On the Performance of PDCCH in LTE and 5G New Radio

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***Abstract*—The 5G New Radio (NR) Release-15 has been frozen in June this year, which brings numerous changes and potential improvements for physical layer data transmission, but only for Point-to-Point (PTP) communication scenarios. Besides, to start transmitting data via data channels, e.g., Physical layer Downlink Shared Channel (PDSCH), it is essential to guarantee a successful transmission of control information. Taking into account these two aspects, in this paper, we first analyse the processing chain of the control channel in both NR PTP and the state-of-the-art LTE (Long Term Evolution) Point-to-Multipoint (PTM) technology, i.e., evolved Multimedia Broadcast Multicast Service (eMBMS). Then, via link level simulations, we compare the performance of LTE eMBMS and NR PTP, regarding Bit/Block Error Rate (BER/BLER) under various scenarios, aiming to identify the performance gap brought by physical layer changes for NR control channels, Physical Downlink Control Channel (PDCCH), as well as provide insightful guidelines on the control channel configuration towards NR PTM scenarios.**

***Index Terms*—LTE, NR, PTM, eMBMS, PDCCH**

I. Introduction

Driven by a massive amount of multimedia content consumptions, the 3rd Generation Partnership Project (3GPP) has standardised the use of Point to Multipoint (PTM), i.e., broadcast and multicast, based on the Long Term Evolution (LTE) from Release (Rel-) 9, namely evolved Multimedia Broadcast Multicast Service (eMBMS). The state-of-the-art specification for eMBMS is the LTE-Advanced, i.e., Rel-14. The PTM service allows the content provider to efficiently deliver services to a large group of users who are interested in the same media content, with a fixed amount of radio resources. The performance of the latest eMBMS technologies has been analysed in our prior work [1], focusing on the data channel transmission. Most recently, the Rel-15 of fifth-generation (5G) New Radio (NR) specifications has been frozen, which brings a lot of physical layer changes. Authors in [2] have studied the traffic channel performance based on NR specification, focusing on the multimedia broadcast multicast services.

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However, the overall system performance should also take into account the control channel. For example, the probability of radio link failure will increase if the Block Error Rate (BLER) of recovering the control information, i.e., Downlink Control Information (DCI), exceeds a certain target threshold. More specifically, the robustness is the key design principle for control channels, e.g., with a more robust Forward Error Correction (FEC) encoder and a smaller modulation order to ensure the control information received correctly. In the literature, the performance of LTE control channels with fixed receivers and perfect channel estimations has been studied in [3], and a potential power-based optimisation for the control information transmission based on the LTE has been discussed in [4]. This motivates us to provide a performance analysis on the control channels based on the NR specifications, such that we can look into how much NR can improve the performance of the control channels without any multiplexing or diversity techniques.

To this end, we present a comprehensive technical overview for both the LTE eMBMS and NR Point-to-Point (PTP) systems (since the first release of 5G, i.e. Rel-15 is a unicast-only solution, but we can use it as a basis or benchmark for evaluating the possible NR PTM solution), concentrating on the main type of physical layer control channels, i.e., Physical Downlink Control Channel (PDCCH). After describing the processing chain of the DCI for both systems in detail, a performance analysis is provided via link-level simulations, based on the evaluation methodology defined by the ITU-R (International Communications Union - Recommendation) for the IMT-2020 (International Mobile Telecommunication) evaluation process [5] as well as the physical layer process defined by 3GPP, i.e. [6] and [7]. The obtained results can be served as a comparison between the current LTE PTM solution and NR-PTP with the physical layer changes made in Rel-15. They can also be considered in the case of evaluating the end-to-end system performance including the cost to enable the data transmission on data channels e.g. Physical layer Downlink Shared Channel (PDSCH), or in the case of proposing a suitable control channel configuration for NR PTM scenarios.

This paper is structured as follows. First, Section II describes the DCI formats for both LTE-eMBMS and NR-PTP, and their individual transmitter side block diagram for the control channel is given in Section III. Section IV presents and discusses their corresponding frame structure. Simulation results of PDCCH regarding BER/BLER performance in various scenarios through link-level simulations are included in Section V. Finally, Section VI concludes the key findings and discusses the potential improvements towards the development of technical solutions for NR PTM in the future.

II. Downlink Control Information generation in LTE and NR

Inside the control region of physical downlink control channels, different types of the control information are transmitted, see Table I.

TABLE I: Control information and corresponding channels

Control Information	Physical Control Channel
Downlink Control Information (DCI)	PDCCH
Control Format Indicator (CFI)	PCFICH
Hybrid-ARQ Indicator (HI)	PHICH

Control information for one or multiple user equipments (UEs) is contained in one Downlink scheduling Control Information message and is transmitted through the PDCCH. Different DCI formats are defined for different purposes of the DCI message. From the eMBMS content transmission point of view, there is no support for the Hybrid Automatic Repeat Request (HARQ) operation, and the transmission of CFI symbols works similarly as DCI information [3] [8]. Therefore, in this paper, we focus on the comparison regarding signal processing and their corresponding Bit/Block Error Rate (BER/BLER) of the DCIs between LTE-eMBMS and NR-PTP configurations.

A. In LTE

In LTE, different formats of DCIs contain diverse information, including Resource Block Assignment, Transmit Power Commands (TPC), HARQ and Precoding Information, etc. Two significant factors that determine which format is used for a specific situation, given as [9]:

- The Radio Network Temporary Identifier (RNTI) type used in the transmission,
- Different transmission modes.

An example is given in Table II [6], which related to the indication of an MBMS specific RNTI, called the M-RNTI [9]. The DCI format 1C (common search space) with M-RNTI is used for notification and includes an 8-bit bitmap to indicate the one or more MBSFN Area(s) in which the Multicast Control Channel (MCCH) changes. In Table II, the X MHz denotes the occupied channel bandwidth.

TABLE II: DCI Format 1C for M-RNTI in LTE

Field Names	Occupied Bits
MCCH Change Notification	8 bits
Reserve	N/A (1.4MHz) 2bits (3MHz) 4bits (5MHz) 5bits (10MHz) 6bits (15MHz) 7bits (20MHz)

B. In NR

For 5G NR, even in the latest version of 3GPP document TS 38.212 [10], there is no specific DCIs defined for eMBMS transmission proposes at the moment. The current available DCI formats specifically for PDSCH scheduling are:

TABLE III: DCI Formats in NR for PDSCH scheduling

Format	Usage
Format 1_0	used for the scheduling of PDSCH in one DL cell
Format 1_1	used for the scheduling of PDSCH in one cell

where Format 1_0 is more suitable for a multicast/broadcast case as it is dedicated for DL cells. The fields that are included in this format are given in Table IV:

TABLE IV: DCI Format 1_0 for C-RNTI in NR

Field Names	Occupied Bits
Identifier for DCI formats	1 bits
Frequency domain resource assignments	Variable
Time domain resource assignments	X bits
VRB-to-PRB mapping	1 bits
Modulation and Coding scheme	5 bits
New data indicator	1 bits
Redundancy version	2 bits
HARQ process number	4 bits
Downlink assignment index	2 bits
TPC command assignment for scheduled PUCCH	2 bits
PUCCH resource indicator	3 bits
PDSCH-to-HARQ feedback timing indicator	3 bits

where, VRB and PRB represent Virtual Resource Block and Physical Resource Block, respectively. However, with this format, the Cyclic Redundancy Check (CRC) is scrambled by C-RNTI since in the current standard, it is defined for the unicast purpose. Moreover, some of the fields do not have strong relations with the eMBMS transmission, for instance, those fields that related to uplink control channels and for HARQ process. Besides, no format supports CRC scrambled by m-RNTI (MBMS-RNTI) or g-RNTI (group-RNTI).

The chosen corresponding DCI bits are then sent to the PDCCH channel processing chain, which is introduced in the next section.

III. Physical Downlink Control Channels in LTE and NR

A. In LTE

DCI bits for different users are individually sent to the Bit-Interleaved Coding and Modulation (BICM) processing chain. DCI bits are encoded with a combination of forwarding error correction (FEC), scrambler and mapper (modulator). More specifically, a CRC sequence with 16 bits is first attached to the DCI information. Then, in the channel coding block, conventional tail-biting encoding (with code rate $R = 1/3$) is employed. Next, rate matching is performed such that the bits inside each coding block are interleaved, circular buffered and punctured/repeated to provide a specific code rate (CR) which is determined by the aggregation level (AL). After rate matching, PDCCH bits for different users are multiplexed and scrambled before sending to the modulator. It is noticeable that the available modulation schemes for LTE PDCCH are Quadrature Phase

Shift Keying (QPSK) only, as the transmission reliability of DCI bits is much more important than the transmission rate. After that, symbols are allocated to all available resource elements (RE) in the corresponding subframe, and finally, before transmission, CP-OFDM (Cyclic Prefix-Orthogonal Frequency Division Multiplexing) is performed.

In LTE, PDCCHs are categorised into Common and UE-specific PDCCHs; each type supports a specific set of searching spaces. Each searching space consists of a group of consecutive Control Channel Elements (CCE) which could be allocated to a PDCCH called a PDCCH candidate. A list of important LTE resource allocation units includes:

- Resource Element (RE);
- Resource Element Group (REG);
- Control Channel Element (CCE);
- Aggregation Level (AL).

The relationship between REG and CCE in LTE is: 1 CCE is made up 9 REGs and 1 REG is made up of 4 resource elements. Moreover, AL denotes the number of CCEs that carries a single PDCCH. To the end, assuming the aggregation level to be 1, the total number of available REs for the whole control region is given as:

$$\begin{aligned} \mathrm{RE}_{\mathrm{tot,LTE}} &= \mathrm{AL} * (\mathrm{REG/CCE}) * (\mathrm{RE/REG}) \\ &= 1 * 9 * 4 = 36\mathrm{REs}, \end{aligned} \tag{1}$$

where (REG/CCE) represents the relationship between REG to CCE, same as RE/REG.

B. In NR

In NR, the PDCCH processing chain was modified. The transmit side block diagram of the NR PDCCH processing chain is shown in Fig.1. In which, the generator polynomial $g_{\mathrm{CRC24C}}(D)$ is used for the Cyclic Redundancy Check Attachment. For the channel coding, instead of using the tail-biting encoding, the polar code is used. The detail of polar encoding can be found in [7]. It is noticeable that given the length of the polar encoded bits N, where $N = 2^n$, the value of n is a positive integer between 5 and 9 (including 5 and 9). Therefore, the maximum length of the encoded bits is fixed at $2^9 = 512$. Regarding the rate matching, it is still operated every coded block and consists of sub-block interleaving, bit collection, and bit interleaving. However, according to the 3GPP specifications, the flag of performing the bit interleaving is set to be 0, i.e., does not perform the bit interleaving. The multiplexing and scrambling operation is also same as in 4G LTE, as well as the modulation scheme, i.e., QPSK only.

Similar to LTE, each PDCCH is still flexibly mapped to CCEs, but the relationship between REG and CCE has been changed in NR, i.e., 1 CCE is now made up of 6 REGs and 1 REG is now consist of one resource block (12 REs in the frequency domain) and one OFDM symbol in time domain. In this case, if we still assume the aggregation level to be 1, the total number of available REs for the whole control region in NR is given as:

$$\begin{aligned} \mathrm{RE}_{\mathrm{tot,NR}} &= \mathrm{AL} * (\mathrm{REG/CCE}) * (\mathrm{RE/REG}) \\ &= 1 * 6 * 12 = 72\mathrm{REs}, \end{aligned} \tag{2}$$

Some new units are defined in NR, including:

- REG Bundle: One REG bundle is made up of multiple REGs.
- Control Resource Set (CORESET): A CORESET is made up of multiples RBs (i.e., multiples of 12 REs) in the frequency domain and 1 or 2 or 3 OFDM symbols in time domain. CORESET is equivalent to the control region in LTE subframe. A UE can be configured with multiple CORESETs, and each CORESET is associated with one CCE-to-REG mapping only [7]. Fig. 2 gives an example to procedure the mapping from RE (REG) to CCE with aggregation level of 1. An example is shown in Fig. 2, in which 3 OFDM symbols in the time domain are used for control region, and there are two CCEs in the CORSET.

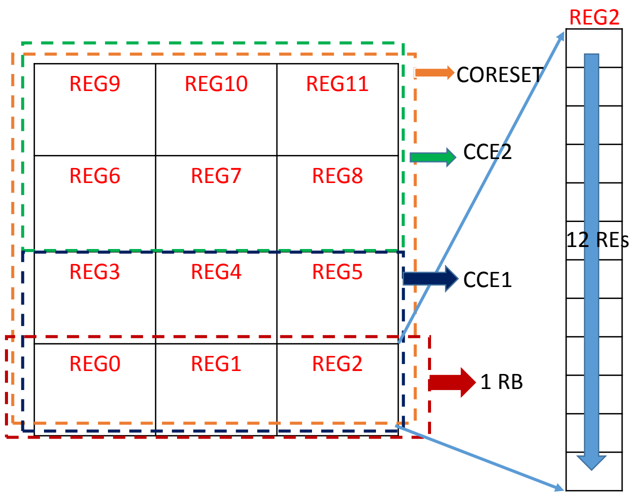

Fig. 2: Illusation of the structure of a CORESET consist of two CCEs

IV. Resource Block Frame Structure and Code Rate Calculation in LTE and NR

Fig. 3 shows the different frame structure for a single RB inside a typical MBSFN subframe in LTE and inside an NR PTP subframe [7]. As Fig. 3 depicted, the number of subcarriers per RB are both 12. Although for LTE-eMBMS (MBSFN), 3 different configurations can be used, corresponding to different subcarrier spacing i.e., 15KHz, 7.5 KHz and 1.25KHz. In this paper, we focus on the multicast mixed-mode, therefore, the subcarrier spacing is set to be 15KHz. The number of OFDM symbols per subcarrier under this condition is 12 and 14 for LTE-eMBMS and NR-PTP, due to the use of extended and normal CP, respectively. It is worth mention that there is no reference signal in the control region for LTE while 9 DMRS are placed in the control region for NR.

Next, we provide an example of the calculation of the effective code rate for PDCCH. Since our focus in this paper is the performance of the control channel from multicast and broadcast points of view. So we further assume that there are no bits used for PHICH, 2 and 3 bits for PCFICH for LTE and NR, respectively. The DCI bits for both LTE and NR is set to be 12, for LTE 12 bits DCI can be seen as Format 1C with 5MHz channel. For NR, since there is no specific format which suitable for multicast/broadcast and consider the fact that the smallest number of DCI bits is 12 [10], we can keep the DCI bits the same in NR as in LTE. If we reuse the assumptions for

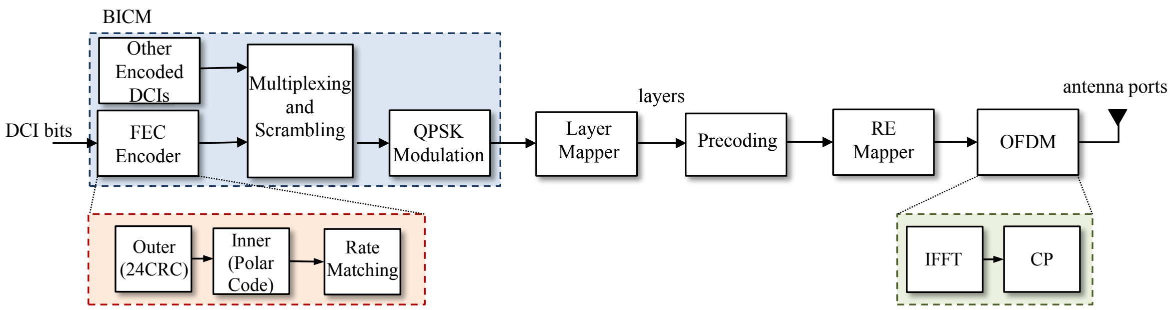

Fig. 1: NR physical layer Point to Point PDCCH transmission block diagram

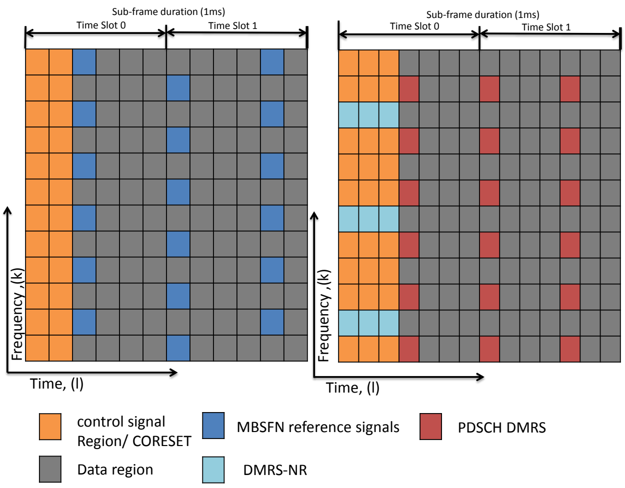

Fig. 3: Resource Block frame structure for LTE-MBSFN (left) and NR-PTP (right), with 15 kHz carrier spacing.

TABLE V: Simulation Parameters

Samulation Parameters	Values
Carrier Frequency	700MHz
System bandwidth	5MHz
FFT size	512
CP types	Extended for LTE-eMBMS Normal for NR-PTP
DCI length	12 bits
Aggregation Level	1,2,4,8
Subcarrier spacing	15 kHz
Channel models	AWGN, TDL-A, TDL-C
Channel estimation types	Perfect or 2-dimensional pilot based estimation with linear interpolation
Equalization type	Minimum mean square error

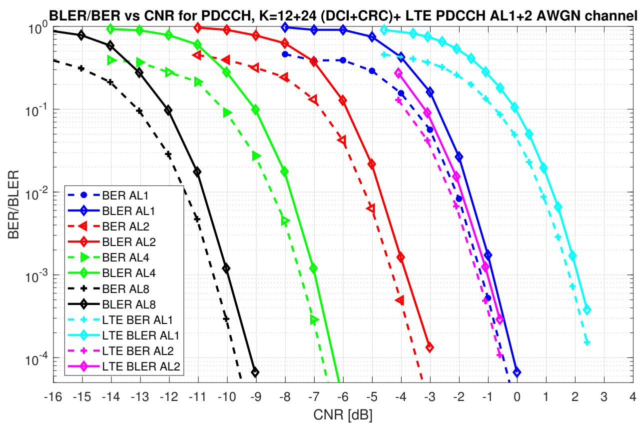

Fig. 4: BER/BLER vs. CNR (dB) for AWGN channel.

Eq.(1) and (2), with QPSK modulation, the total available bits will be 72 and 144 respectively, which means it requires 2 RBs for both LTE and NR to contain all the PDCCH symbols. Therefore, the effective code rate for LTE and NR under these assumptions can be given as:

$$\mathrm{CR_{LTE}} = \frac{12}{72} \approx 0.167 \tag{3}$$

$$\mathrm{CR_{NR}} = \frac{12}{144 - \mathrm{bits_{DMRS}}} = \frac{12}{144 - 9 * 2} \approx 0.095 \tag{4}$$

V. Link-Level Simulation Evaluation

Link-level results for the BER and BLER as a function of the required CNR for LTE-eMBMS and NR are presented in this section. Different channel models including AWGN, TDL-A, TDL-C have been evaluated in order to assess the impact of the adopted configurations. The power delay profile (PDP) for TDL-A channel model is shown in Table.VI (PDP for TDL-C channel is available in [11]) and the simulation parameters are listed in Table.V. Mention that, aggregation level 16 is not simulated here because it requires $\frac{16*6*12}{12*3} = 32$REs, but for a $5MHz$ channel, the maximum available REs is only 25. Besides, we use AWGN channel to compare the performance of LTE-eMBMS and NR-PTP, but for TDL-A and TDL-C channel, we only simulate the NR-PTP PDCCH results.

A. Standstill Receiver

In this section, we assume the standstill receiver with perfect channel estimation. Moreover, at the receiver side, the rate recovery process includes additively combining any repetitions to distinguish the performance difference of higher aggregation level.

1) Additive White Gaussian Noise Channel: From the AWGN channel results i.e. Fig. 4, we can see:

- Higher aggregation level generally gives more protection level to the codewords which reflected on the required CNR for both LTE-eMBMS and NR-PTP situation, by trading more occupied bandwidth.
- Due to the different CRC and aggregation level for LTE and NR, it is not easy to achieve fair comparison. Generally, Polar code should outperform Tail-biting encoding.
- A suitable Quality of Service (QoS) metric can be blocked error rate (BLER) lower than 0.1% for reliable broadcasting [12]. To this end, comparing under same aggregation level (e.g., AL1), NR requires about 2.8dB less than LTE to achieve BLER 1e-3.

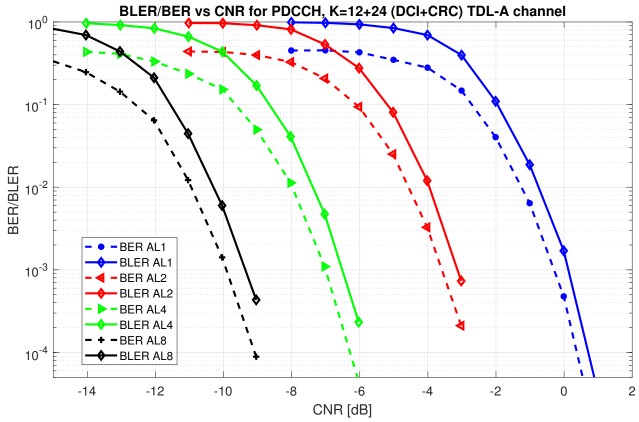

Fig. 5: BER/BLER vs. CNR (dB) for TDL-A channel.

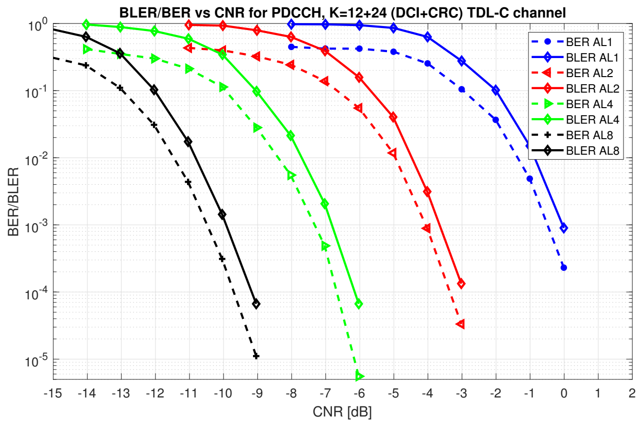

Fig. 6: BER/BLER vs. CNR (dB) for TDL-C channel.

2) TDL Channel Models Considered in IMT-2020 Scenarios: In this subsection, single-input single output BLER performance for the IMT-2020 scenarios is presented, with perfect channel estimation. Fig. 5 shows the BLER results for TDL-A channel model with 30ns delay spread and 3km/h movement speed and Fig. 6 gives the results for TDL-C channel model for a Rural scenario with 300ns delay spread and 30km/h movement speed. From the results, we can see that

- under perfect channel estimation, higher movement speed equivalent to better Doppler diversity which makes the CNR requirement for each aggregation level of the TDL-C channel (with 30km/h movement speed) outperform the corresponding point with TDL-A channel (with 3km/h movement speed).
- Comparing to the AWGN results, at lower aggregation level which equivalent to high code rate, the BLER performance for both TDL-A and TDL-C channel are worse than AWGN result.
- However, because of the fixed codeword length, when aggregation level goes higher, the code rate dramatically decreases, and the TDL channel performances are almost aligned with AWGN channel.

B. Mobility

For mobility evaluation, we only do the performance evaluation with NR configuration. By assuming the RB based 2-dimensional linear channel estimation, following the frame structure introduced in Sec.IV. Regarding the

TABLE VI: Power Delay Profile for TDL-A channel

Tap	Normalized delay	Power in [dB]
1	0.0000	-13.4
2	0.3819	0
3	0.4025	-2.2
4	0.5868	-4.0
5	0.4610	-6.0
6	0.5375	-8.2
7	0.6708	-9.9
8	0.5750	-10.5
9	0.7618	-7.5
10	1.5375	-15.9
11	1.8978	-6.6
12	2.2242	-16.7
13	2.1718	-12.4
14	2.4942	-15.2
15	2.5119	-10.8
16	3.0582	-11.3
17	4.0810	-12.7
18	4.4579	-16.2
19	4.5695	-18.3
20	4.7966	-18.9
21	5.0066	-16.6
22	5.3043	-19.9
23	9.6586	-29.7

pilots/DMRS which are distributed inside each RB for channel estimation, we have:

- Frequency domain: the DMRS will be allocated every 4 subcarriers;
- Time domain, the number of DMRS symbol depends on the $N_{symb}^{CORESET}$ value, which is determined by PCFICH and can be 1,2,3;

In order to reconstruct the channel, the two-dimensional (i.e., frequency and time) sampling should satisfy:

- Frequency domain, the sampling rate must be faster than or equal to the channels maximum delay spread;
- Time domain, the sampling rate must be greater than or equal to the channels maximum Doppler spread;

In the The maximum distance between two Time domain DMRS symbols is given by:

$$n \leq \frac{1}{2 * T_s * d_{max}}, \tag{5}$$

where T_s and d_{max} represents the symbol duration and maximum Doppler spread, respectively. However, due to the fact that we have DMRS covers all the time domain REs on selected subcarriers so the time domain pilot is sufficient enough to capture the time-varying channel with potentially any movement speed. On the other hand, the frequency domain channel estimation depends on the maximum channel delay spread, and the maximum distance between two frequency domain pilots is given by:

$$m \leq \frac{T_s}{2 * \tau_{max}}, \tag{6}$$

where τ_{max} represents the maximum channel delay spread. In our case, we assume 15kHz subcarrier spacing and $m = 4$ as shown in Fig. 3, which gives: $T_s = 1/\Delta_f = 66.7\mu s$. Therefore, the maximum channel delay spread can be tolerated is given as: $\tau_{max} \leq T_s/2m \approx 8.33\mu s$, great than that of the test channels i.e., TDL-A, TDL-C. So as a conclusion, combining with the simulation results shown in Fig.7 (for TDL-A channel), the difference in terms of BLER performance vs required CNR (about 4.5dB for both aggregation level 1,2), which is because of the noise effect

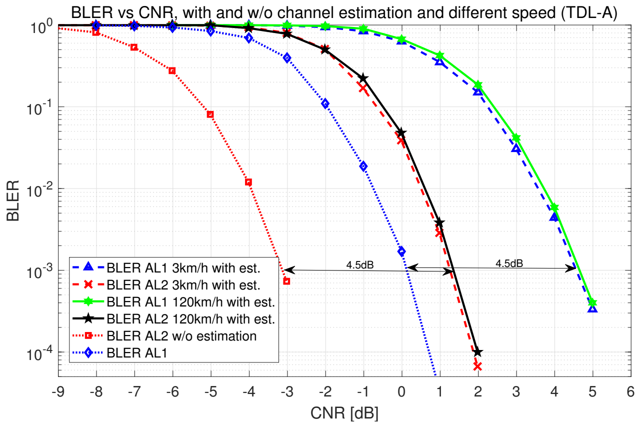

Fig. 7: BICM BER/BLER vs. CNR (dB) for TDL-A channel with real channel estimation.

during the channel estimation. Moreover, we can see that different movement speed i.e., 3km/h and 120km/h almost make no impact to the BLER performance which reflect the rationality of the pilot distribution.

VI. Conclusion

In this paper, the DCI information generation of the state-of-the-art LTE eMBMS and the NR PTP has been introduced. The detailed transmit side technical overview of LTE-eMBMS and NR and their designs have been covered. The BLER performance has been analysed in AWGN channel as well as the TDL-A and TDL-C channel model from Physical Downlink Control Channel perspective. The discussions and simulation results in this paper can be used as the benchmark to evaluate the end-to-end system performance of NR PTP, and more importantly, to propose suitable control channel configurations for possible solutions towards NR PTM transmissions. The potential way forward includes: first, a new DCI format for NR PTM need to be defined; second, most of the PDSCH performance evaluation assumes perfect PDCCH signal recovery, so one can also extend this work onto the performance evaluation of the data channel in the presence of the imperfect PDCCH transmission.

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