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(54) Title: PERSONAL RADAR

(57) Abstract: A phased array radio system that is used to find the direction of a transmitter or receiver by using spatial positioned antenna elements at multiple frequencies. Radio systems and methods for finding an angle or a direction to a radio source are also provided.

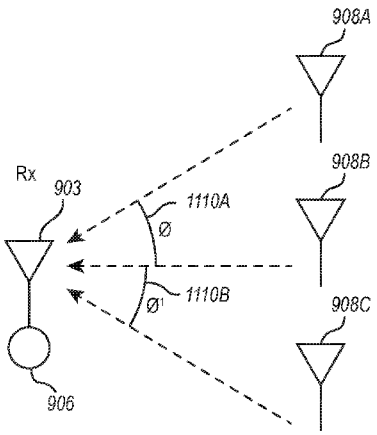


FIG. 11

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PERSONAL RADAR

BACKGROUND OF THE INVENTION

1. The Field of the Invention

[0001] Embodiments of the invention relate to systems and methods for detecting objects and/or the motion of objects. More particularly, embodiments of the invention relate to personal radar, object presence detection, and object localization.

2. The Relevant Technology

[0002] There are many methods on how one can detect objects and/or the motion of an object. Most devices use time of flight from echo, chirp, frequency modulation (FM), or Doppler radar for the detection or to detect the motion of objects. Many use steerable antennas or phase array antennas to detect those objects. Yet others use simple measurements of the received signal strength (RSS) to detect movements within an area. These types of systems are often costly, power hungry, expensive, and/or inaccurate or not sufficiently accurate.

BRIEF DESCRIPTION

[0003] Embodiments described herein are directed to radio systems and methods for finding an angle or a direction to a radio source. In one embodiment, a radio system includes a transmitter with two or more antennas configured to broadcast a first signal at a first frequency, and at a subsequent time broadcast a second signal at a second, different frequency. The radio system includes a receiver having an antenna configured to receive the first and second signals broadcast from the two or more antennas of the transmitter, and also includes a processing unit. The processing unit is configured to measure the amplitude and phase of the first signal at the first frequency as received at the receiver, measure the amplitude and phase of the second signal at the second frequency as received at the receiver, and identify an angle or a direction to the transmitter using the measured amplitude and phase of each signal.

[0004] In another embodiment, a method is provided for finding an angle or a direction to a radio source. The method includes broadcasting two or more signals at different frequencies from two or more antennas at a transmitter, receiving the two or more signals broadcasted at different frequencies at a receiver, measuring each signal's amplitude and phase as received at the receivers, and identifying an angle or a direction to the radio source using the measured amplitude and phase of each signal.

[0005] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter.

[0006] Additional features and advantages will be set forth in the description which follows, and in part will be apparent to one of ordinary skill in the art from the description, or may be learned by the practice of the teachings herein. Features and advantages of embodiments described herein may be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. Features of the embodiments described herein will become more fully apparent from the following description and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] In order to describe the manner in which at least some of the advantages and features of the invention can be obtained, a more particular description of embodiments of the invention briefly described above will be rendered by reference to specific embodiments thereof which are illustrated in the appended drawings. Understanding that these drawings depict only typical embodiments of the invention and are not therefore to be considered to be limiting of its scope, embodiments of the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings, in which:

FIGURE 1 illustrates an example of a ranging system that includes two radios that each include a single antenna;

FIGURE 2 illustrates an example of detecting different types of objects with the ranging system;

FIGURE 3 illustrates measurement results for three different objects of different materials crossing the path of two distance-ranging nodes or radios;

FIGURE 4A illustrates an example of a ranging system that includes two radios. Both radios includes an RF switch with two antennas;

FIGURE 4B illustrates an example of a ranging system that includes two radios where one radio includes an RF switch with multiple antennas and a second radio includes one antenna;

FIGURE 5 illustrates a block diagram of the method for performing measurements;

FIGURE 6 illustrates an example antenna constellation for a virtual steerable antenna;

FIGURE 7 illustrates the resulting virtual antenna pattern if the virtual antennal is pointed towards zero degrees;

FIGURE 8 illustrates the resulting virtual antenna pattern if the virtual antenna is pointed towards 45 degrees;

Figure 9A and 9B illustrate an embodiment of a system for determining direction or angle of arrival using frequency hopping;

Figure 10 illustrates an alternative embodiment of a system for determining direction or angle of arrival using frequency hopping;

Figure 11 illustrates an embodiment in which a receiver calculates an angle of arrival;

Figure 12 illustrates an embodiment in which an RF signal is transmitted in bursts on different antennas using different frequencies;

Figure 13 illustrates an embodiment in which a given frequency is used on multiple different antennas;

Figure 14 illustrates a flowchart of a method for finding an angle or a direction to a radio source.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0008] In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented herein. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the Figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

[0009] Embodiments of the invention relate to systems and methods for detecting and/or measuring and/or tracking objects, the motion of objects or the movement of objects in an area. Embodiments use a novel approach to detect objects or the motion of objects using devices that perform high-accuracy ranging methods. These methods use, in one example, one or more of an angle of arrival, a time difference, and/or a phase

difference for detecting changes in the wave-propagation. The position of objects and the movement of the objects can be determined from the changes in the wave-propagation. Advantageously, the position and movement of objects that interfere with the wave-propagation can also be determined.

[0010] It is often difficult to detect an object in a crowded area or location like a jungle or landscape, with no direct line of sight. In accordance with embodiments of the invention, as long as two devices (e.g., radios) can communicate and measure the effective path distance between them, an object that comes into the path of the two radios can be detected by measuring an increase in the distance the radio signal has to travel to go around the new object in the path. In other words, changes in the effective path distance are indicative of an object that has entered the path between the two radios.

[0011] Conventional methods use signal strength or a link quality indicator, but these methods are unreliable because the signal strength can get stronger by refraction, or weaker depending on the path or position of the object. In addition, conventional devices use time of flight from echo, chirp, frequency modulation (FM), or doppler radar for the detection or to detect the motion of objects. Some conventional devices use steerable antennas or phase array antennas to detect objects. Conventional devices combine the signals in the antenna feed electronics to record multiple radio paths at the same time, or use multiple radios.

[0012] Embodiments of the invention can detect objects and/or the motion of objects using a device (e.g., a device capable of transmitting and/or receiving a signal such as an electromagnetic signal such as a radio) or a pair of devices and a low cost switch to select a single antenna at a time, out of an array of many antennas. Embodiments include a stable system clock and the phase between the antennas can be measured at different times, which differs from conventional units that use multiple radio paths or multiple radios. Advantageously, embodiments of the invention can be implemented at significantly lower cost.

[0013] The embodiments of this invention use a novel approach to detect objects or the motion of objects using high-accuracy ranging methods as described, by way of example, in US Patent US8,274,426, which is incorporated by reference in its entirety. In one embodiment, ranging methods may be employed to find angle of arrival, time difference, and/or phase difference of narrowband signals for detecting changes in the wave-propagation. The position and movement of objects interfering with that

propagation can be determined. Employing high-resolution propagation-path length measurements can overcome conventional problems, and significantly improve accuracy.

[0014] One embodiment uses a single radio and a low cost switch to select a single antenna at a time, out of an array of many. This is possible because the system includes tightly synchronized clocks that are within a few Hz of each other. Because the system clock is stable, the phase between antennas can be measured at different times to get the same information as conventional units, but at a lower cost. The stability also allows an extremely high resolution at the millimeter level.

[0015] The following discussion illustrates embodiments of the invention that are representative of embodiments in different platform configurations. The systems may exhibit different characteristics with respect to detection capabilities, cost, and complexity. In contrast to conventional systems, embodiments provide high-resolution path length measurements that allow new ways of detecting interference with the electromagnetic wave propagation.

[0016] Figure 1 illustrates an example of a ranging system that includes two radios. The ranging system 10 can be used not only for ranging applications but also as a radar system that can detect the presence of objects and well as the motion of objects. Each radio includes a single antenna, although embodiments may contemplate other additional antennas in each radio in the ranging system 10. Figure 1 further illustrates the effective path of the signals between the radios may be different at different frequencies. Although Figure 1 illustrates two radios, embodiments of the invention can be configured to include multiple radios. For example, different pairs of radios in a ranging system that includes multiple radios could each use specific frequencies. In addition, one radio may communicate with different radios using different frequencies.

[0017] Figure 1 illustrates a system that includes a radio 100 and a radio 102 that communicate over an effective path 110 (e.g., line of sight in one example). The radios 100 and 102 can perform high-precision ranging as described in U.S. Patent Application 8,274,426, which is incorporated by reference in its entirety, and have phase measurement capabilities. One of the radios, e.g., the radio 102, includes a high-precision, high-stability controllable oscillator. In this example, the radio 100 is a master and the radio 100 transmits a narrow-band radio signal at a higher frequency than a frequency of the local oscillator. This is achieved, in one example, using a phase-locked loop (PLL) and voltage controlled oscillator (VCO) that are included in the radio 100 (the radio 102 may be similarly configured). This higher frequency signal is sent to the second node or radio

102. The radio 102 tunes to the higher frequency signal using its PLL and VCO. The radio 102 may also adjust its controllable high-stability local oscillator to the incoming signal. In this manner, an ultra-high synchronized system is achieved.

[0018] The higher frequency helps in adjusting the local oscillator with a higher precision. Advantageously, a lower-resolution phase measurement at the higher frequency can be employed, and can be related to the lower frequency clock crystal due to the use of PLLs.

[0019] For example, assume a low-frequency of 16 MHz, and a high-frequency of 2.4 GHz. This gives a multiplier of 150. If the second unit (e.g., the radio 102) uses the 2.4 GHz signal to tune its local 16 MHz signal to achieve phase coherency with the 16 MHz signal of node 1 or the radio 100, then a low-resolution phase measurement unit at the 2.4 GHz signal is enough to achieve extremely high synchronization stability. For example, assume that a 10 degree phase error at the 2.4 GHz signal is corrected every 15 ms. This corresponds to an absolute synchronization stability of 1/15 degree correction every 15 ms, or 4.4 degrees error per second (0.012222 Hz). This equals a synchronization stability of 764 parts-per-trillion.

[0020] The second radio 102 sends a narrow-band signal back to the first node or the radio 100. Due to the highly synchronized oscillators, this second radio 102 acts like an almost perfect active reflector, and it looks as if the incoming radio wave was simply reflected back to the radio 100. The first node or radio 100 can then measure the difference between its local high-frequency signal, and the incoming high-frequency signal. The difference in phase will correspond to the path length.

[0021] If an object (e.g., the object 108) travels through the path 110, the path 110 changes. In other words, the length of the path 110 changes in distance because the radio waves or the transmissions between the radio 100 and the radio 102 travel around the object 108. Because the radios 100 and 102 are configured to detect an accurate range or distance, the change in the distance can be detected. A change in the distance can be interpreted as the presence of a new object – the object 108.

[0022] In addition, a size and/or speed of the object 108 can be measured by looking at the peak-change in distance, and at the time required to achieve the peak change. The peak will reflect the size of the interfering object, while the time to peak correlates with the speed of the object.

[0023] Furthermore, using two or more frequencies, the size of the object 108 can be deduced quickly due to the different propagation properties at different frequencies. For

example, a 900 MHz signal will travel differently around the intruding object 108, compared to a 2.4 GHz signal. This difference in path can be measured due to the high-stability local oscillators and almost perfect active reflector, and thus the size of the object 108 can be determined. The radio 100 can thus emit a signal 104 at a first frequency and a second signal 106 at a second signal. The radio 102 can effectively reflect these frequencies as previously described. The size of the object 108 and the speed of the object can then be determined.

[0024] As described above, the presence of an object can be determined when a change in the distance of the transmission path 110 is detected. The size and/or speed can also be detected.

[0025] Figure 2 illustrates an example of detecting different types of objects with the ranging system 10, which can effectively operate as a radar system. The radar system can be configured for a specific area and the radios can be arranged in the area (e.g., on the perimeter or inside of the area) in a manner than enables objects and their motion to be identified and tracked. Figure 2 illustrates different objects including a Teflon object 202, a steel object 204, and a human arm object 206. Each of the objects 202, 204, and 206 was moved into the path of the nodes or radios 100 and 102.

[0026] The measured phase, and path distance, change are shown on Figure 3. Figure 3 illustrates measurement results 300 for three different materials (or objects of different material) crossing the path of two distance-ranging nodes such as the radio 100 and the radio 102. The materials resided within the path for a while, before they were removed again. The different path changes for the different objects are illustrates and correspond to the different material properties which include size.

[0027] One embodiment of this two-radio system can be used for perimeter control, allowing to protect a certain area by placing a multitude of these two-radio systems around the area, where each link defines the perimeter of the area to be protected. If a foreign object passes through any one of the paths set up by the multitude of two-radio systems, an alarm can be raised, identifying where the path has been broken, and how big the object is. The ability of the radios to use different frequencies may also enhance the ability to control a perimeter. Each link, which may include a pair of radios and each radio may belong to more than one pair of radios, may use the same or different frequencies.

[0028] Figure 4A illustrates an example of a multi-antenna system for the detection of presence or absence of an object and a location at which the object crosses an

electromagnetic wave path. Figure 4A illustrates an electromagnetic wave path 420 that may be established between two radios (node 422 and node 432). The node 422 may include two or more antennas (illustrated as antennas 424 and 426). The node 432 may include two or more antennas (illustrated as antennas 428 and 430). The antennas may be separated in space by any distance, where the distance will determine the angle resolution and detection angle width. In one example, the distance is the frequency wavelength divided by 2 (lambda/2), as this provides a 180 degree detection angle. In another example, the distance may be related to the size of the objects that are being detected. For example, the distance may be half the size of the object to be detected.

[0029] The nodes 422 and 432 may engage in high-resolution ranging as previously described and may switch between antennas. As a result, it is possible to establish and measure or monitor several RF paths or several electromagnetic paths. The electromagnetic wave path 420 can include a paths 438, 440, 442, and 444. The path 438 is established between the antenna 424 and the antenna 430. The path 440 is established between the antennas 426 and 428. The path 442 is between the antennas 424 and 428. The path 444 is between the antennas 426 and 430.

[0030] By establishing multiple paths, the ability to track an object or to track motion of the object is further enhanced. For example, if the object 434 or the object 436 crosses between the two nodes, the various paths 420 between the nodes 422 and 432 will have different changes in distance over time. For example, if the objects 434 and 436 move into the path 420 from below, they will impact the various paths in different ways. For example, the object 434 is detected via the path 440 before the path 438 while the object 436 is detected by the path 438 before the path 440. Because the arrangements of the nodes in any given system can be known, it is possible to infer where an object crosses the path 420 between the nodes 422 and 432.

[0031] For example, the presence of the object 436 may be detected when changes in the path 444 are detected. When changes to the path 438 are detected next instead of to the path 440, the location of the object 436 relative to the nodes 422 and 432 can be inferred. The location of the objects can be inferred even when the antennas are spaced relatively close due to the nature of electromagnetic waves.

[0032] The implications of this one-dimensional localization can be used, for example, in a perimeter alarm system, where it is useful to know not just that an object crossed a line or perimeter, but where the perimeter has been crossed. This is especially important if the distance between the nodes is large.

[0033] An extension to the two node scenario illustrated in Figure 4A is a 2+ node scenario, where the nodes all engage in a high-resolution ranging to each other. Now, the crossing distance can localize an object within the observed area not just by looking at the change in signal strength and attenuation, but by the change in RF path length.

[0034] In another example, the ranging system may include a single radio with multiple antennas and a single illuminator. A basestation may include one receiver radio (or transceiver) with phase measurement capabilities and multiple antennas. Figure 4B, for example, illustrates a basestation 402 containing one receiver radio (or transceiver) 402 and multiple antennas 404. The antennas 404 are connected to the one radio 402 using a network of antenna switches 406. In this example, the radio 402 can be connected to one of the antennas 404 at a time in one embodiment, although the switch 406 may be configured to connect more than one antenna to the radio at a time. A second unit, called an illuminator 408, includes a transmitter radio (or transceiver) and needs only one antenna 410. The second unit or illuminator 408 sends out a narrowband signal, illuminating the environment 400.

[0035] Due to the high-stability of the local clocks as described previously, the basestation 402 can switch between the different antennas 404, and measure the differences between the different received signals. Using a microcontroller unit (e.g., a processing device), the basestation 402 can recombine these signals and create a virtual steerable antenna. This steerable antenna can be used to "map" the different paths 413, 414 the signals take from the illuminator 408 to the basestation 402, essentially producing a signal-strength versus angle map. An object, like an object 411 or an object 412 reflects the signal from the illuminator 408 back to the basestation 402. The virtual steerable antenna will then give a higher signal strength in the direction of object 411, and another one in the direction of object 412. This increase in signal strength in those directions indicates an object, and thus the angle to the object can be determined. In addition to detecting an object, the speed and/or direction of movement can also be determined and tracked. In one example, the history of the object can also be stored in a memory.

[0036] The distances of the object(s) can be found by measuring the path length of the paths 413 and 414. The path length can be determined by using the steerable antenna, and employing a high-precision RF ranging measurement. Knowing the location of the illuminator 408, the basestation 402, and the angle to the object being detected, the object can be triangulated by finding the location given the path length. . The location is not necessarily unique, as there might exist mirror solutions. Adding multiple basestations, or

restricting the detection area can resolve these secondary locations, resulting in a unique object location.

[0037] This system can further track objects by measuring object locations over time. Assume a scene where only object 411 is present, and that the basestation 402 located that object with the aforementioned method. After a certain time, object 411 moves to object 412's location. The basestation 402 will now discover that object 411 is not at its old location anymore, as the signal strength disappeared from that previous angle, but instead there is now a stronger signal from the angle of path 414. Thus, the object 411 has been tracked to have moved from location 411 to location 412. In one example, the identity of the object can be determined, for example by measuring its size.

[0038] A ranging or radar system as illustrated in Figure 4A and/or 4B can also be used to find distance (using phase, similar to the examples previously described) and direction (angle). In one example, two or more basestations 402 can be used. In this case, using direction (angle) measurements can also use two or more basestations and using direction (angle) measurements, the location of a transmitting node can be triangulated.

[0039] In addition, the radios can hop to different frequencies to exploit the differences in propagation characteristics. The radio 408 can hop to different frequencies, exploiting the difference in propagation characteristics.

[0040] Conventional radar systems employ RF chirps or regular FM radar in order to detect passive RF reflecting objects. Embodiments may use a frequency-hopping high-resolution ranging system by observing the change in phase over multiple frequencies to achieve similar results. This provides a radar system using a high frequency-hopping high resolution ranging system.

[0041] Detecting passive RF reflecting components includes the detection of multi-path components in a ranging system. If the objective is to measure the distance between two systems, then multi-path is undesirable, as it will impact the accurate measurement of the distance. But multi-path comes from RF reflecting objects that are at different locations, and thus introduce new path lengths. If the location of the transmitter and receivers are known (for example either through a site survey, or by using an RF localization system), then the change in multi-path indicates the movement of RF reflecting objects, and thus, the system becomes an active personal radar system.

[0042] The personal radar system may include two or more transmit and receive pairs that are engaged in high-resolution ranging. The transmitter and receiver use one (or

more) narrow-band carrier frequency to synchronize their clocks, and then hop over one or more secondary non-continuous frequency carriers in one example. The different frequency carriers have a different wavelength from each other, and thus the receiver will measure a change in phase over the different frequencies. In addition, multi-path will impact the different frequencies differently. The receiving node can now go from the phase domain to a time domain plot by applying a Fast Fourier Transform (FFT) on the measured phases. The different multi-path components will now show up as different peaks in the result of the FFT. By keeping track of the different multi-path lengths, a system with only one transmitter and one receiver can map the change in the environment, and detect if new objects enter or leave the environment.

[0043] Combining the results of several transmit/receive pairs, and knowing the location of those pairs allows to trilaterate the actual reflector location. When more node pairs are present, the trilateration works better.

[0044] Figure 5 illustrates a method for performing ranging methods. Examples of ranging methods include, but are not limited to, determining a distance to an object, tracking motion of the object, determining a size of the object, identifying a location of a transmitter in a system, setting up a perimeter, performing radar in an area, or the like or any combination thereof.

[0045] The systems and methods discussed herein can use radio signals and the propagation paths between these radios. By synchronizing one radio with another radio, high accuracy ranging is achieved and changes in the detected path distance can indicate the presence of an object.

[0046] The method 500 begins by transmitting a signal in box 502. The signal is typically transmitted from one radio to another radio (the radios may be similarly configured). The signal enables the two radios to become highly synchronized and the radios synchronize in the box 504. This can be an ongoing process the continually synchronizes the signal transmitted from one radio and effectively reflected by another radio.

[0047] In box 506, measurements are performed. This can include determining a distance to the object, determining the presence of the object, determining the size and/or speed and/or direction of the object. As additional radios are added to the system or as antennas are added to a single radio, the capabilities of the system expand. As discussed previously, a virtual steerable antenna can be used to determine a direction of a detected object.

[0048] The ranging system 10 can be connected to a server computer over a network. The data collected by the ranging system 10 can then simply be transmitted for remote analysis.

[0049] Figure 6 illustrates an example of a multi-antenna setup for the calculation of a virtual steerable antenna. Multiple antennas can extend the capabilities of a personal radar system or of the examples disclosed herein. Combining the phase measured at each antenna allows to create a virtual steerable antenna that one can point into different directions.

[0050] An example of such an antenna array is depicted in Figure 6 In this configuration, antennas at locations Ant 1: 0/5.9, Ant 2: 5.2/3.0, Ant 3: 5.2/-3.0, Ant 4: 0/-5.9. Knowing the antenna location, a virtual antenna direction can be decided or determined. For example, the virtual antenna could be concentrated at the center 0/0 to the right (0 degrees). Given the wavelength frequency of the signal expected, the expected phase shift is for the different antennas can be calculated. In Figure 6, assuming a frequency of 2.5 GHz, a phase shift at Ant1 of 0, Ant2 of 2.7, Ant3 of 2.7, and Ant4 of 0 radians.

[0051] Knowing these values, these values can be subtracted from the phases measured during a high-resolution ranging operation. This effectively concentrates the antenna into the 0 degree direction. Figure 7 depicts the resulting virtual antenna pattern.

[0052] The advantage of a virtual antenna to a physically tuned phased array is that it is possible to look into all directions at the same time. For example, to "look" at a signal from the 45 degrees direction (see Figure 6), the phase shift can be calculated as Ant1: 2.2, Ant2: 3.0, Ant3: 0.8, and Ant4: -2.2 rad. Again, assuming this signal direction, and looking at the virtual antenna pattern results in the pattern shown on Figure 8.

[0053] Using the virtual antenna on one carrier frequency will provide peak power and angle information of the different multi-path components. However, using high resolution ranging, and hopping over multiple frequencies now allows for calculating the aforementioned FFT pointing into every single virtual antenna direction. This gives the additional information of multi-path distance.

[0054] A high-resolution ranging system with an RF switch to multiple antennas improves on conventional systems as angle, power, and distance for each multi-path component can be determined.

[0055] The innovation can now be combined with a multitude of different receive and transmit combinations with different antenna patterns (line, circle, cross, 2 dimensional

arrays, 3 dimensional cubes, etc). The antenna array can also be only on the transmitter, with a single antenna receiver, or on the receiver, with single antenna transmitter. Coordination can take care of the antenna switching, such that both ends can calculate the angle, distance, and power information of the multi-path components. Combining the information of multiple of these instantiations will allow for a robust radar system where RF reflecting objects can be localized and tracked.

[0056] One general advantage of this innovation is the friendliness to other users of the spectrum. As the frequency hopping doesn't have to be continuous, and can happen in a random fashion, other users can use the spectrum at the same time, without being impacted by the ranging procedure. The frequency hopping has also the advantage that specific frequencies of significant interference can be blocked out and hopped around.

[0057] Embodiments relate to ranging systems, including integrated ranging systems, which are capable of providing precise measurements with minimal bandwidth utilization. Embodiments provide an active-reflector, or transponder-type radio frequency ranging system in which phase and frequency coherency between master and slave devices can be precisely established during periods when measurement data is generated.

[0058] Embodiments enable discontinuous transmissions on multiple frequencies in order to optimize the use of available bandwidth, and to avoid channels which are either being used for unrelated transmissions or beset with noise.

[0059] Embodiments may provide a system of vernier measurement, whereby distances are measures in terms of an integer number of wavelengths plus a fraction of a wavelength that is determined by phase angle differences between two transmissions at different frequencies. Embodiments eliminate multi-path data from ranging calculations in some examples.

[0060] A high-resolution active reflector radio frequency ranging system includes at least two radio frequency transceivers (e.g., devices or nodes) in one example. One of the transceivers, acting as a master device, transmits a radio frequency signal burst to at least one other designated transceiver which acts as a slave device and active reflector. The slave device, actively matches the phase and frequency of the incoming signal and retransmits a signal at the matched phase and frequency. The slave can retain the phase and frequency data that it receives for some time before retransmitting the signal to the master. Within a network, master and slave designations are arbitrary, as those roles can be temporarily assigned as required. In fact, any device that initiates a ranging operation may be a master device. Each transceiver device, or node, may be assigned a unique

address. As the system supports a master with multiple slaves, point-to-point ranging, as well as point-to-multipoint ranging are enabled.

[0061] Operation of the high-resolution active reflector radio frequency ranging system will now be described. A first device (the acting master) transmits a radio signal burst asking for a ranging measurement. A second device (the acting slave) determines, either by default or by decoding a read range data packet, that it is the device from which the acting master is requesting the ranging measurement. Following a positive determination, the acting slave device measures phase and/or frequency drift of the incoming carrier wave and aligns its own oscillator, or clock, so as to achieve commonality of frequency and phase coherence with the incoming signal. Accuracy of oscillator alignment within the slave unit can be enhanced by transmitting multiple packets. The slave extracts phase and frequency data from each packet or determines the phase and frequency data using a phase information unit and averages the results in one example. The more packets that are received over time, the more accurate the calculation of the phase and frequency of the incoming carrier and the readjusting of the slave's internal clock or oscillator.

[0062] For an embodiment of the invention, an adaptive loop is employed to measure the phase of random incoming packets from the master and adjust the slave unit's oscillator so that it is phase coherent with the master unit's oscillator. No continuous wave transmission is required. In fact, the incoming RF signal can transmit multiple packets over multiple frequencies during different periods of time. The preferred embodiment of the invention may also incorporate a delta sigma phase lock loop, which maintains phase coherency of the of the slave unit's oscillator with the incoming signal, regardless of its frequency. Software onboard the slave unit is used to process incoming signal information and reconstruct it in order to maintain phase lock of the slave unit's oscillator with that of the master. This feature facilitates the implementation of frequency hopping, which is used in determining measurement of absolute distances between master and slave units.

[0063] One embodiment employs thermally-insulated reference oscillators, which need be neither highly stable over time, nor highly accurate at a rated temperature. However, the thermally-insulated oscillators are very stable over short periods of time commensurate with the periods required either by the master unit to send a burst signal and receive a burst signal in response, or for a slave unit to receive, analyze, and retransmit a signal burst. A thermally-insulated quartz crystal oscillator can be fabricated

by encapsulating the oscillator within an Aerogel® insulation layer. Aerogel is an ideal insulator for the application, as it has a coefficient of expansion that is virtually identical to that of quartz. Thus, in the case of a slave unit, its thermally-insulated reference oscillator is adjusted in frequency and phase to match those corresponding characteristics of the carrier wave received from the master unit, and the signal is retransmitted to the master. This process occurs over such a short period of time that any frequency drift in the thermally-insulated reference oscillator is negligible. A thermally-insulated reference oscillator (TIRO) has an advantage over an ovenized oscillator in terms of both cost and energy consumption. For battery powered devices, ovenized oscillators are highly impractical, as they must remain heated even when not in actual use in order to maintain stability. A 16 MHz thermally-insulated reference oscillator developed for the prototype high-resolution active reflector radio frequency ranging system has exhibited drift characteristics of less than 2.5 parts per 10 billion over a period of one second. Using this type of reference oscillator, the system is capable of ranging accuracies of better than 0.125 mm.

[0064] When the master unit transmits a radio frequency burst at a particular frequency to a slave unit, the signal is received by the slave unit, mixed with at least one local oscillator signal to create an error signal, which is fed to a digital control system consisting of a central processing unit or state machine. The output from the digital control system is fed to the reference oscillator, which controls the delta sigma phase lock loop, which in turn, controls the local oscillator. Because the individual bursts may be too short to generate an accurate determination of phase and frequency error, several bursts may be required to achieve optimum lock-on of the slave unit's reference oscillator. Thus, the TIRO retains the incoming phase and frequency information so that no matter on which channel the phase lock loop (PLL) is initially set, it derives its phase information from the reference oscillator. Thus, as the TIRO sets the phase and frequency of the PLL, the TIRO also effectively sets the frequency of the slave unit's transmitter and local oscillator.

[0065] There are two major problems associated with divide-by-integer phase lock loops. The first is that if sufficient bandwidth is allocated to the low-pass filter for a required modulation range, there is insufficient step resolution for both frequency generation and frequency modulation. The second is that if smaller frequency steps are utilized, there is insufficient band width at the low-pass filter. Fractional phase lock loops (also known as delta sigma phase lock loops) were developed to solve precisely these

problems. For example, in one embodiment of the invention, the fractional PLL generates 64 clock cycle phase relations (diffs) of the local oscillator for each cycle of the 16 Mhz reference oscillator. However, when a fractional PLL is used, the wave form edges of the generated signal may not directly align with the reference oscillator. This is especially problematic in a ranging system where synchronicity of phase relationship between transmitted and received signals is essential for meaningful distance measurements. In addition, if burst-mode operation or frequency-hopping is envisioned, or if the local oscillator–for the sake of circuit simplicity and minimal power consumption–is shared between transmit and receive functions, it is essential that the phase relationship between the transmitted and the received signal be establishable at all times. Embodiments may employ a phase relationship counter, which keeps track of the fractional time frames of the fractional phase lock loop as a function of the reference oscillator. The phase relationship counter provides absolute phase information for an incoming burst on any channel within the broadcast/receive band, thereby enabling the system to almost instantaneously establish or reestablish the phase relationship of the local oscillator so that it synchronized with the reference oscillator. The phase relationship counter, coupled with the thermally-insulated reference oscillator that ensures synchronicity of master and slave reference oscillators with negligible drift over short periods of time, allows the system to: minimize power consumption by cutting power to all but the reference oscillator and phase-relationship counter when it is not receiving or transmitting signals; utilize a common voltage-controlled local oscillator for both receive and transmit operations; and maintain predictable phase relationships between the local oscillator and the received signal for both discontinuous bursts at the same frequency and bursts at different frequencies (frequency hopping). Frequency hopping greatly enhances the usefulness of the system, as noisy channels can be avoided and the presence of multipath transmissions can be detected and eliminated from ranging calculations. Frequency hopping can be used with any radio technology where adequate bandwidth is provided.

[0066] The radio transceivers used to implement embodiments may employ quadrature phase modulation (QPM). Like all modulation schemes, QPM conveys data by changing some aspect of a carrier signal, or the carrier wave, (usually a sinusoid) in response to a data signal. In the case of QPM, the phase of the carrier is modulated to represent the data signal. Although the invention can be implemented by calculating the

phase shift of incoming data packets, it can also be implemented by demodulating the phase shift of the QPM data packets and using the resulting data to calculate range.

[0067] Vernier measurement techniques can be employed to enhance the accuracy of distance calculations for the present invention. Although vernier measurement has been used in FM radar systems, those systems typically relied on the simultaneous transmission to two or three signals at different frequencies. Embodiments, on the other hand, are unique in that vernier measurement can be implemented using randomly-selected frequencies within randomly-selected channels, which are transmitted during randomly-selected time intervals. This is because the phase relationship counter associated with the slave unit's fractional phase lock loop allows the phase relationship of any received signal to be established as a function of the slave reference oscillator which, for relatively short periods of time, can be considered synchronous with the master reference oscillator. Vernier measurements are made in the following manner: At least two signals, which are in phase at the point of transmission, are transmitted on different frequencies. A course measurement of distance can be made by measuring the phase difference between the signals. Two frequencies suffice if they will not share a common null point over the measured distance. For two-signal measurement, the bandwidth required depends on how accurately phase difference between the two signals can be measured. If measurement accuracy is 3 degrees, then bandwidth can be 0.833 percent of a 400 MHz band, which is a 3.33 MHz-wide band, or two channels that are 3.33 MHz apart. If measurement accuracy is 1 degree, then bandwidth can be 0.277 percent, or 1.11 MHz of the same band. Vernier ranging can be easily implemented on the band specified for wireless personal area network (WPAN) in North America under IEEE specification 802.15.4-2006, as it provides for thirty channels within a bandwidth of 902-928 MHz. If resolution of the receiver is less than 1 wavelength, phase of a received signal can be measured. A coarse measurement provides the number of wavelengths from the transmitter. By calculating absolute phase of the received signals, a fraction of a wavelength can then be added to the number of wavelengths from the transmitter for a more accurate calculation of range. In accordance with the present invention, it is possible to build a radio which can resolve the phase of received signals down to as little as 0.1 degree. With such a radio, phase differences between two adjacent frequencies within a narrow band can be easily resolved. In a band having a wavelength of 12 cm, theoretical resolution for ranging measurements can be better than .005 cm.

[0068] As previously stated, two frequencies can be used for ranging calculations up to a distance where the first null point occurs (i.e., both frequencies once again are momentarily in phase with one another. Two radio signals at different frequencies will, at some distance from the source, eventually null each other out, thereby making measurements beyond that point ambiguous. Thus, at least three frequencies are required to avoid ambiguous measurements. It is particularly helpful if the third frequency and one of the other two frequencies do not possess a divide by n relationship. Because the ranging system of the present invention utilizes a fractional phase lock loop with a phase relationship counter, random frequency hopping can be employed. When operating in the 902-928 MHz band, for example, the present invention can randomly employ any three or more of the 30 channels over time.

[0069] A major advantage of the present invention is that it addresses ranging inaccuracies caused by multipath transmissions. Although a multi-frequency ranging system works well if transmissions are made through a conductor or with a laser, a radio transmission through space generally results in reflections of the transmitted wave front, resulting in multipath transmission paths. As any path other than a straight line between the transmission and reception points is necessarily of greater distance, the signal which provides the correct phase shift for accurate ranging will be accompanied by signals that have traveled greater distances and which, therefore, display increased amounts of phase shift. The ranging systems constructed in accordance with the present invention transmit at least three radio signals at different frequencies and compare the distance-phase relationship between the different frequencies. The ranging system of the present invention utilizes a frequency-hopping approach to identify multipaths, select the shortest path, and calculate the distance of the shortest path. This is uniquely accomplished by constructing a table of measured phase and amplitude vs. frequency for at least three frequencies, which can be randomly selected in order both to avoid noisy channels and utilize only a small portion of available bandwidth at a given time. An analog-to-digital converter inputs phase-amplitude data into the table in frequency order. This data is subjected to a Fourier transform, preferably using a computer system to perform the calculations. The resulting beat-frequency peaks correspond to the various detected paths. The path having the lowest beat frequency is the shortest and actual distance between the system master and slave units. Using digital signal processing, if an inverse fourier transform is performed on the fourier transform data, the inverse fourier transform data can be used to calculate changes in the phase relationships for different frequencies,

and correct for distortion caused by multiple reflective paths as the master and slave units move with respect to one another.

[0070] Vernier distance measurement and multi-path detection and correction work in concert. The process is performed using the following sequence of steps. Firstly, using frequency hopping involving at least frequencies f1, f2 and f3 , phase differences between the various frequency pairs (i.e., between f1 and f2 , f1 and f3, and f2 and f3) are determined. Secondly, multipath correction is performed to eliminate multipath data and determine the integer number of wavelengths at one of those frequencies that separate the master and slave unit antennas for the shortest path. Thirdly, the system switches to a phase accumulation mode and calculates the absolute phase of each received frequency, thereby providing data for calculation of a partial wavelength that must be added to the integer number of wavelengths distance for an accurate measurement. Thus, the ranging system for the present invention provides high resolution range measurements with low bandwidth utilization. Although the transmission of multiple frequencies is required for the initial distance calculation, as long as the object doesn't move more than one-half wavelength between measurement calculations, it can be tracked with a single frequency. In a gaming system, for example, the use of a single frequency between antenna pairs once position acquisition is achieved will greatly reduce computational overhead.

[0071] The uniqueness of the present invention is grounded in synchronization of the reference oscillators of the master and slave units, regardless of frequency, and in the use of thermally-insulated reference oscillators and phase-lock loops to establish and maintain phase coherency between master and slave units across all frequencies. In addition, the use of frequency hopping enables not only the random selection of low-noise channels, but also multipath data elimination, thereby provide high-resolution measurements with minimal bandwidth requirements.

[0072] It will be understood by those having skill in the art that many changes may be made to the details of the above-described embodiments without departing from the underlying principles of the invention. The scope of the present invention should, therefore, be determined by the following claims.

[0073] In an illustrative embodiment, any of the operations, processes, etc. described herein can be implemented as computer-readable instructions stored on a computer-readable medium. E radio may include a processor and/or memory in order to process the signal and perform measurements as discussed herein. The computer-readable

instructions can be executed by a processor of a mobile unit, a network element, and/or any other computing device.

[0074] The foregoing detailed description has set forth various embodiments of the devices and/or processes via the use of block diagrams, flowcharts, and/or examples. Insofar as such block diagrams, flowcharts, and/or examples contain one or more functions and/or operations, it will be understood by those within the art that each function and/or operation within such block diagrams, flowcharts, or examples can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or virtually any combination thereof. Those skilled in the art will recognize that some aspects of the embodiments disclosed herein, in whole or in part, can be equivalently implemented in integrated circuits, as one or more computer programs running on one or more computers (e.g., as one or more programs running on one or more computer systems), as one or more programs running on one or more processors (e.g., as one or more programs running on one or more microprocessors), as firmware, or as virtually any combination thereof, and that designing the circuitry and/or writing the code for the software and or firmware would be well within the skill of one of skill in the art in light of this disclosure. In addition, those skilled in the art will appreciate that the mechanisms of the subject matter described herein are capable of being distributed as a program product in a variety of forms, and that an illustrative embodiment of the subject matter described herein applies regardless of the particular type of signal bearing medium used to actually carry out the distribution. Examples of a signal bearing medium include, but are not limited to, the following: a recordable type medium such as a floppy disk, a hard disk drive, a CD, a DVD, a digital tape, a computer memory, etc.; and a transmission type medium such as a digital and/or an analog communication medium (e.g., a fiber optic cable, a waveguide, a wired communications link, a wireless communication link, etc.).

[0075] Those skilled in the art will recognize that it is common within the art to describe devices and/or processes in the fashion set forth herein, and thereafter use engineering practices to integrate such described devices and/or processes into data processing systems. That is, at least a portion of the devices and/or processes described herein can be integrated into a data processing system via a reasonable amount of experimentation. Those having skill in the art will recognize that a typical data processing system generally includes one or more of a system unit housing, a video display device, a memory such as volatile and non-volatile memory, processors such as

microprocessors and digital signal processors, computational entities such as operating systems, drivers, graphical user interfaces, and applications programs, one or more interaction devices, such as a touch pad or screen, and/or control systems including feedback loops and control motors (e.g., feedback for sensing position and/or velocity; control motors for moving and/or adjusting components and/or quantities). A typical data processing system may be implemented utilizing any suitable commercially available components, such as those typically found in data computing/communication and/or network computing/communication systems.

[0076] Figures 9A, 9B and 10 will now be discussed with reference to embodiments 900A, 900B, and 1000, respectively, in which phased antenna arrays are used. In embodiments 900A and 900B, a transmitter 901 is provided with multiple antennas 908A-908C. These antennas may be said to form a phased array. The transmitter 901 may be configured to control operation of the antennas 908A-908C using a CPU 907 that controls switches 904A-904C. The transmitter CPU 907 may control which antennas are turned on at any given time, and may control which frequencies are used by those antennas. In some cases, the transmitter 901 may initialize different antennas at different times using different frequencies (i.e. the transmitter may implement frequency hopping). This will be explained in greater detail below.

[0077] Phased array antenna systems have traditionally been used to track radio signals and objects. These systems use a pattern of antennas that is combined to beam form the antenna for transmitting or receiving. In receive mode, combining can be done in the digital or RF domains. If the combining is done in the digital domain or in a computer system, many different combinations can be calculated using the same data, allowing many virtual antenna configurations to be processed at the same time. One example of such a system is the Very Large Array in New Mexico, which is used as an astronomical radio observatory. The same type of process can be used for transmitting multiple directional beams from the same array. This allows energy to be directed to different locations with different data from the same antenna.

[0078] When these types of systems are used inside a building or around multiple objects, reflections of the radio waves can cause errors making it difficult to find the location of the radio sources. This has made it a problem for indoor location systems and real-time location systems wherever there are multiple objects that reflect the signals. The embodiments described herein describe various ways to identify the direct and reflected signals for a localization system.

[0079] Embodiments of the present invention provide a system for a low-cost radio frequency direction and/or angle of arrival finding. The system uses phase angle techniques and frequency hopping to provide highly accurate direction and angle of arrival measurements. Embodiments of the invention use two or more transceivers, each having various antennas. Although receivers and transmitters are described herein, one skilled in the art will recognize that these receivers and transmitters can be single-function devices, or can be dual-function transceivers. In some embodiments, a transmitter has multiple antennas, and a receiver has a single antenna (e.g. in Figures 9A and 9B). In other embodiments, the transmitter has a single antenna and the receiver has multiple antennas (e.g. in Figure 10). Angle of arrival can be found ether by transmitting from one antenna to multiple receive antennas, or transmitting from multiple transmit antennas to one receive antennas. As the signals are transmitted between transmitter and receiver, phase array or phase difference techniques may be used to find a direction or angle to a radio source (i.e. a transmitter) including the angle of arrival.

[0080] Embodiments of the invention add to this by changing the frequency of the RF transmission and then repeating the phase measurement. The resulting phase data is phase- and gain-normalized, and then added to the phase array data from the previous measurements. As the different frequencies are summed, the faster moving phase data becomes filtered reducing the effects of the longer signal paths. This leaves the shortest path as the dominant path. Software processed by the CPU 907 (or by another local or remote computer system) then uses this filtered phase data to calculate a highly accurate angle of arrival. In some cases, a smaller number of antennas can be used by mathematically adjusting the measured phase.

[0081] In one embodiment, a radio system (e.g. 900A of Figure 9A) is provided which includes the following: a transmitter 901 with two or more antennas 908A-908C configured to broadcast a first signal (e.g. 902A) at a first frequency, and at a subsequent time, broadcast a second signal (e.g. 902B) at a second, different frequency. The radio system 900A further includes a receiver 906 that has an antenna 903 configured to receive the first and second signals 902A/902B broadcast from the antennas of the transmitter 901. Lastly, the radio system includes a processing unit 907 such as a CPU or programmable microcontroller. The processing unit 907 may be configured to perform the following: measure the amplitude and phase of the first signal 902A at the first frequency as received at the receiver 906, measure the amplitude and phase of the second

signal 902B at the second frequency as received at the receiver, and identify an angle or a direction to the transmitter using the measured amplitude and phase of each signal.

[0082] In some cases, the transmitter 901 may include a third antenna 908C that sends a third signal at a third, different frequency. As indicated by the ellipses, more than three antennas may be used in conjunction with the transmitter 901. The transmitter may use the CPU 907 to provide control instructions 905 to the switches 904A-904C to implement or bypass certain antennas. In some cases, for example, only antennas 908A and 908C may be used, while in other cases, antennas 908B and 908C may be used. Any combination of antennas is possible at any given moment in time. Similarly, each antenna may be used to transmit at a different frequency and, moreover, each antenna may broadcast at different frequencies at different points in time. Thus, for example, antenna 908A may broadcast at 100MHz at time point A, and may broadcast at 150MHz at time point B, and so on. Changing between different frequencies is referred to herein as frequency hopping. Frequency hopping allows the system 900A to generate an accurate direction and/or angle of arrival measurement.

[0083] In the embodiment 900A, the transmitter 901 is electrically connected to a CPU 907. This CPU can control the activation of antennas and control the frequencies used by those antennas. In the embodiment 900B of Figure 9B, the receiver 906 has its own CPU 907 that controls receiving operations. For instance, the receiver CPU 907 may control (905) when the receiver antenna 903 is activated, and may further control which frequency or frequencies it is tuned to. For example, at a first point in time A, the receiver antenna 903 may be tuned to the frequency of signal 902A from antenna 908A, whereas at a second point in time B, the receiver antenna may be tuned to the frequency of signal 902C from antenna 908C. Still further, the receiver antenna 903 may be configured to receive signals at different frequencies from the same antenna. Thus, at point in time A, the receiver antenna 903 may tune to signal 902B from antenna 908B which is transmitting at a first frequency (e.g. 100MHz), and then at a second point in time B, the receiver antenna 903 may tune to the same signal 902B from antenna 908B, but at a second, different frequency (e.g. 150MHz). Thus, the transmitter 901 or the receiver 906 may have an associated CPU that performs calculations and issues control commands. Although not illustrated in the drawings, it will be understood that at least in some embodiments, both the receiver and the transmitter may have associated processing units, or neither of the receiver and transmitter may have associated processing units. Different embodiments may require different electronic components or devices. Indeed, in at least

some cases, the CPU 907 may be communicatively connected with a data store, allowing the CPU to store information related to measured directions or angles of arrival.

[0084] In embodiment 1000 of Figure 10, the receiver 906 has multiple antennas 903A-903C, which may receive different signals from the transmitter 901. For example, a transmitter 901 with a single antenna 908 may transmit signals 902A, 902B and/or 902C at different points in time. The transmitter 901 may send the signals using different frequencies at different points in time. As in the embodiments 900A and 900B above, frequency hopping may be used in embodiment 1000 to determine an angle or direction to a signal source. For example, as shown in Figure 11, an angle of arrival Ø (1110A) may be determined by the receiver 906 using frequency hopping. The receiver switches 906 between antennas 908A, 908B and 908C (and/or potentially other antennas) to measure the phase and amplitude of each signal.

[0085] The receiver 906 thus receives each signal and measures its phase and amplitude. Phase difference techniques may be used to find an angle such as the angle of arrival. For example, receiver 906 may receive signal 902A and determine an angle Ø (1110A) relative to itself (i.e. a fixed reference point) and the signal source (e.g. antenna 908A), or relative to itself and another signal source (e.g. antenna 908B). Similarly, receiver 906 may receive signal 902B and determine an angle Ø' (1110B) relative to itself and the signal source (e.g. antenna 908B), or relative to itself and another signal source (e.g. antenna 908C). Each phase and amplitude measurement may be stored in a data store, along with a determined angle of arrival for the signal. After these initial phase and amplitude measurements and angle determinations have been made, the system may change the frequency of the RF signals and repeat the phase and amplitude measurements. Angle calculations may also be reprocessed to fine tune the determined angles or correct errors in previous calculations.

[0086] Although shown in Figure 11 as having three antennas, the transmitter (Tx) may have substantially any number of antennas. Each of the antennas may broadcast at the same frequency, or at different frequencies. In some cases, the antennas (e.g. antenna 908C) may broadcast a signal at a changing frequency. For instance, as shown in Figure 12, antennas 1, 2, 3...n are shown for a first frequency (1201A), and for a second frequency (1201B). Charts 1202A and 1202B illustrate which antenna is currently transmitting at that frequency. Thus, as can be seen in Figure 12, antenna 2 is broadcasting (or receiving) at frequency 1 (1201A), and antenna 3 is currently broadcasting (or receiving) at frequency 2 (1201B). This chart may be extended to show

any number of frequencies, as indicated by the ellipses. Moreover, while only one antenna is shown as using a frequency at a given time, it will be recognized that multiple more antennas may be used to simultaneously broadcast/receive on the same frequency. Still further, in cases where frequency hopping is used, the charts 1202A and 1202B indicate, for one instant in time, which antenna is using which frequency. The frequencies may change, and thus the charts will be updated to reflect the changes. For instance, if CPU 907 of Figure 9 instructed antenna 2 to stop broadcasting/receiving on frequency 1 and switch to frequency 2, the "X" would be removed from the "ANT 2" box in 1202A and would be added to "ANT 2" of 1202B. Thus, the charts 1202A/1202B may be updated over time, and may show antenna and frequency usage for any one given point in time.

[0087] As each signal is received, the receiver (or more specifically, the CPU 907 at the receiver 906) measures the amplitude and phase of each of the signals broadcast at the various frequencies. The amplitude and phase measurements allow the CPU 907 to identify the angle and/or the direction to the transmitter. Thus, as shown in Figure 11, the receiver may receive signals 902A, 902B and 902C from respective antennas 908A, 908B and 908C. The CPU 907 may calculate the amplitude and phase of signal 902A, 902B and 902C and store the calculated results. The CPU 907 may also determine the phase of signals 902A, 902B and 902C and likewise store the results. The amplitude and phase for each of the three signals may be determine to determine the direction to each individual antenna on the transmitter, or to the transmitter as a whole. The receiver may use the measured and calculated values to identify an angle Ø (1110A) from the receiver antenna 903 to the transmitter antenna 908A. The receiver may also use the measured and calculated values to identify an angle Ø' (1110B) from the receiver antenna 903 to the transmitter antenna 908C. The angle or direction to antenna 908B may likewise be determined individually or relative to signals 902A and 902C.

[0088] In some embodiments, the processing unit (e.g. 907) may be configured to correct for errors using the different frequencies. For example, as shown in Figure 13, antennas (1301) may be shown as 1, 2, 3, n for each frequency (1302). Each antenna may thus use frequency 1 for a period of time, frequency 2 for a period of time, etc. As each antenna hops between frequencies, the CPU 907 may use the inputs from each of the received signals to correct for errors in the direction or angle of arrival determinations. Thus, over time, as signals are received at different frequencies, amplitude and phase measurements will improve, leading to more accurate determinations of direction and

angle of arrival for each signal. The signals (902A-902C) may be sent in continuous streams or in bursts. RF bursts may be transmitted to the receiver 906 using at least one of the transmitter antennas of Figure 9A, for example.

[0089] Additionally or alternatively, the RF burst may be transmitted to the receiver 906 by a plurality of the transmitter antennas. The transmitter may be configured to switch antennas as the transmitter transmits the RF burst. Once the signals from the plurality of antennas have been received, and the amplitude and phase have been measured, the signal frequencies are changed to different frequencies. Then, subsequent determinations of angle or direction to the transmitter performed by the processing unit 907 are determined based on the changed, different frequencies. In this manner, frequency hopping using multiple transmitter antennas (e.g. Figures 9A and 9B), or using multiple receiver antennas (e.g. Figure 10), allows accurate amplitude and phase measurements to be determined for each signal. This then allows the system to calculate highly accurate direction and angle of arrival measurements. These direction and angle of arrival measurements can be used in substantially any environment, even an indoor environment with multiple objects that cause signal interference.

[0090] Turning now to Figure 14, a method 1400 is provided for finding an angle or a direction to a radio source (e.g. a transmitter). The method 1400 includes broadcasting two or more signals at different frequencies from two or more antennas at a transmitter (1410). Thus, as illustrated in Figure 9A, a transmitter 901 broadcasts signal 902A from antenna 908A, signal 902B from antenna 908B, and signal 902C from antenna 908C. Signals 902A-902C may each be broadcast at different frequencies. Thus, in the embodiment 900A of Figure 9A, three antennas 908A-908C may each be transmitting at three different frequencies. Moreover, each antenna may change frequencies over time, such that each antenna transmits at different frequencies at different time periods.

[0091] Method 1400 next includes receiving the two or more signals broadcasted at different frequencies at a receiver (1420). Receiver 906 may receive the signals 902A-902C broadcasted at the various frequencies, and then measure each signal's amplitude and phase as received at the receiver (1430). As shown in Figure 9B, the receiver 906 may be connected to a CPU 907 that is capable of determining signal phase and amplitude for each received signal. The signal phase and amplitude may change over time as different frequencies are used. When two or more signals are transmitted at different frequencies, this allows the CPU 907 to determine a shortest path to the radio source (e.g. transmitter 901). For instance, as the multiple frequencies are received, they may be

summed to identify the faster moving phase data. This phase data then becomes filtered, reducing the effects of the longer paths. This leaves the shortest path as the dominant path.

[0092] Using this determined shortest path, the CPU 907 can identify or derive the direction to the radio source or angle of arrival from the radio source. Indeed, as mentioned above, using multiple frequencies allows the receiver CPU to find which path is the shortest path because the phase shifts faster for the longer paths when the frequency is changed. The CPU may thus use phase and amplitude measurements taken at different frequencies to determine a direction and/or angle of arrival vis a vie a radio source (1440). The distance to the transmitter may also be determined along each angle path using identified phase shifts in the various signals. Accordingly, not only can direction and angle of arrival be determined using frequency hopping, distance to the radio source may also be determined using the measured phase shifts.

[0093] In some embodiments, the CPU 907 may be configured to access phase measurements for each signal and normalize each signal for phase and gain. After this normalization operation has been performed, the CPU may add the normalized signals to a phase array data structure. The phase array data structure may include previously stored measurements, and may also include subsequent phase measurements. The phase array data structure(s) may be stored in a local or remote data store, and may be used in current or future direction, angle or distance calculations. In some cases, a certain frequency or certain set of specified frequencies may be used by the transmitter to identify the range of the antennas in the phase array. For example, by performing a fast Fourier transform on the signal, the CPU 907 can determine the range of each signal path that can be resolved by the system. In cases where fewer antennas are used, the CPU may be configured to mathematically compensate for the lesser amount of antennas, and still accurately determine a direction or angle of arrival relative to a radio source.

[0094] In another embodiment, a radio system is provided (e.g. the radio system 1000 of Figure 10). The radio system 1000 includes a transmitter antenna 908 configured to broadcast a first signal (902A) at a first frequency for a specified amount of time, broadcast a second signal (902b) at a second, different frequency for a specified amount of time, and broadcast a third signal (902C) at a third, different frequency for a specified amount of time. The radio system 1000 also includes two or more receiver antennas (903A-903C) configured to receive the first, second and third signals. Still further, the radio system 1000 includes a processor 907 configured to find an angle and a distance of

multiple radio paths to the antenna. In this embodiment, the CPU may thus be configured to determine not only a direction to a source or an angle of arrival from the source, the CPU may also be configured to determine a distance to the source. Radio frequency (RF) bursts are transmitted by the transmitter 901 using the antenna 908. The receiver 906 switches between its multiple antennas to measure the phase and amplitude of the received signals.

[0095] One receiver antenna may receive signals transmitted at different frequencies at different times, or multiple receiver antennas may each receive signals transmitted at different frequencies simultaneously. Although in Figure 10, three receiver antennas are shown, where receiver 903A receives signal 902A, receiver 903B receives signal 902B, and receiver 903C receives signal 902C, it will be recognized that more or fewer receiver antennas may be used. The CPU 907 may use control signals 905 to control the receiver antennas so that each is operating at designated times, and each is receiving on a specified frequency. The CPU may then take the received signals at different frequencies, determine a shortest path using phase and amplitude measurements, and identify a direction or angle of arrival vis a vie the transmitter 901.

[0096] From the foregoing, it will be appreciated that various embodiments of the present disclosure have been described herein for purposes of illustration, and that various modifications may be made without departing from the scope and spirit of the present disclosure. Accordingly, the various embodiments disclosed herein are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

CLAIMS

We claim:

1. A radio system, comprising:

a transmitter with two or more antennas configured to broadcast a first signal at a first frequency, and at a subsequent time broadcast a second signal at a second, different frequency;

a receiver having an antenna configured to receive the first and second signals broadcast from the two or more antennas of the transmitter; and

a processing unit configured to perform the following:

measure the amplitude and phase of the first signal at the first frequency as received at the receiver;

measure the amplitude and phase of the second signal at the second frequency as received at the receiver; and

identify an angle or a direction to the transmitter using the measured amplitude and phase of each signal.

2. The radio system of claim 1, wherein the receiver switches between the first and second antennas to measure the phase and amplitude of each signal.

3. The radio system of claim 1, wherein the transmitter includes a third antenna configured to broadcast a third signal at a third, different frequency at a time subsequent to the broadcasting of the second signal.

4. The radio system of claim 3, wherein the processing unit measures the amplitude and phase of the third signal broadcast at the third frequency as received at the receiver.

5. The radio system of claim 4, wherein the processing unit identifies the angle or the direction to the transmitter using the measured amplitude and phase of the first, second and third signals.

6. The radio system of claim 5, wherein the processing unit is further configured to correct for errors using the first, second and third frequencies.

7. The radio system of claim 1, wherein a radio frequency (RF) burst is transmitted to the receiver by at least one of the transmitter antennas.

8. The radio system of claim 7, wherein the RF burst is transmitted to the receiver by a plurality of the transmitter antennas, the transmitter being configured to switch antennas as the transmitter transmits the RF burst.

9. The radio system of claim 1, wherein upon measuring the first and second signals from the first and second antennas, the frequencies of signal are changed to different frequencies.

10. The radio system of claim 9, wherein subsequent determinations of angle or direction to the transmitter performed by the processing unit are determined based on the changed, different frequencies.

11. A method for finding an angle or a direction to a radio source, comprising:

broadcasting two or more signals at different frequencies from two or more antennas at a transmitter;

receiving the two or more signals broadcasted at different frequencies at a receiver;

measuring each signal's amplitude and phase as received at the receiver; and

identifying an angle or a direction to the radio source using the measured amplitude and phase of each signal.

12. The method of claim 11, wherein the two or more signals broadcasted at different frequencies allow a shortest path to be determined, from which the angle or direction to the radio source is derived.

13. The method of claim 12, wherein the distance to the transmitter is determined along each angle path using identified phase shifts in the two or more signals.

14. The method of claim 11, further comprising:

accessing phase measurements for each signal;

normalizing each signal for phase and gain; and

adding the normalized signals to a phase array data structure that includes one or more previous and subsequent phase measurements.

15. The method of claim 11, wherein a specified set of frequencies are used by the transmitter to identify a range of at least one of the antennas in the phase array.

16. The method of claim 11, wherein mathematical adjustments are made to at least one signal's phase, allowing fewer antennas to be used.

17. A radio system, comprising:

a transmitter antenna configured to broadcast a first signal at a first frequency for a specified amount of time, broadcast a second signal at a second, different frequency for a specified amount of time, and broadcast a third signal at a third, different frequency for a specified amount of time;

two or more receiver antennas configured to receive the first, second and third signals; and

a processor configured to find an angle and a distance of multiple radio paths to the antenna.

18. The radio system of claim 17, wherein a radio frequency (RF) burst is transmitted by the transmitter over the antenna.

19. The radio system of claim 18, wherein the receiver switches between the two or more antennas to measure the phase and amplitude.

20. The radio system of claim 17, further comprising at least a third receiver antenna that is configured to receive the third signal, such that the first receiver antenna receives the first signal, the second receiver antenna receives the second signal, and the third receiver antenna receives the third signal.

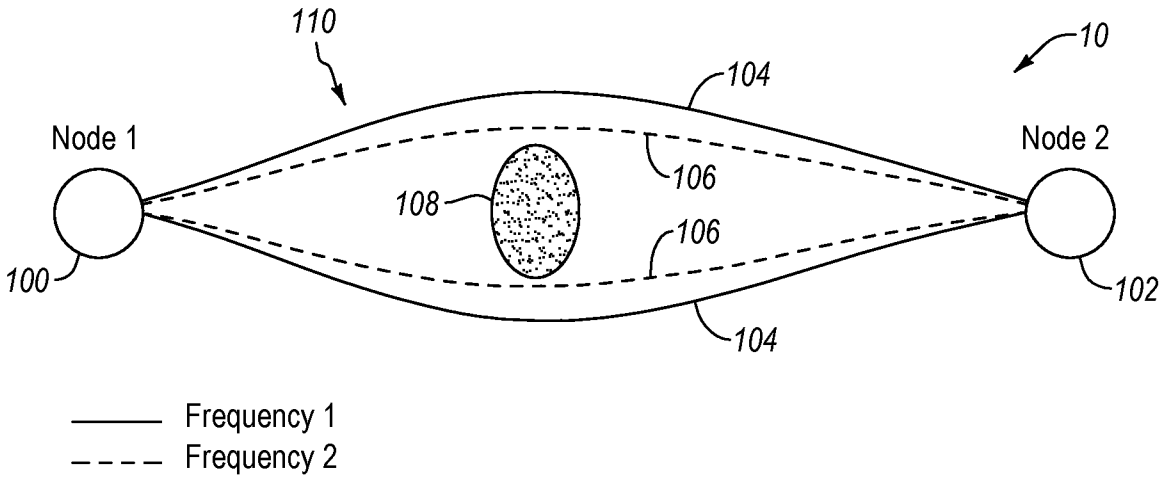

110
10
104
Node 1
Node 2
106
108
106
100
102
104
Frequency 1
Frequency 2

FIG. 1

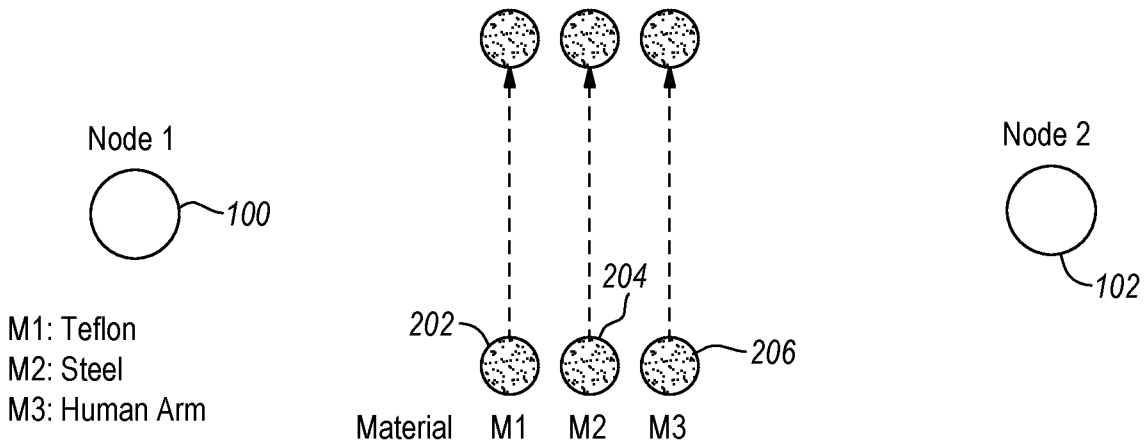

Node 1
100
M1: Teflon
M2: Steel
M3: Human Arm
204
202
206
Material
M1
M2
M3
Node 2
102

FIG. 2

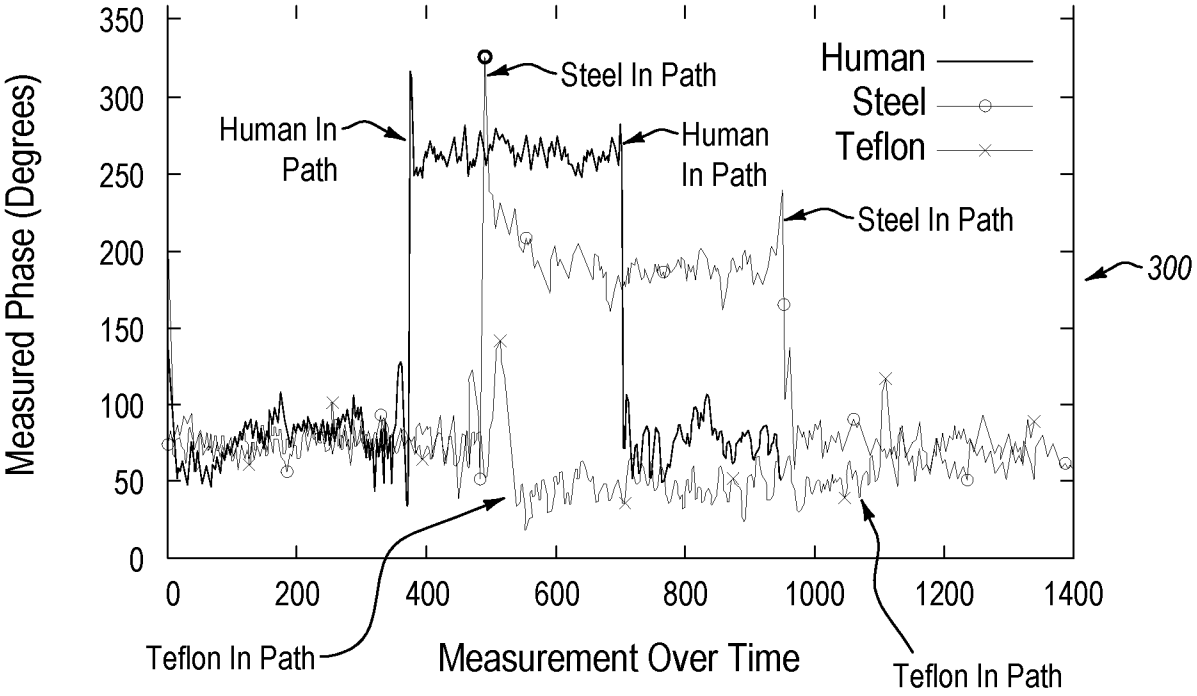

Measured Phase (Degrees)
350
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
Measurement Over Time
Human
Steel
Teflon
Steel In Path
Human In Path
Human In Path
Steel In Path
300
Teflon In Path
Teflon In Path

FIG. 3

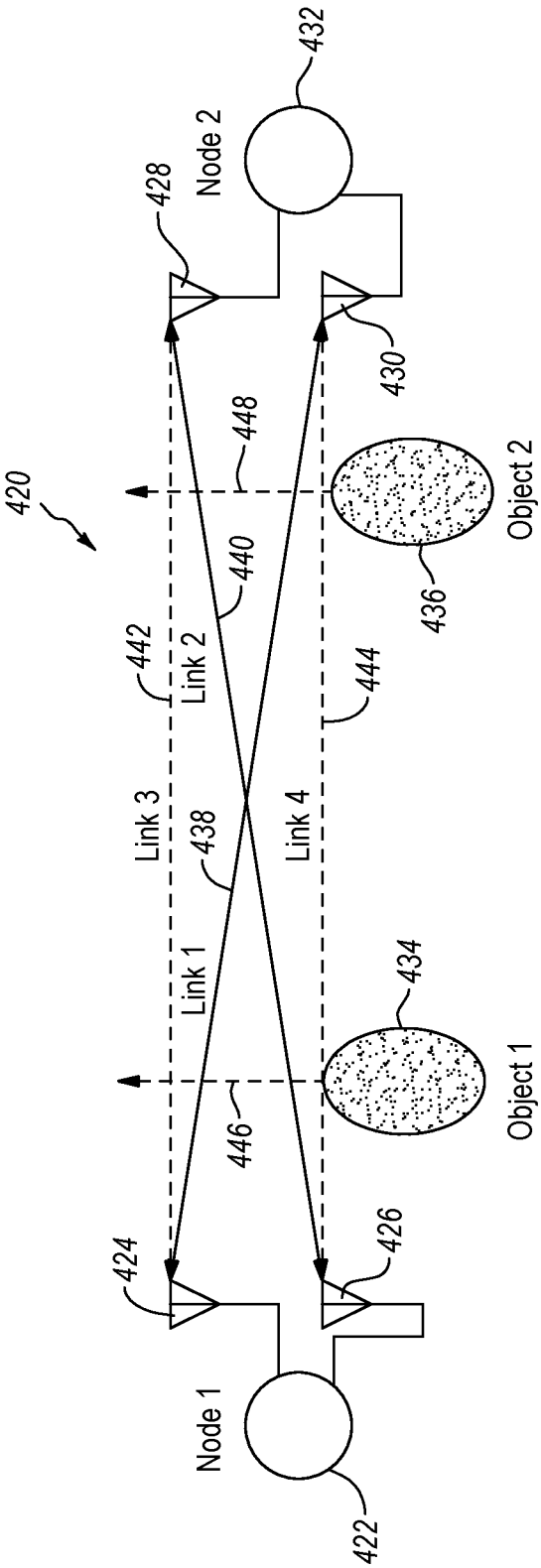

420
Node 1
422
424
426
Node 2
428
430
432
Object 1
434
Object 2
436
438
440
442
444
446
448
Link 1
Link 2
Link 3
Link 4

FIG. 4A

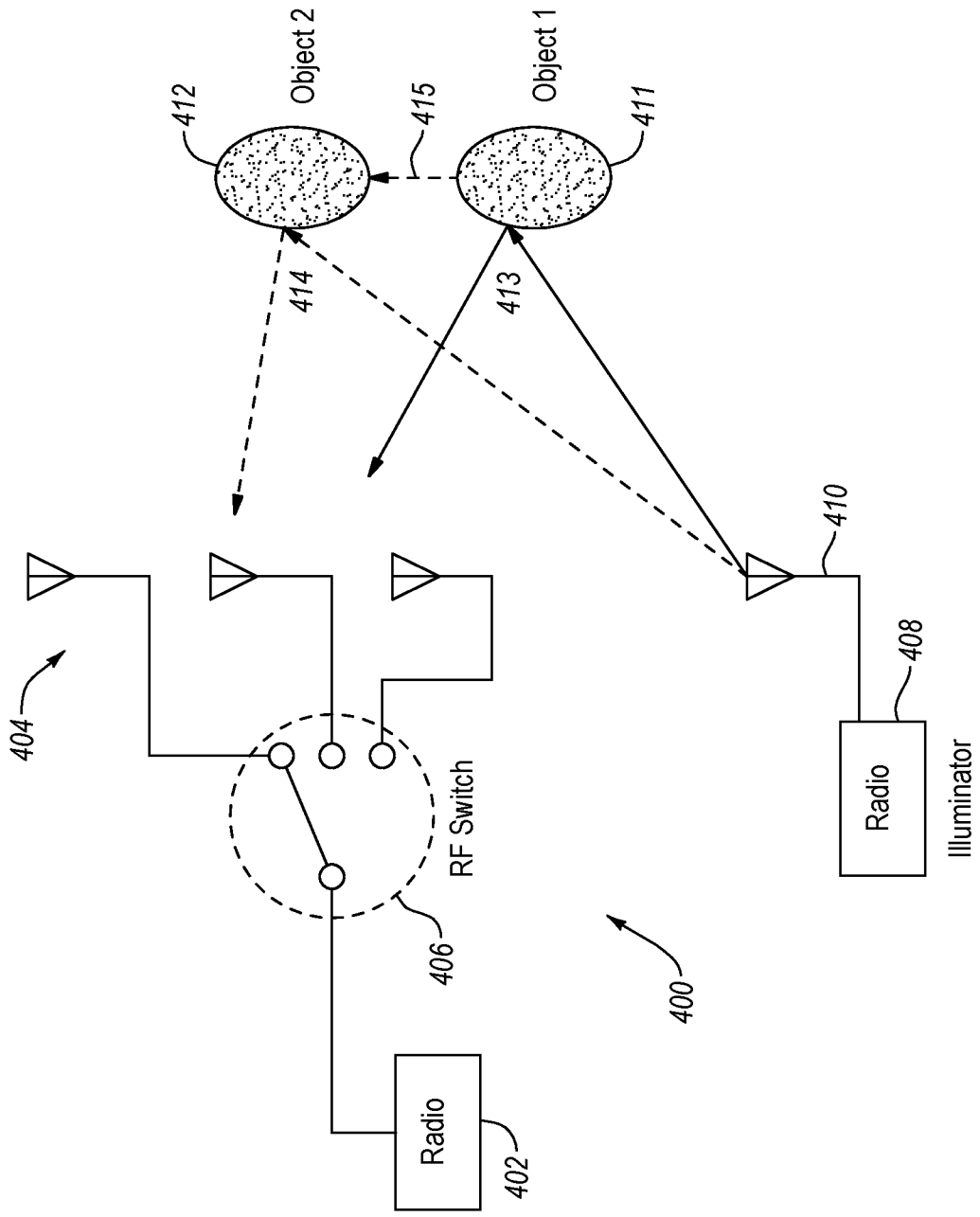

Object 2
Object 1
412
415
411
414
413
410
404
408
RF Switch
406
Radio
Illuminator
400
Radio
402

FIG. 4B

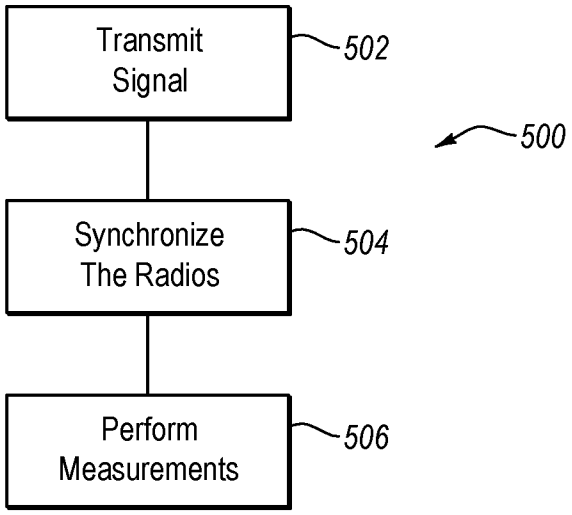

Transmit Signal
502
500
Synchronize The Radios
504
Perform Measurements
506

FIG. 5

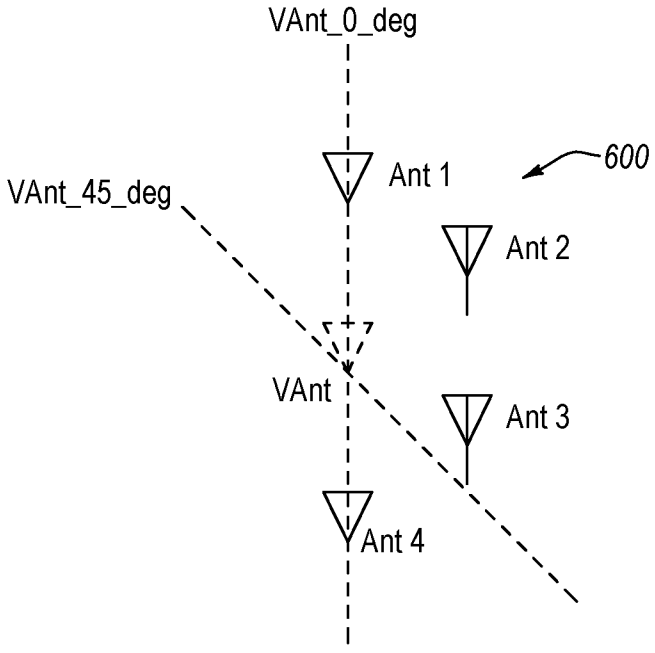

VAnt_0_deg
600
Ant 1
VAnt_45_deg
Ant 2
VAnt
Ant 3
Ant 4

FIG. 6

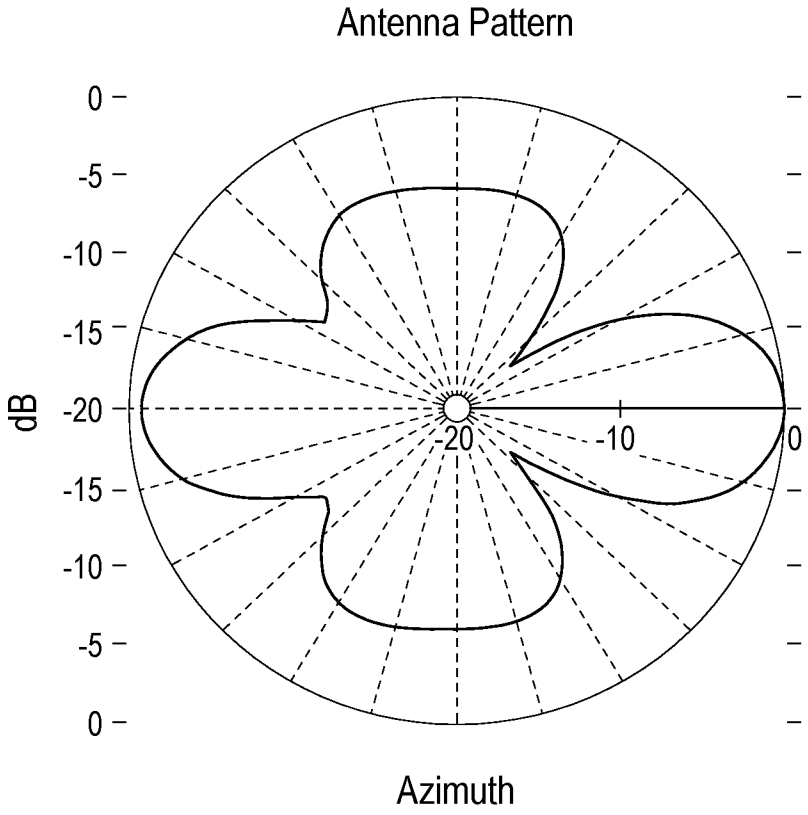

Antenna Pattern
0
-5
-10
-15
dB
-20
-15
-10
-5
0
-20
-10
0
Azimuth

FIG. 7

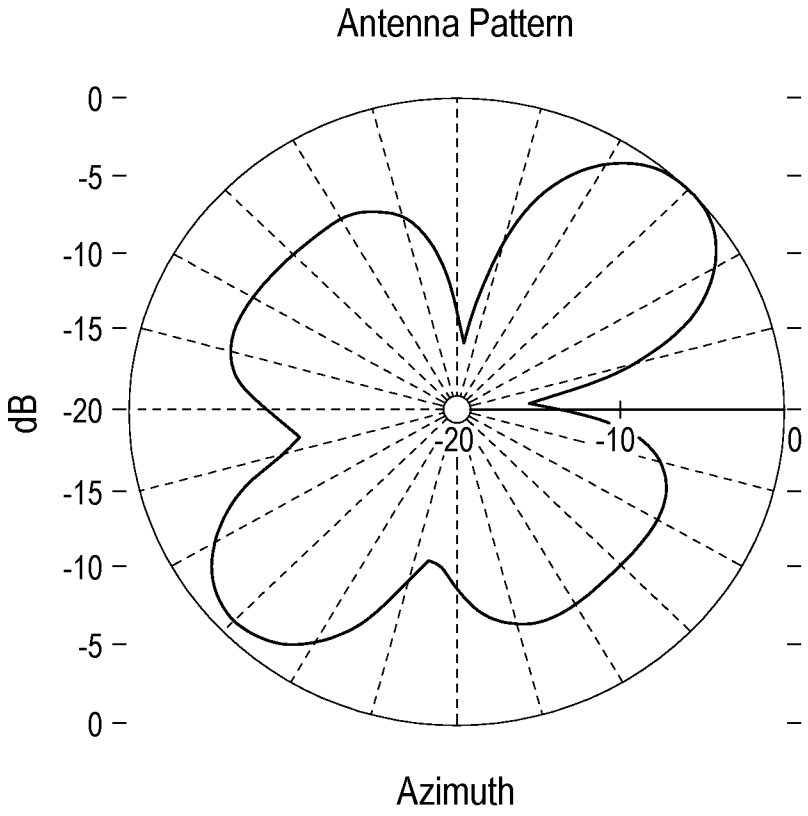

Antenna Pattern
0
-5
-10
-15
dB
-20
-15
-10
-5
0
-20
-10
0
Azimuth

FIG. 8

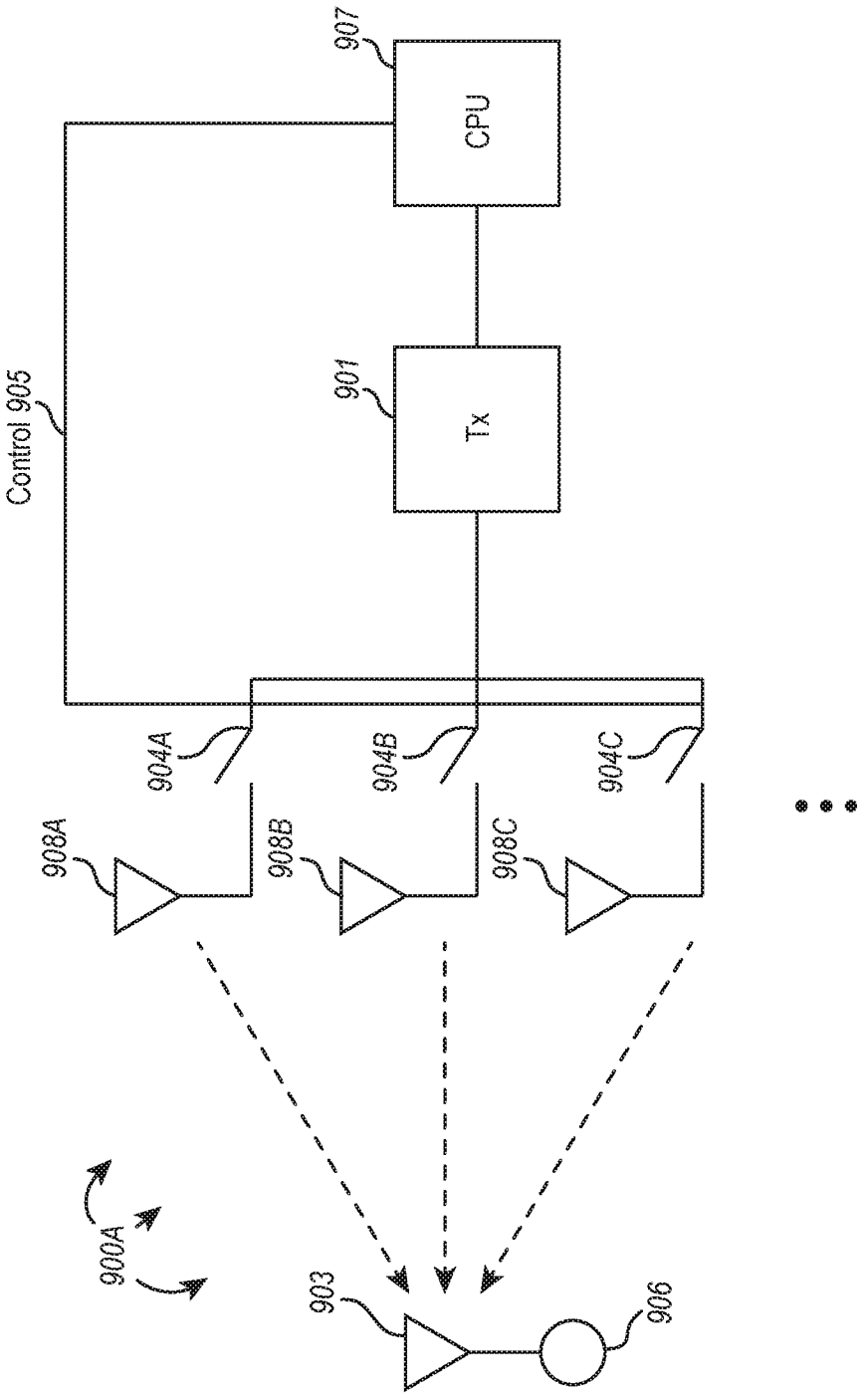

907
CPU
901
Tx
Control 905
904A
904B
904C
908A
908B
908C
900A
903
906

FIG. 9A

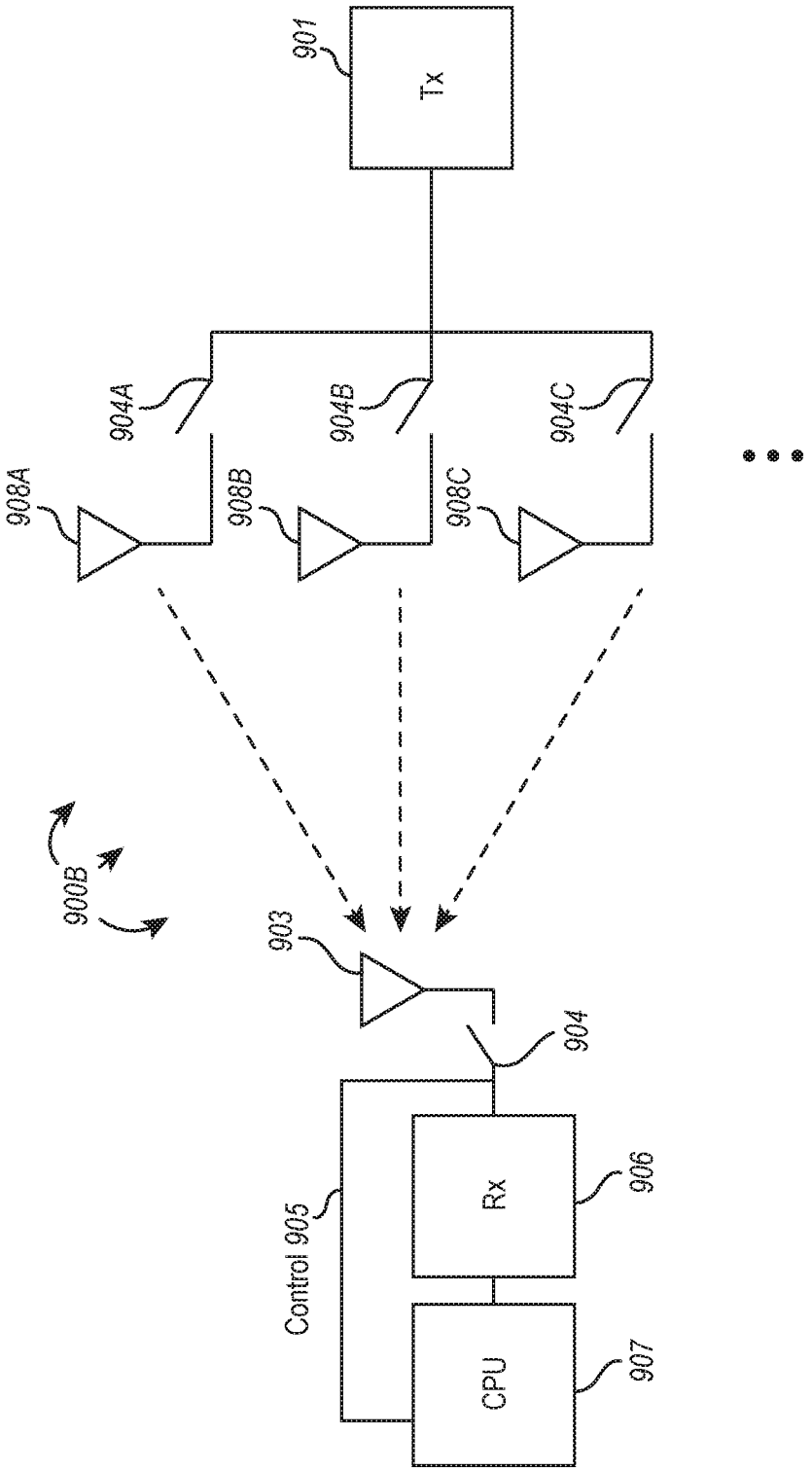

901
Tx
904A
904B
904C
908A
908B
908C
900B
903
904
Control 905
Rx
906
CPU
907

FIG. 9B

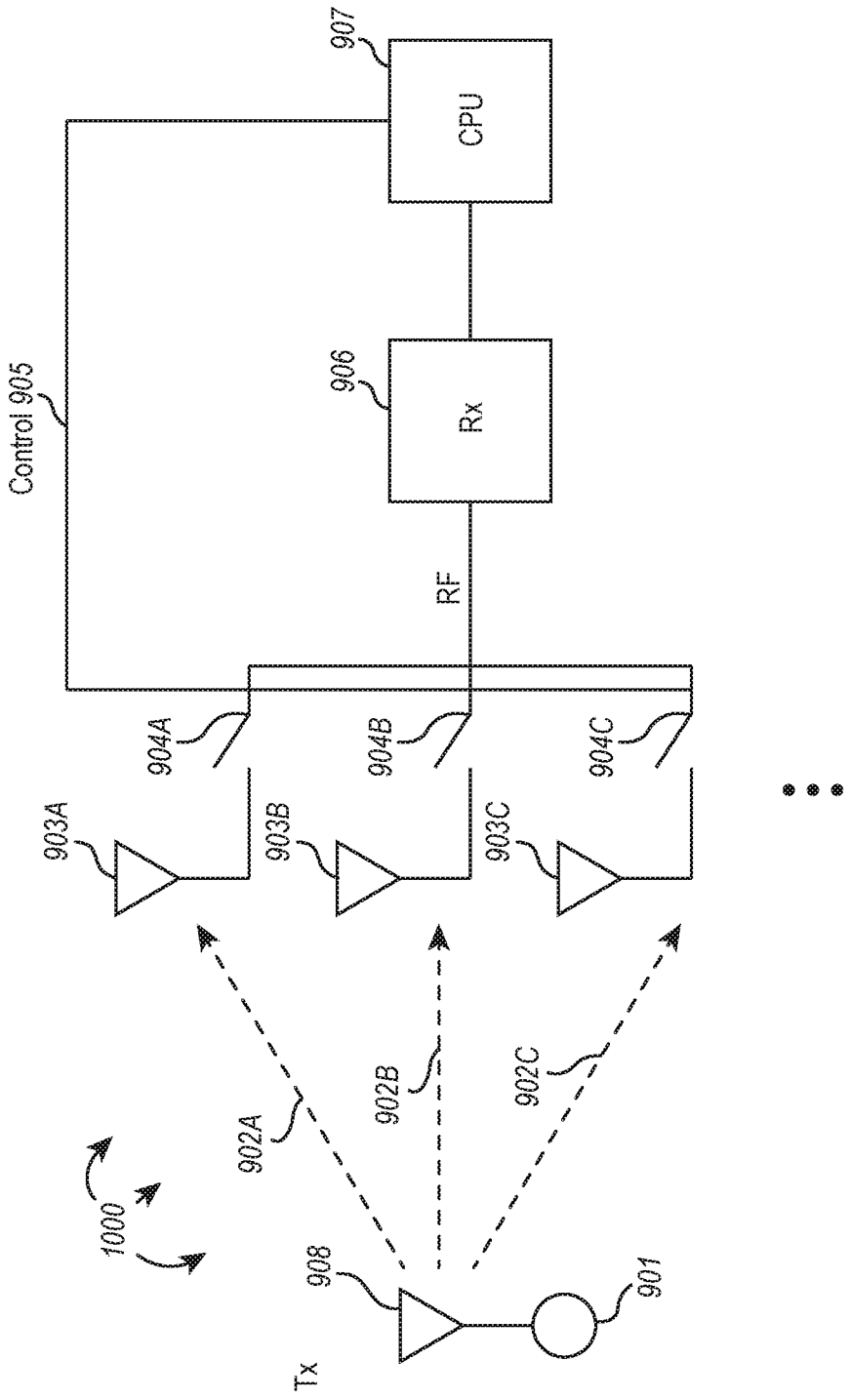

907
CPU
906
Rx
Control 905
RF
904A
904B
904C
903A
903B
903C
902A
902B
902C
1000
908
901
Tx

FIG. 10

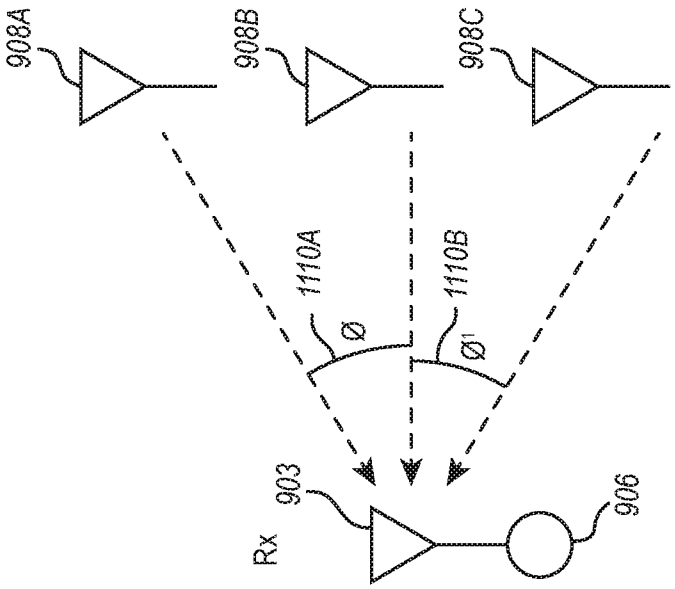


FIG. 11

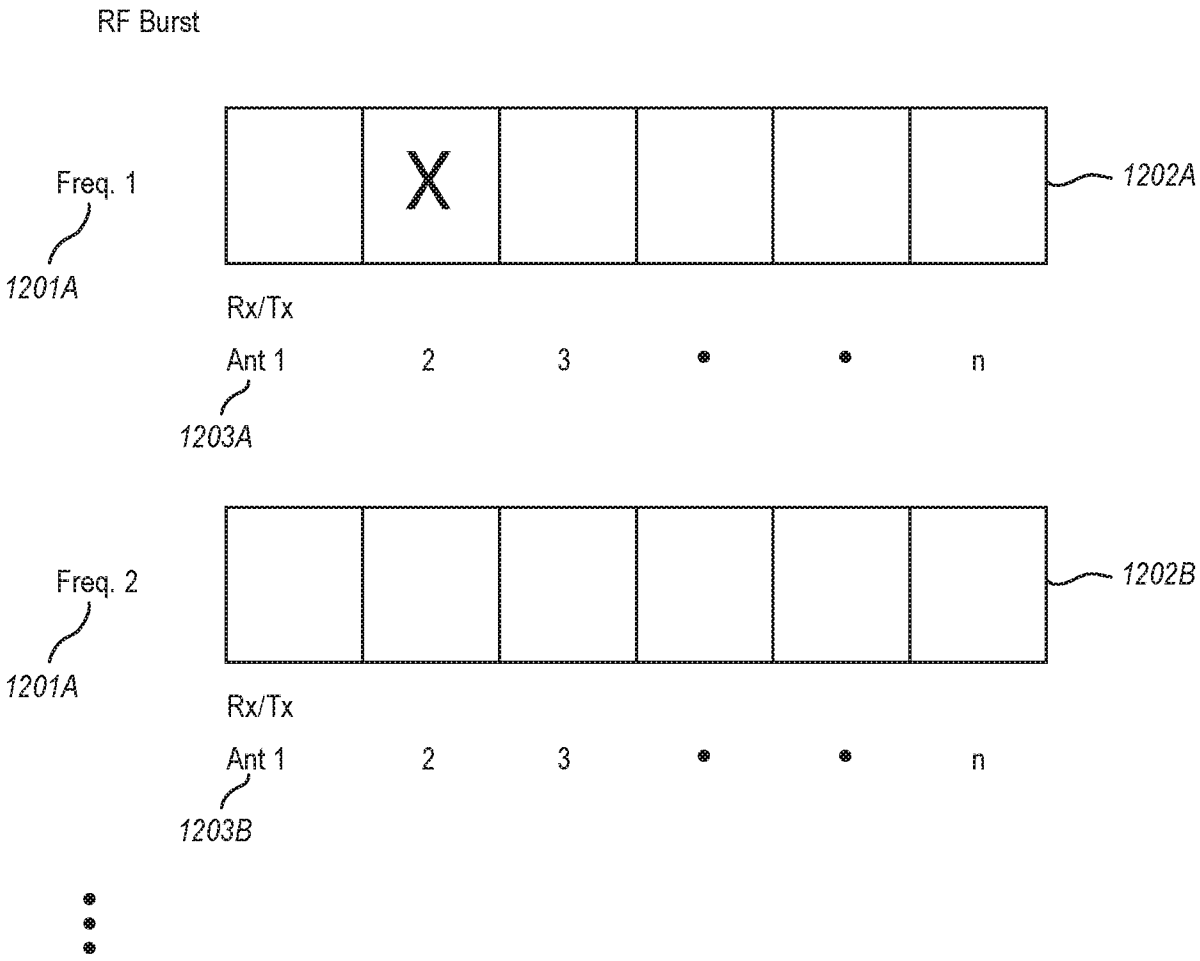

RF Burst
Freq. 1
1201A
X
1202A
Rx/Tx
Ant 1
2
3
n
1203A
Freq. 2
1201A
1202B
Rx/Tx
Ant 1
2
3
n
1203B

FIG. 12

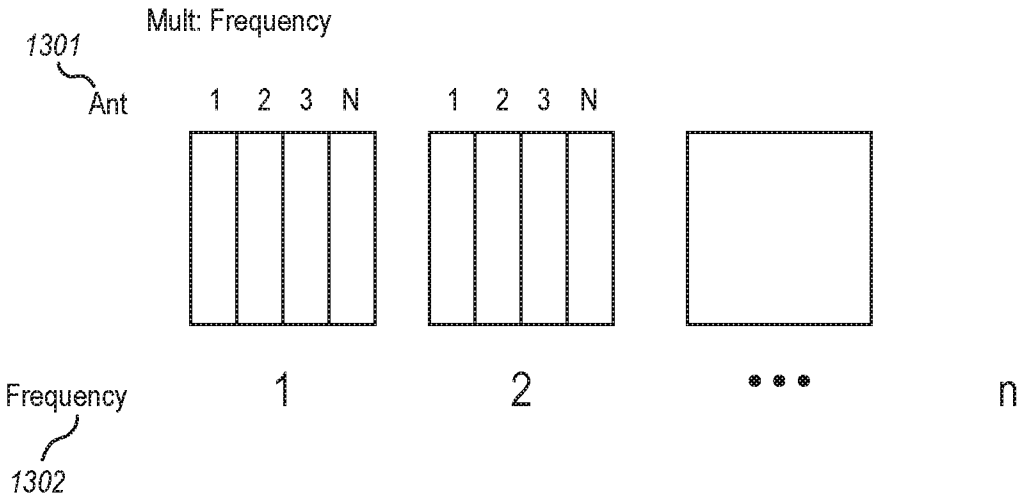

Mult: Frequency
1301
Ant
1 2 3 N
1 2 3 N
Frequency
1
2
n
1302

FIG. 13

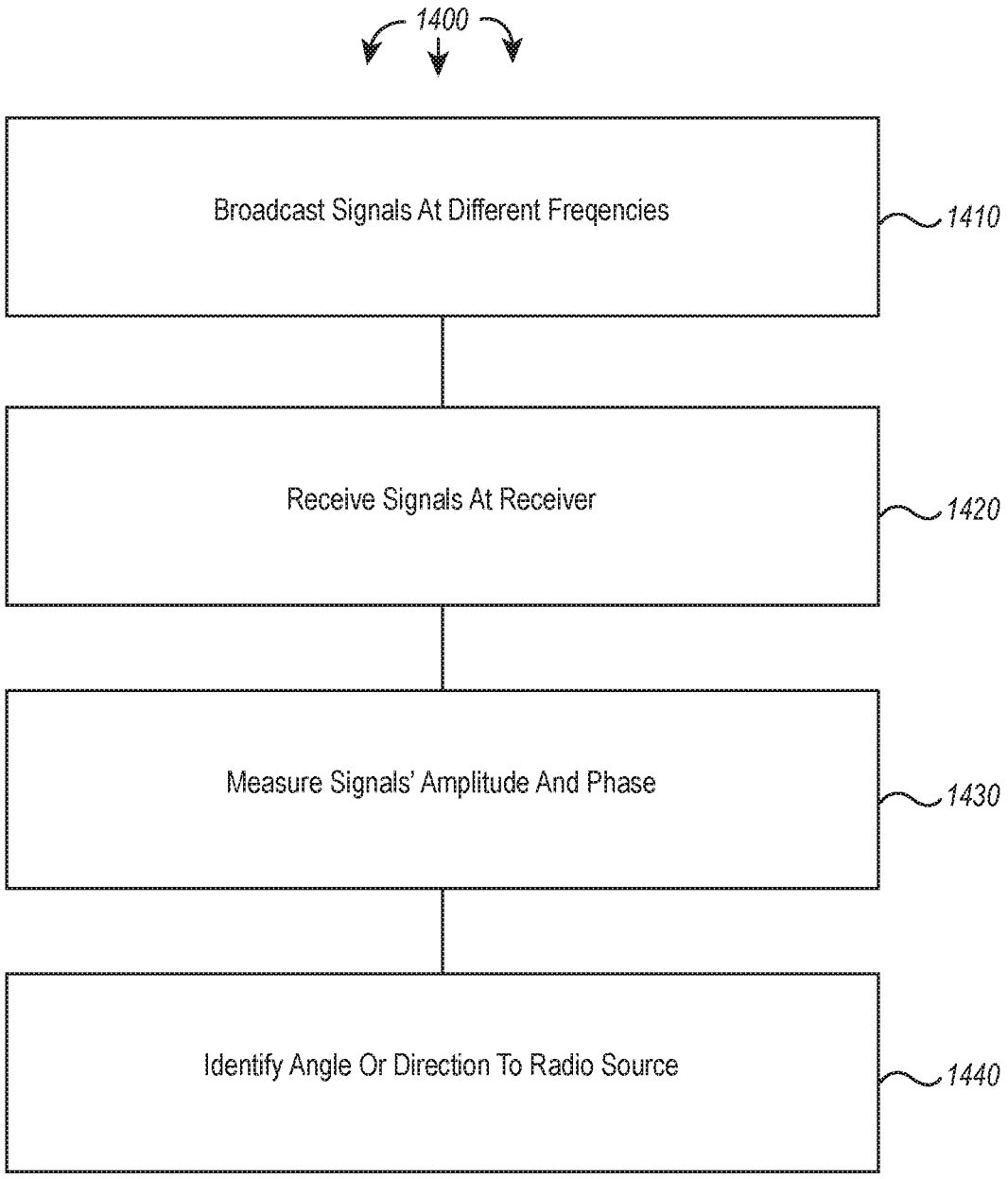

1400
Broadcast Signals At Different Freqencies
1410
Receive Signals At Receiver
1420
Measure Signals' Amplitude And Phase
1430
Identify Angle Or Direction To Radio Source
1440

FIG. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US18/12344

A. CLASSIFICATION OF SUBJECT MATTER
IPC - G01S 13/02, 13/06, 13/48 (2018.01)
CPC - G01S 13/003, 13/02, 13/06, 13/48, 13/588, 13/878

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/0320335 A1 (GREINA TECHNOLOGIES, INC.) October 30, 2014; FIG. 1, paragraphs [0024]-[0031], [0036], [0037], [0040], [0042]-[0047], [0057], [0063], [0068], [0077], [0081], claims	1, 2, 7, & 9-16
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Y	11, 14, 16, 17	3-6, 8, & 17-20
Y	US 2016/0131742 A1 (ROBERT BOSCH GMBH) May 12, 2016; FIG. 1, paragraphs [0013], [0039]-[0042], [0078], [0090]	3-6, 8, & 17-20
A	US 2016/0077204 A1 (GREINA TECHNOLOGIES, INC.) March 17, 2016; entire document	1-20

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
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"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 February 2018 (20.02.2018)	19 MAR 2018
Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (January 2015)