Interference Measurement Methods in 5G NR: Principles and Performance

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***Abstract*—In this paper, we describe and analyze two different interference measurement (IM) methods for 5G New Radio (NR) networks, with particular emphasis on cell-edge users and thus interference limited scenarios. Specifically, the non-zero-power channel state information (CSI) reference signal (NZP CSI-RS) based method and the CSI interference measurement (CSI-IM) method are defined, studied and compared. In general, IMs are an essential ingredient in efficient link adaptation techniques, particularly in the form of channel quality indicator calculations which build on interference and channel response measurements at user equipment. Hence, we specifically study the impact of different IM methods on 5G NR link adaptation and throughput performance, incorporating both inner loop and outer loop link adaptation procedures. Different IM methods are defined, discussed and their basic operation principles are revised, including system overhead aspects, and detailed performance evaluation and comparison is provided. Our results show that NZP CSI-RS method allows to achieve more accurate IM than CSI-IM method, when measuring non-precoded interference and noting practical channel estimation and measurement errors. The CSI-IM method performs better than NZP CSI-RS method with practical channel estimation and measurements when the precoded interference is measured.**

***Index Terms*—5G, New Radio, interference measurements, reference signals, link adaptation.**

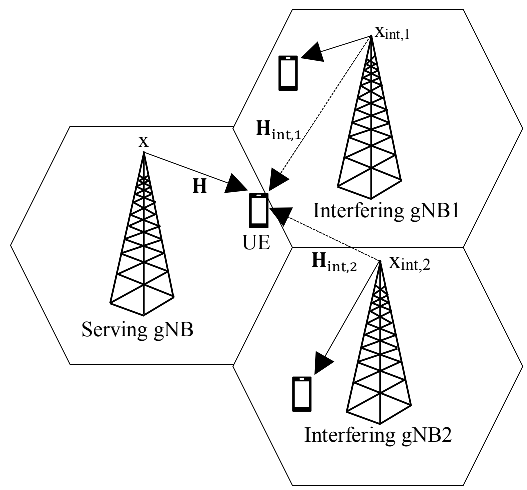


Fig. 1: Interference model consists of one serving cell and two interfering cells. Here $\mathbf{x}$, $\mathbf{x}_{\text{int},1}$ and $\mathbf{x}_{\text{int},2}$ correspond to the transmitted symbols from serving and interfering gNBs respectively, and $\mathbf{H}$, $\mathbf{H}_{\text{int},1}$ and $\mathbf{H}_{\text{int},2}$ correspond to the channel responses of the received signals for each relevant subcarrier index.

I. INTRODUCTION

The Third Generation Partnership Project (3GPP) has recently approved the first specifications of the fifth generation (5G) new radio (NR) interface [1]–[4]. The first 5G NR deployments will depend on existing LTE networks for initial access and mobility management, which is known as non-standalone operation and it is expected to take place in 2019. After the introduction of the 5G core network, support for standalone operation is possible and the 5G NR base stations, denoted as gNBs, connected to the 5G core will provide the full scale support for 5G NR and all related functionalities without the help of LTE base stations or core network.

In this paper, the link level performance of 5G NR downlink data channel is evaluated for user equipment (UE) on the cell edge while noting the inter-cell-interference from neighboring cells (or gNBs). In this model, the link between the serving cell (or gNB) and one UE is modeled, and two interfering signals from neighboring gNBs are modeled as illustrated in Fig. 1. The serving cell is using link adaptation (LA) techniques to follow channel state information (CSI) reports from the UE. The CSI consists of channel quality indicator (CQI), precoding matrix index, CSI-RS resource indicator, layer indication, rank indication, and layer-1 reference signal received power [5]. However, in this paper, we focus only on CQI as one of the CSI components that reflects average channel conditions and interference levels at the UE location.

In LA process, transmission settings, e.g., modulation and coding scheme (MCS), are defined based on reported CQI from the UE. In order to calculate CQI, an accurate interference measurement (IM) and channel measurement are needed. In the notation of this paper, *measurements* relate to some estimated value that is reported back to the gNB. If the UE itself uses the estimated information, then we use the term *estimation*, e.g., channel estimation from demodulation reference signals (DM-RSs) to estimate the channel between the UE and the serving gNB to equalize and detect the allocated UE specific data symbols. Since the quality of the channel and interference measurements needed to calculate CQI strongly affects the quality of the LA process, two different IM methods are studied in this paper.

The first IM method relies on the non-zero-power CSI reference signals (NZP CSI-RSs), where NZP CSI-RSs are used for two purposes. Firstly, to get channel measurements from serving cell, and secondly, to obtain the residual IM based on the channel measurements. The second IM method is based on the CSI interference measurement (CSI-IM) resource elements (REs), which allow direct IM from the received samples. Both of these methods are discussed in detail and also the different interference types that can be used in measurements are described.

The main novelty of this paper is in the introduction and description of different IM methods available for 5G NR and extensive performance evaluations in ideal or practical channel estimation and measurement scenarios. Based on the authors best knowledge, no prior literature on the comparison of CSI-IM and NZP CSI-RS are available. In addition, it is shown that depending on the interference type estimated, different IM methods provide better performance.

The rest of this paper is organized as follows: Section II describes LA concept, CQI calculations, and outer loop LA (OLLA) scheme. In Section III, the interference model and the different IM methods are discussed including different interference types. In Section IV, performance comparison between the discussed IM methods are provided and evaluated. Finally, conclusions are drawn in Section V.

II. Link Adaptation

The LA is a key feature of any modern mobile communication cellular system [3]. It refers to adapting transmission settings to take advantage of the time and frequency varying channel response. The purpose of LA is to improve system capacity, peak data rates, and coverage. System capacity is improved by more efficient utilization of frequency spectrum, as it is very scarce and expensive resource in wireless communications. Peak data rates are achieved when maximizing the used MCS for UEs in good channel conditions. Coverage can be improved through improved system capacity, and also by accurate IM enabling accurate MCS adaptation for cell edge UEs in time varying interference conditions.

LA is performed at the gNB and decisions about the next transmission settings, e.g. MCS, are based on CQI reports provided by the UE [6]. The CQI frequency granularity and periodicity is configured by the gNB. The frequency granularity of the CQI reports can be Wideband CQI, gNB-configured sub-band CQI, or UE-selected sub-band CQI. In time domain, CQI reports support periodic, aperiodic, or semi-persistent reporting modes [3]. In this paper, periodic wideband CQI is reported every 5 subframes, corresponding to time interval of 5 ms, where a single wideband CQI index is reported that reflects the average channel condition for the UE specific transmission bandwidth.

A. Channel Quality Indicator Definition and Calculation

The performance of the LA is greatly affected by the accuracy of CQI reports, which is strongly dependent on the accuracy of the channel and interference measurements at the UE. The CQI provides a recommendation about the next transmission MCS, so that a certain target block error rate (BLER) can be achieved [3]. An ideal CQI report would thus be the true signal-to-interference-and-noise-ratio (SINR) on a physical resource block (PRB) basis as observed by the UE. This would provide a very accurate information on the channel and interference responses to LA, but it is not practical as the SINR estimation always contains some errors and a PRB wise signaling implies a very high uplink overhead.

In this paper, wideband CQI is used to reduce uplink overhead and it is calculated as follows. First, serving cell channel is measured using the scheduled NZP CSI-RS signal. Then, the instantaneous interference-plus-noise covariance matrix is measured using either the scheduled CSI-IM or NZP CSI-RS resources. Next, the post detection SINR per RE of the received signal is calculated using minimum-mean-squared-error interference-rejection-combining (MMSE-IRC) receiver [7]. In this paper, mean mutual information per bit (MMIB) is evaluated as presented in [8], and is used as a link quality metric. Post detection RE wise SINRs are mapped to mutual information per bit values using pre-calculated and stored look-up tables, and the average of these values corresponds to MMIB. The obtained MMIB is used to get the MCS that delivers the highest throughput by searching through all possible MCS indices. For example, starting from the first MCS index, number of transmitted bits and the code block size is calculated as a function of MCS. Then using a BLER prediction algorithm defined in [9], having parameters code block size, MCS, and MMIB as inputs, the BLER is estimated for this transmission and is used to calculate throughput. This throughput is stored and then compared to the obtained throughput of the next MCS index until the highest possible throughput and corresponding MCS is found. The obtained MCS is mapped to the closest CQI index in a CQI table [5]. Finally, BLER is estimated for the selected CQI to ensure that the target BLER is achieved. If the estimated BLER is larger than the target BLER, the selected CQI index is reduced by one.

B. Outer Loop Link Adaptation

The OLLA is a scheme that aims to correct inaccuracies of CQI calculations so that a certain target BLER of the first hybrid automatic repeat request (HARQ) transmission can be achieved. There are different sources for these inaccuracies, e.g., estimation errors in channel and interference measurements performed by UE, and in practice there is always a delay between CQI calculations and when it is available at the gNB. OLLA is performed by the gNB and different schemes are proposed in the literature to cope with inaccuracies of CQI calculations. In [10], a scheme that subtracts an adaptive offset (Δ_{OLLA}) from the reported signal quality based on the HARQ acknowledgments is proposed as

$$CQI = CQI_{\text{reported}} - \Delta_{\text{OLLA}}. \tag{1}$$

In the above equation, it assumed that the used values are in logarithmic domain. If the transmitted block is correctly decoded, then positive acknowledgement is received and Δ_{OLLA} is decreased by Δ_{down}. If negative acknowledgement is received, then Δ_{OLLA} is increased by Δ_{up}. The values of Δ_{down} and Δ_{up} are related to the target BLER as follows

$$BLER_{\text{Target}} = \frac{1}{1 + \frac{\Delta_{\text{up}}}{\Delta_{\text{down}}}} \approx \frac{\Delta_{\text{down}}}{\Delta_{\text{up}}}, \tag{2}$$

if $\Delta_{\text{up}} \gg \Delta_{\text{down}}$.

TABLE I: Physical layer parameterization

Parameter	Configuration
Carrier frequency [GHz]	4
Channel model	TDL-a-30ns
User equipment mobility [km/h]	3
Sub-carrier spacing [kHz]	15
Bandwidth [MHz / PRBs]	20 / 100
Transmission mode	Single-layer-two-antenna ports
FFT size	2048
CP length	144
Modulation	Adaptive
Channel code	LDPC
Antenna configuration	2 Tx $\times$ 2 Rx
Waveform	CP-OFDM
OFDM symbols per slot	14
SCs per PRB	12
DM-RS allocation density	2 OFDM symbols
Channel and SINR estimation	Ideal or Practical
Receiver algorithm	MMSE-IRC
Number of interfering gNBs	2
DIP profile	DIP1 = -1.73 dB DIP2 = -8.66 dB
CQI channel measurement	Ideal or Practical
CQI delay in subframes	1
CQI reporting periodicity in subframes	5

In this paper, Δ_{OLLA} is limited to [-3,3] dB range. It is also assumed that $BLER_{\text{Target}}$ is 10% and in order to get fast and smooth convergence of OLLA factor, Δ_{up} and Δ_{down} have values of 1 dB and 0.1 dB, respectively.

III. Interference Model and IM Methods

A. Total Interference Model

The considered interference model consists of one serving gNB and two interfering gNBs as shown in Fig. 1, where we have omitted the subcarrier index k for simplicity. In order to reduce the link evaluation complexity, only the closest two interferers are modeled and the other distant interferers are assumed to be observed as additional noise. The total interference received from interfering gNBs plus thermal noise, for subcarrier k, is defined as follows:

$$\mathbf{y}_{\text{int,k}} = \sum_{l=1}^{L} \mathbf{H}_{\text{int},k,l}\mathbf{x}_{\text{int},k,l} + \mathbf{n}_k, \tag{3}$$

where $\mathbf{y}_{\text{int,k}} = [y_{\text{int},k}(0), y_{\text{int},k}(1), ..., y_{\text{int},k}(N-1)]^T$ corresponds to the total received interference per receiving antenna, N denotes the number of receiving antennas, and $(\cdot)^T$ defines a matrix transpose. Transmitted symbol vector from l^{th} interfering gNB is denoted by $\mathbf{x}_{\text{int},k,l} = [x_{\text{int},k,l}(0), x_{\text{int},k,l}(1), ..., x_{\text{int},k,l}(M-1)]^T$, $\mathbf{H}_{\text{int},k,l}$ is the channel response matrix for the l^{th} interfering gNB, and $\mathbf{n}_k$ is the thermal noise vector. The number of interfering cells is denoted by L, and M is the number of transmitting antennas in all interfering gNBs. In this paper, a 3GPP standardization compliant link-level simulator is used to carry out all evaluations. The interference model with $L = 2$, follows the dominant interferer proportion power (DIP) model. DIP profile defines power ratios between the explicitly modeled interferers and the overall interference-plus-noise power [11, Sec. 6.2]. In this study, a DIP profile of [-1.73 -8.66] dB is used for evaluations [12]. The main physical layer parameters are summarized in Table I.

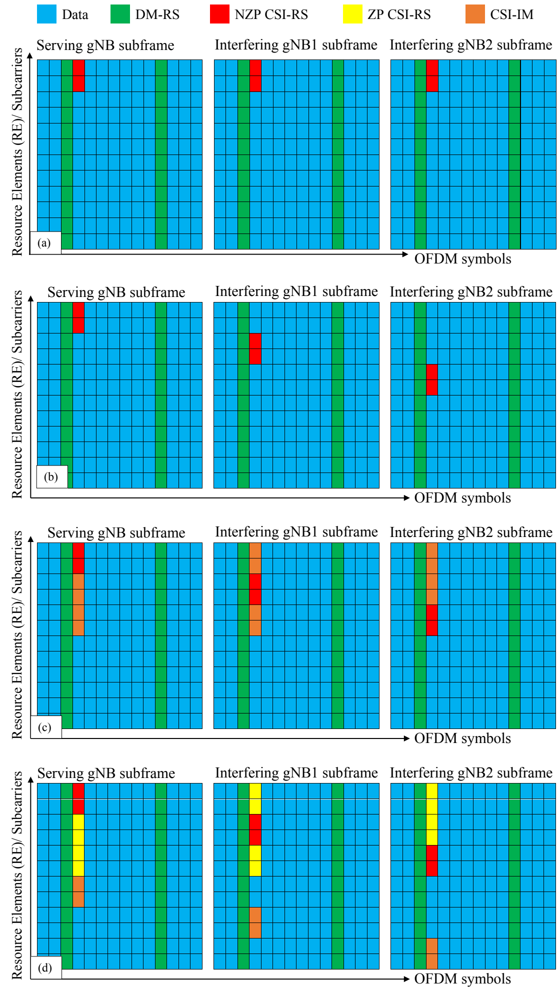


Fig. 2: Illustration of different CSI-RS configurations enabling non-precoded (a and c), or precoded (b and d) interference measurement through using either NZP CSI-RS method (a and b) or CSI-IM method (c and d).

B. CSI-RS Configurations for IM

In Fig. 2, the different CSI-RS configurations evaluated in this paper are shown. In Fig. 2 (a) and (b), the NZP CSI-RS method for IM based on non-precoded and precoded interference, respectively, is shown. In Fig. 2 (c) and (d), the CSI-RS configurations for CSI-IM method are shown, either measuring the non-precoded and precoded interference, respectively. By non-precoded interference, we refer to measuring interference from NZP CSI-RS resources transmitted by interfering gNB, as these resources are not precoded by any channel specific precoder. By precoded interference, we refer to scenarios where the measurement is made over REs where interfering gNBs are transmitting user data, which is precoded by a user specific precoder.

1) NZP CSI-RS Method: The main purpose of NZP CSI-RS is to have a separate reference signal to obtain CSI by the UE. However, it can be used to get IM by subtracting the product of estimated channel and transmitted RSs from the received signal. This approach is denoted as residual IM, where term residual stems from the fact that IM is obtained after subtracting the desired signal from the overall received signal. Fig. 2 (a), shows scheduled subframe of serving gNB where two NZP CSI-RS resources are allocated on the 4^{th} OFDM symbol colliding with NZP CSI-RS resource elements of subframes of interfering gNBs. In this case, the interference measured corresponds to non-precoded interference. In the case of Fig. 2 (b), the NZP CSI-RS overlaps with precoded user data from other gNBs and the estimated interference depends on the user specific precoding used in interfering cells. In both cases, the following evaluations hold, but the content of estimated interference-plus-noise component is different. The received reference symbol at subcarrier k can be represented as

$$\mathbf{y}_{\text{ref},k} = \mathbf{H}_k \mathbf{x}_{\text{ref},k} + \mathbf{y}_{\text{int},k}, \tag{4}$$

where $\mathbf{H}_k$ is channel response matrix of serving gNB, $\mathbf{x}_{\text{ref},k}$ is the transmitted reference symbol vector, and $\mathbf{y}_{\text{int},k}$ was defined in (3). Then interference-plus-noise component per scheduled NZP CSI-RS resource $\tilde{\mathbf{y}}_{\text{int},k}$ can be calculated as

$$\tilde{\mathbf{y}}_{\text{int},k} = \mathbf{y}_{\text{ref},k} - \hat{\mathbf{H}}_k \mathbf{x}_{\text{ref},k}, \tag{5}$$

where $\hat{\mathbf{H}}_k$ is the estimated channel from desired gNB obtained by using the NZP CSI-RS. Instantaneous interference-plus-noise covariance matrix estimate is then obtained for subcarrier k as

$$\mathbf{R}_{\text{NZP CSI-RS},k} = \tilde{\mathbf{y}}_{\text{int},k} \tilde{\mathbf{y}}_{\text{int},k}^H, \tag{6}$$

where $(\cdot)^H$ corresponds to conjugate-transpose. The obtained covariance matrix is a square matrix of size N, and it represents the estimated instantaneous interference-plus-noise covariance matrix per scheduled NZP CSI-RS RE. The diagonal elements represent interference-plus-noise power per receiving antenna, whereas the off-diagonal elements represents the correlation between the receiving antennas. Next, frequency domain interpolation is performed to obtain estimates for REs between the scheduled NZP CSI-RS resources. The subcarrier-wise instantaneous coveriance matrices are used for all OFDM symbols in the subframe.

2) CSI-IM Method: In CSI-IM method, a set of REs in one subframe are configured by the network on which the interference can be measured directly by the UE. These are denoted as CSI-IM. Practically, CSI-IM resources contain zero power REs. It should be clear that CSI-IM and ZP CSI-RS have different functions, where CSI-IM defines the set of resource elements from which the interference is measured, and ZP CSI-RS defines a set of resource elements where physical downlink shared channel (PDSCH) is not mapped and UE can not make any assumptions of the content of these resources [3].

In the case of CSI-IM, as shown in Fig. 2 (c) and (d), each gNB reserves two REs for NZP CSI-RS for channel estimation and IM is performed over the dedicated CSI-IM resources. In CSI-IM method, the NZP CSI-RSs are protected from inter-cell-interference by allocating either CSI-IM or ZP CSI-RS to the REs overlapping with NZP CSI-RSs from other gNBs. This allows the UE to obtain higher quality channel measurement due to reduced interference on top of the NZP CSI-RS.

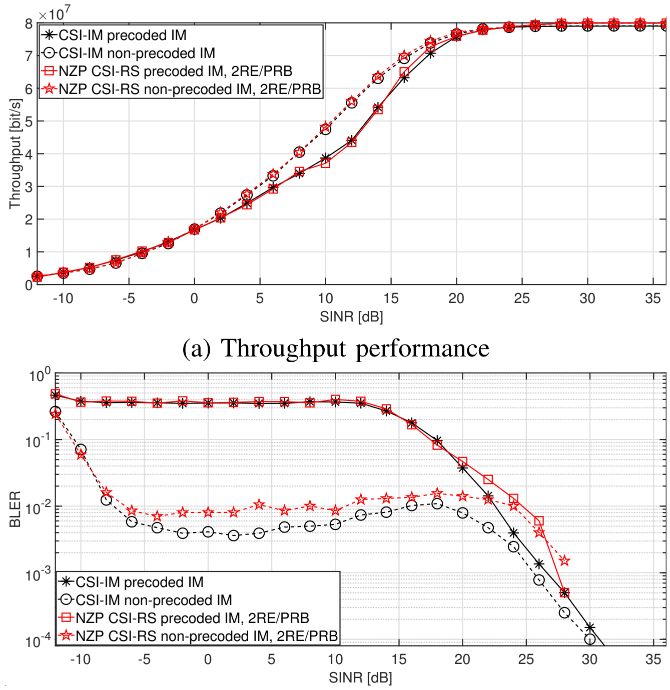
In Fig. 2 (c), a CSI-RS configuration is shown where four CSI-IM resources are allocated in the 4^{th} OFDM symbol colliding with the NZP CSI-RS transmitted by the interfering gNBs. Additionally, two NZP CSI-RS resources are colliding with CSI-IM REs of interfering gNBs to get accurate channel measurement. In this case, the UE measures instantaneous interference-plus-noise covariance matrix from all CSI-IM resources, and then combines them to generate a measurement of the total non-precoded interference. Fig. 2 (d), shows a configuration where the CSI-IM is colliding with data REs of interfering gNBs, thus allowing to estimate directly the precoded interference. Additionally, two NZP CSI-RS resources are colliding with ZP CSI-RSs of interfering gNBs to get accurate channel measurement. In this case, the channel estimation quality is similar to the scenario illustrated in Fig. 2 (c), but the IM is performed over precoded user data. The received signal on CSI-IM REs from interfering gNBs is used by the UE to construct instantaneous interference-plus-noise covariance matrix estimate. The total received interference signal, defined in (3), does not carry any useful data for the UE. Hence, an instantaneous interference-plus-noise covariance matrix ($\mathbf{R}_{\text{CSI-IM},k}$) per CSI-IM RE can be calculated as follows:

$$\mathbf{R}_{\text{CSI-IM},k} = \mathbf{y}_{\text{int,k}} \mathbf{y}_{\text{int,k}}^H. \tag{7}$$

3) CSI-RS Configuration Overheads: The main difference between different IM methods, in addition to what kind of CSI-RSs are used, is the overhead. In the following considerations, we assume that CSI-RSs are allocated to only one OFDM symbol and that 2 REs are allocated per gNB for NZP CSI-RS and CSI-IM, when applicable.

In NZP CSI-RS method, each gNB uses two REs per PRB to transmit NZP CSI-RS. In the case of Fig. 2 (a), there is no direct upper limit how many gNBs can be transmitting simultaneously, as all of their NZP CSI-RSs are overlapping and the total interference is available in the instantaneous interference-plus-noise covariance matrix measurement, as in (6). In the case of measuring precoded interference as shown in Fig. 2 (b), the simultaneously measurable gNBs is limited to six, assuming two REs allocated for the NZP CSI-RS.

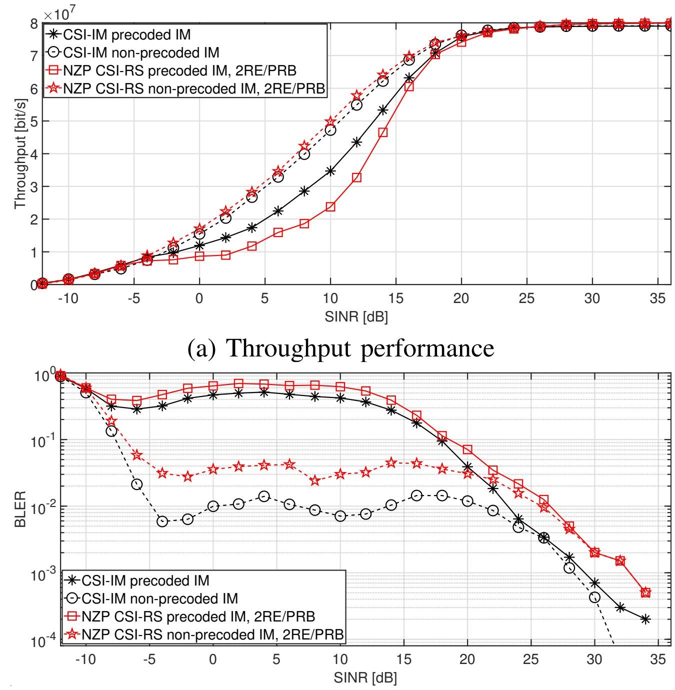
In the case of CSI-IM method and non-precoded interference, as shown in Fig. 2 (c), the number of simultaneously measuring gNBs is limited to six. This is due to the smart design where the dual role of CSI-IM allows to simultaneously protect NZP CSI-RS based channel measurement from inter-cell-interference and direct measurement of non-precoded interference per gNB. For CSI-IM method estimating precoded interference, as shown in Fig. 2 (d), the number of simultaneously measuring gNBs is limited to three. This is due to protecting NZP CSI-RS used for channel measurement with ZP CSI-RS allocations, and reserving CSI-IM resources for interference covariance measurements in each gNB. This way, both considered CSI-IM RS configurations provide



(a) Throughput performance

(b) BLER performance

Fig. 3: Performance comparison between CSI-IM and NZP CSI-RS scemes measuring either precoded and non-precoded interference assuming ideal channel estimation and measurement without OLLA.



(a) Throughput performance

(b) BLER performance

Fig. 4: Performance comparison between CSI-IM and NZP CSI-RS methods measuring either precoded and non-precoded interference assuming practical channel estimation and measurement without OLLA.

better channel measurement performance than NZP CSI-RS method due to limited interference from neighboring gNBs.

At large, the total overhead of CSI-RS used for IM with both methods is very small, because these resources are allocated only in every fifth subframe, and they consume resources only from one OFDM symbol. The minimum overhead is from NZP CSI-RS method estimating non-precoded interference, corresponding to approximately 0.2%, and in the evaluated scenario the largest overhead is with CSI-IM method estimating precoded interference, leading to approximately 1.4% overhead.

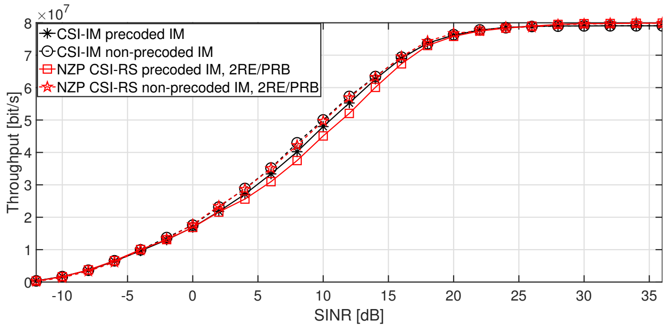
IV. Performance Comparison of Different IM Methods

The main physical layer parameters and interference measurement related assumptions used for the evaluations are defined in Table I.

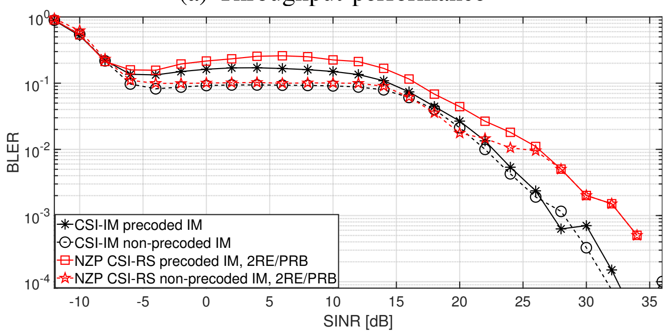
A. Performance Comparison of IM Methods Without OLLA

Performance of the proposed IM methods is evaluated by received data throughput and BLER. In the first set of results shown in Fig. 3, in order to evaluate the IM performance with minimal number of uncertainties, it is assumed that the channel and SINR estimation used for data demodulation is ideal, and channel measurement used for CQI calculation is also ideal. It can be seen from Fig. 3 (a) that NZP CSI-RS and CSI-IM methods measuring non-precoded interference provide the best throughput at SNR range from 0 dB to 20 dB. The CSI-IM and NZP CSI-RS methods measuring precoded interference provide slightly worse throughput in this interval. There is a very small difference between CSI-IM and NZP CSI-RS methods for both measured interference types, as expected in the case of ideal channel estimates and measurements. From Fig. 3 (b), it can be observed that when measuring the non-precoded interference, the realized BLER is approximately at level of 1% for a wide SNR range. This implies that the measured interference power is larger than realized interference power, and the reported CQI is too conservative. On the other hand, when measuring interference power over precoded resources, the measured interference power is in average too small, leading to approximately 40% realized BLER, which is observed as throughput loss in the medium SNR range. In this case, the reported CQI is too aggressive. Neither of the schemes is able to accurately achieve the targeted 10% BLER target, noting the need for OLLA.

In Fig. 4, performance results with practical channel and SINR estimation used for data demodulation and practical channel measurements for CQI calculation are shown. In this case, NZP CSI-RS method measuring non-precoded interference provides the best throughput performance, while CSI-IM method provides slightly worse throughput performance. From Fig. 4 (b) we can observe, that the estimation errors have actually shifted the achieved BLER closer to the 10% BLER target when estimating non-precoded interference, leading to a very robust performance with both IM methods. Moreover, the throughput performance for these IM methods is close to the ideal case shown in Fig. 3 (a). In Fig. 4 (a), we observe also a clear difference between CSI-IM and NZP CSI-RS methods measuring precoded interference. CSI-IM provides clearly better throughput than NZP CSI-RS method, although both of them clearly lose to estimating non-precoded interference. From Fig. 4 (b) it is noted that the IM methods



(a) Throughput performance



(b) BLER performance

Fig. 5: Performance comparison between CSI-IM and NZP CSI-RS methods measuring either precoded and non-precoded interference assuming practical channel estimation and measurement with OLLA.

estimating precoded interference are even more optimistic than in Fig. 3 (b), leading to clear throughput degradation when compared to ideal channel estimation and measurement case.

Based on the presented results, NZP CSI-RS method measuring non-precoded interference seems to provide best practical throughput performance with smaller overhead than CSI-IM, with the cost of higher complexity in the receiver IM processing. On the other hand, the results also suggest that measuring different interference types, either precoded or non-precoded, leads to either over-estimating or under-estimating the interference power. Thus, as a future research topic, combination of these metrics could provide a more robust operation and optimized throughput performance.

B. Performance Comparison of IM Methods With OLLA

In this section the performance of the proposed IM methods is analyzed with OLLA which allows to correct some of CQI's calculation inaccuracies at the UE, providing a highly realistic conlusion to the presented evaluations. It should still be highlighted, that although OLLA can correct partially the estimation errors of the underlying IM method, the more accurate is the IM method, the faster is the OLLA convergence rate, and the better is the throughput performance over short active periods. In Fig. 5, the throughput performance (a) and BLER performance (b) are shown assuming practical channel estimation and measurement with OLLA. It can be observed that the throughput performance with CSI-IM and NZP CSI-RS methods are nearly identical and slightly better than ideal performance without OLLA when measuring non-precoded interference. Also the realized BLER is very close to 10% target at SNR range from -4 dB to 14 dB, after which the BLER starts to drop as there are no more higher MCS options available. In the case of estimating precoded interference, the performance of both methods is clearly improved by OLLA, but they do not achieve the performance of non-precoded interference. These results indicate that 5G NR basically provides a freedom to apply different IM methods to estimate either non-precoded and precoded interference. The NZP CSI-RS method has lower overhead and relatively good performance. On the other hand, CSI-IM method allows to estimate gNB wise interference power profile, which may be useful for advanced receiver algorithms.

V. Conclusions

In this paper, we described and investigated the performance of NZP CSI-RS method and CSI-IM method for interference measurement, and also discussed and evaluated the effect of measuring either precoded or non-precoded interference. Overall, best throughput performance was achieved by measuring non-precoded interference, and in this case NZP CSI-RS method provided the best performance without OLLA, and both methods provided equal performance with OLLA. In the case of measuring precoded interference, CSI-IM based method outperforms NZP CSI-RS based method with or without OLLA. Both methods have a low system overhead and allow new degrees of freedom for interference measurements. As a future topic, the combination of precoded and non-precoded interference measurements to further improve the quality of the CSI reports will be considered.

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