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Triggering of Aperiodic channel state information reference signals with mixed numerology

Abstract

Devices, systems, and methods described herein may improve aperiodic CSI-RS handling in mixed numerology environments. An exemplary method includes operations of receiving a downlink control information (DCI) message carried by a Physical Downlink Control Channel (PDCCH) on a second carrier, wherein the second carrier uses a second OFDM numerology, obtaining an aperiodic CSI-RS slot offset from the DCI message, determining a reference slot in the first numerology, determining the slot of the aperiodic CSI-RS based on the reference slot and the aperiodic CSI-RS slot offset, and receiving or transmitting the aperiodic CSI-RS in the determined slot.

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Background/Summary

RELATED APPLICATIONS (1) This application is a continuation of U.S. patent application Ser. No. 17/298,890, Jun. 1, 2024, now granted as U.S. Pat. No. 12,004,210 on Jun. 4, 2024, which is a national stage application of International Patent Application No. PCT/IB2019/060375, filed Dec. 2, 2019, and claims priority to and the benefit of U.S. Provisional Application No. 62/774,091, filed on Nov. 30, 2018 and entitled “TRIGGERING OF APERIODIC CHANNEL STATE INFORMATION REFERENCE SIGNALS WITH MIXED NUMEROLOGY,” the disclosure of which are incorporated in their entirety by reference.

TECHNICAL FIELD

(1) The present disclosure generally relates to the field of wireless network communications, and more particularly, to deploying aperiodic channel state information reference signals in mixed numerology environments.

INTRODUCTION

(2) Generally, all terms used herein are to be interpreted according to their ordinary meaning in the relevant technical field, unless a different meaning is clearly given and/or is implied from the context in which it is used. All references to a/an/the element, apparatus, component, means, step, etc. are to be interpreted openly as referring to at least one instance of the element, apparatus, component, means, step, etc., unless explicitly stated otherwise. The steps of any methods disclosed herein do not have to be performed in the exact order disclosed, unless a step is explicitly described as following or preceding another step and/or where it is implicit that a step must follow or precede another step. Any feature of any of the embodiments disclosed herein may be applied to any other embodiment, wherever appropriate. Likewise, any advantage of any of the embodiments may apply to any other embodiments, and vice versa. Other objectives, features and advantages of the enclosed embodiments will be apparent from the following description.

BACKGROUND

(3) The next generation mobile wireless communication system (5G) or new radio (NR), supports a diverse set of use cases and a diverse set of deployment scenarios. Some deployment scenarios include deployment at both low frequencies (100 s of MHz), similar to LTE today, and very high frequencies (mm waves in the tens of GHz).

(4) Similar to LTE, NR uses orthogonal frequency division multiplexing (OFDM) in the downlink (i.e., from a network node, gNB, eNB, or base station, to a user equipment (UE). In the uplink (i.e., from UE to gNB), both discrete Fourier transform spread (DFT-spread) OFDM and OFDM is supported.

(5) The basic NR physical resource can thus be seen as a time-frequency grid as illustrated in FIG. **1**, where each resource element corresponds to one OFDM subcarrier during one OFDM symbol interval. Resource allocation in a slot is described in terms of resource blocks (RBs) in the frequency domain and number of OFDM symbols in the time domain. An RB corresponds to 12 contiguous subcarriers and a slot consists of 14 OFDM symbols.

(6) Different subcarrier spacing values are supported in NR. The supported subcarrier spacing values (also referred to as numerologies) in NR are given by Δf=(15×2.sup.μ) kHz where μ=0, 1, 2, 3, 4. The possible subcarrier spacings are summarized in Table 1.

(7) TABLE-US-00001 TABLE 1 Slot length at different numerologies. Numerology Slot length RB BW 15 kHz 1 ms 180 kHz 30 kHz 0.5 ms 360 kHz 60 kHz 0.25 ms 720 kHz 120 kHz 125 μs 1.44 MHz 240 kHz 62.5 μs 2.88 MHz

(8) In the time domain, downlink and uplink transmissions in NR are organized into equally-sized subframes, similar to LTE, as shown in FIG. **2**. A subframe is further divided into slots and the number of slots per subframe is 2.sup.μ for a numerology of (15×2.sup.μ) kHz.

(9) NR supports “slot based” transmission. In each slot, the gNB transmits downlink control information (DCI) about which UE data is to be transmitted to and what resources in the current downlink slot the data is transmitted on. The DCI is carried on the Physical Control Channel (PDCCH) and data is carried on Physical Downlink Shared Channel (PDSCH).

SUMMARY

(10) One general aspect includes a method. The method also includes receiving a downlink control information (DCI) message carried by a physical downlink control channel (PDCCH) on a second carrier, where the second carrier uses a second OFDM numerology; obtaining an aperiodic CSI-RS slot offset from the DCI message, determining a reference slot in the first numerology, determining the slot of the aperiodic CSI-RS based on the reference slot and the aperiodic CSI-RS slot offset,

and receiving or transmitting the aperiodic CSI-RS in the determined slot. Other embodiments of this aspect include corresponding computer systems, apparatus, and computer programs recorded on one or more computer storage devices, each configured to perform the actions of the methods.

(11) Implementations may include one or more of the following features. The method where the first OFDM numerology is different from the second OFDM numerology. The OFDM numerology is characterized by its subcarrier spacing. The method where additionally the wireless device transmits a channel state information (CSI) report based on a measurement of the received aperiodic CSI-RS. The slot of the aperiodic CSI-RS is determined as the slot X slots later than the reference slot, where X is the aperiodic CSI-RS slot offset. The slot of the aperiodic CSI-RS is determined as the slot X slots later than the reference slot, where X is the aperiodic CSI-RS slot offset. Implementations of the described techniques may include hardware, a method or process, or computer software on a computer-accessible medium.

(12) One general aspect includes a user equipment (UE) for receiving an aperiodic CSI-RS on a first carrier. The user equipment also includes an antenna configured to send and receive wireless signals; radio front-end circuitry connected to the antenna and to processing circuitry, and configured to condition signals communicated between the antenna and the processing circuitry; the processing circuitry being configured to perform operations may include: receiving a downlink control information (DCI) message carried by a physical downlink control channel (PDCCH) on a second carrier, where the second carrier uses a second OFDM numerology; obtaining an aperiodic CSI-RS slot offset from the DCI message; determining, on the first carrier, a reference slot in the first numerology; determining the slot of the aperiodic CSI-RS based on the reference slot and the aperiodic CSI-RS slot offset; and receiving the aperiodic CSI-RS in the determined slot of the aperiodic CSI-RS or transmitting an associated CSI-RS report in the determined slot. The equipment also includes a battery connected to the processing circuitry and configured to supply power to the UE. Other embodiments of this aspect include corresponding computer systems, apparatus, and computer programs recorded on one or more computer storage devices, each configured to perform the actions of the methods.

(13) Implementations may include one or more of the following features. The user equipment where the first OFDM numerology is different from the second OFDM numerology. The OFDM numerology is characterized by its subcarrier spacing. The user equipment where the wireless device transmits a channel state information (CSI) report based on a measurement of the received aperiodic CSI-RS. Implementations of the described techniques may include hardware, a method or process, or computer software on a computer-accessible medium.

(14) One general aspect includes a communication system. The communication system includes processing circuitry configured to provide user data; and a communication interface configured to forward the user data to a cellular network for transmission to a user equipment (UE), where the cellular network may include at least one base station having a radio interface and processing circuitry, the processing circuitry being configured to transmit CSI-RS information aperiodically on a first carrier according to a first numerology and on a second carrier according to a second numerology. Other embodiments of this aspect include corresponding computer systems, apparatus, and computer programs recorded on one or more computer storage devices, each configured to perform the actions of the methods.

(15) Implementations may include one or more of the following features. The communication system where the at least one base station may include a first base station and a second base station, where the first base station transmits via the first carrier and the second base station transmits via the second carrier. The first base station and the second base station are non-collocated base stations. The UE is configured to communicate with the base station. Implementations of the described techniques may include hardware, a method or process, or computer software on a computer-accessible medium.

(16) One general aspect includes a method. The method also includes transmitting a downlink

control information (DCI) message carried by a physical downlink control channel (PDCCH) on a second carrier, where the DCI message includes an aperiodic CSI-RS slot offset; transmitting the aperiodic CSI-RS in the determined slot of the aperiodic CSI-RS according to the aperiodic CSI-RS slot offset. Other embodiments of this aspect include corresponding computer systems, apparatus, and computer programs recorded on one or more computer storage devices, each configured to perform the actions of the methods.

(17) Implementations may include one or more of the following features. The method where the first carrier uses a first OFDM numerology and the second carrier uses a second OFDM numerology that is different than the first OFDM numerology. The first OFDM numerology and the second OFDM numerology are characterized by respective subcarrier spacings. The method may include receiving, from a wireless device, a channel state information (CSI) report based on a measurement of the received aperiodic CSI-RS. The slot of the aperiodic CSI-RS is determined as the slot X slots later than the reference slot, where X is the aperiodic CSI-RS slot offset. Implementations of the described techniques may include hardware, a method or process, or computer software on a computer-accessible medium.

Description

BRIEF DESCRIPTION OF DRAWINGS

(1) FIG. **1**: An example of NR physical resources.

(2) FIG. **2**: NR time-domain structure with 15 kHz subcarrier spacing.

(3) FIG. **3**: Illustration of aperiodic CSI reporting.

(4) FIG. **4**: Illustration of mixed numerology triggering of aperiodic CSI-RS according to the method.

(5) FIG. **5**: Flow diagram illustrating an example method in a UE for receiving an aperiodic CSI-RS on a first carrier that uses a first OFDM numerology.

(6) FIG. **6**: A wireless network in accordance with some embodiments.

(7) FIG. **7**: User Equipment in accordance with some embodiments.

(8) FIG. **8**: Virtualization environment in accordance with some embodiments.

(9) FIG. **9**: Telecommunication network connected via an intermediate network to a host computer in accordance with some embodiments.

(10) FIG. **10**: Host computer communicating via a base station with a user equipment over a partially wireless connection in accordance with some embodiments.

(11) FIG. **11**: Methods implemented in a communication system including a host computer, a base station and a user equipment in accordance with some embodiments.

(12) FIG. **12**: Methods implemented in a communication system including a host computer, a base station and a user equipment in accordance with some embodiments.

(13) FIG. **13**: Methods implemented in a communication system including a host computer, a base station and a user equipment in accordance with some embodiments.

(14) FIG. **14**: Methods implemented in a communication system including a host computer, a base station and a user equipment in accordance with some embodiments.

(15) These figures will be better understood by reference to the following detailed description.

DETAILED DESCRIPTION

(16) The PDCCH is typically transmitted in control resource sets (CORSETs) in the first few OFDM symbols in each slot. In operation, a UE may first decode PDCCH and, if a PDCCH is decoded successfully, though UE may then decode the corresponding PDSCH based on the decoded DCI in the PDCCH.

(17) Uplink data transmissions are also dynamically scheduled using PDCCH. For example, similar to the downlink scenario, a UE first decodes an uplink grant in a DCI carried by PDCCH and then

transmits data over the Physical Uplink Shared Channel (PUSCH) based the decoded control information in the uplink grant such as modulation order, coding rate, and uplink resource allocation, etc.
(18) Each UE is assigned with a unique C-RNTI (Cell Radio Network Temporary Identifier) during network connection. The CRC (cyclic redundancy check) bits attached to a DCI for a UE may be scrambled by the UE's C-RNTI, so that a UE can recognize its own DCI by checking the CRC bits of the DCI against the assigned C-RNTI.
(19) DCI Format for Scheduling PUSCH
(20) For UL scheduling of PUSCH, at least the following bit fields are included in a UL DCI: Frequency domain resource assignment Time domain resource assignment Modulation and coding scheme—5 bits New data indicator—1 bit Redundancy version—2 bits HARQ process number—4 bits TPC command for scheduled PUSCH—2 bits CSI request—0, 1, 2, 3, 4, 5, or 6 bits determined by higher layer parameter ReportTriggerSize
DCI Format for Scheduling PDSCH
(21) For DL scheduling of PDSCH, at least the following bit fields are included in an DL DCI Frequency domain resource assignment Time domain resource assignment Modulation and coding scheme—5 bits New data indicator—1 bit Redundancy version—2 bits HARQ process number—4 bits ZP CSI-RS trigger—2 bits
CSI Reporting
(22) Channel state information (CSI) feedback is used by gNB to obtain DL CSI from a UE in order to determine how to transmit DL data to a UE over plurality of antenna ports. The CSI typically includes a channel rank indicator (RI), a precoding matrix indicator (PMI), and a channel quality indicator (CQI). RI is used to indicate the number of data layers that can be transmitted simultaneously to a particular UE; PMI is used to indicate the precoding matrix over the indicated data layers; and CQI is used to indicate the modulation and coding rate that can be achieved with the indicated rank and the precoding matrix. A special type of CSI reporting is beam reporting, where the gNB transmits multiple CSI-RS resources in a plurality of beams and the UE feeds back a number of the strongest beams of the plurality of beams in the form of multiple CSI-RS resource indicators (CRIs) together with L1-RSRP (reference signal received power) for each selected resource.
(23) In NR, in addition to periodic and aperiodic CSI reporting as in LTE, semi-persistent CSI reporting is also supported. Thus, three types of CSI reporting may be supported in NR as follows:
(24) First, periodic CSI (P-CSI) Reporting on PUCCH. CSI is reported periodically by a UE. Parameters such as periodicity and slot offset are configured semi-statically by higher layer RRC signaling from the gNB to the UE
(25) Second, aperiodic CSI (A-CSI) Reporting on PUSCH. This type of CSI reporting involves a single-shot (i.e., one time) CSI report by a UE which is dynamically triggered by the gNB using DCI. Some of the parameters related to the configuration of the aperiodic CSI report is semi-statically configured by RRC but the triggering is dynamic
(26) Third, semi-persistent CSI (SP-CSI) Reporting on PUSCH. Similar to periodic CSI reporting, semi-persistent CSI reporting has a periodicity and slot offset which may be semi-statically configured. However, a dynamic trigger from a gNB to a UE may be needed to allow the UE to begin semi-persistent CSI reporting. A dynamic trigger from the gNB to the UE is needed to request the UE to stop the semi-persistent CSI reporting.
(27) CSI Reference Signal (NZP CSI-RS)
(28) Non-zero power (NZP) CSI-RS is used for measuring downlink CSI by a UE. CSI-RS is transmitted over each transmit (Tx) antenna port at the gNB and for different antenna ports, the CSI-RS are multiplexed in time, frequency, and code domains such that the channel between each Tx antenna port at the gNB and each receive antenna port at a UE can be measured by the UE. A time frequency resource used for transmitting CSI-RS may be referred to as a CSI-RS resource.

(29) In NR, the following three types of CSI-RS transmissions are supported:
(30) First, periodic CSI-RS (P CSI-RS): CSI-RS is transmitted periodically in certain slots. This CSI-RS transmission is semi-statically configured using parameters such as CSI-RS resource, periodicity and slot offset.
(31) Second, aperiodic CSI-RS (AP CSI-RS). This is a one-shot CSI-RS transmission that can happen in any slot. Here, one-shot means that CSI-RS transmission only happens once per trigger. The CSI-RS resources within a slot (i.e., the resource element locations which consist of subcarrier locations and OFDM symbol locations) for aperiodic CSI-RS are semi-statically configured. The transmission of aperiodic CSI-RS is triggered by dynamic signaling through PDCCH using the CSI request field in UL DCI. Multiple aperiodic CSI-RS resources can be included in a CSI-RS resource set and the triggering of aperiodic CSI-RS is on a resource set basis. The slot offset of the CSI-RS relative to the triggering DCI is given by the RRC parameter aperiodicTriggeringOffset which is given on an CSI-RS resource set level.
(32) Third, semi-persistent CSI-RS (SP CSI-RS). Similar to periodic CSI-RS, resources for semi-persistent CSI-RS transmissions are semi-statically configured with parameters such as periodicity and slot offset. However, unlike periodic CSI-RS, dynamic signaling is needed to activate and deactivate the CSI-RS transmission.
(33) In the case of aperiodic CSI-RS and/or aperiodic CSI reporting, the gNB RRC configures the UE with S_c CSI triggering states. Each triggering state contains the aperiodic CSI report setting to be triggered along with the associated aperiodic CSI-RS resource sets.
(34) CSI Frame Work in NR
(35) In NR, a UE can be configured with N≥1 CSI reporting settings (i.e., ReportConfigs), M≥1 resource settings (i.e., ResourceConfigs). At least the following configuration parameters may be signaled via RRC for CSI acquisition. N, M, and L are indicated either implicitly or explicitly In each CSI reporting setting, at least the followings are included: reported CSI parameter(s) such as RI, PMI, CQI CSI Type if reported such Type I or Type II Codebook configuration including codebook subset restriction Time-domain behavior such as P-CSI, SP-CSI, or A-CSI Frequency granularity for CQI and PMI such as wideband, partial band, or sub-band Measurement restriction configurations such as RBs in frequency domain and slots in time domain Carrier information, in case of cross carrier triggering In each CSI-RS resource setting: A configuration of S≥1 CSI-RS resource set(s) A configuration of Ks≥1 CSI-RS resources for each resource set s, including at least: mapping to REs, the number of antenna ports, time-domain behavior, etc. Time domain behavior: aperiodic, periodic or semi-persistent
A-CSI Reporting on PUSCH
(36) A-CSI reporting over PUSCH is triggered by a DCI for scheduling PUSCH, i.e., an UL DCI. A special CSI request bit field in the DCI is defined for the purpose. Each value of the CSI request bit field defines a codepoint and each codepoint can be associated with a higher layer configured CSI report trigger state. The first codepoint with all “0”s corresponds to a no CSI request. For A-CSI reporting, each of the S.sub.C triggering states comprise indication of one or more A-CSI reports to be triggered. Optionally, each triggered A-CSI report may also trigger aperiodic NZP CSI-RS resource sets for channel measurements, aperiodic CSI-IM and/or aperiodic NZP CSI-RS for interference measurements. Thus, each CSI report trigger state defines at least the following information: Resource configurations CSI reference signal (CSI-RS) resource for channel measurement Interference measurement resource for interference measurement CSI report configuration: The type of CSI report, i.e., wideband or sub-band, Type I or Type II codebook used, etc.
(37) The bit width, L.sub.c, of the CSI request field is configurable from 0 to 6 bits. When the number of CSI triggering states, S.sub.c, is larger than the number of codepoints, i.e., S.sub.c>2.sup.L.sup.c−1, MAC (Medium Access Control) CE (control element) is used to select a subset of 2.sup.L.sup.c−1 triggering states from the S.sub.c triggering states so that there is a one-

to-one mapping between each codepoint and a CSI triggering state. Some of these aspects may be seen in the illustration of aperiodic CSI reporting in FIG. **3**.
(38) There currently exist certain challenges. The current aperiodic CSI-RS triggering procedure in NR is not well-defined for the case where the DCI triggering the aperiodic CSI-RS and the aperiodic CSI-RS itself are transmitted on carriers or bandwidth parts which use different numerologies. For instance, it is not clear how to derive in which slot the aperiodic CSI-RS resource is transmitted due to the different numerologies resulting in different slot lengths and, therefore, different slot indexing. Another issue is that the aperiodic CSI-RS could be transmitted non-causally in case the CSI-RS subcarrier spacing (SCS) is larger than the PDCCH SCS, which would require a UE implementation to buffer OFDM symbols for several slots in the carrier with larger SCS in anticipation of potential aperiodic CSI-RS triggers in the carrier with the smaller SCS, which increases UE implementation complexity and memory consumption.
(39) Certain aspects of the present disclosure and their embodiments may provide solutions to these or other challenges, decreasing UE implementation complexity and memory consumption. In this disclosure, a predefined rule is introduced to map the PDCCH reception slot in the numerology of the triggering PDCCH to a reference slot in the numerology of the CSI-RS such that the reference slot is the latest slot overlapping in time with PDCCH reception slot. The triggering offset of the aperiodic CSI-RS is then applied relative to the reference slot in the CSI-RS numerology.
(40) Additionally, a restriction of aperiodic CSI-RS slot offset may be applied in the case where the PDCCH SCS is smaller than the aperiodic CSI-RS SCS, such that PDCCH decoding can be assured to be completed earlier in time than the occurrence of the aperiodic CSI-RS.
(41) There are, proposed herein, various embodiments which address one or more of the issues disclosed herein. For example, FIG. **5** illustrates a method **500** according to some embodiments the present disclosure, performed by a wireless device, for receiving an aperiodic CSI-RS on a first carrier that uses a first OFDM numerology may include several operations. Such operations may include receiving a DCI message carried by a PDCCH) on a second carrier that uses a second OFDM numerology (operation **502**), obtaining an aperiodic CSI-RS slot offset from the DCI message (operation **504**), determining, on the first carrier, a reference slot in the first numerology (operation **506**), determining the slot of the aperiodic CSI-RS based on the reference slot and the aperiodic CSI-RS slot offset (operation **508**), and receiving the aperiodic CSI-RS in the determined slot of the aperiodic CSI-RS (operation **510**). Additional embodiments of the method **500** may include additional operations beyond those enumerated in FIG. **5**. For example, embodiments of the method **500** may include additional operations before, after, in between, or as part of the enumerated operations. Some embodiments of the method **500** include a set of instructions stored on a computer readable medium that can be executed by a processor to perform associated operations.
(42) Certain embodiments may provide one or more of the following technical advantage. Aperiodic triggering of CSI-RS may be seamlessly supported irrespective of the numerology of the PDCCH and CSI-RS. Existing RRC configurations of aperiodic CSI-RS triggering offset can be reused for the mixed numerology aperiodic CSI-RS triggering case. By mapping the PDCCH reception slot to a reference slot in the CSI-RS numerology which is the latest overlapping slot, the number of OFDM symbols of the CIS-RS numerology the UE needs to buffer in anticipation of potential aperiodic CSI-RS triggering is minimized, which minimizes UE memory consumption and complexity.
(43) The herein presented technology discloses a method for aperiodic CSI-RS triggering where the PDCCH carrying the triggering DCI is transmitted on a different carrier or bandwidth part than the triggered aperiodic CSI-RS, where additionally the carrier or bandwidth part of the PDCCH uses a different numerology than the carrier or bandwidth part whereon the aperiodic CSI-RS is transmitted. Here, numerology is equated to subcarrier spacing (SCS) and the SCSs may be represented with μ.sub.CSIRS and μ.sub.PCCH respectively (corresponding to a SCS of Δf=

(15×2.sup.μ) kHz). The presented technology may provide a general solution applicable to all of the possible relationships between with μ.sub.CSIRS and μ.sub.PDCCH, i.e., μ.sub.CSIRS>μ.sub.PDCCH, μ.sub.CSIRS<μ.sub.PDCCH, and μ.sub.CSIRS=μ.sub.PDCCH.
(44) In prior art solutions, only aperiodic CSI-RS triggering where the CSI-RS and triggering PDCCH have the same numerology have been considered. In such cases, it is relatively simple to determine the slot of the aperiodic CSI-RS as the slot X slots after the slot wherein the PDCCH is received. For example, if the PDCCH is received in slot n, the CSI-RS is transmitted in slot n+X, where X is the RRC configured aperiodic CSI-Rs slot offset. However, for the mixed numerology triggering case, it is ambiguous how to interpret such a slot offset.
(45) The solutions presented in the present disclosure may rely on defining a predefined mapping between the PDCCH reception slot in the numerology of the PDCCH to a reference slot n′ in the numerology of the CSI-RS. The indicated slot offset X in is then mapped to a slot a n′+X in the numerology of the CSI-RS.
(46) In some embodiments, the reference slot n′ is a slot overlapping in time with the slot of the PDCCH. For instance, the latest slot in the numerology of the CSI-RS overlapping in time with the slot of the PDCCH is determined as the reference slot. Alternatively, the first slot in the numerology of the CSI-RS overlapping in time with the slot of the PDCCH is determined as the reference slot (or more generally, a pre-determined slot).
(47) In another embodiment, a slot not overlapping in time is selected as the reference slot, such as the first slot in the CSI-RS numerology not overlapping in time with the reference slot. The term “overlapping slot” includes two concepts. In one embodiment the slot timing of the two carriers/bandwidth parts as received by the UE is used to determine if slots are overlapping. In another embodiment, the UE compensates for any potential receive timing difference before determining the reference slot, i.e., first slot in a subframe of both numerologies have same start time. The two carriers could be transmitted by non co-located base stations or transmission points and, thus, the propagation delays are different resulting in different receive times.
(48) In some embodiments, the UE may implicitly determine the reference slot as part of the procedure for determining the slot of the aperiodic CSI-RS, i.e., it may use the reference slot as an intermediate calculation in the process of determining the aperiodic CSI-RS slot and may not determiner the reference slot explicitly.
(49) In one example, the reference slot may be determined as
(50) $n' =$ .Math. $(n+1)\frac{2^{\mu_{\mathrm{CSIRS}}}}{2^{\mu_{\mathrm{PDCCH}}}} - 1$ .Math. ,
where n is the slot of the triggering PDCCH. The slot counters n and n′ are typically re-started at every subframe boundary. This would map the reference slot as: the latest slot overlapping with the PDCCH slot in case μ.sub.CSIRS>μ.sub.PDCCH, the same slot as the PDCCH in case μ.sub.CSIRS=μ.sub.PDCCH, and, the overlapping slot of the PDCCH slot in case μ.sub.CSIRS<μ.sub.PDCCH, which is desirable.
(51) An illustration of the above example is given in FIG. **4**.
ADDITIONAL EXPLANATION
(52) Some of the embodiments contemplated herein will now be described more fully with reference to the accompanying drawings. Other embodiments, however, are contained within the scope of the subject matter disclosed herein, the disclosed subject matter should not be construed as limited to only the embodiments set forth herein; rather, these embodiments are provided by way of example to convey the scope of the subject matter to those skilled in the art.
(53) In one embodiment, a restriction on the slot offset X is imposed when μ.sub.CSIRS>μ.sub.PDCCH, such that the aperiodic slot offset must be larger than some value, for instance zero. Enforcing a non-zero slot offset assures that the aperiodic CSI-RS is always transmitted after PDCCH reception is complete, which removes the need for the UE to buffer OFDM symbols on the CSI-RS carrier in anticipation of a potential aperiodic CSI-RS trigger on the PDCCH carrier.

(54) In another embodiment the slot offset X is scaled based on the numerology ratio, i.e., CSI-RS is transmitted in slot

(55) $n' = n + \frac{2^{\mu_{\mathrm{CSIRS}}}}{2^{\mu_{\mathrm{PDCCH}}}} X,$

with n the reference slot as determined above and X the indicated slot offset. Using the scaled X instead of X directly could be limited to case μ.sub.CSIRS>μ.sub.PDCCH. Slots with higher μ values are shorter, so the scaling compensates for that and guarantees the UE has sufficient time.

(56) Using the specification language of TS 38.214, the herein presented method may be implemented as follows:

(57) When aperiodic CSI-RS is used with aperiodic reporting, the CSI-RS offset X is configured per resource set by the higher layer parameter aperiodicTriggeringOffset. The CSI-RS triggering offset has the range of 0 to 4 slots. The UE shall transmit a CSI report or receive the CSI-RS in slot

(58) .Math. $(n+1)\frac{2^{\mu_{\mathrm{CSIRS}}}}{2^{\mu_{\mathrm{PDCCH}}}} - 1$ .Math. $+ X,$

where n is the slot with the triggering DCI in the numerology of the PDCCH, X is the CSI-RS triggering offset in the numerology of CSI-RS according to the higher layer parameter aperiodicTriggeringOffset, and μ.sub.CSIRS and μ.sub.PDCCH are the subcarrier spacing configurations for CSI-RS and PDCCH, respectively. If all the associated trigger states do not have the higher layer parameter qcl-Type set to 'QCL-TypeD' in the corresponding TCI states, the CSI-RS triggering offset is fixed to zero. If the PDCCH SCS is smaller than the CSI-RS SCS, the CSI-RS triggering offset is larger than zero. The aperiodic triggering offset of the CSI-IM follows offset of the associated NZP CSI-RS for channel measurement.

(59) For CSI-RS resource sets associated with Resource Settings configured with the higher layer parameter resourceType set to 'aperiodic', 'periodic', or 'semi-persistent', trigger states for Reporting Setting(s) (configured with the higher layer parameter reportConfigType set to 'aperiodic') and/or Resource Setting for channel and/or interference measurement on one or more component carriers are configured using the higher layer parameter CSI-AperiodicTriggerStateList. For aperiodic CSI report triggering, a single set of CSI triggering states are higher layer configured, wherein the CSI triggering states can be associated with any candidate DL BWP. A UE is not expected to receive more than one DCI with non-zero CSI request per slot. A UE is not expected to be configured with different TCI-StateId's for the same aperiodic CSI-RS resource ID configured in multiple aperiodic CSI-RS resource sets with the same triggering offset in the same aperiodic trigger state. A UE is not expected to receive more than one aperiodic CSI report request for transmission in a given slot. A UE is not expected to be triggered with a CSI report for a non-active DL BWP. A trigger state is initiated using the CSI request field in DCI.

(60) When all the bits of CSI request field in DCI are set to zero, no CSI is requested.

(61) When the number of configured CSI triggering states in CSI-AperiodicTriggerStateList is greater than 2.sup.N.sup.TS−1, where N.sub.TS is the number of bits in the DCI CSI request field, the UE receives a selection command [10, TS 38.321] used to map up to 2.sup.N.sup.TS−1 trigger states to the codepoints of the CSI request field in DCI. N.sub.TS is configured by the higher layer parameter reportTriggerSize where N.sub.TS∈{0.1.2.3.4.5.6}. When the HARQ/ACK corresponding to the PDSCH carrying the selection command is transmitted in the slot n, the corresponding action in [10, TS 38.321] and UE assumption on the mapping of the selected CSI trigger state(s) to the codepoint(s) of DCI CSI request field shall be applied starting from slot n+3N.sub.slot.sup.subframe,μ+1.

(62) When the number of CSI triggering states in CSI-AperiodicTriggerStateList is less than or equal to 2.sup.N.sup.TS−1, the CSI request field in DCI directly indicates the triggering state

(63) For each aperiodic CSI-RS resource in a CSI-RS resource set associated with each CSI triggering state, the UE is indicated the quasi co-location configuration of quasi co-location RS source(s) and quasi co-location type(s), as described in Subclause 5.1.5, through higher layer signaling of qcl-info which contains a list of references to TCI-State's for the aperiodic CSI-RS resources associated with the CSI triggering state. If a State referred to in the list is configured with

a reference to an RS associated with ‘QCL-TypeD’, that RS may be an SS/PBCH block located in the same or different CC/DL BWP or a CSI-RS resource configured as periodic or semi-persistent located in the same or different CC/DL BWP.

(64) If the scheduling offset, in the numerology of the aperiodic CSI-RS, between the last symbol of the PDCCH carrying the triggering DCI and the first symbol of the aperiodic CSI-RS resources in a NZP-CSI-RS-ResourceSet configured without higher layer parameter trs-Info and without the higher layer parameter repetition is smaller than the UE reported threshold beamSwitchTiming, as defined in [13, TS 38.306], when the reported value is one of the values of {14, 28, 48}, if there is any other DL signal with an indicated TCI state in the same symbols as the CSI-RS, the UE applies the QCL assumption of the other DL signal also when receiving the aperiodic CSI-RS. The other DL signal refers to PDSCH scheduled with offset larger than or equal to the threshold timeDurationForQCL, as defined in [13, TS 38.306], aperiodic CSI-RS scheduled with offset larger than or equal to the UE reported threshold beamSwitchTiming when the reported values is one of the values {14,28,48}, periodic CSI-RS, semi-persistent CSI-RS.

(65) If the scheduling offset, in the numerology of the aperiodic CSI-RS, between the last symbol of the PDCCH carrying the triggering DCI and the first symbol of the aperiodic CSI-RS resources is equal to or greater than the UE reported threshold beamSwitchTiming when the reported value is one of the values of {14,28,48}, the UE is expected to apply the QCL assumptions in the indicated TCI states for the aperiodic CSI-RS resources in the CSI triggering state indicated by the CSI trigger field in DCI.

(66) A non-zero codepoint of the CSI request field in the DCI is mapped to a CSI triggering state according to the order of the associated positions of the up to 2.sup.N.sup.TS−1 trigger states in CSI-AperiodicTriggerStateList with codepoint ‘1’ mapped to the triggering state in the first position.

(67) For a UE configured with the higher layer parameter CSI-AperiodicTriggerStateList, if a Resource Setting linked to a CSI-ReportConfig has multiple aperiodic resource sets, only one of the aperiodic CSI-RS resource sets from the Resource Setting is associated with the trigger state, and the UE is higher layer configured per trigger state per Resource Setting to select the one CSI-IM/NZP CSI-RS resource set from the Resource Setting.

(68) When aperiodic CSI-RS is used with aperiodic reporting, the CSI-RS offset X is configured per resource set by the higher layer parameter aperiodicTriggeringOffset. The CSI-RS triggering offset has the range of 0 to 4 slots. The UE shall transmit the CSI-RS in slot

(69) .Math. $(n+1)\frac{2^{\mu_{\mathrm{CSIRS}}}}{2^{\mu_{\mathrm{PDCCH}}}}$ - 1 .Math. $+X$,

where n is the slot with the triggering DCI in the numerology of the PDCCH, X is the CSI-RS triggering offset in the numerology of CSI-RS according to the higher layer parameter aperiodicTriggeringOffset, and μ.sub.CSIRS and μ.sub.PDCCH are the subcarrier spacing configurations for CSI-RS and PDCCH, respectively. If all the associated trigger states do not have the higher layer parameter qcl-Type set to ‘QCL-TypeD’ in the corresponding TCI states, the CSI-RS triggering offset is fixed to zero. If the PDCCH SCS is smaller than the CSI-RS SCS, the CSI-RS triggering offset is larger than zero. The aperiodic triggering offset of the CSI-IM follows offset of the associated NZP CSI-RS for channel measurement.

(70) The UE does not expect that aperiodic CSI-RS is transmitted before the OFDM symbol(s) carrying its triggering DCI. If interference measurement is performed on aperiodic NZP CSI-RS, a UE is not expected to be configured with a different aperiodic triggering offset of the NZP CSI-RS for interference measurement from the associated NZP CSI-RS for channel measurement. If the UE is configured with a single carrier for uplink, the UE is not expected to transmit more than one aperiodic CSI report triggered by different DCIs on overlapping OFDM symbols.

(71) Although the subject matter described herein may be implemented in any appropriate type of system using any suitable components, the embodiments disclosed herein are described in relation to a wireless network, such as the example wireless network illustrated in FIG. **6**. For simplicity,

the wireless network of FIG. **6** only depicts network **606**, network nodes **660** and **660***b*, and WDs **610**, **610***b*, and **610***c*. In practice, a wireless network may further include any additional elements suitable to support communication between wireless devices or between a wireless device and another communication device, such as a landline telephone, a service provider, or any other network node or end device. Of the illustrated components, network node **660** and wireless device (WD) **610** are depicted with additional detail. The wireless network may provide communication and other types of services to one or more wireless devices to facilitate the wireless devices' access to and/or use of the services provided by, or via, the wireless network.

(72) The wireless network may comprise and/or interface with any type of communication, telecommunication, data, cellular, and/or radio network or other similar type of system. In some embodiments, the wireless network may be configured to operate according to specific standards or other types of predefined rules or procedures. Thus, particular embodiments of the wireless network may implement communication standards, such as Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), Long Term Evolution (LTE), and/or other suitable 2G, 3G, 4G, or 5G standards; wireless local area network (WLAN) standards, such as the IEEE 802.11 standards; and/or any other appropriate wireless communication standard, such as the Worldwide Interoperability for Microwave Access (WiMax), Bluetooth, Z-Wave and/or ZigBee standards.

(73) Network **606** may comprise one or more backhaul networks, core networks, IP networks, public switched telephone networks (PSTNs), packet data networks, optical networks, wide-area networks (WANs), local area networks (LANs), wireless local area networks (WLANs), wired networks, wireless networks, metropolitan area networks, and other networks to enable communication between devices.

(74) Network node **660** and WD **610** comprise various components described in more detail below. These components work together in order to provide network node and/or wireless device functionality, such as providing wireless connections in a wireless network. In different embodiments, the wireless network may comprise any number of wired or wireless networks, network nodes, base stations, controllers, wireless devices, relay stations, and/or any other components or systems that may facilitate or participate in the communication of data and/or signals whether via wired or wireless connections.

(75) As used herein, network node refers to equipment capable, configured, arranged and/or operable to communicate directly or indirectly with a wireless device and/or with other network nodes or equipment in the wireless network to enable and/or provide wireless access to the wireless device and/or to perform other functions (e.g., administration) in the wireless network. Examples of network nodes include, but are not limited to, access points (APs) (e.g., radio access points), base stations (BSs) (e.g., radio base stations, Node Bs, evolved Node Bs (eNBs) and NR NodeBs (gNBs)). Base stations may be categorized based on the amount of coverage they provide (or, stated differently, their transmit power level) and may then also be referred to as femto base stations, pico base stations, micro base stations, or macro base stations. A base station may be a relay node or a relay donor node controlling a relay. A network node may also include one or more (or all) parts of a distributed radio base station such as centralized digital units and/or remote radio units (RRUs), sometimes referred to as Remote Radio Heads (RRHs). Such remote radio units may or may not be integrated with an antenna as an antenna integrated radio. Parts of a distributed radio base station may also be referred to as nodes in a distributed antenna system (DAS). Yet further examples of network nodes include multi-standard radio (MSR) equipment such as MSR BSs, network controllers such as radio network controllers (RNCs) or base station controllers (BSCs), base transceiver stations (BTSs), transmission points, transmission nodes, multi-cell/multicast coordination entities (MCEs), core network nodes (e.g., MSCs, MMEs), O&M nodes, OSS nodes, SON nodes, positioning nodes (e.g., E-SMLCs), and/or MDTs. As another example, a network node may be a virtual network node as described in more detail below. More generally, however,

network nodes may represent any suitable device (or group of devices) capable, configured, arranged, and/or operable to enable and/or provide a wireless device with access to the wireless network or to provide some service to a wireless device that has accessed the wireless network.

(76) In FIG. **6**, network node **660** includes processing circuitry **670**, device readable medium **680**, interface **690**, auxiliary equipment **684**, power source **686**, power circuitry **687**, and antenna **662**. Although network node **660** illustrated in the example wireless network of FIG. **6** may represent a device that includes the illustrated combination of hardware components, other embodiments may comprise network nodes with different combinations of components. It is to be understood that a network node comprises any suitable combination of hardware and/or software needed to perform the tasks, features, functions and methods disclosed herein. Moreover, while the components of network node **660** are depicted as single boxes located within a larger box, or nested within multiple boxes, in practice, a network node may comprise multiple different physical components that make up a single illustrated component (e.g., device readable medium **680** may comprise multiple separate hard drives as well as multiple RAM modules).

(77) Similarly, network node **660** may be composed of multiple physically separate components (e.g., a NodeB component and a RNC component, or a BTS component and a BSC component, etc.), which may each have their own respective components. In certain scenarios in which network node **660** comprises multiple separate components (e.g., BTS and BSC components), one or more of the separate components may be shared among several network nodes. For example, a single RNC may control multiple NodeB's. In such a scenario, each unique NodeB and RNC pair, may in some instances be considered a single separate network node. In some embodiments, network node **660** may be configured to support multiple radio access technologies (RATs). In such embodiments, some components may be duplicated (e.g., separate device readable medium **680** for the different RATs) and some components may be reused (e.g., the same antenna **662** may be shared by the RATs). Network node **660** may also include multiple sets of the various illustrated components for different wireless technologies integrated into network node **660**, such as, for example, GSM, WCDMA, LTE, NR, WiFi, or Bluetooth wireless technologies. These wireless technologies may be integrated into the same or different chip or set of chips and other components within network node **660**.

(78) Processing circuitry **670** is configured to perform any determining, calculating, or similar operations (e.g., certain obtaining operations) described herein as being provided by a network node. These operations performed by processing circuitry **670** may include processing information obtained by processing circuitry **670** by, for example, converting the obtained information into other information, comparing the obtained information or converted information to information stored in the network node, and/or performing one or more operations based on the obtained information or converted information, and as a result of said processing making a determination.

(79) Processing circuitry **670** may comprise a combination of one or more of a microprocessor, controller, microcontroller, central processing unit, digital signal processor, application-specific integrated circuit, field programmable gate array, or any other suitable computing device, resource, or combination of hardware, software and/or encoded logic operable to provide, either alone or in conjunction with other network node **660** components, such as device readable medium **680**, network node **660** functionality. For example, processing circuitry **670** may execute instructions stored in device readable medium **680** or in memory within processing circuitry **670**. Such functionality may include providing any of the various wireless features, functions, or benefits discussed herein. In some embodiments, processing circuitry **670** may include a system on a chip (SOC).

(80) In some embodiments, processing circuitry **670** may include one or more of radio frequency (RF) transceiver circuitry **672** and baseband processing circuitry **674**. In some embodiments, radio frequency (RF) transceiver circuitry **672** and baseband processing circuitry **674** may be on separate chips (or sets of chips), boards, or units, such as radio units and digital units. In alternative

embodiments, part or all of RF transceiver circuitry **672** and baseband processing circuitry **674** may be on the same chip or set of chips, boards, or units

(81) In certain embodiments, some or all of the functionality described herein as being provided by a network node, base station, eNB or other such network device may be performed by processing circuitry **670** executing instructions stored on device readable medium **680** or memory within processing circuitry **670**. In alternative embodiments, some or all of the functionality may be provided by processing circuitry **670** without executing instructions stored on a separate or discrete device readable medium, such as in a hard-wired manner. In any of those embodiments, whether executing instructions stored on a device readable storage medium or not, processing circuitry **670** can be configured to perform the described functionality. The benefits provided by such functionality are not limited to processing circuitry **670** alone or to other components of network node **660**, but are enjoyed by network node **660** as a whole, and/or by end users and the wireless network generally.

(82) Device readable medium **680** may comprise any form of volatile or non-volatile computer readable memory including, without limitation, persistent storage, solid-state memory, remotely mounted memory, magnetic media, optical media, random access memory (RAM), read-only memory (ROM), mass storage media (for example, a hard disk), removable storage media (for example, a flash drive, a Compact Disk (CD) or a Digital Video Disk (DVD)), and/or any other volatile or non-volatile, non-transitory device readable and/or computer-executable memory devices that store information, data, and/or instructions that may be used by processing circuitry **670**. Device readable medium **680** may store any suitable instructions, data or information, including a computer program, software, an application including one or more of logic, rules, code, tables, etc. and/or other instructions capable of being executed by processing circuitry **670** and, utilized by network node **660**. Device readable medium **680** may be used to store any calculations made by processing circuitry **670** and/or any data received via interface **690**. In some embodiments, processing circuitry **670** and device readable medium **680** may be considered to be integrated.

(83) Interface **690** is used in the wired or wireless communication of signalling and/or data between network node **660**, network **606**, and/or WDs **610**. As illustrated, interface **690** comprises port(s)/terminal(s) **694** to send and receive data, for example to and from network **606** over a wired connection. Interface **690** also includes radio front end circuitry **692** that may be coupled to, or in certain embodiments a part of, antenna **662**. Radio front end circuitry **692** comprises filters **698** and amplifiers **696**. Radio front end circuitry **692** may be connected to antenna **662** and processing circuitry **670**. Radio front end circuitry may be configured to condition signals communicated between antenna **662** and processing circuitry **670**. Radio front end circuitry **692** may receive digital data that is to be sent out to other network nodes or WDs via a wireless connection. Radio front end circuitry **692** may convert the digital data into a radio signal having the appropriate channel and bandwidth parameters using a combination of filters **698** and/or amplifiers **696**. The radio signal may then be transmitted via antenna **662**. Similarly, when receiving data, antenna **662** may collect radio signals which are then converted into digital data by radio front end circuitry **692**. The digital data may be passed to processing circuitry **670**. In other embodiments, the interface may comprise different components and/or different combinations of components.

(84) In certain alternative embodiments, network node **660** may not include separate radio front end circuitry **692**, instead, processing circuitry **670** may comprise radio front end circuitry and may be connected to antenna **662** without separate radio front end circuitry **692**. Similarly, in some embodiments, all or some of RF transceiver circuitry **672** may be considered a part of interface **690**. In still other embodiments, interface **690** may include one or more ports or terminals **694**, radio front end circuitry **692**, and RF transceiver circuitry **672**, as part of a radio unit (not shown), and interface **690** may communicate with baseband processing circuitry **674**, which is part of a digital unit (not shown).

(85) Antenna **662** may include one or more antennas, or antenna arrays, configured to send and/or

receive wireless signals. Antenna **662** may be coupled to radio front end circuitry **690** and may be any type of antenna capable of transmitting and receiving data and/or signals wirelessly. In some embodiments, antenna **662** may comprise one or more omni-directional, sector or panel antennas operable to transmit/receive radio signals between, for example, 2 GHz and 66 GHz. An omni-directional antenna may be used to transmit/receive radio signals in any direction, a sector antenna may be used to transmit/receive radio signals from devices within a particular area, and a panel antenna may be a line of sight antenna used to transmit/receive radio signals in a relatively straight line. In some instances, the use of more than one antenna may be referred to as MIMO. In certain embodiments, antenna **662** may be separate from network node **660** and may be connectable to network node **660** through an interface or port.

(86) Antenna **662**, interface **690**, and/or processing circuitry **670** may be configured to perform any receiving operations and/or certain obtaining operations described herein as being performed by a network node. Any information, data and/or signals may be received from a wireless device, another network node and/or any other network equipment. Similarly, antenna **662**, interface **690**, and/or processing circuitry **670** may be configured to perform any transmitting operations described herein as being performed by a network node. Any information, data and/or signals may be transmitted to a wireless device, another network node and/or any other network equipment.

(87) Power circuitry **687** may comprise, or be coupled to, power management circuitry and is configured to supply the components of network node **660** with power for performing the functionality described herein. Power circuitry **687** may receive power from power source **686**. Power source **686** and/or power circuitry **687** may be configured to provide power to the various components of network node **660** in a form suitable for the respective components (e.g., at a voltage and current level needed for each respective component). Power source **686** may either be included in, or external to, power circuitry **687** and/or network node **660**. For example, network node **660** may be connectable to an external power source (e.g., an electricity outlet) via an input circuitry or interface such as an electrical cable, whereby the external power source supplies power to power circuitry **687**. As a further example, power source **686** may comprise a source of power in the form of a battery or battery pack which is connected to, or integrated in, power circuitry **687**. The battery may provide backup power should the external power source fail. Other types of power sources, such as photovoltaic devices, may also be used.

(88) Alternative embodiments of network node **660** may include additional components beyond those shown in FIG. **6** that may be responsible for providing certain aspects of the network node's functionality, including any of the functionality described herein and/or any functionality necessary to support the subject matter described herein. For example, network node **660** may include user interface equipment to allow input of information into network node **660** and to allow output of information from network node **660**. This may allow a user to perform diagnostic, maintenance, repair, and other administrative functions for network node **660**.

(89) As used herein, wireless device (WD) refers to a device capable, configured, arranged and/or operable to communicate wirelessly with network nodes and/or other wireless devices. Unless otherwise noted, the term WD may be used interchangeably herein with user equipment (UE). Communicating wirelessly may involve transmitting and/or receiving wireless signals using electromagnetic waves, radio waves, infrared waves, and/or other types of signals suitable for conveying information through air. In some embodiments, a WD may be configured to transmit and/or receive information without direct human interaction. For instance, a WD may be designed to transmit information to a network on a predetermined schedule, when triggered by an internal or external event, or in response to requests from the network. Examples of a WD include, but are not limited to, a smart phone, a mobile phone, a cell phone, a voice over IP (VoIP) phone, a wireless local loop phone, a desktop computer, a personal digital assistant (PDA), a wireless cameras, a gaming console or device, a music storage device, a playback appliance, a wearable terminal device, a wireless endpoint, a mobile station, a tablet, a laptop, a laptop-embedded equipment

(LEE), a laptop-mounted equipment (LME), a smart device, a wireless customer-premise equipment (CPE). a vehicle-mounted wireless terminal device, etc., A WD may support device-to-device (D2D) communication, for example by implementing a 3GPP standard for sidelink communication, vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-everything (V2X) and may in this case be referred to as a D2D communication device. As yet another specific example, in an Internet of Things (IoT) scenario, a WD may represent a machine or other device that performs monitoring and/or measurements, and transmits the results of such monitoring and/or measurements to another WD and/or a network node. The WD may in this case be a machine-to-machine (M2M) device, which may in a 3GPP context be referred to as an MTC device. As one particular example, the WD may be a UE implementing the 3GPP narrow band internet of things (NB-IoT) standard. Particular examples of such machines or devices are sensors, metering devices such as power meters, industrial machinery, or home or personal appliances (e.g. refrigerators, televisions, etc.) personal wearables (e.g., watches, fitness trackers, etc.). In other scenarios, a WD may represent a vehicle or other equipment that is capable of monitoring and/or reporting on its operational status or other functions associated with its operation. A WD as described above may represent the endpoint of a wireless connection, in which case the device may be referred to as a wireless terminal. Furthermore, a WD as described above may be mobile, in which case it may also be referred to as a mobile device or a mobile terminal.

(90) As illustrated, wireless device **610** includes antenna **611**, interface **614**, processing circuitry **620**, device readable medium **630**, user interface equipment **632**, auxiliary equipment **634**, power source **636** and power circuitry **637**. WD **610** may include multiple sets of one or more of the illustrated components for different wireless technologies supported by WD **610**, such as, for example, GSM, WCDMA, LTE, NR, WiFi, WiMAX, or Bluetooth wireless technologies, just to mention a few. These wireless technologies may be integrated into the same or different chips or set of chips as other components within WD **610**.

(91) Antenna **611** may include one or more antennas or antenna arrays, configured to send and/or receive wireless signals, and is connected to interface **614**. In certain alternative embodiments, antenna **611** may be separate from WD **610** and be connectable to WD **610** through an interface or port. Antenna **611**, interface **614**, and/or processing circuitry **620** may be configured to perform any receiving or transmitting operations described herein as being performed by a WD. Any information, data and/or signals may be received from a network node and/or another WD. In some embodiments, radio front end circuitry and/or antenna **611** may be considered an interface.

(92) As illustrated, interface **614** comprises radio front end circuitry **612** and antenna **611**. Radio front end circuitry **612** comprise one or more filters **618** and amplifiers **616**. Radio front end circuitry **614** is connected to antenna **611** and processing circuitry **620**, and is configured to condition signals communicated between antenna **611** and processing circuitry **620**. Radio front end circuitry **612** may be coupled to or a part of antenna **611**. In some embodiments, WD **610** may not include separate radio front end circuitry **612**; rather, processing circuitry **620** may comprise radio front end circuitry and may be connected to antenna **611**. Similarly, in some embodiments, some or all of RF transceiver circuitry **622** may be considered a part of interface **614**. Radio front end circuitry **612** may receive digital data that is to be sent out to other network nodes or WDs via a wireless connection. Radio front end circuitry **612** may convert the digital data into a radio signal having the appropriate channel and bandwidth parameters using a combination of filters **618** and/or amplifiers **616**. The radio signal may then be transmitted via antenna **611**. Similarly, when receiving data, antenna **611** may collect radio signals which are then converted into digital data by radio front end circuitry **612**. The digital data may be passed to processing circuitry **620**. In other embodiments, the interface may comprise different components and/or different combinations of components.

(93) Processing circuitry **620** may comprise a combination of one or more of a microprocessor, controller, microcontroller, central processing unit, digital signal processor, application-specific

integrated circuit, field programmable gate array, or any other suitable computing device, resource, or combination of hardware, software, and/or encoded logic operable to provide, either alone or in conjunction with other WD **610** components, such as device readable medium **630**, WD **610** functionality. Such functionality may include providing any of the various wireless features or benefits discussed herein. For example, processing circuitry **620** may execute instructions stored in device readable medium **630** or in memory within processing circuitry **620** to provide the functionality disclosed herein.

(94) As illustrated, processing circuitry **620** includes one or more of RF transceiver circuitry **622**, baseband processing circuitry **624**, and application processing circuitry **626**. In other embodiments, the processing circuitry may comprise different components and/or different combinations of components. In certain embodiments processing circuitry **620** of WD **610** may comprise a SOC. In some embodiments, RF transceiver circuitry **622**, baseband processing circuitry **624**, and application processing circuitry **626** may be on separate chips or sets of chips. In alternative embodiments, part or all of baseband processing circuitry **624** and application processing circuitry **626** may be combined into one chip or set of chips, and RF transceiver circuitry **622** may be on a separate chip or set of chips. In still alternative embodiments, part or all of RF transceiver circuitry **622** and baseband processing circuitry **624** may be on the same chip or set of chips, and application processing circuitry **626** may be on a separate chip or set of chips. In yet other alternative embodiments, part or all of RF transceiver circuitry **622**, baseband processing circuitry **624**, and application processing circuitry **626** may be combined in the same chip or set of chips. In some embodiments, RF transceiver circuitry **622** may be a part of interface **614**. RF transceiver circuitry **622** may condition RF signals for processing circuitry **620**.

(95) In certain embodiments, some or all of the functionality described herein as being performed by a WD may be provided by processing circuitry **620** executing instructions stored on device readable medium **630**, which in certain embodiments may be a computer-readable storage medium. In alternative embodiments, some or all of the functionality may be provided by processing circuitry **620** without executing instructions stored on a separate or discrete device readable storage medium, such as in a hard-wired manner. In any of those particular embodiments, whether executing instructions stored on a device readable storage medium or not, processing circuitry **620** can be configured to perform the described functionality. The benefits provided by such functionality are not limited to processing circuitry **620** alone or to other components of WD **610**, but are enjoyed by WD **610** as a whole, and/or by end users and the wireless network generally.

(96) Processing circuitry **620** may be configured to perform any determining, calculating, or similar operations (e.g., certain obtaining operations) described herein as being performed by a WD. These operations, as performed by processing circuitry **620**, may include processing information obtained by processing circuitry **620** by, for example, converting the obtained information into other information, comparing the obtained information or converted information to information stored by WD **610**, and/or performing one or more operations based on the obtained information or converted information, and as a result of said processing making a determination.

(97) Device readable medium **630** may be operable to store a computer program, software, an application including one or more of logic, rules, code, tables, etc. and/or other instructions capable of being executed by processing circuitry **620**. Device readable medium **630** may include computer memory (e.g., Random Access Memory (RAM) or Read Only Memory (ROM)), mass storage media (e.g., a hard disk), removable storage media (e.g., a Compact Disk (CD) or a Digital Video Disk (DVD)), and/or any other volatile or non-volatile, non-transitory device readable and/or computer executable memory devices that store information, data, and/or instructions that may be used by processing circuitry **620**. In some embodiments, processing circuitry **620** and device readable medium **630** may be considered to be integrated.

(98) User interface equipment **632** may provide components that allow for a human user to interact with WD **610**. Such interaction may be of many forms, such as visual, audial, tactile, etc. User

interface equipment **632** may be operable to produce output to the user and to allow the user to provide input to WD **610**. The type of interaction may vary depending on the type of user interface equipment **632** installed in WD **610**. For example, if WD **610** is a smart phone, the interaction may be via a touch screen; if WD **610** is a smart meter, the interaction may be through a screen that provides usage (e.g., the number of gallons used) or a speaker that provides an audible alert (e.g., if smoke is detected). User interface equipment **632** may include input interfaces, devices and circuits, and output interfaces, devices and circuits. User interface equipment **632** is configured to allow input of information into WD **610**, and is connected to processing circuitry **620** to allow processing circuitry **620** to process the input information. User interface equipment **632** may include, for example, a microphone, a proximity or other sensor, keys/buttons, a touch display, one or more cameras, a USB port, or other input circuitry. User interface equipment **632** is also configured to allow output of information from WD **610**, and to allow processing circuitry **620** to output information from WD **610**. User interface equipment **632** may include, for example, a speaker, a display, vibrating circuitry, a USB port, a headphone interface, or other output circuitry. Using one or more input and output interfaces, devices, and circuits, of user interface equipment **632**, WD **610** may communicate with end users and/or the wireless network, and allow them to benefit from the functionality described herein.
(99) Auxiliary equipment **634** is operable to provide more specific functionality which may not be generally performed by WDs. This may comprise specialized sensors for doing measurements for various purposes, interfaces for additional types of communication such as wired communications etc. The inclusion and type of components of auxiliary equipment **634** may vary depending on the embodiment and/or scenario.
(100) Power source **636** may, in some embodiments, be in the form of a battery or battery pack. Other types of power sources, such as an external power source (e.g., an electricity outlet), photovoltaic devices or power cells, may also be used. WD **610** may further comprise power circuitry **637** for delivering power from power source **636** to the various parts of WD **610** which need power from power source **636** to carry out any functionality described or indicated herein. Power circuitry **637** may in certain embodiments comprise power management circuitry. Power circuitry **637** may additionally or alternatively be operable to receive power from an external power source; in which case WD **610** may be connectable to the external power source (such as an electricity outlet) via input circuitry or an interface such as an electrical power cable. Power circuitry **637** may also in certain embodiments be operable to deliver power from an external power source to power source **636**. This may be, for example, for the charging of power source **636**. Power circuitry **637** may perform any formatting, converting, or other modification to the power from power source **636** to make the power suitable for the respective components of WD **610** to which power is supplied.
(101) FIG. **7** illustrates one embodiment of a UE **700** in accordance with various aspects described herein. For example, the UE **700** may perform embodiments of the method **500** and provide other features as described herein. As used herein, a user equipment or UE may not necessarily have a user in the sense of a human user who owns and/or operates the relevant device. Instead, a UE may represent a device that is intended for sale to, or operation by, a human user but which may not, or which may not initially, be associated with a specific human user (e.g., a smart sprinkler controller). Alternatively, a UE may represent a device that is not intended for sale to, or operation by, an end user but which may be associated with or operated for the benefit of a user (e.g., a smart power meter). UE **700** may be any UE identified by the 3.sup.rd Generation Partnership Project (3GPP), including a NB-IoT UE, a machine type communication (MTC) UE, and/or an enhanced MTC (eMTC) UE. UE **700**, as illustrated in FIG. **7**, is one example of a WD configured for communication in accordance with one or more communication standards promulgated by the 3.sup.rd Generation Partnership Project (3GPP), such as 3GPP's GSM, UMTS, LTE, and/or 5G standards. As mentioned previously, the term WD and UE may be used interchangeable.

Accordingly, although FIG. **7** is a UE, the components discussed herein are equally applicable to a WD, and vice-versa.

(102) In FIG. **7**, UE **700** includes processing circuitry **701** that is operatively coupled to input/output interface **705**, radio frequency (RF) interface **709**, network connection interface **711**, memory **715** including random access memory (RAM) **717**, read-only memory (ROM) **719**, and storage medium **721** or the like, communication subsystem **731**, power source **733**, and/or any other component, or any combination thereof. Storage medium **721** includes operating system **723**, application program **725**, and data **727**. In other embodiments, storage medium **721** may include other similar types of information. Certain UEs may utilize all of the components shown in FIG. **7**, or only a subset of the components. The level of integration between the components may vary from one UE to another UE. Further, certain UEs may contain multiple instances of a component, such as multiple processors, memories, transceivers, transmitters, receivers, etc.

(103) In FIG. **7**, processing circuitry **701** may be configured to process computer instructions and data. Processing circuitry **701** may be configured to implement any sequential state machine operative to execute machine instructions stored as machine-readable computer programs in the memory, such as one or more hardware-implemented state machines (e.g., in discrete logic, FPGA, ASIC, etc.); programmable logic together with appropriate firmware; one or more stored program, general-purpose processors, such as a microprocessor or Digital Signal Processor (DSP), together with appropriate software; or any combination of the above. For example, the processing circuitry **701** may include two central processing units (CPUs). Data may be information in a form suitable for use by a computer.

(104) In the depicted embodiment, input/output interface **705** may be configured to provide a communication interface to an input device, output device, or input and output device. UE **700** may be configured to use an output device via input/output interface **705**. An output device may use the same type of interface port as an input device. For example, a USB port may be used to provide input to and output from UE **700**. The output device may be a speaker, a sound card, a video card, a display, a monitor, a printer, an actuator, an emitter, a smartcard, another output device, or any combination thereof. UE **700** may be configured to use an input device via input/output interface **705** to allow a user to capture information into UE **700**. The input device may include a touch-sensitive or presence-sensitive display, a camera (e.g., a digital camera, a digital video camera, a web camera, etc.), a microphone, a sensor, a mouse, a trackball, a directional pad, a trackpad, a scroll wheel, a smartcard, and the like. The presence-sensitive display may include a capacitive or resistive touch sensor to sense input from a user. A sensor may be, for instance, an accelerometer, a gyroscope, a tilt sensor, a force sensor, a magnetometer, an optical sensor, a proximity sensor, another like sensor, or any combination thereof. For example, the input device may be an accelerometer, a magnetometer, a digital camera, a microphone, and an optical sensor.

(105) In FIG. **7**, RF interface **709** may be configured to provide a communication interface to RF components such as a transmitter, a receiver, and an antenna. Network connection interface **711** may be configured to provide a communication interface to network **743*a***. Network **743*a*** may encompass wired and/or wireless networks such as a local-area network (LAN), a wide-area network (WAN), a computer network, a wireless network, a telecommunications network, another like network or any combination thereof. For example, network **743*a*** may comprise a Wi-Fi network. Network connection interface **711** may be configured to include a receiver and a transmitter interface used to communicate with one or more other devices over a communication network according to one or more communication protocols, such as Ethernet, TCP/IP, SONET, ATM, or the like. Network connection interface **711** may implement receiver and transmitter functionality appropriate to the communication network links (e.g., optical, electrical, and the like). The transmitter and receiver functions may share circuit components, software or firmware, or alternatively may be implemented separately.

(106) RAM **717** may be configured to interface via bus **702** to processing circuitry **701** to provide

storage or caching of data or computer instructions during the execution of software programs such as the operating system, application programs, and device drivers. ROM **719** may be configured to provide computer instructions or data to processing circuitry **701**. For example, ROM **719** may be configured to store invariant low-level system code or data for basic system functions such as basic input and output (I/O), startup, or reception of keystrokes from a keyboard that are stored in a non-volatile memory. Storage medium **721** may be configured to include memory such as RAM, ROM, programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), magnetic disks, optical disks, floppy disks, hard disks, removable cartridges, or flash drives. In one example, storage medium **721** may be configured to include operating system **723**, application program **725** such as a web browser application, a widget or gadget engine or another application, and data file **727**. Storage medium **721** may store, for use by UE **700**, any of a variety of various operating systems or combinations of operating systems.

(107) Storage medium **721** may be configured to include a number of physical drive units, such as redundant array of independent disks (RAID), floppy disk drive, flash memory, USB flash drive, external hard disk drive, thumb drive, pen drive, key drive, high-density digital versatile disc (HD-DVD) optical disc drive, internal hard disk drive, Blu-Ray optical disc drive, holographic digital data storage (HDDS) optical disc drive, external mini-dual in-line memory module (DIMM), synchronous dynamic random access memory (SDRAM), external micro-DIMM SDRAM, smartcard memory such as a subscriber identity module or a removable user identity (SIM/RUIM) module, other memory, or any combination thereof. Storage medium **721** may allow UE **700** to access computer-executable instructions, application programs or the like, stored on transitory or non-transitory memory media, to off-load data, or to upload data. An article of manufacture, such as one utilizing a communication system may be tangibly embodied in storage medium **721**, which may comprise a device readable medium.

(108) In FIG. **7**, processing circuitry **701** may be configured to communicate with network **743***b* using communication subsystem **731**. Network **743***a* and network **743***b* may be the same network or networks or different network or networks. Communication subsystem **731** may be configured to include one or more transceivers used to communicate with network **743***b*. For example, communication subsystem **731** may be configured to include one or more transceivers used to communicate with one or more remote transceivers of another device capable of wireless communication such as another WD, UE, or base station of a radio access network (RAN) according to one or more communication protocols, such as IEEE 802.11, CDMA, WCDMA, GSM, LTE, UTRAN, WiMax, or the like. Each transceiver may include transmitter **733** and/or receiver **735** to implement transmitter or receiver functionality, respectively, appropriate to the RAN links (e.g., frequency allocations and the like). Further, transmitter **733** and receiver **735** of each transceiver may share circuit components, software or firmware, or alternatively may be implemented separately.

(109) In the illustrated embodiment, the communication functions of communication subsystem **731** may include data communication, voice communication, multimedia communication, short-range communications such as Bluetooth, near-field communication, location-based communication such as the use of the global positioning system (GPS) to determine a location, another like communication function, or any combination thereof. For example, communication subsystem **731** may include cellular communication, Wi-Fi communication, Bluetooth communication, and GPS communication. Network **743***b* may encompass wired and/or wireless networks such as a local-area network (LAN), a wide-area network (WAN), a computer network, a wireless network, a telecommunications network, another like network or any combination thereof. For example, network **743***b* may be a cellular network, a Wi-Fi network, and/or a near-field network. Power source **713** may be configured to provide alternating current (AC) or direct current (DC) power to components of UE **700**.

(110) The features, benefits and/or functions described herein may be implemented in one of the components of UE **700** or partitioned across multiple components of UE **700**. Further, the features, benefits, and/or functions described herein may be implemented in any combination of hardware, software or firmware. In one example, communication subsystem **731** may be configured to include any of the components described herein. Further, processing circuitry **701** may be configured to communicate with any of such components over bus **702**. In another example, any of such components may be represented by program instructions stored in memory that when executed by processing circuitry **701** perform the corresponding functions described herein. In another example, the functionality of any of such components may be partitioned between processing circuitry **701** and communication subsystem **731**. In another example, the non-computationally intensive functions of any of such components may be implemented in software or firmware and the computationally intensive functions may be implemented in hardware.
(111) FIG. **8** is a schematic block diagram illustrating a virtualization environment **800** in which functions implemented by some embodiments may be virtualized. In the present context, virtualizing means creating virtual versions of apparatuses or devices which may include virtualizing hardware platforms, storage devices and networking resources. As used herein, virtualization can be applied to a node (e.g., a virtualized base station or a virtualized radio access node) or to a device (e.g., a UE, a wireless device or any other type of communication device) or components thereof and relates to an implementation in which at least a portion of the functionality is implemented as one or more virtual components (e.g., via one or more applications, components, functions, virtual machines or containers executing on one or more physical processing nodes in one or more networks).
(112) In some embodiments, some or all of the functions described herein may be implemented as virtual components executed by one or more virtual machines implemented in one or more virtual environments **800** hosted by one or more of hardware nodes **830**. Further, in embodiments in which the virtual node is not a radio access node or does not require radio connectivity (e.g., a core network node), then the network node may be entirely virtualized.
(113) The functions may be implemented by one or more applications **820** (which may alternatively be called software instances, virtual appliances, network functions, virtual nodes, virtual network functions, etc.) operative to implement some of the features, functions, and/or benefits of some of the embodiments disclosed herein. Applications **820** are run in virtualization environment **800** which provides hardware **830** comprising processing circuitry **860** and memory **890**. Memory **890** contains instructions **895** executable by processing circuitry **860** whereby application **820** is operative to provide one or more of the features, benefits, and/or functions disclosed herein.
(114) Virtualization environment **800**, comprises general-purpose or special-purpose network hardware devices **830** comprising a set of one or more processors or processing circuitry **860**, which may be commercial off-the-shelf (COTS) processors, dedicated Application Specific Integrated Circuits (ASICs), or any other type of processing circuitry including digital or analog hardware components or special purpose processors. Each hardware device may comprise memory **890-1** which may be non-persistent memory for temporarily storing instructions **895** or software executed by processing circuitry **860**. Each hardware device may comprise one or more network interface controllers (NICs) **870**, also known as network interface cards, which include physical network interface **880**. Each hardware device may also include non-transitory, persistent, machine-readable storage media **890-2** having stored therein software **895** and/or instructions executable by processing circuitry **860**. Software **895** may include any type of software including software for instantiating one or more virtualization layers **850** (also referred to as hypervisors), software to execute virtual machines **840** as well as software allowing it to execute functions, features and/or benefits described in relation with some embodiments described herein.
(115) Virtual machines **840**, comprise virtual processing, virtual memory, virtual networking or interface and virtual storage, and may be run by a corresponding virtualization layer **850** or

hypervisor. Different embodiments of the instance of virtual appliance **820** may be implemented on one or more of virtual machines **840**, and the implementations may be made in different ways.

(116) During operation, processing circuitry **860** executes software **895** to instantiate the hypervisor or virtualization layer **850**, which may sometimes be referred to as a virtual machine monitor (VMM). Virtualization layer **850** may present a virtual operating platform that appears like networking hardware to virtual machine **840**.

(117) As shown in FIG. **8**, hardware **830** may be a standalone network node with generic or specific components. Hardware **830** may comprise antenna **8225** and may implement some functions via virtualization. Alternatively, hardware **830** may be part of a larger cluster of hardware (e.g. such as in a data center or customer premise equipment (CPE)) where many hardware nodes work together and are managed via management and orchestration (MANO) **8100**, which, among others, oversees lifecycle management of applications **820**.

(118) Virtualization of the hardware is in some contexts referred to as network function virtualization (NFV). NFV may be used to consolidate many network equipment types onto industry standard high volume server hardware, physical switches, and physical storage, which can be located in data centers, and customer premise equipment.

(119) In the context of NFV, virtual machine **840** may be a software implementation of a physical machine that runs programs as if they were executing on a physical, non-virtualized machine. Each of virtual machines **840**, and that part of hardware **830** that executes that virtual machine, be it hardware dedicated to that virtual machine and/or hardware shared by that virtual machine with others of the virtual machines **840**, forms a separate virtual network elements (VNE).

(120) Still in the context of NFV, Virtual Network Function (VNF) is responsible for handling specific network functions that run in one or more virtual machines **840** on top of hardware networking infrastructure **830** and corresponds to application **820** in FIG. **8**.

(121) In some embodiments, one or more radio units **8200** that each include one or more transmitters **8220** and one or more receivers **8210** may be coupled to one or more antennas **8225**. Radio units **8200** may communicate directly with hardware nodes **830** via one or more appropriate network interfaces and may be used in combination with the virtual components to provide a virtual node with radio capabilities, such as a radio access node or a base station.

(122) In some embodiments, some signalling can be effected with the use of control system **8230** which may alternatively be used for communication between the hardware nodes **830** and radio units **8200**.

(123) With reference to FIG. **9**, in accordance with an embodiment, a communication system includes telecommunication network **910**, such as a 3GPP-type cellular network, which comprises access network **911**, such as a radio access network, and core network **914**. Access network **911** comprises a plurality of base stations **912***a*, **912***b*, **912***c*, such as NBs, eNBs, gNBs or other types of wireless access points, each defining a corresponding coverage area **913***a*, **913***b*, **913***c*. Each base station **912***a*, **912***b*, **912***c* is connectable to core network **914** over a wired or wireless connection **915**. A first UE **991** located in coverage area **913***c* is configured to wirelessly connect to, or be paged by, the corresponding base station **912***c*. A second UE **992** in coverage area **913***a* is wirelessly connectable to the corresponding base station **912***a*. While a plurality of UEs **991**, **992** are illustrated in this example, the disclosed embodiments are equally applicable to a situation where a sole UE is in the coverage area or where a sole UE is connecting to the corresponding base station **912**.

(124) Telecommunication network **910** is itself connected to host computer **930**, which may be embodied in the hardware and/or software of a standalone server, a cloud-implemented server, a distributed server or as processing resources in a server farm. Host computer **930** may be under the ownership or control of a service provider, or may be operated by the service provider or on behalf of the service provider. Connections **921** and **922** between telecommunication network **910** and host computer **930** may extend directly from core network **914** to host computer **930** or may go via

an optional intermediate network **920**. Intermediate network **920** may be one of, or a combination of more than one of, a public, private or hosted network; intermediate network **920**, if any, may be a backbone network or the Internet; in particular, intermediate network **920** may comprise two or more sub-networks (not shown).

(125) The communication system of FIG. **9** as a whole enables connectivity between the connected UEs **991**, **992** and host computer **930**. The connectivity may be described as an over-the-top (OTT) connection **950**. Host computer **930** and the connected UEs **991**, **992** are configured to communicate data and/or signaling via OTT connection **950**, using access network **911**, core network **914**, any intermediate network **920** and possible further infrastructure (not shown) as intermediaries. OTT connection **950** may be transparent in the sense that the participating communication devices through which OTT connection **950** passes are unaware of routing of uplink and downlink communications. For example, base station **912** may not or need not be informed about the past routing of an incoming downlink communication with data originating from host computer **930** to be forwarded (e.g., handed over) to a connected UE **991**. Similarly, base station **912** need not be aware of the future routing of an outgoing uplink communication originating from the UE **991** towards the host computer **930**.

(126) Example implementations, in accordance with an embodiment, of the UE, base station and host computer discussed in the preceding paragraphs will now be described with reference to FIG. **10**. In communication system **1000**, host computer **1010** comprises hardware **1015** including communication interface **1016** configured to set up and maintain a wired or wireless connection with an interface of a different communication device of communication system **1000**. Host computer **1010** further comprises processing circuitry **1018**, which may have storage and/or processing capabilities. In particular, processing circuitry **1018** may comprise one or more programmable processors, application-specific integrated circuits, field programmable gate arrays or combinations of these (not shown) adapted to execute instructions. Host computer **1010** further comprises software **1011**, which is stored in or accessible by host computer **1010** and executable by processing circuitry **1018**. Software **1011** includes host application **1012**. Host application **1012** may be operable to provide a service to a remote user, such as UE **1030** connecting via OTT connection **1050** terminating at UE **1030** and host computer **1010**. In providing the service to the remote user, host application **1012** may provide user data which is transmitted using OTT connection **1050**.

(127) Communication system **1000** further includes base station **1020** provided in a telecommunication system and comprising hardware **1025** enabling it to communicate with host computer **1010** and with UE **1030**. Hardware **1025** may include communication interface **1026** for setting up and maintaining a wired or wireless connection with an interface of a different communication device of communication system **1000**, as well as radio interface **1027** for setting up and maintaining at least wireless connection **1070** with UE **1030** located in a coverage area (not shown in FIG. **10**) served by base station **1020**. Communication interface **1026** may be configured to facilitate connection **1060** to host computer **1010**. Connection **1060** may be direct or it may pass through a core network (not shown in FIG. **10**) of the telecommunication system and/or through one or more intermediate networks outside the telecommunication system. In the embodiment shown, hardware **1025** of base station **1020** further includes processing circuitry **1028**, which may comprise one or more programmable processors, application-specific integrated circuits, field programmable gate arrays or combinations of these (not shown) adapted to execute instructions. Base station **1020** further has software **1021** stored internally or accessible via an external connection.

(128) Communication system **1000** further includes UE **1030** already referred to. Its hardware **1035** may include radio interface **1037** configured to set up and maintain wireless connection **1070** with a base station serving a coverage area in which UE **1030** is currently located. Hardware **1035** of UE **1030** further includes processing circuitry **1038**, which may comprise one or more programmable

processors, application-specific integrated circuits, field programmable gate arrays or combinations of these (not shown) adapted to execute instructions. UE **1030** further comprises software **1031**, which is stored in or accessible by UE **1030** and executable by processing circuitry **1038**. Software **1031** includes client application **1032**. Client application **1032** may be operable to provide a service to a human or non-human user via UE **1030**, with the support of host computer **1010**. In host computer **1010**, an executing host application **1012** may communicate with the executing client application **1032** via OTT connection **1050** terminating at UE **1030** and host computer **1010**. In providing the service to the user, client application **1032** may receive request data from host application **1012** and provide user data in response to the request data. OTT connection **1050** may transfer both the request data and the user data. Client application **1032** may interact with the user to generate the user data that it provides.

(129) It is noted that host computer **1010**, base station **1020** and UE **1030** illustrated in FIG. **10** may be similar or identical to host computer **930**, one of base stations **912***a*, **912***b*, **912***c* and one of UEs **991**, **992** of FIG. **9**, respectively. This is to say, the inner workings of these entities may be as shown in FIG. **10** and independently, the surrounding network topology may be that of FIG. **9**.

(130) In FIG. **10**, OTT connection **1050** has been drawn abstractly to illustrate the communication between host computer **1010** and UE **1030** via base station **1020**, without explicit reference to any intermediary devices and the precise routing of messages via these devices. Network infrastructure may determine the routing, which it may be configured to hide from UE **1030** or from the service provider operating host computer **1010**, or both. While OTT connection **1050** is active, the network infrastructure may further take decisions by which it dynamically changes the routing (e.g., on the basis of load balancing consideration or reconfiguration of the network).

(131) Wireless connection **1070** between UE **1030** and base station **1020** is in accordance with the teachings of the embodiments described throughout this disclosure. One or more of the various embodiments improve the performance of OTT services provided to UE **1030** using OTT connection **1050**, in which wireless connection **1070** forms the last segment. More precisely, the teachings of these embodiments may improve the operation and performance of a UE using the OTT connection **1050** to access OTT services.

(132) A measurement procedure may be provided for the purpose of monitoring data rate, latency and other factors on which the one or more embodiments improve. There may further be an optional network functionality for reconfiguring OTT connection **1050** between host computer **1010** and UE **1030**, in response to variations in the measurement results. The measurement procedure and/or the network functionality for reconfiguring OTT connection **1050** may be implemented in software **1011** and hardware **1015** of host computer **1010** or in software **1031** and hardware **1035** of UE **1030**, or both. In embodiments, sensors (not shown) may be deployed in or in association with communication devices through which OTT connection **1050** passes; the sensors may participate in the measurement procedure by supplying values of the monitored quantities exemplified above, or supplying values of other physical quantities from which software **1011**, **1031** may compute or estimate the monitored quantities. The reconfiguring of OTT connection **1050** may include message format, retransmission settings, preferred routing etc.; the reconfiguring need not affect base station **1020**, and it may be unknown or imperceptible to base station **1020**. Such procedures and functionalities may be known and practiced in the art. In certain embodiments, measurements may involve proprietary UE signaling facilitating host computer **1010**'s measurements of throughput, propagation times, latency and the like. The measurements may be implemented in that software **1011** and **1031** causes messages to be transmitted, in particular empty or ‘dummy’ messages, using OTT connection **1050** while it monitors propagation times, errors, etc.

(133) FIG. **11** is a flowchart illustrating a method implemented in a communication system, in accordance with one embodiment. The communication system includes a host computer, a base station and a UE which may be those described with reference to FIGS. **9** and **10**. For simplicity of

the present disclosure, only drawing references to FIG. **11** will be included in this section. In step **1110**, the host computer provides user data. In substep **1111** (which may be optional) of step **1110**, the host computer provides the user data by executing a host application. In step **1120**, the host computer initiates a transmission carrying the user data to the UE. In step **1130** (which may be optional), the base station transmits to the UE the user data which was carried in the transmission that the host computer initiated, in accordance with the teachings of the embodiments described throughout this disclosure. In step **1140** (which may also be optional), the UE executes a client application associated with the host application executed by the host computer.

(134) FIG. **12** is a flowchart illustrating a method implemented in a communication system, in accordance with one embodiment. The communication system includes a host computer, a base station and a UE which may be those described with reference to FIGS. **9** and **10**. For simplicity of the present disclosure, only drawing references to FIG. **12** will be included in this section. In step **1210** of the method, the host computer provides user data. In an optional substep (not shown) the host computer provides the user data by executing a host application. In step **1220**, the host computer initiates a transmission carrying the user data to the UE. The transmission may pass via the base station, in accordance with the teachings of the embodiments described throughout this disclosure. In step **1230** (which may be optional), the UE receives the user data carried in the transmission.

(135) FIG. **13** is a flowchart illustrating a method implemented in a communication system, in accordance with one embodiment. The communication system includes a host computer, a base station and a UE which may be those described with reference to FIGS. **9** and **10**. For simplicity of the present disclosure, only drawing references to FIG. **13** will be included in this section. In step **1310** (which may be optional), the UE receives input data provided by the host computer. Additionally or alternatively, in step **1320**, the UE provides user data. In substep **1321** (which may be optional) of step **1320**, the UE provides the user data by executing a client application. In substep **1311** (which may be optional) of step **1310**, the UE executes a client application which provides the user data in reaction to the received input data provided by the host computer. In providing the user data, the executed client application may further consider user input received from the user. Regardless of the specific manner in which the user data was provided, the UE initiates, in substep **1330** (which may be optional), transmission of the user data to the host computer. In step **1340** of the method, the host computer receives the user data transmitted from the UE, in accordance with the teachings of the embodiments described throughout this disclosure.

(136) FIG. **14** is a flowchart illustrating a method implemented in a communication system, in accordance with one embodiment. The communication system includes a host computer, a base station and a UE which may be those described with reference to FIGS. **9** and **10**. For simplicity of the present disclosure, only drawing references to FIG. **14** will be included in this section. In step **1410** (which may be optional), in accordance with the teachings of the embodiments described throughout this disclosure, the base station receives user data from the UE. In step **1420** (which may be optional), the base station initiates transmission of the received user data to the host computer. In step **1430** (which may be optional), the host computer receives the user data carried in the transmission initiated by the base station.

(137) Any appropriate steps, methods, features, functions, or benefits disclosed herein may be performed through one or more functional units or modules of one or more virtual apparatuses. Each virtual apparatus may comprise a number of these functional units. These functional units may be implemented via processing circuitry, which may include one or more microprocessor or microcontrollers, as well as other digital hardware, which may include digital signal processors (DSPs), special-purpose digital logic, and the like. The processing circuitry may be configured to execute program code stored in memory, which may include one or several types of memory such as read-only memory (ROM), random-access memory (RAM), cache memory, flash memory devices, optical storage devices, etc. Program code stored in memory includes program instructions

for executing one or more telecommunications and/or data communications protocols as well as instructions for carrying out one or more of the techniques described herein. In some implementations, the processing circuitry may be used to cause the respective functional unit to perform corresponding functions according one or more embodiments of the present disclosure.

ABBREVIATIONS

(138) At least some of the following abbreviations may be used in this disclosure. If there is an inconsistency between abbreviations, preference should be given to how it is used above. If listed multiple times below, the first listing should be preferred over any subsequent listing(s). 1× RTT CDMA2000 1× Radio Transmission Technology 3GPP 3rd Generation Partnership Project 5G 5th Generation ABS Almost Blank Subframe ARQ Automatic Repeat Request AWGN Additive White Gaussian Noise BCCH Broadcast Control Channel BCH Broadcast Channel CA Carrier Aggregation CC Carrier Component CCCH SDU Common Control Channel SDU CDMA Code Division Multiplexing Access CGI Cell Global Identifier CIR Channel Impulse Response CP Cyclic Prefix CPICH Common Pilot Channel CPICH Ec/No CPICH Received energy per chip divided by the power density in the band CQI Channel Quality information C-RNTI Cell RNTI CSI Channel State Information DCCH Dedicated Control Channel DL Downlink DM Demodulation DMRS Demodulation Reference Signal DRX Discontinuous Reception DTX Discontinuous Transmission DTCH Dedicated Traffic Channel DUT Device Under Test E-CID Enhanced Cell-ID (positioning method) E-SMLC Evolved-Serving Mobile Location Centre ECGI Evolved CGI eNB E-UTRAN NodeB ePDCCH enhanced Physical Downlink Control Channel E-SMLC evolved Serving Mobile Location Center E-UTRA Evolved UTRA E-UTRAN Evolved UTRAN FDD Frequency Division Duplex FFS For Further Study GERAN GSM EDGE Radio Access Network gNB Base station in NR GNSS Global Navigation Satellite System GSM Global System for Mobile communication HARQ Hybrid Automatic Repeat Request HO Handover HSPA High Speed Packet Access HRPD High Rate Packet Data LOS Line of Sight LPP LTE Positioning Protocol LTE Long-Term Evolution MAC Medium Access Control MBMS Multimedia Broadcast Multicast Services MBSFN Multimedia Broadcast multicast service Single Frequency Network MBSFN ABS MBSFN Almost Blank Subframe MDT Minimization of Drive Tests MIB Master Information Block MME Mobility Management Entity MSC Mobile Switching Center NPDCCH Narrowband Physical Downlink Control Channel NR New Radio OCNG OFDMA Channel Noise Generator OFDM Orthogonal Frequency Division Multiplexing OFDMA Orthogonal Frequency Division Multiple Access OSS Operations Support System OTDOA Observed Time Difference of Arrival O&M Operation and Maintenance PBCH Physical Broadcast Channel P-CCPCH Primary Common Control Physical Channel PCell Primary Cell PCFICH Physical Control Format Indicator Channel PDCCH Physical Downlink Control Channel PDP Profile Delay Profile PDSCH Physical Downlink Shared Channel PGW Packet Gateway PHICH Physical Hybrid-ARQ Indicator Channel PLMN Public Land Mobile Network PMI Precoder Matrix Indicator PRACH Physical Random Access Channel PRS Positioning Reference Signal PSS Primary Synchronization Signal PUCCH Physical Uplink Control Channel PUSCH Physical Uplink Shared Channel RACH Random Access Channel QAM Quadrature Amplitude Modulation RAN Radio Access Network RAT Radio Access Technology RLM Radio Link Management RNC Radio Network Controller RNTI Radio Network Temporary Identifier RRC Radio Resource Control RRM Radio Resource Management RS Reference Signal RSCP Received Signal Code Power RSRP Reference Symbol Received Power OR

Reference Signal Received Power RSRQ Reference Signal Received Quality OR

Reference Symbol Received Quality RSSI Received Signal Strength Indicator RSTD Reference Signal Time Difference SCH Synchronization Channel SCell Secondary Cell SDU Service Data Unit SFN System Frame Number SGW Serving Gateway SI System Information SIB System Information Block SNR Signal to Noise Ratio SON Self Optimized Network SS Synchronization Signal SSS Secondary Synchronization Signal TDD Time Division Duplex TDOA Time Difference of Arrival TOA Time of Arrival TSS Tertiary Synchronization Signal TTI Transmission Time Interval UE User Equipment UL Uplink UMTS Universal Mobile Telecommunication System USIM Universal Subscriber Identity Module UTDOA Uplink Time Difference of Arrival UTRA Universal Terrestrial Radio Access UTRAN Universal Terrestrial Radio Access Network WCDMA Wide CDMA WLAN Wide Local Area Network

Claims

1. A method performed by a user equipment, the method comprising, receiving a downlink control information (DCI) message carried by a Physical Downlink Control Channel (PDCCH) on a first carrier, wherein the first carrier uses a first orthogonal frequency division multiplexing (OFDM) numerology; obtaining an aperiodic channel state information reference signal (CSI-RS) slot offset from the DCI message; determining the slot of the aperiodic CSI-RS based on the aperiodic CSI-RS slot offset; and receiving the aperiodic CSI-RS in the determined slot on a second carrier, where the second carrier uses a second orthogonal frequency division multiplexing (OFDM) numerology.
2. The method of claim 1, wherein the first OFDM numerology is different from the second OFDM numerology.
3. The method of claim 1, wherein the first and second OFDM numerologies are characterized by their respective subcarrier spacing.
4. The method of claim 1, further comprising transmitting a Channel State Information (CSI) report based on a measurement of the received aperiodic CSI-RS.
5. The method of claim 1, wherein the slot of the aperiodic CSI-RS is determined as the slot X slots later than a reference slot, where X is the aperiodic CSI-RS slot offset.
6. The method of claim 1, wherein determining the slot of the aperiodic CSI-RS based on the aperiodic CSI-RS slot offset comprises calculating a slot .Math. $(n+1)\frac{2^{\mu_{\mathrm{CSIRS}}}}{2^{\mu_{\mathrm{PDCCH}}}}$ - 1 .Math. $+X$, wherein: n is the slot with the triggering DCI in the numerology of the PDCCH, X is the CSI-RS triggering offset in the numerology of CSI-RS according to the higher layer parameter aperiodicTriggeringOffset, and μ.sub.CSIRS and μ.sub.PDCCH are the subcarrier spacing configurations for CSI-RS and PDCCH, respectively.
7. A user equipment comprising: an antenna configured to send and receive wireless signals; radio front-end circuitry connected to the antenna and to processing circuitry, the processing circuitry being configured to perform operations comprising: receiving a downlink control information (DCI) message carried by a Physical Downlink Control Channel (PDCCH) on a first carrier, wherein the first carrier uses a first orthogonal frequency division multiplexing (OFDM) numerology; obtaining an aperiodic CSI-RS slot offset from the DCI message; determining a slot of the aperiodic CSI-RS based on the aperiodic CSI-RS slot offset; and receiving the aperiodic CSI-RS in the determined slot of the aperiodic CSI-RS on a second carrier, wherein the second carrier uses a second OFDM numerology; and a battery connected to the processing circuitry and configured to supply power to the user equipment.
8. The user equipment of claim 7, wherein the first OFDM numerology is different from the second OFDM numerology.
9. The user equipment of claim 7, wherein the first and second OFDM numerologies are characterized by their respective subcarrier spacings.
10. The user equipment of claim 7, wherein the operations further comprise transmitting a Channel State Information (CSI) report based on a measurement of the received aperiodic CSI-RS.
11. The method of claim 1, wherein the slot of the aperiodic CSI-RS is determined as the slot X slots later than a reference slot, where X is the aperiodic CSI-RS slot offset.
12. The method of claim 1, wherein determining the slot of the aperiodic CSI-RS based on the aperiodic CSI-RS slot offset comprises calculating a slot .Math. $(n+1)\frac{2^{\mu_{\mathrm{CSIRS}}}}{2^{\mu_{\mathrm{PDCCH}}}}$ - 1 .Math. $+X$,

wherein: n is the slot with the triggering DCI in the numerology of the PDCCH, X is the CSI-RS triggering offset in the numerology of CSI-RS according to the higher layer parameter aperiodicTriggeringOffset, and μ.sub.CSIRS and μ.sub.PDCCH are the subcarrier spacing configurations for CSI-RS and PDCCH, respectively.

13. A base station comprising: a radio interface and processing circuitry, the processing circuitry being configured to transmit channel state information reference signal (CSI-RS) information aperiodically on a first carrier according to a first numerology and on a second carrier according to a second numerology.

14. The base station of claim 13, wherein the base station comprises a first base station and a second base station, wherein the first base station transmits via the first carrier and the second base station transmits via the second carrier.

15. The base station of claim 14, wherein the first base station and the second base station are non-collocated base stations.

16. The base station of claim 13, further including the UE, wherein the UE is configured to communicate with the base station.

17. A method performed by a base station, the method comprising, transmitting a downlink control information (DCI) message carried by a Physical Downlink Control Channel (PDCCH) on a first carrier, wherein the DCI message includes an aperiodic CSI-RS slot offset; transmitting the aperiodic CSI-RS in the determined slot of the aperiodic CSI-RS according to the aperiodic CSI-RS slot offset, wherein the aperiodic CSI-RS is transmitted on a second carrier.

18. The method of claim 17, wherein the first carrier uses a first OFDM numerology and the second carrier uses a second OFDM numerology that is different than the first OFDM numerology.

19. The method of claim 18, wherein the first OFDM numerology and the second OFDM numerology are characterized by respective subcarrier spacings.

20. The method of claim 17, further comprising receiving, from a wireless device, a Channel State Information (CSI) report based on a measurement of the received aperiodic CSI-RS.