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(54) **INTERFERENCE AND/OR CLUTTER CANCELLATION USING CROSS-CHANNEL EQUALIZATION**

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H04L 25/03 (2006.01)

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CPC ***H04L 27/01*** (2013.01); ***H04L 25/03343*** (2013.01); *H04L 2025/03426* (2013.01)

(58) **Field of Classification Search**
CPC H04L 27/01; H04L 25/03343; H04L 2025/03426
See application file for complete search history.

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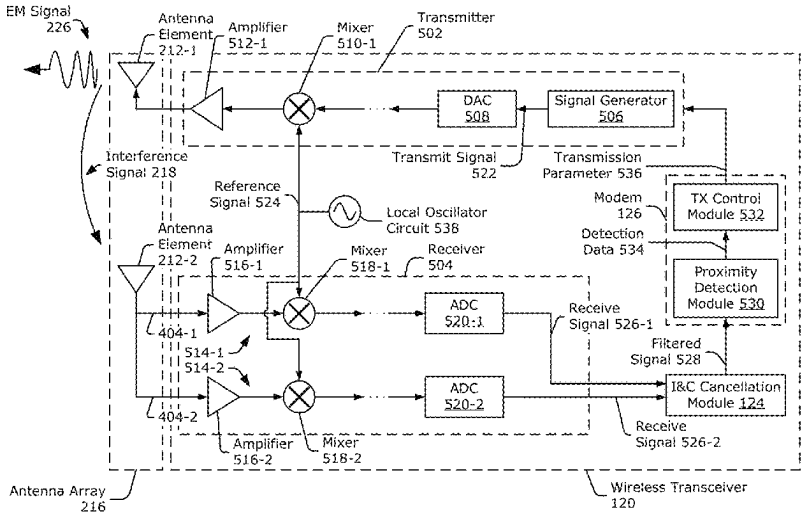
(57) **ABSTRACT**

An apparatus is disclosed that implements interference and/or clutter cancellation using cross-channel equalization. In example aspects, the apparatus includes a wireless transceiver configured to be connected to multiple feed ports. The wireless transceiver is also configured to transmit an electromagnetic signal using a first feed port of the multiple feed ports. A modulated spur is generated based on the transmission of the electromagnetic signal. The wireless transceiver is additionally configured to receive two versions of a receive signal respectively via two feed ports of the multiple feed ports. The receive signal comprises the modulated spur and a mutual-coupling component associated with the transmission of the electromagnetic signal. The wireless transceiver is further configured to generate a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization.

30 Claims, 10 Drawing Sheets



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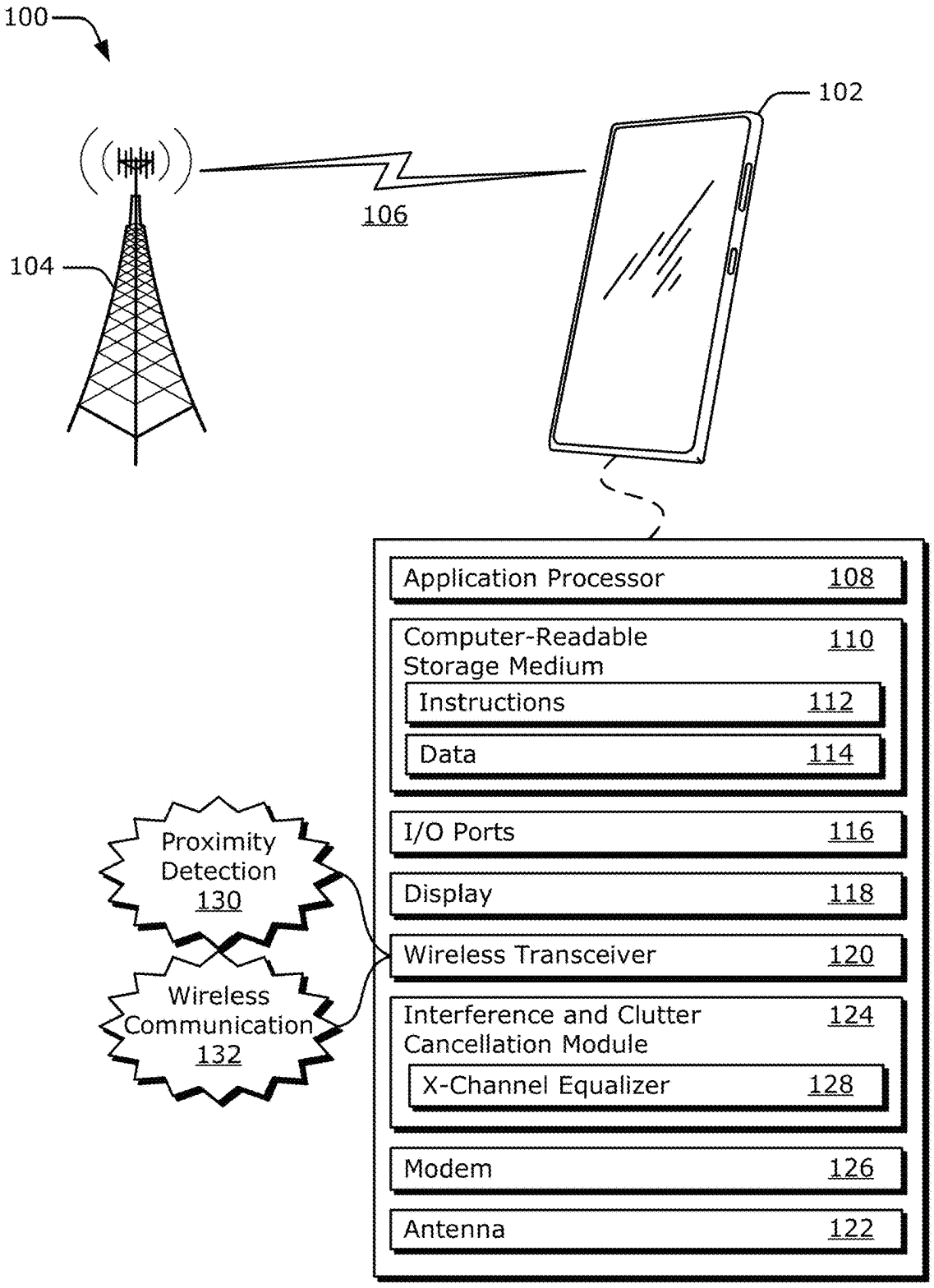
100
102
106
104
Application Processor 108
Computer-Readable Storage Medium 110
Instructions 112
Data 114
I/O Ports 116
Display 118
Wireless Transceiver 120
Interference and Clutter Cancellation Module 124
X-Channel Equalizer 128
Modem 126
Antenna 122
Proximity Detection 130
Wireless Communication 132

FIG. 1

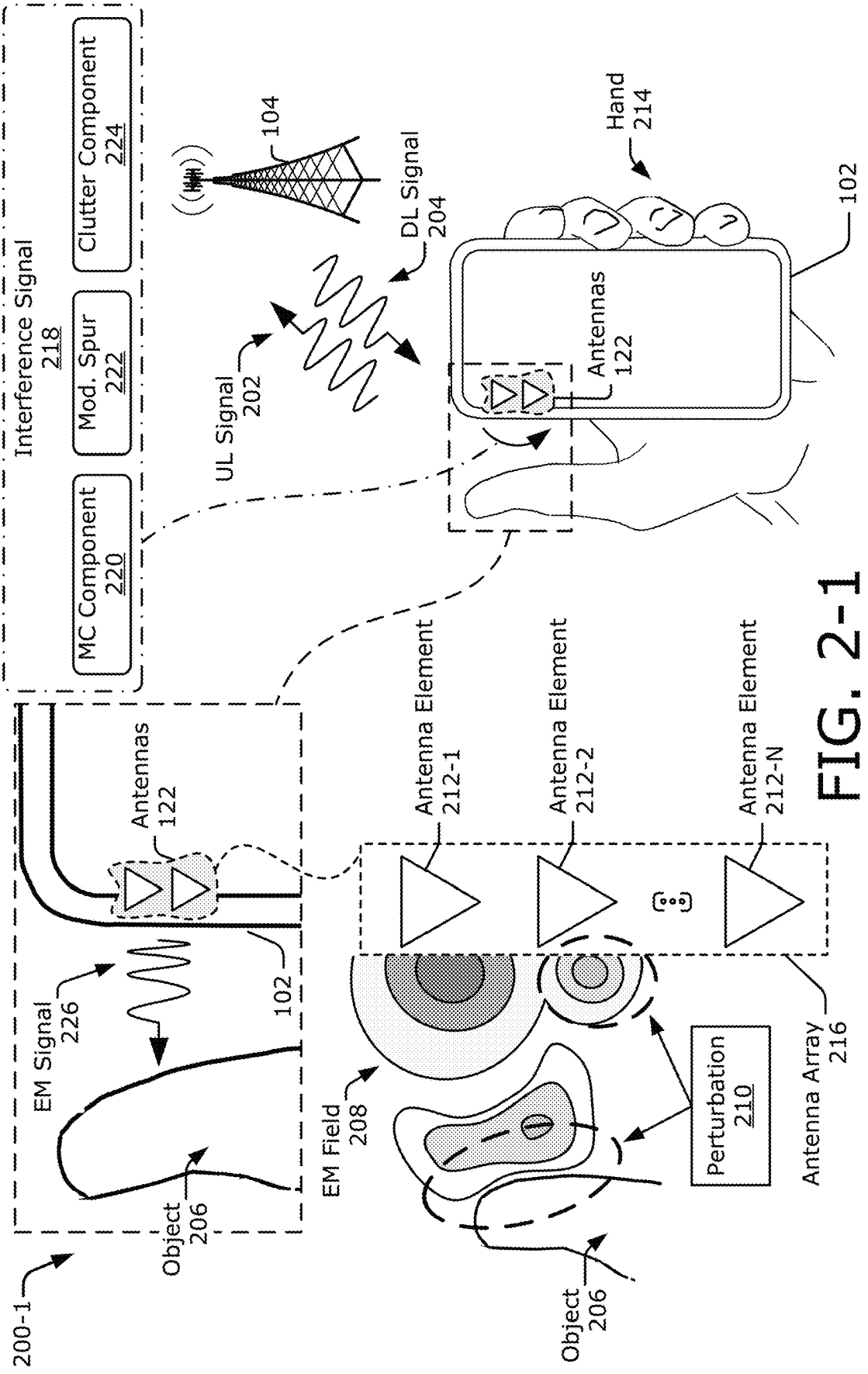
200-1
Object 206
EM Signal 226
Antennas 122
102
Interference Signal 218
MC Component 220
Mod. Spur 222
Clutter Component 224
104
UL Signal 202
DL Signal 204
Hand 214
102
Antennas 122
EM Field 208
Antenna Element 212-1
Antenna Element 212-2
Antenna Element 212-N
Perturbation 210
Antenna Array 216
Object 206

FIG. 2-1

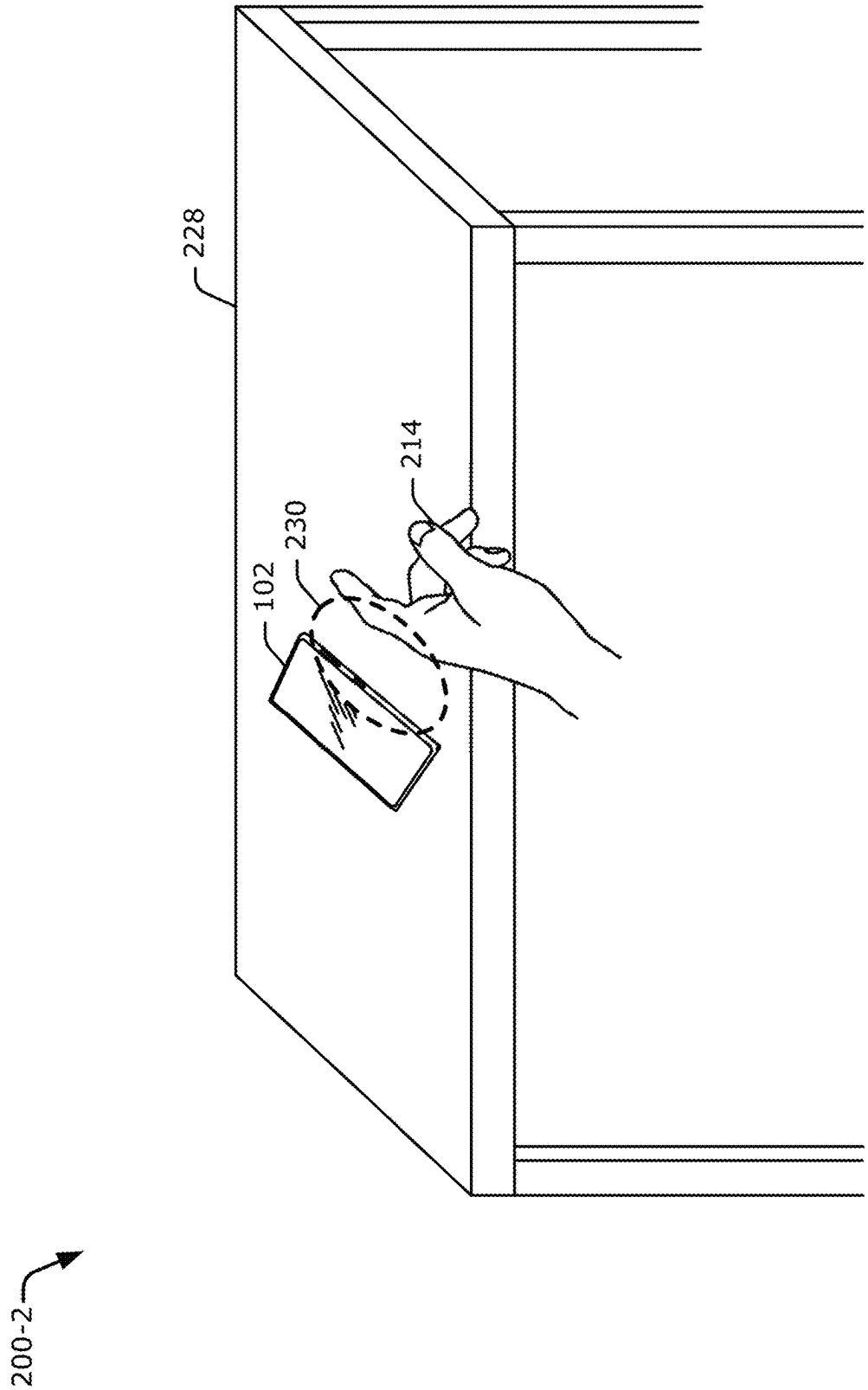

FIG. 2-2

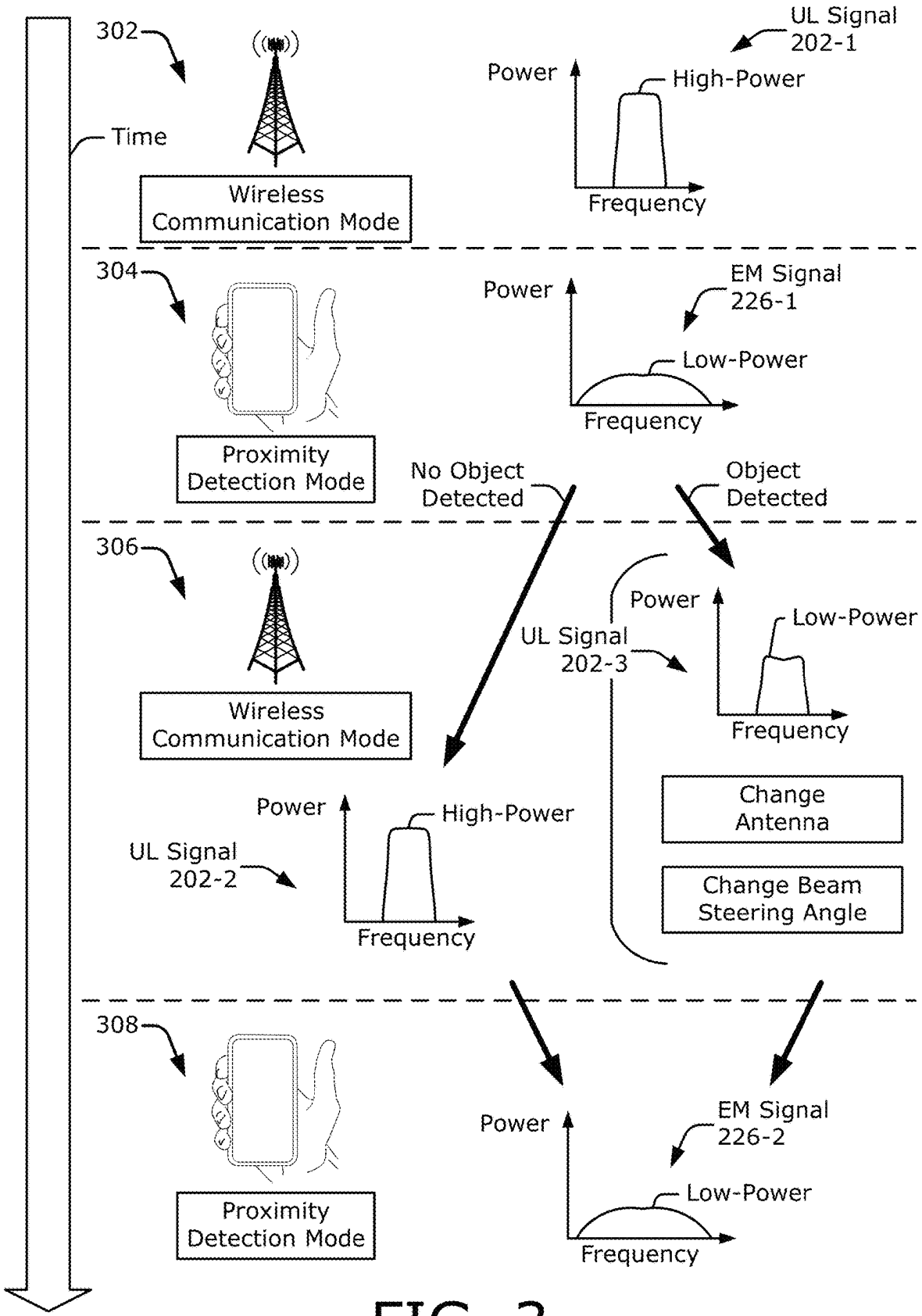
302
Time
Wireless Communication Mode
UL Signal 202-1
Power
High-Power
Frequency
304
Proximity Detection Mode
Power
EM Signal 226-1
Low-Power
Frequency
No Object Detected
Object Detected
306
Wireless Communication Mode
Power
Low-Power
UL Signal 202-3
Frequency
Change Antenna
Change Beam Steering Angle
Power
High-Power
UL Signal 202-2
Frequency
308
Proximity Detection Mode
Power
EM Signal 226-2
Low-Power
Frequency

FIG. 3

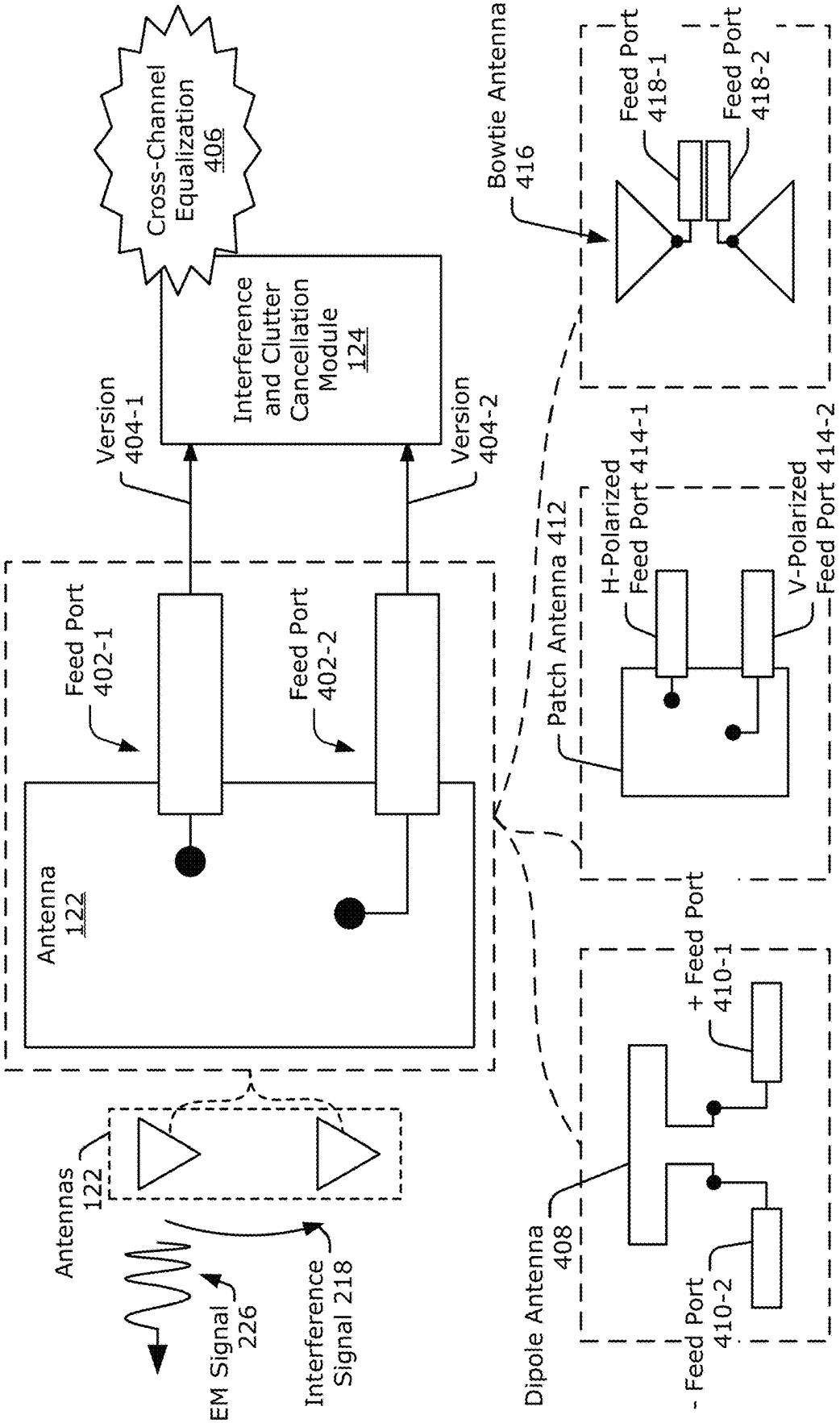
Cross-Channel Equalization 406
Interference and Clutter Cancellation Module 124
Version 404-1
Version 404-2
Feed Port 402-1
Feed Port 402-2
Antenna 122
Antennas 122
EM Signal 226
Interference Signal 218
Bowtie Antenna 416
Feed Port 418-1
Feed Port 418-2
Patch Antenna 412
H-Polarized Feed Port 414-1
V-Polarized Feed Port 414-2
Dipole Antenna 408
+ Feed Port 410-1
- Feed Port 410-2

FIG. 4

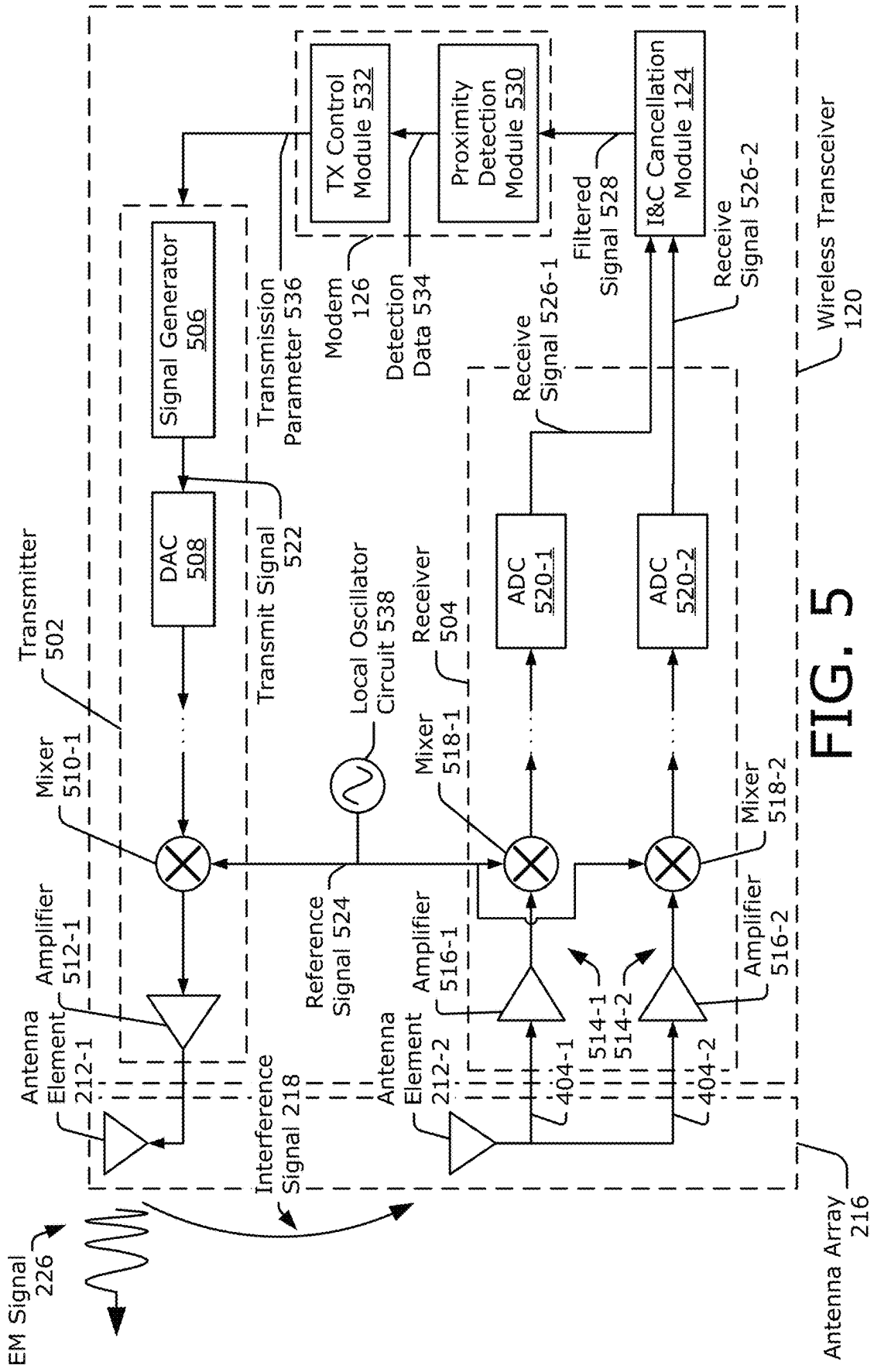
EM Signal 226
Antenna Array 216
Wireless Transceiver 120
Transmitter 502
Receiver 504
Antenna Element 212-1
Antenna Element 212-2
Amplifier 512-1
Amplifier 516-1
Amplifier 516-2
Mixer 510-1
Mixer 518-1
Mixer 518-2
Local Oscillator Circuit 538
Signal Generator 506
DAC 508
ADC 520-1
ADC 520-2
TX Control Module 532
Proximity Detection Module 530
I&C Cancellation Module 124
Modem 126
Transmission Parameter 536
Transmit Signal 522
Reference Signal 524
Interference Signal 218
Detection Data 534
Receive Signal 526-1
Filtered Signal 528
Receive Signal 526-2
404-1
404-2
514-1
514-2

FIG. 5

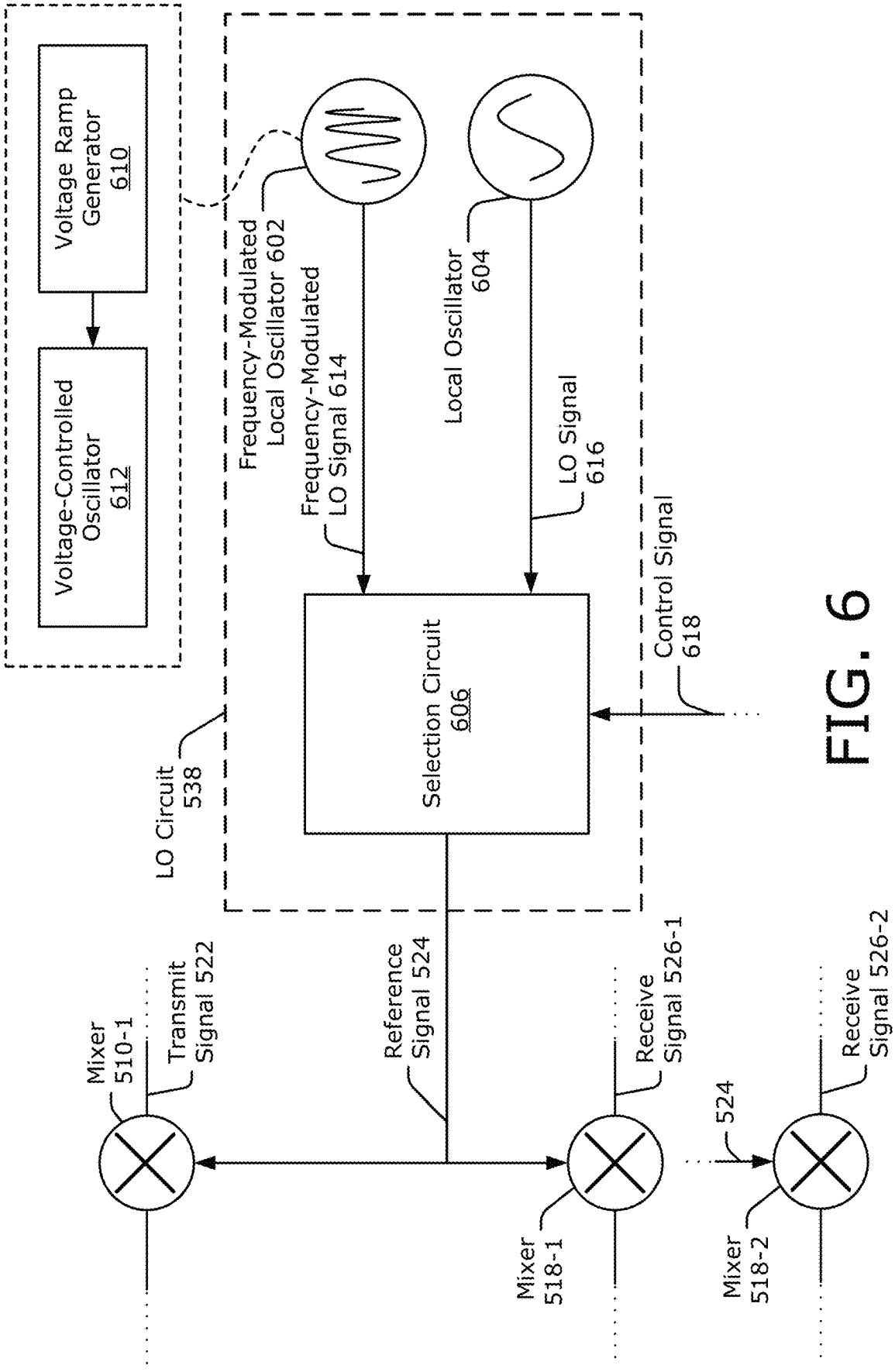
Voltage Ramp Generator 610
Voltage-Controlled Oscillator 612
Frequency-Modulated Local Oscillator 602
Frequency-Modulated LO Signal 614
Local Oscillator 604
LO Signal 616
Control Signal 618
LO Circuit 538
Selection Circuit 606
Reference Signal 524
Mixer 510-1
Transmit Signal 522
Receive Signal 526-1
Mixer 518-1
524
Receive Signal 526-2
Mixer 518-2

FIG. 6

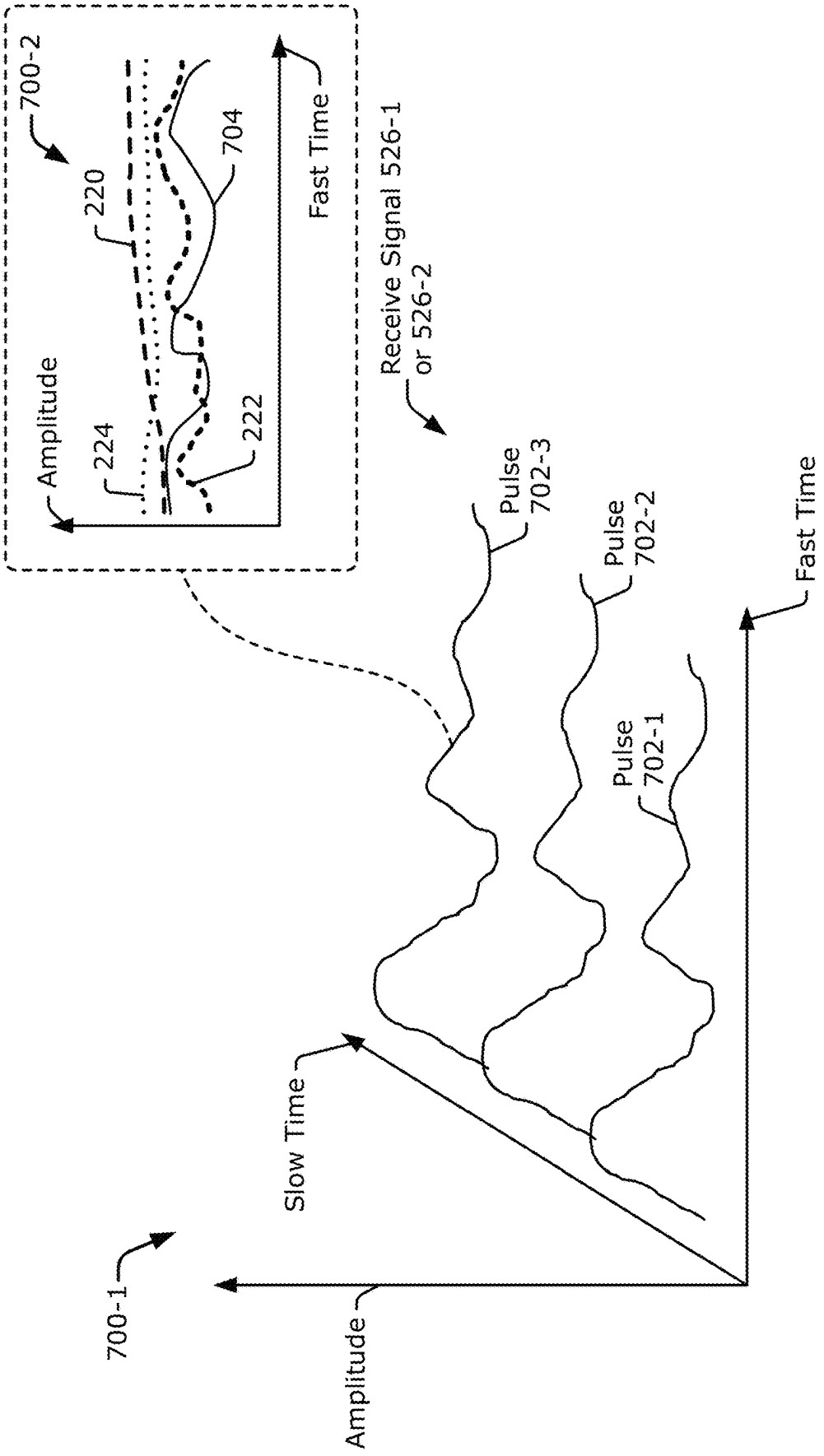
700-1
Amplitude
Slow Time
Fast Time
Pulse 702-1
Pulse 702-2
Pulse 702-3
Receive Signal 526-1 or 526-2
700-2
Amplitude
Fast Time
220
224
222
704

FIG. 7

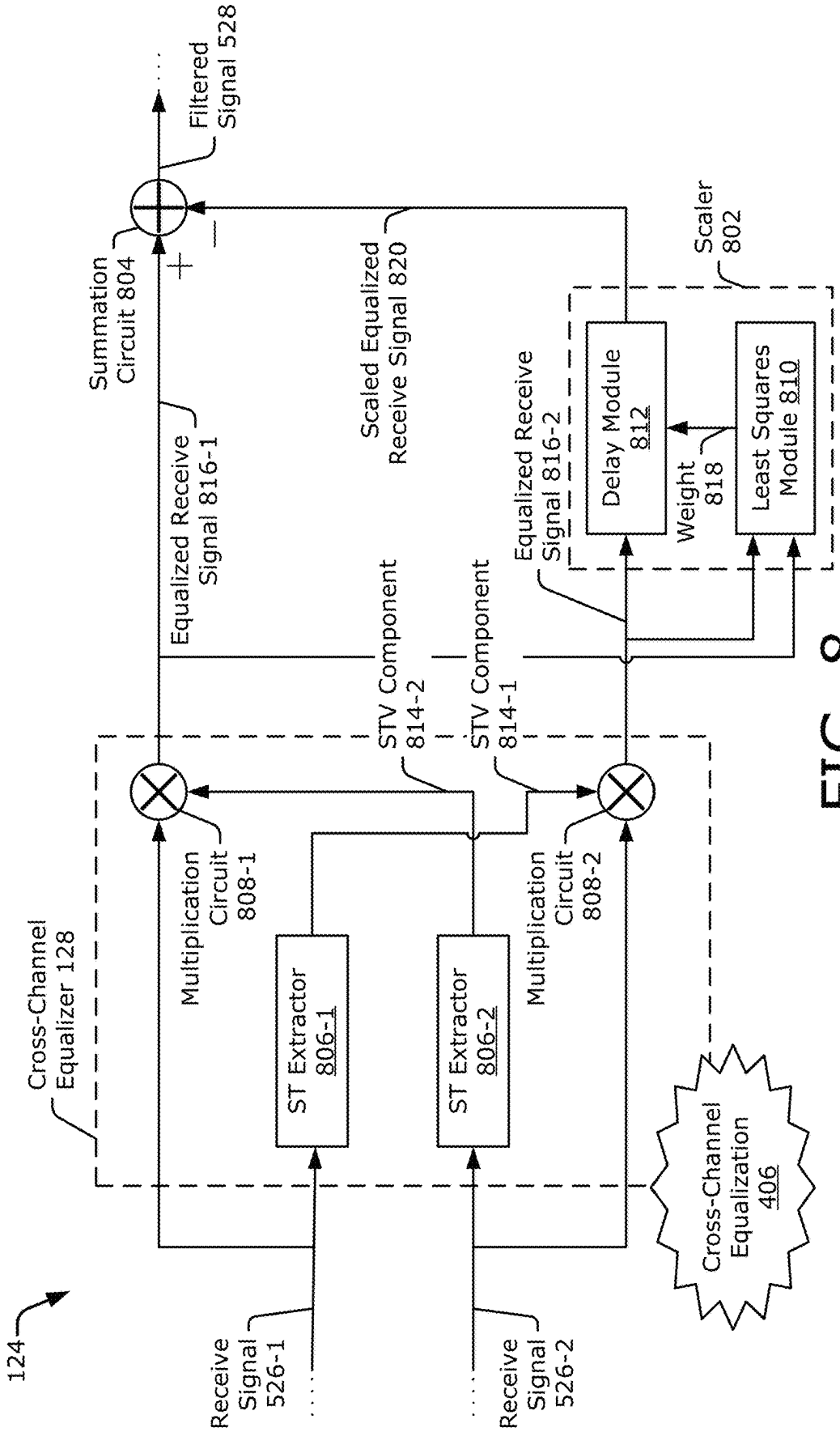
124
Receive Signal 526-1
Receive Signal 526-2
Cross-Channel Equalizer 128
ST Extractor 806-1
ST Extractor 806-2
Multiplication Circuit 808-1
Multiplication Circuit 808-2
STV Component 814-2
STV Component 814-1
Equalized Receive Signal 816-1
Equalized Receive Signal 816-2
Scaled Equalized Receive Signal 820
Summation Circuit 804
Filtered Signal 528
Scaler 802
Delay Module 812
Weight 818
Least Squares Module 810
Cross-Channel Equalization 406

FIG. 8

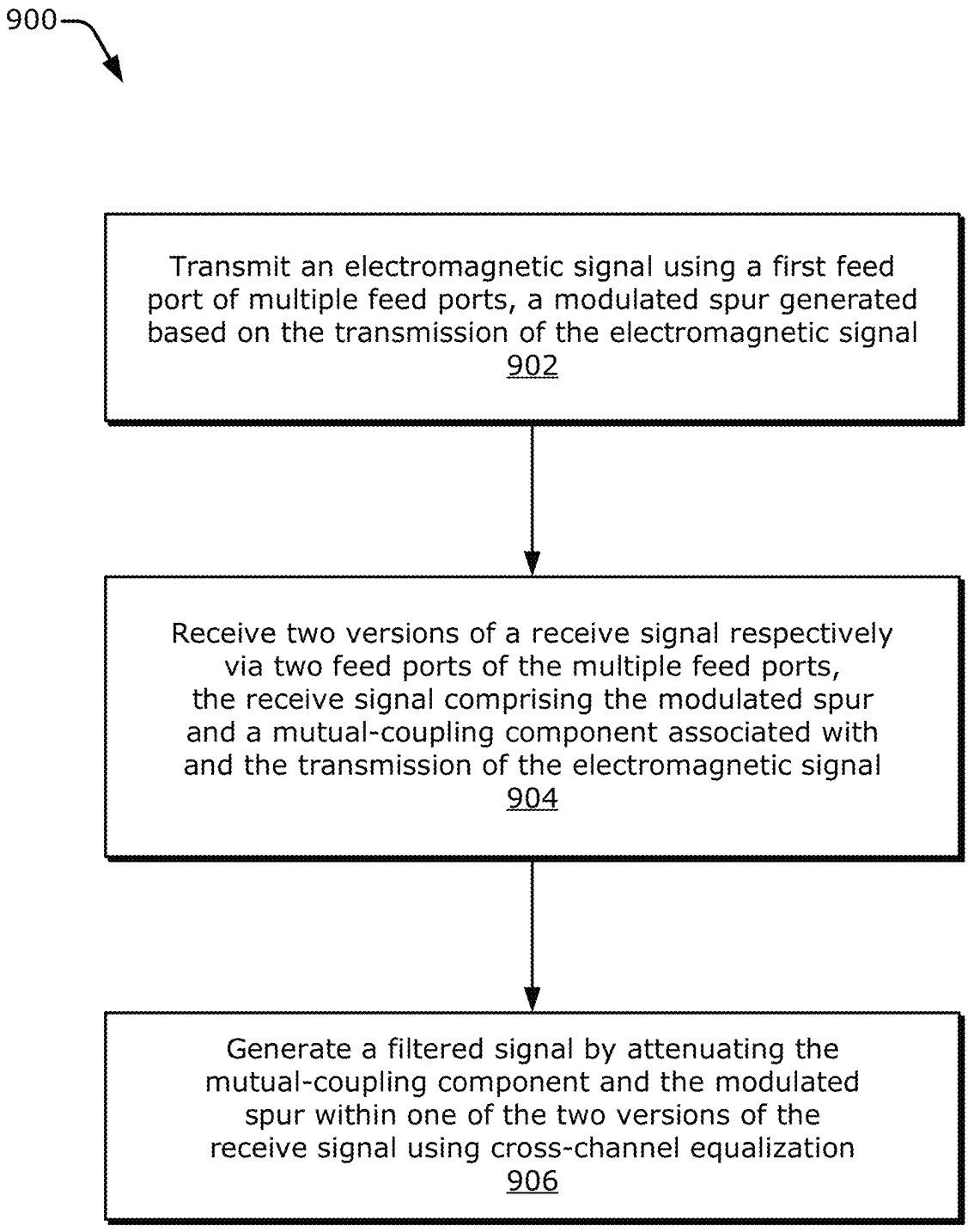
900
Transmit an electromagnetic signal using a first feed port of multiple feed ports, a modulated spur generated based on the transmission of the electromagnetic signal
902
Receive two versions of a receive signal respectively via two feed ports of the multiple feed ports, the receive signal comprising the modulated spur and a mutual-coupling component associated with and the transmission of the electromagnetic signal
904
Generate a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization
906

FIG. 9

INTERFERENCE AND/OR CLUTTER CANCELLATION USING CROSS-CHANNEL EQUALIZATION

CROSS-REFERENCE TO RELATED APPLICATION(S)

This application claims the benefit of U.S. Provisional Application No. 63/373,838, filed 29 Aug. 2022, the disclosure of which is hereby incorporated by reference in its entirety herein.

TECHNICAL FIELD

This disclosure relates generally to wireless transceivers and, more specifically, to attenuating self-made interference and/or environmental clutter within a receiver.

BACKGROUND

To increase transmission rates and throughput, cellular and other wireless networks are using signals with higher frequencies and smaller wavelengths. As an example, 5^{th}-generation (5G)-capable devices communicate with networks using frequencies that include those at or near the extremely-high frequency (EHF) spectrum (e.g., frequencies greater than 25 gigahertz (GHz)) with wavelengths at or near millimeter wavelengths. These signals have various technological challenges, such as higher path loss as compared to signals for earlier generations of wireless communications. In certain scenarios it can be difficult for a 5G wireless signal to travel far enough to make cellular communications feasible at these higher frequencies.

Transmit power levels can be increased or beamforming can concentrate energy in a particular direction to compensate for the higher path loss. These types of compensation techniques, however, increase power densities. The Federal Communications Commission (FCC) has determined a maximum permitted exposure (MPE) limit to accommodate these higher power densities. To meet targeted guidelines based on this MPE limit, devices balance performance with transmission power and other considerations. This balancing act can be challenging to realize given cost, size, functional design objectives and/or involved constraints.

SUMMARY

An apparatus is disclosed that implements interference and/or clutter cancellation using cross-channel equalization. In example implementations, a computing device employs proximity detection to detect nearby objects and adjusts transmission parameters for wireless communication based on relative positions of these objects. The computing device includes an interference and clutter cancellation module to attenuate or suppress self-made interference and/or environmental clutter. The self-made interference can include slow time-varying mutual coupling between antennas and/or fast time-varying modulated spurs generated during proximity detection. The environmental clutter represents another type of slow time-varying signal component. To attenuate the interference and/or clutter, the interference and clutter cancellation module employs cross-channel equalization, which equalizes the slow time-varying components across at least two channels of a receiver. After cross-channel equalization, one of the channels is used as a reference to cancel the slow time-varying component and/or fast time-varying component that is present within the other channel. This cancellation enables detection of weak reflections to be processed for proximity detection and a desired false-alarm rate to be realized.

In an example aspect, an apparatus is disclosed. The apparatus includes a wireless transceiver configured to be connected to multiple feed ports. The wireless transceiver is configured to transmit an electromagnetic signal using a first feed port of the multiple feed ports. A modulated spur is generated based on the transmission of the electromagnetic signal. The wireless transceiver is also configured to receive two versions of a receive signal respectively via two feed ports of the multiple feed ports. The receive signal comprises a mutual-coupling component associated with the transmission of the electromagnetic signal and the modulated spur. The wireless transceiver is additionally configured to generate a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization.

In an example aspect, an apparatus is disclosed. The apparatus includes means for transmitting an electromagnetic signal using a first feed port of multiple feed ports. A modulated spur is generated based on the transmission of the electromagnetic signal. The apparatus also includes means for receiving two versions of a receive signal respectively via two feed ports of the multiple feed ports. The receive signal comprises the modulated spur and a mutual-coupling component associated with the transmission of the electromagnetic signal. The apparatus additionally includes means for generating a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization.

In an example aspect, a method for interference and/or clutter cancellation using cross-channel equalization is disclosed. The method includes transmitting an electromagnetic signal using a first feed port of multiple feed ports. A modulated spur is generated based on the transmission of the electromagnetic signal. The method also includes receiving two versions of a receive signal respectively via two feed ports of the multiple feed ports. The receive signal comprises the modulated spur and a mutual-coupling component associated with the transmission of the electromagnetic signal. The method additionally includes generating a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization.

In an example aspect, an apparatus is disclosed. The apparatus includes a wireless transceiver configured to be connected to multiple feed ports. The wireless transceiver is configured to transmit an electromagnetic signal using a first feed port of the multiple feed ports. A modulated spur is generated based on the transmission of the electromagnetic signal. The modulated spur comprises a fast time-varying component having a magnitude or phase that varies substantially within a duration of a pulse of the electromagnetic signal. The wireless transceiver is also configured to receive two versions of a receive signal respectively via two feed ports of the multiple feed ports. The receive signal comprises the modulated spur. The wireless transceiver is further configured to satisfy a target false-alarm rate in the presence of the modulated spur.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** illustrates an example operating environment for interference and/or clutter cancellation using cross-channel equalization.

FIG. **2-1** illustrates an example operating environment for performing proximity detection using cross-channel equalization.

FIG. **2-2** illustrates another example operating environment for performing proximity detection using cross-channel equalization.

FIG. **3** illustrates an example sequence flow diagram for proximity detection using cross-channel equalization.

FIG. **4** illustrates multiple examples of an antenna for interference and/or clutter cancellation using cross-channel equalization.

FIG. **5** illustrates examples of a wireless transceiver, an interference and clutter cancellation module, and a modem for interference and/or clutter cancellation using cross-channel equalization.

FIG. **6** illustrates an example local oscillator circuit for supporting proximity detection and wireless communication.

FIG. **7** illustrates an example plot of a receive signal for interference and clutter cancellation using cross-channel equalization.

FIG. **8** illustrates an example implementation of an interference and clutter cancellation module for interference and/or clutter cancellation using cross-channel equalization.

FIG. **9** is a flow diagram illustrating an example process for interference and/or clutter cancellation using cross-channel equalization.

DETAILED DESCRIPTION

Current high-frequency and small-wavelength communications balance performance with a need to meet the Federal Communications Commission's maximum permitted exposure limit (e.g., the FCC's MPE limit). Inefficient balancing can prevent devices from taking full advantage of increased data rates (e.g., those enabled by 5G wireless communications). Because exposure is affected by a proximity of a user to a device's antenna, however, techniques described in this document enable greater wireless performance while staying within the FCC's MPE limit. To do so, these techniques detect a user's proximity to a device. Based on the detected proximity, the device can balance a power density of transmitted wireless signals with the requirement to meet the MPE limit. As a result, the device is permitted to transmit wireless signals with higher average power levels, which enables the wireless signals to travel farther, such as between a smart phone and a remote cellular base station. Devices and techniques described herein may additionally or alternatively be used to comply with radio frequency exposure requirements promulgated by an organization or jurisdiction outside of the United States.

Some proximity-detection techniques may use a dedicated sensor to detect the user, such as a camera or an infrared sensor. However, these sensors may be bulky or expensive. Furthermore, a single electronic device can include multiple antennas that are positioned on different surfaces (e.g., on a top, a bottom, or opposite sides). To account for each of these antennas, multiple cameras or sensors may need to be installed near each of these antennas, which further increases a cost and size of the electronic device.

In contrast, techniques for proximity detection with interference and/or clutter cancellation using cross-channel equalization are described herein. The described techniques utilize a wireless transceiver and antennas within a computing device to perform proximity detection and optionally determine a relative position of an object (e.g., a range and/or angle to the object). With proximity detection, a transmission parameter that is used for wireless communication can be adjusted to enable the wireless transceiver to meet guidelines promulgated by the government or the wireless industry, such as a Maximum Permitted Exposure (MPE) limit as determined by the Federal Communications Commission (FCC). Furthermore, by actively detecting an object's relative position, a surrounding environment can be continually monitored and the transmission parameter can be incrementally adjusted to account for movement by the object while achieving a desired false-alarm rate. Additionally, devices and techniques described herein may additionally or alternatively be used for or modified for purposes other than exposure compliance, for example to detect objects other than a user, to map an environment, for other forms of radio frequency (RF) or millimeter-wave (mmW) sensing, for sensor assisted communication or joint communicating and sensing, etc.

Due to a proximity of the antennas with respect to each other, the antennas can be mutually coupled such that energy leaks between a transmitting antenna and a receiving antenna. During proximity detection, this mutual coupling can raise a noise floor of the wireless transceiver and make it challenging to detect objects. The wireless transceiver can also receive modulated spurs (or modulated spurious signals), which are generated by the wireless transceiver during transmission. Additionally or alternatively, the wireless transceiver can receive reflections of clutter within an external environment. During proximity detection, the computing device can incorrectly identify the modulated spur and/or environmental clutter as an object-of-interest, which can degrade the false-alarm-rate performance of the computing device.

To detect the object in the presence of this self-made interference and/or environmental clutter, an interference and clutter cancellation module of the computing device processes at least two receive signals in such a way as to suppress or attenuate slow time-varying components (e.g., the mutual coupling or environmental clutter) and/or fast time-varying components (e.g., the modulated spurs) within at least one of the two receive signals. The at least two receive signals can be obtained from at least two feed ports that are associated with a same antenna or different antennas. To attenuate the interference and/or clutter, the interference and clutter cancellation module employs cross-channel equalization, which equalizes the slow time-varying components across the at least two receive signals. After cross-channel equalization, one of the equalized receive signals is used as a reference to cancel the slow time-varying component and/or fast time-varying component within the other equalized receive signal. This cancellation enables detection of weak reflections to be processed for proximity detection and enables the computing device to realize a desired false-alarm rate.

Some embodiments may offer a relatively inexpensive approach that can utilize existing transceiver hardware and antennas. The interference and clutter cancellation module may marginally impact a design of the wireless transceiver and can be implemented in software or hardware. The described techniques need not utilize a calibration procedure or training sequence (e.g., those involving a characterization of a mutual coupling channel, a modulated spur, or clutter). Instead, estimations of the interference and/or environmental clutter is made in real-time, thereby enabling responsive adaptation to various changes, including changes in antenna impedance (e.g., changes in a proximity of a user's hand to an antenna), antenna load variations (e.g., changes in solar

loading), or changes in the environment. With this adaptive capability, proximity detection can be performed using a variety of different antenna designs or antenna array configurations.

In some implementations, the computing device may be utilized in stand-alone proximity-detection applications. For example, the computing device can be implemented as an automotive bumper sensor to assist with parking or autonomous driving. As another example, the computing device can be installed on a drone to provide collision avoidance. In other implementations, the computing device can selectively perform proximity detection or wireless communication. In such cases, dual-use of components within the wireless transceiver of a computing device may be enabled, which decreases cost and size of the wireless transceiver, as well as the computing device. Based on the proximity detection, and as described herein, transmission parameters can be adjusted for wireless communication to enable the wireless transceiver to meet safety guidelines promulgated by the government or the wireless industry, such as the MPE limit as determined by the FCC.

FIG. **1** illustrates an example environment **100** for interference and clutter cancellation using cross-channel equalization. In the environment **100**, a computing device **102** communicates with a base station **104** through a wireless communication link **106** (wireless link **106**). In this example, the computing device **102** is depicted as a smartphone. However, the computing device **102** can be implemented as any suitable computing or electronic device, such as a modem, a cellular base station, a broadband router, an access point, a cellular phone, customer premises equipment (CPE), a gaming device, a navigation device, a media device, a laptop computer, a desktop computer, a tablet computer, a wearable computer, a server, a network-attached storage (NAS) device, a smart appliance or other internet of things (IoT) device, a medical device, a vehicle-based communication system, a radar, a radio apparatus, and so forth.

The base station **104** communicates with the computing device **102** via the wireless link **106**, which can be implemented as any suitable type of wireless link. Although depicted as a tower of a cellular network, the base station **104** can represent or be implemented as another device, such as a satellite, a server device, a terrestrial television broadcast tower, an access point, a peer-to-peer device, another smartphone, a mesh network node, and so forth. Therefore, the computing device **102** may communicate with the base station **104** or another device via a wireless connection.

The wireless link **106** can include a downlink of data or control information communicated from the base station **104** to the computing device **102**, an uplink of other data or control information communicated from the computing device **102** to the base station **104**, or both a downlink and an uplink. The wireless link **106** can be implemented using any suitable communication protocol or standard, such as 2^{nd}-generation (2G), 3^{rd}-generation (3G), 4^{th}-generation (4G), or 5^{th}-generation (5G) cellular; IEEE 802.11 (e.g., Wi-Fi®); IEEE 802.15 (e.g., Bluetooth® or UWB); IEEE 802.16 (e.g., WiMAX®); and so forth. In some implementations, the wireless link **106** may wirelessly provide power and the base station **104** or the computing device **102** may comprise a power source.

As shown, the computing device **102** includes an application processor **108** and a computer-readable storage medium **110** (CRM **110**). The application processor **108** can include any type of processor, such as a multi-core processor, that executes processor-executable code stored by the CRM **110**. The CRM **110** can include any suitable type of data storage media, such as volatile memory (e.g., random access memory (RAM)), non-volatile memory (e.g., Flash memory), optical media, magnetic media (e.g., disk), and so forth. In the context of this disclosure, the CRM **110** is implemented to store instructions **112**, data **114**, and other information of the computing device **102**, and thus does not include transitory propagating signals or carrier waves.

The computing device **102** can also include input/output ports **116** (I/O ports **116**) and a display **118**. The I/O ports **116** enable data exchanges or interaction with other devices, networks, or users. The I/O ports **116** can include serial ports (e.g., universal serial bus (USB) ports), parallel ports, audio ports, infrared (IR) ports, user interface ports such as a sensing portion of a touchscreen, and so forth. The display **118** presents graphics of the computing device **102**, such as a user interface associated with an operating system, program, or application. Alternatively or additionally, the display **118** can be implemented as a display port or virtual interface, through which graphical content of the computing device **102** is presented, and/or the display **118** can be omitted.

A wireless transceiver **120** of the computing device **102** provides connectivity to respective networks and other electronic devices connected therewith. The wireless transceiver **120** can facilitate communication over any suitable type of wireless network, such as a wireless local area network (WLAN), peer-to-peer (P2P) network, mesh network, cellular network, ultra-wideband (UWB) network, wireless wide-area-network (WWAN), and/or wireless personal-area-network (WPAN). In the context of the example environment **100**, the wireless transceiver **120** enables the computing device **102** to communicate with the base station **104** and networks connected therewith. However, the wireless transceiver **120** can also enable the computing device **102** to communicate "directly" with other devices or networks.

The wireless transceiver **120** includes circuitry and logic for transmitting and receiving signals via an antenna **122**. Components of the wireless transceiver **120** can include amplifiers, switches, mixers, analog-to-digital converters, digital-to-analog converters, filters, and so forth for conditioning signals (e.g., for generating or processing signals). The wireless transceiver **120** can also include logic to perform in-phase/quadrature (I/Q) operations, such as synthesis, encoding, modulation, decoding, demodulation, and so forth. In some cases, components of the wireless transceiver **120** are implemented as separate transmitter and receiver entities. Additionally or alternatively, the wireless transceiver **120** can be realized using multiple or different sections to implement respective transmitting and receiving operations (e.g., separate transmit and receive chains). In general, the wireless transceiver **120** processes data and/or signals associated with communicating data of the computing device **102** over the antenna **122** and/or processes signals associated with proximity detection.

In the example shown in FIG. **1**, the computing device **102** includes at least one interference and clutter cancellation module **124** and at least one modem **126**. The interference and clutter cancellation module **124** can be a separate module or integrated within the wireless transceiver **120** and/or the modem **126**. In general, the interference and clutter cancellation module **124** can be incorporated in or realized using software, firmware, hardware, fixed logic circuitry, or combinations thereof. The interference and clutter cancellation module **124** can be implemented within an integrated circuit or as part of the modem **126** or other electronic component of the computing device **102**. In some

implementations, the modem **126** may execute computer-executable instructions that are stored within the CRM **110** to implement the interference and clutter cancellation module **124**.

In operation, the interference and clutter cancellation module **124** can cancel self-made interference (e.g., interference due to mutual coupling or modulated spurs) as well as environmental clutter to enable detection of relatively weak signal components that are analyzed for proximity detection. Attenuating the self-made interference and environmental clutter also enables the computing device **102** to operate within a target false-alarm rate. To achieve this, the interference and clutter cancellation module **124** implements an adaptive scheme that can estimate both slow time-varying components and fast time-varying components for subsequent cancellation. The slow time-varying components vary detectably in magnitude and/or phase across successive pulses (e.g., across an inter-pulse period (IPP) of an electromagnetic signal **226**). The fast time-varying components vary detectably in magnitude and/or phase within each pulse (e.g., across a duration of each pulse of the electromagnetic signal **226**). In comparison, the fast time-varying components vary appreciably more in magnitude and/or phase relative to the slow time-varying components across a given pulse (or during a given pulse). The amount of variation in magnitude or phase can be approximately 5% or more (e.g., approximately 10%, 20%, 50% or more) of a median value for a given time frame.

The interference and clutter cancellation module **124** includes at least one cross-channel equalizer **128** (x-channel equalizer **128**), which can at least partially implement cross-channel equalization. In particular, the cross-channel equalizer equalizes the slow time-varying components across at least two receive channels. This equalization enables the interference and clutter cancellation module **124** to use one of the receive channels as a reference channel to cancel the slow time-varying component and/or fast time-varying component from the other receive channel. By cancelling these components, the interference and clutter cancellation module **124** reduces a likelihood of the computing device **102** making false detections, particularly false detections based on the slow time-varying component and/or the fast time-varying component. As a result, the computing device **102** can satisfy a target false-alarm-rate performance in the presence of mutual coupling, a modulated spur, and/or clutter. The computing device **102** satisfies a target false-alarm-rate performance by declaring fewer false alarms within a set amount of time compared to a false-alarm-rate threshold.

The modem **126**, which can be implemented as a processor, controls the wireless transceiver **120** and enables proximity detection **130** or wireless communication **132** to be performed. The modem **126** can include a portion of the CRM **110** or can access the CRM **110** to obtain computer-readable instructions. The modem **126** can include baseband circuitry to perform high rate sampling processes that can include analog-to-digital conversion, digital-to-analog conversion, Fourier transforms, gain correction, skew correction, frequency translation, and so forth. The modem **126** can provide communication data to the wireless transceiver **120** for transmission. The modem **126** can also process a baseband version of a signal obtained from the wireless transceiver **120** to generate data, which can be provided to other parts of the computing device **102** via a communication interface for proximity detection **130** or wireless communication **132**.

The computing device **102** can also include a controller (not separately shown), e.g., to realize the interference and clutter cancellation module **124**. The controller can include at least one processor and CRM, which stores computer-executable instructions (such as the application processor **108**, the CRM **110**, and the instructions **112**). The processor and the CRM can be localized at one module or one integrated circuit chip or can be distributed across multiple modules or chips. Together, a processor and associated instructions can be realized in separate circuitry, fixed logic circuitry, hard-coded logic, and so forth. The controller can be implemented as part of the wireless transceiver **120**, the modem **126**, the application processor **108**, a special-purpose processor configured to perform MPE techniques, a general-purpose processor, some combination thereof, and so forth.

In an example implementation, the wireless transceiver **120** supports proximity detection **130** and wireless communication **132**. In other words, the wireless transceiver **120** can be configured to perform proximity detection **130** during a first time interval and perform wireless communication **132** during a second time interval. In other example implementations, the wireless transceiver **120** supports proximity detection **130** and does not support wireless communication **132**. In this case, the wireless transceiver **120** can be a transceiver of a dedicated radar system, which is integrated within the computing device **102** or a stand-alone radar system. In still other example implementations, the wireless transceiver **120** supports other applications, which can benefit from aspects of interference and/or clutter cancellation using cross-channel equalization. In other examples, separate transceivers are respectively configured for proximity detection **130** and wireless communication **132**.

FIG. **2-1** illustrates an example operating environment **200-1** for proximity detection **130**. In the example environment **200-1**, a hand **214** of a user holds the computing device **102**. In one aspect, the computing device **102** communicates with the base station **104** by transmitting an uplink signal **202** (UL signal **202**) or receiving a downlink signal **204** (DL signal **204**) via the two or more antennas **122**. A user's thumb, however, can represent a proximate object **206** that may be exposed to radiation via the uplink signal **202**. Other situations are also possible in which the user represents the proximate object **206**, including those in which the user is near the computing device **102** but not physically touching the computing device **102**, as later shown in FIG. **2-2**.

To detect whether the object **206** exists or is within a detectable range, the computing device **102** generally transmits an electromagnetic (EM) signal **226** (EM signal **226**) via at least one of the antennas **122**. In a near field, the electromagnetic signal **226** can be referred to as an electromagnetic (EM) field **208**. In a far field, the electromagnetic signal **226** can be referred to as a radar transmit signal (not shown in FIG. **2-1**). In some cases, the electromagnetic signal **226** may be generated such that it includes a single frequency or tone or multiple frequencies or tones. For example, the electromagnetic signal **226** can include a frequency-modulated continuous wave (FMCW) signal (e.g., a linear frequency-modulated (LFM) continuous wave signal or chirp signal, a triangular frequency-modulated continuous wave signal, a sawtooth frequency-modulated continuous wave signal, and so forth).

The antennas **122** may be arranged via modules and/or arrays and may have a variety of configurations. For example, the antennas **122** may comprise at least two different antennas, at least two antenna elements **212** of an antenna array **216** (as shown towards the bottom of FIG.

2-1), at least two antenna elements **212** associated with different antenna arrays **216**, or any combination thereof. The antenna array **216** is shown to include multiple antenna elements **212-1** to **212**-N, where N represents a positive integer greater than one. Further, the array **216** may be a multi-dimensional array. Additionally or alternatively, the antenna array **216** may be configured for beam management techniques, such as beam determination, beam measurement, beam reporting, or beam sweeping. A distance between the antenna elements **212** in the antenna array **216** can be based on frequencies that the wireless transceiver **120** emits. For example, the antenna elements **212** in the antenna array **216** can be spaced by approximately half a wavelength from each other (e.g., by approximately half a centimeter apart for frequencies around 30 GHz). The antennas **122** may be implemented using any type of antenna, including patch antennas, dipole antennas, bowtie antennas, or a combination thereof, as further described with respect to FIG. **4**.

An example near-field case is further illustrated at the bottom left of FIG. **2-1**. Here, an amplitude of the electromagnetic field **208** is illustrated with different shades of grey, where darker shades represent higher amplitudes and lighter shades represent lower amplitudes. If the object **206** is proximate to one of the antenna elements **212** (e.g., one of the antennas **122**), interactions of the object **206** with the electromagnetic field **208** produce one or more perturbations (e.g., disturbances or changes) in the electromagnetic field **208**, such as perturbation **210**. The perturbation **210** represents a variation in a magnitude or phase of the electromagnetic field **208** due to the object **206** causing different constructive or destructive patterns to occur within the electromagnetic field **208**. In some implementations, the electromagnetic field **208** is configured such that objects **206** within approximately five centimeters (cm) can be detected, including objects within three or four centimeters. For some frequencies of the electromagnetic field **208**, this distance can be associated with a near-field region.

In the depicted example, a first antenna element **212-1** emits the electromagnetic field **208**, and a second antenna element **212-2** senses the perturbation **210** for proximity detection **130**. The second antenna element **212-2** may be co-located with respect to the first antenna element **212-1** as part of the antenna array **216** or otherwise proximate to the first antenna element **212-1**. In some cases, the second antenna element **212-2** is adjacent to the first antenna element **212-1** within a same antenna array **216** (e.g., there are no antenna elements **212** physically located between the first antenna element **212-1** and the second antenna element **212-2**). The same antennas **122** or a subset of the same antennas **122** used to communicate with the base station **104** can be used for proximity detection **130**. In other examples, one or more of the antennas **122** used for proximity detection **130** are not used for communicating with the base station **104**.

A response of the second antenna element **212-2** to the electromagnetic field **208** is affected by the object **206** reflecting or absorbing the electromagnetic field **208** and also by any mutual coupling or interference. This interference is represented by interference signal **218**, which can include a mutual-coupling component **220** (MC component **220**), a modulated spur **222** (mod. spur **222**), and/or a clutter component **224**.

The mutual-coupling component **220** represents energy that leaks between a transmitting antenna **122** and a receiving antenna **122** during proximity detection **130**. A magnitude and phase of the mutual-coupling component **220** can vary slowly across each pulse of the electromagnetic signal **226** (e.g., across each pulse of the electromagnetic field **208** or the radar transmit signal). As such, the mutual-coupling component **220** can be referred to as a slow time-varying component. Variations in the mutual-coupling component **220** can be caused, at least in part, by changes in antenna impedance or load variations. For example, such variations can occur due to a proximity of the user's hand **214** to the antennas **122**, solar loading, or temperature fluctuations.

The modulated spur **222** represents a spurious signal that is generated based on the transmission of the electromagnetic signal **226** (e.g., based on the transmission of the electromagnetic field **208** or the radar transmit signal) and is modulated in frequency similar to the electromagnetic signal **226**. The modulated spur **222** can be inherently produced by components within the wireless transceiver **120** that have realistic (e.g., non-ideal) performance characteristics. Example components that can produce a spur include amplifiers and mixers. In comparison to the mutual-coupling component **220**, a magnitude and/or phase of the modulated spur **222** can vary quickly across each pulse of the electromagnetic signal **226**. In other words, a frequency of the modulated spur **222** can be substantially higher than a frequency of the mutual-coupling component **220**. The modulated spur **222** can be referred to as a fast time-varying component.

The mutual-coupling component **220** and the modulated spur **222** can be co-linear due to their relationship to a common transmitter (e.g., because they are associated with a same transmit path). This means that the mutual-coupling component **220** and the modulated spur **222** present within one receive channel can be related to the mutual-coupling component **220** and the modulated spur **222** that is present within another receive channel by a scaling factor.

The clutter component **224** represents a portion of the electromagnetic signal **226** (e.g., the electromagnetic field **208** or the radar transmit signal) that is reflected by environmental clutter. The environmental clutter can include an object that exists outside of the computing device **102** or a component that is internal to the computing device **102**, such as a housing of the computing device **102**. In many situations, the clutter is stationary and/or present at close ranges to the antennas **122**. The clutter component **224** can have a magnitude and phase that vary slowly across each pulse of the electromagnetic signal **226**. As such, the clutter component **224** can be referred to as a slow time-varying component. The mutual-coupling component **220**, the modulated spur **222**, and the clutter component **224** are further described with respect to FIG. **6**.

In some implementations, the wireless transceiver **120** can generate the electromagnetic signal **226** via the first antenna element **212-1** during a same time that the second antenna element **212-2** is used to receive a version of the electromagnetic signal **226** (e.g., to sense the electromagnetic field **208** or receive a reflected version of the radar transmit signal). In the near-field case, energy from the electromagnetic field **208** induces a current in the second antenna element **212-2**, which is used to measure the perturbation **210** or the resulting electromagnetic field **208** that is disturbed by the object **206**. By sensing the perturbation **210**, a determination can be made as to whether the object **206** is present or outside a detectable range (e.g., not present). The detectable range may be within approximately 5 cm from the antennas **122**, between 0 and 4 cm from the antennas **122**, and so forth.

In the far-field case, the second antenna element **212-2** receives a version of the radar transmit signal that is

reflected by the object **206**. This reflected version of the radar transmit signal is referred to as a radar receive signal. The radar receive signal can have a different phase and/or frequency relative to the radar transmit signal and the interference signal **218** based on reflection properties and/or motion of the object **206**. In general, the radar receive signal contains information that can be used for detecting the object **206** and for determining a range to the object **206**.

In general, the detectable range can vary based on transmission power or sensitivity of the wireless transceiver **120**. A duration for which the electromagnetic signal **226** is generated can also be based on the detectable range. Example durations can range from approximately one microsecond to several tens of microseconds.

In the far-field case, the detectable range can include ranges that can be readily measured using radar-based techniques. In the near-field case, however, the detectable range can include ranges that are not readily measured using radar-based techniques. For example, the radar-based techniques can be limited to ranges that are farther than a minimum range, which is proportional to a bandwidth of the FMCW signal. Example minimum ranges include 4 cm or 2 cm for a FMCW signal having a bandwidth of 4 GHz or 8 GHz, respectively. Therefore, to detect closer distances using radar-based techniques, the wireless transceiver **120** generates larger bandwidth signals at an expense of increased design complexity or increased cost of the wireless transceiver **120**. Using the described techniques, however, the range to the object **206** can be measured at distances closer than these minimum ranges. In this way, the described techniques can be used to augment close-range detection even if radar-based techniques are used for far-range detection.

A propagation distance between the antenna element **212** and the object **206** and a partial absorption of the electromagnetic signal **226** via the object **206** may cause the received signal (e.g., the sensed perturbation **210** or the radar receive signal) to be weaker relative to the interference signal **218**. In general, responses of the receiving antennas **122** contain information that can be used for detecting the object **206** and optionally determining a relative position of the object **206** (e.g., determining a range and/or angle to the object **206**).

In one aspect, the interference signal **218** can exist within the responses of the receiving antennas **122** due to a direct or indirect coupling between the transmitting antenna **122** and the receiving antennas **122** (e.g., the antennas **122** are mutually coupled). In the depicted configuration, the antennas **122** are co-located or otherwise proximate to one another. Due to this proximity, the antennas **122** are mutually coupled electromagnetically such that a portion of the energy that is radiated via one of the antennas **122** generates interference that makes it challenging to detect the object **206** (assuming the object **206** is present). In another aspect, the interference signal **218** additionally or alternatively exists within the response due to a direct or indirect coupling between a transmitter, which generates the electromagnetic signal **226**, and a receiver, which receives the antenna response.

In some cases, the interference signal **218** is significantly stronger in magnitude than a portion of a received signal that is associated with the object **206** (e.g., a portion of the receive signal that is associated with the perturbation **210** or the radar receive signal). As such, the interference signal **218** can prevent the computing device **102** from detecting the object **206**, absent implementation of a technique to cancel (e.g., attenuate or suppress) the interference signal **218**. For example, the portion of the receive signal that is associated with the object **206** can be obscured by sidelobes of the interference signal **218**. The interference and clutter cancellation module **124**, however, attenuates the interference signal **218** to enable the object **206** to be detected (if present) in the presence of mutual coupling **220**, modulated spurs **222**, and/or environmental clutter **224**. This attenuation also enables the computing device **102** to avoid false detections, including in situations in which the object **206** is not present. Based on the proximity detection **130**, a transmission parameter can be adjusted for use during wireless communication **132**.

FIG. **2-2** illustrates another example operating environment **200-2** for performing proximity detection **130**. In contrast to the environment **200-1** of FIG. **2-2**, the computing device **102** is not held by the user in environment **200-2**. In the example environment **200-2**, the computing device **102** is positioned on a table **228** (or more generally a surface) and is within arm's reach to the user. Other situations are also possible, such as the computing device **102** being propped up on a table and the user watching a video on the computing device **102** from a distance.

As the user moves around within a proximity of the computing device **102**, their hand **214** can move into a detectable range, as indicated at **230**. By performing proximity detection **130** with cross-channel equalization, the computing device **102** can detect the user's hand **214** and attenuate any interference signals **218**. An example sequence of the computing device **102** switching between proximity detection **130** and wireless communication **132** is further described with respect to FIG. **3**.

FIG. **3** illustrates an example sequence flow diagram for proximity detection **130**, with time elapsing in a downward direction. Examples of a wireless communication mode are shown at **302** and **306**, and examples of a proximity detection mode are shown at **304** and **308**. The proximity detection mode can occur at fixed time intervals, between active data cycles that occur during wireless communication **132**, at predetermined times as set by the modem **126**, as part of an initialization process before wireless communications **132** occur, responsive to detection of device movement, or based on indications that the user may be proximate to the device (e.g., based on the wireless transceiver **120** observing a decrease in power in a downlink signal **204** or the application processor **108** determining that the user is interacting with the display **118** of the computing device **102**), etc.

At **302**, the wireless transceiver **120** transmits a high-power (e.g., normal) uplink signal **202-1** configured to provide sufficient range to a destination, such as a base station **104**. After transmitting the uplink signal **202-1**, the electromagnetic signal **226-1** (or proximity detection signal) is transmitted via the wireless transceiver **120** and the antennas **122** at **304**. As described above, the electromagnetic signal **226** enables the computing device **102** to detect an object **206** and determine if the object **206** is near the computing device **102**. In this case, the electromagnetic signal **226-1** is represented by a low-power wide-band signal. Based on a detection, the wireless transceiver **120** can adjust a transmission parameter for a next uplink signal **202** to account for MPE compliance guidelines.

The proximity detection mode can also determine the range to the object **206** in some examples, thereby enabling transmission of the uplink signal **202** to comply with range-dependent guidelines, such as a maximum power density. Because power density is proportional to transmit power and inversely proportional to range, an object **206** at a closer

range is exposed to a higher power density than another object **206** at a farther range for a same transmit power level. Therefore, a similar power density at the object **206** can be achieved by increasing the transmit power level if the object **206** is at a farther range and decreasing the transmit power level if the object **206** is at a closer range. In this way, the wireless transceiver **120** can adjust transmission of the uplink signal **202** to enable the power density at the object **206** for both the closer range and the farther range to be below the maximum power density. At the same time, because the range is known, the transmit power level can be increased to a level that facilitates wireless communication **132** and comports with the compliance guideline.

At **306**, the wireless transceiver **120** transmits a next uplink signal **202**. In the depicted example, a high-power uplink signal **202-2** is transmitted if an object **206** is not detected. Alternatively, a low-power uplink signal **202-3** is transmitted if the object **206** is detected. The low transmit power can be, for example, between approximately five and twenty decibel-milliwatts (dBm) less than the high-power signal at **302**. In addition to or instead of changing a power of the next uplink signal **202**, the uplink signal **202** can be transmitted using a different antenna within the computing device **102** or using a different beam steering angle (e.g., different than the antennas **122** or the beam steering angle used for transmitting the uplink signal **202-1** at **302**). Although not shown, the wireless transceiver **120** can alternatively skip the wireless communication mode at **306** and perform another proximity detection mode using another antenna **122** or a different transmit power level to detect objects **206** at various locations or distances around the computing device **102**. While certain operations were described above based on a range to the object **206**, it will be appreciated that operations in the wireless communication mode at **306** or adjustments made pursuant to the proximity detection mode at **304** may be based merely upon whether the object **206** is present or not, irrespective of the range thereto.

At **308**, the wireless transceiver **120** and antennas **122** transmit another electromagnetic signal **226-2** (e.g., another proximity detection signal) to attempt to detect the object **206**. By scheduling multiple proximity detection modes over some time period, transmission of the uplink signal **202** can be dynamically adjusted based on a changing environment or movement by the object **206**. Furthermore, appropriate adjustments can be made to balance communication performance with compliance or radiation requirements.

The sequence described above can also be applied to other antennas. The other antennas and the antennas **122** may transmit multiple electromagnetic signals **226** sequentially or in parallel. To enable proximity detection **130** in the presence of self-made interference and/or environmental clutter, the wireless transceiver **120** receives antenna responses via at least two feed ports, which are further described with respect to FIG. **4**.

FIG. **4** illustrates an example antenna **122** for interference and/or clutter cancellation using cross-channel equalization and three example implementations thereof. The example antenna **122** illustrated in FIG. **4** can be used to implement either of the antennas **122** (e.g., a transmitting antenna or a receiving antenna). In general, the antenna **122** in FIG. **4** is described with respect to a receiving antenna **122**. In the depicted configuration (in the top half of FIG. **4**), the antenna **122** includes multiple feed ports **402**, such as a first feed port **402-1** and a second feed port **402-2**. The response of the antenna **122** to the electromagnetic signal **226** is separated into multiple versions **404**, such as versions **404-1** and **404-2** respectively obtained via the feed ports **402-1** and **402-2**. Although similar, the multiple versions **404** of the antenna response vary due to differences in a type of feed port **402** or differences due to location or orientation of the feed ports **402-1** and **402-2**. These versions **404-1** and **404-2** are used by the interference and clutter cancellation module **124** to perform cross-channel equalization **406**, which is further described with respect to FIG. **8**.

Three example types of antenna **122** are depicted towards the bottom of FIG. **4**. In one example, the antenna **122** comprises a dipole antenna **408**, which includes a pair of differential feed ports **410** (e.g., a positive (+) feed port **410-1** and a negative (−) feed port **410-2**). Thus, the feed ports **402-1** and **402-2** can be implemented using the differential feed ports **410-1** and **410-2** such that the versions **404-1** and **404-2** are out-of-phase with respect to each other (e.g., differ in phase by approximately 180 degrees). As another example, the antenna **122** comprises a patch antenna **412**, which includes a horizontally-polarized feed port **414-1** and a vertically-polarized feed port **414-2**. Accordingly, the versions **404-1** and **404-2** have orthogonal polarities if the feed ports **402-1** and **402-2** are implemented using the polarized feed ports **414**. In this instance, the versions **404-1** and **404-2** respectively represent a horizontally-polarized version and a vertically-polarized version, but diagonal or other polarizations may be implemented. As yet another example, the antenna **122** comprises a bowtie antenna **416**, which includes directional feed ports **418-1** and **418-2**. In this case, the versions **404-1** and **404-2** represent different angular directions that are sensed along different angles of arrival.

In FIG. **4**, the feed ports **402** and the versions **404** of the antenna responses are shown to be associated with the antenna **122**. Alternatively, the feed ports **402** and the versions **404** may be obtained using two different antennas **122**. In some implementations, the interference and clutter cancellation module **124** accepts versions **404** of the antenna response that are each associated with multiple antennas **122**.

Consider a case in which the wireless transceiver **120** performs analog or hybrid beamforming. In this case, beamforming circuitry (not shown) is coupled between the feed ports **402** and the interference and clutter cancellation module **124**. During operation, the beamforming circuitry combines corresponding versions **404** of the antenna responses across multiple antennas **122**. For example, the beamforming circuitry combines versions **404-1** of the antenna responses between two or more antennas **122** by coupling the feed ports **402-1** of the two or more antennas **122** together. Also, the beamforming circuitry combines versions **404-2** of the antenna responses between the two or more antennas **122** by coupling the feed ports **402-2** of the two or more antennas **122** together. In this manner, each version **404** of the antenna response that is accepted at the interference and clutter cancellation module **124** can correspond to one feed port **402** of an antenna **122** or can correspond to feed ports **402** of multiple antennas **122**.

In general, any type of feed port **402** (including the feed ports **410-1**, **410-2**, **414-1**, **414-2**, **418-1**, or **418-2**) may be used to produce the multiple versions **404** if the feed ports **402** are distinct from one another (e.g., sense different phases, polarizations, angles of arrivals, or are otherwise associated with different antennas that are placed at different physical locations). By using multiple feed ports **402**, the described techniques for interference and/or clutter cancellation using cross-channel equalization **406** can operate without an extensive calibration process that characterizes a

mutual coupling channel, a modulated spur, or environmental clutter. As described in further detail with respect to FIG. **5**, some of the components of the wireless transceiver **120** can be utilized for both proximity detection **130** and wireless communication **132**.

FIG. **5** illustrates examples of a wireless transceiver **120**, an interference and clutter cancellation module **124** (I&C cancellation module **124**), and a modem **126**. The wireless transceiver **120** can be implemented as a direct-conversion transceiver or a superheterodyne transceiver. In the depicted configuration, the wireless transceiver **120** includes a transmitter **502** and a receiver **504**. The transmitter **502** is coupled between the modem **126** and the antenna array **216**. The transmitter **502** is shown to include at least one signal generator **506**, at least one digital-to-analog converter (DAC) **508**, at least one mixer **510-1**, and at least one amplifier **512-1** (e.g., a power amplifier). The signal generator **506** can generate a digital signal (e.g., a transmit signal **522**), which may be used to derive the electromagnetic signal **226** or the uplink signal **202** (of FIGS. **2** and **3**). The signal generator **506** or a portion thereof may be implemented in the modem **126**. The transmitter **502** is connected to at least one feed port **402-1** or **402-2** of the antenna element **212-1**, such as at least one of the differential feed ports **410** of the dipole antenna **408**, at least one of the polarized feed ports **414** of the patch antenna **412**, or at least one of the directional feed ports **418** of the bowtie antenna **416**, as shown in FIG. **4**.

The receiver **504** is coupled between the interference and clutter cancellation module **124** and the antenna array **216**. In general, the receiver **504** includes at least two channels **514** (or layers), which are coupled to different feed ports **402** of one or more antenna elements **212**. In the depicted configuration, channels **514-1** and **514-2** represent two parallel channels within the receiver **504** that are respectively connected to two feed ports **402-1** and **402-2** (of FIG. **4**) of the antenna element **212-2**. Although a single antenna element **212-2** is shown to be connected to the two channels **514-1** and **514-2**, the channels **514-1** and **514-2** can alternatively be respectively connected to two different antenna elements **212**, such as the second antenna element **212-2** and the Nth antenna element **212**-N of FIG. **2**. The channels **514-1** and **514-2** respectively include at least one amplifier **516-1** and **516-2** (e.g., a low-noise amplifier), at least one mixer **518-1** and **518-2**, and analog-to-digital converters (ADC) **520-1** and **520-2**. The digital-to-analog converter **508** and/or the analog-to-digital converters **520** may be implemented in the modem **126**, or may be implemented in the wireless transceiver **120**.

The wireless transceiver **120** also includes a local oscillator circuit **538**, which generates a reference signal **524**. The reference signal **524** enables the mixers **510-1**, **518-1**, and **518-2** to upconvert or downconvert analog signals within the transmitter **502** and the receiver **504**. The reference signal **524** can have a continuous tone or can be modulated in frequency, as further described with respect to FIG. **6**. During operation, the local oscillator circuit **538** provides an appropriate version of the reference signal **524** to support proximity detection **130** or wireless communication **132**. The transmitter **502** and the receiver **504** can also include other additional components that are not depicted in FIG. **5** such as filters (e.g., low-pass filters or band-pass filters), phase shifters, additional mixers, switches, and so forth.

During wireless communication **132**, the wireless transceiver **120** can transmit the uplink signal **202** or receive the downlink signal **204** (of FIGS. **2** and **3**). In particular, the signal generator **506** generates the transmit signal **522**, which includes communication data. The digital-to-analog converter **508** converts the transmit signal **522** from the digital domain to the analog domain. The local oscillator circuit **538** generates the reference signal **524** having a steady (e.g., constant) frequency. The mixer **510-1** upconverts the transmit signal **522** to radio frequencies using the reference signal **524**. The amplifier **512-1** amplifies the transmit signal **522**, and the antenna element **212-1** transmits the transmit signal **522** as the uplink signal **202**.

During wireless communication **132**, the antenna element **212-2** can receive the downlink signal **204**. At least one of the receive channels within the receiver **504** processes the downlink signal **204**. For example, the amplifier **516-1** amplifies the downlink signal **204**, and the mixer **518-1** downconverts the downlink signal **204** using the reference signal **524**, which is the local oscillator signal. The analog-to-digital converter **520-1** converts the downlink signal **204** from the analog domain to the digital domain. The digital version of the downlink signal **204** can be passed to the modem **126** or a data processor in the modem for further processing. The interference and clutter cancellation module **124** can be bypassed during wireless communication **132**.

During proximity detection **130**, the transmitter **502** transmits the electromagnetic signal **226** via the antenna element **212-1**. In particular, the signal generator **506** can generate the transmit signal **522**, which can include a single continuous tone. The digital-to-analog converter **508** converts the transmit signal **522** from the digital domain to the analog domain. The local oscillator circuit **538** generates the reference signal **524**, which is modulated in frequency. The mixer **510-1** upconverts and modulates the transmit signal **522** using the reference signal **524**. The amplifier **512-1** amplifies the upconverted and modulated transmit signal **522**, and the antenna element **212-1** transmits the amplified, upconverted, and modulated transmit signal **522** as the electromagnetic signal **226**.

The receiver **504** receives different versions **404** of the antenna responses via the antenna element **212-2**. The response of the antenna element **212-2** is separated into the versions **404-1** and **404-2** via the feed ports **402-1** and **402-2**. Using the mixers **518-1** and **518-2**, the channels **514-1** and **514-2** of the receiver **504** demodulate the versions **404-1** and **404-2** of the antenna response using the reference signal **524** and produce receive signals **526-1** and **526-2**, respectively, which may be converted into digital version of the signals **526-1** and **526-2** using the ADCs **520-1** and **520-2**.

The receive signals **526-1** and **526-2** can have one or more signal components or characteristics that are indicative of a presence of the object **206** and/or range to the object **206**. The interference and clutter cancellation module **124** attenuates the interference signal **218** within one of the receive signals **526-1** and **526-2** to generate a filtered signal **528**. In particular, the interference and clutter cancellation module **124** uses cross-channel equalization **406** to equalize the slow time-varying components of the interference signal **218** across the receive signals **526-1** and **526-2**. After equalization, the interference and clutter cancellation module **124** uses one of the equalized receive signals to cancel the slow time-varying component and fast time-varying component within the other equalized receive signal. By attenuating the interference signal **218**, the interference and clutter cancellation module **124** can prevent false detections and enable the signal component or characteristic associated with the object **206** to be detected. In this way, the filtered signal **528** substantially includes information representative of the object **206** (if present) and omits or filters the mutual-

coupling component **220**, the modulated spur **222**, and/or the clutter component **224** associated with the interference signal **218**.

In FIG. **5**, the modem **126** includes at least one proximity detection module **530** and at least one transmitter control module **532** (TX control module **532**). The proximity detection module **530** obtains the filtered signal **528** and generates detection data **534**, which indicates whether or not the object **206** is detected. The detection data **534** can include a range to the object **206**.

Based on the detection data **534**, the transmitter control module **532** generates at least one transmission parameter **536** that controls one or more transmission attributes for wireless communication **132**. The transmission parameter **536** can specify one or more transmission-related aspects of the uplink signal **202**, such as a power level, polarization, frequency, duration, beam shape, beam steering angle, a selected antenna that transmits the uplink signal **202** (e.g., another antenna that is on a different surface of the computing device **102** and is not obstructed by the object **206**), or combinations thereof. Some transmission parameters **536** may be associated with beam management, such as those that define an unobstructed volume of space for beam sweeping. By specifying the transmission parameter **536**, the modem **126** can, for example, cause the transmitter **502** to decrease power if an object **206** is close to the computing device **102** or increase power if the object **206** is at a farther range or is not detectable. The ability to detect the object **206** and control the transmitter **502** enables the modem **126** to balance the performance of the computing device **102** with regulatory compliance guidelines. In other implementations, the application processor **108** can perform one or more of these functions.

Although not explicitly shown, multiple antennas **122** (or multiple antenna elements **212**) can be used to generate additional versions **404** of the antenna response (e.g., a third version or a fourth version) and provide additional receive signals **526** to the interference and clutter cancellation module **124** (e.g., a third receive signal **526** or a fourth receive signal **526**). For example, two or more patch antennas **412** may be used to generate the antenna responses. With multiple filtered signals **528**, the computing device **102** can increase a probability of detecting the object **206** (or accurately determining a range thereof) or decrease a probability of false alarms. The transmitter control module **532** can also make different adjustments based on which antennas **122** or what quantity of antennas **122** detect the object **206**. In some cases, these adjustments may impact beam management by focusing available beams or targeting a spatial area for beam determination.

For example, in some situations, the object **206** may be closer to one of the antennas **122** than another, which enables the one antenna **122** to detect the object **206** while the other antenna **122** is unable to detect the object **206**. In this case, the transmitter control module **532** can decrease a transmit power of the antenna **122** that detected the object **206** relative to the other antenna **122**. In some implementations, the multiple antennas **122** can be used to further characterize the relationship between the object **206** and the antennas **122**, such as by using triangulation or digital beamforming to estimate an angle to the object **206**. In this way, the transmitter control module **532** can adjust the transmission parameter **536** to steer the uplink signal **202** away from the object **206**. In general, the interference and clutter cancellation module **124** can provide interference and/or clutter cancellation between any two or more receive signals **526**. Components of the local oscillator circuit **538** that enable the wireless transceiver **120** to selectively perform proximity detection **130** and wireless communication **132** are further described with respect to FIG. **6**.

FIG. **6** illustrates an example local oscillator circuit **538** (LO circuit **538**) for supporting proximity detection **130** and wireless communication **132**. In the depicted configuration, the local oscillator circuit **538** includes a frequency-modulated local oscillator **602**, a local oscillator **604**, and a selection circuit **606**. The frequency-modulated local oscillator **602** can be implemented using a voltage ramp generator **610** and a voltage-controlled oscillator **612**. As an example, the voltage-controlled oscillator **612** can be implemented using a wideband open-loop voltage-controlled oscillator. By controlling an input voltage to the voltage-controlled oscillator **612**, the voltage ramp generator **610** can provide a variety of different voltage ramps to enable the voltage-controlled oscillator **612** to generate a variety of different frequency-modulated local oscillator signals **614** (e.g., a linear-frequency modulated (LFM) signal, a sawtooth-frequency modulated signal, a triangular-frequency modulated signal, and so forth).

The local oscillator **604** can include, for example, a quartz crystal, an inductor-capacitor (LC) oscillator, an oscillator transistor (e.g., a metal-oxide semiconductor field-effective transistor (MOSFET)), a transmission line, a diode, a piezoelectric oscillator, and so forth. A configuration of the local oscillator **604** can enable a target phase noise and quality factor to be achieved for wireless communication **132**. In general, the local oscillator **604** generates a local oscillator signal **616** (LO signal **616**) with a steady (e.g., constant) frequency. Although not explicitly shown, the local oscillator circuit **538** can also include a phase lock loop or automatic gain control circuit. Either of these components can be coupled to the local oscillator **604** to enable the local oscillator **604** to oscillate at a (e.g., selectable) steady frequency.

The selection circuit **606** can include a switch or a multiplexer that is controlled by the modem **126** via a control signal **618**. Based on the control signal **618**, the selection circuit **606** connects or disconnects the frequency-modulated local oscillator **602** or the local oscillator **604** to or from the mixers **510-1**, **518-1**, and **518-2**. If the control signal **618** is indicative of the wireless transceiver **120** performing proximity detection **130**, the selection circuit **606** connects the frequency-modulated local oscillator **602** to the mixers **510-1**, **518-1**, and **518-2** to provide the frequency-modulated local oscillator signal **614** as the reference signal **524**. Alternatively, if the control signal **618** is indicative of the wireless transceiver **120** performing wireless communication **132**, the selection circuit **606** connects the local oscillator **604** to the mixers **510-1**, **518-1**, and **518-2** to provide the local oscillator signal **616** as the reference signal **524**. The selection circuit **606** enables the wireless transceiver **120** to quickly transition between performing operations for proximity detection **130** or wireless communication **132**.

Although the frequency-modulated local oscillator **602** and the selection circuit **606** are shown in FIG. **6**, other implementations of the local oscillator circuit **538** may not include these components. In this case, the local oscillator **604** can provide the local oscillator signal **616** as the reference signal **524** for both proximity detection **130** and wireless communication **132**. In this case, the signal generator **506** can apply a frequency modulation to the transmit signal **522** to enable proximity detection **130**. In other examples, respective local oscillator circuitry for wireless communication **132** and proximity detection **130** are imple-

mented, and respective reference signals **524** are provided to the mixers **510-1**, **518-1**, and **518-2** shared for wireless communication **132** and proximity detection **130** or to respective mixers. Operations of the cross-channel equalizer **128** are further described with respect to FIGS. **7** and **8**.

FIG. **7** illustrates an example plot **700-1** of an amplitude of the receive signal **526-1** or **526-2** across fast time and slow time. A duration of the receive signal **526-1** or **526-2** across the fast time corresponds to a duration of each pulse **702** within the receive signal **526-1** or **526-2**. A duration of the receive signal **526-1** or **526-2** across slow time represents an inter-pulse period (IPP) of the receive signal **526-1** or **526-2** (e.g., a duration between successive pulses of the electromagnetic signal **226**). For simplicity, the receive signal **526-1** or **526-2** is shown to include three pulses **702-1**, **702-2**, and **702-3** in FIG. **7**. The receive signal **526-1** or **526-2**, however, can include any quantity of pulses **702**.

The amplitude (and phase) of each pulse **702** represents a summation of the receive signal **526-1** or **526-2** and the interference signal **218**. As described with respect to FIG. **3**, the interference signal **218** can include the mutual-coupling component **220**, the modulated spur **222**, the clutter component **224**, or some combination thereof. These component signals are illustrated in plot **700-2** for one of the pulses **702-1** to **702-3**. As seen in the plot **700-2**, the mutual-coupling component **220** and the clutter component **224** represent slow time-varying components (or slow time-varying component signals). The amplitude and phase of the slow time-varying components do not change frequently over the duration of the pulse **702**. As such, the frequency of the slow time-varying components can be close to a baseband frequency. In contrast, an object-based signal component **704**, which represents the perturbation **210** associated with the near field or the radar receive signal associated with the far field, and the modulated spur **222** represent fast time-varying components (or fast time-varying component signals). The amplitude and/or phase of fast time-varying components can change frequently over the duration of a pulse **702**. The frequency of the fast time-varying components can be closer to the beat frequency compared to the baseband frequency.

In general, the object-based signal component **704** is uncorrelated between the two channels **514** due to random fluctuations in magnitude and/or phase caused by the object **206**. The object-based signal component **704** is also uncorrelated to the slow time-varying components. Components of the interference signal **218**, however, can be correlated between the two channels **514** within each pulse **702** of the receive signal **526-1** or **526-2**. The components of the interference signal **218** may be uncorrelated over successive pulses **702**. The mutual-coupling component **220** and the modulated spur **222** are co-linear because of their relationship to a same transmitter **502**. Also, the mutual-coupling component **220** and the modulated spur **222** are similar across the channels **514** within a scale factor, which may be a complex scale factor. To attenuate the interference signal **218**, the interference and clutter cancellation module **124** uses cross-channel equalization **406**, which is further described with respect to FIG. **8**.

FIG. **8** illustrates an example implementation of the interference and clutter cancellation module **124**. In the depicted configuration, the interference and clutter cancellation module **124** includes the cross-channel equalizer **128**, an optional scaler **802**, and a summation circuit **804**. The cross-channel equalizer **128** is coupled to at least two channels **514** of the receiver **504**, the scaler **802**, and the summation circuit **804**. During operation, the cross-channel equalizer **128** performs aspects of cross-channel equalization **406**.

The cross-channel equalizer **128** includes at least two slow-time extractors **806**, such as slow-time extractors **806-1** and **806-2** (ST extractors **806-1** and **806-2**). The cross-channel equalizer **128** also includes at least two multiplication circuits **808**, such as multiplication circuits **808-1** and **808-2**. The slow-time extractors **806-1** and **806-2** track and extract the slow time-varying components of the interference signal **218** (e.g., the mutual-coupling component **220** and/or the clutter component **224**). The slow-time extractors **806-1** and **806-2** can be implemented using, for example, an infinite-impulse-response (IIR) low-pass filter.

The scaler **802** determines and applies a scaling factor to enable one of the receive signals **526** to cancel slow time-varying components and correlated fast time-varying components within another one of the receive signals **526**. The scaling factor can have a magnitude component and/or a phase component. In an example implementation, the scaler **802** includes a least-squares module **810** and a delay module **812**.

During proximity detection **130**, the cross-channel equalizer **128** accepts at least two receive signals **526**, such as receive signals **526-1** and **526-2**. The slow-time extractor **806-1** extracts a first slow time-varying component **814-1** (STV component **814-1**) from the receive signal **526-1**. Similarly, the slow-time extractor **806-2** extracts a second slow time-varying component **814-2** (STV component **814-2**) from the receive signal **526-2**. The slow time-varying components **814-1** and **814-2** can each include the mutual-coupling component **220** and/or the clutter component **224**.

The cross-channel equalizer **128** equalizes (or makes similar) the slow time-varying components **814** within the receive signals **526**. In particular, the cross-channel equalizer **128** applies the slow time-varying component associated with one channel to the receive signal **526** associated with another channel. For example, the multiplication circuit **808-1** generates a first equalized receive signal **816-1** by multiplying the receive signal **526-1** with the second slow time-varying component **814-2**. Also, the multiplication circuit **808-2** generates a second equalized receive signal **816-2** by multiplying the receive signal **526-2** with the first slow time-varying component **814-1**.

The scaler **802** uses the least-squares module **810** and the equalized receive signals **816-1** and **816-2** to produce at least one weight **818** for scaling the equalized receive signal **816-2**. The scaler **802** generates a scaled equalized receive signal **820** by aligning and applying the weights **818** to the equalized receive signal **816-2** using the delay module **812**. Due to the cross-channel equalization **406** and the scaling, the scaled equalized receive signal **820** includes slow time-varying components and fast time-varying components with substantially similar amplitudes and phases as the slow time-varying components and the fast time-varying components within the equalized receive signal **816-1**.

The summation circuit **804** combines the equalized receive signal **816-1** and the scaled equalized receive signal **820** together in a way that attenuates the interference signal **218**. In the depicted configuration, the summation circuit **804** subtracts the scaled equalized receive signal **820** from the equalized receive signal **816-1** to generate the filtered signal **528**, but the equalized receive signal **816-1** may be scaled and subtracted from the equalized receive signal **816-2** in other implementations. In this way, the slow time-varying components and fast time-varying components associated with the interference signal **218** are attenuated

within the filtered signal **528** without meaningfully attenuating the object-based signal component **704**.

With cross-channel equalization **406**, the interference signal **218** is attenuated by a sufficient amount such that the computing device **102** does not detect or determine the mutual-coupling component **220**, the modulated spur **222**, and/or the clutter component **224** to be an object of interest. In some implementations, the magnitude of the mutual-coupling component **220**, the modulated spur **222**, and/or the clutter component **224** is less than a detection threshold and causes the computing device **102** to determine that these components are not associated with an object of interest. At the same time, the magnitude of the object-based signal component **704** is above the detection threshold and causes the computing device **102** to detect the one or more objects **206** that caused the object-based signal component **704**. This cancellation enables detection of weak signal components within the filtered signal **528** to be processed for proximity detection **130** and enables the computing device **102** to realize a target false-alarm rate performance.

The techniques for interference and clutter cancellation using cross-channel equalization **406** can be applied to more than two receive signals **526** (or more than two receive channels). For example, the interference and clutter cancellation module **124** can perform similar operations using a third and fourth receive signal **526**.

Although described with respect to proximity detection **130**, the techniques of implementing interference and/or clutter cancellation using cross-channel equalization can also be applied in other wireless applications, including those that utilize full-duplex operation in which transmission and reception occur during a same time interval.

FIG. **9** is a flow diagram illustrating an example process **900** for interference and/or clutter cancellation using cross-channel equalization. The process **900** is described in the form of a set of blocks **902-906** that specify operations that can be performed. However, operations are not necessarily limited to the order shown in FIG. **9** or described herein, for the operations may be implemented in alternative orders or in fully or partially overlapping manners. Operations represented by the illustrated blocks of the process **900** may be performed by a wireless transceiver **120** (e.g., of FIG. **1** or **5**). More specifically, the operations of the process **900** may be performed, in part, by an interference and clutter cancellation module **124** of FIGS. **1** and **8**.

At block **902**, an electromagnetic signal is transmitted using a first feed port of multiple feed ports. A modulated spur is generated based on the transmission of the electromagnetic signal. For example, the computing device **102** transmits the electromagnetic signal **226** using a first feed port **402** of multiple feed ports **402**, as shown in FIGS. **2-1** and **4**. The modulated spur **222** is generated based on the transmission of the electromagnetic signal **226**. The modulated spur **222** represents a fast time-varying component. The electromagnetic signal **226** produces the electromagnetic field **208** in a near field and the radar transmit signal in a far field.

At block **904**, two versions of a receive signal are respectively received via two feed ports of the multiple feed ports. The receive signal comprises a mutual-coupling component associated with the modulated spur and the transmission of the electromagnetic signal. For example, the computing device **102** receives two versions of the receive signal **404-1** and **404-2** using two feed ports **402-1** and **402-2** of the multiple feed ports **402**, as shown in FIGS. **4** and **5**. The receive signal comprises a component corresponding to a mutual-coupling component **220** associated with the modulated spur **222** and the transmission of the electromagnetic signal **226**. The mutual-coupling component **220** represents a type of slow time-varying component. The receive signal can also include a clutter component **224**, which represents another type of slow time-varying component. If an object **206** is present, the receive signal can further include the object-based signal component **704**.

At block **906**, a filtered signal is generated by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization. For example, the interference and clutter cancellation module **124** generates the filtered signal **528** by attenuating the mutual-coupling component **220** and the modulated spur **222** within one of the two versions of the receive signal **404-1** or **404-2** using cross-channel equalization **406**, as described with respect to FIG. **8**. Cross-channel equalization **406** involves equalizing magnitudes of the slow time-varying components of the interference signal **218** across the receive signals **526-1** and **526-2** and using one of the equalized receive signals **816** to attenuate the slow time-varying component and/or the correlated fast time-varying component within the other equalized receive signal **816**.

Some aspects are described below.

Aspect 1: An apparatus comprising:

a wireless transceiver configured to:

be connected to multiple feed ports;

transmit an electromagnetic signal using a first feed port of the multiple feed ports, a modulated spur generated based on the transmission of the electromagnetic signal;

receive two versions of a receive signal respectively via two feed ports of the multiple feed ports, the receive signal comprising the modulated spur and a mutual-coupling component associated with the transmission of the electromagnetic signal; and

generate a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization.

Aspect 2: The apparatus of aspect 1, wherein:

the receive signal comprises a clutter component; and

the wireless transceiver is configured to generate the filtered signal by attenuating the mutual-coupling component, the modulated spur, and the clutter component within the one of the two versions of the receive signal using the cross-channel equalization.

Aspect 3: The apparatus of aspect 1 or 2, wherein the wireless transceiver is configured to:

generate two equalized receive signals by equalizing the mutual-coupling component within the two versions of the receive signal; and

combine the two equalized receive signals to generate the filtered signal.

Aspect 4: The apparatus of aspect 3, wherein:

the two versions of the receive signal comprise a first receive signal and a second receive signal; and

the wireless transceiver is configured to:

extract a first mutual-coupling component from the first receive signal;

extract a second mutual-coupling component from the second receive signal;

generate a first equalized receive signal by multiplying the first receive signal by the second mutual-coupling component; and

generate a second equalized receive signal by multiplying the second receive signal by the first mutual-coupling component.

Aspect 5: The apparatus of aspect 4, wherein the wireless transceiver is configured to:

generate a scaled equalized receive signal by applying a scale factor to the second equalized receive signal; and

generate the filtered signal by subtracting the scaled equalized receive signal from the first equalized receive signal.

Aspect 6: The apparatus of any previous aspect, wherein the mutual coupling component has a magnitude or phase that varies across successive pulses of the electromagnetic signal but that remains relatively constant across an individual pulse of the electromagnetic signal.

Aspect 7: The apparatus of any previous aspect, wherein the modulated spur has a magnitude or phase that varies across one pulse of the electromagnetic signal.

Aspect 8: The apparatus of any previous aspect, wherein the two feed ports of the multiple feed ports are associated with a same antenna.

Aspect 9: The apparatus of any one of aspects 1 to 7, wherein the two feed ports of the multiple feed ports are associated with different polarizations.

Aspect 10: The apparatus of any previous aspect, wherein the two feed ports of the multiple feed ports are associated with different antennas.

Aspect 11: The apparatus of any previous aspect, wherein the wireless transceiver is configured to adjust a transmission parameter based on the filtered signal, the transmission parameter varying based on detection of an object.

Aspect 12: The apparatus of any previous aspect, wherein the wireless transceiver comprises a modem configured to generate the filtered signal.

Aspect 13: An apparatus comprising:

means for transmitting an electromagnetic signal using a first feed port of multiple feed ports, a modulated spur generated based on the transmission of the electromagnetic signal;

means for receiving two versions of a receive signal respectively via two feed ports of the multiple feed ports, the receive signal comprising the modulated spur and a mutual-coupling component associated with the transmission of the electromagnetic signal; and

means for generating a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization.

Aspect 14: The apparatus of aspect 13, wherein:

the receive signal comprises a clutter component; and

the means for generating the filtered signal is configured to attenuate the mutual-coupling component, the modulated spur, and the clutter component within the one of the two versions of the receive signal using the cross-channel equalization.

Aspect 15: The apparatus of aspect 13 or 14, wherein the means for generating the filtered signal comprises:

means for generating two equalized receive signals by equalizing the mutual-coupling component within the two versions of the receive signal; and

means for combining the two equalized receive signals to generate the filtered signal.

Aspect 16: The apparatus of aspect 15, wherein:

the two versions of the receive signal comprise a first receive signal and a second receive signal; and

the means for generating the two equalized receive signals comprises:

means for extracting a first mutual-coupling component from the first receive signal;

means for extracting a second mutual-coupling component from the second receive signal;

means for generating a first equalized receive signal by multiplying the first receive signal by the second mutual-coupling component; and

means for generating a second equalized receive signal by multiplying the second receive signal by the first mutual-coupling component.

Aspect 17: The apparatus of aspect 16, wherein the means for generating the filtered signal comprises:

means for generating a scaled equalized receive signal by applying a scale factor to the second equalized receive signal; and

means for subtracting the scaled equalized receive signal from the first equalized receive signal.

Aspect 18: A method comprising:

transmitting an electromagnetic signal using a first feed port of multiple feed ports, a modulated spur generated based on the transmission of the electromagnetic signal;

receiving two versions of a receive signal respectively via two feed ports of the multiple feed ports, the receive signal comprising the modulated spur and a mutual-coupling component associated with the transmission of the electromagnetic signal; and

generating a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization.

Aspect 19: The method of aspect 18, wherein:

the receive signal comprises a clutter component; and

the generating of the filtered signal comprises attenuating the mutual-coupling component, the modulated spur, and the clutter component within the one of the two versions of the receive signal using the cross-channel equalization.

Aspect 20: The method of aspect 18 or 19, wherein the generating of the filtered signal comprises:

generating two equalized receive signals by equalizing the mutual-coupling component within the two versions of the receive signal; and

combining the two equalized receive signals to generate the filtered signal.

Aspect 21: The method of aspect 20, wherein:

the two versions of the receive signal comprise a first receive signal and a second receive signal; and

the generating of the two equalized receive signals comprises:

extracting a first mutual-coupling component from the first receive signal;

extracting a second mutual-coupling component from the second receive signal;

generating a first equalized receive signal by multiplying the first receive signal by the second mutual-coupling component; and

generating a second equalized receive signal by multiplying the second receive signal by the first mutual-coupling component.

Aspect 22: The method of aspect 21, further comprising:

generating a scaled equalized receive signal by applying a scale factor to the second equalized receive signal,

wherein the generating of the filtered signal comprises generating the filtered signal by subtracting the scaled equalized receive signal from the first equalized receive signal.

Aspect 23: An apparatus comprising:

a wireless transceiver configured to:

be connected to multiple feed ports;

transmit an electromagnetic signal using a first feed port of the multiple feed ports, a modulated spur generated based on the transmission of the electromagnetic signal, the modulated spur comprising a fast time-varying component having a magnitude or phase that varies substantially within a duration of a pulse of the electromagnetic signal;

receive two versions of a receive signal respectively via two feed ports of the multiple feed ports, the receive signal comprising the modulated spur;

detect at least one object based on the receive signal; and

satisfy a target false-alarm rate in the presence of the modulated spur.

Aspect 24: The apparatus of aspect 23, wherein the wireless transceiver is configured to:

generate an electromagnetic field within a near field based on the transmission of the electromagnetic signal; and

detect at least one object within the near field based on a perturbation in the electromagnetic field.

Aspect 25: The apparatus of claim **23**, wherein the wireless transceiver is configured to:

generate a radar transmit signal within a far field based on the transmission of the electromagnetic signal; and

detect at least one object within the far field based on a reflection version of the radar transmit signal.

Aspect 26: The apparatus of any one of aspects 23 to 25, wherein:

the magnitude or phase of the fast time-varying component has a median value within the duration of the pulse of the electromagnetic signal; and

the magnitude or phase of the fast time-varying component varies by at least 5% from the median value within the duration of the pulse of the electromagnetic signal.

Aspect 27: The apparatus of any one of aspects 23 to 26, wherein the wireless transceiver is configured to attenuate the fast time-varying component within one of the two versions of the receive signal by using cross-channel equalization.

Aspect 28: The apparatus of aspect 27, wherein a magnitude of the attenuated fast time-varying component is less than a detection threshold.

Aspect 29: The apparatus of aspect 27 or 28, wherein: the receive signal comprises a slow time-varying component having a magnitude or phase that varies across multiple pulses associated with the electromagnetic signal but does not substantially vary across an individual pulse associated with the electromagnetic signal; and

the wireless transceiver is configured to attenuate the slow time-varying component within the one of the two versions of the receive signal based, at least in part, on using the cross-channel equalization.

Aspect 30: The apparatus of aspect 29, wherein the slow time-varying component comprises a mutual-coupling component or a clutter component.

Unless context dictates otherwise, use herein of the word "or" may be considered use of an "inclusive or," or a term that permits inclusion or application of one or more items that are linked by the word "or" (e.g., a phrase "A or B" may be interpreted as permitting just "A," as permitting just "B," or as permitting both "A" and "B"). As used herein, a phrase referring to "at least one of" a list of items refers to any combination of those items, including single members. As an example, "at least one of: a, b, or c" is intended to cover: a, b, c, a-b, a-c, b-c, and a-b-c, as well as any combination with multiples of the same element (e.g., a-a, a-a-a, a-a-b, a-a-c, a-b-b, a-c-c, b-b, b-b-b, b-b-c, c-c, and c-c-c or any other ordering of a, b, and c). Further, items represented in the accompanying figures and terms discussed herein may be indicative of one or more items or terms, and thus reference may be made interchangeably to single or plural forms of the items and terms in this written description. Finally, although subject matter has been described in language specific to structural features or methodological operations, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or operations described above, including not necessarily being limited to the organizations in which features are arranged or the orders in which operations are performed.

What is claimed is:

1. An apparatus comprising:

a wireless transceiver configured to:

be connected to multiple feed ports;

transmit an electromagnetic signal using a first feed port of the multiple feed ports, a modulated spur generated based on the transmission of the electromagnetic signal;

receive two versions of a receive signal respectively via two feed ports of the multiple feed ports, the receive signal comprising the modulated spur and a mutual-coupling component associated with the transmission of the electromagnetic signal; and

generate a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization.

2. The apparatus of claim **1**, wherein:

the receive signal comprises a clutter component; and

the wireless transceiver is configured to generate the filtered signal by attenuating the mutual-coupling component, the modulated spur, and the clutter component within the one of the two versions of the receive signal using the cross-channel equalization.

3. The apparatus of claim **1**, wherein the wireless transceiver is configured to:

generate two equalized receive signals by equalizing the mutual-coupling component within the two versions of the receive signal; and

combine the two equalized receive signals to generate the filtered signal.

4. The apparatus of claim **3**, wherein:

the two versions of the receive signal comprise a first receive signal and a second receive signal; and

the wireless transceiver is configured to:

extract a first mutual-coupling component from the first receive signal;

extract a second mutual-coupling component from the second receive signal;

generate a first equalized receive signal by multiplying the first receive signal by the second mutual-coupling component; and

generate a second equalized receive signal by multiplying the second receive signal by the first mutual-coupling component.

5. The apparatus of claim 4, wherein the wireless transceiver is configured to:

generate a scaled equalized receive signal by applying a scale factor to the second equalized receive signal; and

generate the filtered signal by subtracting the scaled equalized receive signal from the first equalized receive signal.

6. The apparatus of claim 1, wherein the mutual-coupling component has a magnitude or phase that varies across successive pulses of the electromagnetic signal but that remains relatively constant across an individual pulse of the electromagnetic signal.

7. The apparatus of claim 1, wherein the modulated spur has a magnitude or phase that varies across one pulse of the electromagnetic signal.

8. The apparatus of claim 1, wherein the two feed ports of the multiple feed ports are associated with a same antenna.

9. The apparatus of claim 1, wherein the two feed ports of the multiple feed ports are associated with different polarizations.

10. The apparatus of claim 1, wherein the two feed ports of the multiple feed ports are associated with different antennas.

11. The apparatus of claim 1, wherein the wireless transceiver is configured to adjust a transmission parameter based on the filtered signal, the transmission parameter varying based on detection of an object.

12. The apparatus of claim 1, wherein the wireless transceiver comprises a modem configured to generate the filtered signal.

13. An apparatus comprising:

means for transmitting an electromagnetic signal using a first feed port of multiple feed ports, a modulated spur generated based on the transmission of the electromagnetic signal;

means for receiving two versions of a receive signal respectively via two feed ports of the multiple feed ports, the receive signal comprising the modulated spur and a mutual-coupling component associated with the transmission of the electromagnetic signal; and

means for generating a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization.

14. The apparatus of claim 13, wherein:

the receive signal comprises a clutter component; and

the means for generating the filtered signal is configured to attenuate the mutual-coupling component, the modulated spur, and the clutter component within the one of the two versions of the receive signal using the cross-channel equalization.

15. The apparatus of claim 13, wherein the means for generating the filtered signal comprises:

means for generating two equalized receive signals by equalizing the mutual-coupling component within the two versions of the receive signal; and

means for combining the two equalized receive signals to generate the filtered signal.

16. The apparatus of claim 15, wherein:

the two versions of the receive signal comprise a first receive signal and a second receive signal; and

the means for generating the two equalized receive signals comprises:

means for extracting a first mutual-coupling component from the first receive signal;

means for extracting a second mutual-coupling component from the second receive signal;

means for generating a first equalized receive signal by multiplying the first receive signal by the second mutual-coupling component; and

means for generating a second equalized receive signal by multiplying the second receive signal by the first mutual-coupling component.

17. The apparatus of claim 16, wherein the means for generating the filtered signal comprises:

means for generating a scaled equalized receive signal by applying a scale factor to the second equalized receive signal; and

means for subtracting the scaled equalized receive signal from the first equalized receive signal.

18. A method comprising:

transmitting an electromagnetic signal using a first feed port of multiple feed ports, a modulated spur generated based on the transmission of the electromagnetic signal;

receiving two versions of a receive signal respectively via two feed ports of the multiple feed ports, the receive signal comprising the modulated spur and a mutual-coupling component associated with the transmission of the electromagnetic signal; and

generating a filtered signal by attenuating the mutual-coupling component and the modulated spur within one of the two versions of the receive signal using cross-channel equalization.

19. The method of claim 18, wherein:

the receive signal comprises a clutter component; and

the generating of the filtered signal comprises attenuating the mutual-coupling component, the modulated spur, and the clutter component within the one of the two versions of the receive signal using the cross-channel equalization.

20. The method of claim 18, wherein the generating of the filtered signal comprises:

generating two equalized receive signals by equalizing the mutual-coupling component within the two versions of the receive signal; and

combining the two equalized receive signals to generate the filtered signal.

21. The method of claim 20, wherein:

the two versions of the receive signal comprise a first receive signal and a second receive signal; and

the generating of the two equalized receive signals comprises:

extracting a first mutual-coupling component from the first receive signal;

extracting a second mutual-coupling component from the second receive signal;

generating a first equalized receive signal by multiplying the first receive signal by the second mutual-coupling component; and

generating a second equalized receive signal by multiplying the second receive signal by the first mutual-coupling component.

22. The method of claim 21, further comprising:

generating a scaled equalized receive signal by applying a scale factor to the second equalized receive signal,

wherein the generating of the filtered signal comprises generating the filtered signal by subtracting the scaled equalized receive signal from the first equalized receive signal.

23. An apparatus comprising:

a wireless transceiver configured to:

be connected to multiple feed ports;

transmit an electromagnetic signal using a first feed port of the multiple feed ports, a modulated spur generated based on the transmission of the electromagnetic signal, the modulated spur comprising a fast time-varying component having a magnitude or phase that varies substantially within a duration of a pulse of the electromagnetic signal;

receive two versions of a receive signal respectively via two feed ports of the multiple feed ports, the receive signal comprising the modulated spur; and

satisfy a target false-alarm rate in the presence of the modulated spur.

24. The apparatus of claim 23, wherein the wireless transceiver is configured to:

generate an electromagnetic field within a near field based on the transmission of the electromagnetic signal; and

detect at least one object within the near field based on a perturbation in the electromagnetic field.

25. The apparatus of claim 23, wherein the wireless transceiver is configured to:

generate a radar transmit signal within a far field based on the transmission of the electromagnetic signal; and

detect at least one object within the far field based on a reflection version of the radar transmit signal.

26. The apparatus of claim 23, wherein:

the magnitude or phase of the fast time-varying component has a median value within the duration of the pulse of the electromagnetic signal; and

the magnitude or phase of the fast time-varying component varies by at least 5% from the median value within the duration of the pulse of the electromagnetic signal.

27. The apparatus of claim 23, wherein the wireless transceiver is configured to attenuate the fast time-varying component within one of the two versions of the receive signal by using cross-channel equalization.

28. The apparatus of claim 27, wherein a magnitude of the attenuated fast time-varying component is less than a detection threshold.

29. The apparatus of claim 27, wherein: the receive signal comprises a slow time-varying component having a magnitude or phase that varies across multiple pulses associated with the electromagnetic signal but does not substantially vary across an individual pulse associated with the electromagnetic signal; and

the wireless transceiver is configured to attenuate the slow time-varying component within the one of the two versions of the receive signal based, at least in part, on using the cross-channel equalization.

30. The apparatus of claim 29, wherein the slow time-varying component comprises a mutual-coupling component or a clutter component.

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