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Thommana et al.

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(54) **FREQUENCY SELECTION ALGORITHM FOR RESILIENT HF COMMUNICATION**

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H04B 1/00	(2006.01)
H04B 1/10	(2006.01)

(52) **U.S. Cl.**

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CPC H04W 40/02; H04W 72/0453; H04W 72/541; H04W 16/20; H04W 40/12; H04W 40/16; H04W 40/20; H04W 40/22; H04W 28/04; H04W 72/04; H04W 72/042; H04W 88/08; H04W 28/08; H04W 28/084; H04W 36/22; H04W 72/12; H04L 5/0007

See application file for complete search history.

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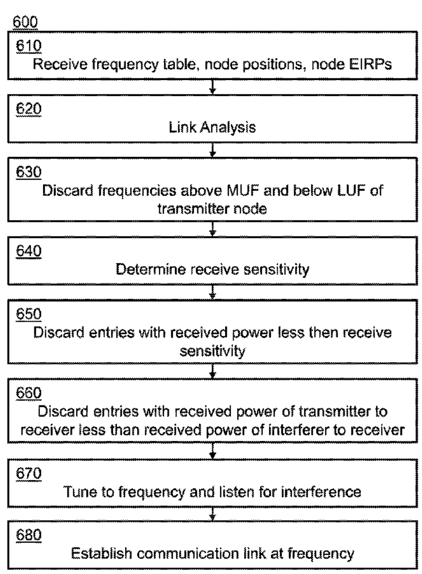
(74) *Attorney, Agent, or Firm* — Suiter Swantz IP

(57) **ABSTRACT**

Techniques for selecting frequencies of operation are described. HF signals may land at the receiver node with power levels dependent upon the transmit frequency. The frequency with the highest power level at the receiver node may be selected when the receiver node is not subject to interfering. The receiver node may be unable to receive a desired signal if an interfering signal has a signal level which is higher than the desired signal. The transmitter node may select a frequency which has a receiver signal level which is higher than the interfering signal for the selected frequency. The receiver node may then receive the transmit signal at the selected frequency even when subject to interfering from the interferer node.

19 Claims, 17 Drawing Sheets



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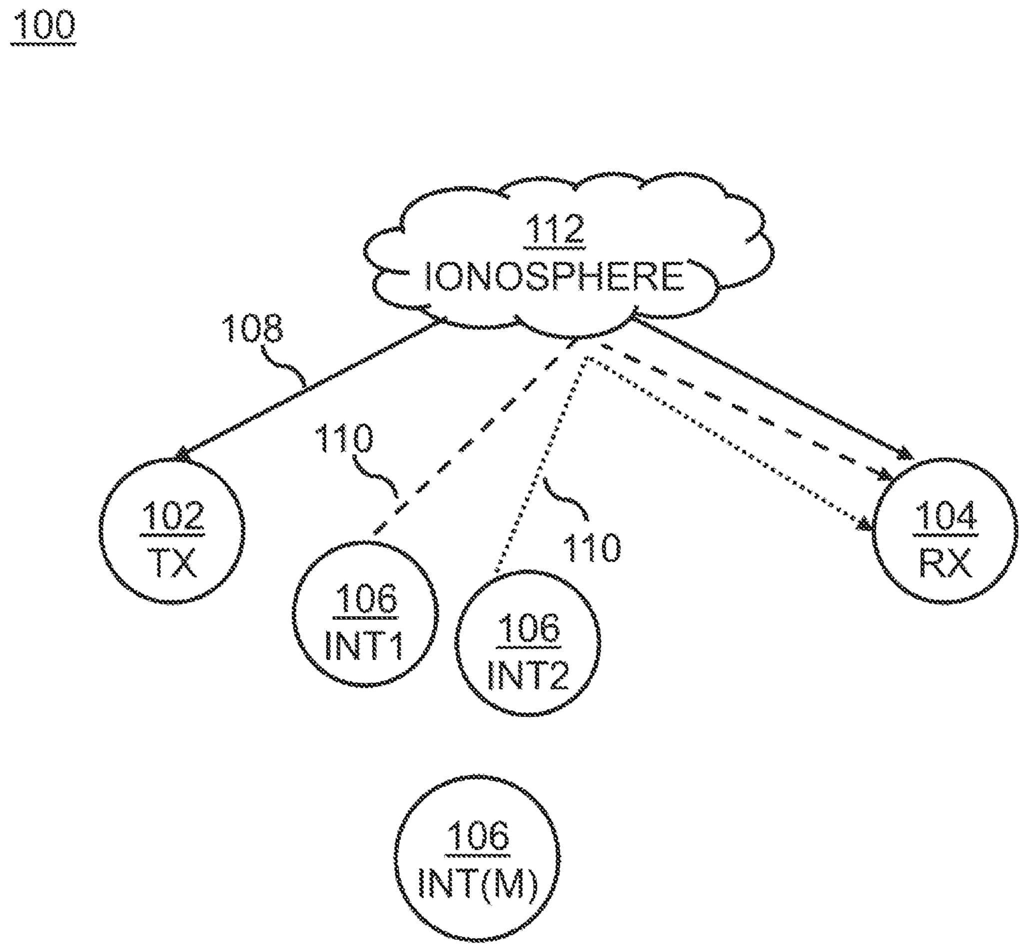
100
112
IONOSPHERE
108
110
102
TX
106
INT1
106
INT2
110
104
RX
106
INT(M)

FIG. 1

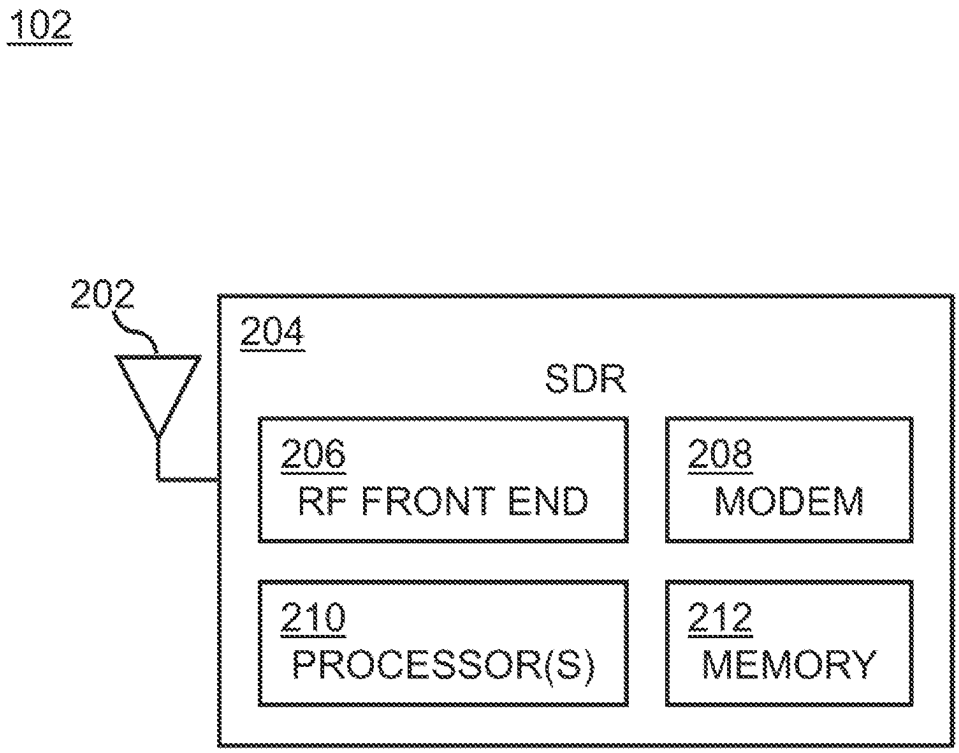
102
202
204
SDR
206
RF FRONT END
208
MODEM
210
PROCESSOR(S)
212
MEMORY

FIG. 2

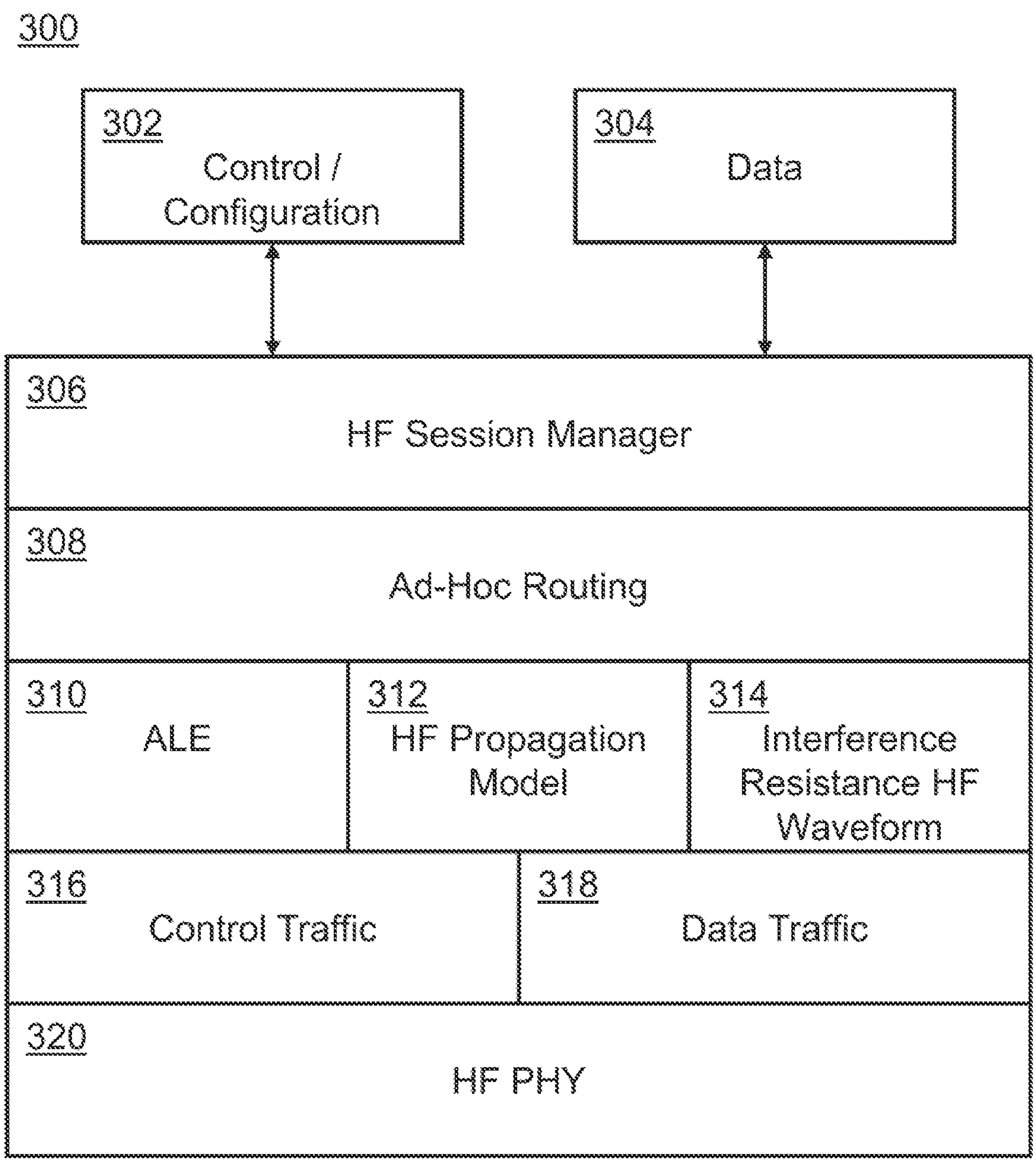
300
302
Control / Configuration
304
Data
306
HF Session Manager
308
Ad-Hoc Routing
310
ALE
312
HF Propagation Model
314
Interference Resistance HF Waveform
316
Control Traffic
318
Data Traffic
320
HF PHY

FIG. 3

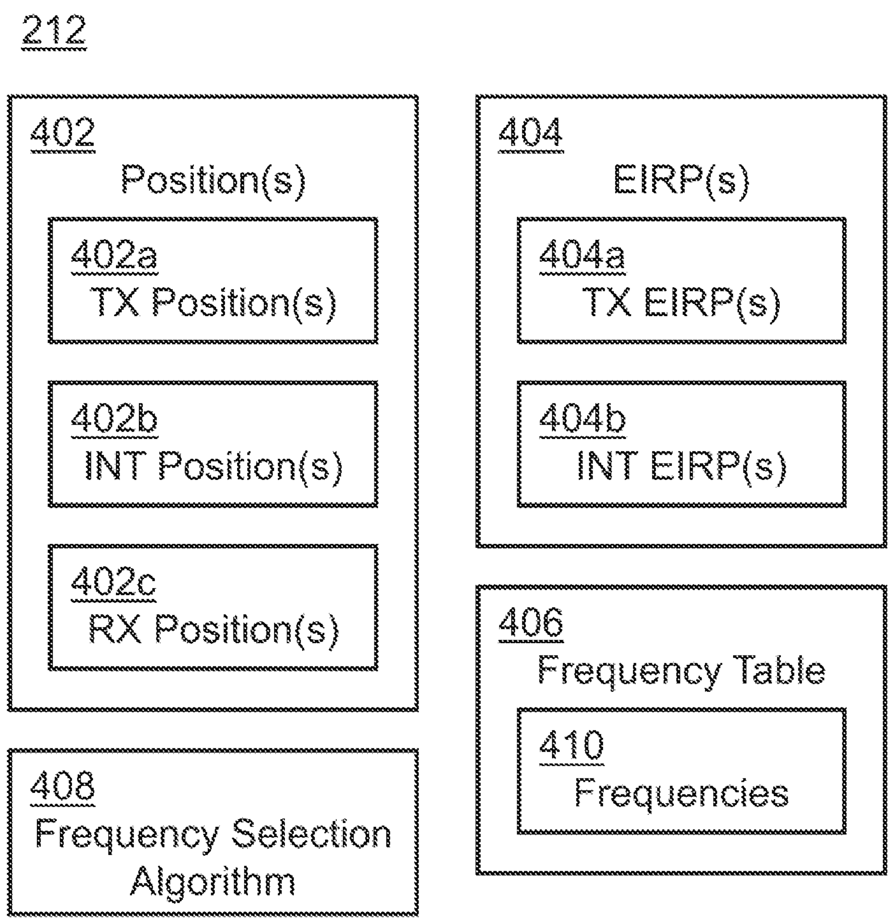
212
402
Position(s)
402a
TX Position(s)
402b
INT Position(s)
402c
RX Position(s)
404
EIRP(s)
404a
TX EIRP(s)
404b
INT EIRP(s)
406
Frequency Table
410
Frequencies
408
Frequency Selection Algorithm

FIG. 4

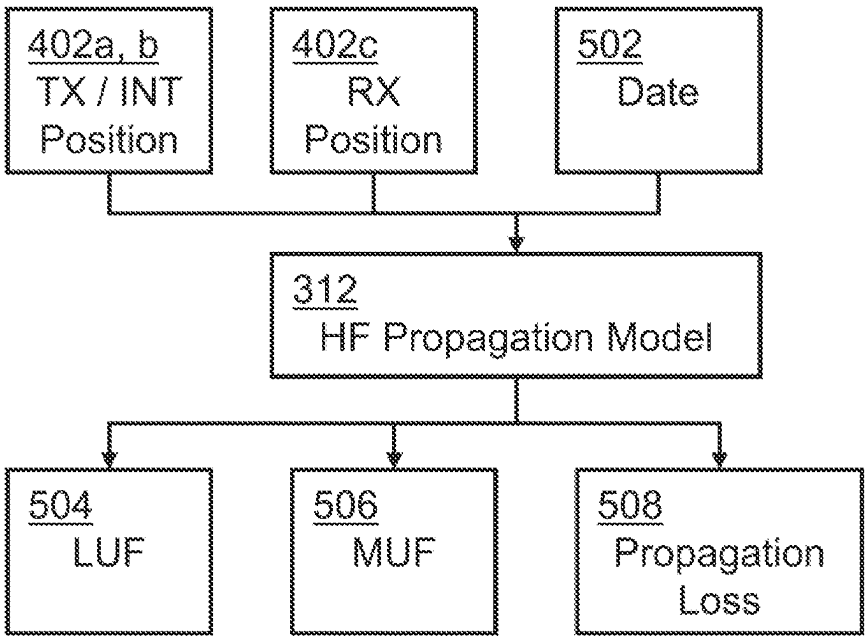
402a, b
TX / INT Position
402c
RX Position
502
Date
312
HF Propagation Model
504
LUF
506
MUF
508
Propagation Loss

FIG. 5

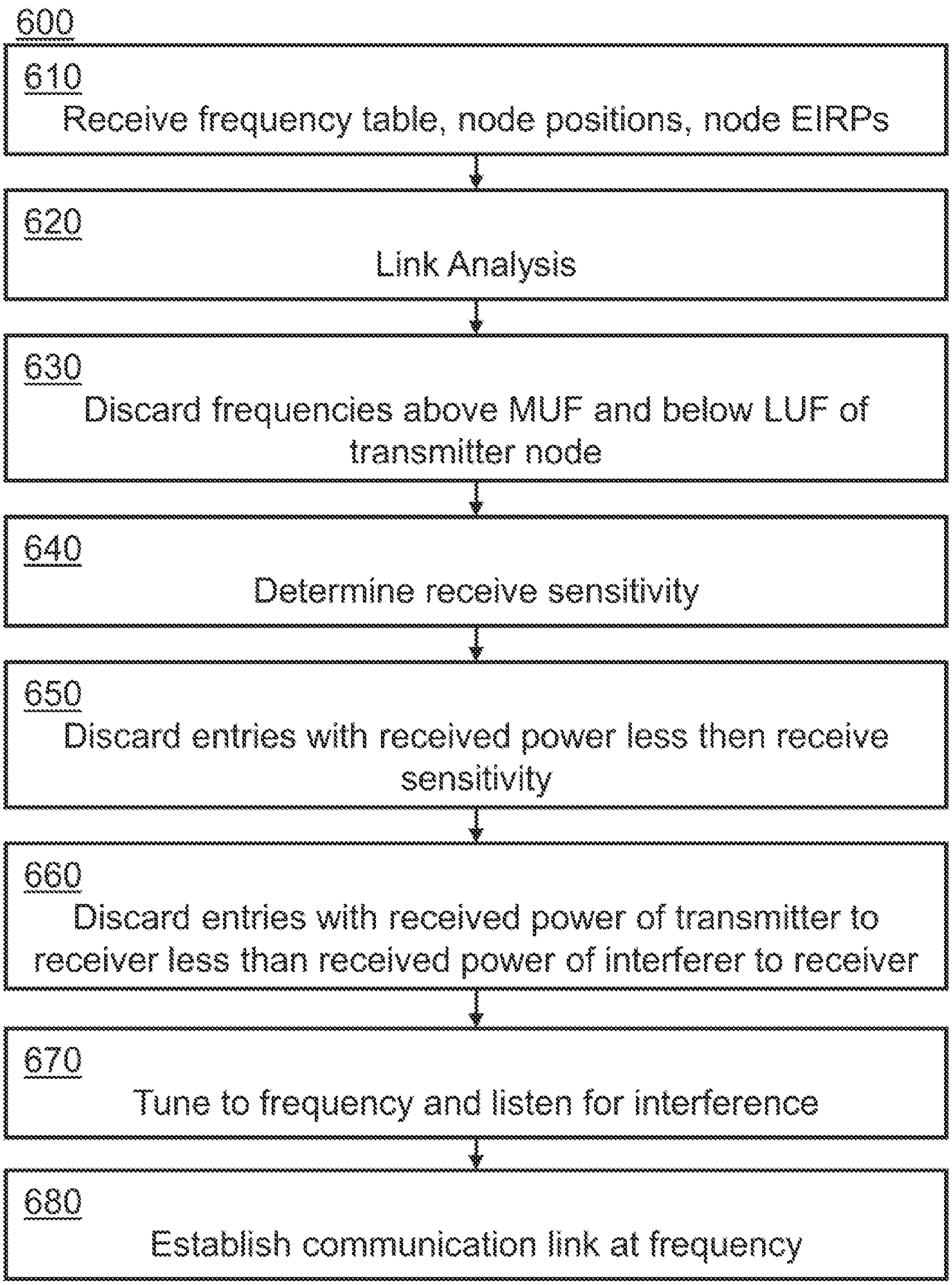
600
610
Receive frequency table, node positions, node EIRPs
620
Link Analysis
630
Discard frequencies above MUF and below LUF of transmitter node
640
Determine receive sensitivity
650
Discard entries with received power less then receive sensitivity
660
Discard entries with received power of transmitter to receiver less than received power of interferer to receiver
670
Tune to frequency and listen for interference
680
Establish communication link at frequency

FIG. 6A

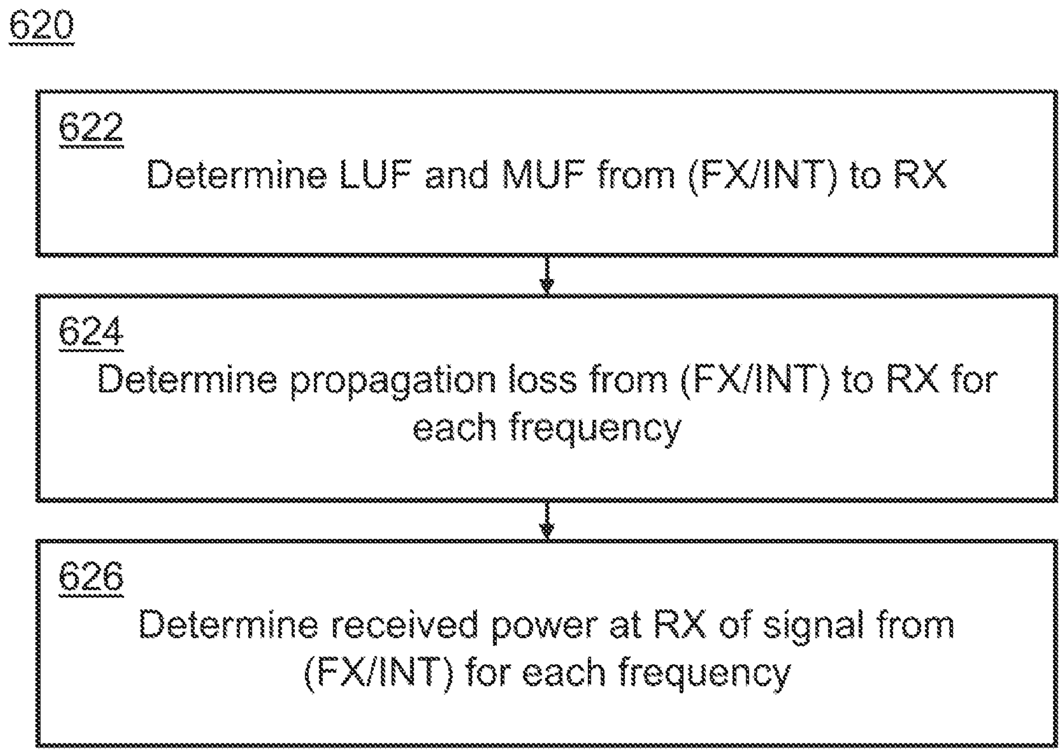
620
622
Determine LUF and MUF from (FX/INT) to RX
624
Determine propagation loss from (FX/INT) to RX for each frequency
626
Determine received power at RX of signal from (FX/INT) for each frequency

FIG. 6B

406

FREQUENCY TABLE
F(1)
F(2)
...
F(N-1)
F(N)

402a-c

	Position
TX	(lat, long)
INT(1)	(lat, long)
INT(2)	(lat, long)
...	...
INT(M)	(lat, long)
RX	(lat, long)

FIG. 7A

404a, b

	F(1)	F(2)	...	F(N-1)	F(N)
TX EIRP	dBm	dBm	...	dBm	dBm
INT(1) EIRP	dBm	dBm	...	dBm	dBm
INT(2) EIRP	dBm	dBm	...	dBm	dBm
...	...	...	...	...	...
INT(M) EIRP	dBm	dBm	...	dBm	dBm

FIG. 7B

504, 506, 508

	LUF	MUF	Prop. Loss at F(1)	Prop. Loss at F(2)	…	Prop. Loss at F (N-1)	Prop. Loss at F(N)
TX to RX	MHz	MHz	dBm	dBm	…	dBm	dBm
INT (1) to RX	MHz	MHz	dBm	dBm	…	dBm	dBm
INT (2) to RX	MHz	MHz	dBm	dBm	…	dBm	dBm
…	…	…	…	…	…	…	…
INT (M) to RX	MHz	MHz	dBm	dBm	…	dBm	dBm

FIG. 7C

702

	Rcv'd Power at F(1)	Rcv'd Power at F(2)	...	Rcv'd Power at F(N-1)	Rcv'd Power at F(N)
TX to RX	dBm	dBm	...	dBm	dBm
INT (1) to RX	dBm	dBm	...	dBm	dBm
INT (2) to RX	dBm	dBm	...	dBm	dBm
...	...	...	...	...	...
INT (M) to RX	dBm	dBm	...	dBm	dBm

FIG. 7D

704

	Rcv'd Power at F(1)	Rcv'd Power at F(2)	...	Rcv'd Power at F(N-1)	Rcv'd Power at F(N)
TX to RX	F(1) Below TX to RX LUF	dBm	...	dBm	F(N) above TX to RX MUF
INT (1) to RX	F(1) Below TX to RX LUF	dBm	...	dBm	F(N) above TX to RX MUF
INT (2) to RX	F(1) Below TX to RX LUF	dBm	...	dBm	F(N) above TX to RX MUF
...	...	...	...	...	...
INT (M) to RX	F(1) Below TX to RX LUF	dBm	...	dBm	F(N) above TX to RX MUF

FIG. 7E

706

	F(1)	F(2)	…	F(N-1)	F(N)
RX Sensitivity	F(1) Below TX to RX LUF	dBm	…	dBm	F(N) above TX to RX MUF

FIG. 7F

708

	Rcv'd Power at F(1)	Rcv'd Power at F(2)	...	Rcv'd Power at F(N-1)	Rcv'd Power at F(N)
TX to RX	F(1) Below TX to RX LUF	TX to RX Rcv'd power below RX Sens.	...	dBm	F(N) above TX to RX MUF
INT (1) to RX	F(1) Below TX to RX LUF	TX to RX Rcv'd power below RX Sens.	...	dBm	F(N) above TX to RX MUF
INT (2) to RX	F(1) Below TX to RX LUF	TX to RX Rcv'd power below RX Sens.	...	dBm	F(N) above TX to RX MUF
...	...	...	...	...	...
INT (M) to RX	F(1) Below TX to RX LUF	TX to RX Rcv'd power below RX Sens.	...	dBm	F(N) above TX to RX MUF

FIG. 7G

710

Frequency	F(3)	F(4)	...	F(N-2)	F(N-1)
Link Margin	dB	dB	...	dB	dB

FIG. 7H

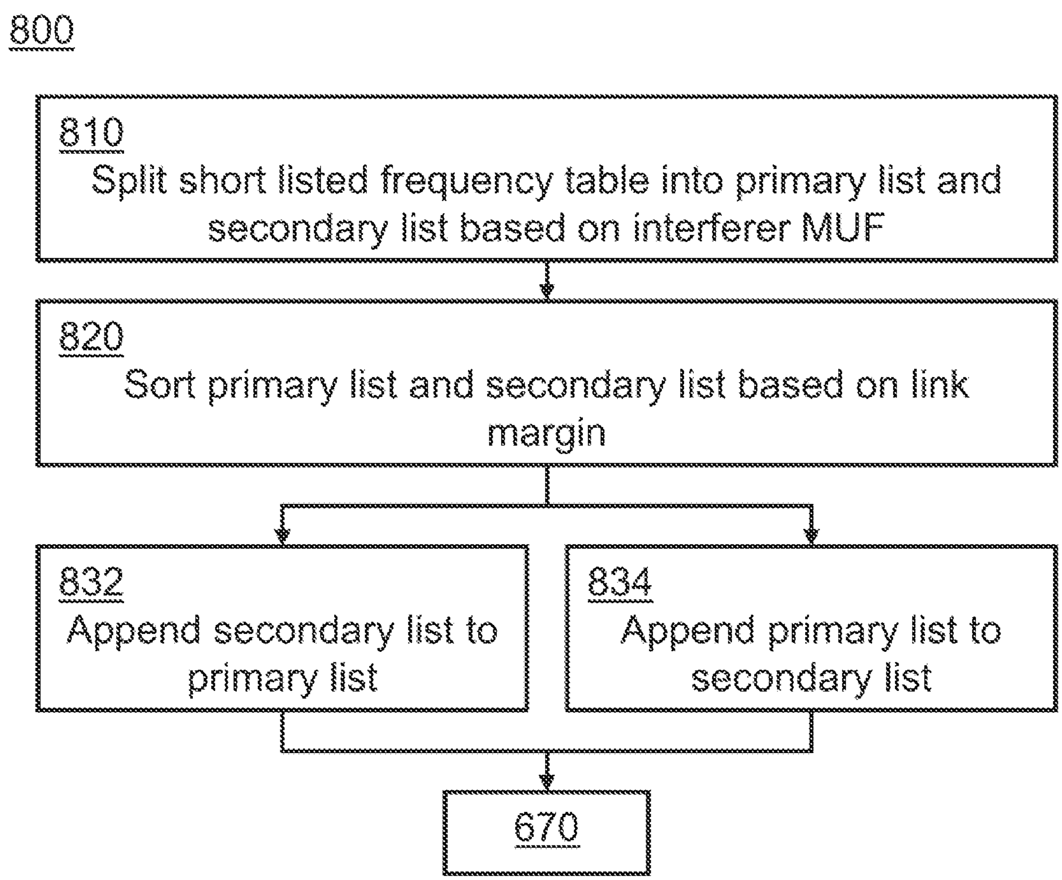
800
810
Split short listed frequency table into primary list and secondary list based on interferer MUF
820
Sort primary list and secondary list based on link margin
832
Append secondary list to primary list
834
Append primary list to secondary list
670

FIG. 8

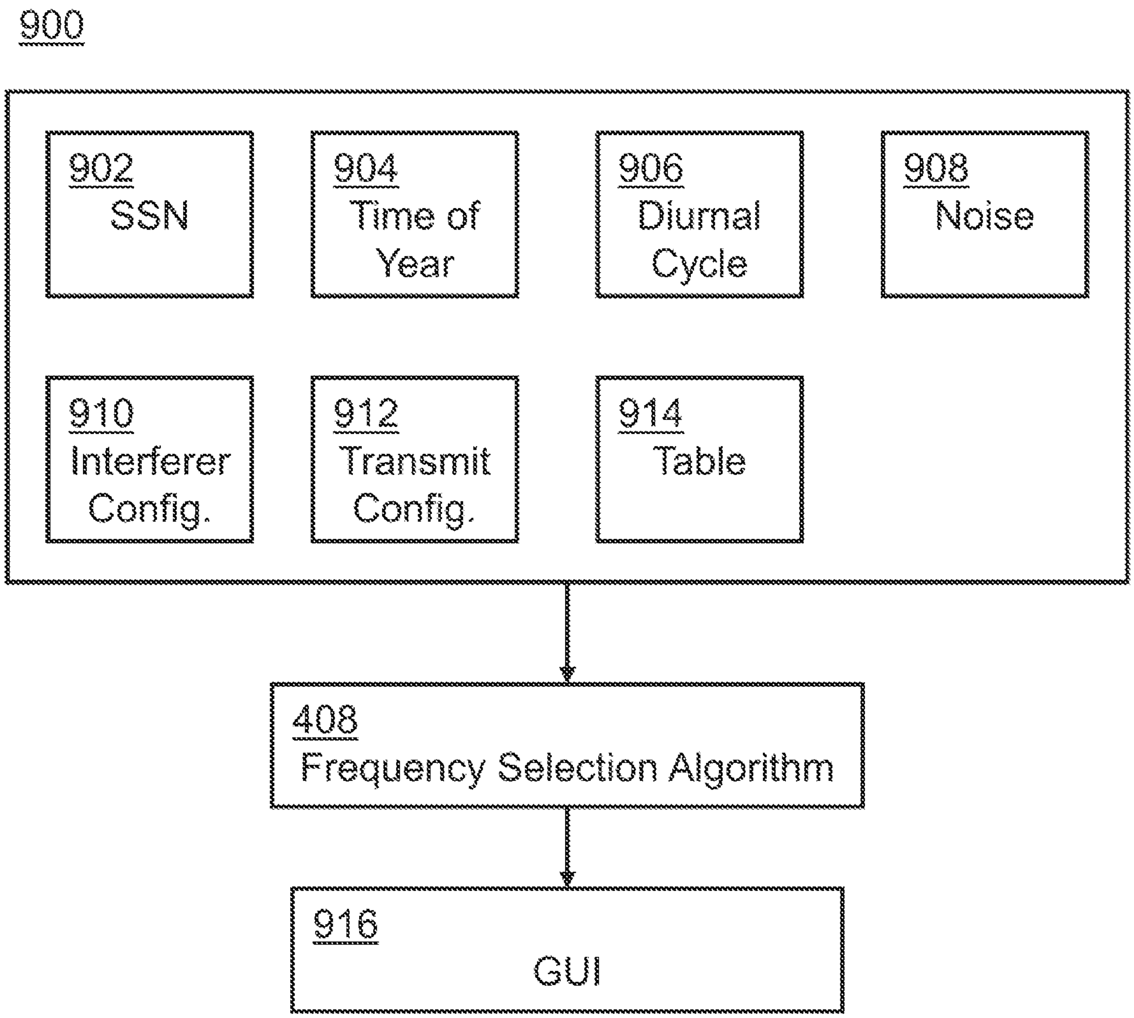
900
902
SSN
904
Time of Year
906
Diurnal Cycle
908
Noise
910
Interferer Config.
912
Transmit Config.
914
Table
408
Frequency Selection Algorithm
916
GUI

FIG. 9

FREQUENCY SELECTION ALGORITHM FOR RESILIENT HF COMMUNICATION

TECHNICAL FIELD

The present invention generally relates to communication systems, and more specifically to resilient and resistant HF communication.

BACKGROUND

Radio Frequency (RF) communication provide long-range communication for a plurality of stationary and moving nodes (stations). High Frequency (HF) waveforms may possess qualities specifically suited for long range communication. However, the HF waveforms are not designed to operate during periods of active denial and intentional/unintentional interference. The long-range communication can then be denied by the active intentional and unintentional interference. Therefore, it would be advantageous to provide a device, system, and method that cures the shortcomings described above.

SUMMARY

A software-defined radio is described in accordance with one or more embodiments of the present disclosure. In some embodiments, the software-defined radio includes a memory maintaining program instructions. In some embodiments, the software-defined radio includes one or more processors configured to execute the program instructions. In some embodiments, the program instructions cause the one or more processors to determine a first lowest usable frequency (LUF) and a first maximum usable frequency (MUF). The first LUF and the first MUF are from a transmitter node to a receiver node. In some embodiments, the program instructions cause the one or more processors to determine a first plurality of received powers at the receiver node for a plurality of frequencies in a high-frequency (HF) band. The first plurality of received powers are signals from the transmitter node. In some embodiments, the program instructions cause the one or more processors to determine a second plurality of received powers at the receiver node for the plurality of frequencies. The second plurality of received powers are signals from an intentional/unintentional interferer node, henceforth known as an interferer node. In some embodiments, the program instructions cause the one or more processors to determine a first subset of the plurality of frequencies by discarding any of the plurality of frequencies which are above the first MUF and by discarding any of the plurality of frequencies which are below the first LUF. In some embodiments, the program instructions cause the one or more processors to determine a plurality of receive sensitivities of the receiver node for each of the first subset. In some embodiments, the program instructions cause the one or more processors to determine a second subset of the first subset by discarding any of the first subset in which the first plurality of received powers are below the plurality of receive sensitivities and in which the first plurality of received powers are below the second plurality of received powers.

A method is described, in accordance with one or more embodiments of the present disclosure. In some embodiments, the method includes determining a first lowest usable frequency (LUF) and a first maximum usable frequency (MUF). The first LUF and the first MUF are from a transmitter node to a receiver node. In some embodiments, the method includes determining a first plurality of received powers at the receiver node for a plurality of frequencies in a high-frequency (HF) band. The first plurality of received powers are signals from the transmitter node. In some embodiments, the method includes determining a second plurality of received powers at the receiver node for the plurality of frequencies. The second plurality of received powers are signals from an interferer node. In some embodiments, the method includes determining a first subset of the plurality of frequencies by discarding any of the plurality of frequencies which are above the first MUF and by discarding any of the plurality of frequencies which are below the first LUF. In some embodiments, the method includes determining a plurality of receive sensitivities of the receiver node for each of the first subset. In some embodiments, the method includes determining a second subset of the first subset by discarding any of the first subset in which the first plurality of received powers are below the plurality of receive sensitivities and in which the first plurality of received powers are below the second plurality of received powers.

An HF mission planner is described, in accordance with one or more embodiments of the present disclosure. In some embodiments, the HF mission planner includes a memory maintaining program instructions. In some embodiments, the HF mission planner includes one or more processors configured to execute the program instructions. In some embodiments, the program instructions cause the one or more processors to determine a first lowest usable frequency (LUF) and a first maximum usable frequency (MUF). The first LUF and the first MUF are from a transmitter node to a receiver node. In some embodiments, the program instructions cause the one or more processors to determine a first plurality of received powers at the receiver node for a plurality of frequencies in a high-frequency (HF) band. The first plurality of received powers are signals from the transmitter node. In some embodiments, the program instructions cause the one or more processors to determine a second plurality of received powers at the receiver node for the plurality of frequencies. The second plurality of received powers are signals from an interferer node. In some embodiments, the program instructions cause the one or more processors to determine a first subset of the plurality of frequencies by discarding any of the plurality of frequencies which are above the first MUF and by discarding any of the plurality of frequencies which are below the first LUF. In some embodiments, the program instructions cause the one or more processors to determine a plurality of receive sensitivities of the receiver node for each of the first subset. In some embodiments, the program instructions cause the one or more processors to determine a second subset of the first subset by discarding any of the first subset in which the first plurality of received powers are below the plurality of receive sensitivities and in which the first plurality of received powers are below the second plurality of received powers.

BRIEF DESCRIPTION OF THE DRAWINGS

Implementations of the concepts disclosed herein may be better understood when consideration is given to the following detailed description thereof. Such description makes reference to the included drawings, which are not necessarily to scale, and in which some features may be exaggerated and some features may be omitted or may be represented schematically in the interest of clarity. Like reference numerals in the drawings may represent and refer to the same or similar element, feature, or function. In the drawings:

FIG. **1** depicts a system including a transmitter node, a receiver node, and interferer nodes, in accordance with one or more embodiments of the present disclosure.

FIG. **2** depicts a simplified block diagram of a node including an antenna and a software-defined radio, in accordance with one or more embodiments of the present disclosure.

FIG. **3** depicts a waveform protocol stack, in accordance with one or more embodiments of the present disclosure.

FIG. **4** depicts a simplified block diagram of a memory, in accordance with one or more embodiments of the present disclosure.

FIG. **5** depicts input and outputs of a high frequency (HF) propagation model, in accordance with one or more embodiments of the present disclosure.

FIGS. **6**A-**6**B depicts a flow diagram of a method, in accordance with one or more embodiments of the present disclosure.

FIG. **7**A depicts a frequency table and node positions, in accordance with one or more embodiments of the present disclosure.

FIG. **7**B depicts node Effective Isotropic Radiated Powers (EIRPs), in accordance with one or more embodiments of the present disclosure.

FIG. **7**C depicts lowest useable frequencies (LUFs), maximum useable frequencies (MUFs), and propagation losses between nodes, in accordance with one or more embodiments of the present disclosure.

FIG. **7**D depicts received powers between nodes, in accordance with one or more embodiments of the present disclosure.

FIG. **7**E depicts discarding frequencies below a LUF and above a MUF between a transmitter node and a receiver node, in accordance with one or more embodiments of the present disclosure.

FIG. **7**F depicts determining receive sensitivities for frequencies between the LUF and the MUF, in accordance with one or more embodiments of the present disclosure.

FIG. **7**G depicts discarding frequencies with a signal from a transmitter node to a receiver node below a receive sensitivity, in accordance with one or more embodiments of the present disclosure.

FIG. **7**H depicts a short-listed frequency table, in accordance with one or more embodiments of the present disclosure.

FIG. **8** depicts a flow diagram of a method, in accordance with one or more embodiments of the present disclosure.

FIG. **9** depicts a simplified block diagram of an HF mission planner, in accordance with one or more embodiments of the present disclosure.

DETAILED DESCRIPTION OF THE INVENTION

Before explaining one or more embodiments of the disclosure in detail, it is to be understood that the embodiments are not limited in their application to the details of construction and the arrangement of the components or steps or methodologies set forth in the following description or illustrated in the drawings. In the following detailed description of embodiments, numerous specific details are set forth in order to provide a more thorough understanding of the disclosure. However, it will be apparent to one of ordinary skill in the art having the benefit of the instant disclosure that the embodiments disclosed herein may be practiced without some of these specific details. In other instances, well-known features may not be described in detail to avoid unnecessarily complicating the instant disclosure.

As used herein a letter following a reference numeral is intended to reference an embodiment of the feature or element that may be similar, but not necessarily identical, to a previously described element or feature bearing the same reference numeral (e.g., **1**, **1***a*, **1***b*). Such shorthand notations are used for purposes of convenience only and should not be construed to limit the disclosure in any way unless expressly stated to the contrary.

Further, unless expressly stated to the contrary, "or" refers to an inclusive or and not to an exclusive or. For example, a condition A or B is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present).

In addition, use of "a" or "an" may be employed to describe elements and components of embodiments disclosed herein. This is done merely for convenience and "a" and "an" are intended to include "one" or "at least one," and the singular also includes the plural unless it is obvious that it is meant otherwise.

Finally, as used herein any reference to "one embodiment" or "some embodiments" means that a particular element, feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment disclosed herein. The appearances of the phrase "in some embodiments" in various places in the specification are not necessarily all referring to the same embodiment, and embodiments may include one or more of the features expressly described or inherently present herein, or any combination or sub-combination of two or more such features, along with any other features which may not necessarily be expressly described or inherently present in the instant disclosure.

Referring generally now to one or more embodiments of the present disclosure. Embodiments of the present disclosure are generally directed to a system and method that enables HF waveforms to operate in environment subject to interfering. A communication link budget with potential interferer link budgets is iteratively computed. A frequency is then selected that can overcome interfering from each interferer.

U.S. Pat. No. 9,282,500, titled "Ad hoc high frequency with advanced automatic link establishment system and related method", filed on Jun. 17, 2014; U.S. Pat. No. 10,116,382, titled "Ad hoc high frequency network", filed on Feb. 24, 2017; and U.S. Pat. No. 11,490,452, titled "Ad-hoc HF time frequency diversity", filed on Jan. 20, 2020; are incorporated herein by reference in the entirety.

Referring now to FIG. **1**, a system **100** is described, in accordance with one or more embodiments of the present disclosure. The system **100** may also be referred to as a communication network, a high frequency (HF) communication network, and/or a beyond line-of-sight (BLOS) communication network.

The system **100** may include one or more nodes, such as, but not limited to, transmitter nodes **102**, receiver nodes **104**, interferer nodes **106**, and the like.

The transmitter nodes **102** and the receiver nodes **104** may be considered a network of nodes. The transmitter nodes **102** may also function as receiver nodes **104**, and vice versa. The transmitter nodes **102** and the receiver nodes **104** may include a common mission and may desire to establish communication. The transmitter node **102** may be considered a node which transmits for the purpose of communication. The nodes may switch between being the transmitter node **102** and the receiver node **104** during bidirectional communication.

The transmitter nodes **102** and the receiver nodes **104** may establish a communication link **108**. The communication link **108** may enable communication between the transmitter nodes **102** and the receiver nodes **104**. For example, the transmitter nodes **102** may transmit a waveform to the receiver nodes **104** to establish the communication link **108**. The communication link **108** may be a connection between the nodes enabling transfer of data over the waveform in space.

The communication link **108** may refer to a beyond line-of-sight communication link in a high frequency (HF) band. The HF band may include a frequency range from 3 MHz to 30 MHz. For example, the waveform may follow a path. The path may refer to a physical path the waveform travels in space between nodes. The waveform may be transmitted from the transmitter node **102**, reflected from the ionosphere **112**, and received by the receiver node **104**.

The transmitter nodes **102** and the receiver nodes **102** may include a frequency table (e.g., frequency table **406**). The frequency table may include a plurality of frequencies (F) in the HF band. The frequency table may include any number (N) of the frequencies in the HF band. For example, the frequency table may commonly include ten or more frequencies (F1-F10) in the HF band, although this is not intended as a limitation of the present disclosure. It is contemplated that the frequency table may include hundreds or more of frequencies in the HF band. The transmitter nodes **102** and the receiver nodes **104** may use any of the frequencies to establish the communication link **108**.

The system **100** may also include intentional/unintentional interferer nodes **106**. The interferer nodes **106** may be considered a node which communicates for the purpose of intentionally or unintentionally interfering communication from other nodes. The interferer nodes **106** may be located at various positions on earth. The interferer nodes **106** may include directional antennas and/or omnidirectional antennas operable in the HF band. The antennas of the interferer nodes **106** may deliver a given Effective Isotropic Radiated Power (EIRP). The EIRP may indicate the transmit power leaving an antenna. The EIRP may account for the impact of the transmitter and the antenna. For example, an antenna gain parameter may be ignored using the EIRP.

The position and/or the EIRP of the interferer nodes **106** may be known by the transmitter nodes **102** and/or the receiver nodes **104**. For example, the interferer nodes **106** may be located at a fixed position (e.g., fixed-site interferer nodes). For example, the fixed-site interferer nodes may have restrictions in changing EIRP such that the EIRP may be determined a priori. The fixed-site interferer nodes are also located at a fixed position or site which is detectable by satellite or another method. The position and EIRP of the interferer nodes **106** may then be provided to the transmitter nodes **102** and/or the receiver nodes **104**.

The fixed-site interferer nodes may achieve a high Effective, Isotropic Radiated Power (EIRP) in the high frequency (HF) band. A high EIRP in the HF band may refer to 1 KW or more. Interferer nodes which are mobile are not as powerful as fixed site interferers. For example, the EIRP of the mobile interferer nodes may be limited by antenna size and antenna gain due to the size of the platform hosting the antenna. The low EIRP of the mobile interferer nodes may reduce the effectiveness of interfering BLOS communications.

The interferer node **106** may transmit a signal **110** to the receiver node **104** intentionally or unintentionally on the same frequency as the signal from the transmitter node **102**. The interfering signal **110** may increase a noise level at the receiver node **104**, or similarly decrease a signal-to-noise ratio of the communication link **108**. The interfering signal **110** may then cause the receiver node to be unable to hear the signal transmitted from the transmitter node **102**. Thus, ensuring the receiver node **104** receives the communication link **108** in the HF band while being subject to the interfering signal **110** by interferer nodes is desirable.

The communication link **108** may reflect from the ionosphere **112** in one or more hops between the transmitter nodes **102** and the receiver nodes **104**. Similarly, the interfering signal **110** may reflect from the ionosphere **112** in one or more hops from the interferer nodes **106** to the receiver nodes **104**. For example, the communication link **108** and interfering signal **110** may reflect from any of the layers (e.g., E layer, F layer) of the ionosphere **112** in one hop or multiple hops before being received by the receiver nodes **104**.

The propagation of HF signals reflected from the ionosphere **112** may be dependent on one or more factors, such as, but not limited to, the time of the day, the season of the year. the sunspot number, ionospheric conditions, transmit power, and the like. The ionospheric conditions may change drastically during solar flares, coronal mass ejections, and manmade scintillation environments. Thus, there is no guarantee that any frequency in the HF band will work for communication between each of the nodes of the system **100**. The time of day, sunspot number, and ionospheric conditions may be the same for each node in the network at a given date and time. The distance and transmit power may vary for each node in the network.

The probability of the communication link **108** from the transmitter node **102** being received by the receiver node **104** may be low when the receiving nodes **104** are subject to the interfering signal **110**. In embodiments, the transmitter nodes **102** may account for the interfering signal **110** when determining a transmit frequency. The transmitter node may pick a frequency that the transmitter node and receiver node may use to communicate which the interferers cannot employ.

Referring now to FIG. **2**, a node **200** is described, in accordance with one or more embodiments of the present disclosure. The node **200** may be an example of the transmitter node **102** and/or the receiver node **104**. The node **200** may include one or more antennas **202** and software-defined radio **204** (SDR).

The software-defined radio **204** may include one or more components, such as, but not limited to, a radio frequency (RF) front end **206**, modem **208**, processors **210**, memory **212**, and the like. As may be understood, the software-defined radio **204** may include a number of components, permutations, and arrangements, which are not set forth herein for clarity.

The antennas **202** may provide an interface between the HF radio waves (e.g., the communication link **108**) and an RF electrical signal. The antennas **202** be coupled to the software-defined radio **204**. For example, the antennas **202** may be coupled to the software-defined radio **204** by one or more switches (not depicted), although this is not intended to be limiting. The antennas **202** may be coupled to RF front end **206** of the of the software-defined radio **204**.

The RF front end **206** may provide one or more functions, such as, but not limited to, process the RF electrical signal. For example, the RF front end **206** may perform frequency up conversion, frequency down conversion, filtering, amplification, signal mixing, and the like.

The modem **208** may provide one or more functions, such as, but not limited to, modulation and/or demodulation functions. For example, the modem **208** may modulate signals to the RF front end **206** and/or demodulate signals from the RF front end **206**.

The software-defined radio **204** may include functionality defined by software. The software-defined radio **204** may include signal processing functionality defined in software, for generating a waveform as sampled digital signals, converting from digital to analog via high-speed Digital-to-Analog Converter (DAC), and then translating to Radio Frequency (RF) for wireless propagation to a receiver. For example, the memory **212** may maintain program instructions. The program instructions may provide the various functionality. The program instructions may be executable by the processors **210** for performing any of the various methods described herein. The processors **210** may also be coupled to the modem **208**. The modem **208** may then provide an interface for modulating and demodulating the waveform with data. In this regard, the processors **210** and modem **208** may host one or more portions layers of a waveform protocol stack. In embodiments, the software-defined radios **204** may host a waveform protocol stack **300**.

Referring now to FIG. **3**, a waveform protocol stack **300** is described, in accordance with one or more embodiments of the present disclosure. The node **200** may use the waveform protocol stack **300** to establish the communication link **108** when the receiver node **104** is subject to the interfering signal **110**. The waveform protocol stack **300** may also be referred to as an HF waveform protocol stack, an ad-hoc waveform protocol stack, a resilient waveform protocol stack, a resistant ad-hoc HF waveform protocol stack, or the like.

The waveform protocol stack **300** may include one or more layers. A layer of the waveform protocol stack **300** may include control/configuration **302** and data **304**.

Another layer of the waveform protocol stack **300** may include an HF session manager **306**. The HF Session Manager **140** may perform various functions to setup and tear down the communication link **108** between nodes. In embodiments, the HF session manager **306** may operate automatic link establishment **310** (ALE), HF propagation model **312**, and HF waveform **314** in a time-shared mode.

Another layer of the waveform protocol stack **300** may include an ad-hoc routing function **308**. Ad-hoc may refer to data forwarding across a wireless network. The nodes in the wireless network may be mobile, such that routing must be performed ad hoc. The ad-hoc routing function **308** may include, but is not limited to, an Optimized Link State Routing Protocol (OLSR) or the like.

Another layer of the waveform protocol stack **300** may include an automatic link establishment **310** (ALE), a HF propagation model **312**, and a resilient HF waveform **314**. In embodiments, the waveform protocol stack **300** may simultaneously perform the automatic link establishment **310**, the HF propagation model **312**, and the HF waveform **314** without disrupting the communication link **108**.

The automatic link establishment **310** may include sounding, call, and answer messages to enable ad-hoc HF. For example, the automatic link establishment **310** may sound a channel. Peer nodes may then record a link quality of the communication link **108** and order frequencies of the communication link **108** in descending order of link quality. The nodes **200** may use the frequency with the highest available link quality to communicate. A rate of the sounding may be selected based on a time or a speed or a change in position of the nodes. The automatic link establishment **310** may include, but is not limited to, sounding in accordance with MIL-STD-188-141D (ALE), although this is not intended to be limiting.

The messages in the automatic link establishment **310** may include various data regarding the nodes, such as, but not limited to, node identity (ID), position, velocity, frequency received, link quality, and the like.

Nodes may cycle through and transmit the sounding burst for each frequency in a frequency table. The other nodes may or may not receive the sounding burst. If the nodes do receive the sounding burst, the nodes record that the sounding burst from the transmitter node **102** was received at the selected frequency and with a given link quality. The nodes may then determine frequencies which propagate between the transmitter nodes **102** and the receiver nodes **104**. If a node desires to initiate a call, the node sends a call request using the frequency with the best link quality. The nodes may then negotiate call parameters, bandwidth, data rate, and the like for establishing the communication link **108**.

The sounding bursts may be transmitted in a matter which is unpredictable. In this regard, the sounding bursts may include a low-probability of being interfered. The nodes may initiate the communication link **108** using a frequency selected based link quality sent over the sounding signals. The interferer nodes **106** may initiate the interfering signals **110** during the communication link **108** at the current frequency of the communication link **108**. The noise from the interfering signals **110** may prevent the receiver nodes **104** from receiving the desired signals above a receiver sensitivity, such that the communication link **108** is broken. For example, the nodes may establish the call parameters. The interferer nodes **106** may then interfere with the receiver node **104** subsequent to the nodes establishing the call parameters. The transmitter node **102** may be aware of the lost communication but unaware of the interfering signal **110**.

In embodiments, the waveform protocol stack **300** may implement a frequency selection algorithm. The frequency selection algorithm selects frequencies which maintain the communication link **108** in the presence of the interfering signal **110**.

The HF propagation model **312** may be in a same layer as the automatic link establishment **310**. The HF propagation model **312** may model the propagation of HF signals in various conditions. The HF propagation model **312** may also be referred to as a coverage analysis program. The HF propagation model **312** may include any propagation model, such as, but not limited to, Voice of America Coverage Analysis Program (VOACAP), PropMan™ **2000**, and the like. The HF propagation model **312** is further described with reference to FIG. **5**.

The HF waveform **314** may be in the same layer as the HF propagation model **312** and the automatic link establishment **310**. The HF waveform **314** may provide continuous maintenance of the communication link **108** and/or the HF waveform to and from nodes of the system **100**.

Another layer of the waveform protocol stack **300** may include control traffic **316** and data traffic **318**. The control traffic **316** may be packetized and sent on a control plane. The data traffic **318** may be packetized and sent on a data plane. Both the control traffic **316** and the data traffic **318** are packetized and transported over the same link by interspersing the packets. Traffic other than the actual data being transported can be characterized as control traffic **316**. For example, the control traffic **316** may include sounding packets or routing packets.

Another layer of the waveform protocol stack **300** may include an HF physical layer **320** (HF PHY). The HF physical layer **320** may refer to the signal in space (e.g., the communication link **108**) transmitted and/or received by the antenna **202**. The HF physical layer **320** may be a time-division multiple access (TDMA) HF waveform.

In embodiments, the waveform protocol stack **300** may be considered denial resistant or resilient. The waveform protocol stack **300** may be operable beyond line-of-sight in an environment subject to interfering. The ability to operate the waveform protocol stack **300** in the interfering environment is desirable to ensure beyond line-of-sight (BLOS) communications between nodes. In embodiments, the waveform may include a level of robustness that is able to operate in an interfering environment. In particular, the waveform may be operable in an interfering environment which is subject to interference from interferers (e.g., interferer nodes **106**) with a high EIRP in the HF band.

The waveform protocol stack **300** may be significantly more robust than existing HF waveforms. For example, the waveform protocol stack **300** may be more robust than the waveforms described in MIL-STD-188-110D. The most robust modes of MIL-STD-188-110D are the Walsh modes. The Walsh mode waveforms have a robustness similar to that of STANAG 4415. Walsh mode waveforms of MIL-STD-188-110D may not be sufficiently robust to counter the intentional interferer nodes. The existing set of Walsh modes waveforms are not robust enough to operate under extreme solar anomalies and/or active interfering conditions. In embodiments, the HF waveform **314** is more robust than waveform number 0 Walsh Mode defined MIL-STD-188-110D, although this is not intended to be limiting.

The waveform protocol stack **300** may also operate under a wide variety of delay spreads and Doppler spreads typically seen under normal/moderately disturbed ionospheric conditions worldwide.

Referring now to FIG. **4**, the memory **212** is described, in accordance with one or more embodiments of the present disclosure. The memory **212** may include positions **402**, EIRPs **404**, a frequency table **406**, a frequency selection algorithm **408**, and the like.

The positions **402** may be positions of the nodes in the system **100**. The positions **402** may be in the form of coordinates (e.g., latitude/longitude coordinates). The positions **402** may include transmitter node positions **402***a* (i.e., position of the transmitter node **102**), interferer node positions **402***b* (i.e., position of the interferer node **106**), and/or receiver node positions **402***c* (i.e., position of the receiver node **104**). The transmitter node positions **402***a* may be determined from a GNSS data. The interferer node positions **402***b* may be determined a priori. The receiver node positions **402***c* may be determined from the automatic link establishment **310**, although this is not intended to be limiting.

Distances between nodes may be computed based on the locations. The distances may be on the order of several hundred kilometers up to thousands of kilometers, although this is not intended to be limiting.

The memory **212** may include a list of EIRPs **404** of the nodes in the system **100**. The EIRPs **404** may include transmitter node EIRPs **404***a* and/or interferer node EIRPs **404***b*. The transmitter node EIRPs **404***a* may be much lower than the interferer node EIRPs **404***b*, where the interferer nodes **106** are fixed-site interferers.

The memory **212** may include a frequency table **406**. The frequency table **406** may include a list of frequencies **410**. The frequencies **410** may be frequencies in the HF band which the receiver nodes **102** and the transmitter nodes **104** use to establish the communication link **108**.

The memory **212** may include a frequency selection algorithm **408**. The frequency selection algorithm **408** may be further understood with reference to the method **600**.

Referring now to FIG. **5**, the HF propagation model **312** is described, in accordance with one or more embodiments of the present disclosure. The HF propagation model **312** may include one or more inputs, such as, but not limited to, transmitter node position **402***a*, interferer node position **402***b*, receiver node position **402***c*, and/or the date **502**.

The HF propagation model **312** may determine one or more parameters based on the date **502**, such as, but not limited to, a sun spot number (SSN), and the like. The HF propagation model **312** may determine one or more parameters based on the transmitter node position **402***a* and/or the interferer node position **402***b* together with the receiver node position **402***c*, such as, but not limited to, a minimum angle in degrees, a distance between the nodes (e.g., distance in nautical miles or kilometers), and the like.

The HF propagation model **312** may include one or more outputs. The outputs may be determined based on the inputs (e.g., transmitter node position **402***a*, interferer node position **402***b*, receiver node position **402***c*, date **502**), the SSN, and the like. The outputs may include a lowest useable frequency **504** (LUF), a maximum useable frequency **506** (MUF), and a propagation loss **508**.

The LUF **504**, the MUF **506**, and the propagation loss **508** may be determined between each of the transmitter nodes and the receiver nodes. The LUF **504**, the MUF **506**, and the propagation loss **508** may also be determined between each of the interferer nodes and the receiver nodes. In this regard, the LUF **504**, the MUF **506**, and the propagation loss **508** may be dependent upon the receiver node position **402***c* and one of the transmitter node position **402***a* or interferer node position **402***b* depending upon whether the transmitter node **102** or the interferer node **106** is being analyzed. In embodiments, the LUF **504**, the MUF **506**, and the propagation loss **508** may be dependent upon distance between nodes, time of day, the sunspot number, and the like.

In embodiments, the HF propagation model **312** may output the LUF **504**. The LUF **504** may refer to a lowest frequency at which the transmission is a lowest frequency in HF having a circuit reliability of 90 percent. Signals transmitted at frequencies below the LUF may experience high propagation loss.

In embodiments, the HF propagation model **312** may output the MUF **506**. Frequencies above the MUF **506** may propagate. However, the probability of propagation for frequencies above the MUF **506** is 50% or less (i.e., the frequency may propagate less than 50% of the days in that month). The frequencies above the MUF **506** may pass through the ionosphere into space the remaining days of the month. Thus, HF signals at frequencies above the MUF **506** may propagate but the probability of propagation cannot be ensured. Signals transmitted at frequencies above the MUF may not be guaranteed to propagate or reflect from the ionosphere and return to ground at the location of the receiver. Instead, the transmission above the MUF may pass through the ionosphere to space.

In embodiments, the HF propagation model **312** may output the propagation loss **508**. The propagation loss **508** may be determined for each of the frequencies **410** in the frequency table **406**. The propagation loss **508** may also be referred to as a total path loss or path attenuation. For example, the path the communication link **108** follows from the transmitter nodes **102** to the receiver nodes **104** may experience a first propagation loss. By way of another example, the path the interfering signal **110** follows from the interferer nodes **102** to the receiver nodes **104** may experience a second propagation loss.

In some embodiments, the HF propagation model **312** may determine the LUF **504**, the MUF **506**, and the propagation loss **508** if the position (+/−50 miles) of the nodes are known.

Referring now to FIG. **6**, a flow diagram of method **600** is described, in accordance with one or more embodiments of the present disclosure. The embodiments and the enabling technology described previously herein in the context of the system **100**, the node **200**, and the waveform protocol stack **300** should be interpreted to extend to the method. For example, the method **600** may be implemented by the system **100**, the node **200**, and the waveform protocol stack **300**. It is further recognized, however, that the method **600** is not limited to the system **100**, the node **200**, and the waveform protocol stack **300**.

The method **600** may also be referred to as the frequency selection algorithm **408**. The method **600** may be used to counter interferers through frequency selection and may ensure beyond line-of-sight (BLOS) communication given a priori knowledge of the location and EIRP of the interferers.

The method **600** may be further understood with reference to the exemplary tables provided in FIGS. **7A-7H**. As an example, the system **100** may include one of the transmitter nodes **102**, one of the receiver nodes **104**, and a number M of the interferer nodes **106**. The frequency table **406** may include N frequencies **410** in the HF band. For each hour of communication, there are then N+N*M computations. If there is one transmitter node, one receiver node, N frequencies, and M Interferer nodes then there are N possible signals related to communications between the transmitter node and receiver node and N×M entries related to signals from the interferer nodes and the receiver node. Thus, the method **600** may process N+(N*M) potential options for a given hour when the transmitter node is selecting a frequency to communicate with the receiver node.

In a step **610**, frequency table **406**, node positions **402**, and node EIRPs **404** are received. The frequency table **406**, node positions **402**, and node EIRPs **404** may be received from memory **212**.

In a step **620**, a link analysis is performed. The link analysis may include performing a link analysis on each of communication links **108** between the transmitter nodes **102** and the receiver nodes **104** and also a link analysis on each of the interfering signals **110** from the interferer nodes **106** to the receiver nodes **104**. The link analysis may be further understood with reference to FIG. **6**B.

The link analysis may include a step **622** of determining LUF **504** and MUF **506**. The LUF **504** and MUF **506** may be determined by computing a propagation analysis using the HF propagation model **312**. The LUF **504** may include a LUF from the transmitter node **102** to the receiver node **104** and/or a LUF from the interferer nodes **106** to the receiver node **104**. The LUF from the transmitter node **102** to the receiver node **104** may also be referred to as a TX to RX LUF or a F-LUF. The LUF from the interferer nodes **106** to the receiver node **104** may also be referred to as a Interferer(1 through M) to RX LUF or a I(1 through M)-LUF, where M is the number of the interferer nodes **106**. The MUF **506** may include a MUF from the transmitter node **102** to the receiver node **104** and/or a MUF from the interferer nodes **106** to the receiver node **104**. The MUF from the transmitter node **102** to the receiver node **104** may also be referred to as a TX to RX MUF or a F-MUF. The MUF from the interferer nodes **106** to the receiver node **104** may also be referred to as a Interferer(1 through M) to RX MUF or a I(1 through M)-MUF, where M is the number of the interferer nodes **106**. In this regard, each of the transmitter nodes **102** and/or interferer nodes **106** may include LUF **504** and MUF **506** to the receiver node **104**.

The link analysis may include a step **624** of determining propagation losses **508** for each of the frequencies **410** in the frequency table **408**. The propagation losses **508** for each of the frequencies **410** may be determined by computing a propagation analysis using the HF propagation model **312**. The propagation losses **508** may include transmitter propagation losses from the transmitter nodes **102** to the receiver nodes **104**. The propagation losses **508** may include interferer propagation losses from the interferer nodes **106** to the receiver nodes **104**.

The link analysis may include a step **626** of determining a plurality of received powers **702** (e.g., Rcv'd power) at the receiver node **106** for each of the frequencies **410**. The received powers **702** may also be referred to as a receiver signal level or a signal level that lands at the receiver node at the selected frequency. The received powers **702** may be computed for signals from the transmitter nodes **102** to the receiver nodes **104** (e.g., for the communication link **108**). The received powers **702** may be computed for signals from the interferer nodes **106** to the receiver nodes **104** (e.g., for the interfering signal **110**). The received powers **702** may be determined by computing a link budget. For example, the link budget may include a transmit power of a node (e.g., EIRP **404**) minus propagation losses **508** between the node (e.g., transmitter nodes **102**, interferer nodes **106**) and the receiver node **104**. The received powers **702** and/or link budgets may be computed for a range of frequencies in the frequency table **406** at a given time of day. The received powers **702** may then indicate signals that the transmitter node **102** and/or the interferer node **106** may land at the receiver node **104**.

The received powers **702** may be determined for every transmitter node **102**, receiver node **104**, and interferer node **106** of the system **100**. The received power **702** may also be determined for every frequency **410** in the frequency table **406**. The received power **702** may also be determined for hours during the day. In this regard, a large number of received powers **702** may be determined.

In a step **630**, the frequencies above the MUF of the transmitter node (e.g., TX to RX MUF or F-MUF) are discarded. The frequencies **410** below the LUF of the transmitter node (e.g., TX to RX LUF or F-LUF) may also be discarded. Discarding the frequencies above the F-MUF and below the F-LUF may be beneficial to reduce the total number of available frequencies required for processing. The frequencies above the F-MUF and below the F-LUF may be discarded to determine a subset **704** of the frequencies **410** and/or received powers **702**. The transmitter node will then not use a frequency above the F-MUF or below the F-LUF after discarding frequencies above the F-MUF and below the F-LUF.

In a step **640**, a plurality of receive sensitivities **706** of the receiver node are determined. Receive sensitivity may refer to the lowest signal that the receiver node **104** can hear. The receiver node **104** is unable to hear signals below the receive sensitivity. The receive sensitivity may be based on an architecture of the receiver node, robustness of the waveform employed, and frequency of operation, and is not intended to be limiting. The receive sensitivities **706** of the receiver node may be determined for each frequency between the LUF and the MUF of the transmitter node. For example, the receive sensitivities **706** of the receiver node may be determined for the subset **704**. In this regard, the receive sensitivities **706** are not determined for the frequencies below the F-LUF or above the F-MUF.

In a step **650**, the received powers **702** at the receiver node which are less than the receive sensitivities **706** are discarded to determine a subset **708**. The received powers **702** being less than the receive sensitivities **706** indicates the receiver node **104** is unable to receive the signal (e.g., the communication link **108** and/or the interfering signal **110** is below the receive sensitivity). There is no point using frequencies with receiver signal levels below the receiver sensitivity because even if the transmitter node may transmit a signal to the receiver node which is higher than the interferer node on that frequency, the receiver node is unable to hear the signal due to limitations with the receiver sensitivity. The subset **708** of available frequencies in the frequency table **406** has now been reduced based on the LUF between the transmitter node and the receiver node, the MUF between the transmitter node and the receiver node, and the receive sensitivity.

In embodiments, the entries may be separated into desired signal entries and interferer entries subsequent to the step **650**. The desired signal entries and the corresponding interferer entries may then be ordered based on frequency (low to high or high to low).

In a step **660**, the received power **702** of the signal from the transmitter node **102** to the receiver node **104** (e.g., TX to RX communication link **108**) is compared with each of the received powers **702** of the signals from the interferer nodes to the receiver node (e.g., Interferer to RX interfering signal **110**) for every frequency in the subset **708**. If any of the interferer entries are above the signal entry at a given frequency then the given frequency cannot be used. The interferer node may interfere with the transmit signal if the signal level from the transmitter node to the receiver node to is less than the signal level from the interferer node to the receive node.

If the received power **702** of the signal from the transmitter node **102** to the receiver node **104** is greater than all of the received powers of the signals from the interferer nodes to the receiver node at a given frequency, then the given frequency may be added to a short-listed frequency table or a subset **710**. The subset **710** may be a subset of the subset **704** and/or the subset **708**. If the received power **702** of the signal from the transmitter node **102** to the receiver node **104** is less than any of the received powers of the signals from the interferer nodes to the receiver node at a given frequency, then the given frequency is discarded from the subset **710**.

The received power of the signal from the transmitter node **102** to the receiver node **104** may be compared with all of the received powers of the signals from the interferer nodes to the receiver node by computing a link margin for every frequency. The link margin may refer to a difference between the desired signal and the interfering signal and for every interfering node. The link margin may be measured in dB. Higher link margins may indicate the given frequency has a higher probability of surviving interfering. The subset **710** may also include link margins over the strongest interferer. The strongest interferer may refer to interferer node with the highest received power at the receiver node.

Thus, the subset **710** includes frequencies which are between the MUF and LUF of the transmitter, are able to be received by the receiver, and have a link margin over the strongest interferer. In this regard, the subset **710** may be determined by discarding any of the subset **704** in which the received powers from the transmitter node to the receiver node are below the receive sensitivities **706** and in which the received powers from the transmitter node to the receiver node are below the received powers from the interferer nodes to the receiver node.

In embodiments, the subset **710** may be sorted based on the link margin. For example, the subset **710** may be sorted such that frequencies with the highest link margin are at the top of the subset **710**.

In a step **670**, the software-defined radio **204** is tuned to a frequency and listen for interference on that frequency. The software-defined radio **204** may be tuned to any of the frequencies in the subset **710**. In embodiments, the software-defined radio **204** is tuned to the frequency with the highest link margin over the interfering nodes. If the interference is greater than a threshold, the software-defined radio may tune to the frequency with the next highest link margin in the subset **710** and listen for interference at that frequency.

In a step **680**, the software-defined radio **204** uses the frequency with interference below the threshold to establish the communication link **108** with the receiver node **106**.

Referring now to FIG. **8**, a flow diagram of a method **800** is described, in accordance with one or more embodiments of the present disclosure. The method **800** may describe an optional step which is performed on the subset **710** between the step **660** and the step **670** of the method **600**.

In embodiments, the subset **710** or short-listed frequency table may be split into a primary list and a secondary list based on the MUF between the interferer nodes **106** and the receiver node **104** (e.g., I-MUF). The frequencies in the subset **710** may be compared with the MUFs **504** (e.g., Interferer to RX or I-MUF). Frequencies in the subset **710** below the I-MUF may be added to the primary list. Frequencies in the subset **710** above the I-MUF may be added to the secondary list.

The interferer node **106** is unable to guarantee that the interfering signal **110** will propagate from the interferer node **106** to the receiver node **104** at frequencies above the I-MUF. In this regard, the interferer node may not pick frequencies to transmit the interfering signal **110** that are above the I-MUF to prevent wasting interfering resources.

In a step **820**, the primary list and the secondary list may be sorted based on link margin. For example, the primary list and the secondary list may be sorted such that the highest link margins are first in the table.

In a step **832**, the short-list or subset **710** may be recreated by appending the secondary list to the primary list. Notably, the short-list or subset **710** is now in a different order due to appending the secondary list to the primary list. Appending may refer to adding the frequencies from the secondary list after the frequency in the primary list. The method **800** may then proceed to step **670** using the subset **710** with the secondary list appended to the primary list. In this case, the transmitter node **102** is unsure of the behavior of the interferer node **106**. For example, the transmitter node **102** is unsure if the interferer node **106** will transmit above the I-MUF.

In another instantiation or a step **834**, the short-list or subset **710** may be recreated by appending the primary list to the secondary list. The method **800** may then proceed to step **670** using the subset **710** with the primary list appended to the secondary list. In this case, the transmitter node **102** is sure of the behavior of the interferer node **106**. For example, the transmitter node **102** is sure that the interferer node **106** will not transmit the interfering signal **110** at frequencies above the I-MUF of the interferer node **106**. The transmitter node **102** may then select frequencies above the I-MUF with the highest link margin (e.g., the secondary list). The primary frequencies are appended to the secondary frequencies to provide a backup in case none of the secondary frequencies are available.

Referring now to FIG. **9**, an HF Mission Planner **900** is described, in accordance with one or more embodiments of the present disclosure. The HF Mission Planner **900** may include the frequency selection algorithm **408**. The embodiments and enabling technologies described previously herein may also be implemented by the HF Mission Planner **900**.

The HF Mission Planner **900** may simulate a mission with different sets of parameters. The parameters may include, but are not limited to, Sun Spot Cycle Period **902** (e.g., a SSN ranging between 0 and 200 or more), a time of the year **904** (e.g., Month, Summer, Winter, Fall, Spring), diurnal cycle **906** (e.g., Dusk, Dawn, Day, Night, and/or time of day), background noise **908** (e.g., location, frequency), interferer configurations **910** (e.g., interferer position, interferer EIRP), transmitter configurations **912** (transmitter node placement, transmitter node EIRP), frequency table **914**, and the like.

In embodiments, the HF Mission Planner **900** may determine the short-listed frequency table or the subset **710** for several hours of communication. In this regard, the subset **710** may include frequencies which are expected to be successfully received over the interfering signal **110**. The frequencies may change between hours throughout the diurnal cycle. The subset **710** with several hours of the frequencies may be referred to as an hourly frequency table, although this is not intended to be limiting.

The HF Mission Planner **900** may output a graphical user interface **916** based on the inputs. The graphical user interface **916** may indicate whether the transmitter nodes are able to establish communication in the presence of the interferer nodes. The graphical user interface **916** may indicate whether communication may work during a mission. The mission may then be implemented using the frequency table **914** with confidence that the BLOS communications will survive interfering from the interferer nodes. The graphical user interface **916** may also provide different transmitter and/or interferer configurations.

The HF mission planner **900** may be used for offensive mission planning. In offensive mission planning, attacking transmitter and attacking receiver node placements may be tested against defensive interferer placements. The HF mission planner **900** may select frequencies and node assets with required EIRP to see if communication may occur in the presence of interfering. The HF mission planner **900** may determine the optimal placement of the transmitter node and receiver node to ensure communication in the presence of interferer nodes. For example, the HF mission planner **900** may determine the placement by iteratively changing the positions of the transmitter node and receiver node until one or more of the frequencies is received above the interfering signal **110**.

The HF mission planner **900** may be used for defensive mission planning. In defensive mission planning, interferer node placements may be tested against interferer transmitter node and interferer receiver node deployments. The HF mission planner **900** may determine if the interferers are successful in interfering with other communication. The HF mission planner **900** may determine the optimal placement of the interferer nodes for denying the communication link **108** (e.g., deny HF BLOS communication) between the transmitter node and the receiver node positioned in a given airspace.

Referring generally again to FIGS. **1-9**.

The waveform protocol stack **300** may include date, time, Sun Spot Number (SSN), transmitter configuration, receiver configuration, and/or interferer configuration. The transmitter configuration may include (position (e.g., latitude, longitude), EIRP, beamwidth, axial direction, and the like). The receiver configuration may include a position (e.g., latitude, longitude), receiver sensitivity, and the like. The interferer configuration may include information about known interferers (position (e.g., latitude, longitude), EIRP, beamwidth, axial direction, and the like). The waveform may also receive interferer configuration updates. The interferer configuration updates may be received over the air (in-band and/or out-of-band).

The method **600** may or may not include discarding interferer signals which are above the MUF of the interferer or below the LUF of the interferer. In this regard, frequencies which are above the MUF of the interferer or below the LUF of the interferer may still propagate from the interferer node to the receiver node but with higher path loss and/or with a likelihood of being lost to space. In embodiments, the higher path loss may be accounted for in a link budget.

In some instances, the subset **710** may be empty indicating that there is no frequency usable to survive the interfering configuration at the given date and time.

Because networks configured in accordance with embodiments of the inventive concepts disclosed herein use a TDMA based waveform, an interruption mechanism can be implemented to interrupt a transmission in progress at time slot boundaries. Since a TDMA transmission is bounded within the time slot boundary, a node can interrupt another node at slot boundaries even if the next slot is not assigned to the interrupting node.

The methods, operations, and/or functionality disclosed may be implemented as sets of instructions or software readable by a device. The steps may include computations which may be performed simultaneously, in parallel, or sequentially. Further, it is understood that the specific order or hierarchy of steps in the methods, operations, and/or functionality disclosed are examples of exemplary approaches. Based upon design preferences, it is understood that the specific order or hierarchy of steps in the methods, operations, and/or functionality can be rearranged while remaining within the scope of the inventive concepts disclosed herein. The accompanying claims may present elements of the various steps in a sample order, and are not necessarily meant to be limited to the specific order or hierarchy presented. It is to be understood that embodiments of the methods according to the inventive concepts disclosed herein may include one or more of the steps described herein. Further, such steps may be carried out in any desired order and two or more of the steps may be carried out simultaneously with one another. Two or more of the steps disclosed herein may be combined in a single step, and in some embodiments, one or more of the steps may be carried out as two or more sub-steps. Further, other steps or sub-steps may be carried in addition to, or as substitutes to one or more of the steps disclosed herein.

A processor may include any processing unit known in the art. For example, the processor may include a multi-core processor, a single-core processor, a reconfigurable logic device (e.g., FPGAs), a digital signal processor (DSP), a special purpose logic device (e.g., ASICs)), or other integrated formats. Those skilled in the art will recognize that 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 skilled in the art in light of this disclosure. Such hardware, software, and/or firmware implementation may be a design choice based on various cost, efficiency, or other metrics. In this sense, the processor(s) may include any microprocessor-type device configured to execute software algorithms and/or instructions. In general, the term "processor" may be broadly defined to encompass any device having one or more processing elements, which execute program instructions from memory, from firmware, or by hardware implemented functions. It should be recognized that the steps described throughout the present disclosure may be carried out by the processors.

A memory may include any storage medium known in the art. For example, the storage medium may include a non-transitory memory medium. For instance, the non-transitory memory medium may include, but is not limited to, a read-only memory (ROM), a random-access memory (RAM), a magnetic or optical memory device (e.g., disk), a solid-state drive and the like. It is further noted that memory may be housed in a common controller housing with the one or more processor(s). For example, the memory and the processor may be housed in a processing unit, a desktop computer, or the like. In an alternative embodiment, the memory may be located remotely with respect to the physical location of the processor. In another embodiment, the memory maintains program instructions for causing the processor(s) to carry out the various steps described through the present disclosure. For example, the program instructions may include a frequency selection algorithm, an HF mission planner, and the like.

From the above description, it is clear that the inventive concepts disclosed herein are well adapted to carry out the objects and to attain the advantages mentioned herein as well as those inherent in the inventive concepts disclosed herein. While presently preferred embodiments of the inventive concepts disclosed herein have been described for purposes of this disclosure, it will be understood that numerous changes may be made which will readily suggest themselves to those skilled in the art and which are accomplished within the broad scope and coverage of the inventive concepts disclosed and claimed herein.

What is claimed:

1. A software-defined radio comprising:

a memory maintaining program instructions; and

one or more processors configured to execute the program instructions causing the one or more processors to:

determine a first lowest usable frequency (LUF) and a first maximum usable frequency (MUF), wherein the first LUF and the first MUF are from a transmitter node to a receiver node;

determine a first plurality of received powers at the receiver node for a plurality of frequencies in a high-frequency (HF) band, wherein the first plurality of received powers are signals from the transmitter node;

determine a second plurality of received powers at the receiver node for the plurality of frequencies, wherein the second plurality of received powers are signals from an interferer node;

determine a first subset of the plurality of frequencies by discarding any of the plurality of frequencies which are above the first MUF and by discarding any of the plurality of frequencies which are below the first LUF;

determine a plurality of receive sensitivities of the receiver node for each of the first subset; and

determine a second subset of the first subset by discarding any of the first subset in which the first plurality of received powers are below the plurality of receive sensitivities and in which the first plurality of received powers are below the second plurality of received powers.

2. The software-defined radio of claim **1**, wherein the plurality of frequencies are from a frequency table maintained in the memory.

3. The software-defined radio of claim **1**, wherein the first plurality of received powers are determined by the one or more processors determining a first plurality of propagation losses between the transmitter node and the receiver node for each of the plurality of frequencies and computing a first plurality of link budgets for each of the plurality of frequencies using the first plurality of propagation losses; and

wherein the second plurality of received powers are determined by the one or more processors determining a second plurality of propagation losses between the interferer node and the receiver node for each of the plurality of frequencies and computing a second plurality of link budgets for each of the plurality of frequencies using the second plurality of propagation losses.

4. The software-defined radio of claim **1**, wherein the one or more processors are configured to determine a plurality of link margins for the second subset based on the first plurality of received powers, the second plurality of received powers, and the plurality of receive sensitivities.

5. The software-defined radio of claim **1**, wherein the software-defined radio is configured to cause the transmitter node to communicate with the receiver node using a time division multiple access (TDMA) waveform at a first frequency of the second subset; wherein the first frequency includes a highest link margin of the second subset.

6. The software-defined radio of claim **5**, wherein the TDMA waveform is more resilient than waveform number 0 Walsh Mode defined in MIL-STD-188-110D.

7. The software-defined radio of claim **5**, wherein the software defined radio is further configured to tune to the first frequency and listen for interference; detect the interference is below a threshold; and cause the transmitter node to communicate with the receiver node using the TDMA waveform at the first frequency in response to detecting the interference is below the threshold.

8. The software-defined radio of claim **5**, wherein the software defined radio is further configured to tune to the first frequency and listen for interference; detect the interference is above a threshold; and cause the transmitter node to communicate with the receiver node using the TDMA waveform at a second frequency of the second subset in response to detecting the interference is below the threshold; wherein the second frequency has a second highest link margin of the second subset.

9. The software-defined radio of claim **1**, wherein the one or more processors are configured to determine a second

MUF and a second LUF; wherein the second MUF and the second LUF are between the interferer node and the receiver node.

10. The software-defined radio of claim **9**, wherein the one or more processors are configured to determine a primary list and a secondary list based on the second subset; wherein the primary list comprises each frequency in the second subset below the second MUF; wherein the secondary list comprises each frequency in the second subset above the second MUF; wherein the one or more processors are configured to sort the primary list and the secondary list based on link margin.

11. The software-defined radio of claim **10**, the one or more processors are configured to generate a frequency table by appending the secondary list to the primary list.

12. The software-defined radio of claim **10**, the one or more processors are configured to generate a frequency table by appending the primary list to the secondary list.

13. The software-defined radio of claim **1**, wherein the first MUF indicates a probability of propagation between the transmitter node and the receiver node may be maintained on 50 percent of days of a month.

14. A method comprising:

determining a first lowest usable frequency (LUF) and a first maximum usable frequency (MUF), wherein the first LUF and the first MUF are from a transmitter node to a receiver node;

determining a first plurality of received powers at the receiver node for a plurality of frequencies in a high-frequency (HF) band, wherein the first plurality of received powers are signals from the transmitter node;

determining a second plurality of received powers at the receiver node for the plurality of frequencies, wherein the second plurality of received powers are signals from an interferer node;

determining a first subset of the plurality of frequencies by discarding any of the plurality of frequencies which are above the first MUF and by discarding any of the plurality of frequencies which are below the first LUF;

determining a plurality of receive sensitivities of the receiver node for each of the first subset; and

determining a second subset of the first subset by discarding any of the first subset in which the first plurality of received powers are below the plurality of receive sensitivities and in which the first plurality of received powers are below the second plurality of received powers.

15. The method of claim **14**, comprising causing the transmitter node to communicate with the receiver node

using a time division multiple access (TDMA) waveform at a first frequency of the second subset; wherein the first frequency includes a highest link margin of the second subset.

16. A HF mission planner comprising:

a memory maintaining program instructions; and

one or more processors configured to execute the program instructions causing the one or more processors to:

determine a first lowest usable frequency (LUF) and a first maximum usable frequency (MUF), wherein the first LUF and the first MUF are from a transmitter node to a receiver node;

determine a first plurality of received powers at the receiver node for a plurality of frequencies in a high-frequency (HF) band, wherein the first plurality of received powers are signals from the transmitter node;

determine a second plurality of received powers at the receiver node for the plurality of frequencies, wherein the second plurality of received powers are signals from an interferer node;

determine a first subset of the plurality of frequencies by discarding any of the plurality of frequencies which are above the first MUF and by discarding any of the plurality of frequencies which are below the first LUF;

determine a plurality of receive sensitivities of the receiver node for each of the first subset; and

determine a second subset of the first subset by discarding any of the first subset in which the first plurality of received powers are below the plurality of receive sensitivities and in which the first plurality of received powers are below the second plurality of received powers.

17. The HF mission planner of claim **16**, wherein the program instructions are configured to cause the one or more processors to generate the second subset for a plurality of hours in a diurnal cycle.

18. The HF mission planner of claim **16**, wherein the program instructions are configured to determine placement of the transmitter node and the receiver node to ensure communication in the presence of the interferer node.

19. The HF mission planner of claim **16**, wherein the program instructions are configured to determine placement of the interferer node to deny the signals from the transmitter node to the receiver node.

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