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Inventor(s)	Hur; Joonhoi et al.

Background noise recorder

Abstract

An electronic device may include wireless circuitry with a transmit antenna that transmits signals and a receive antenna that receives reflected signals. The wireless circuitry may detect a range between the device and an external object based on the transmitted signals and the reflected signals. When the range exceeds a first threshold, the wireless circuitry may use the transmitted signals and received signals to record background noise. When the range is less than a second threshold value, the wireless circuitry may detect the range based on the reflected signals and the recorded background noise. This may allow the range to be accurately measured within an ultra-short range domain even when the device is placed in different device cases, placed on different surfaces, etc.

Inventors: **Hur; Joonhoi (Sunnyvale, CA), Schrattenecker; Jochen (Alberndorf in der Riedmark, AT), Xiao; Bin (San Ramon, CA), Hanke; Andre (San Jose, CA), Pretl; Harald (Schwertberg, AT), Vazny; Rastislav (Saratoga, CA), Sogl; Bernhard (Unterhaching, DE), Menkhoff; Andreas (Oberhaching, DE)**

Applicant: **Apple Inc.** (Cupertino, CA)

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References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
12047101	12/2023	Hur	N/A	G01S 7/038
2002/0163346	12/2001	Arndt et al.	N/A	N/A
2004/0214621	12/2003	Ponce De Leon	455/575.8	H01Q 1/242
2014/0278397	12/2013	Chen et al.	N/A	N/A
2015/0260828	12/2014	Ossowska	N/A	N/A
2015/0382307	12/2014	Harper	455/127.1	H04B 7/022
2019/0072660	12/2018	Wang et al.	N/A	N/A
2020/0271753	12/2019	Va et al.	N/A	N/A
2020/0321928	12/2019	Rao et al.	N/A	N/A
2021/0133399	12/2020	Coelho De Souza	N/A	G06F 3/04883
2021/0302528	12/2020	Wang	N/A	N/A
2021/0323574	12/2020	Yoo	N/A	G01C 21/3407
2022/0291338	12/2021	Hur et al.	N/A	N/A

OTHER PUBLICATIONS

Mauricio Martins Donatti et al., Object identification using VSWR evaluation based on a narrowband microstrip antenna and a tuned amplifier, 2017 IEEE 8th Latin American Symposium On Circuits & Systems (LASCAS), Feb. 2017, pp. 1-4, IEEE, New York, New York, United States. cited by applicant

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Primary Examiner: Vlahos; Sophia

Attorney, Agent or Firm: Treyz Law Group, P.C.

Background/Summary

(1) This application is a continuation of U.S. patent application Ser. No. 17/716,724, filed Apr. 8, 2022, which claims the benefit of U.S. provisional patent application No. 63/248,169, filed Sep. 24, 2021, each of which is hereby incorporated by reference herein in its entirety.

FIELD

(1) This disclosure relates generally to electronic devices and, more particularly, to electronic devices with wireless circuitry.

BACKGROUND

(2) Electronic devices are often provided with wireless capabilities. An electronic device with wireless capabilities has wireless circuitry that includes one or more antennas. The wireless circuitry is sometimes used to perform spatial ranging operations in which radio-frequency signals are used to estimate a distance between the electronic device and an external object.

(3) It can be challenging to provide wireless circuitry that accurately estimates this distance, particularly at short ranges.

SUMMARY

(4) An electronic device may include wireless circuitry controlled by one or more processors. The wireless circuitry may include a transmit antenna and a receive antenna. The transmit antenna may transmit radio-frequency signals. The receive antenna may receive reflected signals corresponding to the transmitted radio-frequency signals. The wireless circuitry may detect a range between the device and an external object based on the transmitted radio-frequency signals and the received reflected signals.

(5) When the range exceeds a first threshold value (e.g., in a long-range domain), the wireless circuitry may use the transmitted and received signals to record background noise associated with the absence of the external object near the device. When the range is less than a second threshold value (e.g., within an ultra-short range (USR) domain), the one or more processors may detect the range based on the received reflected signals and the recorded background noise. For example, the one or more processors may identify phase information from the received reflected signals and may subtract the recorded background noise from the phase information. This may allow the range to be accurately measured within the USR domain even when the device is placed in different device cases, placed on different surfaces, etc.

(6) An aspect of the disclosure provides a method of operating an electronic device. The method can include with wireless circuitry, transmitting radio-frequency signals and receiving reflected signals to identify a range between an external object and the electronic device. The method can include when the range exceeds a threshold value, controlling the wireless circuitry to record background noise using the transmitted radio-frequency signals. The method can include with the wireless circuitry, performing phase measurements from the received reflected signals. The method can include with the wireless circuitry, detecting the range based on the phase measurements and the recorded background noise.

(7) An aspect of the disclosure provides a method of operating an electronic device. The method can include with wireless circuitry, performing frequency-modulated continuous-wave (FMCW) radar operations to identify a range between an external object and the electronic device by transmitting radio-frequency signals and receiving reflected signals. The method can include when the range exceeds a first threshold value, recording background noise at the wireless circuitry using the transmitted radio-frequency signals. The method can include when the range is less than a second threshold value that is lower than the first threshold value, performing phase measurements from the received reflected signals and detecting the range based on the phase measurements and the recorded background noise.

(8) An aspect of the disclosure provides an electronic device. The electronic device can include one or more antennas configured to transmit radio-frequency signals and configured to receive reflected signals. The electronic device can include one or more processors. The one or more processors can be configured to identify a range between the electronic device and an external object based on the reflected signals received by the one or more antennas. The one or more processors can be configured to, when the range exceeds a first threshold value, record background noise using the

radio-frequency signals transmitted by the one or more antennas and corresponding signals received by the one or more antennas. The one or more processors can be configured to, when the range is less than a second threshold value that is lower than the first threshold value, detect the range based on phase measurements from the reflected signals received by the one or more antennas and based on the recorded background noise.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. **1** is a functional block diagram of an illustrative electronic device having radar circuitry in accordance with some embodiments.

(2) FIG. **2** is a circuit diagram of illustrative radar circuitry with reconfigurable filters for performing long range and ultra-short range (USR) detection in accordance with some embodiments.

(3) FIGS. **3** and **4** are diagrams of illustrative transmit signals that may be used by radar circuitry to perform long range and USR detection in accordance with some embodiments.

(4) FIG. **5** is a flow chart of illustrative operations involved in using an electronic device to perform both long range and USR detection in accordance with some embodiments.

(5) FIG. **6** is a plot of group delay as a function of range that shows how using radar circuitry to measure group delay may allow the radar circuitry to detect distance in accordance with some embodiments.

(6) FIG. **7** is a diagram showing how an illustrative high pass filter may be used to maximize signal-to-noise ratio for long range detection in accordance with some embodiments.

(7) FIG. **8** is a flow chart of illustrative operations involved in performing background recording and cancellation in accordance with some embodiments.

(8) FIG. **9** is a flow chart of illustrative operations involved in performing background recording and cancellation for short range and USR detection in accordance with some embodiments.

(9) FIG. **10** is a flow chart of illustrative operations involved in performing background recording and cancellation for a hybrid radar that performs long range and USR detection in accordance with some embodiments.

DETAILED DESCRIPTION

(10) Electronic device **10** of FIG. **1** may be a computing device such as a laptop computer, a desktop computer, a computer monitor containing an embedded computer, a tablet computer, a cellular telephone, a media player, or other handheld or portable electronic device, a smaller device such as a wristwatch device, a pendant device, a headphone or earpiece device, a device embedded in eyeglasses or other equipment worn on a user's head, or other wearable or miniature device, a television, a computer display that does not contain an embedded computer, a gaming device, a navigation device, an embedded system such as a system in which electronic equipment with a display is mounted in a kiosk or automobile, a wireless internet-connected voice-controlled speaker, a home entertainment device, a remote control device, a gaming controller, a peripheral user input device, a wireless base station or access point, equipment that implements the functionality of two or more of these devices, or other electronic equipment.

(11) As shown in the functional block diagram of FIG. **1**, device **10** may include components located on or within an electronic device housing such as housing **12**. Housing **12**, which may sometimes be referred to as a case, may be formed of plastic, glass, ceramics, fiber composites, metal (e.g., stainless steel, aluminum, metal alloys, etc.), other suitable materials, or a combination of these materials. In some situations, parts or all of housing **12** may be formed from dielectric or other low-conductivity material (e.g., glass, ceramic, plastic, sapphire, etc.). In other situations, housing **12** or at least some of the structures that make up housing **12** may be formed from metal

elements.

(12) Device **10** may include control circuitry **14**. Control circuitry **14** may include storage such as storage circuitry **16**. Storage circuitry **16** may include hard disk drive storage, nonvolatile memory (e.g., flash memory or other electrically-programmable-read-only memory configured to form a solid-state drive), volatile memory (e.g., static or dynamic random-access-memory), etc. Storage circuitry **16** may include storage that is integrated within device **10** and/or removable storage media.

(13) Control circuitry **14** may include processing circuitry such as processing circuitry **18**. Processing circuitry **18** may be used to control the operation of device **10**. Processing circuitry **18** may include on one or more microprocessors, microcontrollers, digital signal processors, host processors, baseband processor integrated circuits, application specific integrated circuits, central processing units (CPUs), etc. Control circuitry **14** may be configured to perform operations in device **10** using hardware (e.g., dedicated hardware or circuitry), firmware, and/or software. Software code for performing operations in device **10** may be stored on storage circuitry **16** (e.g., storage circuitry **16** may include non-transitory (tangible) computer readable storage media that stores the software code). The software code may sometimes be referred to as program instructions, software, data, instructions, or code. Software code stored on storage circuitry **16** may be executed by processing circuitry **18**.

(14) Control circuitry **14** may be used to run software on device **10** such as satellite navigation applications, internet browsing applications, voice-over-internet-protocol (VOIP) telephone call applications, email applications, media playback applications, operating system functions, etc. To support interactions with external equipment, control circuitry **14** may be used in implementing communications protocols. Communications protocols that may be implemented using control circuitry **14** include internet protocols, wireless local area network (WLAN) protocols (e.g., IEEE 802.11 protocols-sometimes referred to as Wi-Fi®), protocols for other short-range wireless communications links such as the Bluetooth® protocol or other wireless personal area network (WPAN) protocols, IEEE 802.11ad protocols (e.g., ultra-wideband protocols), cellular telephone protocols (e.g., 3G protocols, 4G (LTE) protocols, 3GPP 5G protocols, 6G protocols, etc.), antenna diversity protocols, satellite navigation system protocols (e.g., global positioning system (GPS) protocols, global navigation satellite system (GLONASS) protocols, etc.), antenna-based spatial ranging protocols (e.g., radio detection and ranging (RADAR) protocols or other desired range detection protocols for signals conveyed at millimeter and centimeter wave frequencies), or any other desired communications protocols. Each communications protocol may be associated with a corresponding radio access technology (RAT) that specifies the physical connection methodology used in implementing the protocol.

(15) Device **10** may include input-output circuitry **20**. Input-output circuitry **20** may include input-output devices **22**. Input-output devices **22** may be used to allow data to be supplied to device **10** and to allow data to be provided from device **10** to external devices. Input-output devices **22** may include user interface devices, data port devices, and other input-output components. For example, input-output devices **22** may include touch sensors, displays (e.g., touch-sensitive and/or force-sensitive displays), light-emitting components such as displays without touch sensor capabilities, buttons (mechanical, capacitive, optical, etc.), scrolling wheels, touch pads, key pads, keyboards, microphones, cameras, buttons, speakers, status indicators, audio jacks and other audio port components, digital data port devices, motion sensors (accelerometers, gyroscopes, and/or compasses that detect motion), capacitance sensors, proximity sensors, magnetic sensors, force sensors (e.g., force sensors coupled to a display to detect pressure applied to the display), etc. In some configurations, keyboards, headphones, displays, pointing devices such as trackpads, mice, and joysticks, and other input-output devices may be coupled to device **10** using wired or wireless connections (e.g., some of input-output devices **22** may be peripherals that are coupled to a main processing unit or other portion of device **10** via a wired or wireless link).

(16) Input-output circuitry **20** may include wireless circuitry **24** to support wireless communications. Wireless circuitry **24** (sometimes referred to herein as wireless communications circuitry **24**) may include two or more antennas **40**. Wireless circuitry **24** may also include baseband processor circuitry, transceiver circuitry, amplifier circuitry, filter circuitry, switching circuitry, radio-frequency transmission lines, and/or any other circuitry for transmitting and/or receiving radio-frequency signals using antennas **40**.

(17) Wireless circuitry **24** may transmit and/or receive radio-frequency signals within a corresponding frequency band at radio frequencies (sometimes referred to herein as a communications band or simply as a “band”). The frequency bands may include wireless local area network (WLAN) frequency bands (e.g., Wi-Fi® (IEEE 802.11) or other WLAN communications bands) such as a 2.4 GHz WLAN band (e.g., from 2400 to 2480 MHz), a 5 GHz WLAN band (e.g., from 5180 to 5825 MHz), a Wi-Fi® 6E band (e.g., from 5925-7125 MHz), and/or other Wi-Fi® bands (e.g., from 1875-5160 MHz), wireless personal area network (WPAN) frequency bands such as the 2.4 GHz Bluetooth® band or other WPAN communications bands, cellular telephone frequency bands (e.g., bands from about 600 MHz to about 5 GHZ, 3G bands, 4G LTE bands, 5G New Radio Frequency Range 1 (FR1) bands below 10 GHz, 5G New Radio Frequency Range 2 (FR2) bands between 20 and 60 GHz, etc.), other centimeter or millimeter wave frequency bands between 10-300 GHz, near-field communications frequency bands (e.g., at 13.56 MHz), satellite navigation frequency bands (e.g., a GPS band from 1565 to 1610 MHz, a Global Navigation Satellite System (GLONASS) band, a BeiDou Navigation Satellite System (BDS) band, etc.), ultra-wideband (UWB) frequency bands that operate under the IEEE 802.15.4 protocol and/or other ultra-wideband communications protocols, communications bands under the family of 3GPP wireless communications standards, communications bands under the IEEE 802.XX family of standards, and/or any other desired frequency bands of interest.

(18) Antennas **40** may be formed using any desired antenna structures. For example, antennas **40** may include antennas with resonating elements that are formed from loop antenna structures, patch antenna structures, inverted-F antenna structures, slot antenna structures, planar inverted-F antenna structures, helical antenna structures, monopole antennas, dipoles, hybrids of these designs, etc. Filter circuitry, switching circuitry, impedance matching circuitry, and/or other antenna tuning components may be adjusted to adjust the frequency response and wireless performance of antennas **40** over time.

(19) The radio-frequency signals handled by antennas **40** may be used to convey wireless communications data between device **10** and external wireless communications equipment (e.g., one or more other devices such as device **10**). Wireless communications data may be conveyed by wireless circuitry **24** bidirectionally or unidirectionally. The wireless communications data may, for example, include data that has been encoded into corresponding data packets such as wireless data associated with a telephone call, streaming media content, internet browsing, wireless data associated with software applications running on device **10**, email messages, etc.

(20) Wireless circuitry **24** may additionally or alternatively perform spatial ranging operations using antennas **40**. In scenarios where wireless circuitry **24** both conveys wireless communications data and performs spatial ranging operations, one or more of the same antennas **40** may be used to both convey wireless communications data and perform spatial ranging operations. In another implementation, wireless circuitry **24** may include a set of antennas **40** that only conveys wireless communications data and a set of antennas **40** that is only used to perform spatial ranging operations.

(21) When performing spatial ranging operations (sometimes referred to herein as range detection operations, ranging operations, or radar operations), antennas **40** may transmit radio-frequency signals **36**. Wireless circuitry **24** may transmit radio-frequency signals **36** in a corresponding radio frequency band such (e.g., a frequency band that includes frequencies greater than around 10 GHz, greater than around 20 GHz, less than 10 GHz, etc.). Radio-frequency signals **36** may reflect off of

objects external to device **10** such as external object **34**. External object **34** may be, for example, the ground, a building, a wall, furniture, a ceiling, a person, a body part, an accessory device, a game controller, an animal, a vehicle, a landscape or geographic feature, an obstacle, or any other object or entity that is external to device **10**. Antennas **40** may receive reflected radio-frequency signals **38**. Reflected signals **38** may be a reflected version of the transmitted radio-frequency signals **36** that have reflected off of external object **34** and back towards device **10**.

(22) Control circuitry **14** may process the transmitted radio-frequency signals **36** and the received reflected signals **38** to detect or estimate the range R between device **10** and external object **34**. If desired, control circuitry **14** may also process the transmitted and received signals to identify a two or three-dimensional spatial location (position) of external object **34**, a velocity of external object **34**, and/or an angle of arrival of reflected signals **38**. In one implementation that is described herein as an example, wireless circuitry **24** performs spatial ranging operations using a frequency-modulated continuous-wave (FMCW) radar scheme. This is merely illustrative and, in general, other radar schemes or spatial ranging schemes may be used (e.g., an OFDM radar scheme, an FSCW radar scheme, a phase coded radar scheme, etc.).

(23) To support spatial ranging operations, wireless circuitry **24** may include spatial ranging circuitry such as radar circuitry **26**. In one embodiment that is sometimes described herein as an example, radar circuitry **26** includes FMCW radar circuitry that performs spatial ranging using an FMCW radar scheme. Radar circuitry **26** may therefore sometimes be referred to herein as FMCW radar circuitry **26**. Radar circuitry **26** may use one or more antennas **40** to transmit radio-frequency signals **36** (e.g., as a continuous wave of radio-frequency energy under an FMCW radar scheme). One or more antennas **40** may also receive reflected signals **38** (e.g., as a continuous wave of radio-frequency energy under the FMCW radar scheme). Radar circuitry **26** may process radio-frequency signals **36** and reflected signals **38** to identify/estimate range R, the position of external object **34**, the velocity of external object **34**, and/or the angle-of-arrival of reflected signals **38**. In embodiments where radar circuitry **26** uses an FMCW radar scheme, doppler shifts in the continuous wave signals may be detected and processed to identify the velocity of external object **34** and the time dependent frequency difference between radio-frequency signals **36** and reflected signals **38** may be detected and processed to identify range R and/or the position of external object **34**. Use of continuous wave signals for estimating range R may allow control circuitry **10** to reliably distinguish between external object **34** and other background or slower-moving objects, for example.

(24) As shown in FIG. **1**, radar circuitry **26** may include transmit (TX) signal generator circuitry such as transmit signal generator **28**. Transmit signal generator **28** may generate transmit signals for transmission over antenna(s) **40**. In some implementations that are described herein as an example, transmit signal generator **28** includes a chirp generator that generates chirp signals for transmission over antenna(s) **40** (e.g., in embodiments where radar circuitry **26** uses an FMCW radar scheme). Transmit signal generator **28** may therefore sometimes be referred to herein as chirp generator **28**. Transmit signal generator **28** may, for example, produce chirp signals that are transmitted as a continuous wave of radio-frequency signals **36**. The chirp signals may be formed by periodically ramping up the frequency of the transmitted signals in a linear manner over time, for example. Radar circuitry **26** may also include digital-to-analog converter (DAC) circuitry such as DAC **32**. DAC **32** may convert the transmit signals (e.g., the chirp signals) from the digital domain to the analog domain prior to transmission by antennas **40** (e.g., in radio-frequency signals **36**). Radar circuitry **26** may also include analog-to-digital converter (ADC) circuitry such as ADC **42**. ADC **42** may convert signals from the analog domain to the digital domain for subsequent processing by control circuitry **14**. If desired, radar circuitry **26** may include distortion circuitry **30**. Distortion circuitry **30** may include predistortion circuitry that predistorts the transmit signals prior to transmission by antennas **40** and/or may include post-distortion circuitry that distorts received signals.

(25) The example of FIG. **1** is merely illustrative. While control circuitry **14** is shown separately from wireless circuitry **24** in the example of FIG. **1** for the sake of clarity, wireless circuitry **24** may include processing circuitry (e.g., one or more processors) that forms a part of processing circuitry **18** and/or storage circuitry that forms a part of storage circuitry **16** of control circuitry **14** (e.g., portions of control circuitry **14** may be implemented on wireless circuitry **24**). As an example, control circuitry **14** may include baseband circuitry (e.g., one or more baseband processors), digital control circuitry, analog control circuitry, and/or other control circuitry that forms part of radar circuitry **26**. The baseband circuitry may, for example, access a communication protocol stack on control circuitry **14** (e.g., storage circuitry **20**) to: perform user plane functions at a PHY layer, MAC layer, RLC layer, PDCP layer, SDAP layer, and/or PDU layer, and/or to perform control plane functions at the PHY layer, MAC layer, RLC layer, PDCP layer, RRC, layer, and/or non-access stratum layer. If desired, the PHY layer operations may additionally or alternatively be performed by radio-frequency (RF) interface circuitry in wireless circuitry **24**.
(26) If desired, radar circuitry **26** may be used to measure the proximity of a human body to antennas **40**. Measurement of this proximity (e.g., range R) may allow the device to adjust the transmit power level of antennas **40** (e.g., based on range R) to ensure that wireless circuitry **24** complies with regulatory requirements on radio-frequency exposure (RFE). For example, the transmit power level and/or transmit duration of the wireless circuitry can be reduced and/or different antennas can be switched into use when range R is small to ensure compliance with these requirements. When no external object **34** is located close to antennas **40** (e.g., when range R is high), wireless circuitry **24** may transmit radio-frequency signals at a maximum transmit power level, thereby maximizing throughput. In general, radar circuitry **26** needs to be very accurate to perform such detection of a human body (sometimes referred to herein as body proximity sensing (BPS)). However, a relatively high dynamic range is needed to resolve a wide number of ranges R (e.g., limits in dynamic range can limit the overall detection range of radar circuitry **26**). If care is not taken, it can be difficult to configure radar circuitry **26** to detect range R over both relatively long distances (e.g., ranges greater than around 10 cm, generally referred to herein as “long range”) and relatively short distances (e.g., ranges less than around 10 cm, generally referred to herein as “ultra-short range (USR)”) with sufficient dynamic range.
(27) To allow radar circuitry **26** to perform spatial ranging operations within both the long range domain (sometimes referred to herein as the far field domain) and within the USR domain, radar circuitry **26** may include reconfigurable high pass filters. FIG. **2** is a circuit diagram of radar circuitry **26** having reconfigurable high pass filters.
(28) As shown in FIG. **2**, radar circuitry **26** may include a transmit chain **52** (sometimes referred to herein as transmitter chain **52**, transmit line-up **52**, or transmit path **52**) and a receive chain **54** (sometimes referred to herein as receiver chain **54**, receive line-up **54**, or receive path **52**). Transmit (TX) chain **52** may include a digital-to-analog converter (DAC) such as DAC **62**. DAC **62** may include an in-phase (I) DAC **62**I that operates on in-phase (I) signals and a quadrature-phase (Q) DAC **62**Q that operates on quadrature-phase (Q) signals (e.g., of an I/Q signal pair). Transmit chain **52** may include mixers **68** (e.g., an in-phase mixer **681** and a quadrature phase mixer **68**Q) having first inputs coupled to the outputs of DACs **62**I and **62**Q and having second inputs coupled to clocking circuitry such as local oscillator (LO) **66**. Mixers **68** may have outputs coupled to the input of power amplifier (PA) **70** in transmit chain **52**. The output of PA **70** may be coupled to a first antenna **40** (FIG. **1**).
(29) Receive (RX) chain **54** may include a low noise amplifier (LNA) **72** and mixers **74** (e.g., an in-phase mixer **74**I and a quadrature-phase mixer **74**Q) having first inputs coupled to the output of LNA **72** and having second inputs coupled to LO **66**. The input of LNA **72** may be coupled to a second antenna **40** (FIG. **1**). Receive chain **54** may include high pass filters **76** having inputs coupled to mixers **74** and having outputs coupled to analog-to-digital converter (ADC) **64** (e.g., an in-phase (I) ADC **64**I and a quadrature-phase (Q) ADC **34**Q). For example, a first high pass filter

76I may be interposed between the output of mixer **74**I and the input of ADC **64**I and a second high pass filter **76**Q may be interposed between the output of mixer **74**Q and the input of ADC **64**Q. The outputs of ADC **64**I and **64**Q and the inputs of DACs **62**I and **62**Q may be coupled to digital signal processor (DSP) **50**. DSP **50** may include a digital background (BG) canceller **56**, FMCW or other long range radar circuitry such as FMCW circuitry **58**, and phase detector **60**.

(30) High pass filters **76**I and **76**Q may be reconfigurable (bypassable). For example, a bypass path **78**I may couple the input of high pass filter (HPF) **76**I to the output of HPF **76**I. Similarly, a bypass path **78**Q may couple the input of HPF **76**Q to the output of HPF **76**Q. Switches such as switches (SW) **80** may be disposed on bypass paths **78**I and **78**Q. If desired, an optional all pass filter (APF) **82** may be disposed on bypass paths **78**I and **78**Q (e.g., between switch **80** and ADC **64**). Switches **80** may have a first state (e.g., where switches **80** are closed or turned on) in which HPFs **76** are bypassed and may have a second state (e.g., where switches **80** are open or turned off) in which HPFs **76** are switched into use and bypass paths **78** form open circuits.

(31) If desired, a feedback path **84** may couple transmit chain **52** to receive chain **54**. A de-chirp path may additionally or alternatively couple transmit chain **52** to a de-chirp mixer in receive chain **54**. As shown in FIG. **2**, feedback path **84** may include an optional multi-tab analog interference canceller **86** having an output coupled to an adder such as adder **87** in receive chain **54**. Adder **87** and/or feedback path **84** may be omitted if desired. The example of FIG. **2** is merely illustrative. In general, other circuit architectures may be used to form radar circuitry **26**. Additional filters, amplifiers, switches, delay stages, splitters, and/or other circuit components may be formed at other locations in radar circuitry **26**.

(32) When performing spatial ranging (radar) operations, transmit signal generator **28** (FIG. **1**) may generate transmit signals (e.g., digital chirp signals) for subsequent transmission by the antenna coupled to transmit chain **52** (e.g., using a continuous wave of radio-frequency energy). FMCW circuitry **58** may, for example, control the transmit signal generator to generate desired transmit signal waveforms. If desired, digital BG canceler **56** may perform background cancellation (pre-compensation) on the generated transmit signals. DAC **62** may convert the transmit signals to the digital domain. Mixers **68** may upconvert the transmit signals to radio frequencies or intermediate frequencies for later upconversion to radio-frequencies (e.g., using a local oscillator (LO) signal from LO **66**). These frequencies may be 5G NR FR1 or FR2 frequencies, for example. PA **70** may amplify the transmit signals for transmission by the corresponding antenna **40** coupled to transmit chain **52** (e.g., as radio-frequency signals **36** of FIG. **1**).

(33) The antenna **40** coupled to receive chain **54** may receive reflected signals **38** (e.g., a reflected version of the transmit signals transmitted over transmit chain **52**). LNA **72** may amplify the received reflected signals **38**. Mixers **74** may downconvert the reflected signals to baseband. During long range detection, switches **80** may be open (e.g., bypass paths **78** may form open circuits) and HPFs **76** may filter the received reflected signals to output filtered signals. ADC **64** may convert the filtered signals to the digital domain for subsequent processing by DSP **50**. FMCW circuitry **58** may process the transmit signals provided to transmit chain **52** and the reflected signals received over receive chain **54** to identify range R to external object **34**. For example, FMCW circuitry **58** may detect (e.g., identify) time delays between the transmitted and received signals, may generate time of flight (TOF) information for the signals, and may identify (e.g., generate, compute, calculate, etc.) range R from the TOF information. HPFs **76** may serve to filter out leakage/interference signal (e.g., from coupling or a dielectric cover layer on device **10** through which the radio-frequency signals and reflected signals pass) from the received reflected signals, thereby maximizing the signal-to-noise ratio SNR and dynamic range of the received signals to allow for accurate long range measurements of range R.

(34) When performing USR measurements, the high dynamic range required for long range detection is not needed. As such, HPFs **76** may be bypassed or switched out of use while performing USR measurements. For example, switches **80** may be closed, allowing the received

reflected signals to pass from mixers **74** directly to ADC **64** without being filtered. If desired, APFs **82** may filter these signals to correct for imperfections in the channel response, for example. Phase detector **60** may process the received reflected signals to identify (e.g., generate, detect, estimate, measure, etc.) the phase and/or phase delay of the signals (e.g., group phase delay), in a process sometimes referred to herein as performing phase measurements. Control circuitry **14** (FIG. **1**) may determine (e.g., identify, generate, calculate, etc.) range R based on the identified phase delay (based on the phase measurements). If desired, digital BG canceller **56** may perform BG noise cancellation on the transmitted and/or received signals used to perform USR detection. HPFs **76** may be replaced with DC notch filters if desired.
(35) FIG. **3** is a diagram (in frequency as a function of time) of illustrative transmit signals that may be transmitted over transmit chain **52** for performing long range and USR detection. Curve **100** plots a digital FMCW or continuous FMCW signal (e.g., a frequency ramp or chirp signal) that may be transmitted for performing long range detection (e.g., while HPFs **76** are switched into use in the receive chain). Curve **102** plots discrete frequencies (e.g., a step function in frequency versus time) that may be used in the transmit signal for performing USR detection. If desired, LO **66** may generate coarse steps LO_**1** through LO_N used in generating the transmit signal whereas the finer steps or continuous steps are provided from DAC **62** of FIG. **2**. The example of FIG. **3** is merely illustrative and, in general, curves **100** and **102** may have other shapes.
(36) FIG. **4** is a plot of the transmit signals associated with curve **102** of FIG. **3** that may be used in performing USR detection, but in units of power as a function of frequency. As shown in FIG. **4**, the transmit signal involves a series of peaks (lines) **104** each separated by frequency gap Δf. Control circuitry **14** may process the transmit signal associated with peaks **104** as well as the reflected version of the transmit signal (e.g., as received while HPFs **76** are bypassed) to identify range R to the external object (e.g., using equation **106**). As shown by equation **106**, distance d (range R) may be computed as a function of the measured phase delay detected by phase detector **60** from the received reflected version of transmit signal **104** (e.g., where **52***a* is a factor that accounts for the phase delay, co is the speed of light, and t is a complex phase delay factor). Control circuitry **14** may identify range R (distance d) using equation **106** or by comparing the measured phase delay to a look up table of predetermined phase delays stored on device **10** (e.g., where each stored phase delay corresponds to a stored distance d that is retrieved by comparing the measured phase delay to the predetermined phase delays in the look up table).
(37) FIG. **5** is a flow chart of illustrative operations involved in performing ranging using radar circuitry **26**. At operation **110**, radar circuitry **26** may begin recording (gathering) background noise measurements. For example, radar circuitry **26** may perform USR detection when no objects are present near device **10** to measure background noise associated with the housing for device **10**, a removable case on device **10**, etc. This background noise may later be subtracted off of subsequent USR detections to generate accurate ranges R for objects within 10 cm.
(38) At operation **112**, radar circuitry **26** may perform long range detection (e.g., using the transmit signal associated with curve **100** of FIG. **3**, such as using an FMCW scheme and transmit signal). HPFs **76** may be switched into use and may filter the received reflected signals to maximize dynamic range. Control circuitry **14** may identify range R based on the transmitted and reflected signals (e.g., by identifying TOF information from time delays between the transmitted and reflected signals).
(39) At operation **114**, radar circuitry **26** may perform USR detection (e.g., using the transmit signal associated with curve **102** of FIG. **3**). HPFs **76** may be switched out of use (bypassed). Phase detector **60** may measure the phase delay of the received reflected signals (e.g., may perform phase measurements). Control circuitry **14** may process the phase delay to identify range R based on the phase delay (e.g., either as input to a function or by comparison to stored information such as look up table information mapping predetermined/calibrated ranges to phase delays). Control circuitry **14** may also perform background noise cancellation using the gathered BG measurements to ensure

that the identified range R is accurate (at operation **116**). The background noise cancellation may occur in the digital domain, for example (e.g., at DSP **50** of FIG. **2**). Processing may then loop back to operation **112** via path **118** (e.g., radar circuitry **26** may perform long range detection and USR detection in a time-interleaved/duplexed manner).

(40) If desired, analog interference cancellation may also be performed using multi-tab AIC **86** of FIG. **2**. For example, AIC **86** may be used to perform coefficient adaption from background measurements and analog multi-tab cancellation may be performed. However, analog interference cancellation may undesirably increase RF hardware complexity, reduce tunability, and degrade SNR. Performing digital BG cancellation using digital BG canceller **56** of FIG. **2** may allow DSP **50** to perform coefficient adaptation from background measurements, where the background measurements are subtracted in the complex domain from the transmitted and/or received signals (e.g., at operation **116** of FIG. **5**). Digital BG cancellation may involve greater hardware flexibility than analog cancellation.

(41) FIG. **6** is a plot showing how measured group delay may vary as a function of distance (range R) to external object **34**. As shown by curve **120**, group delay generally increases as range (distance) R increases. Bypassing HPFs **76** and performing digital BG cancellation may allow device **10** to perform USR detection based on the measured group delay with finer resolution than would otherwise be possible (e.g., within 4 cm or less).

(42) FIG. **7** is a plot showing how HPFs **76** may be used to maximize dynamic range for long range detection (in power spectral density (PSD) as a function of frequency). Curve **132** of FIG. **7** plots the PSD at the antennas generated by signal leakage or coupling as the transmit signals and reflected signals pass through the cover layer(s) of device **10** from free space to antennas **40**. Curve **132** may peak at a frequency such as frequency F**0**. Curve **134** plots the expected PSD produced at the antennas by reflection of the transmit signals off external object **34** located within the USR domain (e.g., within 10 cm). Curve **134** may peak at a frequency such as frequency F**1**. Curve **136** plots the expected PSD produced by reflection of the transmit signals off external object **34** located within the long range domain (e.g., beyond 10 cm). Curve **136** may peak at a frequency such as frequency F**3**.

(43) Curve **130** plots the filter response of HPFs **76**. As shown by curve **130**, HPFs **76** may have a roll off (edge) frequency F**2**, a pass band at frequencies greater than F**2**, and a stop band (e.g., notch) at frequencies less than F**2**. Frequency F**2** may be selected to be greater than frequency F**1** and less than frequency F**3**. In this way, HPFs **76** may filter out the PSD associated with leakage or coupling (curve **132**) from the reflected signals received and measured by radar circuitry **26**. This may serve to maximize dynamic range for detecting range R to external object **34** in the long range domain. Since curve **134** is below frequency F**2**, HPFs **76** need to be disabled (bypassed) to allow radar circuitry **26** to receive the PSD produced by reflection off external object **34** (curve **134**), which is then used to identify the range to the external object (e.g., within 10 cm).

(44) As described above, USR detection may involve the cancellation (subtraction) of background noise (e.g., at operation **116** of FIG. **5**). Background noise cancellation may allow for USR detection with fine range resolution. FIG. **8** is a flow chart of illustrative operations involved in gathering background measurements (e.g., as begun at operation **110** of FIG. **5**) and in applying the gathered background measurements to USR detection operations (e.g., via background subtraction).

(45) At operation **150**, radar circuitry **26** may perform radar operations (e.g., long range detection or USR detection at operations **112**/**114** of FIG. **5**). Radar circuitry **26** may identify range R by performing radar operations, for example. Radar circuitry **26** may perform background recording operations/algorithm **152** (e.g., gathering and storing of background noise measurements for use in later background cancellation while performing USR operations) periodically, upon boot up, in the factory, upon software update, and/or in response to any desired trigger condition.

(46) At operation **154**, control circuitry **14** may determine whether range R exceeds a long threshold value (e.g., 2 m, 10 cm, 1 m, other values greater than or equal to 1 m or 0.5 m, etc.). If

range R is less than this threshold value, there is an external object **34** located relatively close to device **10** and any subsequent measurements will not be indicative of the true background noise of the radar circuitry. As such, if range R does not exceed the long threshold value, processing may loop back to operation **150** via path **164**. Range R may be determined using range circuitry **26** and/or other sensors on device **10** if desired.

(47) If range R is greater than the long threshold value, there are no external objects **34** located relatively close to device **10** and processing may proceed to operation **156**. At operation **156**, radar circuitry **26** may perform other object detection (e.g., inanimate object detection) if desired. This may involve performing object detection using other proximity sensors such as a voltage standing wave ratio (VSWR) sensor coupled to one or more antennas **40**.

(48) At operation **158**, control circuitry **14** may determine whether an object was detected at operation **156**. This may involve, for example, comparing VSWR values to stored VSWR values associated with known inanimate objects or may involve tracking changes in measured VSWR values over time (e.g., where the amount of change in the VSWR values over time is less than a threshold amount over a predetermined time period). If no inanimate object is detected, processing may loop back to path **150** via path **164**. If an inanimate object is detected, this may be indicative of a device case or other inanimate object being present on device **10**. It would therefore be desirable to be able to characterize the background noise effects (e.g., which produces the PSD associated with curve **132** of FIG. **7**) that such an inanimate object has on radar circuitry **26** (e.g., for later subtraction of the effects of the inanimate object on measurements of range R due to signal reflections, attenuation, diffraction, etc. as the signals pass through the inanimate object). In other words, if an inanimate object is detected, processing may proceed to operation **160**.

(49) At operation **160**, radar circuitry **16** may enter a USR background recording mode in which radar circuitry **16** gathers (measures) and stores background noise using the transmitted and received signals. For example, control circuitry **14** may switch HPFs **76** (FIG. **2**) out of use and may switch APF **82** on bypass paths **78** into use. TX signal generator **28** may transmit N tones over transmit chain **52**. The N tones may be defined from channel conditions such as resonance removal conditions (e.g., to measure channel performance). Control circuitry **14** may then memorize/record (e.g., measure and store) the amplitude and/or phase of each of the N tones as received over receive chain **54** (e.g., using measurement of offset phases, least mean squares (LMS), least squares (SQ), etc. using a multi tab filter).

(50) At operation **162**, control circuitry **14** may run a background (BG) stabilizer on the recorded amplitudes and/or phases. The BG stabilizer may include decimation, averaging, and/or interpolation of the gathered amplitudes and/or phases (e.g., stabilization operations that minimize noise or otherwise enhance the time-stability of the data).

(51) At operation **166**, control circuitry **14** may determine whether the phase and/or magnitude values are sufficiently stable after running the BG stabilizer. If the values are not sufficiently stable (e.g., exhibit excessive change over a period of time, exhibit a stability value less than a threshold stability value, etc.), the values may be insufficient for use in background cancellation and can be discarded (e.g., processing may loop back to operation **150** via path **164**). If the values are sufficiently stable (e.g., exhibit relatively little change over a period of time, exhibit a stability value greater than a threshold stability value, etc.), the values may be satisfactory for use in background cancellation and processing may proceed to operation **170** via path **168**.

(52) At operation **170**, control circuitry **14** (radar circuitry **26**) may perform BG subtraction operations that configure radar circuitry **26** (e.g., digital BG canceller **56**) to mitigate/cancel/subtract out the measured/recorded background noise during subsequent radar operations. Processing may proceed to operation **150** and radar operations may be performed while subtracting out the background noise as configured during operation **170**. For example, digital BG canceller **56** may perform complex subtraction, multi-tab LMS, and/or LS on subsequently transmitted and/or received signals used in performing USR detection (e.g., at operation **114** of

FIG. **5**).

(53) FIG. **9** is a flow chart showing how these operations may be adapted to implementations in which radar circuitry **26** is operable to perform short range detection and then USR detection. At operation **180**, radar circuitry **26** may perform short range (SR) detection using transmitted and reflected signals. SR detection may be at longer ranges than USR but shorter ranges than far field detection. Radar circuitry **26** may then perform background recording operations/algorithm **152**.

(54) At operation **166**, control circuitry **14** may determine whether the phase and/or magnitude values are sufficiently stable after running the BG stabilizer in background recording operations/algorithm **152**. If the values are not sufficiently stable, processing may loop back to operation **180** via path **164**. If the values are sufficiently stable, processing may proceed to operation **170** via path **168**.

(55) At operation **170**, radar circuitry **26** may perform USR detection using transmitted and reflected signals (e.g., transmit signals as shown by curve **102** of FIG. **3**). Radar circuitry **26** may perform USR detection while subtracting/cancelling out background noise as recorded while performing background recording operations/algorithm **152** after operation **180**. Radar circuitry **26** may then repeat the background recording operations/algorithm as background recording operations/algorithm **152**′. Background recording operations/algorithm **152**′ may loop back to operation **170**.

(56) FIG. **10** is a flow chart showing how these operations may be adapted to implementations in which radar circuitry **26** is operable to perform long range detection and then USR detection. At operation **200**, radar circuitry **26** may perform long range detection using transmitted and reflected signals (e.g., using FMCW signals such as the signals associated with curve **100** of FIG. **3**). Radar circuitry **26** may gather measurements of range R during operation **200**.

(57) If/when range R exceeds the long threshold value (e.g., 2 m) during the long range radar operations, radar circuitry **26** may proceed with performing background recording operations/algorithm **152**. Background recording operations/algorithm **152** may produce and store background noise values for use during later USR operations, and processing may loop back to operation **200** via path **202**.

(58) During the long range radar operations, control circuitry **14** may determine whether range R falls below a short threshold value (e.g., 10 cm) (at operation **204**). If range R does not fall below the short threshold value, processing may loop back to operation **200** via path **206**. If range R falls below the short threshold value, processing may proceed to operation **206**.

(59) At operation **206**, radar circuitry **26** may perform a stable statistic determination (e.g., operation **166** of FIG. **8**) on the background measurements gathered during background recording operations/algorithm **152**. If the background measurements are sufficiently stable, radar circuitry **26** may perform USR detection (e.g., by transmitting and receiving signals such as the signals associated with curve **102** of FIG. **3**) while performing background cancellation using the background measurements gathered during background recording operations/algorithm **152** (e.g., via complex subtraction of the background measurements from the phase measurements gathered in the USR detection). If the background measurements are not sufficiently stable, radar circuitry **26** may perform SR detection (e.g., operation **180** of FIG. **9**).

(60) At operation **208**, control circuitry **14** may determine if range R has fallen below the short threshold (e.g., 10 cm). If range R as detected during SR detection falls below 10 cm, processing may loop back to operation **206** via path **210**. If range R is not below 10 cm, processing may loop back to operation **200** via path **206**. HPF filters **76** (FIG. **2**) may be switched into use on receive chain **54** at operation **200**. Performing background noise subtraction may allow radar circuitry **26** to detect ranges R that are less than 10 cm, for example.

(61) Device **10** may gather and/or use personally identifiable information. It is well understood that the use of personally identifiable information should follow privacy policies and practices that are generally recognized as meeting or exceeding industry or governmental requirements for

maintaining the privacy of users. In particular, personally identifiable information data should be managed and handled so as to minimize risks of unintentional or unauthorized access or use, and the nature of authorized use should be clearly indicated to users.
(62) The methods and operations described above may be performed by the components of device **10** using software, firmware, and/or hardware (e.g., dedicated circuitry or hardware). Software code for performing these operations may be stored on non-transitory computer readable storage media (e.g., tangible computer readable storage media) stored on one or more of the components of device **10** (e.g., storage circuitry **16** of FIG. **1**). The software code may sometimes be referred to as software, data, instructions, program instructions, or code. The non-transitory computer readable storage media may include drives, non-volatile memory such as non-volatile random-access memory (NVRAM), removable flash drives or other removable media, other types of random-access memory, etc. Software stored on the non-transitory computer readable storage media may be executed by processing circuitry on one or more of the components of device **10** (e.g., processing circuitry **18** of FIG. **1**, etc.). The processing circuitry may include microprocessors, central processing units (CPUs), application-specific integrated circuits with processing circuitry, or other processing circuitry.
(63) The foregoing is merely illustrative and various modifications can be made to the described embodiments. The foregoing embodiments may be implemented individually or in any combination.

Claims

1. A method of operating an electronic device comprising: measuring, using wireless circuitry, a voltage standing wave ratio (VSWR) of one or more antennas; measuring, using the wireless circuitry, background noise while the measured VSWR is within a predetermined range; transmitting, using the wireless circuitry, a radio-frequency signal; receiving, using the wireless circuitry, a reflected signal associated with the radio-frequency signal; and estimating, using one or more processors, a range between an external object and the wireless circuitry based on the reflected signal and the measured background noise, wherein the predetermined range is associated with an additional external object being near the electronic device.
2. The method of claim 1, wherein the additional external object is a removable case.
3. The method of claim 2, wherein the VSWR values are outside of the predetermined range while the removable case is not on the electronic device.
4. The method of claim 1, further comprising: measuring, using the wireless circuitry, a phase of the reflected signal.
5. The method of claim 4, wherein estimating the range comprises estimating the range based on the measured phase of the reflected signal.
6. The method of claim 1, wherein estimating the range comprises subtracting the measured background noise from the reflected signal.
7. The method of claim 6, wherein measuring the background noise comprises: transmitting, using the wireless circuitry, an additional radio-frequency signal; and receiving, using the wireless circuitry, an additional reflected signal associated with the additional radio-frequency signal.
8. The method of claim 7, wherein measuring the background noise further comprises: decimating the additional reflected signal prior to subtracting the measured background noise from the reflected signal.
9. The method of claim 7, wherein measuring the background noise further comprises: averaging the additional reflected signal prior to subtracting the measured background noise from the reflected signal.
10. The method of claim 7, wherein receiving the reflected signal comprises receiving the reflected signal using an antenna from the one or more antennas and wherein receiving the additional

reflected signal comprises receiving the additional reflected signal using the antenna from the one or more antennas.

11. An electronic device comprising: one or more antennas; wireless circuitry configured to measure background noise while a voltage standing wave ratio (VSWR) of the one or more antennas is within a predetermined range, transmit a radio-frequency signal, and receive a reflected signal associated with the radio-frequency signal; and one or more processors configured to estimate a range between the electronic device and an external object based on the reflected signal and the measured background noise, wherein the predetermined range is associated with an additional external object being near the electronic device.

12. The electronic device of claim 11, wherein the additional external object is a removable case.

13. The electronic device of claim 11, wherein the wireless circuitry is configured to measure a phase of the reflected signal, the one or more processors being configured to estimate the range based on the measured phase of the reflected signal.

14. The electronic device of claim 11, wherein the wireless circuitry is configured to transmit the radio-frequency signal using the one or more antennas.

15. The electronic device of claim 11, wherein the wireless circuitry is configured to receive the reflected signal using the one or more antennas.

16. The electronic device of claim 11, the one or more processors being further configured to estimate the range by subtracting the measured background noise from the reflected signal.

17. A method of operating an electronic device comprising: measuring, using wireless circuitry, a voltage standing wave ratio (VSWR) of an antenna; measuring, using the wireless circuitry, background noise while the VSWR of the antenna is indicative of the electronic device being in a removable case; generating, using the wireless circuitry, a radar measurement based on a transmitted signal and a reflected signal; and removing, using one or more processors, the background noise from the radar measurement.

18. The method of claim 17, wherein measuring the background noise comprises: transmitting an additional signal while the VSWR of the antenna is indicative of the electronic device being in the removable case; and receiving an additional reflected signal while the VSWR of the antenna is indicative of the electronic device being in the removable case.

19. The method of claim 17, further comprising: estimating, using the one or more processors, a range to an external object based on the radar measurement after removal of the background noise from the radar measurement.

20. The electronic device of claim 11, wherein the wireless circuitry comprises: a VSWR sensor configured to measure the VSWR; and radar circuitry configured to transmit the radio-frequency signal and configured to receive the reflected signal.