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5G NR Power Saving Enhancements in Release 17

Power consumption optimizations for devices in idle, inactive, and connected modes

White Paper

Release date: 2022-12-01

Introduction

The industry has seen unprecedented growth and adoption of 5G. Owing to its flexibility and holistic implementations, 5G New Radio (NR) has achieved a steady stream of deployments worldwide. The 3rd Generation Partnership Project (3GPP) continues the evolution of 5G technologies and recently completed the standardization of Release 17. This release includes further enhancements and new capabilities that improve not only enhanced Mobile Broadband (eMBB) services but also extended support for the industry's verticals and new use cases. Thus, 5G technologies will continue delivering an end-to-end improvement to the system performance that will surely sustain the strong deployment momentum of commercial 5G networks and devices worldwide.

5G NR features in Release 17 include enhancements for user equipment (UE) power saving, uplink coverage, multiple-input multiple-output (MIMO), positioning, among others. Additionally, new 5G services and capabilities have been introduced in Release 17, such as multicast and broadcast services (MBS), reduced-capability (RedCap) devices, and non-terrestrial networks (NTN). Hence, Release 17 becomes the baseline for the upcoming Release 18 5G technologies, dubbed 5G-Advanced.

5G, by default, implements wide channel bandwidths and enables operations at higher frequencies to achieve higher throughput, which has presented some serious power consumption challenges for 5G devices. It also came with great physical layer scalability that allows it to address the various traffic models and requirements of verticals efficiently. Release 15 included baseline features in NR that enabled UE power saving, such as Discontinuous Reception (DRX) in Radio Resource Control (RRC) connected state (RRC_CONNECTED) and Bandwidth Part (BWP) adaptation, to reduce the UE processing bandwidth when high throughput demand is not needed, as described in [1]. Release 16 introduced more enhancements to UE power saving with a focus on reducing background activity whenever possible and simplifying the ways in which UE power management can dynamically adapt to the varying traffic conditions. A summary of those Release 16 features are as follows:

- BWP adaptation framework
    - Physical Downlink Control Channel (PDCCH) monitoring reduction
    - Secondary Cell (SCell) dormancy
    - MIMO layers adaptation
    - Cross-Slot scheduling
- Wake-Up Signal (WUS) for connected mode discontinuous reception (C-DRX) optimization
- Radio Resource Management (RRM) measurements relaxation
- Extended UE Assistance Information (UAI)
    - DRX preference
    - Maximum bandwidth (BW) and Maximum component carrier (CC) preference
    - Minimum scheduling preference for timeline adaptation
    - Release Preference for efficient Radio Resource Control (RRC) state transition

Furthermore, the optimizations of UE power consumption in Release 17 include enhancements for UEs in RRC idle (RRC_IDLE) and inactive (RRC_INACTIVE) states related to paging. Also, UE subgrouping, as well as the additional provision of reference signals (tracking reference signal/channel state information reference signal - TRS/CSI-RS) for synchronization before the reception of paging occasions, are introduced in Release 17. For UEs in connected mode (i.e. RRC_CONNECTED), UE power saving is further enhanced by additional PDCCH monitoring reduction, and by relaxation of UE measurements for radio link monitoring (RLM), and beam failure detection (BFD). An evaluation of these Release 17 power saving features is described in this paper.

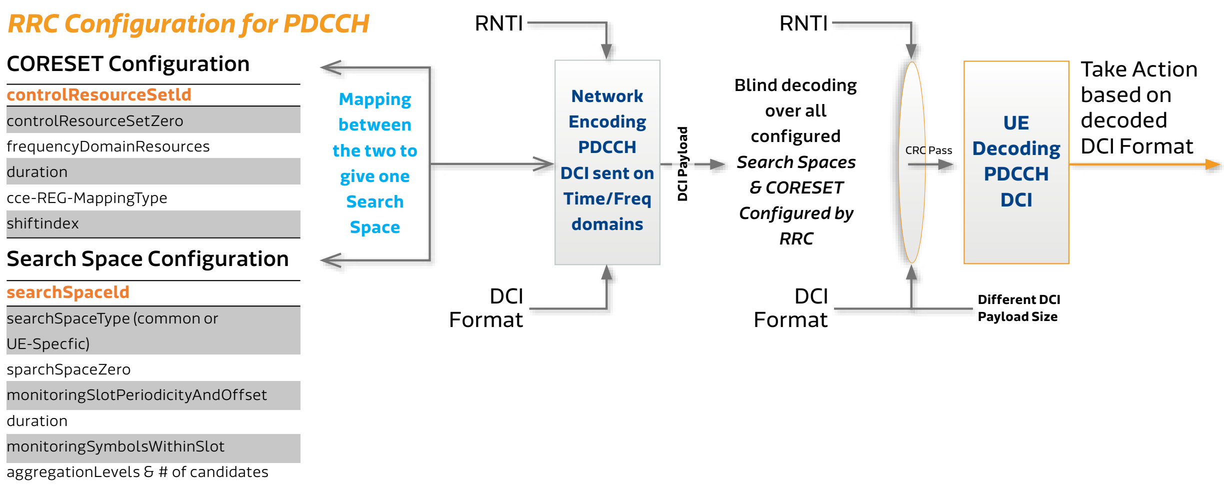
Overview of Mechanisms Affecting UE Power Saving

Different radio interface mechanisms operate between the UE and the NR cell in different RRC states, as follows:

- Idle mode: this is a state where there is no active data or voice connectivity between the UE and the cell. In this state the UE performs mechanisms such as reading system information and any update to them, cell re-selection and paging monitoring.
- Connected mode: this is a state that the UE and the cell are in an active communication where scheduling activities are taking place.
- Inactive mode: a state similar in functionality to idle mode but with UE context saved in the network so that the delay in state transition from inactive to connected mode is reduced.

The main factors contributing to power consumption in 5G NR are the paging monitoring for UEs in idle and inactive RRC states, and the downlink assignment/uplink grant scheduling for UEs in connected mode. The aspects of paging monitoring procedures and the access delays during the paging procedure are discussed in detail in [2]. Meanwhile, in RRC connected mode, one of the main contributors to power consumption is the period and frequency of monitoring PDCCH to read the scheduled grants on the uplink and downlink. The concept of PDCCH monitoring is described in Figure 1.

Figure 1 PDCCH DCI Blind Decoding.



PDCCH is decoded by the UE in every slot as illustrated in Figure 1. Control Resource Set (CORESET) is about "Where to search for PDCCH candidates" which includes a time-frequency region where the UE monitors for PDCCH transmission. Search space is about "How to search for PDCCH candidates" and is configured per BWP. Search space configures to the UE the sets of Control Channel Elements (CCE) and Aggregation Levels. Initially, and based on the RRC state the UE is served with, the UE knows which search space to monitor among different search space types, which can be a Common Search Space (CSS) or UE-specific search space (USS). For instance, Type0-PDCCH CSS for decoding System Information Blocks that are encoded with System Information Radio Network Temporary Identifier (SI-RNTI), Type2-PDCCH for paging encoded with P-RNTI, or UE-specific PDCCH used for scheduling data encoded with C-RNTI. Then with the received information from CORESET and search spaces, the UE can apply blind decoding hypothesis to detect the corresponding downlink control information (DCI) among the candidates in each aggregation level. The DCI consists of scheduling information for uplink such as formats 0_0 or 0_1, or for downlink with formats 1_0 or 1_1, among several other DCI formats used for different purposes. At this point the UE has sufficient information sent to it from the cell, and with the DCI contents it can continue to receive or transmit other channels such as Physical Downlink Shared Channel (PDSCH), or Physical Uplink Shared Channel (PUSCH). PDCCH is explained in detail in [3].

Release 17 UE Power Saving Enhancements

Release 17 enhancements for UE power saving are addressed in Release 17, based on the 3GPP radio access network (RAN) work item (WI) described in RP-212630 [4]. This WI consisted of two main objectives:

a) Power saving enhancements for UEs in idle and inactive modes, including reduction of unnecessary paging reception and the provision of additional TRS/CSI-RS occasions.

b) Power saving enhancements for UEs in connected mode, including PDCCH monitoring reduction for C-DRX and relaxation of UE measurements for RLM and/or BFD

As specified up to Release 16 in 3GPP TS 38.304 [5], UEs in idle and inactive modes are required to monitor a paging occasion (PO), i.e., decode PDCCH and corresponding PDSCH for paging messages, within each DRX cycle. To be able to monitor the PO, the UE is required to first receive one or multiple synchronization signal (SS) bursts at a configured periodicity for synchronization with the network. Each SS burst is composed of one or multiple SS blocks (SSB), where each SSB consists of synchronization signals (primary and secondary synchronization signals) and Physical Broadcast Channel (PBCH). Each UE needs to perform this process before the reception of its PO, even though it is unknown whether a paging PDCCH/PDSCH targeting the UE is present within the PO.

An example of the UE power consumption related to PO monitoring in idle and inactive modes based on Release 16 is illustrated in Figure 2(a). It should be noted that SSB is typically transmitted with a periodicity of 20 msec. In case of low Signal to Interference Noise Raito (SINR), a UE could potentially need to wake up 60 msec before the paging occasion to decode multiple SS bursts to properly achieve time and frequency synchronization, automatic gain control (AGC) adjustment, as well as identify the SSB of the serving cell and neighboring cell required to perform measurements. Also, the paging occasion in NR can depend on the SSB beam concept, which leads to an extra 4 msec for PO processing to complete the decoding of PDCCH/PDSCH. As a result, in NR standalone (SA) deployments, more UE power is spent on paging monitoring because of the extended duration of PO and because of the time spent before the paging occasion, which can also be unnecessary when the UE is not paged by the network. On the other hand, in NR non-standalone (NSA) deployments, where LTE is the anchor carrier handling the control plane signaling, UEs in idle mode do not need to receive SS bursts or any NR paging messages because all the information can be sent to the UE through the LTE carrier. Hence, NR capable UEs are just required to receive few LTE cell specific reference signals (CRS) right before monitoring the paging occasion, which is much shorter and requires less power consumption than receiving multiple SS bursts in NR. Therefore, power saving enhancements for UEs in idle and inactive modes are specified in Release 17 to improve the UE power consumption in NR SA.

Likewise, UEs in connected mode are required to monitor PDCCH in every slot which contributes to more UE power consumption. Although NR is specified with a flexible PDCCH search space configuration, the distinct characteristics of the UE traffic can be challenging for the network to provide an optimized configuration to schedule corresponding resources to the UE [1]. Also, the required UE measurements for RLM and BFD to determine the radio link quality can contribute to a large extension of UE power consumption. Hence, Release 17 UE power saving enhancements introduce further improvements to the power consumption performance in connected mode, as described below.

Power Saving Enhancements in Idle and Inactive Modes

To improve the UE power saving in idle and inactive modes, Release 17 specifies that the UE may receive a Paging Early Indication (PEI). PEI can avoid unnecessary PO reception by indicating to the UE whether to decode paging (PDCCH/PDSCH) in its PO. As described in Release 17 3GPP TS 38.304 [5], system information provided by the network can include PEI configuration to be used by UEs. UEs supporting PEI utilize the received PEI configuration to monitor one PEI occasion (PEI-O) per DRX cycle. For PEI monitoring, Type2A-PDCCH common search space set is configured for DCI format 2_7, as defined in Release 17 3GPP TS 38.213 [6]. Based on this, PEI becomes an essential mechanism for device power saving in 5G NR SA deployments as UEs are not required to frequently wake up for paging monitoring in idle and inactive modes when paging is not sent to them.

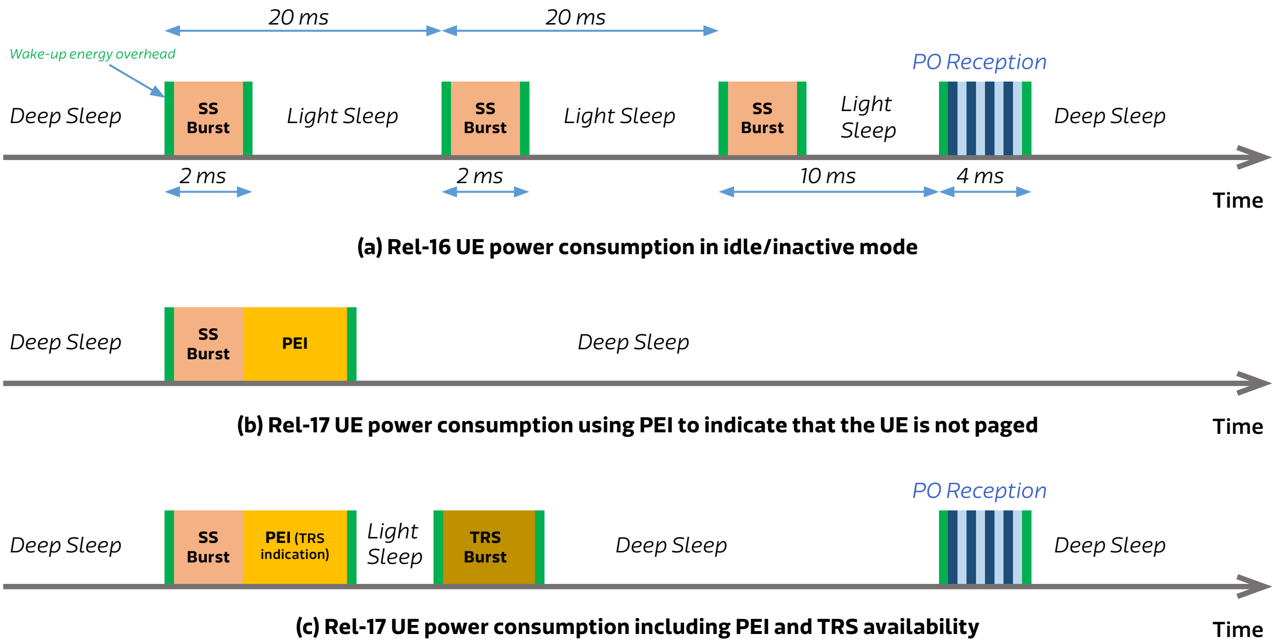
Furthermore, to optimize the UE power consumption the UEs monitoring the same PO can be split into multiple subgroups to reduce false paging alarms, i.e., an unpaged UE still needs to monitor its PO due to another UE within its paging group being paged. The PEI can then provide an indication per subgroup, where the value specifies whether the UE is required to monitor the PO. Therefore, the UE can determine whether to skip a PO and the associated required synchronization based on the PEI indication. This mechanism avoids unnecessary UE power consumption. For the case that a UE is not able to monitor the PEI-O associated to its PO, the UE is required to monitor its paging occasion.

When PEI and subgrouping are configured, subgrouping can be core network (CN) controlled, where the access and mobility management (AMF) function assigns a subgroup ID to the UE. Also, subgrouping can be UE ID based, where the subgroup ID is based on the UE ID and the total number of subgroups for UE ID based subgrouping defined by the gNB. Up to eight (8) subgroups (including CN controlled subgroups and UE ID based subgroups) are allowed within a cell. A UE supporting PEI is required to support at least UE ID based subgrouping.

Besides reducing UE power consumption associated to synchronization required before PO monitoring, additional TRS/CSI-RS reference signals can also be provisioned by the network for paging reception in Release 17. The configuration of additional TRS resources can be provided via system information, system information block type 17 (SIB17), for UEs in idle and inactive modes. TRS can then be utilized for synchronization based on an explicit layer 1 TRS availability indication via DCI format 2_7 and DCI format 1_0, as described in Release 17 38.213 [6]. Thereby, the reception of required SS bursts before a PO reception can be minimized. This can lead to achieving longer periods of time where the UE stays in (deep) sleep mode within a DRX cycle, and by that optimizing the number of occasions that a UE is required to wake up in idle and inactive modes.

Figure 2 depicts an example of the optimization of power consumption for UEs in idle and inactive modes with the use of PEI and TRS synchronization in figure 2(b) and figure 2(c) respectively, compared to Release 16 UE power consumption figure 2(a). Figure 2(b) illustrates the case that PEI is configured to indicate that the UE's group is not required to monitor its PO. Likewise, this case can also be extended to the configuration of PEI with subgrouping, where the PEI provides a better granularity indicating that the UE's subgroup is not required to monitor its PO. Figure 2(c) illustrates the case that PEI is used to indicate that the UE's paging group is required to monitor its PO as well as including the explicit L1-based availability indication for the use of TRS for synchronization before PO reception.

Figure 2 5G NR Release 17 UE power saving enhancements compared to Release 16 in idle inactive modes.



To evaluate the aforementioned power saving enhancements in idle and inactive modes, system level simulation evaluations were performed based on the 3GPP UE power consumption model defined in 3GPP TR 38.840 [7] and the agreements described in R1 2007501 [8]. For the system power consumption evaluation of UEs in idle and inactive modes, the relative power consumption values for non-sleep power states are defined by scaling the reference bandwidth from 100 MHz to 20 MHz. Table 1 summaries the general power consumption model values used for these evaluations, and the results are further analyzed below.

Table 1. 3GPP power consumption model for idle and inactive modes

Power State	Relative Power
Deep Sleep	1
Light Sleep	20
Micro Sleep	45
PDCCH-only	50
PDCCH + PDSCH	120
SSB or CSI-RS processing	50

The evaluation included three cases: configuration of PEI only, PEI combined with the use of TRS for synchronization, and PEI configured with subgrouping. Figure 3 and Figure 4 show the Release 17 UE power saving benefits in idle and inactive modes compared to Release 16 UE power consumption at different SINR conditions and group paging rates (R_{po}), respectively.

Figure 3 Release 17 Power saving benefits compared to Release 16 power consumption in idle and inactive modes, with an original group paging rate of 10% (10 UEs sharing the same PO).

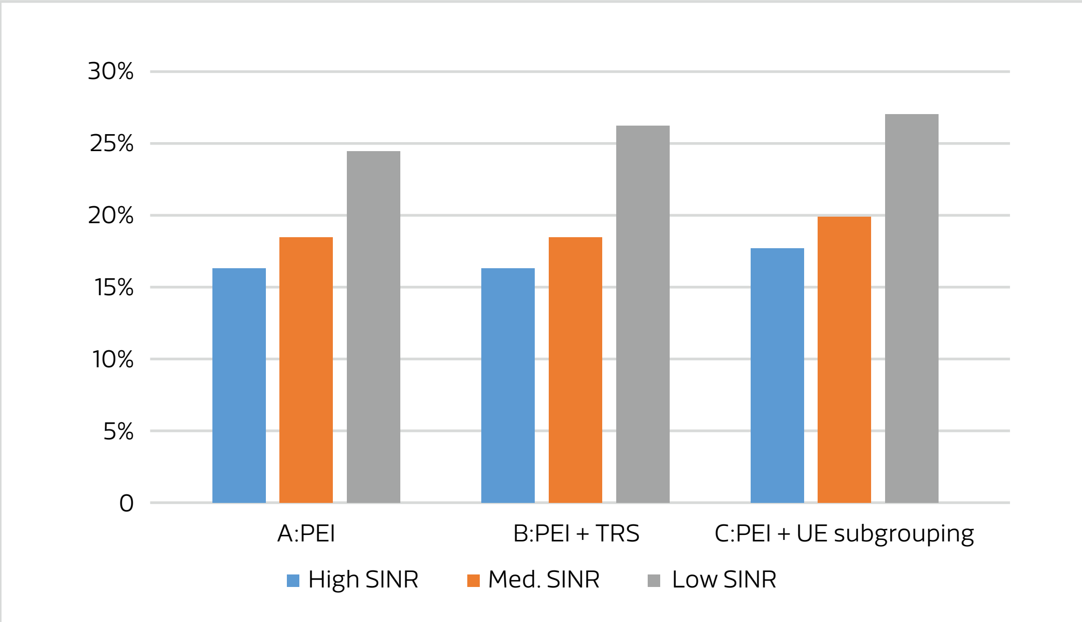


Figure 4 Release 17 Power saving benefits compared to Release 16 power consumption in idle and inactive modes, with an original group paging rate of 40% (50 UEs sharing the same PO).

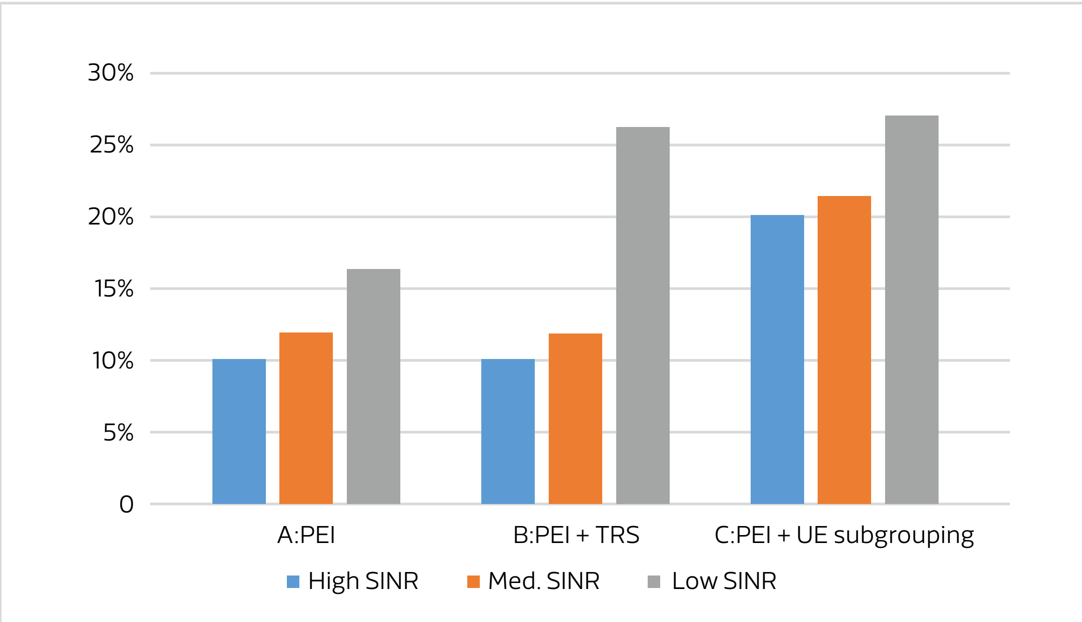


Table 2 summaries the power saving gains described in Figure 3 and Figure 4. As observed, by only using PEI a UE power saving gain of 16% can be achieved in high SINR conditions and low group paging rate. A similar gain can also be achieved for a worst case scenario in low SINR conditions and high group paging rate, which is the result of avoiding PO reception when the UE's group is not paged.

As illustrated in the simulation results, when PEI and subgrouping are configured, power saving gains are further extended due to the reduction of false paging alarms. A 27% gain can be obtained when PEI is combined with subgrouping at low SINR conditions and high (original) group paging rates. Similar gains of around 20% can also be observed from medium to high SINR conditions with low and high group paging rates when PEI and subgrouping are configured.

When PEI is used with TRS for synchronization, the UE power saving gains are similar to the ones obtained by configuring PEI and subgrouping at low SINR conditions. However, additional benefits were not observed by using TRS from medium to high SINR conditions when compared to the case of only configuring PEI. This considers that in good radio conditions the UE is not required to receive multiple SS bursts to properly decode PDCCH in its PO.

Table 2 Release 17 UE Power Saving Gains Compared to Release 16 UE Power Consumption in idle and inactive modes

Power Saving Features	High SINR	Medium SINR	Low SINR
	Power saving gain (%)	Power saving gain (%)	Power saving gain (%)
A: PEI	16% (R_{PO} = 10%) 10% (R_{PO} = 40%)	18% (R_{PO} = 10%) 12% (R_{PO} = 40%)	24% (R_{PO} = 10%) 16% (R_{PO} = 40%)
B: PEI + TRS	16% (R_{PO} = 10%) 10% (R_{PO} = 40%)	18% (R_{PO} = 10%) 12% (R_{PO} = 40%)	27% (R_{PO} = 10%) 26% (R_{PO} = 40%)
C: PEI + UE subgrouping	18% (R_{PO} = 10%) 20% (R_{PO} = 40%)	20% (R_{PO} = 10%) 21% (R_{PO} = 40%)	27% (R_{PO} = 10%) 27% (R_{PO} = 40%)

Power Saving Enhancements in Connected Mode

In Release 15 and Release 16 several UE power saving techniques are specified to provide improvements to power consumption for UEs in connected mode. Some of these techniques are BWP adaptation framework (e.g., PDCCH monitoring reduction, MIMO layer adaptation, SCell dormancy, and cross-slot scheduling), wakeup signal for C-DRX, and UE assistance information (UAI). Release 17 introduces additional techniques to further reduce UE power consumption in PDCCH monitoring within an active BWP during DRX active time, as well as enabling UE measurements relaxation for RLM and BFD, which are further described below.

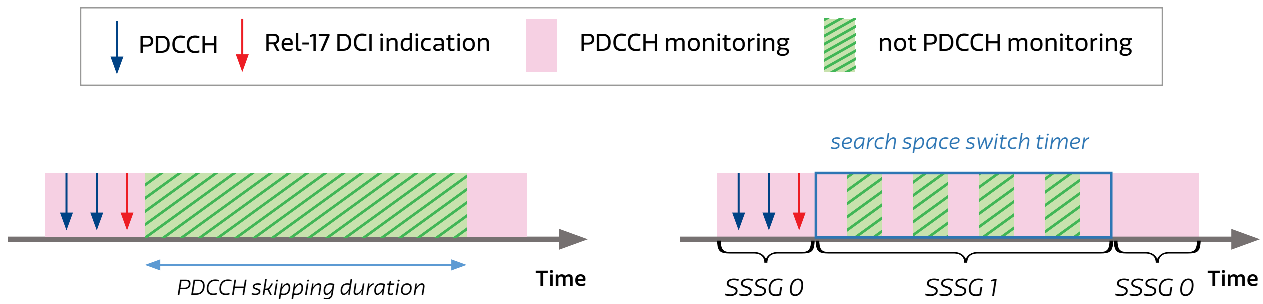
Optimization of PDCCH Monitoring Adaptation

The introduced optimization of PDCCH monitoring adaptation provides enhancements for the support of new use cases. Extended reality (XR) services (including augmented reality (AR) and virtual reality (VR) applications) and cloud gaming are examples that require much shorter packet inter-arrival times, where PDCCH-only monitoring can dominate the UE power consumption. This enhanced PDCCH monitoring adaptation includes PDCCH skipping and dynamic search space set group (SSSG) switching. PDCCH skipping and SSSG switching apply to Type3-PDCCH CSS set or UE-specific search space (USS) set for PDCCH monitoring on an active downlink (DL) BWP of a serving cell, and are based on an indication in DCI formats 0_1/0_2/1_1/1_2, as defined in Release 17 38.213 [6].

Based on the corresponding PDCCH monitoring adaptation indication in DCI formats 0_1/0_2/1_1/1_2, the UE can be triggered to skip PDCCH monitoring during a specific period from the next slot after the indication is received. After this duration the UE is required to monitor PDCCH again. Likewise, the UE can be indicated to switch to a specific SSSG and stop PDCCH monitoring in any other SSSG in order to perform reduced PDCCH monitoring. When SSSG switching is configured with a search space switch timer, the UE is required to switch to the SSSG with the lowest group index once the timer is expired. As specified in Release 17, a UE can be configured with up to three different SSSGs on the active DL BWP of the serving cell.

Figure 5 illustrates examples where PDCCH monitoring is reduced by configuring the UE with PDCCH skipping or SSSG switching. For instance, as depicted in figure 5(a), reduction of PDCCH monitoring can be achieved during long periods by configuring long PDCCH skipping duration values. Likewise, long periods of reduced PDCCH monitoring can be enabled by switching to another SSSG, e.g. an SSSG with a highly reduced or empty search space set (i.e. with very few or without PDCCH candidates to monitor), during a long search space switch timer. Reduction of PDCCH monitoring for short periods, as depicted in figure 5(b), can be configured by switching to another SSSG with a search space set with sparser PDCCH monitoring occasions. Similarly, short reduced PDCCH monitoring can be achieved by enabling PDCCH skipping with short durations.

Figure 5 Release 17 PDCCH monitoring adaptation enhancements for UE power saving in connected mode.



(a) Reduced PDCCH monitoring by PDCCH skipping

(b) Reduced PDCCH monitoring by SSSG switching

The enhanced PDCCH monitoring adaptation in Release 17 comprises different cases for the use of PDCCH skipping and SSSG switching, as follows:

- **PDCCH skipping:** A UE can be provided a set of PDCCH skipping durations related to PDCCH monitoring on an active DL BWP of a serving cell. For that, DCI formats 0_1/0_2/1_1/1_2 can include a PDCCH monitoring adaptation field of 1 bit or 2 bits, as described in Table 3.

Table 3 PDCCH skipping configurations

PDCCH monitoring adaptation field	Value	UE indication
1 bit	'0'	PDCCH monitoring is not skipped
	'1'	PDCCH monitoring is skipped for a duration provided by the first PDCCH skipping duration value
2 bits	'00'	PDCCH monitoring is not skipped
	'01'	PDCCH monitoring is skipped for a duration provided by the first PDCCH skipping duration value
	'10'	PDCCH monitoring is skipped for a duration provided by the second PDCCH skipping duration value
	'11'	PDCCH monitoring is skipped for a duration provided by the third PDCCH skipping duration value. If the set of PDCCH skipping durations only includes two values, then the value '11' is reserved

- **SSSG switching:** A UE can be provided up to three group indexes corresponding to SSSGs for PDCCH monitoring on an active DL BWP of a serving cell. Additionally, the UE can be provided a set of PDCCH skipping durations. For that, DCI formats 0_1/0_2/1_1/1_2 can include a PDCCH monitoring adaptation field of 1 bit or 2 bits.

Table 4 describes the SSSG switching configurations for the case that a set of PDCCH skipping durations is not provided.

Table 4 SSSG switching configurations without PDCCH skipping

PDCCH monitoring adaptation field	Value	UE indication
1 bit	'0'	Switch to SSSG with group index 0, i.e. start of PDCCH monitoring in SSSG with index 0 and stop of PDCCH monitoring in SSSG with other group indexes
	'1'	Switch to SSSG with group index 1, i.e. start of PDCCH monitoring in SSSG with index 1 and stop of PDCCH monitoring in SSSG with other group indexes. The UE initiates the provided search space switch timer
2 bits	'00'	Switch to SSSG with group index 0, i.e. start of PDCCH monitoring in SSSG with index 0 and stop of PDCCH monitoring in SSSG with other group indexes
	'01'	Switch to SSSG with group index 1, i.e. start of PDCCH monitoring in SSSG with index 1 and stop of PDCCH monitoring in SSSG with other group indexes. The UE initiates the provided search space switch timer
	'10'	Switch to SSSG with group index 2, i.e. start of PDCCH monitoring in SSSG with index 2 and stop of PDCCH monitoring in SSSG with other group indexes. The UE initiates the provided search space switch timer
	'11'	Reserved

For the case that SSSG switching is combined with a set of PDCCH skipping durations, only two SSSGs can be configured and the PDCCH monitoring adaptation field consists of 2 bits. Table 5 describes the case that the set of PDCCH skipping durations includes one value, and Table 6 the case that the set of PDCCH skipping durations includes two values.

Table 5 SSSG switching configuration with PDCCH skipping with one duration value

PDCCH monitoring adaptation field	Value	UE indication
2 bits	'00'	Switch to SSSG with group index 0, i.e. start of PDCCH monitoring in SSSG with index 0 and stop of PDCCH monitoring in SSSG with group index 1
	'01'	Switch to SSSG with group index 1, i.e. start of PDCCH monitoring in SSSG with index 1 and stop of PDCCH monitoring in SSSG with group index 0. The UE initiates the provided search space switch timer
	'10'	Skip PDCCH monitoring for a duration provided by the PDCCH skipping duration value
	'11'	Reserved

Table 6 SSSG switching configuration with PDCCH skipping with two duration values

PDCCH monitoring adaptation field	Value	UE indication
2 bits	'00'	Switch to SSSG with group index 0, i.e. start of PDCCH monitoring in SSSG with index 0 and stop of PDCCH monitoring in SSSG with group index 1
	'01'	Switch to SSSG with group index 1, i.e. start of PDCCH monitoring in SSSG with index 1 and stop of PDCCH monitoring in SSSG with group index 0. The UE initiates the provided search space switch timer
	'10'	Skip PDCCH monitoring for a duration provided by the first PDCCH skipping duration value
	'11'	Skip PDCCH monitoring for a duration provided by the second PDCCH skipping duration value

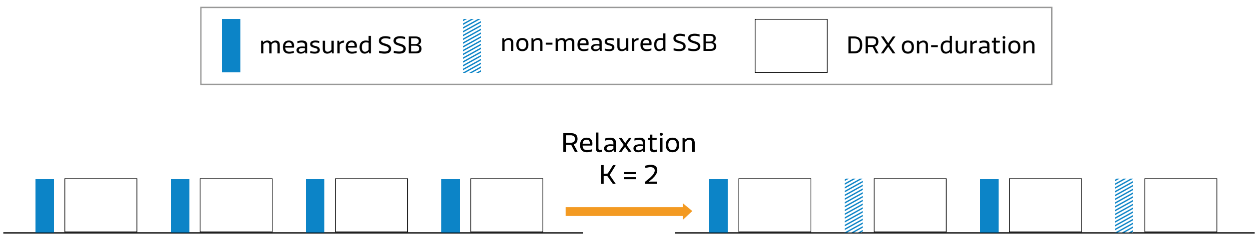
UE Measurements Relaxation for RLM and BFD

Reductions in UE power consumption can further be enabled by relaxing UE measurements for RLM and/or BFD in connected mode. For that, as specified in Release 17 3GPP TS 38.331 [9] and Release 17 3GPP TS 38.133 [10], a UE can be configured to enable RLM and/or BFD relaxation when the relaxed measurement criteria are met. For that, the relaxed measurement criteria for low mobility and good serving cell quality are specified and can be configured in the UE via RRC dedicated signaling. RLM relaxation can be configured per cell group (CG), i.e., separately between primary cell (PCell) and primary secondary cell group cell (PSCell), whilst BFD relaxation can be configured per serving cell, i.e., separately between PCell/PSCell and SCell.

The evaluation of the low mobility criterion and good serving cell quality criterion is initiated by the UE when the corresponding configuration is received. As specified in Release 17 38.331 [9] and Release 17 38.133 [10], the low mobility criterion evaluation uses Layer 3 (L3) Synchronization Signal Reference Signal Received Power (SS-RSRP) measurements of the serving cell based on SSB. The good serving cell quality criterion is evaluated based on the downlink radio link quality on the configured RS resources, e.g., SSB and/or CSI-RS, using SINR measurements for RLM and/or BFD.

When the good serving cell quality criterion and, if configured, the low mobility criterion are fulfilled, the UE is allowed to apply the relaxed requirements to RLM and/or BFD measurements. With the relaxed requirements, the UE uses only one of every K samples for the relaxed RLM/BFD measurements within an extended evaluation period, where K is the relaxation factor. The UE can further be configured by the network to report the relaxation state of RLM and BFD measurements via UE assistance information. Figure 6 illustrates the case of enabling RLM/BFD measurement relaxation with the relaxation scaling factor, K, of 2.

Figure 6 SSB-based RLM/BFD measurement relaxation by a relaxation scaling factor K = 2



Evaluation of Connected Mode Enhancements

To evaluate the described power saving enhancements in connected mode, system level simulation evaluations were performed based on the 3GPP UE power consumption model defined in 38.840 [7] for a system bandwidth of 100 MHz and a subcarrier spacing of 30 kHz. Table 7 summaries the general power consumption model values used for these evaluations, and the results are further analyzed below. For the evaluations, voice over NR (VoNR) and XR (AR/VR) traffic models were considered, as described in 38.840 [7] and 3GPP TR 38.838 [11], respectively. For the case of XR traffic, 1 CC and 2 CCs were considered, whilst 1 CC was considered for VoNR traffic.

Table 7. 3GPP power consumption model for connected mode

Power State	Relative Power
Deep Sleep	1
Light Sleep	20
Micro Sleep	45
PDCCH-only	100
PDCCH + PDSCH	300
SSB or CSI-RS processing	100

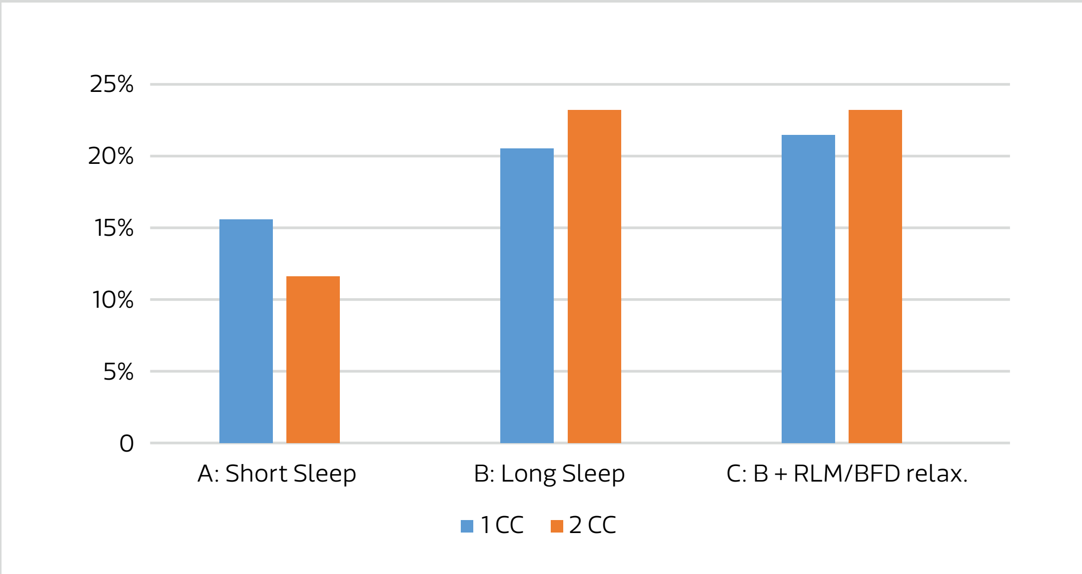
The evaluation consisted of the following three cases:

A) reduced PDCCH monitoring during short periods (i.e. enabling UE short-sleeps),
B) reduced PDCCH monitoring during long periods (i.e. enabling UE long-sleeps), and
C) reduced PDCCH monitoring during long periods configured with RLM/BFD measurement relaxation.

For the short-sleep case (case A), SSSG switching was configured with a period of 2 msec (4 slots) during data inactivity times, wherein the UE monitored PDCCH in the first slot and skipped it for the remaining 3 slots. Thereby, the UE was allowed to enter micro-sleep state for the 3 slots duration. For the long-sleep case (case B), PDCCH skipping was configured with a duration of 10 msec allowing the UE to enter light-sleep state. The long-sleep case, likewise, could also be configured by switching to an SSSG with very few or without PDCCH candidates to monitor during data inactivity periods. For case C, RLM/BFD measurement relaxation was enabled with a relaxation scaling factor K of 4. As the comparison reference, the following Release 16 power saving features were considered: BWP switch from 100 MHz to 20 MHz including cross-slot scheduling for PCell, and SCell dormancy for the case of 2 CC. The BWP switch and SCell dormancy were enabled after 8 msec data inactivity.

Figure 7 and Figure 8 show the benefits of Release 17 UE power saving enhancements compared to Release 16 UE power saving features in connected mode for XR and VoNR, respectively. Table 8 summaries the power saving gains described in Figure 7 and Figure 8.

Figure 7 Release 17 Power saving benefits compared to Release 16 power saving in connected mode for XR traffic.

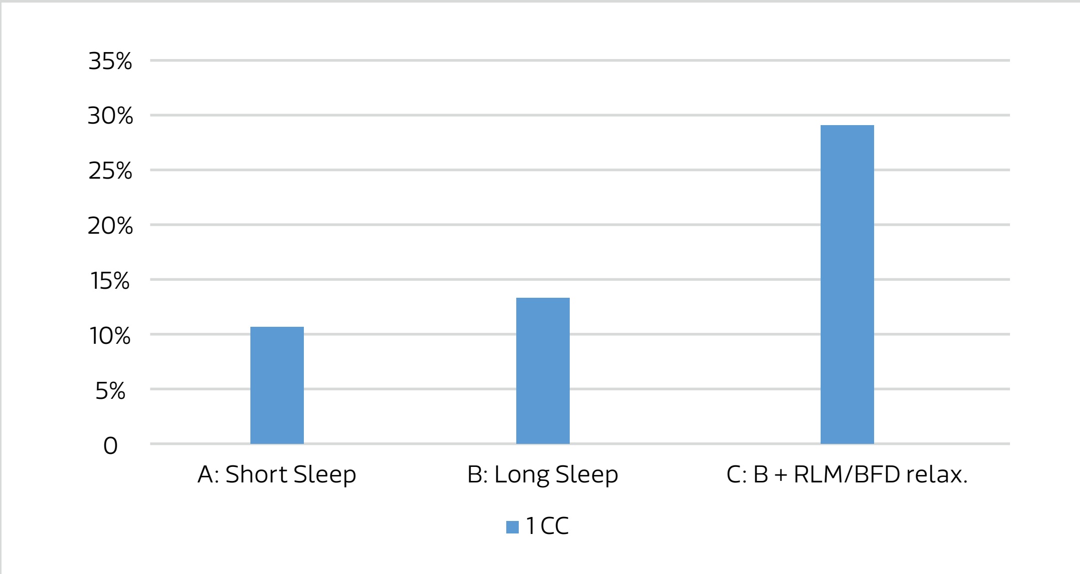


As observed in Figure 7 for the case of XR traffic and 1 CC, reduced PDCCH monitoring during long periods provides UE power saving gains around 20%, which is higher than configuring reduced PDCCH monitoring during short periods (15% gain). The higher gains become obvious due to the availability to configure the UE with longer sleeping periods, i.e., the UE can enter light sleep state. For the case of 2 CC, the achieved gains for reduced PDCCH monitoring during long periods were even higher, considering that the Release 17 PDCCH monitoring adaptation is applied to both PCell and SCell from next slot after the indication is received, while Release 16 BWP adaptation and SCell dormancy are applied only after 8 msec of data inactivity. The difference between these delays is because Release 17 PDCCH monitoring adaptation does not cause data interruption, while Release 16 BWP adaptation can cause between 2.5 msec and 3 msec of data interruption time during BWP switch. Thereby, for the case of high data rate traffic types with short packet inter-arrival times, e.g., a mean packet arrival period of 16.67 msec for XR traffic, the gains are higher as the UE can enter a power saving state earlier. On the other hand, it can be observed in Figure 7 for the case of 2 CC that SCell dormancy provides more effective power saving gains by completely stopping PDCCH monitoring in the SCell, than reducing PDCCH monitoring just for short periods.

Based on these results, it becomes evident that Release 16 power saving features like BWP adaptation and SCell dormancy are very effective mechanisms for the reduction of the device power consumption for traffic types with longer packet inter-arrival times, e.g., 40 msec or longer, as shown in [1]. On the other hand, traffic types with short packet inter-arrival times can obtain further benefits from the use of Release 17 power saving features, like PDCCH skipping and SSSG switching.

For the case of reduced PDCCH monitoring during long periods (case B in Figure 7), the evaluation additionally included that retransmissions were properly handled to avoid any performance impact in XR while enabling long-sleeps. This aspect is especially relevant considering that if a retransmission is required while a long sleep is enabled then the UE would need to wait longer to be able to receive/transmit the missing packet, which would impact the XR performance. Retransmission handling for PDCCH monitoring adaptation was not specified in Release 17 and therefore, it is an important aspect to be addressed in the related Release 18 work on XR enhancements.

Figure 8 Release 17 Power saving benefits compared to Release 16 power consumption in connected mode for VoNR traffic.



For the case of VoNR traffic shown in Figure 8, which comprised a packet inter-arrival time of 40 msec, PDCCH monitoring adaptation features showed UE power saving benefits of 10% and 12%, respectively. These gains are less than the ones observed for XR considering that VoNR is normally a low throughput service with longer packet inter-arrival times. Hence, Release 16 power saving features like BWP switching are already contributing to a large extension to the reduction on power consumption, as shown in [1].

On the other hand, the UE power saving gains in case C, where reduced PDCCH monitoring during long periods is configured with RLM/BFD relaxation, is much higher for VoNR compared to the same case in XR. VoNR traffic achieved a UE power saving gain around 30% for case C. Such a high gain is achieved considering that the low data rate typical of VoNR implies that less power consumption is required for PDCCH/PDSCH reception, and therefore, the required RLM/BFD measurements contribute to a larger portion of the overall power consumption. This is not the case for XR, which does imply high data rates and consequently a much higher power consumption is required for PDCCH/PDSCH reception than for RLM/BFD measurements.

Table 8 Release 17 UE Power Saving Gains Compared to Release 16 UE Power saving in connected mode

Power Saving Features	XR (AR/VR)	VoNR
	Power saving gain (%)	Power saving gain (%)
A: SSSG switching	15.51% (1CC) 12.09% (2CC)	10.85%
B: PDCCH Skipping	20.39% (1CC) 23.14% (2CC)	12.96%
C: PDCCH skipping + RLM/BFD relaxation	22.02% (1CC) 23.48%(2CC)	29.29%

Conclusions

Release 17 UE power saving enhancements can provide further benefits to the required UE power consumption compared to Release 16. The introduction of PEI in Release 17 represents a major optimization to the UE power consumption in idle and inactive modes and can be considered an essential mechanism for device power saving in 5G NR SA deployments. Above 10% gains are observed with the use of PEI by indicating to the UE whether it is required to decode paging carried on PDCCH/PDSCH in its PO. Furthermore, combining PEI with subgrouping or the use of TRS for synchronization before PO reception can further enhance the UE power savings, especially in low SINR conditions. Configuring PEI and subgrouping provides the largest gains to the required power consumption for UEs in idle and inactive modes at different SINR conditions and group paging rates. Up to 27% gains can be achieved with PEI and subgrouping at low SINR conditions. Also, leveraging the provision of TRS in combination with PEI for UEs in idle and inactive modes can bring further power saving benefits to the UE. These benefits become relevant at low SINR conditions when the UE is required to monitor multiple SS bursts. Therefore, the use of TRS for synchronization can enable that the UE reduces the number of wakeups required for SS bursts before PO reception.

Furthermore, for the case of UE power saving enhancements in connected mode specified in Release 17, PDCCH monitoring adaptation such as PDCCH skipping and SSSG switching provide higher power saving benefits than Release 16 features for the case of traffic types with short packet inter-arrival times like XR (AR/VR). When enabling reduced PDCCH monitoring during long periods, gains above 20% can be expected considering that the UE is able to enter longer sleep states earlier. These gains can be achieved while properly handling retransmissions to avoid impacts in the service performance, which becomes relevant to be addressed in Release 18. The achievable gains of Release 17 power saving features, however, can be less (around 10-15%) for the case of reduced PDCCH monitoring during short periods or when longer packet inter-arrival times, like in VoNR, are considered. In these cases, Release 16 UE power saving features like BWP adaptation and SCell dormancy (for the case of more than 1 CC) already provide considerable reductions to the device power consumption.

On the other hand, configuring the UE with reduced PDCCH monitoring and RLM/BFD measurement relaxation for traffic types consisting of low data rates, like VoNR, can provide power saving gains around 30%. Since low data rates imply that less power consumption is required for PDCCH/PDSCH reception, enabling relaxation of RLM/BFD measurements on top of less PDCCH monitoring can significantly reduce the overall required power consumption in connected mode.

Acknowledgements

MediaTek Carrier Engineering Services (CES) is a team working under Wireless System Design and Partnership (WSP) division. CES team has an extensive global experience in modems and use it to assist mobile network operators in network optimization and strategy planning. CES team is responsible for working with network operators on new technology evaluations and with partners to improve the end-user experience. The work in this paper and others in 5G are sourced from the team's vast experience in 5G deployment scenarios. We wish to express our appreciation to our colleagues in MediaTek R&D and System Design teams who developed extensive studies on device power saving enhancements, and were the main drivers for the specified features in 3GPP Release 17. Through it all, MediaTek maintains its active role working with the whole ecosystem to further enhance and improve device power consumption in 5G.

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References

[1] MediaTek White Paper “Bandwidth Part Adaptation”

[2] MediaTek White Paper “5G NR Voice Solutions Overview and Deployment Guidelines”

[3] “Understanding the Heart of the 5G Air Interface: An Overview of Physical Downlink Control Channel for 5G New Radio (NR)”

[4] 3GPP RP-212630 “ Revised WID UE Power Saving Enhancements for NR”

[5] 3GPP TS 38.304 “NR; User Equipment (UE) procedures in idle mode and in RRC Inactive state”

[6] 3GPP TS 38.213 “NR; Physical layer procedures for control”

[7] 3GPP TR 38.840 “NR; Study on User Equipment (UE) power saving in NR”

[8] 3GPP R1-2007501 “Final Report of 3GPP TSG RAN WG1 #102-e v1.0.0”

[9] 3GPP TS 38.331 “NR; Radio Resource Control (RRC); Protocol specification”

[10] 3GPP TS 38.133 “NR; Requirements for support of radio resource management”

[11] 3GPP TR 38.838 “Study on XR (Extended Reality) evaluations for NR”