Qualcomm

2023
Benefit of 3GPP Rel.17 Power Saving Features

(PDCCH Skip || SSSG-Switching)

Contents

1. Introduction: Rel17 DCI-based PDCCH Skip & SSSG-switching

While 3GPP introduced various connected-mode power-saving measures in Rel.15 and Rel.16 to optimize UE battery-consumption while operating at larger channel bandwidth, battery-consumption pertaining to PDCCH-monitoring continues to be one of the primary contributors to modem-RF power consumption. Accordingly, 3GPP Rel.17 introduced two new techniques to further reduce the duration of time that UE would need to monitor PDCCH during the active part of CDRX of the active bandwidth-part (BWP) of the serving cell.

1.1 DCI-based PDCCH Skipping

PDCCH Skip allows a UE to reduce the amount of time it spends in monitoring PDCCH, which in turn helps reduce the power consumption. The gNB can send a DCI to the UE indicating the length (time-duration) that UE should skip PDCCH monitoring.

Figure 1 below represents the sequence of events taking place in course of DCI-based PDCCH Skip process, with an example of 16-slot skip duration (Note : Dummy-DCI below refers to a DCI to continue with PDCCH Skip in absence of any payload).

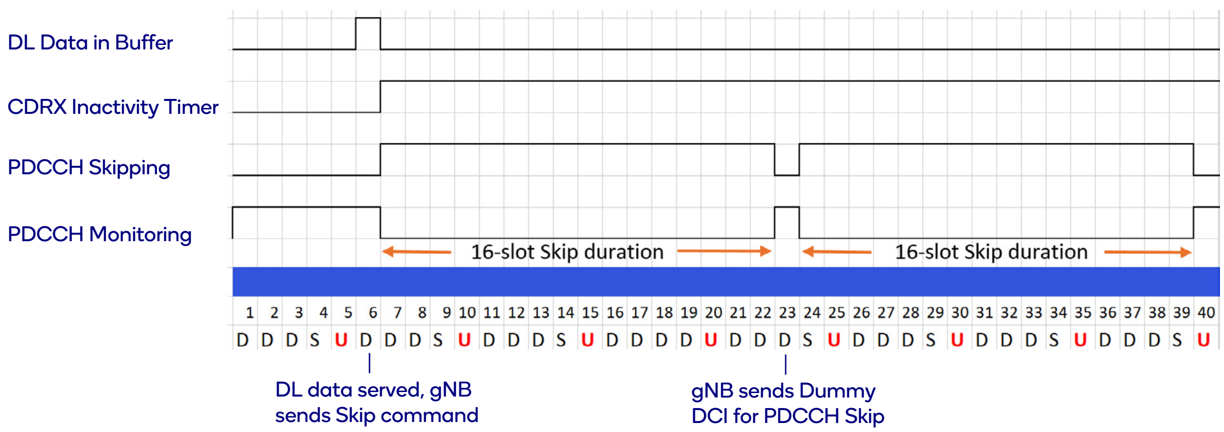

Figure 1: 3GPP Rel.17 DCI-based PDCCH Skip

At a high-level, PDCCH skipping involves the following steps:

- The gNB can configure up to 3 different PDCCH Skip durations via RRC messages.
- The gNB monitors the buffer occupancy and determines when to initiate PDCCH skipping
  - The gNB also determines which of the 3 skip durations to initiate. If the gNB is aware of a certain traffic pattern, the skip duration is chosen to last until the next packet's expected arrival.
  - If the gNB is not aware of the traffic pattern, the skip duration can be fixed or can be chosen based on factors like the current PDCCH load.

- The gNB transmits a DCI containing the PDCCH monitoring adaptation field (or simply, PDCCH skip order). For this, new 1-bit or 2-bit structure had been introduced associated with a specific set of DCI formats.
  - The DCI may indicate a new DL or UL scheduling, or it may signal a retransmission of a previously decoded transport block, just to initiate the PDCCH Skip when no new payload data is available. The latter case is referred to as Dummy PDCCH Skip DCI.
- The UE stops monitoring PDCCH for the indicated number of slots after receiving a DCI containing the PDCCH skip order.

To maximize UE power saving when no data is available, the gNB may need to send a new dummy-DCI containing another PDCCH skip indication upon expiry of the current PDCCH skip duration. In certain extreme scenarios, a gNB may not have enough PDCCH capacity to continuously send dummy-DCIs to multiple UEs simultaneously, in which case UEs might experience a loss of power saving efficiency.

On the other hand, if a UE sends a Scheduling Request (SR), or if a previous SR-response is pending indicating the need for the UE to receive UL-grant while already in PDCCH skip mode, the UE may start monitoring PDCCH immediately, in anticipation of a new UL-grant to finish pending UL data transmission.

Figure 2 below shows an example of UE starting to monitor PDCCH immediately after

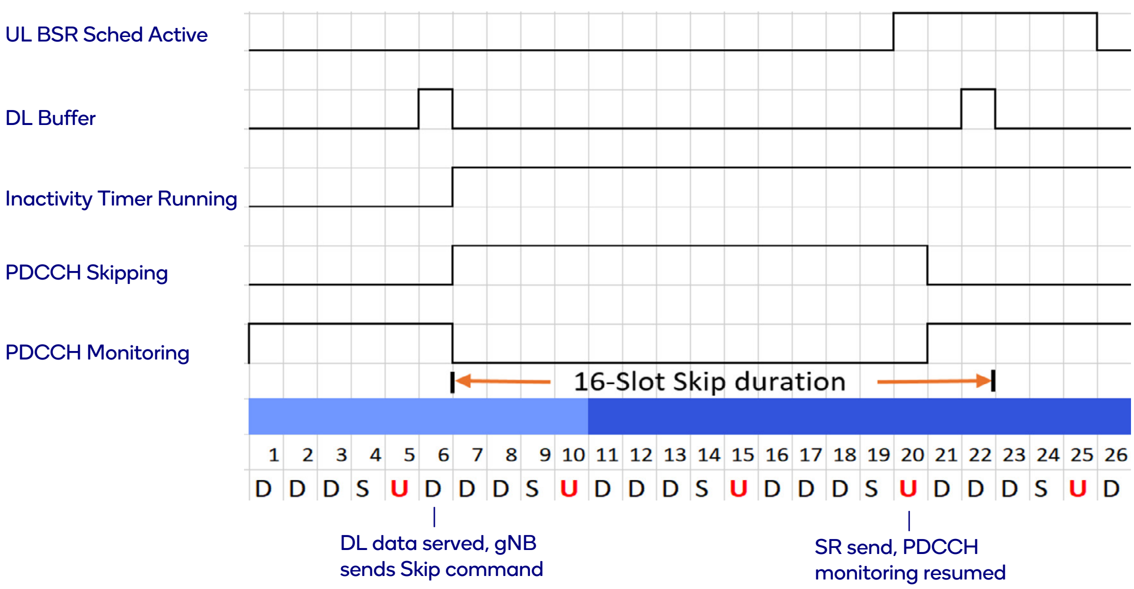

Figure 2: 3GPP Rel.17 PDCCH Skip Termination Upon Arrival of SR

1.2 SSSG (Search Space Set Group) Switching

The goal of SSSG switching is to allow a UE to dynamically switch between a set of SSSGs that is already configured on the active DL BWP of the serving cell.

While exact implementation may vary based on RAN-infra solution, at a high-level, SSSG switching involves the following steps:

- The gNB configures through RRC two SSSGs (SSSG0 and SSSG1) per BWP where SSSG switching is supported.
- The gNB may monitor traffic and buffer occupancy to determine when to initiate a SSSG switching.
- The gNB may transmit a DCI that causes the UE to switch SSSGs.
- The gNB may also configure the UE, with a timer for switching between SSSG0 and SSSG1. The timer may represent a fixed time duration or an inactivity timer in SSSG1.
- The UE stops monitoring the old SSSG and starts to monitor the new SSSG in the beginning of the first slot after the switch delay.

In DCI-based SSSG switching, it may be expected that SSSG0 configures discontinuous PDCCH monitoring to reduce UE power consumption, while SSSG1 configures PDCCH monitoring at every downlink slot. In such case, the gNB scheduler may switch the UE to SSSG1 for high throughput or low-latency data transmission, while switching the UE back to SSSG0 for low throughput, latency-tolerant traffic.

Figure 3 below shows an example of UE monitoring PDCCH infrequently in SSSG0 during low data activity period, while also switching to SSSG1 during high data-burst and monitoring PDCCH at every slot.

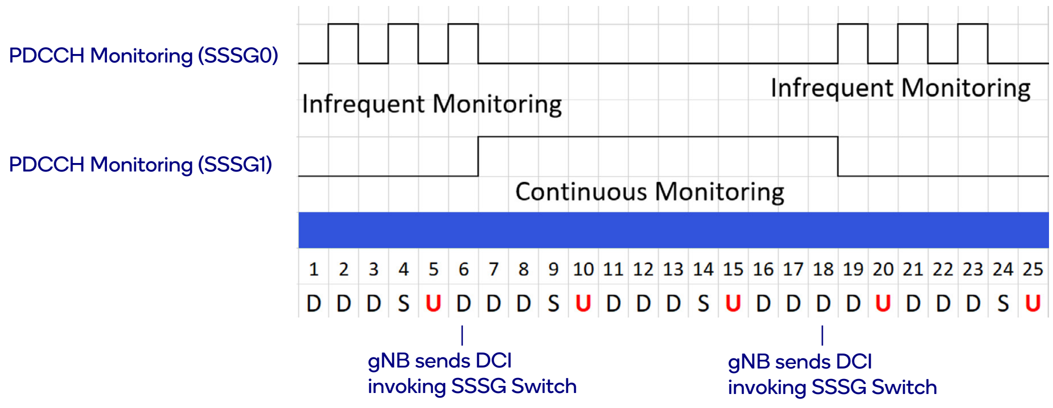

Figure 3: 3GPP Rel.17 SSSG Switching

1.3 PDCCH Skip & SSSG Switching: How Do They Compare

While both schemes aim to achieve the same power-saving goal, with very similar switching mechanism driven by PDCCH-DCI command, there are subtle differences between the two, as outlined below.

It may also be noted that both could co-exist, leading to additional power-saving opportunity, as a function of their implementation as well as types of application.

Table 1: PDCCH Skipping vs. SSSG switching comparison

Description	PDCCH Skipping	SSSG switching
Procedural delay	Immediately after the DCI or after last data scheduling	After the switching delay (typically 2 slots)
Missed DCI impact	UE keeps monitoring PDCCH	UE stays in the wrong SSSG
SR handling	SR causes the UE to resume monitoring PDCCH	UE continues to monitor the current SSSG (SR has no impact)
Timer trigger	Each skip duration is pre-determined (i.e., based on a timer)	Fallback from one SSSG to another may be based on timer
Early termination of CDRX active time	Trigger PDCCH skipping for rest of the CDRX inactivity timer in the last newTx/reTx/ dummy DCI.	Switch to an SSSG with large periodicity for CDRX inactivity timer to expire before the next PDCCH monitoring occasion (PMO). UE may still have one extra PMO before the CDRX inactivity timer expires as PMOs are periodic and fixed in time.
Continued skipping / sparse PDCCH monitoring	Requires a constant flow of DCIs (dummy-DCIs)	UE remains in current SSSG (assuming fallback timer is not configured)
Impact to network PDCCH capacity	High	Low
Impact on DL Latency	At max equals to skip duration	At max equals to periodicity value
Impact on UL latency	No impact since PDCCH monitoring resumes once UE sends SR	At max equals to periodicity value since PDCCH monitoring does not resume due to SR

2. UE and Infrastructure Requirement

2.1 UE Capability Requirement

Being a 3GPP Rel17 feature, explicit UE-support indication is used as part of the capability message to inform gNB of its capability to support either or both features.

- UE must have appropriate capabilities to support Rel.17 PDCCH skip and Rel.17 SSSG-switching.
- UE must be able to monitor the PDCCH and decode DCI messages.
- UE must be able to switch between different SSSGs.
- UE must be able to handle BWP adaptation.

The following UE-capability indications are defined in 3GPP Rel17 to standardize the process.

- **pdcch-SkippingWithoutSSSG-r17:** Indicates whether the UE supports up to 2-bit indication of PDCCH skipping by scheduling DCI if SSSG is not configured
- **pdcch-SkippingWithSSSG-r17:** Indicates whether the UE supports 2-bit indication of SSSG switching between 2 SSSGs, PDCCH skipping by scheduling DCI, and timer based SSSG switching
- **sssg-Switching-1BitInd-r17:** Indicates whether the UE supports 1-bit indication of SSSG switching between 2 SSSGs by scheduling DCI, and timer based SSSG switching, if pdcch-SkippingDurationList is not configured.
- **sssg-Switching-2BitInd-r17:** Indicates whether the UE supports 2-bit indication of SSSG switching among 3 SSSGs by scheduling DCI and timer based SSSG switching, if pdcch-SkippingDurationList is not configured.

2.2 gNB Infrastructure Requirement

Similar to the UE-capability and being a 3GPP Rel17 feature, gNB is required to support either or both of the two features, although no explicit indication is sent out to the UE indicating its ability to support. However, upon receipt of UE-capability-message, gNB may decide to configure the UE appropriately, which could be treated as an indirect indication of its capability to support such features.

- gNB shall be configured to support Rel.17 PDCCH skip and/or Rel.17 SSSG-switching power saving features.
- gNB shall be able to send PDCCH commands (DCI with specific format) that are compatible with PDCCH skipping and SSSSG-switching.
- For PDCCH skip, in addition to opportunistically sending DCI message with the last grant, gNB shall also be able to send dummy-DCIs after encountering DL empty buffers.
- For SSSG-switching, gNB shall be able to send DCI message indicating which SSSG shall be used and how the PDCCH monitoring shall happen within a particular SSSG.
- gNB shall be able to track the UE's state and ensure that it is not skipped over when a new DCI message is sent.

3. Simulation Result: UE Power-Consumption Benefit

In order to estimate realistic power-saving benefit against a baseline reference of current Rel.16 ecosystem that includes other power-saving features like CDRX and BWP, simulations were done for both features, while estimating the benefit over multiple popular application types.

Two sets of comparative results as outlined below are discussed in the subsequent sections:

- PDCCH skip vs Baseline.
- SSSG-switching vs Baseline.

The baseline simulations are also based on the same set of network-configuration assumptions except for the fact that they use neither PDCCH skip nor SSSG-switching power saving features. The result tables provide power saving as well as the impact on the average downlink air-interface latency associated with the power saving feature for different periodicities or skip durations. The results presented here also cover various popular applications.

The assumptions and the power model we used for these simulations as well as the comparative results are presented in the following sections.

3.1 FR1 Study (100MHz TDD with M-MIMO || n77/n78/n41)

3.1.1 Simulation Assumption

The assumptions used for the simulations are as follows:

- Baseline Assumption
  - CDRX 100ms (Inactivity)-10ms (On)-160 ms (Long-DRX)
  - SCS 30 KHz || TDD-Config 7DSUU || #CC 1CC 100 MHz
  - RF Condition Mid-cell
  - Bandwidth Part (BWP) BWP1 20MHz, BWP2 100MHz
- DCI-based PDCCH Skip Skip duration: {2.5, 10, 40} ms
  - Simulations were run with a fixed skip duration and swept across multiple values to do a comparative analysis.
  - PDCCH skip is applied in both BWPs.
- DCI-based SSSG-switching Switching between SSSG0 and SSSG1 is latency-based.
  - SSSG0 performs infrequent PDCCH monitoring, i.e., monitors 1 slot every X ms, where X = periodicity of PDCCH monitoring. SSSG1 does dense PDCCH monitoring, i.e., monitors every single PDCCH slot.
  - SSSG0 SSSG1 switching happens if estimated latency exceeds a configurable threshold
  - Conversely, SSSG1 SSSG0 switching happens if estimated latency falls below a configurable threshold
  - Each simulation was run with a fixed-periodicity and repeated with 3-different periodicities of {2.5, 10, 40} ms to assess sensitivity to power-saving and latency impact.

3.1.2 Simulation Results

In the result tables below, we provide with a summary of estimated UE-battery-saving as a function of PDCCH or SSSG skip duration, as well as across a set of popular applications. In addition, as gNB may not be aware of the application-type and hence may not be able to accurately estimate data-arrival in gNB-buffer, such skip duration may also impact scheduling latency, which is also captured to highlight the power-latency tradeoff.

Table below provides the results summary for PDCCH skip vs baseline scenario. It shows that PDCCH skip feature can provide significant power savings with acceptable impact to average DL latencies. For skip duration of 10 ms, we can see the power savings in the range of 10-20% for most of the apps while the increment in the average DL latencies at max is 3 ms.

Keeping in mind the tradeoff between power-saving and latency-impact, PDCCH-Skip duration of up to 10ms could be a safe bet and may be considered for initial implementation.

Table 2: PDCCH Skip vs Baseline Results (FR1-TDD)

PDCCH Skip w.r.to Baseline						
	Modem-RF Power Saving			Increase in Avg DL latency (ms)		
App	2.5 ms	10 ms	40 ms	2.5 ms	10 ms	40 ms
Chrome	5%	9%	34%	<1	2	5
TIKTOK	7%	15%	28%	<1	3	5
WeChat-Video	5%	7%	9%	<1	2	3
Sync & Idle	5%	23%	29%	<1	3	6

Note: Numbers are representative in nature, and may vary depending on factors like network/device implementation and parametric configuration

Similarly, the table below provides the summary of results for SSSG-switching vs baseline scenario. The power saving and latency impacts are very similar to the PDCCH skip, although, depending on application type, SSSG-Switching may offer slightly higher power-saving benefit.

Table 3: SSSG-switching vs Baseline Results (FR1-TDD)

SSSG-Switching wrt Baseline						
	Modem-RF Power Saving			Increase in Avg DL latency (ms)		
App	2.5 ms	10 ms	40 ms	2.5 ms	10 ms	40 ms
Chrome	6%	10%	41%	1	5	14
TIKTOK	9%	17%	40%	1	5	16
WeChat-Video	8%	12%	41%	1	5	17
Sync & Idle	5%	23%	31%	<1	5	19

Note: Numbers are representative in nature, and may vary depending on factors like network/device implementation and parametric configuration

Based on the simulation results above, we could conclude the following for FR1-TDD

- Either feature shall offer measurable power-saving benefit, so recommended for expedited commercialization.
- Considering the tradeoff between power-saving and latency-impact, an initial skip-duration of up to 10ms could be targeted, subject to further optimization based on actual implementation and type of application.
- Both features may not be required simultaneously, as incremental benefit is not significant.

4. Deployment Recommendation

Based on the results above, it is imperative that ecosystem should focus on expedited commercialization of either of the two features. However, both features may not be needed simultaneously.

Given the benefits, it is also evident that such implementation should be expedited for FR1-TDD. For FR1-FDD however, considering that baseline modem-RF power-consumption is not very high, implementation of such feature could be considered optionally.

As for the skip-duration, higher values tend to save more power, but also come at a cost of increased latency. Given this, ideal strategy would be for the gNB to apply different values on an application-specific basis. One example of such implementation could be as under.

- Create multiple categories of applications as a function of their latency-requirement viz. low-latency, medium-latency, and latency-tolerant.
- Create individual group of QCI or network-slices. As for example, create slice-1 for low-latency-app, slice-2 for medium-latency apps, while using default network configuration for latency-tolerant apps.
- Create a mapping table of skip-duration pertaining to each slice. As for example, avoid configuring any skip-duration for low-latency slice, but configure 10ms for medium-latency slice, and 40ms for all other application types.
- Such approach would help maximize power-saving benefit, without sacrificing user-experience from latency perspective.
- If such implementation is not feasible at the network-side, 10ms could be considered as the static setting for initial implementation.

Once deployed, it is important to monitor the performance of the network to identify any potential issues.

These features are most effective in low-traffic areas. In high-traffic area therefore, adjustment to the parameters may be needed to make sure user-experience is not impacted.

5. Conclusion

Both power saving features, namely Rel.17 PDCCH Skip and Rel.17 SSSG-switching based PDCCH monitoring, are expected to save modem-RF power significantly, when compared against baseline Rel.16 implementation, and hence recommended for expedited commercialization.

For FR1-TDD, the estimated power savings would depend on the application type, varying in the range of 10-20% at 10 ms periodicity/skip duration.

The marginal latency benefit of PDCCH skip over SSSG-switching is attributable to the fact that SR can interrupt PDCCH skip for the UE to resume PDCCH-monitoring which also happens to help the DL packets to be served earlier that otherwise would have waited until the end of skip duration.

In case of PDCCH Skip however, close monitoring of PDCCH-resource utilization might be needed, to make sure that the need for dummy-DCI does not cause any unwanted performance impact.

Considering power-latency trade-off of the skip-duration, it is desirable to optimize skip-duration on application-specific basis, either using QCI-type or network-slices.

Abbreviations

3GPP	3rd Generation Partnership Project (www.3gpp.org)
BWBandwidth	
BWP	Bandwidth Part
CC	Component Carrier
CDRX	Connected mode Discontinuous Reception
DCI	Downlink Control Indication
DL	Downlink
DRX	Discontinuous Reception
gNB	5G NR NodeB (the 5G NR base station)
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PUSCH	Physical Uplink Shared Channel
RRC	Radio Resource Control
SCS	Sub Carrier Spacing
SPEF	Spectral Efficiency
SSSG	Search Space Set Group
TDD	Time Division Duplexing
UE	User Equipment (the cellphone, cellular IoT device, …)
UL	Uplink

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