

Agenda item: 7.2.9.1
Source: Qualcomm Incorporated
Title: PDCCH-based power saving channel design
Document for: Discussion/Decision

1 Introduction

In RAN plenary #83, TR 38.840 [1] for UE power saving study was approved and the study item was concluded. It was observed and concluded that support for power saving signal/channel triggering UE adaptation can be beneficial for UE power saving. In the same meeting, the following objectives were approved as part of the WID [2]:

The objective is to specify the UE power saving techniques with UE adaption in achieving UE power saving. The power saving technique should address latency and performance in NR as well as network impact. The objective of the UE power saving includes the following.

- 1) *Specify power saving techniques with UE adaptation with focus in RRC_CONNECTED mode [RAN1, RAN4]*
 - a) *Specify the power saving techniques with power saving signal/channel*
 - i) *Specify the PDCCH-based power saving signal/channel triggering UE adaptation in RRC_CONNECTED*
 - ii) *Note: this objective shall not duplicate DRX operation and impact to DRX is studied at RAN2*
 - iii) *Note: Any change of PDCCH channel coding and payload interleaver is not in the scope*
 - b) *Specify the procedure of cross-slot scheduling power saving techniques*
 - i) *Note: The procedure is in addition to Rel-15 cross-slot scheduling procedure*
- 2) *Evaluate the required switching and interruption times for UE dynamic adaptation to the maximum number of MIMO layers [RAN4]*
 - a) *Note: Switching on/off the RF is part of the evaluation*

Note:

- *These objectives are RAN1/RAN4 focus and do not consider RAN2 impact.*
- *The objectives are subject to further update in RAN#84. The update will be based on recommendations from the completion of RAN2 study and remaining RAN1 recommendations based on the conclusion of RAN1 study.*

In this contribution, the aspects for 1-a will be discussed.

2 Discussion

2.1 Requirements and design considerations for different use cases

In our view, there are two main use cases of PDCCH-based power saving channels in the RRC_CONNECTED mode:

- (1) For wake-up signaling (WUS) during the inactive state (e.g., C-DRX off periods)
- (2) For triggering UE adaptation signaling during the active state (e.g., DRX active time or non-DRX configuration)

The above categorization can be justified by the fact that power saving in the two cases (i.e., inactive and active states) has different requirements and points of consideration.

For the WUS use case (1), it should be noted that the most power saving benefits lie in the two-stage wake-up procedure [4], shown in Figure 1; This is a distinguishing feature of PDCCH-based WUS from mere Rel-15 C-DRX configuration of

very short (e.g., 1-slot) onDuration. At the WUS occasion during the inactive state, UE enters the first stage for monitoring a wake-up PDCCH. At this stage, UE's capability may be strictly limited for power saving. For example, the UE does not expect to receive a same-slot scheduling grant for PDSCH or to be ready to transmit PUCCH in response to the PDSCH reception. Also, once the UE decodes a wake-up PDCCH in the WUS occasion, there is a time offset to the onDuration. Therefore, in the first stage, a lower power implementation can be achieved by optimizing, at least: (i) the PDCCH processing timeline, (ii) the amount of hardware needed to be online, (iii) the voltage/clock operating point of hardware, and potentially (iv) the Rx bandwidth and the number of antennas. Only when a wake-up PDCCH is decoded, the UE transitions to the second stage, by waking up additional hardware and processing (e.g., BWP/CC switching, CSI-RS processing, etc.), to get ready for DL/UL data scheduling. This second stage wake-up consumes additional energy but can be skipped for empty C-DRX cycles.

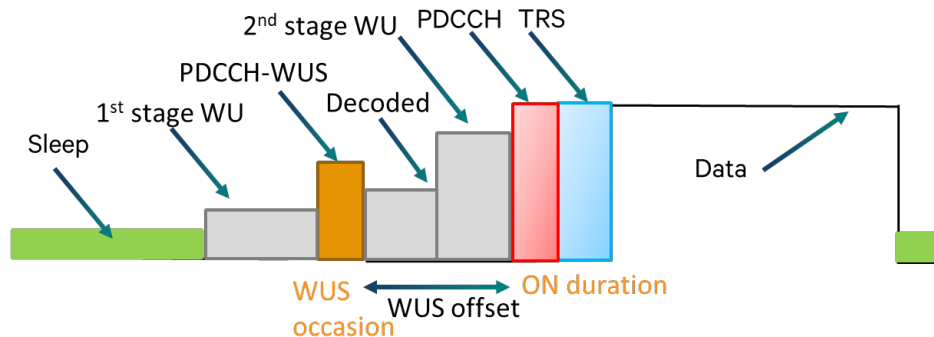


Figure 1: Two-stage wake-up timeline for PDCCH-based WUS (y-axis roughly proportional to power consumption)

During the first-stage wake-up, due to the aforementioned restriction, the UE may not be able to or be required to monitor all PDCCH candidates that it is configured to monitor during the active state. Instead, a new wake-up PDCCH, optimized for the two-stage wake-up procedure, may only need to be monitored. The detailed design of wake-up PDCCH may include a CORESET/Search space/BWP configuration for power-efficient WUS detection, DCI format/contents facilitating seamless transition to the second stage, and multiplexing with other UEs' WUS, etc.

For the use case (2) during the active state, the UE would keep monitoring the control channel in the serving cells, at least for DL/UL scheduling grants. Therefore, PDCCH-based power saving channels may be a natural option. Among the power saving schemes categorized in the studies on UE power saving [1], some are particularly well-suited with PDCCH/DCI-based triggering. However, in general, different power saving schemes require different sets and amounts of triggering information, and therefore it would be challenging to design a unified PDCCH/DCI format for different power saving schemes. For example, among the schemes discussed in [1], triggering of PDCCH skipping may require the information about skip duration or pattern, while triggering of dynamic CORESET/search space set adaptation may require the index in the set of multiple configurations. Therefore, it would be more efficient to come up with different designs tied to specific power saving techniques. Also, the introduction of power saving channels should not burden the UE with additional complication or power consumption for monitoring the power saving channel, which may dilute the overall benefit of the power saving schemes.

Furthermore, in general, as PDCCH is not backed up by a retransmission protocol, such as HARQ, any error events in the detection of PDCCH-based power saving channel may result in unexpected behaviors, both at gNB and UE sides. Therefore, a mechanism for handling the misdetection event may be needed.

Bearing in mind the aforementioned requirements and principles, we provide our views on the PDCCH-based power saving channel design in the following sections.

2.2 Design for WUS scheme for C-DRX

In RAN2 #105, RAN2 discussed UE power saving issues and an LS [3] was sent to RAN1 include the following:

1. RAN1 can focus on the design on the signal/channel. From RAN2 perspective, the power saving signal/channel scheme is considered jointly with c-DRX. RAN2 assumes that the WUS scheme is linked/associated to c-DRX. RAN2 should study the impact to c-DRX.

It is at least assumed by RAN2 that power saving signal/channel can be used in the WUS (wake-up signaling) scheme with C-DRX. Therefore, when RAN1 considers the requirements and the design for the power saving signal/channel, it is extremely important to consider the WUS scheme for C-DRX as one of the main use cases.

For the UE power saving work item [2], it was agreed to specify a PDCCH-based wake-up signal/channel. This decision is based on the results from the study item on UE power saving [1] that show PDCCH-based WUS providing significant power saving gain in different use cases, including to signal whether the UE needs to wake up for an upcoming C-DRX on-duration. These results utilized a DCI payload carried over the PDCCH channel to provide flexibility beyond a single-bit wake-up indicator and to minimize specification impact. Therefore, we propose to utilize this structure for the PDCCH-based WUS, especially in light of the note in the work item description explicitly excluding changes to PDCCH channel coding and payload interleaving.

Proposal 1: The wake-up signal for C-DRX is a DCI payload carried over the PDCCH channel, following the NR Release 15 PDCCH coding chain.

The primary function of the wake-up signal for C-DRX is to indicate whether the UE should wake-up and be prepared for transmission and reception in the upcoming C-DRX on-duration. The UE will change its internal state during the off-duration to conserve power and will require a transition period after the wake-up PDCCH is received. Therefore, the wake-up PDCCH should arrive before the C-DRX on-duration to eliminate impact on scheduling during the on-duration.

Observation 1: Having the wake-up PDCCH arrive before the on-duration with sufficient transition time helps the UE conserve power and eliminates scheduling impact during the on-duration.

Proposal 2: For the design of the wake-up PDCCH, it is assumed that the wake-up PDCCH should arrive before the C-DRX on-duration and provide the UE with sufficient transition time.

In the remainder of this section, we first discuss different wake-up modes then the configuration of the wake-up PDCCH for C-DRX and the content of the wake-up DCI it carries.

2.2.1 Periodic and Semi-persistent Operations

When the UE wakes up and transitions into the active state, it can expect to be scheduled to transmit or receive data, reference signals, and measurement reports. In addition to the dynamic, and aperiodic, scheduled transmissions, the UE also may be configured with periodic events, such as periodic CSI and SRS, as well as configured uplink grants and semi-persistently scheduled downlink grants.

In case where the network does not intend to schedule any dynamic transmissions, the UE can save power by only waking up to perform the a priori known preconfigured transmissions and receptions in the associated on-duration and going to sleep in the remaining slots in the on-duration. Whether the UE can skip periodic/semi-persistent operation based on wake-up signal is discussed in our RAN2 contribution [5]. RAN1 can discuss whether some signaling in the wake-up PDCCH or its absence can indicate that the UE skip periodic/semi-persistent operations as well as how to indicate to the UE that only periodic/semi-persistent operations are to be performed.

Proposal 3: Discuss whether the wake-up PDCCH or its absence can indicate that the UE should skip all operations including periodic, semi-persistent, and/or configured transmissions in the associated on-duration.

Proposal 4: Discuss whether the wake-up PDCCH or its absence can indicate that only periodic, semi-persistent, and/or configured transmissions will occur in the associated on-duration.

For aperiodic CSI, a trigger field can be added to the wake-up DCI as will be discussed in Section 2.2.3.

2.2.2 Wake-up PDCCH Configuration

2.2.2.1 Wake-up CORESET

It is advantageous for a CORESET containing the wake-up PDCCH to have a configuration that can be distinct from CORESETs containing PDCCH scheduling transmissions. Having smaller bandwidth for example can lead to further power savings and having different starting slots and duration helps multiplex more UEs. Another benefit is the ability to associate the wake-up CORESETs with beams (TCI states) that can be different from those used in the on-duration.

Proposal 5: CORESETs containing the wake-up PDCCH should be configurable independently of other CORESETs.

Up to three CORESETs can be configured for a bandwidth part. The wake-up PDCCH can also benefit from having multiple CORESETs configured. For example, the different CORESETs can be associated with different TCI states and the wake-up PDCCH can be transmitted using different beams (i.e., beam sweeping – see Appendix for analysis). Another benefit of having multiple wake-up CORESETs is configuring the CORESET in a manner suitable for single-UE and multi-UE wake-up PDCCH, which could have different sizes and precoding. More details on the single-UE and multi-UE wake-up PDCCH design are in Section 2.2.3.

Proposal 6: Wake-up CORESETs follows Rel-15 behavior of configuring up to three CORESETs per BWP.

There are two configurations for mapping of PDCCH DMRS within a CORESET: *sameAsREG-bundle* where DMRS symbols are mapped only to the REGs on which PDCCH is transmitted and *allContiguousRBs* where DMRS symbols are mapped to all REGs in the CORESET where PDCCH is transmitted regardless whether an REG carries PDCCH or not. Having DMRS transmitted on all REGs in the CORESET when PDCCH is transmitted improves channel estimation performance and also improves the UE's ability to detect the presence of PDCCH. In addition, it also improves tracking loop convergence at the UE, especially after a long off-duration. Therefore, it is beneficial for the wake-up PDCCH to have DMRS transmitted on all REGs in the CORESET.

Proposal 7: Wake-up CORESETs have DMRS symbols mapped to all contiguous RBs in the CORESET when a wake-up PDCCH is transmitted.

2.2.2.2 Wake-up Search Space

As discussed earlier, having the wake-up PDCCH arrive sufficiently earlier than the beginning of the on-duration eliminates any impact on scheduling during the on-duration. This could be achieved by restricting the search space monitoring periodicity to be aligned with the DRX cycle or by introducing new configuration parameters tying the monitoring occasion slot to the DRX cycle. When multiple wake-up CORESETs and search spaces are configured, UE power consumption can be reduced if all CORESETs are monitored in a single slot during the off-duration and the UE only has to wake up once during the off-duration to monitor for the wake-up PDCCH in that single slot instead of multiple slots.

Proposal 8: Wake-up search spaces associated with wake-up CORESETs are all monitored in a single slot during the C-DRX off-duration.

There are two potential wake-up PDCCHs: multi-UE and single-UE wake-up PDCCH. The multi-UE wake-up PDCCH has to be transmitted in a common search space. In this case, Type-3 common search space can be used and there is no need to introduce a new type of CSS. The single-UE wake-up PDCCH can be transmitted on a UE-specific search space. The Rel-15 mechanism of configuring multiple search spaces for a BWP and associating them with a CORESETs is sufficient.

Proposal 9: Type-3 CSS is reused for the multi-UE wake-up PDCCH if introduced.

To keep complexity and power consumption low, no PDCCH other than the wake-up PDCCH will be monitored during the off-duration and the UE would expect only one such wake-up PDCCH. Therefore, a reduced number of candidates per aggregation level should be used to reduce the complexity of receiving the wake-up PDCCH at the UE, similar to the limitation applied to DCI format 2-0 carrying slot format indication.

Proposal 10: A reduced set of candidates, aggregation levels, blind decodes, and CCE limits is used for the search space associated with the wake-up CORESET.

2.2.2.3 Wake-up Bandwidth Part

Sections 2.2.2.1 and 2.2.2.2 discussed the design and benefits of having CORESETs and search spaces dedicated to the wake-up PDCCH. Up to three CORESET and up to 10 search spaces are configured for a bandwidth part. The simplest method, and the one with the least specification impact, to support the wake-up CORESETs and search spaces is to follow current design and introduce the notion of a wake-up bandwidth part and associate the CORESETs and search spaces with it. This wake-up BWP can exist separately from the other four configurable BWPs: the UE implicitly activates the wake-up BWP when it goes to sleep and activates a different BWP after waking up. In addition to including the wake-up CORESET and search space configurations, a wake-up BWP allows configuration suitable for the wake-up PDCCH that could be different from other, scheduling BWPs. For example, the wake-up BWP could have narrower bandwidth than other BWPs.

Proposal 11: A wake-up bandwidth part is introduced and is associated with wake-up CORESETs and search spaces.

Proposal 12: The wake-up BWP is either independent of the other four BWPs in a cell and is implicitly activated/deactivated when the UE goes to sleep/wakes up or is one of the four BWPs per cell.

If one of the four BWPs per cell is used as the wake-up BWP, some limitations on which CORESETs and search space can contain the wake-up PDCCH are needed. For example, such a BWP could contain CORESETs not associated with wake-up operation and such CORESETs should not be used to monitor the wake-up PDCCH.

Proposal 13: If one of the existing four BWPs per cell is used as the wake-up BWP, only CORESETs and search spaces designated for wake-up operation are used to monitor the wake-up PDCCH.

2.2.3 Wake-up DCI Design

A wake-up PDCCH could be designed to target a single UE or multiple UEs. For the single-UE wake-up PDCCH, the DCI CRC can be scrambled with C-RNTI and the UE would still be able to distinguish between this DCI format and others associated with C-RNTI from the DCI size and as a result for of the wake-up PDCCH being the only PDCCH associated with C-RNTI monitored during the off-duration. The presence of the single-UE wake-up PDCCH indicates whether the UE wakes up or not. Other fields in the DCI of the wake-up PDCCH are important and increase system flexibility and reduce latency. Specifically, BWP id is included so that the UE will have already switched to a BWP appropriate for the expected traffic by the time the C-DRX on-duration starts. Triggers for aperiodic CSI and TRS in the DCI of the wake-up PDCCH ensure that the UE will be ready to transmit a CSI report and TRS at the beginning of the on-duration and enable the gNB to adapt early in the on-duration if the UE channel conditions have changed since the last on-duration.

Proposal 14: The DCI of a single-UE wake-up PDCCH has its CRC scrambled with C-RNTI and contains fields at least for BWP indication and A-CSI and A-TRS triggering.

To reduce PDCCH resources used to indicate wake-up, it might be desirable to have a wake-up PDCCH targeting multiple UEs. Since C-RNTI is UE-specific, a dedicated RNTI is needed for the multi-UE wake-up PDCCH. One important aspect to consider is that the reduction in PDCCH resources should not come at the cost of significant increase in UE power consumption, i.e. the multi-UE wake-up PDCCH should provide a mechanism to wake up a subset of the UEs in the group. To reduce RRC reconfiguration overhead, the multi-UE wake-up PDCCH should support a variable group size without notifying all UEs in the group, e.g. without changing the DCI or UE indication determination parameters.

Proposal 15: The DCI of a multi-UE group wake-up PDCCH, if adopted, has its CRC scrambled with a dedicated RNTI and supports waking up a subset of the UEs in the group.

Proposal 16: The multi-UE wake-up PDCCH should support a variable number of target UEs without changing the DCI size.

2.2.4 Multi-Cell Considerations

Not monitoring PDCCH during the off-duration is a significant source of power savings in C-DRX. When the UE is configured with multiple cells, monitoring the wake-up PDCCH on every cell unnecessarily increases UE power use, especially in light of C-DRX being a UE-wide operation. Monitoring the wake-up PDCCH on PCell and PSCell provides sufficient system flexibility and does not reduce the power saving benefits of the wake-up PDCCH.

Proposal 17: The UE only monitors the wake-up PDCCH on PCell and PSCell.

In some cases, for example small data transmission, not all cells will be scheduled with transmissions; therefore, it is beneficial to provide flexibility in indicating different wake-up states for the different cells. This can be achieved by means of BWP indication in the wake-up DCI.

Proposal 18: BWP indication in wake-up DCI can provide per-cell, not only per-UE, indication.

2.3 Design for triggering UE adaptation during active time

2.3.1 PDCCH-based Power Saving Channel Configuration

2.3.1.1 DCI Format of PDCCH-based Power Saving Channel

In order to minimize the specification effort during the limited Rel-16 timeline, the existing PDCCH configuration framework in Rel-15 (e.g., BWP, CORESET, and search space set configuration) can be mostly reused for the PDCCH-based power saving channel. Considering the design principles of power saving channels stated above, adding dedicated resources that the UE should monitor for power saving channels may not be encouraged. Instead, it would be desirable to transmit the power saving channel using the resources (e.g., common and/or UE-specific control resources) that the UE is already configured to monitor for other types of PDCCHs.

Proposal 19: During the active time, PDCCH-based power saving channel can share the same resources with other types of PDCCHs that the UE is already configured to monitor.

A possible concern of sharing PDCCH resources is the increased chance of blocking. However, monitoring of PDCCH-based power saving channel can be sparser than other control channels and thus the impact would be marginal.

One of the simplest strategies of introducing PDCCH-based power saving channels in Rel-16 is modifying existing DCI formats (e.g., scheduling DCI formats) by appending a new information field. The presence of the new field should be configurable, since only Rel-16 or later devices can recognize it. Although it looks straightforward, this strategy reveals several issues. For example, an increased DCI payload size may negatively affect the PDCCH decoding complexity as well as the performance. Thus, the size of the appended field should be maintained small, which may limit the functionalities of power saving schemes. Also, if we use the scheduling DCI formats as baseline, the power saving scheme may only be triggered with data transmission/reception, while some power saving schemes can be used independently from the UE's traffic status.

As a workaround for the aforementioned issues, separated from existing DCI formats, new DCI formats that are dedicated for triggering of different power saving schemes may be defined. As we proposed above, the power saving PDCCH with a new DCI format can be transmitted within the same CORESETs/search space sets that the UE is already configured to monitor.

Proposal 20: New dedicated DCI formats for triggering power saving schemes during the active time can be defined.

2.3.1.2 Payload Size of PDCCH-based Power Saving Channel

In Rel-15, a UE expects to monitor PDCCH candidates for up to 4 sizes of DCI formats. Adding a new DCI format in UE's blind-decoding hypotheses may either require an increase of blind decoding budget or result in a reduction in the number of PDCCH candidates for other purposes. In order to avoid such drawbacks, the size of the new DCI format for power saving should be matched to the one of the existing DCI formats that the UE is configured to monitor. The size matching can be achieved by different techniques, such as configuration, padding, or truncation. At the same time, by using the same set of CCE(s) as the existing PDCCH candidates, the PDCCH-based power saving channel does not increase the number of blind-decoding hypotheses.

Proposal 21: PDCCH-based power saving channel should use the same DCI size and set of CCE(s) as existing PDCCH candidates.

Among the different sizes of DCI formats that the UE is configured to monitor during the active time, the size of fallback DCI formats (i.e., DCI formats 0_0 and 1_0) may be selected as the size of power saving PDCCHs. However, depending on the search space configurations and/or the required DCI payload size for a specific power saving scheme, the other sizes, such as DCI formats 0_1 and 1_1 can also be considered. If the UE is configured by higher layers with parameter *SlotFormatIndicator*, the size of DCI format 2_0 can be another option.

2.3.1.3 Identification of PDCCH-based Power Saving Channel

Polar decoding of PDCCH candidates, which is the first step of blind decoding, is oblivious of the DCI format. Therefore, if multiple DCI formats share the same size, the second step of distinguishing them is necessary. Rel-15 already supports

several methods for DCI format identification. For example, different RNTI values can be configured for DCIs of different purposes. Note that the additional computation required by an additional cycle redundancy check with a different RNTI is marginal, compared to the complexity of Polar decoding. If different DCI formats have the same size and RNTI value, an explicit identifier can be included in the DCI format. Note that DCI formats 0_0 and 1_0 include a one-bit identifier for this purpose.

When new DCI formats for power saving are added, the same principle can be applied. That is, a special RNTI, e.g., PS-RNTI, can be configured either in a UE-specific or group-common manner. When a UE monitors more than one power saving channels, those power saving channels may use different PS-RNTI values or share the same PS-RNTI. Among different power saving channels sharing the same PS-RNTI, a DCI format/scheme identifier field can be added in the payload.

Proposal 22: PDCCH-based power saving channels can be identified by a special RNTI and/or identifier field in the DCI.

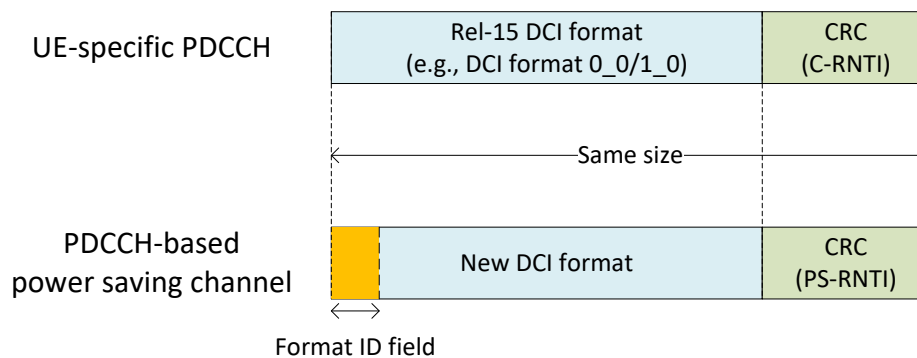


Figure 2: Configuration of PDCCH-based power saving channels

2.3.2 Error Handling for PDCCH-based Power Saving Channel

As discussed in Subclause 2.3.1.1, there are benefits in separating the DCI formats for PDCCH-based power saving channel from existing DCI formats, e.g., for DL/UL scheduling. In general, a control channel requires a more stringent performance target than data channels at least for the initial transmission of a HARQ process. However, since the control channel is not backed up by a retransmission protocol, any error events in the detection of PDCCH-based power saving channel may conclude in unexpected behaviors, both at gNB and UE sides. Therefore, a mechanism for handling the misdetection event may be needed. It is noted that the false alarm event for the control channel is extremely rare due to the 24-bit CRC and may not need any handling.

The impact of misdetection of the power saving channel may vary. In a lenient situation, it may end up with a small increase of power consumption. However, in some cases, particularly when the power saving scheme is associated with a relatively long-term behavior or a semi-persistent change of power states, it may result in a significant system impact. A similar problem is encountered in Rel-15 BWP switching; if the UE fails in detecting the BWP switching DCI, it may result in the repeated failure of PDCCHs during a long period. Therefore, to prevent the propagation of the failure, Rel-15 allows configuration of a BWP inactivity timer and default BWP.

For some power saving schemes triggered by PDCCH, the same principle can be applied. If possible, PDCCH-based triggering of any permanent power state changes should be avoided. Also, configuration of a timer and default mode for a power saving scheme may provide the second-level protection. The timer can be either be an activity timer or inactivity timer; for some power saving scheme, the 'inactivity' may be the desired mode during power saving operation.

While the timer-based implicit mechanism can help recovery from the misdetection event of power saving channels, it involves some latency during which the UE may unnecessarily waste power. The latency would be controlled by configuring the timer to be short enough. However, short timer may require more frequent transmission of power saving channels, which leads to the increased system overhead and power consumption. In addition, based on the experience of specifying the BWP activity timer, the effort is substantial and would involve RAN2. Overall, this approach to ensure

robustness is not preferred. In the next paragraph, a more preferred solution to this issue, borrowed from LTE or NR Rel-15, is described.

Observation 2: When a power saving scheme is triggered by PDCCH, configuration of a timer and default power mode can provide protection from the misdetection event of the power saving channel. However, it is not the most preferred approach due to potentially long latency for error recovery and substantial specification effort.

In Rel-15, if a UE is configured with DL semi-persistent scheduling, it can receive a PDCCH indicating SPS PDSCH activation or release. Also, in response to a PDCCH for SPS PDSCH release, the UE is expected to feedback HARQ-ACK information to the gNB. This is an explicit mechanism that is also useful for PDCCH-based power saving channels. Along with the timer-based mechanism, the explicit ACK feedback can complement the robustness against the detrimental misdetection event.

Observation 3: Rel-15 supports HARQ-ACK feedback in response to a PDCCH for SPS PDSCH release.

Proposal 23: HARQ-ACK feedback in response to a PDCCH-based power saving channel can be considered for robust power saving adaptation operation.

2.3.3 DCI Contents of PDCCH-based Power Saving Channel

Many candidate power saving techniques have been discussed in [1] for UE's adaptation during the active time. As different power saving schemes require different triggering information, the design of DCI contents of the triggering PDCCH need to be coupled with the individual scheme. In the same line of discussion as previous subclauses, a power saving scheme may be associated with a specific DCI format. Some examples of power saving schemes during the active time, and the corresponding contents of triggering DCI are discussed in the following subclauses.

2.3.3.1 DCI for triggering PDCCH skipping

For various traffic models, it is observed that reducing PDCCH monitoring shows 5%-85% power saving gains compared to Rel-15 baseline [1]. The principle of PDCCH skipping is putting the UE into sleep between two adjacent bursts of traffic arrivals. This can be done by indicating a duration or pattern of sleep to the UE via a triggering DCI. The statistics of the gap between two adjacent traffic bursts suggests that the sleep duration is on a relatively small-time scale and, thus, the power saving gain is mostly from the extended micro-sleep. As a complement, a longer duration of traffic inactivity can better be handled by C-DRX, which can put the UE into deeper sleep.

Ideally, if the natural gap between arrivals of traffic bursts matches exactly the indicated sleep duration, there would be no or little performance impact at the cost of the power saving gains. However, sometimes the exact gap may not be predictable or, due to the limited payload, may not be accurately indicated. This comes to the reduced UPT and increased latency.

For a better tradeoff between the power saving gain and the performance loss, a logical way of indicating a duration or pattern of sleep is using a look-up table (LUT). The LUT contains multiple candidates of sleep duration or pattern, and may be semi-statically configured for the UE depending on the service type or statistics of traffic. The triggering DCI then contains a field for the index in the LUT. The size of the field is determined by the size of the LUT, and vice versa.

If the UE is served by more than one serving cells, a single DCI may trigger the sleep/PDCCH skipping in different cells. For this purpose, the DCI can be further extended to include multiple fields as illustrated in Figure 3. Alternatively, in the case that the PDCCH power saving channel is shared by a group of UEs, each of the fields can be intended for an individual (or sub-group of) UE(s).

Notably, in Rel-15, the dynamic slot-format indication (SFI) in Rel-15 is based on the same principle. Therefore, we believe that it can be a good reference for the design of PDCCH-based power saving channel, at least for PDCCH skipping purpose.

Observation 4: Slot format indication in Rel-15 can be considered as the baseline for the indication of PDCCH skipping.

In Subclause 2.3.2, it is discussed that some power saving channels may require HARQ-ACK for robustness. This is particularly true for power saving schemes that trigger semi-persistent power state change. However, as noted above,

PDCCH skipping does not incur semi-persistent change and only spans relatively small time duration. Therefore, at least for the power saving channel triggering PDCCH skipping, no HARQ-ACK feedback is needed.

Observation 5: For PDCCH-based power saving channel triggering PDCCH skipping, HARQ-ACK feedback is not required.

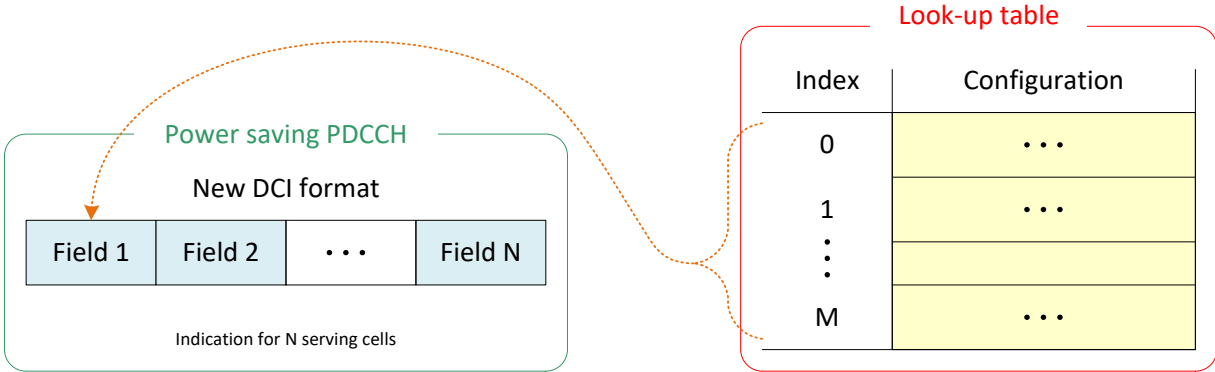


Figure 3: DCI contents for triggering UE sleep for an indicated duration or pattern.

2.3.3.2 DCI for triggering CORESET/search space set adaptation

Along with PDCCH skipping, an alternative discussed in the study [1] for reducing PDCCH monitoring during the active time is dynamically changing the configuration of CORESETs or search space sets. Compared to PDCCH skipping, which applies temporary restriction on UE’s behavior, the adaptation of CORESET/search space set configuration can persist for a longer time and is proper for mid- or long-term adaptation.

In Rel-15, up to three CORESETs and ten search space sets can be configured per BWP, each of which can be individually configurable. Therefore, a simplest design for CORESET/search space set adaptation is selecting, or activating or deactivating, a proper subset of configured CORESETs/search space sets depending on the UE’s power and traffic situation. The PDCCH power saving channel to this end may have a similar format with Figure 3. That is, the DCI may have multiple fields corresponding to multiple serving cells. Each field may be a bitmap for configured CORESETs/SS-sets for the current active BWP in the corresponding cell. Each bit in the bitmap can indicate whether the corresponding CORESET/SS-set is active or not.

Observation 6: A PDCCH-based power saving channel may trigger activation/deactivation of configured CORESETs/search space sets.

Observation 7: Activation/deactivation of configured CORESETs/search space sets by a power saving DCI may require a HARQ-ACK feedback.

2.3.3.3 DCI for BWP adaptation

Since UE’s behavior is governed by the UE’s configuration, it is evident that dynamic adaptation of configuration parameters to the traffic can reduce UE’s power consumption. Although most of the UE configuration is managed by higher layers in a semi-static manner, the Rel-15 BWP concept offers a nice framework for dynamic configuration adaptation.

In Rel-15, the usage of the BWP framework for general adaptation of UE’s power state (i.e., set of configuration parameters – or, so called “power profile” in some sources) may be limited due to some shortcomings. Some of them as well as the potential enhancements have already been discussed in our previous contribution [4]. Considering that many power-related parameters already have BWP-specific configuration in Rel-15, rather than reinventing another adaptation framework, our preference is to address the shortcomings of the BWP framework and extend it for general adaptation of UE’s power state. One shortcoming with BWP switching is that it is only triggered by scheduling DCIs, e.g., DCI formats 0_1 and 1_1. Also, if the bandwidth, the center frequency, and SCS do not change during a BWP switch, a shorter BWP transition time than currently specified in TS 38.133 may be feasible. Considering the application of BWP switching for UE’s power state adaptation, having another switching mechanism (i.e., power saving channels) decoupled from data scheduling may be beneficial in some respects. For example, in the low traffic condition, the gNB may want to put the UE in the “power saving

BWP” as early as possible, without having to wait for the arrival of traffic to be scheduled. Also, proactive adaptation of UE’s state before the arrival of traffic may alleviate the UPT/latency impact.

Observation 8: A PDCCH-based power saving channel may trigger BWP adaptation without DL/UL scheduling to better serve as a general framework for adaptation of power-related parameters.

For BWP adaptation, the power saving channel may have a similar format with Figure 3. In this case, each field in the DCI may contain an index of BWP, or more generally, an index of UE’s power states in the LUT.

Also, as discussed in Subclause 2.3.2, the power saving channel triggering BWP adaptation may need HARQ-ACK feedback – especially for the purpose of power-related parameters adaptation it may not be always easy to disambiguate between different BWPs based on PDCCH detection alone.

3 Conclusion

Observation 1: Having the wake-up PDCCH arrive before the on-duration with sufficient transition time helps the UE conserve power and eliminates scheduling impact during the on-duration.

Observation 2: When a power saving scheme is triggered by PDCCH, configuration of a timer and default power mode can provide protection from the misdetection event of the power saving channel. However, it is not the most preferred approach due to potentially long latency for error recovery and substantial specification effort.

Observation 3: Rel-15 supports HARQ-ACK feedback in response to a PDCCH for SPS PDSCH release.

Observation 4: Slot format indication in Rel-15 can be considered as the baseline for the indication of PDCCH skipping.

Observation 5: For PDCCH-based power saving channel triggering PDCCH skipping, HARQ-ACK feedback is not required.

Observation 6: A PDCCH-based power saving channel may trigger activation/deactivation of configured CORESETs/search space sets.

Observation 7: Activation/deactivation of configured CORESETs/search space sets by a power saving DCI may require a HARQ-ACK feedback.

Observation 8: A PDCCH-based power saving channel may trigger BWP adaptation without DL/UL scheduling to better serve as a general framework for adaptation of power-related parameters.

Observation 9: PDCCH-WUS meets the misdetection rate criterion and provides extremely low false alarm rate.

Proposal 1: The wake-up signal for C-DRX is a DCI payload carried over the PDCCH channel, following the NR Release 15 PDCCH coding chain.

Proposal 2: For the design of the wake-up PDCCH, it is assumed that the wake-up PDCCH should arrive before the C-DRX on-duration and provide the UE with sufficient transition time.

Proposal 3: Discuss whether the wake-up PDCCH or its absence can indicate that the UE should skip all operations including periodic, semi-persistent, and/or configured transmissions in the associated on-duration.

Proposal 4: Discuss whether the wake-up PDCCH or its absence can indicate that only periodic, semi-persistent, and/or configured transmissions will occur in the associated on-duration.

Proposal 5: CORESETs containing the wake-up PDCCH should be configurable independently of other CORESETs.

Proposal 6: Wake-up CORESETs follows Rel-15 behavior of configuring up to three CORESETs per BWP.

Proposal 7: Wake-up CORESETs have DMRS symbols mapped to all contiguous RBs in the CORESET when a wake-up PDCCH is transmitted.

Proposal 8: Wake-up search spaces associated with wake-up CORESETs are all monitored in a single slot during the C-DRX off-duration.

Proposal 9: Type-3 CSS is reused for the multi-UE wake-up PDCCH if introduced.

Proposal 10: A reduced set of candidates, aggregation levels, blind decodes, and CCE limits is used for the search space associated with the wake-up CORESET.

Proposal 11: A wake-up bandwidth part is introduced and is associated with wake-up CORESETs and search spaces.

Proposal 12: The wake-up BWP is either independent of the other four BWPs in a cell and is implicitly activated/deactivated when the UE goes to sleep/wakes up or is one of the four BWPs per cell.

Proposal 13: If one of the existing four BWPs per cell is used as the wake-up BWP, only CORESETs and search spaces designated for wake-up operation are used to monitor the wake-up PDCCH.

Proposal 14: The DCI of a single-UE wake-up PDCCH has its CRC scrambled with C-RNTI and contains fields at least for BWP indication and A-CSI and A-TRS triggering.

Proposal 15: The DCI of a multi-UE group wake-up PDCCH, if adopted, has its CRC scrambled with a dedicated RNTI and supports waking up a subset of the UEs in the group.

Proposal 16: The multi-UE wake-up PDCCH should support a variable number of target UEs without changing the DCI size.

Proposal 17: The UE only monitors the wake-up PDCCH on PCell and PSCell.

Proposal 18: BWP indication in wake-up DCI can provide per-cell, not only per-UE, indication.

Proposal 19: During the active time, PDCCH-based power saving channel can share the same resources with other types of PDCCHs that the UE is already configured to monitor.

Proposal 20: New dedicated DCI formats for triggering power saving schemes during the active time can be defined.

Proposal 21: PDCCH-based power saving channel should use the same DCI size and set of CCE(s) as existing PDCCH candidates.

Proposal 22: PDCCH-based power saving channels can be identified by a special RNTI and/or identifier field in the DCI.

Proposal 23: HARQ-ACK feedback in response to a PDCCH-based power saving channel can be considered for robust power saving adaptation operation.

4 References

- [1] R1-1903832, “Study on UE Power Saving (Release 16)”, TR 38.840.
- [2] RP-190727, “New WID: UE Power Saving in NR”, CATT, CAICT
- [3] R1-1903765, “LS to RAN1 on power saving”, RAN2
- [4] R1-1903016, “Potential Techniques for UE Power Saving”, RAN1#96, Qualcomm
- [5] R2-1903047, “Wakeup signaling and its RAN2 impact,” RAN2#105bis, Qualcomm

5 Appendix

5.1 Wake-up PDCCH Performance in FR1

The minimum DCI size is 12 bits, ensured by padding, in addition to a 24-bit CRC, resulting in a minimum size of 36 bits. Figure 4 shows the SNR required to reach 10^{-3} misdetection rate for three DCI sizes (including the 24-bit CRC): 36, 44, and 54. Performance results are provided for different aggregation levels and number of receiver antennas. It can be observed that PDCCH-WUS provides good mis-detection rate, especially with the smaller DCI sizes. Performance can be further improved by using aggregation-level 16. These simulation results assume that DCI carries a payload, the UE detects whether it is the intended recipient based on the RNTI used to scramble the CRC (standard PDCCH reception procedure).

The false alarm rate of PDCCH was extensively studied and was found to be less than 1.5×10^{-21} when a polar decoder with list size of 8 was used (as was used for the performance results in Figure 4).

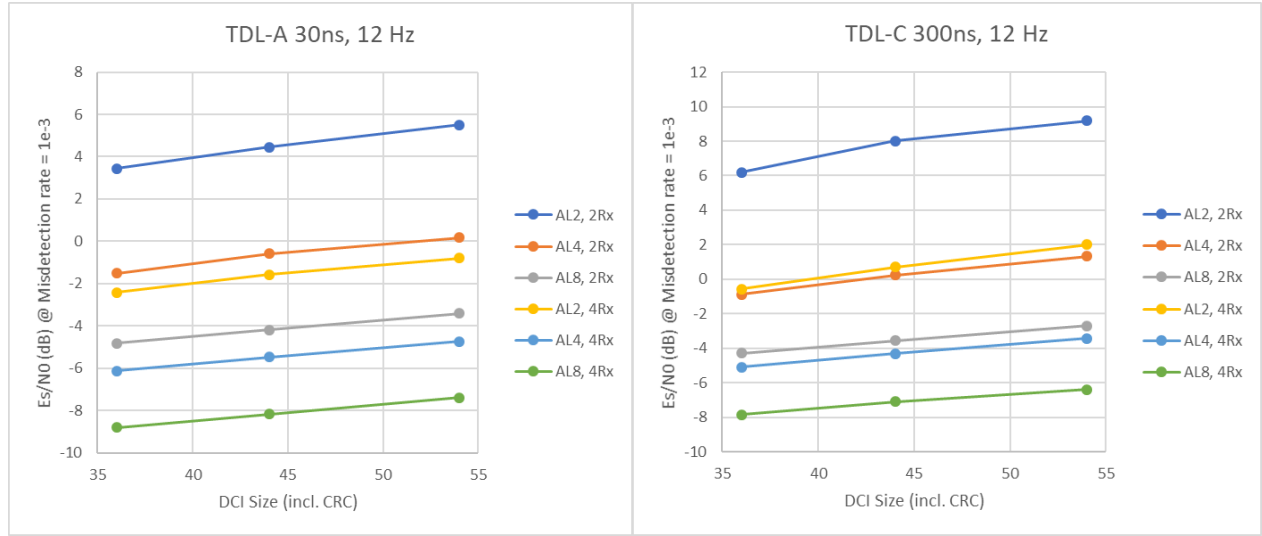


Figure 4 SNR required to reach PDCCH misdetection rate of 10^{-3} for different DCI sizes with realistic channel estimation.

Observation 9: PDCCH-WUS meets the misdetection rate criterion and provides extremely low false alarm rate.

5.2 Wake-up PDCCH Performance in FR2

The goal is to quantify the relationship between the WUS misdetection probability and the beam deviation during a C-DRX off period. For the modeling of the spatial/angular-domain channel variation, we assume that the UE's orientation changes at a constant rate, e.g., 180 degrees per second. Initially, the UE has a uniformly random bearing angle, while the downtilt and slant angles are fixed to zero, and a set of N best beam pairs in terms of L1 RSRP is found. Then, the UE goes to sleep during a certain length of C-DRX off period and wakes up to detect WUS. For simplicity, we further assume that the length of C-DRX off period is equal to the length of the C-DRX cycle (i.e., the length of ON duration and WUS occasion is ignored), and there is no additional (e.g., SSB-based) beam refinement during the C-DRX off period. Therefore, the total angular deviation of the channel is determined as

$$\text{Angular deviation: } \Delta\alpha = 180 \cdot \Delta t \text{ [deg]},$$

where Δt is length of the C-DRX cycle in seconds.

As captured in [1], the link-level simulation parameters specified in Table A1.5-1 in TR38.802 are assumed. Additional information for PDCCH-WUS configuration can be found in [4].

In Figure 5 and Figure 6, the misdetection performance of PDCCH-WUS is presented for different numbers of sweeping beams. The SINR values of interest are 3dB and -6dB for Figure 5 and Figure 6, respectively, where the SINR is defined for the post-beamforming signal with the best beam pair in terms of L1 RSRP.

Setting the target misdetection probability to 0.1%, in Figure 5 (SINR=3dB), the target performance can be achieved for 40ms C-DRX cycle without any beam sweeping. However, with 160ms C-DRX cycle, it is observed that beam sweeping is inevitable. For example, with AL8, using 3 or more beams to sweep for PDCCH-WUS can achieve the target performance with 160ms C-DRX cycle. Also, with AL4, the target performance can still be attained for 160ms C-DRX cycle, with a larger number of beams (e.g. 7 beams) than AL8. However, for a longer C-DRX cycle, such as 320ms, the target performance cannot be attained for all cases. As a consequence, in rapid beam deviation scenarios, the C-DRX cycle should be chosen to be short enough or additional beam management during C-DRX off period should be considered.

In Figure 6 (SINR=-6dB), even the baseline performance (w/o beam deviation) cannot achieve the target performance and the gain of WUS beam sweeping is not advocated. In principle, at a very low SINR regime, despite additional efforts and resource requirements for adopting PDCCH-WUS, only marginal return would be expected. In such a case, the UE may choose to operate in a legacy C-DRX mode (Rel-15 C-DRX operation).

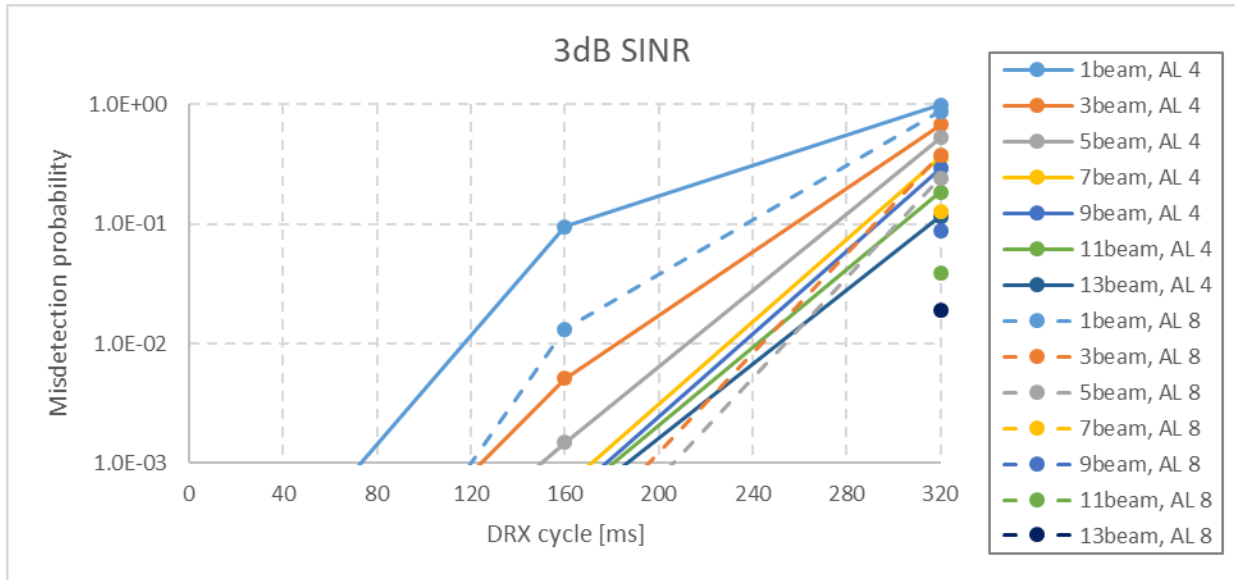


Figure 5: PDCCH-WUS misdetection probability at SINR=3dB

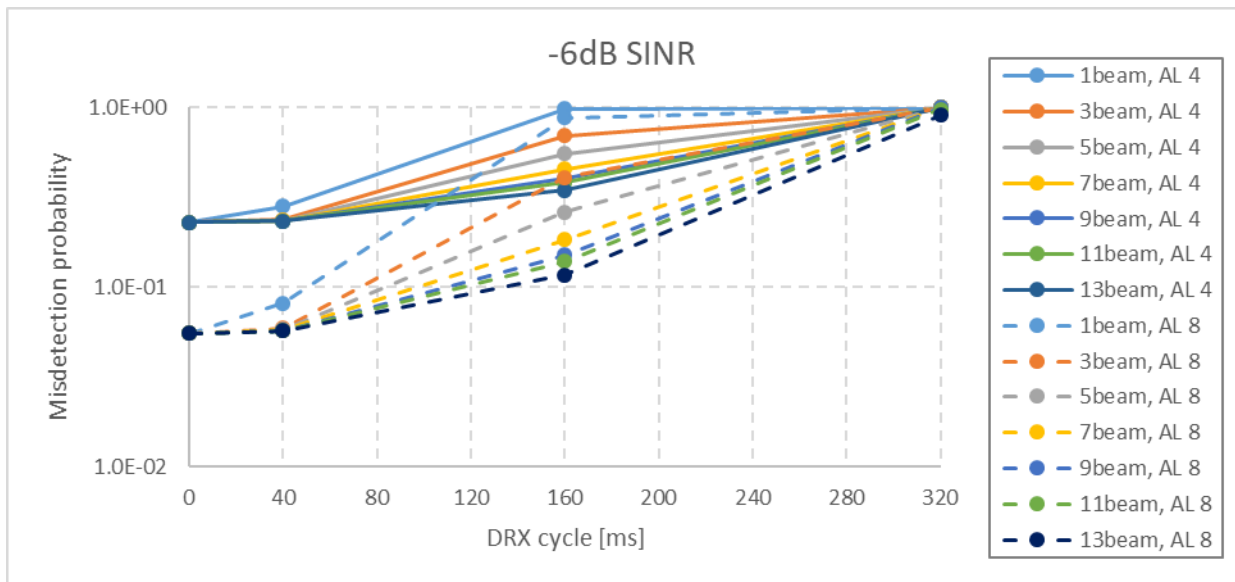


Figure 6: PDCCH-WUS misdetection probability at SINR=-6dB