Varatharaajan, Sutharshun; Großmann, Marcus; Del Galdo, Giovanni

5G new radio physical downlink control channel reliability enhancements for multiple transmission-reception-point communications

Original published in:	IEEE access / Institute of Electrical and Electronics EngineersNew York, NY : IEEE. - 10 (2022), p. 97394-97407.
Original published:	2022-09-20
ISSN:	2169-3536
DOI:	10.1109/ACCESS.2022.3206027
[*Visited:*	2022-10-12]

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 10 August 2022, accepted 31 August 2022, date of publication 12 September 2022, date of current version 20 September 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3206027

STANDARDS

5G New Radio Physical Downlink Control Channel Reliability Enhancements for Multiple Transmission-Reception-Point Communications

SUTHARSHUN VARATHARAAJAN, MARCUS GROSSMANN,
AND GIOVANNI DEL GALDO, (Member, IEEE)
Electronic Measurements and Signal Processing Group, Fraunhofer Institute for Integrated Circuits IIS, 98693 Ilmenau, Germany

Corresponding author: Sutharshun Varatharaajan (sutharshun.varatharaajan@iis.fraunhofer.de)

This work was supported by the Federal Ministry of Education and Research (BMBF), Germany, within the 6G Research and Innovation Center (6G-RIC), under Grant 16KISK020K.

ABSTRACT Non-coherent transmission from multiple transmission-reception-points (TRPs), i.e., base stations, or base station panels to a user equipment (UE) is exploited in 5G New Radio (NR) to improve downlink reliability and cell-edge throughput. Ultra reliable low-latency communications (URLLC) and enhanced Mobile BroadBand (eMBB) are prominent target use-cases for multi-TRP or multi-panel transmissions. In Third-Generation Partnership Project (3GPP) Release 17 specifications, multi-TRP-based transmissions were specified for the physical downlink control channel (PDCCH) specifically to enhance its reliability and robustness. In this work, a comprehensive account of various multi-TRP reliability enhancement schemes applicable for the 5G NR PDCCH, including the ones supported by the 3GPP Release 17 specifications, is provided. The impact of the specifications for each scheme, UE and network complexity and their utility in various use-cases is studied. Their error performances are evaluated via link-level simulations using the evaluation criteria agreed in the 3GPP proceedings. The 3GPP-supported multi-TRP PDCCH repetition schemes, and the additionally proposed PDCCH repetition and diversity schemes are shown to be effective in improving 5G NR PDCCH reliability and combating link blockage in mmWave scenarios. The link-level simulations also provide insights for the implementation of the decoding schemes for the PDCCH enhancements under different channel conditions. Analysis of the performance, complexity and implementation constraints of the proposed PDCCH transmission schemes indicate their suitability to UEs with reduced-capability or stricter memory constraints and flexible network scheduling.

INDEX TERMS 5G, new radio (NR), multi-transmission-reception-point (multi-TRP), physical downlink control channel (PDCCH), single frequency network (SFN), log-likelihood ratio (LLR), soft-combining, selection decoding.

I. INTRODUCTION

The Third Generation Partnership Project (3GPP) Radio Access Network (RAN) working group (WG) 1 specified the physical layer methods to support non-coherent joint transmissions (NCJT) from multiple TRPs, i.e., base stations, or base station panels in Fifth Generation (5G) New Radio (NR) standards starting from 3GPP Release (Rel.) 16. A user equipment (UE) may receive physical downlink shared channel (PDSCH) transmission(s) that are multiplexed in space, time or frequency using two different reception settings [1], wherein each reception setting may correspond to a different TRP or base station panel. Independent scheduling of simultaneous PDSCH receptions from different TRPs within a cell, repetition of a PDSCH transmission from different TRPs and PDSCH diversity - a single PDSCH

The associate editor coordinating the review of this manuscript and approving it for publication was Bilal Khawaja.

transmission is received in parts from multiple TRPs - are supported in 3GPP Rel. 16. With enhancements targeting both cell-edge throughput and reliability, multi-TRP operation was exploited only for the PDSCH in Rel. 16. The 3GPP MIMO work item for Rel. 17 [2] agreed to extend multi-TRP-based reliability and robustness enhancements to the physical downlink control channel (PDCCH), the physical uplink shared channel (PUSCH) and the physial uplink control channel (PUCCH). The focus of this paper is on the multi-TRP enhancements for the PDCCH in Rel. 17.

The PDCCH carries the downlink control information (DCI) that is used to schedule the PDSCH, the PUSCH and the New radio (NR) or Long Term Evolution (LTE) sidelink channel. Additionally, it is also used to indicate slot formats, power control commands, cancellation of UL transmissions and power saving information [3]. Considerable work has been published on the analysis of the design principles, performance and enhancements of the PDCCH for 5G NR systems. In [4], an overview of the PDCCH design in 3GPP Rel. 15 is provided along with the rationales involved in the standardization process. The work in [5] proposes a novel mapping of the PDCCH to time-frequency resources, overbooking and precoder cycling for PDCCH transmit diversity in the 5G NR context. An evaluation of the PDCCH performance due to physical layer changes from LTE to 5G NR and insights regarding PDCCH multicast or broadcast are provided in [6]. An in-depth summary of the 5G NR PDCCH configuration, precoding methods, channel estimation and the associated simulation results are provided in [7].

The PDCCH enhancements specified via the MIMO work item in 3GPP Rel. 17 targeted multi-TRP-based ultra-reliable deployments, high-speed trains that use single-frequency networks and millimeter wave (mmWave) scenarios. This paper elaborates and provides insights on the multi-TRP-based enhancements for the 5G NR PDCCH. The contributions of the paper are as follows:

- PDCCH enhancements are considered for two categories of multi-TRP deployments: single-frequency network (SFN) and non-SFN. The PDCCH enhancement schemes supported in 3GPP Rel. 17 and the additional schemes proposed in this work for PDCCH repetition and diversity for these deployment categories are described along with their impacts on the 3GPP specifications.
- The applicability of the enhancement schemes to various use-cases, the associated receiver processing and implementation aspects are studied in detail. The procedures employed in the 3GPP specifications to enable backward compatibility with previous releases are described to offer further insights into the standardization rationales for the PDCCH design.
- Link-level simulation results are presented for the PDCCH transmission schemes along with the applicable decoding schemes in Frequency Range 1 (FR1) and Frequency Range 2 (FR2) (the frequency ranges are specified by 3GPP in [8]) according to the evaluation methodology agreed by 3GPP RAN WG1 in [9].
- An analysis on the trade-offs involved in each scheme with respect to error performance, network complexity, UE complexity and PDCCH overhead provides insights regarding target use-cases and supported UE/network-types, which are elaborated towards the end of the paper.

The paper is organized as follows. Section II gives a brief introduction to the 5G NR PDCCH. Section III provides a detailed account of various PDCCH reliability enhancements for multi-TRP scenarios including the 3GPP-supported transmission schemes. Section IV describes the associated receiver processing. The impacts on the 5G NR specifications and various implementation issues concerning the receiver processing methods are provided in Section V. Section VI presents numerical results on the performance of the PDCCH enhancements and decoding complexity. Section VII concludes the paper by summarizing the key aspects regarding each multi-TRP-based PDCCH enhancement.

II. 5G NEW RADIO PHYSICAL DOWNLINK CONTROL CHANNEL

The hierarchy of components that constitute the physical downlink control channel configuration are as follows: the control resource set (CORESET), the search space set and the PDCCH candidate. PDCCH transmissions are performed on predefined spaces in time and frequency in the NR radio frame called the Control Resource Set (CORESET) [10]. A carrier component or cell that the UE is configured with may comprise multiple bandwidth parts (BWP). Each BWP in a cell can be configured with one or more CORESETs. Each CORESET is associated with one or more search space sets. A search space set is associated with a CORESET and comprises one or more PDCCH candidates. An individual PDCCH transmission is performed in a PDCCH candidate of a search space set [11], [12]. These components of the PDCCH are explained in detail in this section.

A. CONTROL RESOURCE SETS

A CORESET comprises $N_{\mathrm{RB}}^{\mathrm{CORESET}}$ resource blocks and $N_{\mathrm{symb}}^{\mathrm{CORESET}} \in \{1, 2, 3\}$ symbols. A resource block is an orthogonal frequency division multiplexing (OFDM) symbol comprising 12 subcarriers or resource elements (REs) [10]. The frequency domain allocation can be contiguous or non-contiguous and the value of $N_{\mathrm{RB}}^{\mathrm{CORESET}}$ is a multiple of six. The downlink BWP is divided into parts of six resource blocks and one or more parts are allocated for a CORESET. Each CORESET comprises one or more control channel elements (CCEs) and each CCE comprises six resource element groups (REGs), where each REG equals one resource block in an OFDM symbol. Resource-element groups within a CORESET are numbered in increasing order in a time-first manner, starting with zero for the first OFDM symbol and the lowest-numbered resource block in the control resource set. A CORESET is also associated with a CCE-to-REG mapping which is described using REG bundles. A REG bundle comprises 2, 3 or 6 REGs. In a non-interleaved CCE-to-REG mapping, the CCEs are mapped in increasing order of indices to groups of six REGs which is also ordered. In case of interleaved CCE-to-REG mapping, an interleaving function is used to map the REG bundles of a CCE [10]. The type of CCE-to-REG mapping used in a CORESET – interleaved or non-interleaved – and details regarding the mapping are provided in the corresponding CORESET configuration to the UE [11]. The number of CCEs that constitute a PDCCH is indicated by an 'aggregation level' (AL). The possible values for AL are 1, 2, 4, 8 and 16. A PDCCH of AL L comprises L continuously numbered CCEs.

B. SEARCH SPACE SETS

Each search space set is associated with a CORESET and comprises one or more PDCCH candidates, each configured with a certain AL [11], [12]. The number of PDCCH candidates of a specific AL L present in the search space set are provided to the UE in the search space set configuration. The indexes of the CCEs in the CORESET corresponding to a PDCCH candidate in a given search space set is provided via the hash function described in [12] and [4]. A DCI payload is attached with cyclic redundancy check (CRC), encoded, rate-matched and modulated to generate the PDCCH that is mapped to a PDCCH candidate at the transmitter as shown in Fig. 1. Interleaving and scrambling are performed at various steps of the encoding process which is omitted from the figure for brevity. Along with the PDCCH payload, the demodulation reference signals (DMRS) required for coherent demodulation of the PDCCH are also embedded either throughout the CORESET or the REGs corresponding to the search space set(s) in a CORESET. An illustration of a CORESET and its components are provided in Fig. 2 [7].

The configuration of a search space set is provided with monitoring slot periodicity, offset and monitored symbols within a slot. These parameters determine the slots or a span of symbols in which the UE has to monitor or search the PDCCH candidates in the search space set for valid DCIs. A group of symbols in which a UE monitors a search space set for PDCCHs is called a monitoring occasion. The search space set configuration also comprises the DCI formats that the UE needs to search or monitor while decoding the PDCCH candidates. A DCI format is used in determining the purpose of the DCI and the size of the DCI payload.

The search for a PDCCH (i.e., a valid DCI) in a PDCCH candidate involves 'blind decoding' of the PDCCH candidate as every PDCCH candidate does not need to contain a PDCCH and there is no prior knowledge of the PDCCH candidates that comprise valid DCIs at the UE. The exact Radio Network Temporary Identifier (RNTI) value which is used in scrambling the cyclic redundancy check (CRC) bits of the PDCCH is also not known apriori at the UE for a given PDCCH. Therefore, the blind decoding process, in addition to error correction decoding, involves the unscrambling of the CRC bits of a PDCCH candidate with various RNTI values that its CRC can be possibly scrambled with and a CRC check to verify if the CCEs corresponding to the PDCCH candidate comprise a valid DCI according to the DCI formats to be monitored for the given search space set.

C. PDCCH TRANSMISSION IN 5G NR

A DCI comprising a payload of K bits is attached with a CRC of $C = 24$ bits scrambled with the applicable RNTI, as mentioned above. The $K + C$ message bits are polar-encoded and rate-matched to E bits that are then modulated to the resource elements corresponding to the DCI [3]. The first step in the encoding involves inserting the $K+C$ message bits in a $N = 2^n$-bit sequence (row vector) $\boldsymbol{x}$ with $N \geq K + C$. The value of n is determined based on the DCI payload size K and the number of rate-matched bits E as described in [3]. The positions of the $K + C$ message bits in the N-length sequence and the rest $N-(K+C)$ 'frozen' bits are determined from the universal reliability sequence provided in 3GPP Technical Specification 38.212 [3]. The sequence $\boldsymbol{x}$ is then applied with the polar code generator $\boldsymbol{G}_n \triangleq \boldsymbol{F}_n\boldsymbol{B}_N$, where $\boldsymbol{F}_n = \left[\begin{smallmatrix} 1 & 0 \\ 1 & 1 \end{smallmatrix}\right]^{\otimes n}$ and $\boldsymbol{B}_N$ is a bit-reversal permutation matrix, to obtain $\boldsymbol{x}_p = \boldsymbol{x}\boldsymbol{G}_n$. This N-bit sequence $\boldsymbol{x}_p$ is then rate-matched to E bits and modulated with Quadrature Phase Shift Keying (QPSK). The number of rate-matched bits, E, mapped to the CCE(s) of a PDCCH candidate with AL L is equal to $E = 2 \cdot N_{\mathrm{RE}}^{\mathrm{PDCCH}}$, where $N_{\mathrm{RE}}^{\mathrm{PDCCH}} = (L \cdot 6 \cdot 12 - N_{\mathrm{RE}}^{\mathrm{DMRS}})$, is the net number of resource elements for the PDCCH and $N_{\mathrm{RE}}^{\mathrm{DMRS}}$ is the number of resource elements in the CCEs associated with the PDCCH that are used for DMRS. Depending on the values of N and E, the rate-matching may be performed using repetition, puncturing or shortening [3]. Interleaving is performed before polar-coding and before rate-matching, but they are left out of Fig. 1 and Fig. 3 for compactness of illustration.

D. PDCCH RECEPTION AT THE UE

The receive-processing for a PDCCH after the collection of the associated CCEs and equalization is shown in Fig. 3. The LLRs of the E transmitted bits obtained from the $E/2$ equalized symbols after soft demodulation is fed to the polar decoder after rate dematching. The CRC polynomial is provided to the decoder in Fig. 3 considering list-based polar decoding [13].

The UE has limited capability for the number of PDCCHs it can decode in a given slot or in a span of symbols which is reported to the network [4], [12]. The network may schedule PDCCH candidates more than the UE's capability to decode, which is called PDCCH overbooking [4]. The 3GPP specification instructs the UE to decode the scheduled PDCCH candidates in a slot or span of symbols via an assignment of priority to them. The PDCCH candidates lower in priority and ultimately outside the UE's blind decoding capability are dropped. This understanding is shared by the network due to the UE's reporting of its blind decoding capability. The reported value may depend on the memory available at the UE and waveform numerology, among other parameters.

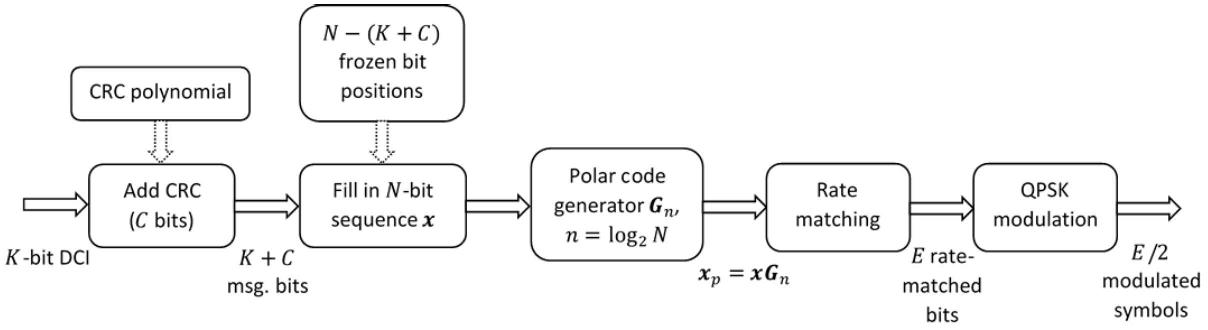


FIGURE 1. Transmit-processing for a PDCCH (interleaving and scrambling steps omitted).

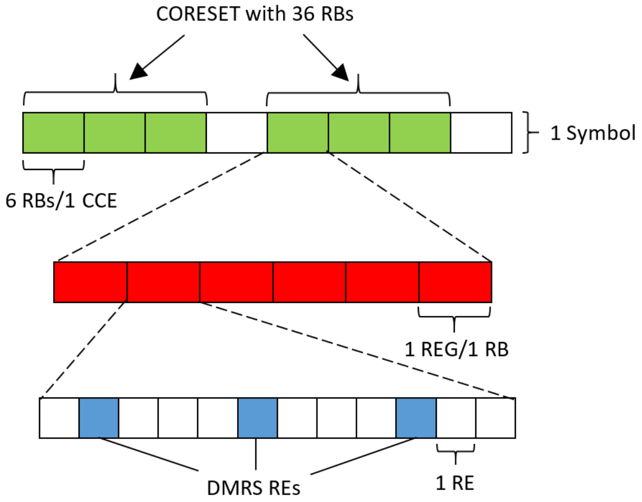


FIGURE 2. Composition of an example CORESET configured for one symbol and 6 resource blocks with non-contiguous frequency domain allocation.

III. MULTI-TRP PDCCH RELIABILITY ENHANCEMENTS

The multi-TRP reliability enhancement schemes for 5G NR PDCCH can be categorized according to the two possible deployment types: single-frequency network (SFN) and non-SFN. The non-SFN-based schemes can be further classified into PDCCH repetition and split-PDCCH transmission. The categorization of the transmission schemes is illustrated in Fig. 4. The transmission schemes are discussed below in detail.

A. SFN-BASED PDCCH ENHANCEMENT

PDCCH enhancement in SFN deployments entails the transmission of the same PDCCH from different TRPs or panels on identical time and frequency resources. In the 5G NR context, this implies the transmission of a PDCCH on a given PDCCH candidate in a search space set from multiple TRPs or panels as shown in Fig. 5a with identical PDCCH DMRS configuration, positions and sequences used by all the TRPs or panels. The UE is provided with multiple reception settings, i.e., Transmission Configuration Indication (TCI) States, for the reception of the PDCCH candidate simultaneously from multiple TRPs. A TCI-state indicates the reception settings such as delay spread, Doppler shift/spread and Rx-beam that are to be used for a DL channel or reference signal (RS) with reference to another reference signal such as a Synchronization Signal Block (SSB) or a Channel State Information Reference Signal (CSI-RS) [1]. The reference RS in each TCI-state may be associated with a different TRP to implicitly configure multi-TRP reception at the UE. No explicit specification of configurations or parameters are thus required to identify the TRPs transmitting to the UE. This transmission scheme is supported in 3GPP Rel. 17 by enabling the assignment of a CORESET with multiple TCI-states [14]. The reception settings corresponding to all the indicated TCI-states are applied by the UE for the demodulation and decoding of the PDCCHs transmitted on the PDCCH candidates on the CORESET. The PDCCH overhead for SFN-based repetition is identical to the single-TRP transmission as the PDCCH is repeated on the same PDCCH candidate by all the TRPs. However, this scheme poses stringent synchronization requirements among the TRPs as the repetitions should be received on the same resources in time and frequency at the UE. This may be realized only with ideal or near-ideal backhaul across the TRPs.

B. NON-SFN-BASED PDCCH ENHANCEMENTS

In the case of non-SFN deployments, two different methods of multi-TRP PDCCH transmission are possible as follows.

1) MULTIPLEXING PDCCH REPETITIONS USING MULTIPLE TRPs

The PDCCH repetitions are multiplexed in time and/or frequency via multiple TRPs in this scheme. An example is shown in Fig. 5b, where the PDCCHs generated from a given DCI are repeated in full on each of the two different PDCCH candidates P_i and P_j. By associating the PDCCH candidates with different TCI-states, each corresponding to a different TRP, multi-TRP transmission of the repetitions is enabled. Assigning identical TCI-states to the repetitions leads to single-TRP-based repetition. This scheme does not require stringent time synchronization as in the case of SFN. It can be implemented even with non-ideal backhaul across

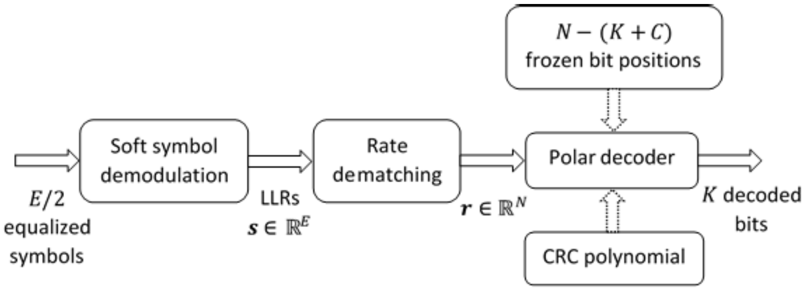


FIGURE 3. Receive-processing for a PDCCH (interleaving and scrambling steps omitted).

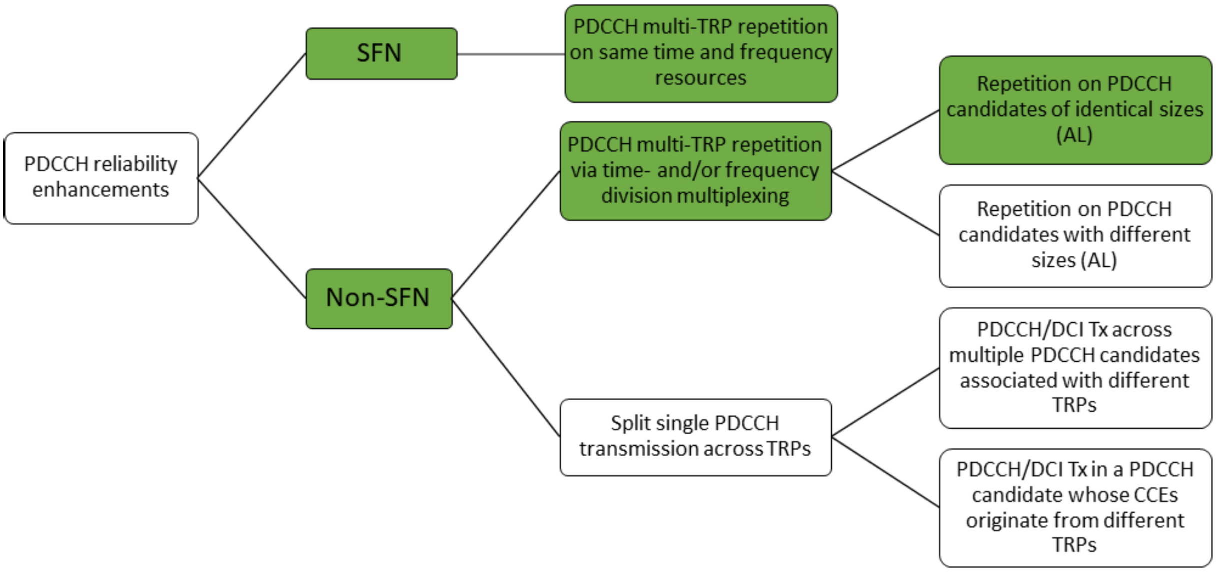


FIGURE 4. Categorization of 5G NR PDCCH reliability enhancement schemes in multi-TRP scenarios based on deployment types. The ones marked in green are supported in 3GPP Rel. 17.

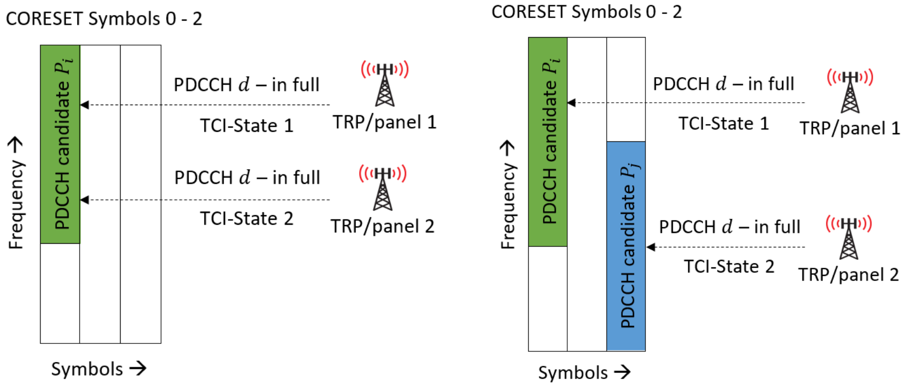
the co-operating TRPs by trading off latency and/or overhead for reliability.

A version of this scheme is supported in 3GPP Rel. 17. A search space set can be linked with another search space set via a higher layer configuration, where both search space sets have an identical number of PDCCH candidates [12]. The linked search space sets also comprise an identical number of PDCCH candidates for a given AL. A PDCCH candidate of AL L with a given index in a first search space set is associated with a PDCCH candidate of identical AL and index in the linked second search space set for PDCCH repetition. A further restriction that the PDCCHs on any two linked PDCCH candidates are identical is also specified in 3GPP Rel. 17. The repetition is performed with an identical DCI payload (CRC-attached DCI that is encoded), polar encoding settings, interleaving and rate-matched bits. The 3GPP specifications allow the association of a CORESET with only one TCI-state for this method. If two linked search space sets are transmitted on different CORESETs, the PDCCH repetition is enabled from one or multiple TRPs/panels at the UE transparently by assigning the CORESETs to the same or different TCI-states, respectively. On the other hand, if the linked search space sets are from a single CORESET, the TCI-state indicated for the CORESET applies to both the linked search space sets, allowing only for single-TRP/panel-based PDCCH repetition.

The network can be offered higher flexibility of scheduling if PDCCH repetition on PDCCH candidates of different AL values is enabled. This method, although not supported in 3GPP Rel. 17, provides varying degrees of reliability based on the AL values chosen for the repetitions. It enables the network to adapt to instantaneous channel conditions, PDCCH overhead limitations, UE memory constraints and target use-cases. With suitable specification changes for the dynamic modification of the ALs used for PDCCH repetitions, swift adaptation to the aforementioned conditions or use-cases can be realized by the network.

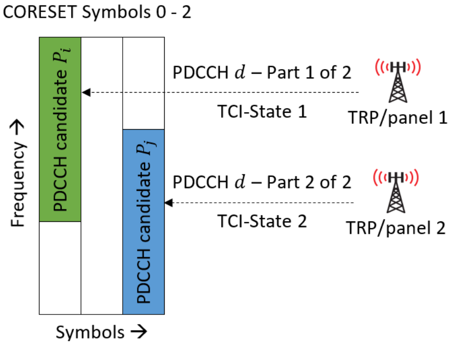
2) SPLITTING A PDCCH TRANSMISSION ACROSS TRPs

The splitting of a PDCCH transmission across different TRPs or ‘split-PDCCH’ scheme is proposed as an alternative with lower overhead and complexity compared to PDCCH repetition. The split-PDCCH scheme incurs the



(a) SFN-based repetition

(b) Non-SFN: TDM/FDM-based repetition



(c) Non-SFN: PDCCH split across TRPs

FIGURE 5. Illustration of SFN-based and non-SFN-based multi-TRP PDCCH transmissions.

same overhead as single-TRP PDCCH transmission and the same decoding complexity. One method to realize a split-PDCCH scheme is to map a PDCCH of L CCEs to $q > 1$ different PDCCH candidates that comprise the L CCEs in total, wherein each PDCCH candidate is assigned a unique TCI-state. This method is illustrated in Fig. 5c, where a PDCCH is mapped to two PDCCH candidates P_i and P_j whose combined aggregation level is equal to the aggregation level of the PDCCH. Configuring P_i and P_j on two different CORESETs (i.e., assigning different TCI-states to the two CORESETs) enables multi-TRP split-PDCCH transmission. Another method for splitting the PDCCH across different TRPs is to assign different parts of the associated PDCCH candidate with different TCI states.

The multiplexing of the PDCCH repetitions or the splitting of the PDCCH discussed above is performed in time and/or frequency on a single transmission layer. Spatial multiplexing of PDCCH repetitions or splitting of a PDCCH with multiple spatial layers across TRPs is not possible in the current 5G NR standard. The PDCCH DMRS supports only one port, i.e., the PDCCH transmissions have only a single layer. Such spatial multiplexing can be supported only after enhancing the PDCCH DMRS, and is hence left out of this paper.

IV. RECEIVER PROCESSING FOR PDCCH REPETITION SCHEMES

The processing of a DCI at the UE is shown in Fig. 3 for the case of decoding an individual PDCCH candidate. The applicable receiver processing for both SFN- and non-SFN-based PDCCH transmission schemes are provided in Table 1. For the SFN-based repetition and the split-PDCCH transmission case, the channel estimation on the CCEs corresponding to the PDCCH are performed according to the TCI-states indicated for the CCEs followed by a single PDCCH blind decoding. For non-SFN-based repetition, the combining of the repetitions before blind decoding is an obvious method to achieve SNR or coding gain. Performing multiple PDCCH blind decoding attempts from two or more PDCCH candidates that carry the same DCI content is another possibility considered in 3GPP and in this work. The various possible receiver processing methods for non-SFN-based PDCCH repetition are described in the following.

A. SOFT-COMBINING

Symbol-level and bit-level soft-combining (SC) are considered for PDCCH repetitions. Symbol-level combining or maximum ratio combining (MRC) is performed on the received symbols of the PDCCH repetition instances [15]

TABLE 1. Multi-TRP transmission schemes for 5G NR PDCCH and applicable receiver processing. 'Legacy decoding' indicates the collection of CCEs associated with the PDCCH followed by one PDCCH blind decoding.

Multi-TRP deployment	Transmission scheme	Receiver processing applicable
SFN	-	Legacy decoding
Non-SFN	Repetition with PDCCH candidates of same AL - identical DCI payload, K, N, positions of frozen bits, rate-matching and interleaving settings for all repetitions	Selection decoding, Symbol-level or bit-level soft-combining
	Repetition with PDCCH candidates of same or different AL - identical payload, K, N and positions of frozen bits for all repetitions	Selection decoding, Bit-level soft-combining
	Repetition with PDCCH candidates of different AL - different values of N for the repetitions	Selection decoding
	PDCCH split across multiple PDCCH candidates and/or TCI-states	Legacy decoding

and requires that the underlying transmitted symbols that are combined are identical, i.e., their DCI payloads, polar encoding and rate-matching settings are identical. Bit-level-combining involves combining of the soft-demodulated LLRs from the repetitions [15] and is feasible with fewer constraints among the combined PDCCHs than symbol-level combining. It suffices that the DCI payloads, the positions of frozen bits and the value of N of the polar encoder are identical. The polar decoder processes the LLRs of the combined symbols or the combined LLRs for blind decoding.

The ALs used for a given PDCCH repetition determines the value of N chosen for the repetition [3]. Hence, even bit-level soft-combining may not be feasible in cases of repetitions with PDCCH candidates of different ALs. Here, different values of N are used for the repetitions. In such cases, selection decoding, which is described in the following, may be the only decoding option.

B. SELECTION DECODING

For selection decoding (SD), each PDCCH repetition instance is blindly decoded individually until a valid DCI is detected. Since the repetitions are decoded individually, there is no requirement that the DCI payload, encoding or rate-matching parameters are identical across repetitions.

It is noted that the term 'identical DCI payload' for PDCCH repetition means that each DCI that is processed to obtain the PDCCH on the linked PDCCH candidates has the same K information bits and C CRC bits fed to the polar encoder. Any modifications of the field(s) in the DCI of one of the repetitions due to specification directives due to the timing or position of the corresponding PDCCH may not support soft-combining of the repetitions.

C. HYBRID DECODING

Hybrid decoding (HD) employs a combination of selection decoding and soft-combining. For a PDCCH repetition on M PDCCH candidates, selection decoding of $m \leq M$ individual PDCCH candidates is performed along with soft-combining of one or more subsets of the M repetitions with each subset comprising $2 \leq r \leq M$ PDCCH candidates. The decoding process is carried out until a valid DCI is detected.

V. SPECIFICATION IMPACTS AND IMPLEMENTATION CONSIDERATIONS IN RECEIVER PROCESSING

Receiver processing for SFN-based PDCCH repetition, other than the channel estimation for the PDCCH, involves just one PDCCH blind decoding similar to the legacy 5G NR PDCCH, resulting in only minor changes of UE complexity, PDCCH latency and specification impact. For the non-SFN-based schemes, however, varying degrees of complexity, latency and specification impacts are possible. An analysis of such aspects along with their utility, performance and applicable use-cases is crucial for their implementation.

In the case of non-SFN-based repetition, SD and HD provide error performances that are either worse or equal to that of SC as combining with every additional repetition improves the SNR or coding gain [16]. However, the advantages posed by methods involving multiple decoding attempts such as SD and HD are in terms of reducing PDCCH latency, PDCCH scheduling flexibility, memory usage and supporting reduced capability UEs.

SC and SD or HD require almost the same amount of memory to store the PDCCH symbols or LLRs when all the PDCCH candidates of a PDCCH repetition are obtained during a single monitoring occasion of the search space set or across few OFDM symbols. However, if two repetitions of the PDCCH are obtained on PDCCH candidates whose monitoring occasions are well separated in time, i.e., separated by multiple symbols within a slot or monitored on different slots altogether, then the LLRs from the first repetition have to be retained on memory until the second repetition for soft-combining the LLRs. This memory cannot be used for decoding of another PDCCH until the arrival of the second linked PDCCH repetition. Since the number of blind decoding attempts per slot or span of symbols is limited, as described above, holding this memory for a given duration implies the dropping of other PDCCHs due to memory shortage. SC thus requires higher memory when PDCCH repetitions across monitoring occasions are well separated in time. To increase the reliability of the PDCCH and/or to accommodate UEs that do not have sufficient memory to store the LLRs or symbols of each repetition before combining them, e.g., reduced-capability UEs, SD can be considered as an alternative. In addition, SD has the advantage of not waiting on the second PDCCH candidate, and therefore it is well suited to linked PDCCH transmissions across different monitoring occasions. Furthermore, for PDCCH repetitions employing different values of N, SD is the only applicable method as SC is not feasible. For these reasons, SD serves as a memory-efficient, lower-latency alternative to soft combining, albeit with poorer error performance. HD matches the error performance of SC, but involves a higher number of blind decoding attempts. It offers a lower PDCCH decoding latency than SC, but incurs higher memory usage than SD. It suits UEs with higher capacity for blind decoding and PDCCH memory, and to URLLC use-cases.

The Rel. 17 5G NR specification supports only inter-span repetition i.e., a repetition on two different monitoring occasions separated by one or more symbols within a slot. Inter-slot repetition is not supported.

The split-PDCCH transmission scheme incurs the same amount of blind decoding attempts per PDCCH as the legacy 5G NR PDCCH transmission. The receiver implementation only differs in terms of the collection of the CCEs or the application of the TCI-states to a PDCCH candidate. Since the PDCCH may be split across PDCCH candidates and time-division-multiplexed across symbols, monitoring occasions or slots, memory and latency issues impact the split-PDCCH scheme similar to the non-SFN-based PDCCH repetition with soft-combining. For inter-span or inter-slot PDCCH split, the memory has to hold the first part of the PDCCH until the second part arrives which may block other PDCCHs from being decoded.

With the pros and cons of each method with respect to memory storage, performance and complexity discussed above, the issues regarding PDCCH overbooking and the common understanding regarding the PDCCHs attempted for blind decoding at the UE need to be addressed. The next subsection discusses how these issues are handled in the 3GPP specifications at least for the non-SFN-based repetition scheme.

A. UE CAPABILITY REPORTING AND BACKWARD COMPATIBILITY IN 3GPP

3GPP Rel. 17 specifies rules for PDCCH decoding priority and UE reporting mechanisms to handle memory occupancy issues in non-SFN-based repetition and to share a common understanding between the UE and the network regarding the PDCCH candidates decoded in a given monitoring occasion.

The UE reports the number of blind decoding attempts, which can be either 2 or 3 [17], to be counted for a pair of PDCCH candidates linked for repetition [17] along with the blind decoding capability reporting of Rel. 15/16 as described above. The decoding method that is implemented - SC, SD or HD - is not explicitly revealed to the network. It is noted that the value reported is the number of PDCCH blind decoding attempts to be counted by the network for a pair of linked PDCCHs which may not correspond to the exact number of blind decoding attempts performed by the UE. For example, if a UE implements only SC to process a pair of linked PDCCH candidates, it performs just one blind decoding attempt after soft-combining the PDCCHs. But, it may report a value of 2 or 3 depending on implementation factors such as the memory buffer for LLR storage, number of PDCCH blind decoding attempts withheld due to decoding a pair of linked candidates, etc. With this additional reporting and a renewed set of priority rules for decoding specified in Rel. 17 based on the search space set ID associated with the linked PDCCH candidates, the UE and the network have a common understanding of the PDCCH candidates attempted for decoding in a slot or a span of symbols comprising both legacy PDCCH candidates and linked PDCCH candidates for repetition [12]. This enables backward compatibility with legacy 5G NR PDCCH scheduling.

To address the memory usage across spans of symbols for inter-span repetition, the UE is enabled to report the number of PDCCH candidates that can be received in a span of symbols, each of which has a linked PDCCH candidate that is yet to be received (in a future slot or span of symbols). This enables the network to gauge the buffer memory of the UE that is blocked for linked PDCCH candidates spread across different spans of symbols, and thereby limit the number of scheduled inter-span PDCCH repetitions to the UE's capability.

B. DECODING ORDER FOR SD AND HD

For both SD and HD, the decoding order of the PDCCH candidates determines how soon a valid DCI is detected, i.e., the number of blind decodes required until a valid DCI is detected, thereby improving the PDCCH decoding latency. Such an ordering makes sense for repetitions within a monitoring occasion or across a series of a few symbols. When the repetitions are within a PDCCH monitoring occasion, the decoding may be performed in a determined order after the reception of all the PDCCH repetitions using a metric related to the PDCCH candidates used for the repetitions. Doing the same for inter-slot or inter-span PDCCH repetition, however, may result in significantly higher decoding latency. Two metrics that can be considered for the decoding criterion are as follows:

- *Received power on the PDCCH DMRS:* The PDCCH candidate with the higher received power on its DMRS or on the DMRS in any part of the CORESET which is received with the same TCI-state as the PDCCH candidate is decoded with higher priority to improve the probability of earlier decoding. The DMRS-RSRP (DMRS-Reference Signal Received Power) may be computed similar to the RSRP provided in Section 5.1.2 of [18], but using the resource elements of the DMRS instead of that of the CSI-RS. A previously measured RSRP in the same CORESETs or any reference signals or channels associated with the TCI-states of the PDCCH candidates to be received may also be used for the selection of the PDCCH candidate. This criterion is especially efficient when the pathloss differences among the repetitions are significant.

- *Aggregation level of the PDCCH candidate:* If the linked PDCCH candidates have different AL values, the UE can prioritize the decoding of the candidate with higher AL as the DCI would be rate-matched with a lower code-rate in it. This may improve the chances of earlier decoding when the power differences among the linked PDCCH candidates are not significant.

The pros and cons of choosing a given metric and the scenarios in which they are advantageous are discussed in the next section.

VI. SIMULATION RESULTS

The simulation parameters used for the numerical evaluations are based on the criteria agreed in 3GPP for the evaluation of multi-TRP PDCCH enhancements [9], and are summarized in Table 2. For FR1, an urban macro cell scenario is considered with a carrier frequency of 4 GHz. In the case of FR2, a mmWave indoor scenario with 30 GHz carrier frequency is considered. In addition, the effect of blockage or shadowing is included in FR2. A blockage probability of 0.1 is assumed with a 10 dB blockage power loss. This means the probability that the link between the TRP and UE suffers blockage is 0.1 with a 10 dB power drop in the received signal during a blockage event. The signal-to-noise ratio (SNR) definition used in the simulations is the ratio of the average signal constellation (QPSK for PDCCH) energy E_s and the additive white Gaussian noise (AWGN) power N_0 per resource element.

A fully digital beamforming is considered for the FR1 scenario with two antenna ports at the UE and TRP, i.e., there are two antenna elements, and each antenna element has a corresponding RF chain. In the FR2 scenario, a hybrid antenna array structure is employed. The layer(s) of the data are mapped to the antenna ports via digital beamforming which are then mapped to the antenna elements using analog beamformers using the TXRU model 1 for planar arrays [19]. The RF chains are connected to the antenna array elements via a phased-array beamformer. The beamformer used for transmission or reception is typically determined after a beam search and association phase. To imitate a high-resolution beam search and association process, the elevation and azimuth angles corresponding to the dominant path of the channel are assumed to be the scan angles for the beamformer at the UE and the TRPs. Each TRP is configured with a dual-polarized 4×8 planar array and the UE with a 2×4 planar array, wherein all the elements corresponding to a polarization are associated with a single RF chain via the phased-array beamformer. Therefore, each RF chain corresponds to a different antenna polarization with the beamformers aimed at the direction of the dominant path of the channel. For digital beamforming/precoding in both FR1 and FR2 that maps the PDCCH to the antenna ports, open-loop precoder cycling is performed. The precoder is applied per REG using the 5G NR DFT codebook [1].

TABLE 2. Simulation parameters for BLER performance evaluation.

Parameter	Value
Carrier frequency	FR1: 4 GHz, FR2: 30 GHz
Subcarrier spacing	FR1: 30 KHz, FR2: 60 KHz
Number of antenna ports	2 Tx ports in a TRP, 2 Rx ports in a UE
DCI size	40 bits payload + 24 bits CRC
Number of RBs per CORESET	54 (Contiguous allocation)
Number of CORESET symbols	2
Channel model	FR1: TDL-C, FR2: CDL-A [20]
UE speed	FR1: 30 kmph, FR2: 3 kmph
Delay spread	FR1: 100 ns, FR2: 20ns
Precoding settings	REG level open-loop precoder cycling
CCE-to-REG interleaving settings	REG bundle size = 6, Interleaver size = 3
Channel estimation	2D-MMSE
Channel equalization	MMSE
Blockage settings (applicable only for FR2)	Blockage probability = 0.1 and blockage power loss = 10 dB

For the non-SFN-based PDCCH repetition scheme, the DCI is transmitted from two different TRPs on two different CORESETs. The CCE-to-REG mapping for both TRPs is interleaved with the interleaving parameters shown in Table 2. When the PDCCH repetitions are obtained on two different PDCCH candidates of the same AL, the transmit-processing parameters for the PDCCH repetitions are identical. For PDCCH repetitions with different ALs, the CRC-attached DCI is rate-matched for a baseline PDCCH with AL L and a PDCCH of AL $2L$ or $L/2$ for transmission from a first TRP and second TRP, respectively. The parameters of the encoding and rate-matching schemes are determined as described in [3]. Note that in the case of PDCCH repetitions with different ALs, for the DCI size chosen in Table 2, the values of N determined according to the 5G NR specifications [3] are 256, 512, 512 and 512 for ALs of 2, 4, 8 and 16, respectively. Therefore, soft-combining PDCCH repetitions with any combination of AL values among 4, 8 and 16 are possible. If the repetition is performed with a first PDCCH of AL 4, 8 or 16 and a second PDCCH of AL 2, soft-combining of the two PDCCHs is not possible.

In the case of single-TRP transmission, the PDCCH is transmitted by a single TRP. For split-PDCCH transmission, the first half of the PDCCH's CCEs is transmitted on a first PDCCH candidate from the first TRP and the remaining CCEs on a second PDCCH candidate from the second TRP. SFN-based repetition is realized by the superposition of the PDCCHs from two TRPs.

SFN-based repetition and split-PDCCH transmission incur only one PDCCH blind decoding as mentioned earlier. For non-SFN PDCCH repetitions, SD and SC, wherever applicable, are implemented. The decoding process is stopped for SD after a valid DCI is detected.

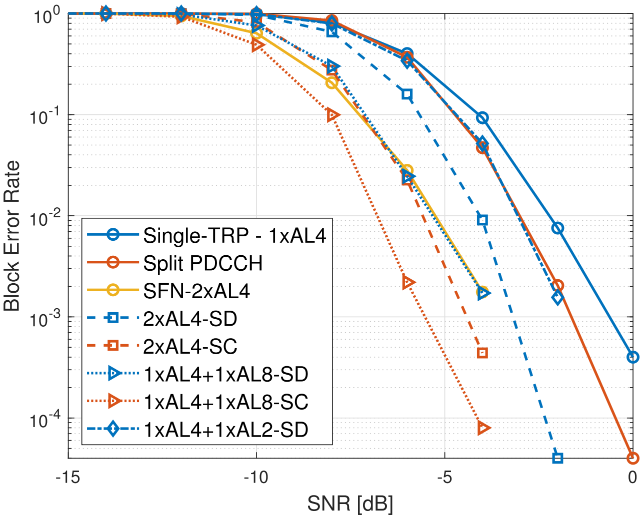


FIGURE 6. BLER for various PDCCH reliability enhancement methods with a baseline PDCCH of AL 4 in FR1.

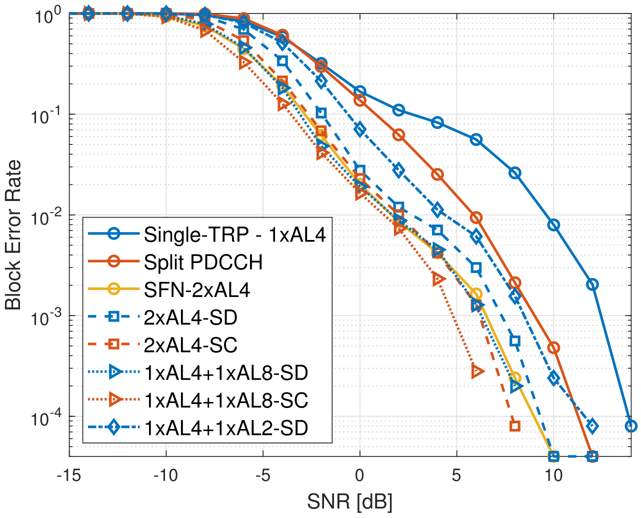


FIGURE 8. BLER for various PDCCH reliability enhancement methods with a baseline PDCCH of AL 4 in FR2.

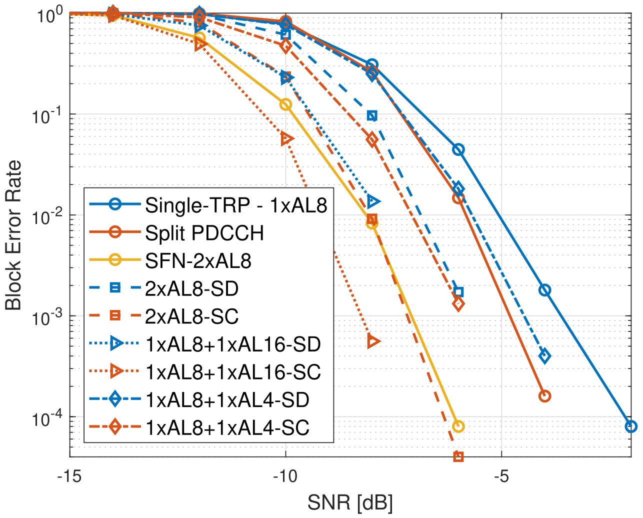


FIGURE 7. BLER for various PDCCH reliability enhancement methods with a baseline PDCCH of AL 8 in FR1.

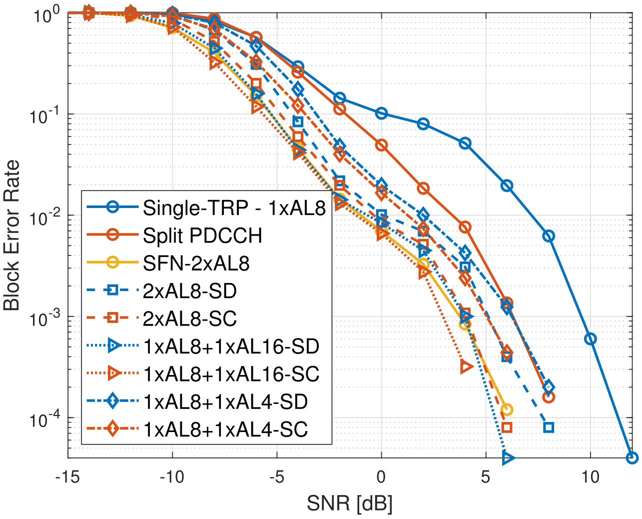


FIGURE 9. BLER for various PDCCH reliability enhancement methods with a baseline PDCCH of AL 8 in FR2.

A. BLER PERFORMANCE

The BLER performances in the FR1 scenario for a baseline PDCCH with AL 4 and 8 are shown in Fig. 6 and Fig. 7, respectively. Single-TRP PDCCH transmission with AL L is compared with SFN, split-PDCCH scheme and non-SFN-based PDCCH repetition with PDCCH candidates of AL L, $L/2$ and $2L$. The non-SFN methods are denoted in the legends of the plots by the AL of the PDCCHs used for the repetitions followed by the decoding method. The split-PDCCH scheme provides only a slight improvement over the single-TRP transmission scheme as a gain of around 0.75 dB is observed for both AL 4 and 8. The performance is similar to performing SD with non-SFN-based PDCCH repetition with AL $L/2$. Soft-combining with a PDCCH candidate of AL $L/2$, when applicable (for AL 8), provides a gain of around 2 dB over single-TRP transmission. A gain of 3 dB is observed for SFN-based PDCCH repetition for both AL 4 and 8, demonstrating the doubling of the received power at the UE. For non-SFN-based repetition with AL L, which has been specified in Rel. 17, SD provides a gain of around 2 dB over single-TRP transmission for both AL 4 and 8 at a BLER of 10^{-2}. For SC, a gain of 3 dB is observed. Soft-combining with a PDCCH of AL $2L$ provides a gain of over 4 dB over single-TRP transmission, while consuming three times the amount of resources compared to single-TRP transmission.

A noteworthy difference in the performance of SFN-based repetition and non-SFN-based repetition with AL L and SC decoding can be observed between AL 4 and 8. The performance of SFN-based repetition is better at lower SNRs while non-SFN-based repetition with AL L and SC decoding performs better at higher SNRs. This results in BLER curves crossing each other. The crossing point, however, is lower for

AL 8 compared to AL 4, indicating an improvement in SFN-based repetition or a degradation in non-SFN-based repetition with AL L and SC decoding with increasing AL. The SNR gain of SFN-based repetition over single-TRP transmission stays constant at 3 dB for both AL 4 and 8, whereas for non-SFN-based repetition with AL L, the gain drops from 3.5 dB with AL 4 to 3 dB with AL 8. This degradation in performance can be attributed to the noise characteristics of the reception in SFN- and non-SFN-based repetition. The noise level per PDCCH candidate in SFN is the same as that of single-TRP while the SNR per PDCCH candidate is doubled. The non-SFN case, on the other hand, can be considered as two separate single-TRP transmissions; while twice the power is received cumulatively on two different PDCCH candidates for the decoding of a single PDCCH, and hence the SNR per PDCCH candidate is the same as that in the case of a single TRP transmission. The collective noise power across the PDCCH candidates in the non-SFN case is twice than that of single-TRP or SFN. As the PDCCH block size increases, the disparity in the total noise power across all resource elements of associated the PDCCH candidates for single-TRP/SFN and non-SFN case increases, resulting in a drop in performance for higher block sizes in the non-SFN case.

The results for the FR2 scenario using the CDL channel parameters given in Table. 2 are provided in Fig. 8 and Fig. 9. Although SFN deployments are more common in FR1 than FR2, they are included for comparison. An initial drop in the BLER is observed for all methods, following which the BLER curve is flattened. At lower SNRs, the effect of noise dominates the blockage effect as the BLER curve initially drops. However, for mid-range SNRs, the effect of blockage becomes predominant, thereby flattening the BLER curve. The flattening is widest in the case of single-TRP transmission, indicating least robustness against blockage. When further PDCCH repetitions are added from other TRPs, or PDCCH is split across TRPs, the flattening of the BLER curve is less pronounced and the BLER drop is steeper at much lower SNRs compared to single-TRP, demonstrating higher robustness against blockage. The robustness improves with soft-combining of the repetitions or an increase in the AL of the PDCCH candidate used for the repetition. In addition, multi-TRP transmissions provide higher gain than the FR1 scenario under blockage. Even with split-PDCCH, a gain of more than 3 dB can be observed. In essence, it can be understood that, as the power differences between TRPs becomes steeper, the SNR gain for both PDCCH repetition and split-PDCCH over single-TRP transmissions becomes higher which improves PDCCH reliability.

It can be observed that the gains of SC over SD are meagre when the effect of blockage is prominent. A PDCCH may provide very little new information if the link has a significant power drop. Hence, soft-combining a strong first link and a considerably weak second link is effectively as good as decoding the strong link alone.

The performance comparisons between SFN and non-SFN-based repetition with identical AL values, with respect to the BLERs in various SNR ranges and the crossing of the BLER curves for different ALs, are similar to that of the FR1 scenario.

In both FR1 and FR2 scenarios, SFN and non-SFN-based repetition with AL L for both PDCCHs performs better than single-TRP transmission with AL $2L$. In addition, any multi-TRP based repetition for a baseline PDCCH of AL L performs better than the transmission of the PDCCH with AL $2L$ from a single TRP in FR2. This means single-TRP-based PDCCH transmissions with a lower coding rate perform worse than PDCCH transmissions from multiple TRPs with higher coding rates. These results lead to the following conclusions. Multi-TRP PDCCH transmissions can be exploited in handover or cell-edge procedures in both FR1 and FR2 to improve the SNR. With the prominence of link blockage in FR2, diversifying PDCCH transmission via repetition or split via multiple TRPs is important for the robustness of the transmission.

SFN-based repetition provides a good trade-off between error performance and PDCCH overhead, UE complexity and PDCCH latency compared to the other methods, by leveraging network complexity. Tight frame synchronization and near-ideal backhaul across TRPs, at the very least, are crucial for PDCCH repetition with identical scheduling from the TRPs. Minor changes regarding TCI-state application are required at the UE, while existing PDCCH processing rules including overbooking and blind decoding capabilities can be reused for SFN-based repetitions. There is only a marginal increase in PDCCH channel estimation complexity at the UE. The channel estimation has to be performed with respect to the TCI-states of all the involved TRPs instead of just one TCI-state as in the single-TRP case. The impact of the SFN-based repetitions on the 3GPP specifications is also minimal as all the burden is shifted to the network implementation. From the perspective of UE implementation, SFN-based repetition is better suited among the discussed methods to improve PDCCH reliability.

The split-PDCCH scheme provides considerable gains in FR2 which demonstrates the effectiveness of multi-TRP diversity transmissions in the presence of blockage. There is a slight increase in UE complexity compared to SFN-based repetition in terms of processing the CCEs associated with a PDCCH, but it incurs the same overhead as the baseline single-TRP-based PDCCH scheme. When PDCCH split is performed within a slot, span or monitoring occasion, the UE's blind decoding capability and PDCCH overbooking can be reused from existing 3GPP specifications which simplifies UE implementation. With such a PDCCH split, the improved PDCCH robustness is traded for higher network complexity and a marginal increase in PDCCH latency and/or UE complexity.

For non-SFN-based repetitions, the UE incurs higher complexity than the other PDCCH enhancements, while the network complexity is lower compared to SFN-based repetitions. The gains are more pronounced than the split-PDCCH scheme and match that of SFN-based repetition when the repetition is performed using the same AL as the baseline PDCCH. The gains are further improved at the cost of increased PDCCH overhead. The use of soft-combining improves the BLER performance significantly. Repetition of the baseline PDCCH of AL L with a PDCCH of AL less than L and employing soft-combining performs better than selection decoding with PDCCH repetition using identical AL values in FR1 scenarios. It also provides comparable performance at higher SNRs in FR2 scenarios. Although repetition provides diversity, with one of the candidates having a higher code rate, the effect of blockage severely affects the decoding reliability of the PDCCH with lower AL. Such a repetition scheme may therefore be suitable in FR1 for UEs with limited LLR buffering capability and bit-level soft-combining. Repetition of a PDCCH of AL L with a PDCCH of AL higher than L provides consistently higher reliability than SFN at the cost of additional overhead and UE complexity.

Employing selective decoding instead of soft-combining does not achieve the complete potential of PDCCH repetition in terms of error performance. Its utility is purely in accommodating reduced-capability UEs, PDCCH latency reduction and exceptional cases of PDCCH repetition (e.g., repetitions with different values of N). Using a hybrid decoding scheme that involves both selection decoding and soft-combining is helpful in reaping the advantages provided by both methods at the cost of higher UE decoding complexity. A wider range of use-cases, UE and network capabilities and reliability requirements can be supported by non-SFN-based repetition compared to SFN due to the variations of repetitions that can be configured. The following subsection discusses the decoding complexity involved in non-SFN-based repetitions and proposals for the order of decoding with selection and hybrid decoding.

B. USE OF MULTIPLE PDCCH BLIND DECODING ATTEMPTS

The implementation of decoding methods such as SD and HD that involve multiple PDCCH blind decoding attempts for non-SFN-based PDCCH repetitions is analysed in this subsection. The order in which the PDCCH candidates are decoded in SD or HD greatly influences the number of PDCCH candidates decoded on average. In Fig. 10 and Fig. 11, the average number of decoding attempts is plotted over SNR for the FR1 and FR2 scenarios, respectively, with AL 8 using selection decoding. HD with two blind decoding attempts incurs the same number of decoding attempts as selection decoding - the first decoding in both HD and SD is assumed to be determined by a predetermined selection criterion and the second decoding used by HD is soft-combining. The candidate decoded first or the method used for choosing the first candidate is indicated after the hyphen in the legend of the plots. 'Seq.' indicates that sequential decoding is performed - the first PDCCH candidate from the first TRP is decoded first followed by the other PDCCH candidate. 'RSRP' denotes that the candidate with the higher DMRS-RSRP is chosen to decode first.

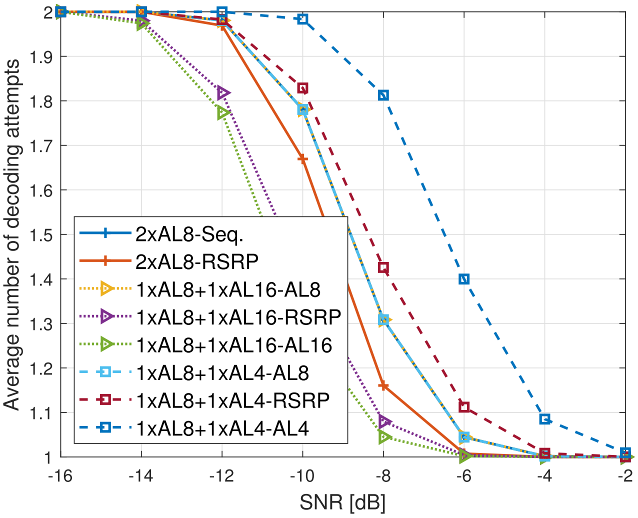


FIGURE 10. **Average number of decoding attempts with SD in FR1 with a baseline PDCCH of AL 8.**

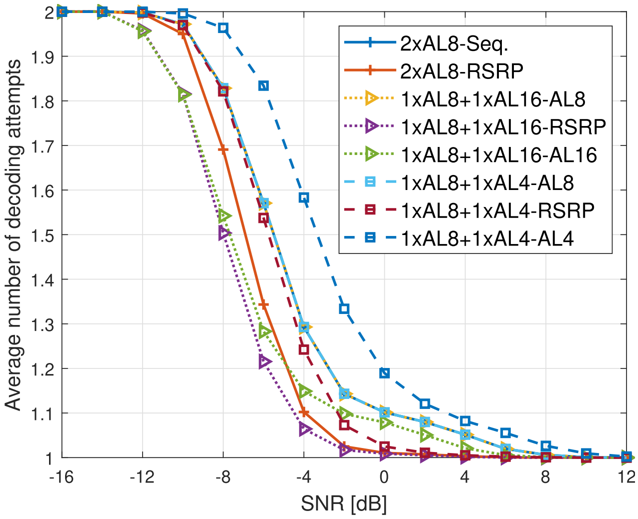


FIGURE 11. **Average number of decoding attempts with SD in FR2 with a baseline PDCCH of AL 8.**

For PDCCH repetition with the same AL L as the baseline PDCCH, decoding using RSRP leads to consistently lower average number of decoding attempts than sequential decoding for both FR1 and FR2 scenarios (the curve for sequential decoding coincides with the cyan and yellow curves). In the case of repetition with a PDCCH of AL $L/2$, either the same or a higher number of decoding attempts on average are required compared to other methods in the FR1 scenario. PDCCH repetition with AL $2L$ performs the best in FR1 when decoding is started with the PDCCH candidate of higher AL or RSRP.

A stark contrast is observed between the FR1 and FR2 scenarios for the PDCCH repetition methods with AL $L/2$ and $2L$. In FR1, choosing to decode the candidate with higher

AL first provides the best performance among the three different possibilities available, while in FR2, choosing to decode the candidate with higher RSRP first provides the best performance. If there is blockage leading to a steep power drop in a PDCCH candidate decoded first, regardless of the AL of the PDCCH, the SNR loss because of the blockage leads to higher probability of decoding error and hence requiring a second blind decoding. Therefore, when the power differences between the two PDCCH candidates are negligible, prioritizing the PDCCH candidate with higher AL for decoding is preferable. However, when the power differences across the PDCCHs are significant, the PDCCH candidate with higher RSRP shall be prioritized.

VII. CONCLUSION

This paper provides a comprehensive account of various multi-TRP-based 5G NR PDCCH enhancements. The 3GPP-supported enhancements of SFN-based PDCCH repetition and non-SFN-based repetition on PDCCH candidates with identical AL values are compared with two additional schemes: repetition on PDCCH candidates with different AL values and split-PDCCH transmission. The analysis of the numerical results, specification impacts, implementation issues and UE and network complexity lead to the following conclusions:

- *SFN-based PDCCH repetition* provides robustness while requiring only a single blind decoding at the receiver. There is no increase in PDCCH latency or overhead compared to single-TRP PDCCH transmission. Moreover, SFN-based repetition results in only a marginal increase in PDCCH channel estimation complexity due to the association of a PDCCH candidate with multiple TCI-states. It therefore offers the best trade-off between error performance and, UE complexity and PDCCH latency. The drawback of this method is in terms of network complexity as near-ideal backhaul among the TRPs is required for the synchronization of the PDCCH transmissions.
- *Non-SFN-based PDCCH repetition with identical AL values* incurs twice the PDCCH overhead compared to SFN- or single-TRP transmission. Enabling soft-combining of the repetitions at the UE considerably improves PDCCH reliability. This method poses lower network complexity compared to SFN as tight synchronization among the TRPs is not crucial. However, the memory requirements in case of inter-span or inter-slot repetition and the handling of the decoding of a combination of linked and individual PDCCH candidates in a given monitoring occasion result in an increased UE complexity. Different use-cases are supported by this repetition scheme depending on the scheduling of the PDCCH in the time domain. Networks with non-ideal backhaul across TRPs are best suited to implement non-SFN-based PDCCH enhancements. 3GPP Rel. 17 supports this enhancement with UE capability reporting and specification of PDCCH decoding priority rules, thereby providing compatibility and co-existence with the PDCCH from previous releases.
- *Non-SFN-based PDCCH repetition with non-identical AL values* incurs varying overhead compared to SFN- and single-TRP transmissions based on the AL value used for the repetitions. Accordingly, it provides varying degrees of PDCCH robustness. For a baseline PDCCH of AL L, performing a repetition using a PDCCH of AL lower than L, provides a reduced-overhead option for PDCCH reliability enhancement and supports UEs with limited PDCCH buffering capability. Due to the flexibility on the choices of the AL for the PDCCH repetitions, this method offers varying degrees of robustness. Moreover, network adaptability to PDCCH overhead changes and channel variations, among other UE and network conditions, is possible with suitable specification changes. Since the choice of the AL values used for the PDCCH repetitions determine the feasibility of soft-combining at the UE, gNodeB scheduling is crucial to reaping the performance gains of the repetitions.
- *Non-SFN-based split-PDCCH transmission* offers significant gains when blockage is taken into account in FR2 scenarios with no extra PDCCH overhead. Intra-slot- or intra-span-based split provides similar PDCCH latency to that of the single-TRP case. It is therefore attractive in FR2 scenarios with tightly synchronized TRPs and/or reduced-capability UEs, and provides robustness against blockage with negligible additional costs.

The enhancements discussed in this paper are restricted to PDCCH diversity in time and/or frequency domain using multiple TRPs. Multi-layered PDCCH transmission, with different layers transmitted from different TRPs, similar to the PDSCH in 3GPP Rel. 16, is an enhancement worth examining in the future. Moreover, as 3GPP RAN1 discusses the potential support for coherent joint transmissions (or cell-free massive MIMO) in 3GPP Rel. 18 [21], a further avenue of PDCCH reliability enhancement is opened up for study.

REFERENCES

[1] *NR; Physical Layer Procedures for Data*, 3GPP document TS 38.214 v17.2.0, Jun. 2022.

[2] Samsung, *Revised WID: Further Enhancements on MIMO for NR*, 3GPP TSG RAN Meeting 93-e, Electronic Meeting, document RP-212535, Sep. 2021.

[3] *NR; Multiplexing and Channel Coding*, 3GPP document TS 38.212 v17.2.0, Jun. 2022.

[4] K. Takeda, H. Xu, T. Kim, K. Schober, and X. Lin, "Understanding the heart of the 5G air interface: An overview of physical downlink control channel for 5G new radio," *IEEE Commun. Standards Mag.*, vol. 4, no. 3, pp. 22–29, Sep. 2020.

[5] V. Braun, K. Schober, and E. Tiirola, "5G NR physical downlink control channel: Design, performance and enhancements," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2019, pp. 1–6.

[6] H. Chen, D. Mi, M. Fuentes, E. Garro, J. L. Carcel, B. Mouhouche, P. Xiao, and R. Tafazolli, "On the performance of PDCCH in LTE and 5G new radio," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2018, pp. 1–6.

[7] F. Hamidi-Sepehr, Y. Kwak, and D. Chatterjee, "5G NR PDCCH: Design and performance," in *Proc. IEEE 5G World Forum (5GWF)*, Jul. 2018.

[8] *NR; User Equipment (UE) Radio Transmission and Reception; Part 1: Range 1 Standalone*, 3GPP document TS 38.101-1 v17.6.0, Jun. 2022.

[9] *Final Report of 3GPP TSG RAN WG1 102-e V1.0.0 (Online Meeting, 17th–28th August 2020)*, 3GPP TSG RAN WG1 Meeting 103-e, document R1-2007501, 2020.

[10] *NR; Physical Channels and Modulation*, 3GPP document TS 38.211 v17.2.0, Jun. 2022.

[11] *NR; Radio Resource Control (RRC) Protocol Specification*, 3GPP document TS 38.331 v17.1.0, Jul. 2022.

[12] *NR; Physical Layer Procedures for Control*, 3GPP document TS 38.213 v17.2.0, Jun. 2022.

[13] A. Balatsoukas-Stimming, M. B. Parizi, and A. Burg, "LLR-based successive cancellation list decoding of polar codes," *IEEE Trans. Signal Process.*, vol. 63, no. 19, pp. 5165–5179, Oct. 2015.

[14] *NR; Medium Access Control (MAC) Protocol Specification*, 3GPP document TS 38.321 v17.1.0, Jul. 2022.

[15] E. W. Jang, J. Lee, H.-L. Lou, and J. M. Cioffi, "On the combining schemes for MIMO systems with hybrid ARQ," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 836–842, Feb. 2009.

[16] J.-F. T. Cheng, "Coding performance of hybrid ARQ schemes," *IEEE Trans. Commun.*, vol. 54, no. 6, pp. 1017–1029, Jun. 2006.

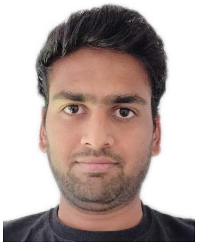
[17] *Final Report of 3GPP TSG RAN WG1 104bis-e v1.0.0 (Online Meeting, 12th–20th April 2021)*, 3GPP TSG RAN WG1 Meeting 105-e, document R1-2104151, 2021.

[18] *NR; Physical Layer Measurements*, 3GPP document TS 38.215 v17.1.0, Apr. 2022.

[19] *Study on Elevation Beamforming/Full-Dimension (FD) MIMO for LTE*, 3GPP documet TR 36.897 v13.0.0, Jul. 2015.

[20] *5G; Study on Channel Model for Frequencies From 0.5 to 100 GHz*, 3GPP document TR 38.901 v14.0.0, May 2017.

[21] Samsung, *New WID: MIMO Evolution for Downlink and Uplink*, 3GPP TSG RAN Meeting 94-e, Electronic Meeting, document RP-213598, Dec. 2021.



SUTHARSHUN VARATHARAAJAN received the M.Sc. degree in electrical engineering from the Ilmenau University of Technology, in 2016, where he is currently pursuing the Ph.D. degree. Since then, he has been working with the Electronic Measurements and Signal Processing Group, Fraunhofer Institute of Integrated Circuits IIS, Ilmenau. He has been a Standardization Delegate for NR in 3GPP RAN WG1, since 2018. His research interests include multi-transmission-reception-point communications and mmWave beam management.

MARCUS GROSSMANN received the Dipl.-Ing. (M.S.) and Dr.-Ing. degrees in electrical engineering from the Ilmenau University of Technology, in 2004 and 2012, respectively. He joined the Fraunhofer Institute for Integrated Circuits IIS, in 2011, and has since worked on multi-antenna processing and mmWave communications. Since 2016, he has been a Standardization Delegate for NR in 3GPP RAN WG1.

GIOVANNI DEL GALDO (Member, IEEE) received the Laurea degree in telecommunications engineering from the Politecnico di Milano, in 2002, and the Dr.-Ing. degree from Technische Universität Ilmenau, in 2007, on MIMO channel modeling. Then, he joined the Fraunhofer Institute for Integrated Circuits IIS, focusing on audio water marking and spatial sound. Since 2012, he has been leading a joint research group composed of a department at Fraunhofer IIS and as a Full Professor and the Chair with TU Ilmenau, in the research area of electronic measurements and signal processing. His current research interests include analysis, modeling, and manipulation of multi-dimensional signals, over-the-air testing, and sparsity promoting reconstruction methods.

• • •