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Injecting a frequency-modulated signal into a receiver

Abstract

An apparatus is disclosed for injecting a frequency-modulated signal into a receiver. In an example aspect, the apparatus includes a receiver, a local oscillator circuit, and an injection circuit. The receiver comprises a signal propagation path. The local oscillator circuit is configured to generate a frequency-modulated signal. The injection circuit is coupled to the receiver and the local oscillator circuit. The injection circuit is configured to selectively connect the local oscillator circuit to the signal propagation path of the receiver to inject the frequency-modulated signal into the signal propagation path of the receiver. The injection circuit is also configured to disconnect the local oscillator circuit from the signal propagation path of the receiver.

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Background/Summary

TECHNICAL FIELD

(1) This disclosure relates generally to wireless transceivers and, more specifically, to measuring a frequency response of a receiver.

BACKGROUND

(2) To increase transmission rates and throughput, cellular and other wireless networks are using signals with higher-order modulations, such as 64 or 256 quadrature amplitude modulation (QAM). Use of these higher-order modulations, however, is limited based on a signal-to-noise ratio that can be achieved in a receiver. If the signal-to-noise ratio is insufficient, a bit error rate of the receiver may become unacceptable.

SUMMARY

(3) An apparatus is disclosed that injects a frequency-modulated signal into a receiver. In some implementations, the frequency-modulated signal can be injected at various points within a signal propagation path of the receiver. For example, the frequency-modulated signal can be injected at a point associated with radio frequencies, intermediate frequencies, and/or baseband frequencies. Starting at the point of injection, the frequency-modulated signal propagates through the receiver and is subjected to any distortion that occurs along the signal propagation path. The frequency response of the receiver is measured based on the propagated frequency-modulated signal, and a response of an inverse filter is determined to compensate for the distortion. By compensating for the distortion, a signal-to-noise ratio performance of the receiver can be, for example, sufficient to

enable use of higher-order modulations for wireless communication while achieving an acceptable bit error rate. Additionally or alternatively, the distortion compensation can improve position and/or movement accuracies associated with proximity detection.
(4) In an example aspect, an apparatus for injecting a frequency-modulated signal into a receiver is disclosed. The apparatus includes a receiver, a local oscillator circuit, and an injection circuit. The receiver comprises a signal propagation path. The local oscillator circuit is configured to generate a frequency-modulated signal. The injection circuit is coupled to the receiver and the local oscillator circuit. The injection circuit is configured to selectively connect the local oscillator circuit to the signal propagation path of the receiver to inject the frequency-modulated signal into the signal propagation path of the receiver. The injection circuit is also configured to disconnect the local oscillator circuit from the signal propagation path of the receiver.
(5) In an example aspect, an apparatus for injecting a frequency-modulated signal into a receiver is disclosed. The apparatus includes means for receiving a wireless communication signal during a wireless communication mode. The means for receiving the wireless communication signal includes a signal propagation path. The apparatus also includes means for generating a frequency-modulated signal during a calibration mode. The apparatus additionally includes means for injecting the frequency-modulated signal within the signal propagation path during the calibration mode.
(6) In an example aspect, a method for injecting a frequency-modulated signal into a receiver is disclosed. The method includes disconnecting a local oscillator circuit from a mixer of a receiver based on a calibration mode. The method also includes connecting the local oscillator circuit to an input or an output of a component that is disposed within a signal propagation path of the receiver based on the calibration mode. The method additionally includes generating, by the local oscillator circuit, a frequency-modulated signal in accordance with the calibration mode. The method further includes injecting the frequency-modulated signal into the signal propagation path of the receiver.
(7) In an example aspect, an apparatus is disclosed for injecting a frequency-modulated signal into a receiver. The apparatus includes a modem configured to generate a mode control signal. The apparatus also includes a wireless transceiver coupled to the modem and including a portion of a signal propagation path of a receiver. The wireless transceiver is configured to accept a mode control signal. The wireless transceiver is also configured to receive a downlink signal using the portion of the signal propagation path of the receiver based on the mode control signal indicating a wireless communication mode. The wireless transceiver is also configured to inject a frequency-modulated signal into the signal propagation path of the receiver based on the mode control signal indicating a calibration mode.

Description

BRIEF DESCRIPTION OF DRAWINGS
(1) FIG. **1** illustrates an example computing device for injecting a frequency-modulated signal into a receiver.
(2) FIG. **2-1** illustrates an example operating environment for a computing device.
(3) FIG. **2-2** illustrates another example operating environment for a computing device.
(4) FIG. **3** illustrates an example sequence flow diagram for operating a computing device.
(5) FIG. **4** illustrates examples of a wireless transceiver and modem for injecting a frequency-modulated signal into a receiver.
(6) FIG. **5** illustrates an example local oscillator circuit for injecting a frequency-modulated signal into a receiver.
(7) FIG. **6** illustrates example implementations of a local oscillator circuit and an injection circuit for injecting a frequency-modulated signal into a receiver.

(8) FIG. **7** illustrates an example implementation of a radio-frequency integrated circuit for injecting the frequency-modulated signal into a receiver.
(9) FIG. **8-1** illustrates an example configuration of a radio-frequency integrated circuit during a calibration mode.
(10) FIG. **8-2** illustrates an example configuration of a radio-frequency integrated circuit during a wireless communication mode.
(11) FIG. **8-3** illustrates an example configuration of a radio-frequency integrated circuit during a proximity detection mode.
(12) FIG. **9** is a flow diagram illustrating an example process for injecting a frequency-modulated signal into a receiver.

DETAILED DESCRIPTION

(13) To increase transmission rates and throughput, cellular and other wireless networks are using signals with higher-order modulations, such as 64 or 256 quadrature amplitude modulation (QAM). Use of these higher-order modulations, however, is limited based on a signal-to-noise ratio that can be achieved in a receiver. If the signal-to-noise ratio is insufficient, a bit error rate of the receiver may become unacceptable.
(14) One source of degradation that can impact the signal-to-noise ratio of the receiver includes distortion within passbands of filters within the receiver. Example types of distortion can include ripples within the passband or droop at an edge of the passband. To improve the signal-to-noise ratio, it is desirable for the receiver to have a near distortion-less frequency response. To address this challenge, some techniques measure an overall frequency response of the receiver and implement an inverse filter to compensate for the distortion. However, these techniques can be quite complex by utilizing internal noise sources to estimate the overall frequency response of the receiver. Sometimes these noise sources do not behave as white noise. As such, the frequency spectrum of the noise is not necessarily flat unless averaged over a significant period of time, which can be on the order of seconds. While estimating the overall frequency response of the receiver, the receiver is unable to support wireless communication operations, which can be undesirable for this length of time.
(15) In contrast, techniques for injecting a frequency-modulated signal into a receiver are described herein. In some implementations, the frequency-modulated signal can be injected at various points within a signal propagation path of the receiver. For example, the frequency-modulated signal can be injected at a point associated with radio frequencies, intermediate frequencies, and/or baseband frequencies. Starting at the point of injection, the frequency-modulated signal propagates through the receiver and is subjected to any distortion that occurs along the signal propagation path. The frequency response of the receiver is measured based on the propagated frequency-modulated signal, and a response of an inverse filter is determined to compensate for the distortion. By compensating for the distortion, a signal-to-noise ratio performance of the receiver can be, for example, sufficient to enable use of higher-order modulations for wireless communication while achieving an acceptable bit error rate. Additionally or alternatively, the distortion compensation can improve position and/or movement accuracies associated with proximity detection.
(16) The frequency-modulated signal can have a sufficiently large bandwidth and a substantially flat frequency response to enable the receiver's frequency response to be measured quickly (e.g., on the order of microseconds) compared to other techniques that rely on an internal noise source. Also, the frequency response of the receiver can be readily extracted from time-domain samples of the frequency-modulated signal. As such, it can be less computationally intensive to determine an appropriate response of an inverse filter that compensates for the distortion.
(17) FIG. **1** illustrates an example environment **100** for injecting a frequency-modulated signal into a receiver. 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 customer premises equipment (CPE), a broadband router, an access point, a cellular phone, 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.

(18) 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, 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.

(19) 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 2nd-generation (2G), 3rd-generation (3G), 4th-generation (4G), or 5th-generation (5G) cellular; IEEE 802.11 (e.g., Wi-Fi®); IEEE 802.15 (e.g., Bluetooth®); 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.

(20) 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.

(21) The computing device **102** can also include input/output ports **116** (I/O ports **116**) and/or 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 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.

(22) 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.

(23) The wireless transceiver **120** includes circuitry and logic for transmitting and receiving communication signals via an antenna **124**. Components of the wireless transceiver **120** can include amplifiers, switches, mixers, analog-to-digital converters, filters, and so forth for conditioning the communication 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 **124**.
(24) The computing device **102** also includes a modem **122**, which is coupled to the wireless transceiver **120**. The modem **122**, which may comprise one or more processors, can be implemented within or separate from the wireless transceiver **120**. Although not explicitly shown, the modem **122** can include a portion of the CRM **110** or can access the CRM **110** to obtain computer-readable instructions. The modem **122** controls the wireless transceiver **120** and enables a variety of different modes to be executed. The modem **122** 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 **122** can provide communication data to the wireless transceiver **120** for transmission. The modem **122** can also process baseband signals obtained from the wireless transceiver **120** to generate data, which can be provided to the computing device **102**.
(25) To increase transmission rates and throughput using higher-order modulations, the computing device **102** can perform distortion compensation by applying a filter that compensates for at least a portion of the distortion generated by a receiver of the computing device **102**. During a calibration mode **126**, the computing device **102** injects a frequency-modulated signal into a signal propagation path of the receiver to determine an appropriate frequency response of the filter.
(26) The computing device **102** can also increase transmission rates and throughput by using signals with higher frequencies and smaller wavelengths. As an example, the computing device **102** can represent a 5.sup.th-generation (5G)-capable device that uses frequencies that include those at or near the extremely-high frequency (EHF) spectrum (e.g., frequencies greater than 24 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.
(27) Transmit power levels can be increased or transmit 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.
(28) To meet targeted guidelines based on the MPE limit, the computing device **102** can balance performance with transmit power and other considerations. To realize this balancing act, some implementations of the computing device **102** perform proximity detection in addition to wireless communication. In this case, the computing device **102** can operate in accordance with the wireless communication mode **128** to perform wireless communication and operate in accordance with the proximity detection mode **130** to perform proximity detection.
(29) To support the calibration mode **126** and the wireless communication mode **128** (and optionally the proximity detection mode **130**), the wireless transceiver **120** includes at least one local oscillator circuit **132** and at least one injection circuit **134**. The local oscillator circuit **132** generates a reference signal that supports an active mode. For the calibration mode **126** and/or the proximity detection mode **130**, the reference signal can be a frequency-modulated signal. For the wireless communication mode **128**, the reference signal can be a local oscillator signal.
(30) The injection circuit **134** enables the frequency-modulated signal provided by the local oscillator circuit **132** to be injected into the signal propagation path of the receiver during the

calibration mode **126**. The injection circuit **134** provides this injection point for the calibration mode **126** without substantially impacting performance of the other modes, such as the wireless communication mode **128** or the proximity detection mode **130**. Together, the local oscillator circuit **132** and the injection circuit **134** implement, at least in part, aspects of injecting a frequency-modulated signal into a receiver.
(31) The modem **122** includes a distortion-compensation circuit **136**. During the calibration mode **126**, the distortion-compensation circuit **136** measures a frequency response of the receiver based on the injected frequency-modulated signal. During the wireless communication mode **128** and/or the proximity detection mode **130**, the distortion-compensation circuit **136** applies a filter that at least partially compensates for the distortion previously measured during the calibration mode **126**. By compensating for this distortion, the distortion-compensation circuit **136** enables the computing device **102** to support the use of higher-order modulations during the wireless communication mode **128** and/or enables more accurate target detection in the proximity detection mode **130**. Aspects of the wireless communication mode **128** and the proximity detection mode **130** are further described with respect to FIGS. **2-1**, **2-2**, and **3**.
(32) FIG. **2-1** illustrates an example operating environment **200** for the computing device **102**. In the example environment **200**, a hand **202** of a user holds the computing device **102**. During the wireless communication mode **128**, the computing device **102** communicates with the base station **104** by transmitting an uplink signal **204** (UL signal **204**) or receiving a downlink signal **206** (DL signal **206**) via antennas **124**. A user's thumb, however, can represent an object **208** that may be exposed to radiation via the uplink signal **204** and obstruct one or more of the antennas **124**.
(33) To detect whether the object **208** exists or is within a detectable range and angle, the computing device **102** operates in accordance with the proximity detection mode **130**. During the proximity detection mode **130**, the computing device **102** transmits a proximity detection signal **210** via at least one of the antennas **124**. The proximity detection signal **210** can be a frequency-modulated continuous-wave (FMCW) signal or a frequency-modulated pulsed signal. The type of frequency modulation can include a linear frequency modulation, a triangular frequency modulation, a sawtooth frequency modulation, and so forth. The proximity detection signal **210** propagates through space and is reflected, at least partially, by the object **208**.
(34) The computing device **102** additionally receives, via one or more of the antennas **124**, a reflected proximity detection signal **212**, which represents a version of the proximity detection signal **210** that is reflected by the object **208**. Based on the reflected proximity detection signal **212**, the presence of the object **208** can be determined. In some implementations, the computing device **102** also determines a position (e.g., slant range, azimuth, and/or elevation) of the object **208**.
(35) FIG. **2-2** illustrates another example operating environment **214** for the computing device **102**. In the depicted configuration, the computing device **102** includes antenna arrays **216-1** and **216-2**. Through the antenna arrays **216-1** and **216-2**, the computing device **102** can communicate with the base station **104** through multiple signal paths **218-1** to **218-3**. A first signal path **218-1** represents a direct signal path between the antenna array **216-1** and the base station **104**. A second signal path **218-2** represents an indirect signal path between the antenna array **216-1**, a reflector **220**, and the base station **104**. A third signal path **218-3** represents an indirect signal path between the antenna array **216-2**, the reflector **220**, and the base station **104**.
(36) In the depicted environment, an object **208** (e.g., a finger) blocks the first signal path **218-1**. Through proximity detection, the computing device **102** determines that the antenna array **216-1** is obstructed. As such, the computing device **102** can adjust transmission parameters for the uplink signal **204** based on the detection. In some implementations, the transmission parameters specify a different beam steering angle that enables the uplink signal **204** to be transmitted via the antenna array **216-1** using the second signal path **218-2** instead of the first signal path **218-1**. The beam steering angle can decrease radiation exposure at the object **208** by directing a main-lobe of the uplink signal **204** away from the object **208**. Additionally or alternatively, a transmit power for the

uplink signal **204** can be reduced for the second signal path **218-2** or the first signal path **218-1**.

(37) In other situations, the transmission parameters can specify a different antenna array **216** for transmitting the communication signal. For example, the antenna array **216-2** can be used instead of the antenna array **216-1** to transmit the uplink signal **204** using the third signal path **218-3**. By adjusting the transmission parameters, the computing device **102** can maintain communication with the base station **104** while ensuring compliance. An example sequence for switching between the wireless communication mode **128** and the proximity detection mode **130** is further described with respect to FIG. **3**

(38) FIG. **3** illustrates an example sequence flow diagram **300** for operating the computing device **102**, with time elapsing in a downward direction. Examples of the wireless communication mode **128** are shown at **302** and **306**, and examples of the proximity detection mode **130** are shown at **304** and **308**. The proximity detection modes **130** can occur at fixed time intervals, between active data cycles that occur during wireless communication, at predetermined times as set by the modem **122**, during an unused random access channel (RACH) time slot, as part of an initialization process before wireless communications occur, responsive to detection of device movement, 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 **206** or the application processor **108** determining that the user is interacting with the display **118** of the computing device **102**), or during other times or in response to other events. In some situations, the computing device **102** measures a position of the object **208** during the proximity detection mode **130**.

(39) At **302**, the computing device **102** transmits a high-power (e.g., normal) uplink signal **204-1** configured to provide sufficient range to a destination, such as a location of the base station **104**. After transmitting the uplink signal **204-1**, the computing device **102** transmits the proximity detection signal **210-1** at **304**. As described above, the proximity detection signal **210** may enable the computing device **102** to detect an object **208** and determine if the object **208** is near the computing device **102**. In this case, the proximity detection signal **210-1** is represented by a low-power wide-band signal. Based on a detection, the wireless transceiver **120** can adjust a transmission parameter for a subsequent uplink signal **204** to account for MPE compliance guidelines.

(40) The proximity detection mode **130** can also determine the range and/or angle to the object **208**, thereby enabling transmission of the uplink signal **204** to comply with range-dependent and/or angle-dependent guidelines, such as a maximum power density. Because power density is proportional to transmit power and inversely proportional to range, an object **208** at a closer range is exposed to a higher power density than another object **208** at a farther range for a same transmit power level. Therefore, a similar power density at the object **208** can be achieved by increasing the transmit power level if the object **208** is at a farther range and decreasing the transmit power level if the object **208** is at a closer range

(41) The power density at the object **208** can also be dependent upon a beam steering angle (e.g., an angle of a main lobe of a radiation pattern). Directing the beam steering angle away from the angle to the object **208** can decrease the power density at the object **208**, for instance. By controlling transmission power and/or the beam steering angle, the computing device **102** can customize transmission of the uplink signal **204** to enable the power density at the object **208** to be below the maximum power density. At the same time, because the range and/or the angle is known, the transmit power level can be increased to a level that facilitates wireless communication and comports with the compliance guideline.

(42) At **306**, the computing device **102** transmits a subsequent uplink signal **204**. In the depicted example, a high-power uplink signal **204-2** is transmitted if an object **208** is not detected. Alternatively, a low-power uplink signal **204-3** is transmitted if the object **208** 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

subsequent uplink signal **204**, the uplink signal **204-3** can be transmitted using a different antenna array within the computing device **102**, using a different beam steering angle, using a different frequency, or using a different communication protocol (e.g., relative to the antenna array, the beam steering angle, the frequency, or the communication protocol used to transmit the uplink signal **204-1** at **302**). Although not shown, the computing device **102** can alternatively skip the wireless communication mode at **306** and perform another proximity detection mode using another antenna array or a different transmit power level to detect objects **208** at various locations or distances around the computing device **102**.

(43) At **308**, the computing device **102** transmit another proximity detection signal **210-2** to attempt to detect the object **208**. By scheduling multiple proximity detection signals **210** over some time period, transmission of the uplink signal **204** can be dynamically adjusted based on a changing environment or movement by the object **208**. Furthermore, appropriate adjustments can be made to balance communication performance with compliance or radiation requirements.

(44) The sequence described above can also be applied to other antennas **124** within the computing device **102**. The other antennas **124** can transmit multiple proximity detection signals **210** sequentially or in parallel. Components of the computing device **102** that enable wireless communication, proximity detection, and distortion compensation are further described with respect to FIG. **4**. As noted above, it is optional for the computing device **102** to support the proximity detection mode **130**. Thus, while proximity detection is described above, and certain references to the proximity detection mode **130** are included below, it will be understood that aspects described herein (for example, injecting a frequency-modulated signal into a receiver) may be performed in the absence of proximity detection or in a device that is not configured to detect proximity.

(45) FIG. **4** illustrates examples of a wireless transceiver **120** and a modem **122** for injecting a frequency-modulated signal into a receiver. The wireless transceiver **120** and the modem **122** together implement a transmitter **402** and a receiver **404**. The transmitter **402** and the receiver **404** can be coupled to a same antenna **124** or to different antennas **124**.

(46) In the depicted configuration, the wireless transceiver **120** represents a superheterodyne transceiver, which includes a radio-frequency integrated circuit **406** (RF IC **406**), an intermediate-frequency integrated circuit **408** (IF IC **408**), and a baseband integrated circuit **410** (baseband IC **410**). In other implementations (not shown), the wireless transceiver **120** can be implemented as a direct-conversion transceiver (or zero-IF transceiver) with the radio-frequency integrated circuit **406** and the baseband integrated circuit **410** and without the intermediate-frequency integrated circuit **408**. In some examples in which superheterodyne transceiver is implemented, the intermediate-frequency and baseband circuits are included in a single integrated circuit instead of in separate integrated circuits as illustrated in FIG. **4**.

(47) The radio-frequency integrated circuit **406** can represent a radio-frequency front-end of the wireless transceiver **120**. In general, the radio-frequency integrated circuit **406** includes components that are designed to operate on analog signals having radio frequencies. The intermediate-frequency integrated circuit **408** includes components that are designed to operate on analog signals having intermediate frequencies. The baseband integrated circuit **410** includes components that are designed to operate at analog and/or digital signals having baseband frequencies. Components of the radio-frequency integrated circuit **406**, the intermediate-frequency integrated circuit **408**, and the baseband integrated circuit **410** can include amplifiers, phase shifters, filters, mixers, and switches. The baseband integrated circuit **410** can also include analog-to-digital converters and digital-to-analog converters.

(48) The local oscillator circuit **132** can be integrated within the radio-frequency integrated circuit **406**, the intermediate-frequency integrated circuit **408**, or some combination thereof. The injection circuit **134** can be integrated within the radio-frequency integrated circuit **406**, the intermediate-frequency integrated circuit **408**, the baseband integrated circuit **410**, or some combination thereof.

In some implementations, the local oscillator circuit **132** and the injection circuit **134** are implemented within a same integrated circuit (e.g., within the radio-frequency integrated circuit **406** or the intermediate-frequency integrated circuit). In other implementations, the local oscillator circuit **132** and the injection circuit **134** are implemented across multiple integrated circuits. The distortion-compensation circuit **136** is implemented at least partially within the modem **122**. In general, the injection circuit **134** and the distortion-compensation circuit **136** are at least partially disposed within a signal propagation path of the receiver **404**.

(49) The receiver **404** can include components, such as filters, that introduce distortion during the wireless communication mode **128** and/or the proximity detection mode **130**. A first example filter includes a low-pass filter that is applied after a downconversion mixer to attenuate harmonic frequencies or intermodulation products. This filter can be implemented within the radio-frequency integrated circuit **406**, the intermediate-frequency integrated circuit **408**, or the baseband integrated circuit **410**. A second example filter includes an anti-aliasing filter that is applied before an analog-to-digital converter to reduce aliasing. This filter can be implemented within the baseband integrated circuit **410**. A third example filter can include a digital filter, such as a cascaded integrator-comb (CIC) filter, which can be implemented by the modem **122**.

(50) During the calibration mode **126**, the local oscillator circuit **132** generates the frequency-modulated signal, as further described with respect to FIG. **5**. The injection circuit **134** injects the frequency-modulated signal into the receiver **404** at some point along a signal propagation path. For example, the injection circuit **134** can inject the frequency-modulated signal into the radio-frequency integrated circuit **406**, the intermediate-frequency integrated circuit **408**, or the baseband integrated circuit **410**. The receiver **404** propagates the frequency-modulated signal along the signal propagation path to the distortion-compensation circuit **136**. The distortion-compensation circuit **136** measures the distortion within the receiver **404** based on the propagated frequency-modulated signal and determines an appropriate frequency response to compensate for the distortion. Due to the time-frequency duality associated with the frequency-modulated signal, the distortion-compensation circuit **136** can readily measure the frequency response of the receiver **404** based on time-domain samples of the propagated frequency-modulated signal.

(51) During the wireless communication mode **128** and/or the proximity detection mode **130**, the modem **122** generates a transmit signal **412**, which can include communication data based on the wireless communication mode **128**. The modem **122** also provides control information **414** to the radio-frequency integrated circuit **406**. In some implementations, the modem **122** uses frequency-division multiplexing to enable both the transmit signal **412** and the control information **414** to be passed by a single communication path within the wireless transceiver **120**. In other implementations, the transmit signal **412** and the control information **414** are passed to the radio-frequency integrated circuit **406** using separate communication paths.

(52) The control information **414** includes at least one transmission parameter and/or at least one reception parameter that configures at least one component within the transmitter **402** or the receiver **404**, respectively. As an example, the control information **414** specifies a gain of an amplifier (e.g., a power amplifier, a low-noise amplifier, or a variable-gain amplifier), phase-shift information for an analog phase shifter, an operational state of a switch that connects an antenna element of a selected antenna array **216** to the transmitter **402** or the receiver **404**, and so forth. In some cases, the control information **414** enables the computing device **102** to satisfy the MPE limits, as described with respect to FIG. **3**.

(53) Depending on the operational mode of the wireless transceiver **120**, the transmitter **402** uses the transmit signal **412** to generate the uplink signal **204** or the proximity detection signal **210**. For example, the baseband integrated circuit **410** can convert the transmit signal **412** from a digital domain to an analog domain. The intermediate-frequency integrated circuit **408** can upconvert the transmit signal **412** from baseband frequencies to intermediate frequencies. The radio-frequency integrated circuit **406** can upconvert the transmit signal **412** from intermediate frequencies to radio

frequencies, shift a phase of the transmit signal **412**, and/or amplify the transmit signal **412** to generate the uplink signal **204** or the proximity detection signal **210**. In some implementations, the local oscillator circuit **132** generates a local oscillator signal to enable upconversion of the transmit signal **412** during the wireless communication mode **128**. The local oscillator circuit **132** can also generate a frequency-modulated signal to upconvert and modulate the transmit signal **412** during the proximity detection mode **130**. The radio-frequency integrated circuit **406** provides the uplink signal **204** or the proximity detection signal **210** to the antenna **124** for transmission. The antenna **124** can represent a stand-alone antenna or an antenna element of an antenna array **216** (of FIG. **2-2**).

(54) The antenna **124** can additionally receive the downlink signal **206** during the wireless communication mode **128** or receive the reflected proximity detection signal **212** during the proximity detection mode **130**. Depending on the operational mode of the wireless transceiver **120**, the receiver **404** generates a receive signal **416** based on the downlink signal **206** or the reflected proximity detection signal **212**. For example, the radio-frequency integrated circuit **406** amplifies the downlink signal **206** or the reflected proximity detection signal **212**, shifts a phase of the downlink signal **206** or the reflected proximity detection signal **212**, and/or downconverts the downlink signal **206** or the reflected proximity detection signal **212** from radio frequencies to intermediate (or baseband) frequencies to generate the receive signal **416**. In some implementations, the local oscillator circuit **132** generates a local oscillator signal to enable downconversion of the downlink signal **206** during the wireless communication mode **128**. During the proximity detection mode **130**, the radio-frequency integrated circuit **406** performs a beating operation using the proximity detection signal **210** and the reflected proximity detection signal **212** to generate the receive signal **416**.

(55) The intermediate-frequency integrated circuit **408** downconverts the receive signal **416** from intermediate frequencies to baseband frequencies. The baseband integrated circuit **410** converts the receive signal **416** from the analog domain to the digital domain. The modem **122** analyzes a digital version of the receive signal **416** to perform other operations associated with the wireless communication mode **128** or the proximity detection mode **130**. One of these operations can include applying a filter of the distortion-compensation circuit **136** to compensate for distortion artifacts introduced by the receiver **404**.

(56) The modem **122** also generates a mode control signal **418**, which can appropriately configure the local oscillator circuit **132** and/or the injection circuit **134** for the active mode (e.g., the calibration mode **126**, the wireless communication mode **128**, or the proximity detection mode **130**). The local oscillator circuit **132** is further described with respect to FIG. **5**.

(57) FIG. **5** illustrates an example local oscillator circuit **132** for injecting a frequency-modulated signal into the receiver **404** according to the calibration mode **126**. In the depicted configuration, the local oscillator circuit **132** includes at least one frequency-modulated local oscillator **502**, at least one local oscillator **504**, and at least one selection circuit **506**. The frequency-modulated local oscillator **502** can be implemented using a voltage ramp generator **508** and a voltage-controlled oscillator **510**. As an example, the voltage-controlled oscillator **510** can be implemented using a wideband open-loop voltage controlled oscillator. By controlling an input voltage to the voltage-controlled oscillator **510**, the voltage ramp generator **508** can provide a variety of different voltage ramps to enable the voltage-controlled oscillator **510** to generate a variety of different frequency-modulated signals **512** (e.g., a linear-frequency-modulated (LFM) signal, a sawtooth-frequency-modulated signal, a triangular-frequency-modulated signal, chirp, and so forth).

(58) During the calibration mode **126**, the frequency-modulated local oscillator **502** can generate the frequency-modulated signal **512** with a first bandwidth. In some implementations, the bandwidth is similar to a wireless communication bandwidth used during the wireless communication mode **128**. During the proximity detection mode **130**, the frequency-modulated local oscillator **502** can generate the frequency-modulated signal **512** with a second bandwidth,

which can be larger than the first bandwidth. In general, larger bandwidths result in better range resolution for proximity detection.

(59) The local oscillator **504** 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 **504** can enable a target phase noise and quality factor to be achieved for the wireless communication mode **128**. In general, the local oscillator **504** generates a local oscillator signal **514** with a steady (e.g., constant) frequency. Although not explicitly shown, the local oscillator circuit **132** can also include a phase lock loop or automatic gain control circuit. Either of these components can be coupled to the local oscillator **504** to enable the local oscillator **504** to oscillate at a steady frequency.

(60) The selection circuit **506** can include a switch or a multiplexer that is controlled by the mode control signal **418**. The selection circuit **506** generates a reference signal **516**, which is passed to other components within the wireless transceiver **120** and/or the injection circuit **134**. The reference signal **516** can be the frequency-modulated signal **512** or the local oscillator signal **514** based on the mode control signal **418**. If the mode control signal **418** indicates that the calibration mode **126** or the proximity detection mode **130** is active, the selection circuit **506** provides the frequency-modulated signal **512** as the reference signal **516**. Alternatively, if the mode control signal **418** indicates that the wireless communication mode **128** is active, the selection circuit **506** provides the local oscillator signal **514** as the reference signal **516**. The selection circuit **506** enables the wireless transceiver **120** to quickly transition between the various modes. The injection circuit **134** is further described with respect to FIG. **6**.

(61) FIG. **6** illustrates an example implementation of the injection circuit **134** for injecting the frequency-modulated signal **512** into the receiver **404**. In the depicted configuration, the injection circuit **134** can optionally include at least one buffer **602** and/or at least one frequency translation circuit **604**. The buffer **602** can provide isolation and/or amplification. The frequency translation circuit **604** can adjust a frequency of the frequency-modulated signal **512**. In a first example implementation, the frequency translation circuit **604** can include a frequency multiplier, which increases the frequency of the frequency-modulated signal **512**. For example, the frequency translation circuit **604** can increase the frequency of the frequency-modulated signal **512** by a factor of approximately 1.5 or 2. In a second example implementation, the frequency translation circuit **604** can include a frequency divider, which decreases the frequency of the frequency-modulated signal **512**. For example, the frequency translation circuit **604** can decrease the frequency of the frequency-modulated signal **512** by a factor of approximately 2 or 4.

(62) In general, the amount that the frequency translation circuit **604** increases or decreases the frequency of the frequency-modulated signal **512** depends on the point within the signal propagation path **608** that the frequency-modulated signal **512** is injected and a target wireless communication frequency band that is used during the wireless communication mode **128**. For example, the frequency translation circuit **604** can increase the frequency of the frequency-modulated signal **512** for injection within a point of the signal propagation path **608** that is associated with radio frequencies. Additionally or alternatively, the frequency translation circuit **604** can decrease the frequency of the frequency-modulated signal **512** for injection within a point of the signal propagation path **608** that is associated with intermediate or baseband frequencies. In some cases in which the frequency-modulated signal **512** is generated with the desired frequencies, the injection circuit **134** can bypass or be implemented without the frequency translation circuit **604**.

(63) The injection circuit **134** also includes at least one switch **606**. The switch **606** is disposed within a signal propagation path **608** of the receiver **404**. The switch **606** enables the injection circuit **134** to connect the local oscillator circuit **132** to the signal propagation path **608** of the receiver **404** during the calibration mode **126**. In this way, the injection circuit **134** can inject the

frequency-modulated signal **512** into the signal propagation path **608**. The switch **606** also enables the injection circuit **134** to disconnect the local oscillator circuit **132** from the signal propagation path **608** during the wireless communication mode **128** and the proximity detection mode **130**. In this case, the switch **606** enables the receiver **404** to propagate the downlink signal **206**, the reflected proximity detection signal **212**, or the receive signal **416** along the signal propagation path **608**. A configuration of the switch **606** is set according to the mode control signal **418**, as further described with respect to FIGS. **8-1** to **8-3**. An example implementation of the injection circuit **134** within the wireless transceiver **120** is further described with respect to FIG. **7**.
(64) FIG. **7** illustrates an example implementation of a radio-frequency integrated circuit **406** for injecting the frequency-modulated signal **512** into the receiver **404**. In the depicted configuration, the radio-frequency integrated circuit **406** includes a portion of the transmitter **402**, a portion of the receiver **404**, the local oscillator circuit **132**, and the injection circuit **134**. The radio-frequency integrated circuit **406** also includes a mixer **702** (e.g., an upconversion mixer) and an amplifier **704** (e.g., a power amplifier), which are implemented as part of the transmitter **402**. Additionally, the radio-frequency integrated circuit **406** includes an amplifier **706** (e.g., a low-noise amplifier) and a mixer **708** (e.g., a downconversion mixer), which are implemented as part of the receiver **404**. Both the amplifier **706** and the mixer **708** are disposed within the signal propagation path **608** of the receiver **404**.
(65) During the wireless communication mode **128** or the proximity detection mode **130**, the radio-frequency integrated circuit **406** can couple the local oscillator circuit **132** to the transmitter **402** and/or the receiver **404** using switches **710-1**, **710-2**, and **712**. During the calibration mode **126**, the radio-frequency integrated circuit **406** can couple the local oscillator circuit **132** to the receiver **404** using the switch **712** and either one of switches **606-1** or **606-2**. The switch **710-1** is coupled between the local oscillator circuit **132** and the mixer **702**. The switch **712** is coupled to the local oscillator circuit **132**, the transmitter **402** (e.g., at an output of the mixer **702**), the switch **710-2**, and the injection circuit **134**. The switch **710-2** is coupled to the switch **712**, the injection circuit **134**, the mixer **708**, and a continuous-wave tone generator **714** of the radio-frequency integrated circuit **406**. In some implementations, the continuous-wave tone generator **714** is implemented as a phase-locked loop, which can be part of the local oscillator circuit **132**.
(66) The injection circuit **134** includes a first buffer **602-1**, a first frequency translation circuit **604-1**, and a first switch **606-1**. The switch **606-1** is coupled to an input of the amplifier **706**. With these components, the injection circuit **134** can inject the frequency-modulated signal **512** into a point along the signal propagation path **608** that is associated with radio frequencies. The injection circuit **134** can also optionally or alternatively include a second buffer **602-2**, a second frequency translation circuit **714-2**, and a second switch **606-2**. The second switch **606-2** is coupled to an output of the mixer **708**. With these components, the injection circuit **134** can inject the frequency-modulated signal **512** into a point along the signal propagation path **608** that is associated with intermediate frequencies in a superheterodyne receiver or baseband frequencies in a direct-conversion receiver. In a superheterodyne receiver, the frequency-modulated signal **512** may also or alternatively be injected at baseband (e.g., after a second downconversion mixer, not illustrated).
(67) Using the switches **710-1**, **710-2**, and **712** of the radio-frequency integrated circuit **406** and the switches **606-1** and **606-2** of the injection circuit **134**, the wireless transceiver **120** can support the calibration mode **126** as described with respect to FIG. **8-1**, the wireless communication mode **128** as described with respect to FIG. **8-2**, and/or the proximity detection mode **130** as described with respect to FIG. **8-3**. The example radio-frequency integrated circuit **406** depicted in FIG. **7** supports the calibration mode **126**, the wireless communication mode **128**, and the proximity detection mode **130**. Other implementations of the radio-frequency integrated circuit **406** may support the calibration mode **126** and the wireless communication mode **128** and may not support the proximity detection mode **130**. In this case, the radio-frequency integrated circuit **406** may not include the switch **712**. As such, the switch **710-2** and the injection circuit **134** are coupled to the

switch **710-1** and the local oscillator circuit **132**.
(68) FIG. **8-1** illustrates an example configuration of the radio-frequency integrated circuit **406** during the calibration mode **126**. In the depicted configuration, the local oscillator circuit **132** generates the frequency-modulated signal **512** as the reference signal **516**. The switch **710-1** is in an open state to disconnect the local oscillator circuit **132** from the mixer **702**. The switch **712** is in a first state to connect the local oscillator circuit **132** to the injection circuit **134**. The switch **710-2** is in a first state to connect the continuous-wave tone generator **714** to the mixer **708**.
(69) At different times, the injection circuit **134** can connect the local oscillator circuit **132** to different points along the signal propagation path **608**. For example, at a first time interval during the calibration mode **126**, the switch **606-1** is in a first state that connects the local oscillator circuit **132** to the input of the amplifier **706**. Also, the switch **606-2** is in a second state that disconnects the local oscillator circuit **132** from the output of the mixer **708** and connects the output of the mixer **708** to another component (not shown) within the signal propagation path **608**. The first state of the switch **606-1** and the second state of the switch **606-2** are represented by solid lines to indicate that these states occur during a same time interval. The states of the switches **606-1**, **606-2**, and **712** enable the frequency-modulated signal **512** to be injected at the input of the amplifier **706** and propagate to the modem **122**.
(70) At a second time interval during the calibration mode **126**, the switch **606-1** is in a second state that disconnects the local oscillator circuit **132** from the amplifier **706**. Also, the switch **606-2** is in a first state that connects the local oscillator circuit **132** to the output of the mixer **708**. The second state of the switch **606-1** and the first state of the switch **606-2** are represented by dashed lines to indicate that these states occur during a same time interval. The states of the switches **606-1**, **606-2**, and **712** enable the frequency-modulated signal **512** to be injected at the output of the mixer **708** and propagate to the modem **122**.
(71) FIG. **8-2** illustrates an example configuration of the radio-frequency integrated circuit **406** during the wireless communication mode **128**. In the depicted configuration, the local oscillator circuit **132** generates the local oscillator signal **514** as the reference signal **516**. During transmission, the switch **710-1** is in a closed state to connect the local oscillator circuit **132** to the mixer **702**. This enables the transmitter **402** to generate the uplink signal **204** by upconverting the transmit signal **412** to radio frequencies using the local oscillator signal **514**.
(72) During reception, the switch **712** is in the first state to connect the local oscillator circuit **132** to the switch **710-2**. The switch **710-2** is in a second state to connect the switch **712** to the mixer **708**. This enables the receiver **404** to generate the receive signal **416** by downconverting the downlink signal **206** to intermediate frequencies using the local oscillator signal **514**. The switches **606-1** and **606-2** are in the second state to enable propagation of the downlink signal **206** and the receive signal **416** along the signal propagation path **608** to the modem **122**.
(73) FIG. **8-3** illustrates an example configuration of the radio-frequency integrated circuit **406** during the proximity detection mode **130**. In the depicted configuration, the local oscillator circuit **132** generates the frequency-modulated signal **512** as the reference signal **516**. The switch **710-1** is in the closed state to connect the local oscillator circuit **132** to the mixer **702**. This enables the transmitter **402** to generate the proximity detection signal **210** by upconverting the transmit signal **412** to radio frequencies and modulating the transmit signal **412** using the frequency-modulated signal **512**.
(74) The switch **712** is in a second state to connect the transmitter **402** to the switch **710-2**. The switch **710-2** is in the second state to connect the switch **712** to the mixer **708**. This enables the receiver **404** to generate the receive signal **416** by downconverting and demodulating the reflected proximity detection signal **212** using the proximity detection signal **210**. The switches **606-1** and **606-2** are in the second state to enable propagation of the reflected proximity detection signal **212** and the receive signal **416** along the signal propagation path **608** to the modem **122**.
(75) Although examples of the local oscillator circuit **132** and the injection circuit **134** are shown to

be implemented within the radio-frequency integrated circuit **406** in FIGS. **7** to **8-3**, other implementations of the wireless transceiver **120** can include the local oscillator circuit **132** and/or the injection circuit **134** implemented within the intermediate-frequency integrated circuit **408** and/or the baseband integrated circuit **410**. In these implementations, the frequency-modulated signal **512** can be injected at other points along the signal propagation path **608**, including points associated with intermediate frequencies and/or baseband frequencies.

(76) FIG. **9** is a flow diagram illustrating an example process **900** for injecting a frequency-modulated signal into a receiver. The process **900** is described in the form of a set of blocks **902-910** 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. Also, more, fewer, and/or different operations may be implemented to perform the process **900**, or an alternative process. Operations represented by the illustrated blocks of the process **900** may be performed by a wireless transceiver **120** and a modem **122** (e.g., of FIG. **1** or **4**). More specifically, the operations of the process **900** may be performed, at least in part, by a local oscillator circuit **132**, as shown in FIG. **5**, and an injection circuit **134**, as shown in FIG. **6**.

(77) At **902**, the local oscillator circuit is disconnected from a mixer of a receiver based on a calibration mode. For example, the switch **710-2** disconnects the local oscillator circuit **132** from the mixer **708** of the receiver **404** based on the mode control signal **418** indicating that the calibration mode **126** is active. The switch **710-1** can also disconnect the local oscillator circuit **132** from the mixer **702** of the transmitter **402**.

(78) At **904**, the local oscillator circuit is connected to an input or an output of a component that is disposed within a signal propagation path of the receiver based on the calibration mode. For example, the switch **712** and either the switch **606-1** or **606-2** connects the local oscillator circuit **132** to an input or an output of a component that is disposed within the signal propagation path **608** of the receiver **404**. In the example shown in FIG. **8-1**, the local oscillator circuit **132** can be connected to an input of the amplifier **706** or an output of the mixer **708**.

(79) At **906**, a frequency-modulated signal is generated by the local oscillator circuit in accordance with the calibration mode. For example, the local oscillator circuit **132** generates the frequency-modulated signal **512** in accordance with the calibration mode **126**, as shown in FIG. **5**. In some examples, the frequency-modulated signal **512** represents a linear-frequency-modulated signal.

(80) At **908**, the frequency-modulated signal is injected into the signal propagation path of the receiver. For example, the injection circuit **134** injects the frequency-modulated signal **512** into the signal propagation path of the receiver **404**, as shown in FIG. **8-1**.

(81) Some aspects are described below.

(82) Aspect 1: An apparatus comprising: a receiver comprising a signal propagation path; a local oscillator circuit configured to generate a frequency-modulated signal; and an injection circuit coupled to the receiver and the local oscillator circuit, the injection circuit configured to selectively: connect the local oscillator circuit to the signal propagation path of the receiver to inject the frequency-modulated signal into the signal propagation path of the receiver; and disconnect the local oscillator circuit from the signal propagation path of the receiver.

(83) Aspect 2: The apparatus of aspect 1, further comprising: a radio-frequency integrated circuit comprising the local oscillator circuit, the injection circuit, and at least a portion of the signal propagation path of the receiver.

(84) Aspect 3: The apparatus of aspect 2, wherein: the radio-frequency integrated circuit comprises an amplifier; and the injection circuit is configured to selectively: connect the local oscillator circuit to an input of the amplifier to inject the frequency-modulated signal into the signal propagation path of the receiver; and disconnect the local oscillator circuit from the input of the amplifier.

(85) Aspect 4: The apparatus of aspect 2 or 3, wherein: the radio-frequency integrated circuit

comprises a mixer; and the injection circuit is configured to selectively: connect the local oscillator circuit to an output of the mixer to inject the frequency-modulated signal into the signal propagation path of the receiver; and disconnect the local oscillator circuit from the output of the mixer.

(86) Aspect 5: The apparatus of any one of aspects 2-4, wherein: the radio-frequency integrated circuit comprises a first component and second component; and the injection circuit is configured to selectively: connect the local oscillator circuit to the first component to inject the frequency-modulated signal into the signal propagation path of the receiver; connect the local oscillator circuit to the second component to inject the frequency-modulated signal into the signal propagation path of the receiver; and disconnect the local oscillator circuit from the first component and the second component.

(87) Aspect 6: The apparatus of any previous aspect, wherein the injection circuit comprises: at least one frequency translation circuit coupled to the local oscillator circuit, the at least one frequency translation circuit configured to increase or decrease frequencies of the frequency-modulated signal; and at least one switch coupled to the at least one frequency translation circuit and disposed within the signal propagation path, the at least one switch configured to selectively: connect the at least one frequency translation circuit to a component within the signal propagation path of the receiver; and disconnect the at least one frequency translation circuit from the component and connect the component to another component within the signal propagation path of the receiver.

(88) Aspect 7: The apparatus of aspect 6, wherein the injection circuit comprises at least one buffer coupled between the local oscillator circuit and the at least one frequency translation circuit.

(89) Aspect 8: The apparatus of any previous aspect, wherein the receiver is configured to propagate the frequency-modulated signal along the signal propagation path in accordance with a calibration mode.

(90) Aspect 9: The apparatus of aspect 8, wherein: the receiver comprises a distortion-compensation circuit disposed within the signal propagation path, the distortion-compensation circuit configured to: accept the propagated frequency-modulated signal; determine a frequency response of the receiver based on the propagated frequency-modulated signal; and apply a filter having a frequency response that at least partially compensates for a distortion artifact present within the frequency response of the receiver.

(91) Aspect 10: The apparatus of aspect 9, wherein: the receiver comprises at least one filter that is disposed within the signal propagation path and coupled between the injection circuit and the distortion-compensation circuit; the at least one filter has a frequency response with ripples in a passband or droop at an edge of the passband; and the distortion artifact is associated with the ripples in the passband or the droop at the edge of the passband.

(92) Aspect 11: The apparatus of any previous aspect, wherein the frequency-modulated signal comprises a linear-frequency-modulated signal.

(93) Aspect 12: The apparatus of any previous aspect, wherein: the local oscillator circuit is configured to selectively: generate the frequency-modulated signal based on a calibration mode; and generate a local oscillator signal based on a wireless communication mode; and the receiver is configured to: receive a downlink signal based on the wireless communication mode; and downconvert a frequency of the downlink signal using the local oscillator signal.

(94) Aspect 13: The apparatus of aspect 12, wherein the local oscillator circuit comprises: a voltage ramp generator and a voltage-controlled oscillator jointly configured to generate the frequency-modulated signal; a local oscillator configured to generate the local oscillator signal; and a selection circuit configured to: provide the frequency-modulated signal to the injection circuit based on the calibration mode; and provide the local oscillator signal to the receiver based on the wireless communication mode.

(95) Aspect 14: The apparatus of any previous aspect, further comprising: a transmitter coupled to

the local oscillator circuit, wherein: the frequency-modulated signal comprises a first frequency-modulated signal; the local oscillator circuit is configured to selectively: generate the first frequency-modulated signal based on a calibration mode; and generate a second frequency-modulated signal based on a proximity detection mode; and the transmitter is configured to generate, based on the proximity detection mode, a proximity detection signal by performing frequency upconversion using the second frequency-modulated signal.
(96) Aspect 15: The apparatus of aspect 14, wherein: the first frequency-modulated signal has a first bandwidth; and the second frequency-modulated signal has a second bandwidth that is larger than the first bandwidth.
(97) Aspect 16: An apparatus comprising: means for receiving a wireless communication signal during a wireless communication mode, the means for receiving including a signal propagation path; means for generating a frequency-modulated signal during a calibration mode; and means for injecting the frequency-modulated signal within the signal propagation path during the calibration mode.
(98) Aspect 17: The apparatus of aspect 16, wherein the means for injecting the frequency-modulated signal comprises means for adjusting a frequency of the frequency-modulated signal.
(99) Aspect 18: The apparatus of aspect 17, wherein the means for adjusting the frequency of the frequency-modulated signal comprises means for increasing the frequency of the frequency-modulated signal.
(100) Aspect 19: The apparatus of aspect 17 or 18, wherein the means for adjusting the frequency of the frequency-modulated signal comprises means for decreasing the frequency of the frequency-modulated signal.
(101) Aspect 20: A method comprising: disconnecting a local oscillator circuit from a mixer of a receiver based on the calibration mode; connecting the local oscillator circuit to an input or an output of a component that is disposed within a signal propagation path of the receiver based on the calibration mode; generating, by the local oscillator circuit, a frequency-modulated signal in accordance with the calibration mode; and injecting the frequency-modulated signal into the signal propagation path of the receiver.
(102) Aspect 21: The method of aspect 20, wherein the frequency-modulated signal exhibits a linear characteristic between a frequency of the frequency-modulated signal and time.
(103) Aspect 22: The method of aspect 20 or 21, further comprising: disconnecting the local oscillator circuit from the input or the output of the component based on a proximity detection mode; connecting the local oscillator circuit to a mixer of a transmitter based on the proximity detection mode; generating, by the local oscillator circuit, another frequency-modulated signal in accordance with the proximity detection mode; and generating a proximity detection signal by upconverting a transmit signal using the other frequency-modulated signal and the mixer of the transmitter.
(104) Aspect 23: The method of aspect 22, further comprising: connecting an output of the mixer of the transmitter to a mixer of the receiver based on the proximity detection mode; and connecting the input or the output of the component to another component that is disposed within the signal propagation path of the receiver based on the proximity detection mode.
(105) Aspect 24: The method of any one of aspects 20-23, further comprising: disconnecting the local oscillator circuit from the input or the output of the component based on a wireless communication mode; connecting the input or the output of the component to another component that is disposed within the signal propagation path of the receiver based on the wireless communication mode; connecting the local oscillator circuit to a mixer of the receiver based on the wireless communication mode; and generating, by the local oscillator circuit, a local oscillation signal in accordance with the wireless communication mode.
(106) Aspect 25: An apparatus comprising: a modem configured to generate a mode control signal; and a wireless transceiver coupled to the modem and comprising a portion of a signal propagation

path of a receiver, the wireless transceiver configured to: accept the mode control signal; receive a downlink signal using the portion of the signal propagation path of the receiver based on the mode control signal indicating a wireless communication mode; and inject a frequency-modulated signal into the signal propagation path of the receiver based on the mode control signal indicating a calibration mode.
(107) Aspect 26: The apparatus of aspect 25, wherein the wireless transceiver is configured to inject the frequency-modulated signal at a point within the signal propagation path that is associated with radio frequencies.
(108) Aspect 27: The apparatus of aspect 25 or 26, wherein the wireless transceiver is configured to inject the frequency-modulated signal at a point within the signal propagation path that is associated with intermediate frequencies.
(109) Aspect 28: The apparatus of any one of aspects 25-27, wherein the wireless transceiver is configured to inject the frequency-modulated signal at a point within the signal propagation path that is associated with baseband frequencies.
(110) Aspect 29: The apparatus of any one of aspects 25-28, wherein the frequency-modulated signal comprises a linear-frequency-modulated signal.
(111) Aspect 30: The apparatus of any one of aspects 25-29, wherein: the wireless transceiver is configured to propagate the frequency-modulated signal through the portion of the signal propagation path of the receiver based on the calibration mode; and the modem comprises: another portion of the signal propagation path of the receiver; and a distortion-compensation circuit disposed within the other portion of the signal propagation path, the distortion-compensation circuit configured to: accept the propagated frequency-modulated signal; determine a frequency response of the receiver based on the propagated frequency-modulated signal; and filter the downlink signal using a filter with a frequency response that at least partially compensates for a distortion artifact present within the frequency response of the receiver.
(112) 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.

Claims

1. An apparatus comprising: a receiver comprising a signal propagation path and a distortion-compensation circuit disposed within the signal propagation path; a local oscillator circuit configured to generate a frequency-modulated signal; and an injection circuit coupled to the receiver and the local oscillator circuit, the injection circuit configured to selectively: connect the local oscillator circuit to the signal propagation path of the receiver to inject the frequency-modulated signal into the signal propagation path of the receiver; and disconnect the local oscillator circuit from the signal propagation path of the receiver, wherein the receiver is configured to

propagate the frequency-modulated signal along the signal propagation path in accordance with a calibration mode, and wherein the distortion-compensation circuit is configured to: accept the propagated frequency-modulated signal; determine a frequency response of the receiver based on the propagated frequency-modulated signal; and apply a filter having a frequency response that at least partially compensates for a distortion artifact present within the frequency response of the receiver.

2. The apparatus of claim 1, further comprising: a radio-frequency integrated circuit comprising the local oscillator circuit, the injection circuit, and at least a portion of the signal propagation path of the receiver.

3. The apparatus of claim 2, wherein: the radio-frequency integrated circuit comprises an amplifier; and the injection circuit is configured to selectively: connect the local oscillator circuit to an input of the amplifier to inject the frequency-modulated signal into the signal propagation path of the receiver; and disconnect the local oscillator circuit from the input of the amplifier.

4. The apparatus of claim 2, wherein: the radio-frequency integrated circuit comprises a mixer; and the injection circuit is configured to selectively: connect the local oscillator circuit to an output of the mixer to inject the frequency-modulated signal into the signal propagation path of the receiver; and disconnect the local oscillator circuit from the output of the mixer.

5. The apparatus of claim 2, wherein: the radio-frequency integrated circuit comprises a first component and second component; and the injection circuit is configured to selectively: connect the local oscillator circuit to the first component to inject the frequency-modulated signal into the signal propagation path of the receiver; connect the local oscillator circuit to the second component to inject the frequency-modulated signal into the signal propagation path of the receiver; and disconnect the local oscillator circuit from the first component and the second component.

6. The apparatus of claim 1, wherein the injection circuit comprises: at least one frequency translation circuit coupled to the local oscillator circuit, the at least one frequency translation circuit configured to increase or decrease frequencies of the frequency-modulated signal; and at least one switch coupled to the at least one frequency translation circuit and disposed within the signal propagation path, the at least one switch configured to selectively: connect the at least one frequency translation circuit to a component within the signal propagation path of the receiver; and disconnect the at least one frequency translation circuit from the component and connect the component to another component within the signal propagation path of the receiver.

7. The apparatus of claim 6, wherein the injection circuit comprises at least one buffer coupled between the local oscillator circuit and the at least one frequency translation circuit.

8. The apparatus of claim 1, wherein: the receiver comprises at least one filter that is disposed within the signal propagation path and coupled between the injection circuit and the distortion-compensation circuit; the at least one filter has a frequency response with ripples in a passband or droop at an edge of the passband; and the distortion artifact is associated with the ripples in the passband or the droop at the edge of the passband.

9. The apparatus of claim 1, wherein the frequency-modulated signal comprises a linear-frequency-modulated signal.

10. The apparatus of claim 1, wherein: the local oscillator circuit is configured to selectively: generate the frequency-modulated signal based on the calibration mode; and generate a local oscillator signal based on a wireless communication mode; and the receiver is configured to: receive a downlink signal based on the wireless communication mode; and downconvert a frequency of the downlink signal using the local oscillator signal.

11. The apparatus of claim 10, wherein the local oscillator circuit comprises: a voltage ramp generator and a voltage-controlled oscillator jointly configured to generate the frequency-modulated signal; a local oscillator configured to generate the local oscillator signal; and a selection circuit configured to: provide the frequency-modulated signal to the injection circuit based on the calibration mode; and provide the local oscillator signal to the receiver based on the

wireless communication mode.

12. The apparatus of claim 1, further comprising: a transmitter coupled to the local oscillator circuit, wherein: the frequency-modulated signal comprises a first frequency-modulated signal; the local oscillator circuit is configured to selectively: generate the first frequency-modulated signal based on the calibration mode; and generate a second frequency-modulated signal based on a proximity detection mode; and the transmitter is configured to generate, based on the proximity detection mode, a proximity detection signal by performing frequency upconversion using the second frequency-modulated signal.

13. The apparatus of claim 12, wherein: the first frequency-modulated signal has a first bandwidth; and the second frequency-modulated signal has a second bandwidth that is larger than the first bandwidth.

14. A method comprising: disconnecting a local oscillator circuit from a mixer of a receiver based on a calibration mode; connecting the local oscillator circuit to an input or an output of a component that is disposed within a signal propagation path of the receiver based on the calibration mode; generating, by the local oscillator circuit, a frequency-modulated signal in accordance with the calibration mode; injecting the frequency-modulated signal into the signal propagation path of the receiver; disconnecting the local oscillator circuit from the input or the output of the component based on a proximity detection mode; connecting the local oscillator circuit to a mixer of a transmitter based on the proximity detection mode; generating, by the local oscillator circuit, another frequency-modulated signal in accordance with the proximity detection mode; generating a proximity detection signal by upconverting a transmit signal using the other frequency-modulated signal and the mixer of the transmitter; connecting an output of the mixer of the transmitter to a mixer of the receiver based on the proximity detection mode; and connecting the input or the output of the component to another component that is disposed within the signal propagation path of the receiver based on the proximity detection mode.

15. The method of claim 14, wherein the frequency-modulated signal exhibits a linear characteristic between a frequency of the frequency-modulated signal and time.

16. The method of claim 14, further comprising: disconnecting the local oscillator circuit from the input or the output of the component based on a wireless communication mode; connecting the input or the output of the component to another component that is disposed within the signal propagation path of the receiver based on the wireless communication mode; connecting the local oscillator circuit to a mixer of the receiver based on the wireless communication mode; and generating, by the local oscillator circuit, a local oscillation signal in accordance with the wireless communication mode.

17. An apparatus comprising: a modem configured to generate a mode control signal; and a wireless transceiver coupled to the modem and comprising a portion of a signal propagation path of a receiver, the wireless transceiver configured to: accept the mode control signal; receive a downlink signal using the portion of the signal propagation path of the receiver based on the mode control signal indicating a wireless communication mode; and inject a frequency-modulated signal into the signal propagation path of the receiver based on the mode control signal indicating a calibration mode, wherein the wireless transceiver is configured to propagate the frequency-modulated signal through the portion of the signal propagation path of the receiver based on the calibration mode, and wherein the modem comprises: another portion of the signal propagation path of the receiver; and a distortion-compensation circuit disposed within the other portion of the signal propagation path, the distortion-compensation circuit configured to: accept the propagated frequency-modulated signal; determine a frequency response of the receiver based on the propagated frequency-modulated signal; and filter the downlink signal using a filter with a frequency response that at least partially compensates for a distortion artifact present within the frequency response of the receiver.

18. The apparatus of claim 17, wherein the wireless transceiver is configured to inject the

frequency-modulated signal at a point within the signal propagation path that is associated with radio frequencies.
19. The apparatus of claim 17, wherein the wireless transceiver is configured to inject the frequency-modulated signal at a point within the signal propagation path that is associated with intermediate frequencies.
20. The apparatus of claim 17, wherein the wireless transceiver is configured to inject the frequency-modulated signal at a point within the signal propagation path that is associated with baseband frequencies.
21. The apparatus of claim 17, wherein the frequency-modulated signal comprises a linear-frequency-modulated signal.
22. An apparatus comprising: a receiver comprising a signal propagation path; and a radio-frequency integrated circuit comprising: a mixer; a local oscillator circuit configured to generate a frequency-modulated signal; an injection circuit coupled to the receiver and the local oscillator circuit, the injection circuit configured to selectively: connect the local oscillator circuit to an output of the mixer to inject the frequency-modulated signal into the signal propagation path of the receiver; and disconnect the local oscillator circuit from the output of the mixer; and at least a portion of the signal propagation path of the receiver.
23. The apparatus of claim 22, wherein the frequency-modulated signal comprises a linear-frequency-modulated signal.
24. The apparatus of claim 22, wherein: the local oscillator circuit is configured to selectively: generate the frequency-modulated signal based on a calibration mode; and generate a local oscillator signal based on a wireless communication mode; and the receiver is configured to: receive a downlink signal based on the wireless communication mode; and downconvert a frequency of the downlink signal using the local oscillator signal.
25. The apparatus of claim 22, further comprising: a transmitter coupled to the local oscillator circuit, wherein: the frequency-modulated signal comprises a first frequency-modulated signal; the local oscillator circuit is configured to selectively: generate the first frequency-modulated signal based on a calibration mode; and generate a second frequency-modulated signal based on a proximity detection mode; and the transmitter is configured to generate, based on the proximity detection mode, a proximity detection signal by performing frequency upconversion using the second frequency-modulated signal.
26. The apparatus of claim 25, wherein: the first frequency-modulated signal has a first bandwidth; and the second frequency-modulated signal has a second bandwidth that is larger than the first bandwidth.
27. An apparatus comprising: a receiver comprising a signal propagation path; and a radio-frequency integrated circuit comprising: a local oscillator circuit configured to generate a frequency-modulated signal; an injection circuit coupled to the receiver and the local oscillator circuit, the injection circuit comprising: at least one frequency translation circuit coupled to the local oscillator circuit, the at least one frequency translation circuit configured to increase or decrease frequencies of the frequency-modulated signal; and at least one switch coupled to the at least one frequency translation circuit and disposed within the signal propagation path, the at least one switch configured to selectively: connect the at least one frequency translation circuit to a component within the signal propagation path of the receiver; and disconnect the at least one frequency translation circuit from the component and connect the component to another component within the signal propagation path of the receiver, wherein the injection circuit is configured to selectively: connect the local oscillator circuit to the signal propagation path of the receiver to inject the frequency-modulated signal into the signal propagation path of the receiver; and disconnect the local oscillator circuit from the signal propagation path of the receiver, and at least a portion of the signal propagation path of the receiver.
28. The apparatus of claim 27, wherein the injection circuit comprises at least one buffer coupled

between the local oscillator circuit and the at least one frequency translation circuit.

29. The apparatus of claim 27, wherein the frequency-modulated signal comprises a linear-frequency-modulated signal.

30. The apparatus of claim 27, wherein: the local oscillator circuit is configured to selectively: generate the frequency-modulated signal based on a calibration mode; and generate a local oscillator signal based on a wireless communication mode; and the receiver is configured to: receive a downlink signal based on the wireless communication mode; and downconvert a frequency of the downlink signal using the local oscillator signal.