitrary tier may be seen as a signal processing node that governs the transmit and receive operations for a plurality antenna elements **306** (e.g., antenna **202**, subarray element **104***a*-**104***n*, subarray **102***a*-**102***n*) in a preceding tier. In some embodiments, a corresponding processor node **108***c* for each of the plurality of subarray elements **104***a*-**104***n* executes an intermediary collation operation to process and cohere data signals and node excitation data (e.g., w**1***a*-wNa, w**1***n*-wNn) for each of the plurality of antenna elements **306** within the preceding tier. In some embodiments, the intermediary collation operation is used to form an aggregated weight vector that is passed to an arbitrary processor node **108***a* as a representative weight vector for a subsequent tier of the tiered array of scalable subarrays **102***a*-**102***n*. Further, an intermediary collation operation can be repeated using all representative weight vectors in the subsequent tier such that the relevant information from the plurality of representative weight vectors for each tier of the phased array **101** are contained in the final aggregated weight vector.

[0047] The node excitation data may include a matrix comprising a weight vector representation (e.g., w**1***a*-wNa, w**1***n*-wNn) for each of the plurality of antenna elements **306**. Thus, the scalable architecture can be used to subdivide phased arrays **101** in an application-specific manner. For example, the subdivision into the plurality of granularly controlled subarrays **102***a*-**102***n* may enable the plurality of subarray elements **104***a*-**104***n* to be divided into unequal groupings such that a first subarray that is directed toward monitoring a wide area may include more elements than a second subarray that may be directed toward scanning a specific frequency range. In further embodiments, the plurality of subarrays **102***a*-**102***n* may be directed toward disparate tasks (e.g., a first subarray directed toward data transmission, a second subarray directed toward spatial nulling, a third subarray directed toward RADAR operations).

[0048] In some embodiments, each subarray element **104***a*-**104***n* may be a modular accumulator that combines the output from the plurality of antenna elements **306** into the representative weight vector. The arbitrary processor node **108***a* may cohere the data signals and node excitation data for each of the subarray elements **104***a*-**104***n* in the arbitrary tier. This arbitrary tier can thus be designated the preceding tier. The tier being cohered by the arbitrary processor **108***a* is a newly arbitrary tier (formerly the subsequent tier). FIG. **3**B illustrates this newly designated arbitrary tier as the plurality of subarrays **102***a*-**102***n* each of which generates an aggregated weight vector for the newly preceding tier (formerly the arbitrary tier) which contains the representative weight vectors from the plurality of array elements **104***a*-**104***n*. In some embodiments, the arbitrary processor node **108***a* for the subsequent tier may be referred to as a central processing node.

[0049] Prior to or simultaneous with the cohering, the arbitrary processor node **108***a* for the subsequent tier may combine the node excitation data (e.g., w**1***a*-wNa, w**1***n*-wNn) for the subarray elements **104***a*-**104***n* into the aggregated weight vector representation W. The arbitrary processor node **108***a* governing the intermediary collation process for the subsequent tier may execute a calibration operation that begins by distributing at least one steering vector routine to each of the plurality of subarrays **102***a*-**102***n*, wherein status information is generated during the at least one steering vector routine. The steering vector routine causes the subarray elements **104***a*-**104***n* to

generate high directionality beams **116** (see FIG. **4** and FIG. **5**) and captures status information about interference sources **110** (see FIG. **4** and FIG. **5**) in an area of interest **103** to generate an interference profile that contains a covariance matrix representation of the plurality of interference sources **110**. The status information may further include information about how the beams generated by the plurality of antenna element **306** in the preceding tier interact with each other. The arbitrary processor node **108***a* may then generate a plurality of subarray-dependent adaptive processes such that a corresponding adaptive process from the plurality of subarray-dependent adaptive processes is associated with each of the plurality of subarray elements. In some embodiments of the subarray-dependent adaptive process, each representative weight vector (e.g., w**1***a*-wNa, w**1***n*-wNn) is deterministically or adaptively processed with respect to the other representative weight vectors to determine how close each beam pattern is to each other and to a desired beam pattern. Further, the representative weight vectors (e.g., w**1***a*-wNa, w**1***n*-wNn) are evaluated to determine if the subarrays **102***a*-**102***n* have nulled the same interferers at the same angular locations. The subarray-dependent adaptive processes may apply a correction factor to each representative weight vector (e.g., w**1***a*-wNa, w**1***n*-wNn) to further tune the response. In this way each subsequent tier of the tiered array of scalable subarrays **102***a*-**102***n* is able to use current status information to modify the calibration operations and subarray-dependent adaptive processes that is sent to the preceding tier of the tiered array of scalable subarrays **102***a*-**102***n*.
[0050] Because the subarray elements **104***a*-**104***n* may function as an SDR, the aggregated weight vector W may be tuned to produce a desired beam output from each of the subarray elements **104***a*-**104***n*. In some embodiments, the central processing node **108***a* dynamically tunes the weight vector W to produce an adaptive beam pattern **114** (see FIG. **4** and FIG. **5** described below) that includes a plurality of high directionality beams **116** (FIG. **5**A) and null beams **118** (FIG. **5**A) oriented at a plurality of targets **120** (FIG. **5**A, **5**B) and interference sources **110** (FIG. **5**A). In some embodiments, the at least one adaptive beam pattern **114** may include a plurality of read beams (e.g., high directionality beams **116**, probe signal **808** (see FIG. **8** described below), and/or data signal **810** (see FIG. **8** described below) disposed in a desired spatial configuration within an area of interest **103** (FIG. **5**A), where each read beam **116** is associated with a corresponding weight vector. Further, weight vector W may be tuned to steer any arbitrary beam within the adaptive beam pattern **114** as desired. In some embodiments, the system is a phased array configured as the tiered array of scalable subarrays **102***a*-**102***n* where a direction vector of the plurality of subarray elements **104***a*-**104***n* is cohered, via the central processing node **108***a*, by multiplying a direction vector for each element **104***a*-**104***n* of the phased array **101** (e.g., system **100**) with a reference signal, wherein the reference signal may include the time aligned data signal.
[0051] When the subarray elements **104***a*-**104***n* and the reference node **106** (FIG. **3**A) receive a data signal (e.g., a response to a probe signal transmitted by the subarray elements that is reflected off an object such as an aircraft), the subarray elements **104***a*-**104***n* and the reference node **106** transmit the received data signal to the central processing node (e.g. DSP **206** (FIG. **2**)). For example, the first subarray element **104***a* and the reference node **106** transmit the received first data signal and a reference data signal, respectively, to the central processing node **206**. The central processing node **206** may then retrieve the first time offset from a storage device (not shown) and apply it to the first data signal to generate a first time aligned data signal of the first subarray element **104***a*. Similarly, the central processing node **206** may apply the second time offset to the second data signal of the second subarray element **104***n* to generate a second time aligned data signal of the second sensor node **104***n*.
[0052] In some embodiments, a plurality of transceiver nodes (e.g., subarrays **102***a*-**102***n*, subarray elements **104***a*-**104***n*, antenna elements **306**) each outputs a corresponding primary beam **112** (FIG. **5**A, FIG. **5**B) composed of the output from the plurality of antenna elements **306**, wherein each of the plurality of transceiver nodes **104***a*-**104***n* is disposed to surveil at least a portion of a range and/or angle extent of the at least one target **120** (FIG. **5**A, **5**B). In some embodiments, the adaptive

beam pattern **114** (FIG. **5**A, **5**B) includes a monostatic configuration used to surveil a transmit sector of the at least one target **120**. Each of the plurality of transceiver nodes **104***a*-**104***n* may be a multi-input-multi-output array. In further embodiments, the adaptive beam pattern **114** includes a bistatic configuration used to surveil at least one of a range and an angle extent of a transmit sector for the at least one target **120**. In supplemental embodiments, the adaptive beam pattern **114** includes an isotropic configuration used to surveil an omnidirectional area of interest **103** (FIG. **5**A) or field of regard **501** (FIG. **5**B).

[0053] In some embodiments, the system **100** (FIG. **1**A, FIG. **1**B) takes a snapshot of each of the subarray elements **104***a*-**104***n* at the synchronized timestamp. The snapshot may include a matrix X comprising a corresponding time aligned data signal (x1-xn) for each of the plurality of antenna elements **306**. In some embodiments, the central processing node **206** directs the plurality of transceiver nodes **104***a*-**104***n* to capture a plurality of snapshots of the at least one target **120** (FIG. **5**A, **5**B), where each of the plurality of snapshots is captured when a corresponding read beam **116** coincides with the at least one target **120**. Accordingly, the central processing node **206** captures snapshots that may characterize the system's **100** response to target acquisition. Because subarray elements **104***a*-**104***n* may be software-defined radios (SDR), any appropriate time aligned snapshot data may be reproduced without distortion for each of the subarray elements **104***a*-**104***n* and their corresponding plurality of antenna elements **306**. In some embodiments, the snapshot data may be included in the status information generated by the subarray elements **104***a*-**104***n*. Additionally, the snapshot data may include information relating to interference sources **110** (FIG. **5**A-e.g., 5G cell towers, jamming equipment, ambient spectrum congestion, ambient electromagnetic interference) within the area of interest **103** (FIG. **5**A). Multiple snapshots (x1-xn) of the subarray elements **104***a*-**104***n* may facilitate the production of multiple simultaneous read beams **116** within a field of regard **501** (FIG. **5**B). In some embodiments, the process of cohering the weight vector W to the time aligned snapshot data X results in the generation of the adaptive beam pattern **114** (FIG. **5**A, **5**B) that adapts in relation to the time aligned snapshot data X. Accordingly the coherence operations executed by the central processing node **206** uses the corresponding weight vector for each of the plurality of snapshots to form a high-gain received signal (e.g., **116** shown in FIG. **5**A, **810** shown in FIG. **8**, etc.).

Example Flowchart(s)

[0054] The example flowchart(s) described herein convey example processing operations of methods that enable the various features and functionality of the system as described in detail above. The processing operations of each method presented below are intended to be illustrative and non-limiting. In some embodiments, for example, the methods may be accomplished with one or more additional operations not described, and/or without one or more of the operations discussed. Additionally, the order in which the processing operations of the methods are illustrated (and described below) is not intended to be limiting.

[0055] In some embodiments, the methods may be implemented in one or more processing devices (e.g., a digital processor, an analog processor, a digital circuit designed to process information, an analog circuit designed to process information, a state machine, and/or other mechanisms for electronically processing information). The processing devices may include one or more devices executing some or all of the operations of the methods in response to instructions stored electronically on an electronic storage medium. The processing devices may include one or more devices configured through hardware, firmware, and/or software to be specifically designed for execution of one or more of the operations of the methods.

[0056] FIG. **4** shows a flowchart of a method **400** for employing the subarray elements **104***a*-**104***n* of the system **100** (FIG. **1**A, FIG. **1**B) to perform intermediary collation operations for phased array signal processing using adaptive beamforming (e.g., 5G co-channel interference mitigation). In some embodiments, the subarray elements **104***a*-**104***n* are a plurality of transceiver nodes **104***a*-**104***n* (e.g., a plurality of isotropic antenna arrays). Method **400** may include calibrating, via an arbitrary processor node **108***a*, a plurality of aggregated weight vectors for a plurality of subarray elements **104***a*-**104***n* within a phased array **101**, where the arbitrary processor node **108***a* is from the plurality of processor nodes **108***a*-**108***n* (block **402**). The calibration operation may enable the system **100** to adaptively tune the plurality of aggregated weight vectors for the plurality of subarray elements **104***a*-**104***n* in relation to each other, the covariance matrix, status information, and at least one desired steering vector. Method **400** may include determining, via a corresponding processor node **108***c*, if a covariance matrix is full rank in relation to each of the plurality of aggregated weight vectors, where each of the plurality of subarray elements **104***a*-**104***n* is associated with the corresponding processor node **108***c* from the plurality of processor nodes **108***a*-**108***n* (block **404**). For example, the corresponding processor node **108***c* may determine if any of the interference sources **110** (FIG. **5**B) are not being spatially nulled by at least one corresponding subarray element **104***a*-**104***n*. Method **400** may include generating, via the corresponding processor node **108***c*, an interference mitigation protocol for each of the plurality of subarray elements **104***a*-**104***n* based on at least one of the aggregated weight vectors and the covariance matrix (block **406**). The interference mitigation protocol may contain the tuning values for W that enable the plurality of subarray elements **104***a*-**104***n* (e.g., the plurality of antenna elements **306**) (FIG. **3**B) to output the desired adaptive beam pattern **114** (FIG. **5**A).

[0057] Method **400** may include subprocesses for performing the intermediary collation process that may include distributing, via the at least one arbitrary processor **108***a*, at least one steering vector routine to each of the plurality of subarrays **102***a*-**102***n*, wherein status information is generated during the at least one steering vector routine. For example, the steering vector routine may direct the plurality of subarray elements to generate an adaptive beam pattern **114** that spatially nulls at least one known interference source **110** or tracks a known target **120**. By assessing known values, the system **100** is able to generate status information and determine the position of interference sources **110** in the area of interest **103** or field of regard **501**. The subprocess may include receiving, via a processor (e.g., DSP **206** shown in FIG. **2**) status information for the plurality of transceiver nodes **104***a*-**104***n*. The transceiver nodes **104***a*-**104***n* may be used to gather status information about the area of interest **103** (FIG. **5**A) and to identify targets within a field of regard **501** (FIG. **5**B) of the system **100**. The subprocess may include determining, via the arbitrary processor node **108***a* (FIG. **1**A, FIG. **1**B), an interference profile for the area of interest **103**, wherein the interference profile includes at least one interference source **110** (FIG. **5**A). The interference profile may include a covariance matrix comprising all relevant characteristics (e.g., angle or direction of approach, location, frequency, directionality, signal strength) for the at least one interference source **110**. Further, the interference profile may contain information gathered from external sources and may be updated based on user preference. For example, the interference profile may specify the adaptive beam pattern **114** (FIG. **5**A, **5**B) directs null beams and/or spatial nulls **118** (FIG. **5**A) toward all but one interference source **110** within the area of interest **103**.

[0058] The subprocess may include identifying, via the arbitrary processor **108***a*, at least one target **120** (FIG. **5**A, **5**B) (block **406**). For example, the system may scan the field of regard **501** (FIG. **5**B) to determine the presence of the target **120** (FIG. **5**A, **5**B and also see FIG. **6**). Additionally, the system may be directed to acquire a target at a known position. The subprocess may include executing, via the least one arbitrary processor **108***a*, the intermediary collation operation based on the status information and the interference profile. The intermediary collation operation generates a plurality of subarray-dependent adaptive processes, and a corresponding adaptive process from the plurality of subarray-dependent adaptive processes is associated with each of the plurality of subarray elements **104***a*-**104***n*. For example, each of the plurality of subarray elements **104***a*-**104***n* may be directed toward performing different tasks that, when viewed in aggregate, enable the phased array **101** (FIG. **1**A) to generate high directionality beams **116** (FIG. **5**A and FIG. **5**B) while simultaneously performing spatial aliasing techniques (see FIG. **7**A and FIG. **7**B) to attenuate the

plurality of interference sources **110**. In some embodiments, the corresponding adaptive process for the arbitrary subarray **102***a* is adapted in response to an output of each of the plurality of subarray elements **104***a*-**104***n*, a desired steering vector, and the covariance matrix. For example, the corresponding adaptive process for each the plurality of subarray elements **104***a*-**104***n* may be updated when the interference source **110** begins transmitting or changes position. This update may direct the plurality of subarray elements **104***a*-**104***n* to repartition the interference source **110** among an appropriate number of fields of regard **501** (FIG. **5**B) such that the covariance matrix remains fully ranked relative to the aggregated weight vector for the arbitrary subarray **102***a*.
[0059] FIG. **5**A illustrates an embodiment where the method **400** may include outputting, via the plurality of transceiver nodes (e.g. subarrays **102***a*-**102***n*, subarray elements **104***a*-**104***n*, antenna elements **306**), an adaptive beam pattern **114** (e.g., high directionality beams **116** and null beams **118**), wherein the adaptive beam pattern **114** includes a at least one high-directionality beam **116** generated by at least one first subarray element **104***a* and at least one mitigation signal modulated by at least one second subarray element **104***n* in accordance with the interference mitigation protocol, wherein the mitigation signal (or null beam **118**) attenuates the interference source, and wherein the plurality of transceiver nodes **104***a*-**104***n* forms a single phased array device (system **100**) (operation **408**). Accordingly, the system **100** may retain similar operational capabilities with a large number of transceiver nodes **104***a*-**104***n* distributed within a large region as with a relatively small number of transceiver nodes **104***a*-**104***n* distributed through the same region or located on a single phased array device. In some embodiments, generating the adaptive beam pattern **114** may employ dynamic frequency allocation adaptive beamforming techniques that can rapidly change frequencies in response to jamming, similar to frequency hopping, to evade jamming attempts. In some embodiments, generating the adaptive beam pattern **114** may employ AI and machine learning cognitive beamforming systems to predict and adapt to jamming strategies more effectively. Further, system **100** may learn from past jamming attempts and continually improve interference countermeasures. Generating the adaptive beam pattern **114** may further include adjusting the power of the transmitted signal to minimize the impact of pulse jamming and managing subarray element **104***a*-**104***n* power output to maintain effective communication without wasting power resources. Generating the adaptive beam pattern **114** may further include encrypting communications and producing jamming-resistant signals (e.g., through signal modulation or redundant signal production).
[0060] FIG. **5**B illustrate an embodiment where the system **100** performs a subarray-specific adaptive process to partition the plurality of interference sources within the fields of regard **501** for each of the plurality of subarray elements **104***a*-**104***n*, wherein the fields of regard **501** are portions of the area of interest (FIG. **5**A). Accordingly, the corresponding processor node **108***c* may determine if the covariance matrix is fully ranked by determining if each of the plurality of interference sources **110** is spatially nulled by at least one subarray element **104***a*-**104***n*. Similarly, system **100** may be used to track the target **120** as it moves. To facilitate this functionality, the block **406** (FIG. **4**) for generating the interference mitigation protocol may include a subprocess that begins by plotting, via the arbitrary processor **108***a* (FIG. **1**A, FIG. **3**B), a path of travel for the at least one target **120**. For example, the at least one target **120** may be a satellite with an orbital path of travel **502** (e.g., polar orbit, walking orbit, sun synchronous orbit, Lagrange point orbit). In some embodiments, the at least one target **120** includes at least one of a fixed satellite service (FSS) and a fixed service (FS) device. Additionally, the system **100** may track terrestrial targets (e.g., vehicles, ships, aircraft, missiles, projectiles, guided munitions). The subprocess may continue by comparing, via the arbitrary processor **108***a*, the status information and the interference profile to determine appropriate output characteristics for the adaptive beam pattern **114** (e.g., high directionality beam **116** (FIG. **5**A) and the at least one mitigation signal (or null beam **118**) along the path of travel. For example, a response of a direction vector for a mainlobe **708** (see FIG. **7**B described below) of the at least one primary beam **112** to a signal at an angle of approach may be

adaptively modified as the angle of approach is varied over the area of interest **103** (FIG. **5**A) or through the field of regard **501** (FIG. **5**B). In some embodiments, the subprocess may continue by directing, via arbitrary processor **108***a*, the plurality of transceiver nodes **104***a*-**104***n* to output the at least one adaptive beam **116** (FIG. **5**B) along the path of travel and the at least one mitigation signal (or null beam **118**) (FIG. **5**B) as at least one spatial null coincident with a direction of the at least one interference source **110** along the path of travel. Accordingly, the system **100** prevents the at least one interference source **110** from undesirably impacting the adaptive beam pattern **114** (e.g., reducing gain, directionality, SNR) regardless of the position, angle of approach, or orientation of the at least one target **120** relative to each element of the system **100**. In some embodiments, the spatial null is greater than 50 decibels (dB).

[0061] FIG. **6** shows a block diagram illustrating signal processing operations **600** for some embodiments of the system **100** (FIG. **1**A, FIG. **1**B) that are used to implement dynamically adaptive distribution (DyAD) processing. In some embodiments the DyAD can be envisioned as a rank one matrix that is formed by the outer product of a vector. DyAD processing entails distributing beam and null direction vectors to the subarray level of the phased array **101**. Thereby, enabling computation a much more efficient DyAD-matrix based adaptive algorithm using only passed parameters and the local subarray elements. The operations **600** may begin at **602** where N array elements **104***a*-**104***n* are partitioned between K subarray processors **108***a*-**108***n* and steering vectors are distributed to each of the N array elements.

[0062] In some embodiments, a steering vector distribution protocol can be executed by the corresponding processor node **108***c* (FIG. **3**B) for the arbitrary tier that is configured to perform the intermediary collation operation for the antenna elements **306** in the preceding tier and to distribute subarray-dependent adaptive processes to the plurality of antenna elements **306** (FIG. **3**B) in the preceding tier. During each of the subarray-dependent adaptive processes, the steering vector for a corresponding antenna element **306** is directed to point a corresponding primary beam **112** (e.g., high-directionality beam **116**, null beam **118** (FIG. **5**B)) toward a position with a desired azimuth and elevation.

[0063] The steering vector distribution protocol may further include pointing the main beam of the arbitrary subarray **104***a* toward the boresight (e.g., zero elevation and zero azimuth) of a capsulated array that is bounded to resolve excitation data from the preceding tier and the arbitrary tier. The system **100** is thus able to calibrate the adaptive beam pattern **114** (FIG. **5**A) for the arbitrary subarray element **104***a* by analyzing the response that the primary beams **112** (FIG. **5**B) of the preceding tier induce on boresight acquisition and retention in the arbitrary subarray element **104***a* in the arbitrary tier. This steering vector distribution protocol may be repeated for each tier of the phased array **101**, executed for a single subarray element **104***n* only, or executed such that there are intervening tiers disposed between the preceding and arbitrary tiers.

[0064] In some embodiments, the steering vector distribution protocol may distribute subarray-dependent adaptive processes to the antenna elements **306** (FIG. **3**B) in a bottom tier of the phased array **101** and point the main beam **116** (FIG. **5**B) of a subarray **102***n* in a top tier toward boresight. Thus, facilitating calibration of the top tier subarray **102***n* without necessitating the processing overhead required to resolve the excitation data from the intervening tiers.

[0065] In further embodiments, the steering vector distribution protocol monitors the response of the main beam **116** to reduce power usage and processing requirements. For example, the number of beams sent from the preceding tier, where the analog and/or digital (A/D) samples (e.g., w**1***a*-wNa, w**1***n*-wNn) are initially sampled by the plurality of antenna elements **306**, can be decreased significantly by determining the response that providing small offset angles between the primary beam **112** of the preceding tier and the main beam **116** of the subsequent tier induce and then removing or deactivating antenna elements **306** that do not impact the desired main beam **116**. For example, a main beam **116** angle will be pointed in a certain direction and a primary beam **112** (e.g., the aggregated weight vector) will be sent from the preceding tier to the subsequent tier. The subsequent tier may use the aggregated weight vector as input to generate the adaptive beam pattern **114** that is relatively similar to the aggregated weight vector produced by the preceding tier. These relatively similar beams can then be angularly tuned to achieve a desired adaptive beam pattern (e.g., a single high-directionality beam **116** or a group of high-directionality beam **116** and/or null beams **118**). Because the adaptive beam pattern **114** in the subsequent tier is similar to the primary beam **112** of the preceding tier, the beams can be produced with small angular offsets applied to their adaptive steering vectors or deterministically beamformed. Thus, the system **100** further reduces processing and power requirements by reducing the number of antenna elements **306** that must be activated or resolved to achieve the desired adaptive beam pattern **114**.

[0066] Operation **600** may continue at **604** where these K subarray processors **108*a*-108*n*** adaptively compute each subarray element's **104*a*-104*n*** representative weight vectors based on a desired steering vector for at least one of the beams generated by array elements **104*a*-104*n***. the adaptive computation may include generating a covariance matrix of interference sources **110** and tuning the representative weight vectors to perform application-specific tasks (spatially nulling interference sources, tracking targets along a path of travel). Operation **600** may continue at **604** by passing the element weights, matrix rank, and adaptively filtered output data to the subsequent level, or tier, of the array. Operation **606** may relate to an intermediary collation process where the plurality of subarray elements from the arbitrary tier are passed to the arbitrary processor node **108*a*** of the subsequent tier for further collation and coherence. Operation **600** may continue at **608** by processing beam weights to determine calibration factors that are passed back to the subarray elements **104*a*-104*n*** thereby creating a feedback loop for adaptive beamforming operations. Operation **600** may continue at **610** by determining if the subarrays adaptive matrix is full rank. That is, the system **100** determines if each of the plurality of interference sources **110** in the covariance matrix is spatially nulled by at least one subarray element **104*a*-104*n*** within each of the plurality of subarrays **102*a*-102*n***. If the adaptive matrix is full rank, then operation **600** continues at **612** by partitioning the nulls between subsets of arrays such that the majority of the subarray elements **104*a*-104*n*** of the phased array **101** may be directed toward transmit and receive operations while a subset of subarray elements **104*a*-104*n*** can be directed toward interference mitigation. Operation **600** may continue at **614** by performing additional signal processing and filtering operations to further refine the data signal received from the preceding tier. At **614** the system **100** may employ statistical analysis of the adaptive weights to overcome imperfect knowledge/construction of array and effectively use jammers as calibration sources to produce spatial nulls. For example, system **100** may improve signal to noise ratio by performing statistical analytical techniques including maximum-likelihood estimation and nonlinear least square estimation. Operation **600** may continue at **616** by performing an additional intermediary collation process to combine the calibrated and nulled output beams. Operation **600** may continue by checking if there is a subsequent tier to pass the output of the intermediary collation operation at **616**. If no subsequent tier exists, then the output is designated as the signal data for the phased array **101**.

[0067] In some embodiments, system **100** employs a distributed adaptive beamforming algorithm that achieves O(NlogN) via each distributed subarray computing partial beams locally at each subarray using only a small number of key beam parameters resulting in fully summed beams at the array level. The system may employ algorithms to generate the spatial filters locally at each subarray in a distributed way and yet calibrate the spatial filters across the array in O(NlogN) to overcome critical synchronization and mismatch errors across the array. Further, system **100** may provide a way to estimate the inverted covariance matrix for the entire array **101** using only passed parameters and the local subarray elements.

[0068] An external signal (e.g., data signal **810** (FIG. **8**)) received by the antenna array **101** (e.g., antenna elements **306** (FIG. **3**B)) is transferred to an analog receiver to be adjusted to account for an internal equalization signal (e.g., calibration signal **304** (FIG. **3**A)). The adjusted signal may then be transferred to an analog-to-digital converter before being transferred to a complex value converter where the received signal is then downconverted to baseband such that the subsequent processing can be done in a complex-valued baseband domain. The signal is then sent to an equalizer where the excitation data (e.g., w**1***a*-wNa, w**1***n*-wNn) (FIG. **3**B)) from the plurality of antenna elements **306** in each transceiver node **104***a*-**104***n* is cohered to form a time aligned signal. As the signal data may then be subjected to cohering, collation, and equalization operations to facilitate the generation of an interference profile. System may then perform the subarray-dependent adaptive processes to direct the plurality of subarrays **102***a*-**102***n* toward generating the adaptive beam pattern **114** (FIG. **5**A, **5**B) and increasing signal quality. The interference mitigation protocol can be broadly seen as a protocol for increasing the SNR of the system **100**. The interference mitigation protocol may employ pulse compression techniques to provide SNR gain, isolation of the target **120** in range, and low range sidelobes to suppress interference sources **110** at other ranges and strong close-range clutter reduction. Similarly, system **100** may further isolate the signal by employing doppler filtering techniques to provide SNR gain, isolation of the target **120** in doppler (which corresponds to range-rate), clutter nulling, and low doppler sidelobes to suppress interference sources **110** at other range-rates.

[0069] In some embodiments, the plurality of processor nodes **108***a*-**108***n* (FIG. **1**A, FIG. **1**B, FIG. **3**B) may employ a machine learning algorithm to implement a software-defined adaptive filter for separating a signal of interest from the at least one interference source **110**. Further, the software-defined adaptive filter enables the system **100** to account for the high variability of interference sources **110** (FIG. **5**A) and target **120** (FIG. **5**A, **5**B) locations when generating the adaptive beam pattern **114** (FIG. **5**A, **5**B). A subprocess for implementing the software-defined adaptive filter may begin by identifying a domain for interference removal prior to separating the signal of interest, wherein the domain is at least one of temporal (fast time, slow time), spatial, polarization, or combinations thereof. Accordingly, the software-defined adaptive filter may determine the optimal combination of primary beams **112** (FIG. **5**A, **5**B) required to maximize directionality, gain, and SNR of the adaptive beam pattern **114**. In some embodiments, the software-defined adaptive filter is trained using the current interference profile as well as previously calculated interference profiles and adaptive beam patterns **114**. Accordingly, the system **100** improves the SNR without the need for user-guided tuning. Further, the software-defined adaptive filter may identify hidden or foreign artifacts in the read beams or data signals exciting the transceiver nodes **104***a*-**104***n*. Thus, the software-defined adaptive filter may increase the data security and fidelity of confidential transmissions. In some embodiments, the software-defined adaptive filter may be concurrently trained on the interference signal **702***a*-**702***n* (see FIG. **7** described below) such that the software-defined adaptive filter continuously improves interference mitigation. In some embodiments, the machine learning algorithm monitors available system data to prevent adversaries from deciphering the beamforming algorithm, predicting adaptive beam patterns **114**, or in any way attaining exploitable operational intelligence.

[0070] In some embodiments, the adaptive filter (FIG. **6**) works in concert with the transceiver nodes **104***a*-**104***n* to enable adaptive digital beamforming operations. Adaptive beamforming may describe the process of generating high gain and/or high-directionality beams while simultaneously generating null beams and/or spatial nulls **118** to mitigate the effects of external interference sources **110** (FIG. **5**A) that may change over time. To facilitate this functionality, the adaptive filter may form a feedback loop with the transceiver nodes **104***a*-**104***n* such that the efficacy of the adaptive beam pattern **114** in mitigating interference and generating beams is continuously monitored and the output for each transceiver node **104***a*-**104***n* can be individually tuned to accommodate for changes in the configuration of the interference sources **110** and the target **120** (e.g., moving targets **120** and interference sources **110**). In some embodiments, operation **616** may execute the following processes for obtaining SNR gain on targets: isolation of the target for a given AOA, (i.e., azimuth and elevation), sidelobe reduction of targets at other AOAs, and for adaptive beamforming, adaptive nulling of interference.

[0071] In some embodiments, the feedback loop of operation **616** (FIG. **6**) is further refined in operation **618** where the central processing node may predict the AOA for any number of interference sources and then perform spatial aliasing to position the interference signal between a pair of sidelobes within the adaptive beam pattern. In some embodiments, the central processing node **206** may employ the plurality of transceiver nodes **104***a*-**104***n* for interferometry operations to estimate a signal's AOA. The interferometry may include pairwise phase comparison to estimate both AOA and a spacing between array elements that is greater than lambda/2.

[0072] FIG. **7**A and **7**B show how the system **100** can utilize adaptive beamforming techniques to create spatial nulls in the direction of interference sources **110** (FIG. **5**A); thereby canceling their interference. In this case, two different sources of interference are canceled by adaptively beamforming to create two null beams in the direction of interference (FIG. **7**B). FIG. **7**A shows the output for a beamforming operation that does not apply sidelobe tuning or spatial nulling. Accordingly, the signal, or a first adaptive pattern **700***a*, has a relatively low level of directionality and relatively high sidelobe magnitude. FIG. **7**B shows the output for a beamforming operation that applies sidelobe tuning and spatial nulling to generate a broadside tapered beam where a plurality of interference signals **702***a*-**702***n* are positioned within spatial nulls **704** between the sidelobes **706**. For example, a r second adaptive beam pattern **700***b* may simultaneously cancel the plurality of interference signals **702***a*-**702***n* being generated by the plurality of interference sources **110** in a plurality of spatial directions (FIG. **5**A and FIG. **7**B). Further, the second adaptive beam pattern **700***b* may generate broadside tapered beam patterns capable of simultaneously nulling a plurality of spatially offset interference signals **702***a*-**702***n*. Operations for generating the interference profile may further include determining, via the arbitrary processor **108***a* (FIG. **1**A, FIG. **1**B, FIG. **3**B), an appropriate configuration of null beams **118** (FIG. **5**A) to direct toward a corresponding interference source from a plurality of interference sources **110** (FIG. **5**A) whenever any of the plurality of targets **120** (FIG. **5**A, **5**B) is within the area of interest **103** (FIG. **5**A) or field of regard **501** (FIG. **5**B). Further, the interference profile may be incorporated into the adaptive beam pattern **114** (FIG. **5**A, **5**B) such that outputting the adaptive beam pattern **114** includes adaptive beamforming techniques to point high-gain and/or high directionality beams **116** (FIG. **5**A) toward the at least one target **120** while simultaneously creating null beams **118** to cancel the plurality of interference sources **110**. In some embodiments, the at least one adaptive beam (pattern) **114** (e.g., second adaptive beam pattern **700***b*) includes a mainlobe **708** and a plurality of sidelobes **706**, wherein a bandwidth of the mainlobe **708** decreases as a magnitude of a direction vector for the plurality of sidelobes **706** increases. Further, the sidelobes **706** may be suppressed up to 40 dB and the adaptive beam pattern **114** (e.g., second adaptive beam pattern **700***b*) may implement up to 70 dB of co-channel interference mitigation through spatial beam nulling. In some embodiments, the system **100** enables up to 2 Gbps communication links while mitigating interference up to 40 dB, via wideband true time achieving 200 MHz bandwidth up to QAM1024 constellations.

[0073] The central processing node may include a subprocess for updating the adaptive beam pattern **114** (FIG. **5**A) in response to user commands or changes in the state of the at least one target **120** (FIG. **5**A, FIG. **5**B), the transceiver nodes **104***a*-**104***n* (FIG. **5**A, **5**B), or the plurality of interference sources **110** (FIG. **5**A). The update subprocess may begin after directing, via the arbitrary processor **108***a* (FIG. **1**B), the plurality of transceiver nodes **104***a*-**104***n* to output at least one first adaptive beam pattern **700***a* (FIG. **7**B). The subprocess may continue by receiving, via the arbitrary processor **108***a* (e.g., plurality of processor nodes **108***a*-**108***n*), an update request. For example, the update request may be a user supplied command that directs the system **100** (FIG. **1**A, FIG. **1**B) to acquire a new target **120** or to attenuate a newly discovered interference source **110**. The subprocess may continue by directing, via the arbitrary processor **108***a*, the plurality of transceiver nodes **104***a*-**104***n* to output at least one second adaptive beam pattern **700***b* in accordance with the update request FIG. **7**B. FIG. **7**A and FIG. **7**B show the signal response as the second adaptive beam pattern **700***b* as the response to an update request directing the system **100** to begin spatial nulling of interference signals **702***a***-702***n*.

[0074] In some embodiments, the system **100** (FIG. **1**A, FIG. **1**B) may be configured to monitor the area of interest **103** (FIG. **5**A) for changes in the plurality of interference sources **110**. For example, the central processing node (e.g., **206** FIG. **2**) may generate an alert when new interference sources are detected and may automatically update the interference profile to account for changes in the state of any identified interference sources **110** (e.g., modifications to frequency, position, directionality, signal strength). The subprocess may begin by identifying, via the processor **108**, a change in the interference profile for the area of interest **103** and updating the interference mitigation protocol based on the identified change. The subprocess may continue by directing, via the processor (e.g., **206**), the plurality of transceiver nodes **104***a***-104***n* to output at least one updated adaptive beam pattern **114** and the at least one mitigation signal (or null beam **118**) as at least one spatial null coincident with the at least one interference source **110**, in accordance with the updated interference mitigation protocol.

[0075] FIG. **8** is a block diagram of a single phased array-based radar system **800** implemented using the system **100** of FIG. **1**A, consistent with various embodiments. The radar system **800** includes a number of subarrays (e.g., sensor nodes **804***a*, **804***b*, **804***c*, **804***d*, and **804***e*) that are configured to facilitate surveillance of a moving object (e.g., detection of an aircraft **802**). In some embodiments, the sensor nodes **804***a***-804***e* are similar to the subarrays **102***a***-102***n* of the system **100**. In some embodiments, one of the sensor nodes **804***a***-804***e* may be designated as a reference node and a central processing node. In some embodiments, all the sensor nodes **804***a***-804***e* are configured as transmit and receive sensor nodes. The sensor nodes **804***a***-804***e* may be time synchronized as described at least with reference to FIGS. **4** and **5**A-**5**B above. Further, the time aligned signals may be cohered as described at least with reference to FIG. **6** above. The radar system **800** may be configured to work in a wide range of frequencies (e.g., 50 MHz to 36 GHz).

[0076] The sensor nodes **804***a***-804***e* are configured to transmit a probe signal **808** in a beamforming pattern. The signals reflected from the aircraft **802** may be received by the sensor nodes as data signals **810**. The data signals **810** are time aligned, cohered, and processed to determine one or more parameters of the aircraft **802** (e.g., distance or speed of the aircraft).

[0077] While FIG. **8** shows a single cluster of sensor nodes **804***a***-804***e*, the radar system **800** may have several clusters. In some embodiments, each black dot in FIG. **8** may be a cluster of sensor nodes. For example, the black dot **804***a* can be a first cluster, the block dot **804***b* can be a second cluster and so on, each of which includes several sensor nodes. In some embodiments, such a configuration enables detection of a moving object at ultra-long range and hypersonic speeds. In some embodiments, the sensor nodes or clusters may be spread over a few hundred meters or distributed across a large geographic region.

[0078] The system **100** may also be implemented as a mobile sensor array system. For example, the subarray elements **104***a***-104***n* may be designed as mobile subarray elements that are battery powered, solar powered, etc. and may be installed in an automobile, an unmanned aerial vehicle (UAV), or other mobile devices.

[0079] While FIG. **8** describes implementation of the system **100** as a radar system, the system **100** may also be implemented as a sonar system to facilitate surveillance of objects moving underwater (e.g., a submarine). For example, the subarray elements **104***a***-104***n* may be configured as hydrophone subarray elements, which can be installed as buoys or as mobile hydrophones (e.g., in submarines). The hydrophone subarray elements **104***a***-104***n* may be associated with above water components that communicate with satellites and have GPS capability.

[0080] In yet another example, the system **100** may be implemented for oil and gas and mining industry to facilitate detection of oil (or any other energy) and metals. For example, the subarray elements **104***a***-104***n* may be configured to work with seismic or acoustic waveforms and the cohered signals may be used to detect oil (or any other energy) and metals.

[0081] In some embodiments, the various components or modules illustrated in the Figures or described in the foregoing paragraphs may include one or more computing devices that are programmed to perform the functions described herein. The computing devices may include one or more electronic storages, one or more physical processors programmed with one or more computer program instructions, and/or other components. The computing devices may include communication lines or ports to enable the exchange of information within a network or other computing platforms via wired or wireless techniques (e.g., Ethernet, fiber optics, coaxial cable, Wi-Fi, Bluetooth, near field communication, or other technologies). The computing devices may include a plurality of hardware, software, and/or firmware components operating together. For example, the computing devices may be implemented by a cloud of computing platforms operating together as the computing devices. Cloud components may include control circuitry configured to perform the various operations needed to implement the disclosed embodiments. Cloud components may include cloud-based storage circuitry configured to electronically store information. Cloud components may also include cloud-based input/output circuitry configured to display information.

[0082] The electronic storages may include non-transitory storage media that electronically stores information. The storage media of the electronic storages may include one or both of (i) system storage that is provided integrally (e.g., substantially non-removable) with servers or client devices or (ii) removable storage that is removably connectable to the servers or client devices via, for example, a port (e.g., a USB port, a firewire port, etc.) or a drive (e.g., a disk drive, etc.). The electronic storages may include one or more of optically readable storage media (e.g., optical disks, etc.), magnetically readable storage media (e.g., magnetic tape, magnetic hard drive, floppy drive, etc.), electrical charge-based storage media (e.g., EEPROM, RAM, etc.), solid-state storage media (e.g., flash drive, etc.), and/or other electronically readable storage media. The electronic storages may include one or more virtual storage resources (e.g., cloud storage, a virtual private network, and/or other virtual storage resources). The electronic storage may store software algorithms, information determined by the processors, information obtained from servers, information obtained from client devices, or other information that enables the functionality as described herein.

[0083] The processors may be programmed to provide information processing capabilities in the computing devices. As such, the processors may include one or more of a digital processor, an analog processor, a digital circuit designed to process information, an analog circuit designed to process information, a state machine, and/or other mechanisms for electronically processing information. In some embodiments, the processors may include a plurality of processing units. These processing units may be physically located within the same device, or the processors may represent processing functionality of a plurality of devices operating in coordination. The processors may be programmed to execute computer program instructions to perform functions described herein. The processors may be programmed to execute computer program instructions by software; hardware; firmware; some combination of software, hardware, or firmware; and/or other mechanisms for configuring processing capabilities on the processors.

[0084] It should be appreciated that the description of the functionality provided by the components or modules described herein is for illustrative purposes, and is not intended to be limiting, as any of the components or modules may provide more or less functionality than is described. For example, one or more of the components or modules may be eliminated, and some or all of its functionality may be provided by other ones of the components or modules. As another example, additional components or modules may be programmed to perform some or all of the functionality attributed herein to one of the components or modules.

[0085] The following list of clauses describes various aspects of the systems and methods described herein, which may be combined in any combination. [0086] 1: A method for scalable on array processing and interference mitigation using adaptive beamforming, may include: calibrating, via an arbitrary processor node, a plurality of aggregated weight vectors for a plurality of subarray elements within a phased array, where the arbitrary processor node is from a plurality of processor nodes; determining, via a corresponding processor node, if a covariance matrix is full rank in relation to each of the plurality of aggregated weight vectors, where each of the plurality of subarray elements is associated with the corresponding processor node from the plurality of processor nodes; generating, via the corresponding processor node, an interference mitigation protocol for each of the plurality of subarray elements based on at least one of the aggregated weight vector and the covariance matrix; and outputting, via the plurality of subarray elements, an adaptive beam pattern in accordance with the interference mitigation protocol, where the adaptive beam pattern includes a at least one high-directionality beam generated by at least one first subarray element and at least one mitigation signal modulated by at least one second subarray element. [0087] 2: The method as clause 1 describes, further may include: distributing, via at least one arbitrary processor, at least one steering vector routine to each of the plurality of subarrays, where status information is generated during the at least one steering vector routine; determining, via the arbitrary processor, an interference profile based on status information for the plurality of subarray elements, where the interference profile includes at least one interference source; and executing, via at least one arbitrary processor, an intermediary collation operation based on the status information and the interference profile, where the intermediary collation operation generates a plurality of subarray-dependent adaptive processes, and where a corresponding adaptive process from the plurality of subarray-dependent adaptive processes is associated with each of the plurality of subarray elements. [0088] 3: The method as either of clauses 1 or 2 describe, where the corresponding adaptive process is adapted in response to an output of each of the plurality of subarray elements, a desired steering vector, and the covariance matrix. [0089] 4: The method as any of clauses 1-3 describe, where the plurality of subarray elements is configured into a tiered operational structure, and where each of a plurality of representative weight vectors is associated with a corresponding subarray element from the plurality of subarray elements within an arbitrary tier of the tiered operational structure, and where the aggregated weight vector is based on a plurality of representative weight vectors, a rank of each representative weight vector, and a desired steering vector. [0090] 5: The method as any of clauses 1-4 describe, where the aggregated weight vector of the arbitrary tier is designated as a new representative weight vector in a subsequent tier of the tiered operational structure, and where an intermediary collation operation is repeated using all representative weight vectors in the subsequent tier. [0091] 6: The method as any of clauses 1-5 describe, where calibrating the aggregated weight vector for the subsequent tier includes relaying all aggregated weight vector data generated in the subsequent tier as status information for preceding tiers of the tiered operational structure. [0092] 7: The method as any of clauses 1-6 describe, where the phased array is disposed to assess an area of interest, and where each of the plurality of subarray elements is configured to attenuate at least one interference source within a field of regard, and where the field of regard is a portion of the area of interest. [0093] 8: The method as any of clauses 1-7 describe, where generating the interference mitigation protocol includes spatial aliasing techniques to attenuate at least one interference source. [0094] 9: The method as any of clauses 1-8 describe, where a covariance matrix model based on the interference mitigation protocol includes both steady-state interference and transient noise. [0095] 10: The method as any of clauses 1-9 describe, where generating the interference mitigation protocol includes improving beam directionality and spatial nulling by performing statistical analytical techniques including maximum-likelihood estimation and nonlinear least square estimation. [0096] 11: A system for scalable on array processing and interference mitigation using adaptive beamforming may include: one or more processors configured to: calibrate, via an arbitrary processor node, a plurality of aggregated weight vectors for a plurality of subarray elements within a phased array, where the arbitrary processor node is from a plurality of processor nodes; determine, via a corresponding processor node, if a covariance matrix is full rank in relation to each of the plurality of aggregated weight vectors, where each of the plurality of subarray elements is associated with the corresponding processor node from the plurality of processor nodes; generate, via the corresponding processor node, an interference mitigation protocol for each of the plurality of subarray elements based on at least one of the aggregated weight vector and the covariance matrix; and output, via the plurality of subarray elements, an adaptive beam pattern in accordance with the interference mitigation protocol, where the adaptive beam pattern includes a at least one high-directionality beam generated by at least one first subarray element and at least one mitigation signal modulated by at least one second subarray element. [0097] 12: The system as clause 11 describes, where the one or more processors are further configured to: distribute, via at least one arbitrary processor, at least one steering vector routine to each of the plurality of subarrays, where status information is generated during the at least one steering vector routine; determine, via the arbitrary processor, an interference profile based on status information for the plurality of subarray elements, where the interference profile includes at least one interference source; and execute, via at least one arbitrary processor, an intermediary collation operation based on the status information and the interference profile, where the intermediary collation operation generates a plurality of subarray-dependent adaptive processes, and where a corresponding adaptive process from the plurality of subarray-dependent adaptive processes is associated with each of the plurality of subarray elements. [0098] 13: The system as either of clauses 11 or 12 describe, where the corresponding adaptive process is adapted in response to an output of each of the plurality of subarray elements, a desired steering vector, and the covariance matrix. [0099] 14: The system as any of clauses 11-13 describe, where the plurality of subarray elements is configured into a tiered operational structure, and each of a plurality of representative weight vectors is associated with a corresponding subarray element from the plurality of subarray elements within an arbitrary tier of the tiered operational structure, and the aggregated weight vector is based on a plurality of representative weight vectors, a rank of each representative weight vector, and a desired steering vector. [0100] 15: The system as any of clauses 11-14 describe, where the aggregated weight vector of the arbitrary tier is designated as a new representative weight vector in a subsequent tier of the tiered operational structure, and an intermediary collation operation is repeated using all representative weight vectors in the subsequent tier. [0101] 16: The system as any of clauses 11-15 describe, where calibrating the aggregated weight vector for the subsequent tier includes relaying all aggregated weight vector data generated in the subsequent tier as status information for preceding tiers of the tiered operational structure. [0102] 17: The system as any of clauses 11-16 describe, where the phased array is disposed to assess an area of interest, and each of the plurality of subarray elements is configured to attenuate at least one interference source within a field of regard, and the field of regard is a portion of the area of interest. [0103] 18: The system as any of clauses 11-17 describe, where generating the interference mitigation protocol includes spatial aliasing techniques to attenuate at least one interference source. [0104] 19: The system as any of clauses 11-18 describe, where a covariance matrix model based on the interference mitigation protocol includes both steady-state interference and transient noise. [0105] 20: The system as any of clauses 11-19 describe, where generating the interference mitigation protocol includes improving beam directionality and spatial nulling by performing statistical analytical techniques including maximum-likelihood estimation and nonlinear least square estimation. [0106] 21: A non-transitory computer-readable medium storing a set of instructions for scalable on array processing and interference mitigation using adaptive beamforming, the set of instructions may include: one or more instructions that, when executed by one or more processors of a device, cause the device to: calibrate, via an arbitrary processor node, a plurality of aggregated weight vectors for a plurality of subarray elements within a phased array, where the arbitrary processor node is from a plurality of processor nodes; determine, via a corresponding processor node, if a covariance matrix is full rank in relation to each of the plurality of aggregated weight vectors, where each of the plurality of subarray elements is associated with the corresponding processor node from the plurality of processor nodes; generate, via the corresponding processor node, an interference mitigation protocol for each of the plurality of subarray elements based on at least one of the aggregated weight vector and the covariance matrix; and output, via the plurality of subarray elements, an adaptive beam pattern in accordance with the interference mitigation protocol, where the adaptive beam pattern includes a at least one high-directionality beam generated by at least one first subarray element and at least one mitigation signal modulated by at least one second subarray element. [0107] 22: The non-transitory computer-readable medium as clause 21 describes, where the one or more instructions further cause the device to: distribute, via at least one arbitrary processor, at least one steering vector routine to each of the plurality of subarrays, where status information is generated during the at least one steering vector routine; determine, via the arbitrary processor, an interference profile based on status information for the plurality of subarray elements, where the interference profile includes at least one interference source; and execute, via at least one arbitrary processor, an intermediary collation operation based on the status information and the interference profile, where the intermediary collation operation generates a plurality of subarray-dependent adaptive processes, and where a corresponding adaptive process from the plurality of subarray-dependent adaptive processes is associated with each of the plurality of subarray elements. [0108] 23: The non-transitory computer-readable medium as either of clauses 21 or 22 describe, where the corresponding adaptive process is adapted in response to an output of each of the plurality of subarray elements, a desired steering vector, and the covariance matrix. [0109] 24: The non-transitory computer-readable medium as any of clauses 21-23 describe, where the plurality of subarray elements is configured into a tiered operational structure, and each of a plurality of representative weight vectors is associated with a corresponding subarray element from the plurality of subarray elements within an arbitrary tier of the tiered operational structure, and the aggregated weight vector is based on a plurality of representative weight vectors, a rank of each representative weight vector, and a desired steering vector. [0110] 25: The non-transitory computer-readable medium as any of clauses 21-24 describe, where the aggregated weight vector of the arbitrary tier is designated as a new representative weight vector in a subsequent tier of the tiered operational structure, and an intermediary collation operation is repeated using all representative weight vectors in the subsequent tier. [0111] 26: The non-transitory computer-readable medium as any of clauses 21-25 describe, where calibrating the aggregated weight vector for the subsequent tier includes relaying all aggregated weight vector data generated in the subsequent tier as status information for preceding tiers of the tiered operational structure. [0112] 27: The non-transitory computer-readable medium as any of clauses 21-26 describe, where the phased array is disposed to assess an area of interest, and each of the plurality of subarray elements is configured to attenuate at least one interference source within a field of regard, and the field of regard is a portion of the area of interest. [0113] 28: The non-transitory computer-readable medium as any of clauses 21-27 describe, where generating the interference mitigation protocol includes spatial aliasing techniques to attenuate at least one interference source. [0114] 29: The non-transitory computer-readable medium as any of clauses 21-28 describe, where a covariance matrix model based on the interference mitigation protocol includes both steady-state interference and transient noise. [0115] 30: The non-transitory computer-readable medium as any of clauses 21-29 describe, where generating the interference mitigation protocol includes improving beam directionality and spatial nulling by performing statistical analytical techniques including maximum-likelihood estimation and nonlinear least square estimation.

[0116] Although the present invention has been described in detail for the purpose of illustration based on what is currently considered to be the most practical and preferred embodiments, it is to be understood that such detail is solely for that purpose and that the invention is not limited to the disclosed embodiments, but, on the contrary, is intended to cover modifications and equivalent arrangements that are within the scope of the appended claims. For example, it is to be understood that the present invention contemplates that, to the extent possible, one or more features of any embodiment can be combined with one or more features of any other embodiment.

Claims

1. A method for scalable on-array processing and interference mitigation using adaptive beamforming, comprising: calibrating, via an arbitrary processor node, a plurality of aggregated weight vectors for a plurality of subarray elements within a phased array, wherein the arbitrary processor node is from a plurality of processor nodes; determining, via a corresponding processor node, if a covariance matrix is full rank in relation to each of the plurality of aggregated weight vectors, wherein each of the plurality of subarray elements is associated with the corresponding processor node from the plurality of processor nodes; generating, via the corresponding processor node, an interference mitigation protocol for each of the plurality of subarray elements based on at least one of the aggregated weight vector and the covariance matrix; and outputting, via the plurality of subarray elements, an adaptive beam pattern in accordance with the interference mitigation protocol, wherein the adaptive beam pattern includes a at least one high-directionality beam generated by at least one first subarray element and at least one mitigation signal modulated by at least one second subarray element.
2. The method of claim 1, further comprising: distributing, via at least one arbitrary processor, at least one steering vector routine to each of the plurality of subarrays, wherein status information is generated during the at least one steering vector routine; determining, via the arbitrary processor, an interference profile based on status information for the plurality of subarray elements, wherein the interference profile includes at least one interference source; and executing, via at least one arbitrary processor, an intermediary collation operation based on the status information and the interference profile, wherein the intermediary collation operation generates a plurality of subarray-dependent adaptive processes, and wherein a corresponding adaptive process from the plurality of subarray-dependent adaptive processes is associated with each of the plurality of subarray elements.
3. The method of claim 2, wherein the corresponding adaptive process is adapted in response to an output of each of the plurality of subarray elements, a desired steering vector, and the covariance matrix.
4. The method of claim 1, wherein the plurality of subarray elements is configured into a tiered operational structure, and wherein each of a plurality of representative weight vectors is associated with a corresponding subarray element from the plurality of subarray elements within an arbitrary tier of the tiered operational structure, and wherein the aggregated weight vector is based on a plurality of representative weight vectors, a rank of each representative weight vector, and a desired steering vector.
5. The method of claim 4, wherein the aggregated weight vector of the arbitrary tier is designated as a new representative weight vector in a subsequent tier of the tiered operational structure, and wherein an intermediary collation operation is repeated using all representative weight vectors in the subsequent tier.
6. The method of claim 5, wherein calibrating the aggregated weight vector for the subsequent tier includes relaying all aggregated weight vector data generated in the subsequent tier as status information for preceding tiers of the tiered operational structure.
7. The method of claim 1, wherein the phased array is disposed to assess an area of interest, and wherein each of the plurality of subarray elements is configured to attenuate at least one interference source within a field of regard, and wherein the field of regard is a portion of the area of interest.
8. The method of claim 1, wherein generating the interference mitigation protocol includes spatial aliasing techniques to attenuate at least one interference source.
9. The method of claim 1, wherein a covariance matrix model based on the interference mitigation protocol includes both steady-state interference and transient noise.

10. The method of claim 1, wherein generating the interference mitigation protocol includes improving beam directionality and spatial nulling by performing statistical analytical techniques including maximum-likelihood estimation and nonlinear least square estimation.
11. A system for scalable on array processing and interference mitigation using adaptive beamforming comprising: one or more processors configured to: calibrate, via an arbitrary processor node, a plurality of aggregated weight vectors for a plurality of subarray elements within a phased array, wherein the arbitrary processor node is from a plurality of processor nodes; determine, via a corresponding processor node, if a covariance matrix is full rank in relation to each of the plurality of aggregated weight vectors, wherein each of the plurality of subarray elements is associated with the corresponding processor node from the plurality of processor nodes; generate, via the corresponding processor node, an interference mitigation protocol for each of the plurality of subarray elements based on at least one of the aggregated weight vector and the covariance matrix; and output, via the plurality of subarray elements, an adaptive beam pattern in accordance with the interference mitigation protocol, wherein the adaptive beam pattern includes a at least one high-directionality beam generated by at least one first subarray element and at least one mitigation signal modulated by at least one second subarray element.
12. The system of claim 11, wherein the one or more processors are further configured to: distribute, via at least one arbitrary processor, at least one steering vector routine to each of the plurality of subarrays, wherein status information is generated during the at least one steering vector routine; determine, via the arbitrary processor, an interference profile based on status information for the plurality of subarray elements, wherein the interference profile includes at least one interference source; and execute, via at least one arbitrary processor, an intermediary collation operation based on the status information and the interference profile, wherein the intermediary collation operation generates a plurality of subarray-dependent adaptive processes, and wherein a corresponding adaptive process from the plurality of subarray-dependent adaptive processes is associated with each of the plurality of subarray elements.
13. The system of claim 12, wherein the corresponding adaptive process is adapted in response to an output of each of the plurality of subarray elements, a desired steering vector, and the covariance matrix.
14. The system of claim 11, wherein the plurality of subarray elements is configured into a tiered operational structure, and each of a plurality of representative weight vectors is associated with a corresponding subarray element from the plurality of subarray elements within an arbitrary tier of the tiered operational structure, and the aggregated weight vector is based on a plurality of representative weight vectors, a rank of each representative weight vector, and a desired steering vector.
15. The system of claim 14, wherein the aggregated weight vector of the arbitrary tier is designated as a new representative weight vector in a subsequent tier of the tiered operational structure, and an intermediary collation operation is repeated using all representative weight vectors in the subsequent tier.
16. The system of claim 15, wherein calibrating the aggregated weight vector for the subsequent tier includes relaying all aggregated weight vector data generated in the subsequent tier as status information for preceding tiers of the tiered operational structure.
17. The system of claim 11, wherein the phased array is disposed to assess an area of interest, and each of the plurality of subarray elements is configured to attenuate at least one interference source within a field of regard, and the field of regard is a portion of the area of interest.
18. The system of claim 11, wherein generating the interference mitigation protocol includes spatial aliasing techniques to attenuate at least one interference source.
19. The system of claim 11, wherein a covariance matrix model based on the interference mitigation protocol includes both steady-state interference and transient noise.
20. The system of claim 11, wherein generating the interference mitigation protocol includes

improving beam directionality and spatial nulling by performing statistical analytical techniques including maximum-likelihood estimation and nonlinear least square estimation.

21. A non-transitory computer-readable medium storing a set of instructions for scalable on array processing and interference mitigation using adaptive beamforming, the set of instructions comprising: one or more instructions that, when executed by one or more processors of a device, cause the device to: calibrate, via an arbitrary processor node, a plurality of aggregated weight vectors for a plurality of subarray elements within a phased array, wherein the arbitrary processor node is from a plurality of processor nodes; determine, via a corresponding processor node, if a covariance matrix is full rank in relation to each of the plurality of aggregated weight vectors, wherein each of the plurality of subarray elements is associated with the corresponding processor node from the plurality of processor nodes; generate, via the corresponding processor node, an interference mitigation protocol for each of the plurality of subarray elements based on at least one of the aggregated weight vector and the covariance matrix; and output, via the plurality of subarray elements, an adaptive beam pattern in accordance with the interference mitigation protocol, wherein the adaptive beam pattern includes a at least one high-directionality beam generated by at least one first subarray element and at least one mitigation signal modulated by at least one second subarray element.

22. The non-transitory computer-readable medium of claim 21, wherein the one or more instructions further cause the device to: distribute, via at least one arbitrary processor, at least one steering vector routine to each of the plurality of subarrays, wherein status information is generated during the at least one steering vector routine; determine, via the arbitrary processor, an interference profile based on status information for the plurality of subarray elements, wherein the interference profile includes at least one interference source; and execute, via at least one arbitrary processor, an intermediary collation operation based on the status information and the interference profile, wherein the intermediary collation operation generates a plurality of subarray-dependent adaptive processes, and wherein a corresponding adaptive process from the plurality of subarray-dependent adaptive processes is associated with each of the plurality of subarray elements.

23. The non-transitory computer-readable medium of claim 22, wherein the corresponding adaptive process is adapted in response to an output of each of the plurality of subarray elements, a desired steering vector, and the covariance matrix.

24. The non-transitory computer-readable medium of claim 21, wherein the plurality of subarray elements is configured into a tiered operational structure, and each of a plurality of representative weight vectors is associated with a corresponding subarray element from the plurality of subarray elements within an arbitrary tier of the tiered operational structure, and the aggregated weight vector is based on a plurality of representative weight vectors, a rank of each representative weight vector, and a desired steering vector.

25. The non-transitory computer-readable medium of claim 24, wherein the aggregated weight vector of the arbitrary tier is designated as a new representative weight vector in a subsequent tier of the tiered operational structure, and an intermediary collation operation is repeated using all representative weight vectors in the subsequent tier.

26. The non-transitory computer-readable medium of claim 25, wherein calibrating the aggregated weight vector for the subsequent tier includes relaying all aggregated weight vector data generated in the subsequent tier as status information for preceding tiers of the tiered operational structure.

27. The non-transitory computer-readable medium of claim 21, wherein the phased array is disposed to assess an area of interest, and each of the plurality of subarray elements is configured to attenuate at least one interference source within a field of regard, and the field of regard is a portion of the area of interest.

28. The non-transitory computer-readable medium of claim 21, wherein generating the interference mitigation protocol includes spatial aliasing techniques to attenuate at least one interference source.

29. The non-transitory computer-readable medium of claim 21, wherein a covariance matrix model based on the interference mitigation protocol includes both steady-state interference and transient noise.

30. The non-transitory computer-readable medium of claim 21, wherein generating the interference mitigation protocol includes improving beam directionality and spatial nulling by performing statistical analytical techniques including maximum-likelihood estimation and nonlinear least square estimation.