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United States Patent	12389356
Kind Code	B2
Date of Patent	August 12, 2025
Inventor(s)	Ballantyne; Wayne et al.

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### Opportunistic calibration of a clock

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#### Abstract

A wireless communication device can include an oscillator circuit. The oscillator circuit can include an oscillator and measurement circuitry coupled to the oscillator. The measurement circuitry can receive an output signal of the oscillator and measure oscillator error by comparing the output signal of the oscillator to a nominal frequency for an amount of time. The oscillator circuit can further include adjustment circuitry to adjust an oscillator frequency of the oscillator based on the measured oscillator error.

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**Inventors:** Ballantyne; Wayne (Chandler, AZ), Jann; Benjamin (Portland, OR), Geren; Bruce (Chandler, AZ), Chance; Gregory (Chandler, AZ)

**Applicant:** Intel Corporation (Santa Clara, CA)

**Family ID:** 1000008750560

**Assignee:** Intel Corporation (Santa Clara, CA)

**Appl. No.:** 17/549042

**Filed:** December 13, 2021

#### Prior Publication Data

Document Identifier	Publication Date
US 20230189182 A1	Jun. 15, 2023

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#### Publication Classification

**Int. Cl.:** H04W56/00 (20090101); H03K3/03 (20060101)

**U.S. Cl.:**

**CPC** H04W56/005 (20130101); H03K3/0315 (20130101);

## Field of Classification Search

**CPC:** H04W (56/005)

**USPC:** 331/44

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## References Cited

### U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
2017/0040985	12/2016	Chen	N/A	H03K 19/00369
2019/0268010	12/2018	Wu	N/A	H03L 7/187

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*Primary Examiner:* Chang; Joseph

*Attorney, Agent or Firm:* Schwegman Lundberg & Woessner, P.A.

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## Background/Summary

### TECHNICAL FIELD

(1) Aspects of the disclosure pertain to radio frequency (RF) communications. More particularly, aspects relate to oscillators used in RF communications.

### BACKGROUND

(2) Some RF front-end (RFFE) chips, such as beamformer chips, power amplifiers, temperature sensors, and power detectors, do not require a precise oscillator and therefore providing such an expensive oscillator may not be justified for those RFFE chips. On the other hand, an on-die clock is used to complete certain operations in these chips, whose accuracy may vary significantly over process and temperature. Therefore, there is a general need to improve accuracy of less expensive oscillators while avoiding use of highly expensive precision oscillators.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

(1) In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components. Some aspects are illustrated by way of example, and not limitation, in the figures of the accompanying drawings in which:

(2) FIG. 1 illustrates an exemplary user device according to some aspects.

(3) FIG. 1A illustrates a mmWave system, which can be used in connection with the device of FIG. 1 according to some aspects.

(4) FIG. 2 illustrates an exemplary base station radio head according to some aspects.

(5) FIG. 3A illustrates exemplary wireless communication circuitry according to some aspects.

(6) FIG. 3B illustrates aspects of exemplary transmit circuitry illustrated in FIG. 3A according to some aspects.

(7) FIG. 3C illustrates aspects of exemplary transmit circuitry illustrated in FIG. 3A according to some aspects.

(8) FIG. 3D illustrates aspects of exemplary radio frequency circuitry illustrated in FIG. 3A

according to some aspects.

(9) FIG. 3E illustrates aspects of exemplary receive circuitry in FIG. 3A according to some aspects.

(10) FIG. 4 illustrates exemplary useable RF circuitry in FIG. 3A according to some aspects.

(11) FIG. 5A illustrates an aspect of an exemplary radio front end module (RFEM) according to some aspects.

(12) FIG. 5B illustrates an alternate aspect of an exemplary radio front end module, according to some aspects.

(13) FIG. 6 illustrates an exemplary multi-protocol baseband processor useable in FIG. 1 or FIG. 2, according to some aspects.

(14) FIG. 7 illustrates an exemplary mixed signal baseband subsystem, according to some aspects.

(15) FIG. 8A illustrates an exemplary digital baseband subsystem, according to some aspects.

(16) FIG. 8B illustrates an alternate aspect of an exemplary baseband processing subsystem, according to some aspects.

(17) FIG. 9 illustrates an exemplary digital signal processor subsystem, according to some aspects.

(18) FIG. 10 illustrates a block diagram of an oscillator circuit in which an oscillator is calibrated using low dropout regulator (LDO) adjustment according to some aspects.

(19) FIG. 11 is a detailed block diagram of measurement circuitry of a system in which an oscillator is calibrated according to some aspects.

(20) FIG. 12 illustrates clock signals according to some aspects.

(21) FIG. 13 illustrates a block diagram of a system in which an oscillator is calibrated using a digital phase detector and a loop filter according to some aspects.

(22) FIG. 14 is a detailed block diagram of measurement circuitry for a precise RF event trigger setting mechanism according to some aspects.

(23) FIG. 15 illustrates a flow diagram of a method for operating an oscillator according to some aspects.

(24) FIG. 16 illustrates a block diagram of a communication device such as an evolved Node-B (eNB), a new generation Node-B (gNB), an access point (AP), a wireless station (STA), a mobile station (MS), or a user equipment (UE), in accordance with some aspects.

(25) FIG. 17 illustrates a system level diagram, depicting an example of an electronic device (e.g., system) that can include, for example, a transmitter configured to selectively fan out a signal to one of multiple communication channels.

#### DETAILED DESCRIPTION

(26) The following description and the drawings sufficiently illustrate specific aspects to enable those skilled in the art to practice them. Other aspects may incorporate structural, logical, electrical, process, and other changes. Portions and features of some aspects may be included in, or substituted for, those of other aspects. Aspects set forth in the claims encompass all available equivalents of those claims.

(27) In mmWave beamformer chips, and other RF front-end (RFFE) chips such as power amplifiers, a precise oscillator or phase-locked loop (PLL) circuit is inappropriate and cannot be justified. Yet, these low-complexity RFFE chips do use on-die clocks to complete certain operations such as running power-up state machines, reading out electronic fuse (EFUSE) data, taking analog-to-digital (ADC) readings of a temperature sensor or power detector, running local timers, and other operations. While less precision is needed from clocks on these RFFE chips, some degree of precision should be present, and improved precision provides several system level benefits.

(28) Some available systems address these concerns by employing a system serial peripheral interface (SPI) clock or similar protocol or communication clock. In these systems, dummy SPI commands are planned to add extra clocks, at the frequency of the SPI clock (typically about 25-50 MHz range) after a SPI command (e.g., a chip select function) is executed, so that the chip can perform other necessary operations (e.g., an ADC conversion) accurately after completion of the

command (e.g., SPI command). For some operations, including initial EFUSE readout, thousands of such dummy SPI clocks may be used, consuming system control bandwidth. Such a system may also be in use in various specifications, for example, in the Mobile Industry Processor Interface (MIPI) RFFE v3.0 specification, in which a Timed Triggers feature was introduced, and makes use of “dummy clocks” similarly to that described above. Such dummy clocks can allow a MIPI RFFE device counter to trigger the desired event execution at a pre-loaded trigger time.

(29) However, most RC oscillators and ring oscillators in use today may not be accurate enough for some operations. Most RC oscillators and ring oscillators are accurate within a  $\pm 10$  to  $\pm 20\%$  range for process variation alone, with temperature adding further variation of 10% or more.

Therefore, oscillator frequencies can swing unpredictably based on temperature and require periodic re-adjustment using characterization or simulation data sets, which increases downtime of the system. Even if the ring oscillator or RC oscillator can be dynamically adjusted in operation, the adjustment process remains slow and requires temperature readings and use of lookup tables to determine a nominal oscillator adjustment based on characterization.

(30) Furthermore, the use of dummy commands (e.g., SPI or MIPI RFFE), in addition to consuming control interface bandwidth, may still be inaccurate due to the possibility of gaps between commands and, if the required on-die clock frequency is higher than the SPI or MIPI RFFE clock frequency, then the dummy command approach cannot be used.

(31) Another approach is to use additional control lines to schedule separate events, e.g., transmit and receive activation/disablement. In this way a clock is not used, and a control command is received instead to perform some functions. However, this approach adds additional control lines, which take up space in an already-densely-packed mmWave beamformer array.

(32) To address these and other concerns, in aspects, the disclosure provides for including an adjustable oscillator on an integrated circuitry (IC) (e.g., a mmWave beamformer), and controlling the IC using a control protocol having a precise clock frequency such as SPI or MIPI RFFE, although aspects of the disclosure are not limited to usage with SPI or MIPI RFFE. During presence or execution of standard control protocol message, the adjustable oscillator is enabled and automatically calibrated based on the number of clocks sent in the control message. Depending on the command sent, the adjustable oscillator will remain enabled (after the control message finishes), for a fixed number of clocks, sufficient for the functionality required (e.g., ADC conversion). After performing the functionality required (e.g., ADC conversion), the adjustable oscillator will shut down without further control protocol commands.

(33) The communication systems, devices, and other components in which an adjustable oscillator in accordance with some aspects are implemented, are described in more detail with respect to FIG. 1-9.

(34) An integrated Radio-Frequency frontend module (FEM) is broadly used in the frontend circuits for cellular handsets or other wireless devices. FIG. 1 illustrates an exemplary user device according to some aspects. The user device **100** may be a mobile device in some aspects and includes an application processor **105**, baseband processor **110** (also referred to as a baseband sub-system), radio front end module (RFEM) **115**, memory **120**, connectivity sub-system **125**, near field communication (NFC) controller **130**, audio driver **135**, camera driver **140**, touch screen **145**, display driver **150**, sensors **155**, removable memory **160**, power management integrated circuit (PMIC) **165**, and smart battery **170**.

(35) In some aspects, application processor **105** may include, for example, one or more central processing unit (CPU) cores and one or more of cache memory, low drop-out voltage regulators (LDOs), interrupt controllers, serial interfaces such as SPI, I2C or universal programmable serial interface sub-system, real time clock (RTC), timer-counters including interval and watchdog timers, general purpose IO, memory card controllers such as SD/MMC or similar, USB interfaces, MIPI interfaces, and/or Joint Test Access Group (JTAG) test access ports.

(36) In some aspects, baseband processor **110** may be implemented, for example, as a solder-down

substrate including one or more integrated circuits, a single packaged integrated circuit soldered to a main circuit board, and/or a multi-chip module including two or more integrated circuits.

(37) Applications of mmWave technology can include, for example, WiGig and future 5G, but the mmWave technology can be applicable to a variety of telecommunications systems. The mmWave technology can be especially attractive for short-range telecommunications systems. WiGig devices operate in the unlicensed 60 GHz band, whereas 5G mmWave operates in the licensed 28 GHz and 39 GHz bands. A block diagram of an example baseband processor **110** and RFEM **115** in a mmWave system is shown in FIG. **1A**.

(38) FIG. **1A** illustrates a mmWave system **100A**, which can be used in connection with the device **100** of FIG. **1** according to some aspects of the present disclosure. The system **100A** includes two components: a baseband processor **110** and one or more radio front end modules (RFEMs) **115**. The RFEM **115** can be connected to the baseband processor **110** by a single coaxial cable **190**, which supplies a modulated intermediate frequency (IF) signal, DC power, clocking signals and control signals.

(39) The baseband processor **110** is not shown in its entirety, but FIG. **1A** rather shows an implementation of analog front end. This includes a transmitter (TX) section **191A** with an upconverter **173** to intermediate frequency (IF) (around 10 GHz in current implementations), a receiver (RX) section **191B** with downconversion **175** from IF to baseband, control and multiplexing circuitry **177** including a combiner to multiplex/demultiplex transmit and receive signals onto a single cable **190**. In addition, power tee circuitry **192** (which includes discrete components) is included on the baseband circuit board to provide DC power for the RFEM **15**. In some aspects, the combination of the TX section and RX section may be referred to as a transceiver, to which may be coupled one or more antennas or antenna arrays of the types described herein.

(40) The RFEM **115** can be a small circuit board including a number of printed antennas and one or more RF devices containing multiple radio chains, including upconversion/downconversion **174** to millimeter wave frequencies, power combiner/divider **176**, programmable phase shifting **178** and power amplifiers (PA) **180**, low noise amplifiers (LNA) **182**, as well as control and power management circuitry **184A** and **184B**. This arrangement can be different from Wi-Fi or cellular implementations, which generally have all RF and baseband functionality integrated into a single unit and only antennas connected remotely via coaxial cables.

(41) This architectural difference can be driven by the very large power losses in coaxial cables at millimeter wave frequencies. These power losses can reduce the transmit power at the antenna and reduce receive sensitivity. In order to avoid this issue, in some aspects, PAs **180** and LNAs **182** may be moved to the RFEM **115** with integrated antennas. In addition, the RFEM **115** may include upconversion/downconversion **174** so that the IF signals over the coaxial cable **190** can be at a lower frequency. Additional system context for mmWave 5G apparatuses, techniques and features is discussed herein below.

(42) FIG. **2** illustrates an exemplary base station or infrastructure equipment radio head according to some aspects. The base station radio head **200** may include one or more of application processor **205**, baseband processors **210**, one or more radio front end modules **215**, memory **220**, power management integrated circuitry (PMIC) **225**, power tee circuitry **230**, network controller **235**, network interface connector **240**, satellite navigation receiver (e.g., GPS receiver) **245**, and user interface **250**.

(43) In some aspects, application processor **205** may include one or more CPU cores and one or more of cache memory, low drop-out voltage regulators (LDOs), interrupt controllers, serial interfaces such as SPI, I2C or universal programmable serial interface, real time clock (RTC), timer-counters including interval and watchdog timers, general purpose IO, memory card controllers such as SD/MMC or similar, USB interfaces, MIPI interfaces and Joint Test Access Group (JTAG) test access ports.

- (44) In some aspects, baseband processor **210** may be implemented, for example, as a solder-down substrate including one or more integrated circuits, a single packaged integrated circuit soldered to a main circuit board or a multi-chip sub-system including two or more integrated circuits.
- (45) In some aspects, memory **220** may include one or more of volatile memory including dynamic random access memory (DRAM) and/or synchronous DRAM (SDRAM), and nonvolatile memory (NVM) including high-speed electrically erasable memory (commonly referred to as Flash memory), phase-change random access memory (PRAM), magnetoresistive random access memory (MRAM), and/or a three-dimensional crosspoint memory. Memory **220** may be implemented as one or more of solder down packaged integrated circuits, socketed memory modules and plug-in memory cards.
- (46) In some aspects, power management integrated circuitry **225** may include one or more of voltage regulators, surge protectors, power alarm detection circuitry and one or more backup power sources such as a battery or capacitor. Power alarm detection circuitry may detect one or more of brown out (under-voltage) and surge (over-voltage) conditions.
- (47) In some aspects, power tee circuitry **230** may provide for electrical power drawn from a network cable. Power tee circuitry **230** may provide both power supply and data connectivity to the base station radio head **200** using a single cable.
- (48) In some aspects, network controller **235** may provide connectivity to a network using a standard network interface protocol such as Ethernet. Network connectivity may be provided using a physical connection which is one of electrical (commonly referred to as copper interconnect), optical or wireless.
- (49) In some aspects, satellite navigation receiver **245** may include circuitry to receive and decode signals transmitted by one or more navigation satellite constellations such as the global positioning system (GPS), Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS), Galileo and/or BeiDou. The receiver **245** may provide, to application processor **205**, data which may include one or more of position data or time data. Time data may be used by application processor **205** to synchronize operations with other radio base stations or infrastructure equipment.
- (50) In some aspects, user interface **250** may include one or more of buttons. The buttons may include a reset button. User interface **250** may also include one or more indicators such as LEDs and a display screen.
- (51) FIG. 3A illustrates exemplary wireless communication circuitry according to some aspects; FIGS. 3B and 3C illustrate aspects of transmit circuitry shown in FIG. 3A according to some aspects; FIG. 3D illustrates aspects of radio frequency circuitry shown in FIG. 3A according to some aspects; FIG. 3E illustrates aspects of receive circuitry in FIG. 3A according to some aspects. Wireless communication circuitry **300** shown in FIG. 3A may be alternatively grouped according to functions. Components illustrated in FIG. 3A are provided here for illustrative purposes and may include other components not shown in FIG. 3A.
- (52) Wireless communication circuitry **300** may include protocol processing circuitry **305** (or processor) or other means for processing. Protocol processing circuitry **305** may implement one or more of medium access control (MAC), radio link control (RLC), packet data convergence protocol (PDCP), radio resource control (RRC) and non-access stratum (NAS) functions, among others. Protocol processing circuitry **305** may include one or more processing cores to execute instructions and one or more memory structures to store program and data information.
- (53) Wireless communication circuitry **300** may further include digital baseband circuitry **310**. Digital baseband circuitry **310** may implement physical layer (PHY) functions including one or more of hybrid automatic repeat request (HARQ) functions, scrambling and/or descrambling, coding and/or decoding, layer mapping and/or de-mapping, modulation symbol mapping, received symbol and/or bit metric determination, multi-antenna port pre-coding and/or decoding which may include one or more of space-time, space-frequency or spatial coding, reference signal generation and/or detection, preamble sequence generation and/or decoding, synchronization sequence

generation and/or detection, control channel signal blind decoding, and other related functions.

(54) Wireless communication circuitry **300** may further include transmit circuitry **315**, receive circuitry **320** and/or antenna array circuitry **330**. Wireless communication circuitry **300** may further include RF circuitry **325**. In some aspects, RF circuitry **325** may include one or multiple parallel RF chains for transmission and/or reception. Each of the RF chains may be connected to one or more antennas of antenna array circuitry **330**.

(55) In some aspects, protocol processing circuitry **305** may include one or more instances of control circuitry. The control circuitry may provide control functions for one or more of digital baseband circuitry **310**, transmit circuitry **315**, receive circuitry **320**, and/or RF circuitry **325**.

(56) FIGS. **3B** and **3C** illustrate aspects of transmit circuitry shown in FIG. **3A** according to some aspects. Transmit circuitry **315** shown in FIG. **3B** may include one or more of digital to analog converters (DACs) **340**, analog baseband circuitry **345**, up-conversion circuitry **350** and/or filtering and amplification circuitry **355**. DACs **340** may convert digital signals into analog signals. Analog baseband circuitry **345** may perform multiple functions as indicated below. Up-conversion circuitry **350** may up-convert baseband signals from analog baseband circuitry **345** to RF frequencies (e.g., mmWave frequencies). Filtering and amplification circuitry **355** may filter and amplify analog signals. Control signals may be supplied between protocol processing circuitry **305** and one or more of DACs **340**, analog baseband circuitry **345**, up-conversion circuitry **350** and/or filtering and amplification circuitry **355**.

(57) Transmit circuitry **315** shown in FIG. **3C** may include digital transmit circuitry **365** and RF circuitry **370**. In some aspects, signals from filtering and amplification circuitry **355** may be provided to digital transmit circuitry **365**. As above, control signals may be supplied between protocol processing circuitry **305** and one or more of digital transmit circuitry **365** and RF circuitry **370**.

(58) FIG. **3D** illustrates aspects of radio frequency circuitry shown in FIG. **3A** according to some aspects. Radio frequency circuitry **325** may include one or more instances of radio chain circuitry **372**, which in some aspects may include one or more filters, power amplifiers, low noise amplifiers, programmable phase shifters and power supplies.

(59) Radio frequency circuitry **325** may also in some aspects include power combining and dividing circuitry **374**. In some aspects, power combining and dividing circuitry **374** may operate bidirectionally, such that the same physical circuitry may be configured to operate as a power divider when the device is transmitting, and as a power combiner when the device is receiving. In some aspects, power combining and dividing circuitry **374** may include one or more wholly or partially separate circuitries to perform power dividing when the device is transmitting and power combining when the device is receiving. In some aspects, power combining and dividing circuitry **374** may include passive circuitry including one or more two-way power divider/combiners arranged in a tree. In some aspects, power combining and dividing circuitry **374** may include active circuitry including amplifier circuits.

(60) In some aspects, radio frequency circuitry **325** may connect to transmit circuitry **315** and receive circuitry **320** in FIG. **3A**. Radio frequency circuitry **325** may connect to transmit circuitry **315** and receive circuitry **320** via one or more radio chain interfaces **376** and/or a combined radio chain interface **378**. In some aspects, one or more radio chain interfaces **376** may provide one or more interfaces to one or more receive or transmit signals, each associated with a single antenna structure. In some aspects, the combined radio chain interface **378** may provide a single interface to one or more receive or transmit signals, each associated with a group of antenna structures.

(61) FIG. **3E** illustrates aspects of receive circuitry in FIG. **3A** according to some aspects. Receive circuitry **320** may include one or more of parallel receive circuitry **382** and/or one or more of combined receive circuitry **384**. In some aspects, the one or more parallel receive circuitry **382** and one or more combined receive circuitry **384** may include one or more Intermediate Frequency (IF) down-conversion circuitry **386**, IF processing circuitry **388**, baseband down-conversion circuitry

**390**, baseband processing circuitry **392** and analog-to-digital converter (ADC) circuitry **394**. As used herein, the term “intermediate frequency” refers to a frequency to which a carrier frequency (or a frequency signal) is shifted as in intermediate step in transmission, reception, and/or signal processing. IF down-conversion circuitry **386** may convert received RF signals to IF. IF processing circuitry **388** may process the IF signals, e.g., via filtering and amplification. Baseband down-conversion circuitry **390** may convert the signals from IF processing circuitry **388** to baseband. Baseband processing circuitry **392** may process the baseband signals, e.g., via filtering and amplification. ADC circuitry **394** may convert the processed analog baseband signals to digital signals.

(62) FIG. 4 illustrates exemplary RF circuitry of FIG. 3A according to some aspects. In an aspect, RF circuitry **325** in FIG. 3A (depicted in FIG. 4 using reference number **425**) may include one or more of the IF interface circuitry **405**, filtering circuitry **410**, up-conversion and down-conversion circuitry **415**, synthesizer circuitry **420**, filtering and amplification circuitry **424**, power combining and dividing circuitry **430**, and radio chain circuitry **435**.

(63) FIG. 5A and FIG. 5B illustrate aspects of a radio front-end module (RFEM) useable in the circuitry shown in FIG. 1 and FIG. 2, according to some aspects. FIG. 5A illustrates an aspect of a RFEM according to some aspects. RFEM **500** incorporates a millimeter wave RFEM **505** and one or more above-six gigahertz radio frequency integrated circuits (RFIC) **515** and/or one or more sub-six gigahertz RFICs **522**. In this aspect, the one or more sub-six gigahertz RFICs **515** and/or one or more sub-six gigahertz RFICs **522** may be physically separated from millimeter wave RFEM **505**. RFICs **515** and **522** may include connection to one or more antennas **520**. RFEM **505** may include multiple antennas **510**.

(64) FIG. 5B illustrates an alternate aspect of a radio front end module, according to some aspects. In this aspect both millimeter wave and sub-six gigahertz radio functions may be implemented in the same physical radio front end module (RFEM) **530**. RFEM **530** may incorporate both millimeter wave antennas **535** and sub-six gigahertz antennas **540**.

(65) FIG. 6 illustrates a multi-protocol baseband processor **600** useable in the system and circuitry shown in FIG. 1 or FIG. 2, according to some aspects. In an aspect, baseband processor may contain one or more digital baseband subsystems **640A**, **640B**, **640C**, **640D**, also herein referred to collectively as digital baseband subsystems **640**.

(66) In an aspect, the one or more digital baseband subsystems **640A**, **640B**, **640C**, **640D** may be coupled via interconnect subsystem **665** to one or more of CPU subsystem **670**, audio subsystem **675** and interface subsystem **680**. In an aspect, the one or more digital baseband subsystems **640** may be coupled via interconnect subsystem **645** to one or more of each of digital baseband interface **660A**, **660B** and mixed-signal baseband subsystem **635A**, **635B**.

(67) In an aspect, interconnect subsystem **665** and **645** may each include one or more of each of buses point-to-point connections and network-on-chip (NOC) structures. In an aspect, audio subsystem **675** may include one or more of digital signal processing circuitry, buffer memory, program memory, speech processing accelerator circuitry, data converter circuitry such as analog-to-digital and digital-to-analog converter circuitry, and analog circuitry including one or more of amplifiers and filters.

(68) FIG. 7 illustrates an exemplary of a mixed signal baseband subsystem **700**, according to some aspects. In an aspect, mixed signal baseband subsystem **700** may include one or more of IF interface **705**, analog IF subsystem **710**, down-converter and up-converter subsystem **720**, analog baseband subsystem **730**, data converter subsystem **735**, synthesizer **725** and control subsystem **740**.

(69) FIG. 8A illustrates a digital baseband processing subsystem **801**, according to some aspects. FIG. 8B illustrates an alternate aspect of a digital baseband processing subsystem **802**, according to some aspects.

(70) In an aspect of FIG. 8A, the digital baseband processing subsystem **801** may include one or



more of each of digital signal processor (DSP) subsystems **805A**, **805B**, . . . **805N**, interconnect subsystem **835**, boot loader subsystem **810**, shared memory subsystem **815**, digital I/O subsystem **820**, and digital baseband interface subsystem **825**.

(71) In an aspect of FIG. **8B**, digital baseband processing subsystem **802** may include one or more of each of accelerator subsystem **845A**, **845B**, . . . **845N**, buffer memory **850A**, **850B**, . . . **850N**, interconnect subsystem **835**, shared memory subsystem **815**, digital I/O subsystem **820**, controller subsystem **840** and digital baseband interface subsystem **825**.

(72) In an aspect, boot loader subsystem **810** may include digital logic circuitry configured to perform configuration of the program memory and running state associated with each of the one or more DSP subsystems **805**. Configuration of the program memory of each of the one or more DSP subsystems **805** may include loading executable program code from storage external to digital baseband processing subsystems **801** and **802**. Configuration of the running state associated with each of the one or more DSP subsystems **805** may include one or more of the steps of: setting the state of at least one DSP core which may be incorporated into each of the one or more DSP subsystems **805** to a state in which it is not running, and setting the state of at least one DSP core which may be incorporated into each of the one or more DSP subsystems **805** into a state in which it begins executing program code starting from a predefined memory location.

(73) In an aspect, shared memory subsystem **815** may include one or more of read-only memory (ROM), static random access memory (SRAM), embedded dynamic random access memory (eDRAM) and/or non-volatile random access memory (NVRAM).

(74) In an aspect, digital I/O subsystem **820** may include one or more of serial interfaces such as Inter-Integrated Circuit (I2C), Serial Peripheral Interface (SPI) or other 1, 2 or 3-wire serial interfaces, parallel interfaces such as general-purpose input-output (GPIO), register access interfaces and direct memory access (DMA). In an aspect, a register access interface implemented in digital I/O subsystem **820** may permit a microprocessor core external to digital baseband processing subsystem **801** to read and/or write one or more of control and data registers and memory. In an aspect, DMA logic circuitry implemented in digital I/O subsystem **820** may permit transfer of contiguous blocks of data between memory locations including memory locations internal and external to digital baseband processing subsystem **801**.

(75) In an aspect, digital baseband interface subsystem **825** may provide for the transfer of digital baseband samples between baseband processing subsystem and mixed signal baseband or radio-frequency circuitry external to digital baseband processing subsystem **801**. In an aspect, digital baseband samples transferred by digital baseband interface subsystem **825** may include in-phase and quadrature (I/Q) samples.

(76) In an aspect, controller subsystem **840** may include one or more of each of control and status registers and control state machines. In an aspect, control and status registers may be accessed via a register interface and may provide for one or more of: starting and stopping operation of control state machines, resetting control state machines to a default state, configuring optional processing features, and/or configuring the generation of interrupts and reporting the status of operations. In an aspect, each of the one or more control state machines may control the sequence of operation of each of the one or more accelerator subsystems **845**. There may be examples of implementations of both FIG. **8A** and FIG. **8B** in the same baseband subsystem.

(77) FIG. **9** illustrates a digital signal processor (DSP) subsystem **900** according to some aspects. In an aspect, DSP subsystem **900** may include one or more of each of DSP core subsystem **905**, local memory **910**, direct memory access (DMA) subsystem **915**, accelerator subsystem **920A**, **920B** . . . **920N**, external interface subsystem **925**, power management circuitry **930** and interconnect subsystem **935**.

(78) In an aspect, the local memory **910** may include one or more of each of read-only memory, static random access memory or embedded dynamic random access memory.

(79) In an aspect, the DMA subsystem **915** may provide registers and control state machine

circuitry adapted to transfer blocks of data between memory locations including memory locations internal and external to DSP subsystem **900**.

(80) In an aspect, external interface subsystem **925** may provide for access by a microprocessor system external to DSP subsystem **900** to one or more of memory, control registers and status registers which may be implemented in DSP subsystem **900**. In an aspect, external interface subsystem **925** may provide for transfer of data between local memory **910** and storage external to DSP subsystem **900** under the control of one or more of the DMA subsystems **915** and the DSP core subsystem **905**.

(81) Opportunistic Calibration of an Adjustable Oscillator

(82) As described earlier herein, there is a general need for an accurate on-chip oscillator (e.g., RC oscillator or ring oscillator) for use with some RFFE ICs for which expensive, highly accurate oscillators would be inappropriate. Apparatuses according to aspects of the disclosure provide an adjustable oscillator for which no dummy messages are used to create the clocks for on-chip functional circuits. The adjustable oscillator can be frequently re-calibrated as a background procedure during SPI or other serial control protocol commands, so that the adjustable oscillator remains accurate over temperature. The oscillator is activated only when needed, however, thus saving power. As a result, additional clocks can be provided for on-chip functions without a PLL or permanent external clock feed.

(83) FIG. **10** illustrates a block diagram of an oscillator circuit **1000** in which an oscillator **1002** is calibrated using low dropout regulator (LDO) **1004** adjustment and adjustment circuitry **1006** according to some aspects. The oscillator circuit **1000** can be included in mmWave beamformer chips, and other RFFE chips such as power amplifiers as described earlier herein, and other components of these chips were described with reference to FIG. **1-9** and are not further discussed with respect to FIG. **10**.

(84) The oscillator circuit **1000** can include an interface **1008** to receive a SPI command (or other command) **1010**, although embodiments are not limited to serial protocol commands or to serial interfaces. These commands are sent based on a precise clock that generates a SPI clock **1012** waveform, for example, although embodiments are not limited to SPI or SPI clocks and can include other protocol clocks that have guaranteed precision.

(85) The oscillator **1002** can operate in a low GHz range (e.g., less than about 20 GHz), with the output **1014** divided down for functional use by, for example, divider **1016** to provide an output **1018** for other circuitry **1020** needing an oscillator signal, for example, ADC circuitry, EFUSE circuitry, etc. For purposes of precise comparison in methods according to some aspects, a divider output signal **1022** of divider **1024** can provide a higher frequency output (e.g., the divider **1024** may divide by a smaller integer than that used by divider **1016**).

(86) The oscillator **1002** may be enabled only upon reception of a specific command. For example, the oscillator **1002** may remain disabled, and be enabled responsive to a SPI chip select being asserted, although aspects are not limited to any particular command or to any particular protocol. Responsive to the specific command being asserted, divider output signal **1022** is fed to measurement circuitry **1026**.

(87) As each SPI command **1010** or other RFFE data is received, a prescaler **1028** can provide a measurement interval pulse **1032** (described in more detail later herein) to the measurement circuitry **1026**. The measurement circuitry **1026** will count a number of cycles of the divider output signal **1022** for an amount of time and based on the frequency of the SPI clock **1012**, wherein that amount of time can be programmed based on a number of SPI clocks that are guaranteed to be present in the SPI command, e.g., **16** or **32** clocks. Because the SPI or MIPI RFFE clock is typically generated by a baseband IC with a precise timing source, the SPI clock and frequency can be very accurate, on the order of about  $\pm 5$  ppm accuracy.

(88) Measurement circuitry **1026**, can receive the divider output signal **1022** of the oscillator **1002** and to measure oscillator error **1030** by comparing the divider output signal **1022** of the oscillator

**1002** to a nominal frequency for an amount of time. The measurement circuitry **1026** can comprise a phase detector to perform the comparison. For example, the phase detector can compare the divider output signal **1022** of the oscillator **1002** to a SPI clock **1012** provided over a serial interface, or frequency derived therefrom. In other aspects, the measurement circuitry **1026** can comprise a period measurement circuit configured to detect a number of clock transitions of the oscillator **1002** or derived frequencies. The number of clock transitions to be measured can be based on the SPI clock **1012**. Further details regarding the measurement circuitry **1026** are provided with respect to FIG. **11** later herein.

(89) The amount of time over which measurements are made can be determined based on a number of clock cycles of the SPI command **1010** (or other command). For example, the nominal frequency can be based on SPI clock **1012** for the SPI or other protocol interface, and the amount of time can be based on the number of clock cycles used for the received command, according to protocol specifications, plus some buffer amount of time in some aspects.

(90) Adjustment circuitry **1006** can adjust the oscillator **1002** frequency based on the measured oscillator error **1030**. For example, the adjustment circuitry **1006** can adjust the ring oscillator frequency (which increases/decreases in the same direction as the LDO voltage) to reduce the frequency error of the oscillator **1002** to zero or near-zero. Adjustment circuitry **1006** can translate the measurement error **1030** into a data word, for example, to be programmed into the LDO **1004**, to adjust the LDO **1004** voltage higher or lower to produce a higher or lower oscillator **1002** frequency, wherein a higher voltage output by the LDO **1004** produces a proportionately higher frequency at the oscillator **1002**. In an aspect, the adjustment circuitry **1006** can process only the sign of the measurement error **1030**, such that if measurement error **1030** is greater than zero, the oscillator **1002** frequency should be set lower by decreasing LDO **1004** voltage. Conversely, if the measurement error **1030** is less than zero, the oscillator **1002** frequency can be set higher, by increasing LDO **1004** voltage.

(91) In some aspects, measurement and adjustment can occur periodically in an oscillator calibration phase, for example based on reception of a SPI command or other protocol command that is received every 25 milliseconds (or with any other periodicity). Measurement of the oscillator error **1030** can occur periodically every 25 milliseconds and the oscillator **1002** frequency can be thereby adjusted about every 25 milliseconds in the illustrated example. This provides periodic adjustment of oscillator **1002** frequency in a background process without further intervention by processing circuitry or upper-layer processes.

(92) The protocol command that is used in oscillator **1002** calibration can include any command that is specific to control of an integrated circuit related to or coupled to the oscillator **1002**, such as a chip select signal from an SPI command, detection of a Sequence Start Condition (SSC) used for starting of a MIPI RFFE command, receive or transmit enable commands, receive or transmit disable commands, etc. Measurement and adjustment of the oscillator **1002** can occur based on reception of any of those protocol commands. Measurement and adjustment can also occur based on reception of a request for power measurement or a request for a temperature measurement, among other preselected commands, periodic commands, etc.

(93) In other aspects, different frequencies derived from or related to the oscillator **1002** frequency can be adjusted by modifying the value of divider/N1 in **1024**.

(94) The oscillator **1002** can remain enabled for a duration subsequent to a last clock cycle of the serial protocol command and terminate operation after the duration. For example, when a measurement needing N clock cycles needs to be performed by an IC that is using the oscillator **1002**, the oscillator **1002** can stay on for N clock cycles subsequent to the last cycle of the relevant serial (or other protocol) command that had initiated the calibration/adjustment of the oscillator **1002**. In at least these aspects, the oscillator **1002** can continue to provide output **1018** to functions of the block **1020** for at least those N clock cycles. In other aspects, the oscillator **1002** can be disabled subsequent to the last clock cycle of the serial protocol command.

(95) By way of illustrative example of the above-described measurement and adjustment process, given a 2 GHz ring oscillator **1002**, divider **1024** may divide the ring oscillator output to give a divider output signal **1022** of 500 MHz. Given the SPI clock (or other reference clock) **1012** is 38.4 MHz, and the amount of time of the measurement is 32 periods of the SPI clock **1012**, then 416 or 417 counts should be counted by the measurement circuitry **1026** (wherein a count is a certain edge transition in the command waveform, e.g., a rising edge transition or a falling edge transition). The oscillator error **1030** can be expressed as a percentage or as a number, and adjustment circuitry **1006** can adjust the oscillator frequency by the derived percentage or number.

(96) In aspects described above, the LDO **1004** output voltage can be reprogrammed to re-center the oscillator **1002**, based on lookup tables or other data that relates frequency sensitivity of the oscillator **1002** to LDO **1004** voltage.

(97) The oscillator circuit **1000** includes a command decoder **1034** to decode, e.g., SPI or MIPI RFFE commands, although aspects are not limited to any particular command protocol. The decoded commands are used to control the IC (not shown in FIG. **10**) according to command protocols and IC standards.

(98) FIG. **11** is a detailed block diagram of measurement circuitry **1026** of an oscillator circuit **1000** in which an oscillator **1002** is calibrated according to some aspects. The measurement error **1030** (FIG. **10**) has been split into a measurement error sign **1100** and a measurement error magnitude **1102**. Furthermore, the measurement circuitry **1026** (FIG. **10**) has been split into a counter **1104** and comparison block **1106** for purposes of additional explanation of the functionality of the measurement circuitry **1026**.

(99) The divider output signal **1022** is provided to a counter **1104**. The divider output signal **1022** is then counted for M periods of the slower SPI or MIPI RFFE clock as provided in signal **1108** output from prescaler **1028**, responsive to a measurement interval pulse **1032** indicating that measurement is to be performed. After M periods are seen by the prescaler **1028**, the measurement interval pulse **1032** will go low, terminating the counter **1104** measurement.

(100) The compare block **1106** is assumed to be pre-loaded with an expected count value according to the nominal frequency of the oscillator **1002**. As described above with reference to FIG. **10**, given an example expected count with M=32 is 417, rounded up from the exact value of 416.7. If the measured count is 410, then a measurement error magnitude **1102** will be 7 (e.g., a 1.67% period error) and measurement error sign **1100** is negative meaning that the actual oscillator **1002** value is low versus the nominal frequency. The counter **1104** can be cleared for a next subsequent measurement and calibration operation using signal **1108**, and the counter **1104** value can be output in signal **1110**.

(101) FIG. **12** illustrates clock signals according to some aspects. The top half of FIG. **12** indicates clock signals in available systems, for purpose of comparison with clock signals according to aspects of the disclosure, shown in the lower half of FIG. **12**. Waveform **1200** is a data signal (e.g., a SPI command signal, although embodiments are not limited thereto) that can be passed to a standard command decoder block (e.g., block **1034** (FIG. **10**)). Waveform **1202** indicates a clock signal, which can have guaranteed precision, and can include a SPI clock (although embodiments are not limited thereto). As can be appreciated by comparing the top half of FIG. **12** to the bottom half of FIG. **12**, after point **1204**, dummy clock signals appear in the upper half, while dummy clock signals are not included in the lower half (e.g., in a clock signal according to aspects of the disclosure). Inclusion of the dummy clock signals is provided in current systems so that a related RFFE IC can complete tasks, as described earlier herein, that use oscillator timing. Inclusion of these dummy clock signals increases overhead and reduces bandwidth of the RFFE IC.

Furthermore, the dummy clock signals may not offer sufficient precision in timing, which can lead to problems with some operations, particularly lengthy operations in which thousands of clock cycles are needed (e.g., EFUSE programming or reading operations).

(102) In contrast, in the lower half of FIG. **12**, upon assertion of a command (e.g., a SPI chip select

command, although aspects are not limited to the chip select command or to SPI commands), the oscillator clock **1208** is initiated (in place of the dummy clock of available systems). Measurement, such as performed by measurement circuitry as described above with reference to FIG. **10-11**, is performed during interval **1210**, and the oscillator clock **1208** can provide the clock for the on-chip operations including ADC, power detector readout, RF timer, etc. subsequent to termination or de-assertion of the command **1206**. Calibration may be performed subsequent to termination or de-assertion of the command **1206**, according to operations described above with reference to FIG. **10** and FIG. **11**.

(103) FIG. **13** illustrates a block diagram of a system **1300** in which an oscillator **1302** is calibrated using a digital phase detector and loop filter circuitry **1304** according to some aspects. Only components that are different than those shown in FIG. **10** will be discussed with reference to FIG. **13**.

(104) In at least these aspects, the digital phase detector and loop filter circuitry **1304** can compare the pre-scaled SPI clock **1306** with the divided-down oscillator signal **1308** and generate phase errors **1309** to provide continual adjustment, with the magnitude of the phase error determining the degree and direction of the LDO adjustment required. In at least these aspects, calibration can be executed upon power up of the relevant RFFE chip so that subsequent oscillator **1302** adjustments can be reduced or minimized. LDO voltage can be controlled and adjusted similarly to that described above with respect to FIG. **10**, except values can be stored in register **1310** for subsequent adjustments and for subsequent power-ons of the RFFE chip. In at least this aspect, the calibration and adjustments are closed-loop relative to the aspect described with respect to FIG. **10**. In some aspects, calibration and adjustment can run continuously in such a closed-loop configuration. In some aspects, including aspects described with reference to FIG. **10** and FIG. **13**, calibration at the beginning of the SPI message can be disabled. For example, calibration may be disabled if temperature has stabilized, or if the magnitude of the measured error is small or switches frequently between a positive and negative error.

(105) In some aspects, the divider values (e.g., the values used in the divider **1024** to divide the oscillator output **1014**) can be modified, instead of modifying the oscillator **1002** frequency through LDO adjustment. At least these aspects have an advantage of being fully-digital, in that no adjustable LDO is used.

(106) FIG. **14** is a detailed block diagram of measurement circuitry **1400** for a precise RF event trigger setting mechanism according to some aspects. Only components that are different than those shown in FIG. **11** will be discussed with reference to FIG. **14**.

(107) In some systems for which LDO **1004** (FIG. **10**) steps are limited, oscillator **1002** variation can be in excess of  $\pm 20\%$ , and calibration accuracy as described herein can be limited in accuracy due to the limited LDO **1004** adjustment range. For example, with 32 LDO steps and a  $\pm 20\%$  total oscillator variation, the oscillator adjustment step (assuming oscillator frequency varies directly with voltage), is  $40/32=1.25\%$ . In systems that set an RF event trigger after the 10th symbol in a 14-symbol 3GPP slot with SCS=120 kHz, (corresponding to a 125 psec slot time), the timing error could be  $(0.0125/2)*125 \text{ psec}*(10/14)=558 \text{ nsec}$ . In at least these situations, the error may be too high for the oscillator **1002** to be used for a TX-to-RX transition.

(108) Aspects of the disclosure address these and other concerns by incorporation of an event trigger block **1402**. In aspects, an expected event trigger value (in RO\_out1 clock cycles) is pre-loaded, along with the expected counter out when the calibration runs for, e.g., 32 SPI clock cycles. After the measurement, which can occur similarly to the process described above with respect to FIG. **11**, the percent error of the RO\_out1 frequency can be applied to the event trigger block **1402**, using a high-precision fixed point multiplication. For example, if RO\_out1=500 MHz, and is used to time the RF event that will occur after the calibration completes, then the accuracy will be on the order of  $\pm 1*(1/500 \text{ MHz})=\pm 2 \text{ nsec}$ . This accuracy is suitable for an RF event such as TX-to-RX transition. In some aspects in which precise RF events are scheduled, the oscillator **1002** will

not need to be adjusted or calibrated or will only be performed infrequently or intermittently.

(109) FIG. 15 illustrates a flow diagram of a method 1500 for operating an oscillator according to some aspects. The method 1500 can be performed by, for example, measurement circuitry 1026 (FIG. 10), adjustment circuitry 1006 (FIG. 10 and FIG. 13), digital phase detector and loop filter circuitry 1304 (FIG. 13) or other another component of FIG. 10-14.

(110) Method 1500 can begin with operation 1502 with measurement circuitry 1026 receiving an output signal (e.g., signal 1022 (FIG. 10) of an oscillator 1002.

(111) Method 1500 can continue with operation 1504 with measurement circuitry 1026 measuring oscillator error 1030 by comparing the output signal 1022 of the oscillator 1002 to a nominal frequency for an amount of time. Operation 1504 can include determining the amount of time over which to measure oscillator error 1030 based on a number of clock cycles of a reference control command.

(112) Method 1500 can continue with operation 1506 with adjusting an oscillator frequency of the oscillator 1002 based on the measured oscillator error 1030. In some aspects, method 1500 the measuring operation 1504 and adjusting operation 1506 can be performed periodically, upon startup of the wireless communication device or in any other interval or in response to any other command or request.

(113) Method 1500 can further comprise receiving at least one of a reference control command and a clock signal over a serial communications interface 1008.

(114) Method 1500 can further comprise operating additional circuitry 1020 (e.g., ADC circuitry or fuse circuitry) based on the output signal 1014 of the oscillator. In examples, this signal 1014 can be divide down as described above, e.g., signal 1018 can be used to operate additional circuitry 1020. In some aspects, the oscillator 1002 can be terminated after a time period subsequent to the reference control command.

(115) As described herein, systems and apparatuses provide an oscillator for timing in RFFE circuits that can use more accurate timing, but for which highly-precise clocks would be inappropriate due to the cost and other factors. Oscillators according to aspects can be calibrated or adjusted during operation of the relevant RFFE circuit to provide increased precision and accuracy in various operating conditions such as increased temperature.

(116) With a precisely adjustable oscillator on-chip, an RF timer with good short-term accuracy can be provided in some aspects. For example, in a mmWave RFFE for a base station, one control command can be provided per slot, and that control command could initiate transmission activity immediately, but the receive mode would be switched in when a counter driven by the adjustable oscillator matches the pre-scheduled time for the receive transition.

(117) Other Systems and Apparatuses

(118) FIG. 16 illustrates a block diagram of a communication device 1800 such as an evolved Node-B (eNB), a new generation Node-B (gNB), an access point (AP), a wireless station (STA), a mobile station (MS), or a user equipment (UE), in accordance with some aspects. In alternative aspects, the communication device 1800 may operate as a standalone device or may be connected (e.g., networked) to other communication devices. In some aspects, the communication device 1800 can use one or more of the techniques and circuits discussed herein, in connection with any of FIG. 1-FIG. 15.

(119) Circuitry (e.g., processing circuitry) is a collection of circuits implemented in tangible entities of the device 1800 that include hardware (e.g., simple circuits, gates, logic, etc.). Circuitry membership may be flexible over time. Circuitries include members that may, alone or in combination, perform specified operations when operating. In an example, hardware of the circuitry may be immutably designed to carry out a specific operation (e.g., hardwired). In an example, the hardware of the circuitry may include variably connected physical components (e.g., execution units, transistors, simple circuits, etc.) including a machine readable medium physically modified (e.g., magnetically, electrically, moveable placement of invariant massed particles, etc.) to

encode instructions of the specific operation.

(120) In connecting the physical components, the underlying electrical properties of a hardware constituent are changed, for example, from an insulator to a conductor or vice versa. The instructions enable embedded hardware (e.g., the execution units or a loading mechanism) to create members of the circuitry in hardware via the variable connections to carry out portions of the specific operation when in operation. Accordingly, in an example, the machine readable medium elements are part of the circuitry or are communicatively coupled to the other components of the circuitry when the device is operating. In an example, any of the physical components may be used in more than one member of more than one circuitry. For example, under operation, execution units may be used in a first circuit of a first circuitry at one point in time and reused by a second circuit in the first circuitry, or by a third circuit in a second circuitry at a different time. Additional examples of these components with respect to the device **1800** follow.

(121) In some aspects, the device **1800** may operate as a standalone device or may be connected (e.g., networked) to other devices. In a networked deployment, the communication device **1800** may operate in the capacity of a server communication device, a client communication device, or both in server-client network environments. In an example, the communication device **1800** may act as a peer communication device in peer-to-peer (P2P) (or other distributed) network environment. The communication device **1800** may be a UE, eNB, PC, a tablet PC, a STB, a PDA, a mobile telephone, a smart phone, a web appliance, a network router, switch or bridge, or any communication device capable of executing instructions (sequential or otherwise) that specify actions to be taken by that communication device. Further, while only a single communication device is illustrated, the term “communication device” shall also be taken to include any collection of communication devices that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein, such as cloud computing, software as a service (SaaS), other computer cluster configurations.

(122) Examples, as described herein, may include, or may operate on, logic or a number of components, modules, or mechanisms. Modules are tangible entities (e.g., hardware) capable of performing specified operations and may be configured or arranged in a certain manner. In an example, circuits may be arranged (e.g., internally or with respect to external entities such as other circuits) in a specified manner as a module. In an example, the whole or part of one or more computer systems (e.g., a standalone, client or server computer system) or one or more hardware processors may be configured by firmware or software (e.g., instructions, an application portion, or an application) as a module that operates to perform specified operations. In an example, the software may reside on a communication device-readable medium. In an example, the software, when executed by the underlying hardware of the module, causes the hardware to perform the specified operations.

(123) Accordingly, the term “module” is understood to encompass a tangible entity, be that an entity that is physically constructed, specifically configured (e.g., hardwired), or temporarily (e.g., transitorily) configured (e.g., programmed) to operate in a specified manner or to perform part or all of any operation described herein. Considering examples in which modules are temporarily configured, each of the modules need not be instantiated at any one moment in time. For example, where the modules comprise a general-purpose hardware processor configured using software, the general-purpose hardware processor may be configured as respective different modules at different times. Software may accordingly configure a hardware processor, for example, to constitute a particular module at one instance of time and to constitute a different module at a different instance of time.

(124) Communication device (e.g., UE) **1800** may include a hardware processor **1802** (e.g., a central processing unit (CPU), a graphics processing unit (GPU), a hardware processor core, or any combination thereof), a main memory **1804**, a static memory **1806**, and mass storage **1816** (e.g., hard drive, tape drive, flash storage, or other block or storage devices), some or all of which may

communicate with each other via an interlink (e.g., bus) **1808**.

(125) The communication device **1800** may further include a display unit **1810**, an alphanumeric input device **1812** (e.g., a keyboard), and a user interface (UI) navigation device **1814** (e.g., a mouse). In an example, the display unit **1810**, input device **1812** and UI navigation device **1814** may be a touch screen display. The communication device **1800** may additionally include a signal generation device **1818** (e.g., a speaker), a network interface device **1820**, and one or more sensors **1821**, such as a global positioning system (GPS) sensor, compass, accelerometer, or other sensor. The communication device **1800** may include an output controller **1828**, such as a serial (e.g., universal serial bus (USB), parallel, or other wired or wireless (e.g., infrared (IR), near field communication (NFC), etc.) connection to communicate or control one or more peripheral devices (e.g., a printer, card reader, etc.).

(126) The storage device **1816** may include a communication device-readable medium **1822**, on which is stored one or more sets of data structures or instructions **1824** (e.g., software) embodying or utilized by any one or more of the techniques or functions described herein. In some aspects, registers of the processor **1802**, the main memory **1804**, the static memory **1806**, and/or the mass storage **1816** may be, or include (completely or at least partially), the device-readable medium **1822**, on which is stored the one or more sets of data structures or instructions **1824**, embodying or utilized by any one or more of the techniques or functions described herein. In an example, one or any combination of the hardware processor **1802**, the main memory **1804**, the static memory **1806**, or the mass storage **1816** may constitute the device-readable medium **1822**.

(127) As used herein, the term “device-readable medium” is interchangeable with “computer-readable medium” or “machine-readable medium”. While the communication device-readable medium **1822** is illustrated as a single medium, the term “communication device-readable medium” may include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) configured to store the one or more instructions **1824**.

(128) The term “communication device-readable medium” may include any medium that is capable of storing, encoding, or carrying instructions for execution by the communication device **1800** and that cause the communication device **1800** to perform any one or more of the techniques of the present disclosure, or that is capable of storing, encoding, or carrying data structures used by or associated with such instructions. Non-limiting communication device-readable medium examples may include solid-state memories, and optical and magnetic media. Specific examples of communication device-readable media may include: non-volatile memory, such as semiconductor memory devices (e.g., Electrically Programmable Read-Only Memory (EPROM), Electrically Erasable Programmable Read-Only Memory (EEPROM)) and flash memory devices; magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; Random Access Memory (RAM), and CD-ROM and DVD-ROM disks. In some examples, communication device-readable media may include non-transitory communication device-readable media. In some examples, communication device-readable media may include communication device-readable media that is not a transitory propagating signal.

(129) The instructions **1824** may further be transmitted or received over a communications network **1826** using a transmission medium via the network interface device **1820** utilizing any one of a number of transfer protocols (e.g., frame relay, internet protocol (IP), transmission control protocol (TCP), user datagram protocol (UDP), hypertext transfer protocol (HTTP), etc.). Example communication networks may include a local area network (LAN), a wide area network (WAN), a packet data network (e.g., the Internet), mobile telephone networks (e.g., cellular networks), Plain Old Telephone (POTS) networks, and wireless data networks (e.g., Institute of Electrical and Electronics Engineers (IEEE) 802.11 family of standards known as Wi-Fi®, IEEE 802.16 family of standards known as Wi Max®, IEEE 802.15.4 family of standards, a Long Term Evolution (LTE) family of standards, a Universal Mobile Telecommunications System (UMTS) family of standards, peer-to-peer (P2P) networks, among others. In an example, the network interface device **1820** may



include one or more physical jacks (e.g., Ethernet, coaxial, or phone jacks) or one or more antennas to connect to the communications network **1826**. In an example, the network interface device **1820** may include a plurality of antennas to wirelessly communicate using at least one of single-input multiple-output (SIMO), MIMO, or multiple-input single-output (MISO) techniques. In some examples, the network interface device **1820** may wirelessly communicate using Multiple User MIMO techniques.

(130) The term “transmission medium” shall be taken to include any intangible medium that is capable of storing, encoding, or carrying instructions for execution by the communication device **1800**, and includes digital or analog communications signals or other intangible medium to facilitate communication of such software. In this regard, a transmission medium in the context of this disclosure is a device-readable medium.

(131) FIG. **16** illustrates a system level diagram, depicting an example of an electronic device (e.g., system) that can include, for example, a transmitter configured to selectively fan out a signal to one of multiple communication channels. FIG. **16** is included to show an example of a higher-level device application for the subject matter discussed above with regards to FIGS. **1-15**. In one aspect, system **1900** includes, but is not limited to, a desktop computer, a laptop computer, a netbook, a tablet, a notebook computer, a personal digital assistant (PDA), a server, a workstation, a cellular telephone, a mobile computing device, a smart phone, an Internet appliance, or any other type of computing device. In some aspects, system **1900** is a system on a chip (SOC) system.

(132) In one aspect, processor **1910** has one or more processor cores **1912**, . . . , **1912N**, where **1912N** represents the Nth processor core inside processor **1910** where N is a positive integer. In one aspect, system **1900** includes multiple processors including **1910** and **1905**, where processor **1905** has logic similar or identical to the logic of processor **1910**. In some aspects, processing core **1912** includes, but is not limited to, pre-fetch logic to fetch instructions, decode logic to decode the instructions, execution logic to execute instructions and the like. In some aspects, processor **1910** has a cache memory **1916** to cache instructions and/or data for system **1900**. Cache memory **1916** may be organized into a hierarchal structure including one or more levels of cache memory.

(133) In some aspects, processor **1910** includes a memory controller **1914**, which is operable to perform functions that enable the processor **1910** to access and communicate with memory **1930** that includes a volatile memory **1932** and/or a non-volatile memory **1934**. In some aspects, processor **1910** is coupled with memory **1930** and chipset **1920**. Processor **1910** may also be coupled to a wireless antenna **1978** to communicate with any device configured to transmit and/or receive wireless signals. In one aspect, an interface for wireless antenna **1978** operates in accordance with, but is not limited to, the IEEE 802.11 standard and its related family, Home Plug AV (HPAV), Ultra Wide Band (UWB), Bluetooth, WiMax, or any form of wireless communication protocol.

(134) In some aspects, volatile memory **1932** includes, but is not limited to, Synchronous Dynamic Random Access Memory (SDRAM), Dynamic Random Access Memory (DRAM), RAMBUS Dynamic Random Access Memory (RDRAM), and/or any other type of random access memory device. Non-volatile memory **1934** includes, but is not limited to, flash memory, phase change memory (PCM), read-only memory (ROM), electrically erasable programmable read-only memory (EEPROM), or any other type of non-volatile memory device.

(135) Memory **1930** stores information and instructions to be executed by processor **1910**. In one aspect, memory **1930** may also store temporary variables or other intermediate information while processor **1910** is executing instructions. In the illustrated aspect, chipset **1920** connects with processor **1910** via Point-to-Point (PtP or P-P) interfaces **1917** and **1922**. Chipset **1920** enables processor **1910** to connect to other elements in system **1900**. In some aspects of the example system, interfaces **1917** and **1922** operate in accordance with a PtP communication protocol such as the Intel® QuickPath Interconnect (QPI) or the like. In other aspects, a different interconnect may be used.

(136) In some aspects, chipset **1920** is operable to communicate with processor **1910**, **1905N**, display device **1940**, and other devices, including a bus bridge **1972**, a smart TV **1976**, I/O devices **1974**, nonvolatile memory **1960**, a storage medium (such as one or more mass storage devices) **1962**, a keyboard/mouse **1964**, a network interface **1966**, and various forms of consumer electronics **1977** (such as a PDA, smart phone, tablet etc.), etc. In one aspect, chipset **1920** couples with these devices through an interface **1924**. Chipset **1920** may also be coupled to a wireless antenna **1978** to communicate with any device configured to transmit and/or receive wireless signals.

(137) Chipset **1920** connects to display device **1940** via interface **1926**. Display **1940** may be, for example, a liquid crystal display (LCD), a plasma display, cathode ray tube (CRT) display, or any other form of visual display device. In some aspects of the example system, processor **1910** and chipset **1920** are merged into a single SOC. In addition, chipset **1920** connects to one or more buses **1950** and **1955** that interconnect various system elements, such as I/O devices **1974**, nonvolatile memory **1960**, storage medium **1962**, a keyboard/mouse **1964**, and network interface **1966**. Buses **1950** and **1955** may be interconnected together via a bus bridge **1972**.

(138) In one aspect, mass storage device **1962** includes, but is not limited to, a solid-state drive, a hard disk drive, a universal serial bus flash memory drive, or any other form of computer data storage medium. In one aspect, network interface **1966** is implemented by any type of well-known network interface standard including, but not limited to, an Ethernet interface, a universal serial bus (USB) interface, a Peripheral Component Interconnect (PCI) Express interface, a wireless interface and/or any other suitable type of interface. In one aspect, the wireless interface operates in accordance with, but is not limited to, the IEEE 802.11 standard and its related family, Home Plug AV (HPAV), Ultra Wide Band (UWB), Bluetooth, WiMax, or any form of wireless communication protocol.

(139) While the modules shown in FIG. **16** are depicted as separate blocks within the system **1900**, the functions performed by some of these blocks may be integrated within a single semiconductor circuit or may be implemented using two or more separate integrated circuits. For example, although cache memory **1916** is depicted as a separate block within processor **1910**, cache memory **1916** (or selected aspects of **1916**) can be incorporated into processor core **1912**.

(140) Discussions herein utilizing terms such as, for example, “processing”, “computing”, “calculating”, “determining”, “establishing”, “analyzing”, “checking”, or the like, may refer to operation(s) and/or process(es) of a computer, a computing platform, a computing system, or other electronic computing device, that manipulate and/or transform data represented as physical (e.g., electronic) quantities within the computer's registers and/or memories into other data similarly represented as physical quantities within the computer's registers and/or memories or other information storage medium that may store instructions to perform operations and/or processes.

(141) The terms “plurality” and “a plurality”, as used herein, include, for example, “multiple” or “two or more”. For example, “a plurality of items” includes two or more items.

(142) References to “one aspect”, “an aspect”, “an example aspect”, “some aspects”, “demonstrative aspect”, “various aspects” etc., indicate that the aspect(s) so described may include a particular feature, structure, or characteristic, but not every aspect necessarily includes the particular feature, structure, or characteristic. Further, repeated use of the phrase “in one aspect” does not necessarily refer to the same aspect, although it may.

(143) As used herein, unless otherwise specified the use of the ordinal adjectives “first”, “second”, “third” etc., to describe a common object, merely indicate that different instances of like objects are being referred to and are not intended to imply that the objects so described must be in a given sequence, either temporally, spatially, in ranking, or in any other manner.

(144) Some aspects may be used in conjunction with various devices and systems, for example, a User Equipment (UE), a Mobile Device (MD), a wireless station (STA), a Personal Computer (PC), a desktop computer, a mobile computer, a laptop computer, a notebook computer, a tablet

computer, a server computer, a handheld computer, a sensor device, an Internet of Things (IoT) device, a wearable device, a handheld device, a Personal Digital Assistant (PDA) device, a handheld PDA device, an on-board device, an off-board device, a hybrid device, a vehicular device, a non-vehicular device, a mobile or portable device, a consumer device, a non-mobile or non-portable device, a wireless communication station, a wireless communication device, a wireless Access Point (AP), a wired or wireless router, a wired or wireless modem, a video device, an audio device, an audio-video (A/V) device, a wired or wireless network, a wireless area network, a Wireless Video Area Network (WVAN), a Local Area Network (LAN), a Wireless LAN (WLAN), a Personal Area Network (PAN), a Wireless PAN (WPAN), and the like.

(145) Some aspects may, for example, be used in conjunction with devices and/or networks operating in accordance with existing IEEE 802.11 standards (including IEEE 802.11-2016 (IEEE 802.11-2016, IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks-Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Dec. 7, 2016); IEEE 802.11ay (P802.11ay Standard for Information Technology—Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks-Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment: Enhanced Throughput for Operation in License-Exempt Bands Above 45 GHz)) and/or future versions and/or derivatives thereof, devices and/or networks operating in accordance with existing WiFi Alliance (WFA) Peer-to-Peer (P2P) specifications (including WiFi P2P technical specification, version 1.5, Aug. 4, 2015) and/or future versions and/or derivatives thereof, devices and/or networks operating in accordance with existing Wireless-Gigabit-Alliance (WGA) specifications (including Wireless Gigabit Alliance, Inc WiGig MAC and PHY Specification Version 1.1, April 2011, Final specification) and/or future versions and/or derivatives thereof, devices and/or networks operating in accordance with existing cellular specifications and/or protocols, e.g., 3rd Generation Partnership Project (3GPP), 3GPP Long Term Evolution (LTE) and/or future versions and/or derivatives thereof, units and/or devices which are part of the above networks, and the like.

(146) Some aspects may be used in conjunction with one way and/or two-way radio communication systems, cellular radio-telephone communication systems, a mobile phone, a cellular telephone, a wireless telephone, a Personal Communication Systems (PCS) device, a PDA device which incorporates a wireless communication device, a mobile or portable Global Positioning System (GPS) device, a device which incorporates a GPS receiver or transceiver or chip, a device which incorporates an RFID element or chip, a Multiple Input Multiple Output (MIMO) transceiver or device, a Single Input Multiple Output (SIMO) transceiver or device, a Multiple Input Single Output (MISO) transceiver or device, a device having one or more internal antennas and/or external antennas, Digital Video Broadcast (DVB) devices or systems, multi-standard radio devices or systems, a wired or wireless handheld device, e.g., a Smartphone, a Wireless Application Protocol (WAP) device, or the like.

(147) Some aspects may be used in conjunction with one or more types of wireless communication signals and/or systems, for example, Radio Frequency (RF), Infra-Red (IR), Frequency-Division Multiplexing (FDM), Orthogonal FDM (OFDM), Orthogonal Frequency-Division Multiple Access (OFDMA), Spatial Divisional Multiple Access (SDMA), FDM Time-Division Multiplexing (TDM), Time-Division Multiple Access (TDMA), Multi-User MIMO (MU-MIMO), Extended TDMA (E-TDMA), General Packet Radio Service (GPRS), extended GPRS, Code-Division Multiple Access (CDMA), Wideband CDMA (WCDMA), CDMA 2000, single-carrier CDMA, multi-carrier CDMA, Multi-Carrier Modulation (MDM), Discrete Multi-Tone (DMT), Bluetooth, Global Positioning System (GPS), Wi-Fi, Wi-Max, ZigBee™, Ultra-Wideband (UWB), Global System for Mobile communication (GSM), 2G, 2.5G, 3G, 3.5G, 4G, Fifth Generation (5G) mobile networks, 3GPP, Long Term Evolution (LTE), LTE advanced, Enhanced Data rates for GSM

Evolution (EDGE), or the like. Other aspects may be used in various other devices, systems and/or networks.

(148) The term “wireless device”, as used herein, includes, for example, a device capable of wireless communication, a communication device capable of wireless communication, a communication station capable of wireless communication, a portable or non-portable device capable of wireless communication, or the like. In some demonstrative aspects, a wireless device may be or may include a peripheral that is integrated with a computer, or a peripheral that is attached to a computer. In some demonstrative aspects, the term “wireless device” may optionally include a wireless service.

(149) The term “communicating” as used herein with respect to a communication signal includes transmitting the communication signal and/or receiving the communication signal. For example, a communication unit, which is capable of communicating a communication signal, may include a transmitter to transmit the communication signal to at least one other communication unit, and/or a communication receiver to receive the communication signal from at least one other communication unit. The verb communicating may be used to refer to the action of transmitting and/or the action of receiving. In one example, the phrase “communicating a signal” may refer to the action of transmitting the signal by a first device and may not necessarily include the action of receiving the signal by a second device. In another example, the phrase “communicating a signal” may refer to the action of receiving the signal by a first device and may not necessarily include the action of transmitting the signal by a second device.

(150) Some demonstrative aspects may be used in conjunction with a wireless communication network communicating over a frequency band above 45 Gigahertz (GHz), e.g., 60 GHz. However, other aspects may be implemented utilizing any other suitable wireless communication frequency bands, for example, an Extremely High Frequency (EHF) band (the millimeter wave (mmWave) frequency band), e.g., a frequency band within the frequency band of between 20 GHz and 300 GHz, a frequency band above 45 GHz, a frequency band below 20 GHz, e.g., a Sub 1 GHz (SIG) band, a 2.4 GHz band, a 5 GHz band, a WLAN frequency band, a WPAN frequency band, a frequency band according to the WGA specification, and the like.

(151) As used herein, the term “circuitry” may, for example, refer to, be part of, or include, an Application Specific Integrated Circuit (ASIC), an integrated circuit, an electronic circuit, a processor (shared, dedicated, or group), and/or memory (shared, dedicated, or group), that execute one or more software or firmware programs, a combinational logic circuit, and/or other suitable hardware components that provide the described functionality. In some aspects, circuitry may include logic, at least partially operable in hardware. In some aspects, the circuitry may be implemented as part of and/or in the form of a radio virtual machine (RVM), for example, as part of a Radio processor (RP) configured to execute code to configured one or more operations and/or functionalities of one or more radio components.

(152) The term “logic” may refer, for example, to computing logic embedded in circuitry of a computing apparatus and/or computing logic stored in a memory of a computing apparatus. For example, the logic may be accessible by a processor of the computing apparatus to execute the computing logic to perform computing functions and/or operations. In one example, logic may be embedded in various types of memory and/or firmware, e.g., silicon blocks of various chips and/or processors. Logic may be included in, and/or implemented as part of, various circuitry, e.g., radio circuitry, receiver circuitry, control circuitry, transmitter circuitry, transceiver circuitry, processor circuitry, and/or the like. In one example, logic may be embedded in volatile memory and/or non-volatile memory, including random access memory, read only memory, programmable memory, magnetic memory, flash memory, persistent memory, and/or the like. Logic may be executed by one or more processors using memory, e.g., registers, buffers, stacks, and the like, coupled to the one or more processors, e.g., as necessary to execute the logic.

(153) The term “antenna” or “antenna array”, as used herein, may include any suitable

configuration, structure and/or arrangement of one or more antenna elements, components, units, assemblies and/or arrays. In some aspects, the antenna may implement transmit and receive functionalities using separate transmit and receive antenna elements. In some aspects, the antenna may implement transmit and receive functionalities using common and/or integrated transmit/receive elements. The antenna may include, for example, a phased array antenna, a single element antenna, a set of switched beam antennas, and/or the like.

#### Additional Notes and Aspects

(154) Example 1 is an oscillator circuit, comprising: an oscillator; measurement circuitry coupled to the oscillator, the measurement circuitry configured to receive an output signal of the oscillator and to measure oscillator error by comparing the output signal of the oscillator to a nominal frequency for an amount of time; and adjustment circuitry to adjust an oscillator frequency of the oscillator based on the measured oscillator error.

(155) In Example 2, the subject matter of Example 1 can optionally include an interface to receive a serial protocol command.

(156) In Example 3, the subject matter of Example 2 can optionally include wherein the amount of time is based on a number of clock cycles of the serial protocol command.

(157) In Example 4, the subject matter of Example 2 can optionally include wherein the measurement circuitry comprises a phase detector, and wherein the phase detector is configured to compare the output signal of the oscillator to a clock signal provided over a serial interface.

(158) In Example 5, the subject matter of Example 4 can optionally include wherein adjustment and measurement are performed periodically and in an oscillator calibration phase.

(159) In Example 6, the subject matter of Example 2 can optionally include wherein the oscillator is configured to remain enabled for a duration subsequent to a last clock cycle of the serial protocol command, and to terminate operation after the duration.

(160) In Example 7, the subject matter of Example 2 can optionally include wherein the measurement circuitry comprises a period measurement circuit, and the period measurement circuit is configured to detect a number of clock transitions of the oscillator or derived frequencies, the number of clock transitions to be measured being based on a clock signal provided over a serial interface.

(161) In Example 8, the subject matter of any one of Examples 1-7 can optionally include wherein the adjustment circuitry comprises a low dropout regulator (LDO).

(162) In Example 9, the subject matter of any one of Examples 1-8 can optionally include divider circuitry to divide the output signal of the oscillator, and the adjustment circuitry is configured to adjust an output of the divider circuitry and to refrain from adjusting the oscillator frequency.

(163) In Example 10, the subject matter of any one of Examples 1-9 can optionally include wherein the adjustment circuitry is configured to adjust an event trigger value and to refrain from adjusting the oscillator frequency.

(164) In Example 11, the subject matter of any one of Examples 1-10 can optionally include wherein the oscillator comprises a ring oscillator and the oscillator frequency is in a range of less than 20 gigahertz (GHz).

(165) Example 12 is a wireless communication device comprising a communications interface configured to provide a reference control command having a number of clock cycles; and radio frequency (RF) circuitry coupled to the communications interface, the RF circuitry comprising an oscillator; measurement circuitry coupled to the oscillator, the measurement circuitry configured to receive an output signal of the oscillator and to measure oscillator error by comparing the output signal of the oscillator relative to a nominal frequency for an amount of time; and adjustment circuitry to adjust one of an oscillator frequency of the oscillator based on the measured oscillator error.

(166) In Example 13, the subject matter of Example 12 can optionally include wherein the communications interface comprises a serial communication interface.

(167) In Example 14, the subject matter of Example 13 can optionally include wherein the reference control command comprises a serial protocol command, and wherein the amount of time is based on a number of clock cycles of the serial protocol command.

(168) In Example 15, the subject matter of Example 13 can optionally include wherein the measurement circuitry comprises a phase detector, and wherein the phase detector is configured to compare the output signal of the oscillator to a clock signal provided over the serial communication interface.

(169) In Example 16, the subject matter of any one of Examples 12-15 can optionally include wherein the oscillator is configured to remain enabled for a duration subsequent to a last clock cycle of the reference control command, and to terminate operation after the duration.

(170) Example 17 is a method for operating an oscillator in a wireless communication device, the method comprising: receiving an output signal of the oscillator; measuring oscillator error by comparing the output signal of the oscillator to a nominal frequency for an amount of time; and adjusting an oscillator frequency of the oscillator based on the measured oscillator error.

(171) In Example 18, the subject matter of Example 17 can optionally include receiving at least one of a reference control command and a clock signal over a serial communications interface.

(172) In Example 19, the subject matter of Example 18 can optionally include determining the amount of time over which to measure oscillator error based on a number of clock cycles of the reference control command.

(173) In Example 20, the subject matter of Example 18 can optionally include operating one of an analog to digital converter (ADC) and fuse circuitry based on the output signal of the oscillator.

(174) In Example 21, the subject matter of Example 20 can optionally include terminating operation of the oscillator after a time period subsequent to the reference control command.

(175) In Example 22, the subject matter of any of Examples 17-21 can optionally include performing the adjusting and measuring upon startup of the wireless communication device and periodically after startup.

(176) The above detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific aspects in which the invention can be practiced. These aspects are also referred to herein as “examples.” Such examples can include elements in addition to those shown or described. However, the present inventors also contemplate examples in which only those elements shown or described are provided. Moreover, the present inventors also contemplate examples using any combination or permutation of those elements shown or described (or one or more aspects thereof), either with respect to a particular example (or one or more aspects thereof), or with respect to other examples (or one or more aspects thereof) shown or described herein.

(177) In this document, the terms “a” or “an” are used, as is common in patent documents, to include one or more than one, independent of any other instances or usages of “at least one” or “one or more.” In this document, the term “or” is used to refer to a nonexclusive or, such that “A or B” includes “A but not B,” “B but not A,” and “A and B,” unless otherwise indicated. In this document, the terms “including” and “in which” are used as the plain-English equivalents of the respective terms “comprising” and “wherein.” Also, in the following claims, the terms “including” and “comprising” are open-ended, that is, a system, device, article, composition, formulation, or process that includes elements in addition to those listed after such a term in a claim are still deemed to fall within the scope of that claim. Moreover, in the following claims, the terms “first,” “second,” and “third,” etc. are used merely as labels, and are not intended to impose numerical requirements on their objects.

(178) The above description is intended to be illustrative, and not restrictive. For example, the above-described examples (or one or more aspects thereof) may be used in combination with each other. Other aspects can be used, such as by one of ordinary skill in the art upon reviewing the above description. The Abstract is provided to allow the reader to quickly ascertain the nature of

the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. This should not be interpreted as intending that an unclaimed disclosed feature is essential to any claim. Rather, inventive subject matter may lie in less than all features of a particular disclosed aspect. Thus, the following claims are hereby incorporated into the Detailed Description, with each claim standing on its own as a separate aspect, and it is contemplated that such aspects can be combined with each other in various combinations or permutations. The scope of the invention should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are legally entitled.

## Claims

1. An oscillator circuit comprising: an oscillator; measurement circuitry coupled to the oscillator, the measurement circuitry configured to receive an output signal of the oscillator and to measure oscillator error by comparing the output signal of the oscillator to a nominal frequency for an amount of time, the amount of time based on a serial protocol command received by the oscillator circuit; and adjustment circuitry to adjust an oscillator frequency of the oscillator based on the measured oscillator error.
2. The oscillator circuit of claim 1, further comprising an interface to receive the serial protocol command.
3. The oscillator circuit of claim 2, wherein the amount of time is based on a number of clock cycles of the serial protocol command.
4. The oscillator circuit of claim 2, wherein the measurement circuitry comprises a phase detector, and wherein the phase detector is configured to compare the output signal of the oscillator to a clock signal provided over a serial interface.
5. The oscillator circuit of claim 4, wherein adjustment and measurement are performed periodically and in an oscillator calibration phase.
6. The oscillator circuit of claim 2, wherein the oscillator is configured to remain enabled for a duration subsequent to a last clock cycle of the serial protocol command, and to terminate operation after the duration.
7. The oscillator circuit of claim 2, wherein the measurement circuitry comprises a period measurement circuit, and the period measurement circuit is configured to detect a number of clock transitions of the oscillator or derived frequencies, the number of clock transitions to be measured being based on a clock signal provided over a serial interface.
8. The oscillator circuit of claim 1, wherein the adjustment circuitry comprises a low dropout regulator (LDO).
9. The oscillator circuit of claim 1, further comprising divider circuitry to divide the output signal of the oscillator, and the adjustment circuitry is configured to adjust an output of the divider circuitry and to refrain from adjusting the oscillator frequency.
10. The oscillator circuit of claim 1, wherein the adjustment circuitry is configured to adjust an event trigger value and to refrain from adjusting the oscillator frequency.
11. The oscillator circuit of claim 1, wherein the oscillator comprises a ring oscillator and the oscillator frequency is in a range of less than 20 gigahertz (GHz).
12. A wireless communication device, comprising: a communications interface configured to provide a reference control command having a number of clock cycles; and radio frequency (RF) circuitry coupled to the communications interface, the RF circuitry comprising: an oscillator; measurement circuitry coupled to the oscillator, the measurement circuitry configured to receive an output signal of the oscillator and to measure oscillator error by comparing the output signal of the oscillator relative to a nominal frequency for an amount of time, the amount of time based on a

serial protocol command received by the wireless communication device; and adjustment circuitry to adjust one of an oscillator frequency of the oscillator based on the measured oscillator error.

13. The wireless communication device of claim 12, wherein the communications interface comprises a serial communication interface.

14. The wireless communication device of claim 13, wherein the reference control command comprises the serial protocol command, and wherein the amount of time is based on a number of clock cycles of the serial protocol command.

15. The wireless communication device of claim 13, wherein the measurement circuitry comprises a phase detector, and wherein the phase detector is configured to compare the output signal of the oscillator to a clock signal provided over the serial communication interface.

16. The wireless communication device of claim 12, wherein the oscillator is configured to remain enabled for a duration subsequent to a last clock cycle of the reference control command, and to terminate operation after the duration.

17. A method for operating an oscillator in a wireless communication device, the method comprising: receiving an output signal of the oscillator; measuring oscillator error by comparing the output signal of the oscillator to a nominal frequency for an amount of time, the amount of time based on a reference control command received by the wireless communication device; and adjusting an oscillator frequency of the oscillator based on the measured oscillator error.

18. The method of claim 17, further comprising: receiving at least one of the reference control command and a clock signal over a serial communications interface.

19. The method of claim 18, further comprising: determining the amount of time over which to measure oscillator error based on a number of clock cycles of the reference control command.

20. The method of claim 18, further comprising: operating one of an analog-to-digital converter (ADC) and fuse circuitry based on the output signal of the oscillator.

21. The method of claim 20, further comprising: terminating operation of the oscillator after a time period subsequent to the reference control command.

22. The method of claim 17, further comprising: performing the adjusting and measuring upon startup of the wireless communication device and periodically after startup.

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