

Agenda item: 7.2.9.1
Source: Nokia, Nokia Shanghai Bell
Title: PDCCH-based power saving signal/channel
Document for: Discussion and Decision

1 Introduction

UE Power Saving WID was approved in RAN#83 [1]. The objectives are as follows:

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, we discuss the PDCCH-based power saving signal/channel design.

2 Discussion

2.1 PDCCH-based power saving signal/channel candidates

In this section, different PDCCH based UE power saving triggering signal/channel candidates for Rel-16 NR are discussed.

Table 1 shows the summary of different PDCCH power saving triggering signal/channel candidates considered during the study item. In general, by using any time domain sequence detection method in an OFDM based system, there are restrictions in multiplexing of other signals/channels into the same OFDM symbol. Regarding the time domain detection of sequence based signals, e.g. as DCI payload + DMRS as a single time domain sequence, flexible multiplexing of different PDCCH candidates associated with control channel elements (CCE)s in frequency per aggregation level of PDCCH is severely restricted. In other words, such single time-domain sequence is fixed to a certain CCE, search space, and aggregation combination in frequency. If CCEs are allocated differently in frequency and the amount of them differs with respect to original one, another time-domain sequence is generated being not compatible with original one. Furthermore, to enable time domain detector operation, guard bands in frequency around the sequences are needed in the transmission to enable

filtering out the transmitted sequence from the received signal. In other words, enabling sequence based detection within resources of a CORESET would basically require configuring RB-symbol level rate matching resources within the CORESET and transmit the “sequence” within those resources. PDCCH candidates that fall upon the rate matching resources are not monitored by the UE. For the “sequence” separate resources not colliding with the CORESET would be more feasible.

Table 1 Summary of different PDCCH based power saving triggering signal candidates for Rel-16.

	Channel based	Sequence Based	
	PDCCH (Rel-15)	DMRS of PDCCH (Rel-15)	DCI + DMRS based Sequence
Pros	Support for efficient multiplexing with existing Rel-15 signals and channels. Support for multiple UE power saving triggering options with minimal specification efforts. For multi-antenna transmission, precoding provides additional detection reliability gain in terms of diversity.	Support for multiplexing within Rel-15 CORESET. For multi-antenna transmission, precoding may provide additional detection reliability gain in term of diversity.	Simple time domain correlator receiver, no need for blind decoding and channel decoding Larger effective sequence length compared with other sequence based schemes.
Cons	Decoding complexity covering; FFT computation, channel estimation for different CCE candidate sets and aggregation levels, blind decoding of different search space candidates, decoding of polar coding.	Detection complexity: When increasing the number of search space set candidates and aggregation levels, the computational complexity of sequence detection increases	Time domain detection of DCI payload + DMRS sequence restricts flexible multiplexing of Rel-15 channels/signals/reference signals into same OFDM symbol.

In RAN1-96 meeting, the detection performance of PDCCH DCI + DMRS based wake-up signal was extensively evaluated with link-level simulations [7]. Based on these results, the following observations were made:

Observation 1: The detection performance of DCI + DMRS degrades significantly in the presence of more frequency selective channel (i.e. 100ns w.r.t. 300ns).

Observation 2: Since precoder cycling associated with PDCCH and related DMRS is UE transparent and precoding is not specified in NR Rel-15, using time domain detection with DCI+ DMRS sequence prevents using precoder cycling.

Based on above observations, it can be concluded that the detection performance of DCI + DMRS based sequence degrades in the presence of frequency selectivity of a channel. Furthermore, due to time-domain detection nature of DCI + DMRS sequence, its multiplexing capability with other existing channels/signals/reference signals is heavily limited. Additionally, Rel-15 based precoder cyclic is not applicable with time domain detection of PDCCH DCI + DMRS. As a result of this, it is not seen as a preferable solution for Rel-16 power saving signal/channel.

Observation 3: DCI + DMRS sequence can not be considered as a preferable solution for Rel-16 power saving signal.

While the design of power saving signal/channel, including the content, has not been determined, it would appear that different triggering options should be considered. When considering pure Rel-15 PDCCH DMRS based power saving signal/channel, it is evident that it can only carry single bit of information (on/off).

Observation 4: Rel-15 DMRS of PDCCH can carry only 1-bit information as payload, and as such is not attractive option for Rel-16 power saving signal/channel.

As noted earlier and discussed further below, using DCI-format/PDCCH based design, can offer efficient multiplexing with other, existing channels and can be designed to support multiple triggering options, making it most attractive solution for power saving signal/channel.

Observation 5: PDCCH enables efficient support for multiplexing with existing Rel-15 channels/signals/reference signals. Furthermore, support for multiple triggering options with minimal specification efforts for Rel-16 can be provided.

Based on the discussion it is proposed:-

Proposal 1: Support PDCCH as a power saving channel for Rel-16.

2.2 PDCCH-based power saving channel design

2.2.1 Components in PDCCH monitoring

Main components in PDCCH monitoring comprise control resource set (CORESET) configuration for determining time and frequency resources for CCEs, search space set configuration for determining how and when UE monitors PDCCH, DCI format (part of search space set configuration) for determining signalled information and RNTI for addressing the information to the certain UE(s), as illustrated in Figure 1 (arrow shows the association direction). In the subsequent sections we discuss about these components.



Figure 1 Components in PDCCH monitoring.

2.2.2 DCI Formats in Rel-15

In this section, different NR Rel-15 DCI formats and their payload sizes are discussed.

To gain more understanding on the detection performance of PDCCH channel based power saving channel, the supported Rel-15 DCI formats are worth to be reviewed. The reduction of payload size decreases the required signal-to-noise-plus-interference level for targeted mis-detection leading to improved reliability and coverage. Therefore, for power saving channel purposes it is beneficial to consider existing Rel-15 DCI formats with small payload sizes.

Observation 6: To reduce specification impacts as well as improve reliability and coverage, it is beneficial to consider existing Rel-15 DCI formats with small payload sizes for power saving wake-up channel.

Table 1 provides a brief summary of supported Rel-15 DCI formats with variable payload sizes. As can be observed, the payload size of different DCI formats can be adapted according to different configurations. The supported Rel-15 DCI formats can carry payload from 1 bit up to 128 bits. DCI formats 0_0, 0_1, 1_0, 1_1 are dedicated for a scheduling unicast UL and DL data transmission. Formats 2_0, 2_1, 2_2 and 2_3 are dedicated for group common PDCCH formats. The group common DCI format can carry small payloads, e.g. 1 bit. Despite of possibility to carry small payloads, for Rel-15 the minimum payload size has been agreed to be 12 bits with zero padding. It is worth noting that Polar encoded bits include also on the top of DCI payload bits cyclic redundancy coded (CRC) bits with length of 24bits.

Table 2 NR Rel-15 DCI formats [TS 38.212].

DCI format	Usage	Payload Size	Notes
0_0	Scheduling of PUSCH in one cell	34 bits	Frequency allocation for PUSCH 100 PRBs, UL/SUL indicator not taken into account.
0_1	Scheduling of PUSCH in one cell	59 bits	Depending on configuration, payload size is configurable
1_0	Scheduling of PDSCH in one cell	41 bits	Frequency allocation for PDSCH 100 PRBs Depending on configuration, the payload size can be adapted
1_1	Scheduling of PDSCH in one cell	50 bits	Frequency allocation for PDSCH 100 PRBs, Depending on configuration, the payload size can be adapted
2_0	Notifying a group of UEs of the slot format	1 to 128 bits	Depending on configuration, the payload size can be adapted. For Rel-15 the minimum payload size has been agreed to be 12 bits.
2_1	Notifying a group of UEs of the PRB(s) and OFDM symbol(s) where UE may assume no transmission is intended for the UE	1 to 126 bits	Depending on configuration, the payload size can be adapted. For Rel-15, the minimum payload size has been agreed to be 12 bits.
2_2	Transmission of TPC commands for PUCCH and PUSCH	-	Depending on configuration, the payload size can be adapted. For Rel-15 the minimum payload size has been agreed to be 12 bits.
2_3	Transmission of a group of TPC commands for SRS transmissions by one or more UEs	-	Depending on configuration, the payload size can be adapted. For Rel-15 the minimum payload size has been agreed to be 12 bits.

Observation 7: The supported Rel-15 DCI formats can carry payload from 1 bit up to 128 bits. For Rel-15 the minimum payload size has been agreed to be 12 bits with zero padding.

By following the agreement in RAN1AH1901, the probability of detection, i.e. miss-detection rate detection performance is evaluated with link-level simulations in TDL-C 100ns and 300ns channels with 15kHz sub-carrier-spacing and carrier central frequency 4GHz. Appendix provides results with 30kHz sub-carrier-spacing and carrier frequency 4GHz. Further details of link-level simulation parameters can be found in Table 4. In these evaluations we have assumed the miss-detection target rate of 0.1%

Figure 2 and Figure 3 show the miss-detection performance comparison of Rel-15 PDCCH configurations with different payload sizes, i.e. 10, 20, 48 bits with different aggregation levels (AL=1,2,4,8,16), corresponding to different amount of PRBs (6, 12, 24, 48, 96), respectively. All of the Rel-15 based PDCCH configurations satisfy the 1% false-alarm performance. As could be expected, the best detection performance can be obtained with PDCCH configuration AL=16 and payload size of 10 bits. To achieve the targeted miss-detection rate for power saving signal/channel, i.e. 0.1%, around 2 dB performance gain can be obtained by reducing the payload size from 48 bits to 10 bits with large ALs of 8 and 16. Larger performance gains are obtained with smaller ALs when the payload bits are reduced.

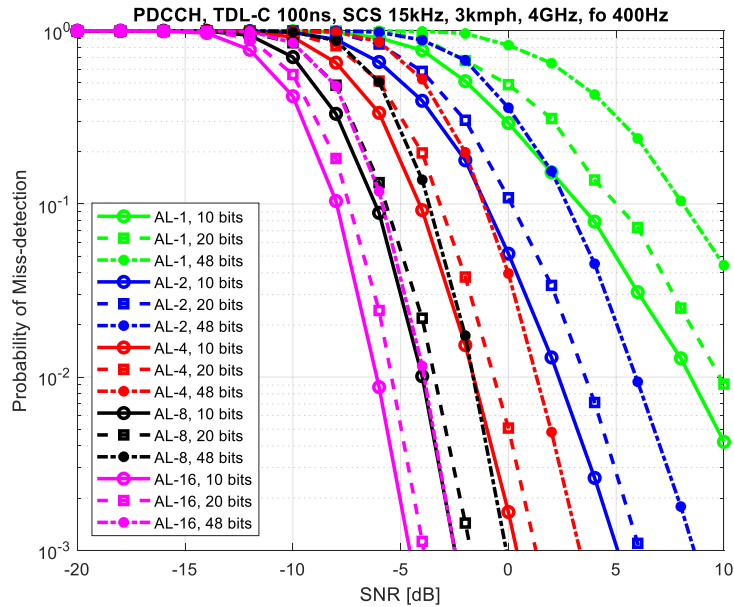


Figure 2. Comparison of miss-detection performance with different Rel-15 PDCCH configurations in TDL-C 100 ns channel w/ velocity of 3km/h and SCS=15kHz.

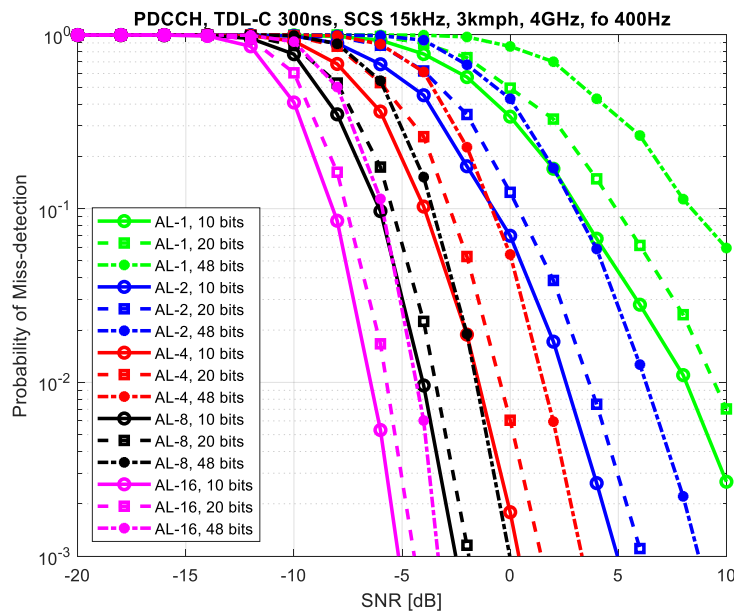


Figure 3. Comparison of miss-detection performance with different Rel-15 PDCCH configurations in TDL-C 300 ns channel w/ velocity of 3km/h and SCS=15kHz.

Observation 8: To achieve the targeted miss-detection rate for wake-up signal/channel, i.e. 0.1%, around 2 dB performance gain can be obtained by reducing the payload size from 48 bits to 10 bits with large ALs=8, 16.

Table 3-summarizes required SNR values to achieve miss-detection rate <0.1% for PDCCH power saving channel for 15 kHz and 30kHz sub-carrier-spacing in TDL-C 100ns and TDL-C 300ns channels.

Table 3 Summary of required SNR values to achieve miss-detection rate < 0.1% for PDCCH power saving channel candidate.

PDCCH Options	TDL-C 100ns	TDL-C 300ns	TDL-C 100ns	TDL-C 300ns
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	SCS 15 kHz	SCS 15 kHz	SCS 30 kHz	SCS 30 kHz
AL-1, 10 bit	>10	>10 dB	-	-
AL-1, 20 bit	>10	>10 dB	>10 dB	>10 dB
AL-1, 48 bit	>10	>10 dB	>10 dB	>10 dB
AL-2, 10 bit	5	5	-	-
AL-2, 20 bit	6	6	6	5
AL-2, 48 bit	8.5	8.5	8	7.5
AL-4, 10 bit	0.5	0.5	-	-
AL-4, 20 bit	1	1	1	1
AL-4, 48 bit	3	3	3	3
AL-8, 10 bit	-2.5	-2.5	-3	-3
AL-8, 20 bit	-2	-2	-2.5	-2.5
AL-8, 48 bit	0	0	-0.5	-0.5
AL-16, 10 bit	-4.5	-5	-5	-5
AL-16, 20 bit	-4	-4.5	-4.5	-4.5
AL-16, 48 bit	-2.5	-3.5	-3.5	-3

Table 4 Link-level simulation parameters for detection performance evaluation.

Parameter	Value
Carrier frequency	4 GHz
Number of TX/RX antennas	2/2
Modulation	QPSK
Channel	TDL-C 100ns, 300 ns
Subcarrier spacing	15, 30 kHz
UE speed	3
PDCCHALs	1, 2, 4, 8, 16
CORESET	1 symbol, 96 PRBs

2.2.3 On DCI format and RNTI

In order to trigger UE specific adaptation using PDCCH-based power saving signal/channel the signal should be able to carry some amount of control information bits. That could be provided by introducing a power saving specific UE-specific DCI format. What one needs to keep in mind is that the number of DCI format sizes a UE can monitor is limited in Rel-15 to 3 UE-specific + 1 non-UE-specific formats. Thus, to avoid increasing the UE complexity, it would be beneficial that the size of new DCI format for power saving signal would be configured to have the same size as some other unicast or non-unicast DCI format configured for the UE. To differentiate to power saving DCI format from other DCI format(s) of the same size a new RNTI, e.g. PS-C-RNTI, could be defined.

Proposal 2: Consider the following principles for PDCCH-based power saving channel:

- define a power saving specific DCI format,
- the size of new DCI format should be able to be configured to have the same size as some other DCI format and
- introduce a new RNTI, e.g. PS-C-RNTI, which the UE searches for new DCI format when configured.

2.2.4 On search space set

A set of PDCCH candidates for a UE to monitor is defined in terms of PDCCH search space sets. A search space set can be a CSS set or a USS set. The UE can be configured up to ten search space sets in Rel-15. The search space set defines how and where to search PDCCH candidates. The parameters include e.g.:

- when
 - o PDCCH monitoring periodicity and offset in slots
 - o a duration in slots how long the search space set exists per period
 - o PDCCH monitoring pattern within a slot
- how
 - o number of candidates per aggregation level
 - o whether search space set is common or UE-specific and
 - o associated DCI formats to be monitored

Considering a new power saving DCI format the next question is whether the DCI format could be associated to search space set(s) associated to other unicast DCI formats or should there be dedicated search space set(s) only for power saving DCI format. The latter may be needed if there would be additional/different rules or monitoring patterns needed for the monitoring of the new DCI format that would be possible with the existing search space set parameters.

Proposal 3: Study further whether power saving signal DCI format is associated to search space set(s) used for existing unicast DCI formats or a new dedicated search space set for the new DCI format.

2.2.5 CORESET

Each search space set is associated with one CORESET. In Rel-15, UE can be configured up to three CORESETs per BWP. Potential dedicated search space set for power saving DCI format could be associated to one of the configured CORESETs or another option would be to configure dedicated CORESET for monitoring power saving channel. A power saving channel specific search space set could be associated to power saving specific CORESET for power saving (CORESET-PS) for monitoring power save DCI format. One example of such special use of CORESET / Search Space relationship is Rel-15 link recovery. A dedicated CORESET is monitored according to recoverySearchSpace configuration and no other search spaces can be configured for that CORESET. Hence the CORESET is specific for beam failure recovery, and does not overlap (in terms of use) with the other configured, up to three, CORESETs.

In similar manner the CORESET-PS could be a special use CORESET that can be only configured with search space for monitoring power save DCI format.

Proposal 4: Investigate the feasibility of using dedicated CORESET for monitoring power saving channel.

2.3 PDCCH-based power saving signal and DRX

Currently UE power saving can be achieved by enabling UE to discontinuously monitor PDCCH according to DRX configuration. When DRX is configured, UE is required to monitor PDCCH only during *onDuration* of the DRX cycle. Network is able to control the UE PDCCH monitoring requirement using the parameters such as *OnDuration-timer*, *inactivity timer* and *DRX cycle length*.

Both longDRX and shortDRX are supported by Rel-15 which together by parametrizing accordingly enables the network to optimize between UE power saving and scheduling latency.

Observation 9: Using Release-15 mechanisms network can optimize between UE power saving and scheduling latency using DRX.

Observation 10: Use of power saving channel should be considered only when DRX is configured.

3 Conclusions

In this contribution we have discussed about PDCCH-based power saving signal/channel design. In section 2.1 we considered different PDCCH-based power saving signal/channel candidates, and make following observations and proposal:-

Observation 1: The detection performance of DCI + DMRS degrades significantly in the presence of more frequency selective channel (i.e. 100ns w.r.t. 300ns).

Observation 2: Since precoder cycling associated with PDCCH and related DMRS is UE transparent and precoding is not specified in NR Rel-15, using time domain detection with DCI+ DMRS sequence prevents using precoder cycling.

Observation 3: DCI + DMRS sequence can not be considered as a preferable solution for Rel-16 power saving signal.

Observation 4: Rel-15 DMRS of PDCCH can carry only 1-bit information as payload, and as such is not attractive option for Rel-16 power saving signal/channel.

Observation 5: PDCCH enables efficient support for multiplexing with existing Rel-15 channels/signals/reference signals. Furthermore, support for multiple triggering options with minimal specification efforts for Rel-16 can be provided.

Observation 6: To reduce specification impacts as well as improve reliability and coverage, it is beneficial to consider existing Rel-15 DCI formats with small payload sizes for power saving wake-up channel.

Proposal 1: *Support PDCCH as a power saving channel for Rel-16.*

Then, in section 2.2, we evaluate the payload size to the performance of the PDCCH with different aggregation levels, as well discuss about the PDCCH-based power saving channel design. In context of PDCCH performance we observe as follows:-

Observation 7: The supported Rel-15 DCI formats can carry payload from 1 bit up to 128 bits. For Rel-15 the minimum payload size has been agreed to be 12 bits with zero padding.

Observation 8: To achieve the targeted miss-detection rate for wake-up signal/channel, i.e. 0.1%, around 2 dB performance gain can be obtained by reducing the payload size from 48 bits to 10 bits with large ALs=8, 16.

For PDCCH-based power saving channel design we make following proposals:-

Proposal 2: *Consider the following principles for PDCCH-based power saving channel:*

- *define a power saving specific DCI format,*
- *the size of new DCI format should be able to be configured to have the same size as some other DCI format and*
- *introduce a new RNTI, e.g. PS-C-RNTI, which the UE searches for new DCI format when configured.*

Proposal 3: *Study further whether power saving signal DCI format is associated to search space set(s) used for existing unicast DCI formats or a new dedicated search space set for the new DCI format.*

Proposal 4: *Investigate the feasibility of using dedicated CORESET for monitoring power saving channel.*

In section 2.3 we consider the applicability of the signal inline with the target of achieving power saving and observe as follows:

Observation 9: Using Release-15 mechanisms network can optimize between UE power saving and scheduling latency using DRX.

Observation 10: Use of power saving channel should be considered only when DRX is configured.

References

- [1] RP-181463, "Study on UE Power Saving in NR", CATT, CMCC, VIVO, Qualcomm, MediaTek
- [2] R1-1903133, "Comparison of DRX with WUS and GTS schemes", Nokia, Nokia Shanghai Bell
- [3] R1-1903136, "UE Power Consumption Reduction in RRM Measurements", Nokia, Nokia Shanghai Bell
- [4] TS38.133
- [5] R1-1901187, "Initial results on DRX settings", Nokia, Nokia Shanghai Bell
- [6] R1-1903137, "Considerations for limiting the PDCCH blind decoding candidates", Nokia, Nokia Shanghai Bell
- [7] R1-1903135, "Potential power saving triggering signals", Nokia, Nokia Shanghai Bell

Appendix A

The miss-detection performance result of different wake-up signal/channel candidates in TDL-C 100ns and 300ns with SCS =30 kHz are shown in Figure 4 and Figure 5.

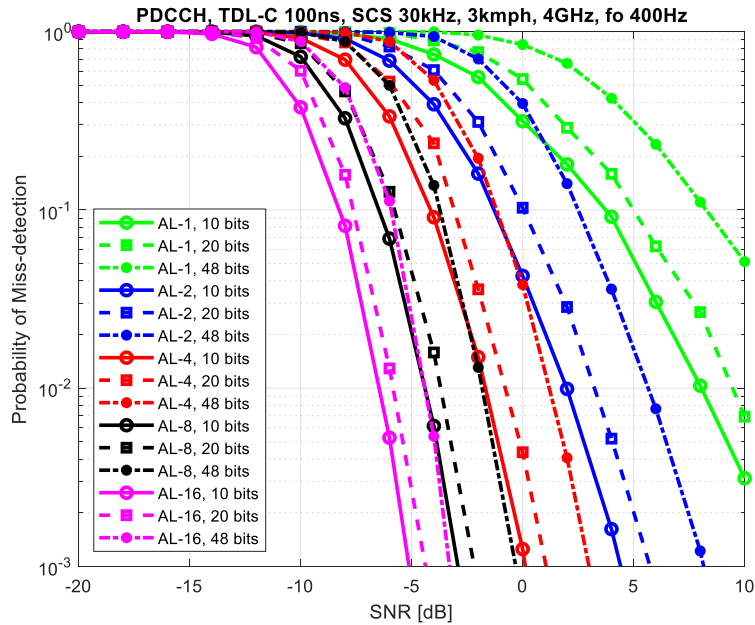


Figure 4. Comparison of miss-detection performance with different Rel-15 PDCCH configurations in TDL-C 100 ns channel w/ velocity of 3km/h and SCS=30 kHz.

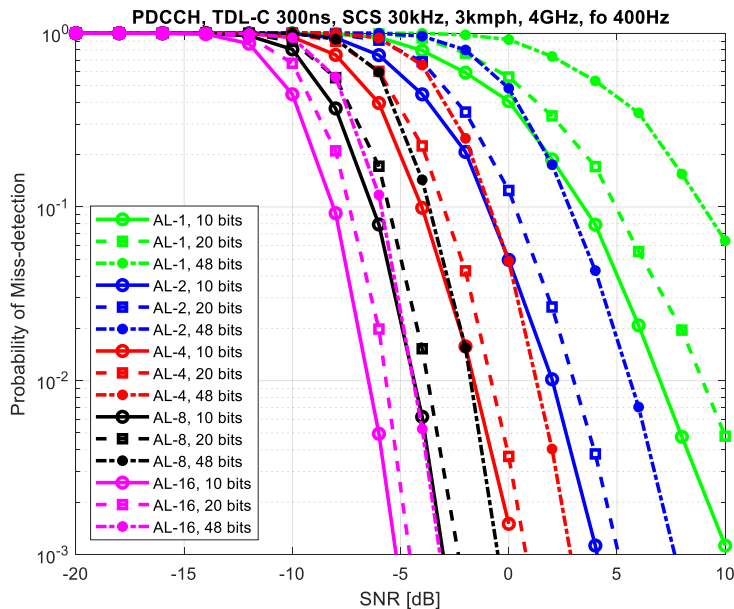


Figure 5. Comparison of miss-detection performance with different Rel-15 PDCCH configurations in TDL-C 300 ns channel w/ velocity of 3km/h and SCS=30 kHz.