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Multi-Cell Reception for Uplink Grant-Free Ultra-Reliable Low-Latency Communications

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ABSTRACT The fifth-generation (5G) radio networks will support ultra-reliable low-latency communications (URLLC). In the uplink, the latency can be reduced by removing the time-consuming and error-prone scheduling procedure and, instead, using the grant-free (GF) transmissions. Reaching the strict URLLC reliability requirements with GF transmissions is, however, particularly challenging due to the wireless channel uncertainties and interference from other URLLC devices. As a consequence, the supported URLLC capacity and, hence, the spectral efficiency are typically low. Multi-cell reception, i.e., joint reception and combining by multiple base-stations (BS), is a technique known from long-term evolution (LTE), with the potential to greatly enhance the reliability. This paper proposes the use of multi-cell reception to increase the URLLC spectral efficiency while satisfying the strict requirements using GF transmissions in a 5G new radio (NR) scenario. We evaluate the achievable URLLC capacity for an elaborate multi-cell reception parameter space and multi-cell combining techniques. In addition, we demonstrate that rethinking of the radio resource management (RRM) in the presence of multi-cell reception is needed to unleash the full potential of multi-cell reception in the context of UL GF URLLC. It is observed that multi-cell reception, compared to a single-cell reception, can provide URLLC capacity gains from 205% to 440% when the BSs are equipped with two receive antennas and 53% to 22% when BSs are equipped with four receive antennas, depending on whether the retransmissions are enabled.

INDEX TERMS 5G new radio, grant-free, multi-cell reception, radio resource management, system level simulation, ultra-reliable low latency communications, uplink, URLLC.

I. INTRODUCTION

The first release of the fifth generation (5G) new radio (NR) has been specified by the third generation partnership project (3GPP) in Release 15 [1]. One of the 5G use cases is Ultra-Reliable Low-Latency Communication (URLLC), which pose highly challenging service requirements [2]. URLLC is set to enable numerous services such as the tactile internet [3] and the factory of the future envisioned for the fourth industrial revolution. Here, URLLC enable controllers to wirelessly control actuators/sensors using fast control loops and mobile robots to safely and efficiently perform cooperative tasks [4]. Air-interface latency requirements for URLLC range from 0.5 ms up to 7 ms with reliability requirements from 99.9% to 99.9999%, depending on the considered use-case [5].

Several technology components have been investigated prior to the specification of 3GPP Release 15, for example a new frame-numerology with mini-slots to facilitate short transmission times [6]. Grant-free (GF) access, aka configured grant in 3GPP terminology, is an attractive solution to reduce the uplink latency by removing the time consuming steps of grant-based (GB) scheduling [1], [7]. In particular, sharing of pre-configured GF resources among multiple User

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Equipments (UEs) is considered to improve the efficiency for sporadic traffic [8]. However, GF transmissions on shared radio resources are prone to inter- and intra-cell interference, which degrades the URLLC transmission reliability and limits the supported uplink URLLC capacity and hence spectral efficiency [9].

Combining multiple sources of diversity is essential to reach the high URLLC reliability requirements and improve the achieved URLLC capacity [7], [10], [11]. Diversity can be achieved in both time, frequency and the spatial domain. Frequency diversity exploits fading differences in the frequency domain and can be harvested through wide-band transmissions or sub-band channel hopping [10]. The coherence time of the radio channel is typical larger than the latency requirement, but the interference conditions can change per mini-slot. For that reason, transmission diversity through hybrid automatic retransmission request (HARQ) can be used to exploit variations in interference [12]. Further, by soft combining the retransmissions, the coverage can be improved. Spatial diversity exploits fading and interference differences by receiving copies from spatially separated antennas or receivers. It can therefore be obtained through signal combining from multiple receive antennas per base station (BS) and from spatially separated receivers with multi-cell reception [13], [14].

Multi-cell reception is a well-known technique from Long Term Evolution (LTE) Release 11, where it was known as coordinated multi-point (CoMP) reception [15], [16]. CoMP encompasses not only multi-cell combining but also interference aware and avoidance schemes. The latter is, however, not well suited for unpredictable GF transmissions. Multi-cell combining is, on the other hand, well suited for GF traffic. Combining across cells can be based on the exchange of complex in-phase and quadrature (IQ) samples, coded bits and also decoded bits [16]. Multi-cell combining based on IQ samples can be considered as a distributed antenna array system, whose complexity scales with the number of receive antennas and the number of cooperating cells [16]. As an evolution of CoMP, the concept of cloud radio access network (RAN) has been considered. Here, a centralized BS are connected to remote radio heads through a high capacity backhaul [17]. The applicability of cloud RAN and IQ based multi-cell reception is therefore best suited for smaller network deployments with few antennas per cell (i.e. below 6 GHz indoor factory or dense urban networks [18]). The complexity of combining based on coded bit exchange scales with the used modulation rate and the number of user equipments (UEs) participating in multi-cell reception [16]. Combining based on decoded bits is the simplest combining option with the lowest backhaul demands. Its usage is therefore well suited for urban macro deployment with moderate UE densities and networks with a capacity limited backhaul [19]. Multi-cell reception is also utilized in other cellular technologies such as Sigfox and LoRaWAN, targeted for non-latency sensitive applications and extreme coverage [20], [21].

Multi-cell reception based on IQ sample exchange has been studied for LTE in [22] and when based on coded- and decoded bits in [23], with the purpose of enhancing the network throughput for GB transmissions. A more recent study is found in [14]. However, neither of these studies include the joint contribution of intra-cell and inter-cell interference. The improved signal quality from multi-cell reception leaves room for efficiency enhancements by multi-cell reception aware radio resource management (RRM) techniques. Such technique is presented in [24], which is based on the uplink power control and in [25] where modulation and coding scheme (MCS) selection is used to achieve spectral efficiency improvements. Both techniques are studied for an LTE system with the objective to maximize the average network throughput.

While the basic uplink multi-cell combining techniques are known, it remains to be understood how this can enhance the URLLC capacity, defined as the maximum tolerable aggregated offered traffic load where the challenging URLLC service requirements are still fulfilled in a 5G NR setting with sporadic traffic bursts of latency critical payloads. Additionally, the cost in terms of backhaul throughput at the achieved URLLC capacity with the different multi-cell combining techniques remains to be fully understood.

In this study, we show that rethinking of the RRM operations, can unleash the full performance gains. Specifically, the MCS configuration for the GF transmissions and the power control settings must be optimized to efficiently leverage the performance benefits of uplink multi-cell reception, both from an intra- and inter-cell interference perspective. That is, exploiting uplink multi-cell reception both for improving the robustness towards intra-cell GF collisions and for reducing the generated other-cell interference to help improve the overall URLLC performance. By doing this, we show that the use of multi-cell reception techniques offers significant gains, even when using such techniques for a sub-set of the deployed UEs to strike an attractive balance between URLLC performance benefits and network complexity.

Our conclusions are confirmed by results from advanced system-level simulations where major performance-determining effects of a multi-user multi-cell 5G NR network, with dynamic URLLC traffic, is carefully modeled according to latest industry standard agreements. That is, simulations are based on fully calibrated and recognized underlying mathematical models, allowing us to present statistically reliable results with a high degree of realism and thereby high practical relevance. Especially the physical layer transmitter and receiver chains, the medium access control (MAC) protocol and the associated parameter configurations via radio resource control (RRC) are modeled.

The reminder of this paper is structured as follows. Section II sets the scene for the work and presents the scenario, GF configuration and applied MAC and RRM mechanisms. Section III presents the multi-cell reception combining techniques. Section IV presents two multi-cell reception aware RRM techniques, one based on power control and the other based on MCS selection. Section V describes the evaluation methodology and simulation assumptions, followed by Section VI which presents the performance evaluation. The main findings and take-aways are summarized in Section VII which also concludes this study.

II. SETTING THE SCENE

We consider a multi-cell multi-user 5G NR urban macro network scenario as described in [26]. The network consists of multiple sites with an equal inter-site distance. Each site consists of three BSs forming sectorized cells. The BSs are assumed to be time and frequency synchronized. An average number of U URLLC UEs are deployed uniformly within each cell. The BSs transmit a cell specific reference sequence, which is used by the UEs to estimate the received signal reference power (RSRP). The UEs are assumed to connect to the cell with the highest estimated RSRP. This cell will be denoted the serving or primary cell (p-cell) in this work. Each URLLC UE is assumed to generate small packets of size P with an uncorrelated Poisson arrival process at an average rate λ. The UEs are assumed to be configured by the p-cell through radio resource control (RRC) signaling, with at least one set of periodic reoccurring radio resources for GF transmission. In order to minimize the latency, the periodicity of GF resources is set to be equal to the transmission time interval (TTI), such that all UEs may transmit in any TTI. This means that the average aggregated offered URLLC load per cell becomes $L = \lambda UP$. Each UE is configured with a unique reference sequence which is transmitted with the GF transmission. This aids identification and channel estimation at the receiving BSs.

A. GF RESOURCE ALLOCATION

The BS configures the UEs with at least one GF configurations through RRC signaling. A GF configuration includes the time and frequency radio resources, MCS and the periodicity where these resources are available. These GF configurations may have radio resources which overlay in time and frequency. Only one configuration can be active at a time per UE, but different UEs may have different active configurations. We use a structured resource allocation scheme as proposed in [9], [27] for fixed packet sized GF resource configuration with multiple-MCS options. In this scheme, a GF configuration with MCS_1 occupies a bandwidth of BW resource blocks (RBs), while configuration with a higher order MCS_k, use an overlaying set of radio resources over a sub-band of BW/k RBs. The use of multiple sub-bands in the network for GF transmissions reduces the probability of fully overlapping transmissions, and therefore provides interference diversity [9], but requires that more energy per bit is collected.

B. RECEIVER

All cells are assumed to be equipped with a the 5G NR baseline receiver which is a linear minimum mean square error and interference rejection combining (MMSE-IRC) receiver with M receive antennas [18], [28]. With all UEs and BSs synchronized, the receiver may account for the intra-cell and inter-cell interference when computing the interference covariance matrix. With this, the desired signal can be projected into an $M-1$ dimensional subspace with minimum mean square error. The multiple receiving antennas therefore improves the receiver capabilities to handle interfering signals which is particular beneficial for GF transmission over shared resources [13], [29].

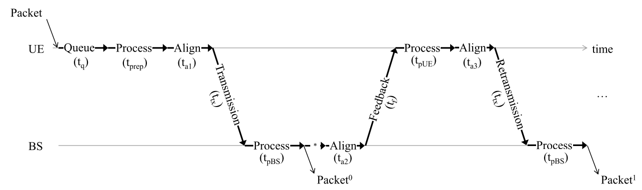

FIGURE 1. **Latency components for GF transmission with a following HARQ retransmission.**

C. RETRANSMISSIONS

A retransmission is triggered upon the reception of feedback from the p-cell. Retransmissions are a proven technique to enhance the reliability [12], but requires that the round trip time (RTT) of to a retransmission fits into the URLLC latency requirement. Retransmissions are supported in 5G NR by HARQ [1, p. 23]. We assume that retransmissions also occur on GF resources, as a GB retransmission requires a separate GB band.

D. LATENCY COMPONENTS

The latency components involved with a retransmission are illustrated in Fig. 1. When a URLLC packet arrives at the UE, if the HARQ queue is not empty the packet will be queued during t_q. Then, the packet is prepared for immediate GF transmission (coded and modulated). This step is assumed to contribute with t_{prep} latency. It is assumed that a GF transmission can only commence at the start of a TTI. This waiting time is denoted as alignment time t_{a1}. The GF transmission delay over the radio interface is defined as $t_{tx} = t_{TTI}$. The BS processes the GF transmissions in t_{pBS}. Depending on whether the packet transmission was successfully decoded by the receiving BS, a positive or negative feedback message is transmitted to the UE. This feedback transmission takes t_f and is carried out after a control channel alignment time t_{a2}. The UE processes the received feedback in t_{pUE} and after another alignment t_{a3} the UE can initiate the HARQ retransmission which also takes t_{tx}.

E. UPLINK POWER CONTROL

Uplink power control for 5G NR use the following expression to calculate the total UE transmit power [30, p. 14]

$$P_u[dBm] = min\{P_{max}, P_0 + 10log_{10}(2^{\mu} \cdot BW/k) + \alpha \cdot PL + f(.)\}, \quad (1)$$

where P_{max} is the UE maximum transmit power, P_0 is the target receive power per RB, BW/k is the number of used RBs for the GF transmission with MCS_k and μ is a sub-carrier spacing index [31, p. 9]. α is the path loss compensation factor and PL is the slow faded UE path loss estimate to its p-cell. The term $f(.)$ covers all closed loop terms which are used to apply UE-specific transmit power adjustments to maintain transmission reliability. In [9] this term was used to define an MCS specific offset and in this study it will be used for UE-specific multi-cell reception adjustments. The open loop power control parameters α and P_0 have been shown in [32] to have a substantial influence on the achievable URLLC capacity. In particular, the use of full path loss compensation ($\alpha = 1$) and empirically optimized P_0 as a function of the load and the scenario is demonstrated to be essential. The use of full path loss compensation is well aligned with the power control recommendations with multi-cell reception [16].

F. PERFORMANCE METRICS

The main key-performance-indicator (KPI) used in this study is the achievable URLLC capacity, which is defined as the maximum average aggregated offered URLLC load L, where the URLLC service requirements can be fulfilled. The baseline URLLC service requirements set by ITU-2020 [2] is considered, which defines that a URLLC transmission must be delivered from the UE to the BS within 1 ms latency with a minimum reliability of 99.999%. A packet transmission is said to be in outage if it is not received within the latency deadline. The outage probability is defined as the complement of the reliability at a given deadline. The average backhaul load as an indicator of the backhaul requirements to sustain achieved URLLC loads. The backhaul load is measured as the average data rate over the backhaul used for multi-cell reception. Only backhaul exchanges between different sites are included.

III. MULTI-CELL RECEPTION

In order to enable multi-cell reception, a set of assisting cells needs to be configured for joint reception. In this Section this procedure is described along with the considered multi-cell combining techniques.

A. ASSISTING CELL SELECTION

The p-cell may request the UE, through RRC signaling, to report a set of N strongest cells based on RSRP measurements. A set of maximum C_{MAX} assisting cells are selected as a subset of the reported N strongest. Only cells with an RSRP not less than T dB weaker than the p-cell RSRP are selected as assisting cells. Both cells from the same site and cells from different sites can be assisting cells. The p-cell is responsible for configuring the assisting cells and collecting data from them over the backhaul for multi-cell combining.

B. COMBINING SCHEMES

Fig. 2 illustrates a simplified 5G NR uplink receiver chain for GF transmission reception. The signals received from M antennas are sampled and converted from the time domain to the frequency domain. One possibility for multi-cell combining is combining of the frequency IQ samples from the M receive antennas [16]. For each detected GF transmission, the interference covariance matrix is calculated, and MMSE-IRC processing is conducted. Note that joint detection using MMSE-IRC in large cell-clusters has been widely studied in the literature [16], [22]. It is, however, not considered in this work.

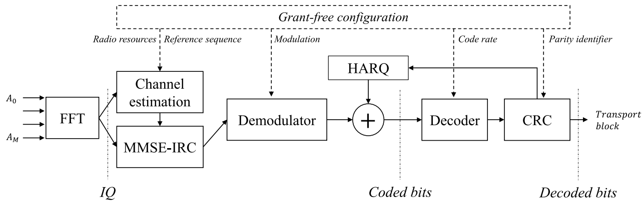

FIGURE 2. Simplified 5G NR uplink OFDM receiver chain for GF transmissions.

After MMSE-IRC processing, the IQ representations of the OFDM symbols are demodulated to estimate the coded bits. Each coded bit is represented by a soft value. Combining based on soft values of coded bits is another option for multi-cell combining. This is sometimes referred to as maximum ratio combining [14] or soft value information combining [23]. This technique is also used for HARQ retransmissions using chase combining [33]. In this work we denote this combining option chase-combining.

After demodulation and potential HARQ combining, the coded bits are decoded. Parity bits are used to check the decoded bits integrity by a cyclic redundancy check (CRC). If the CRC check fails, the coded bits soft representations are saved for combining with the retransmission if HARQ is enabled.

Hard combining, or selection of a successfully decoded packet from one of the assisting cells is a third option of multi-cell combining. We refer to this option as selection-combining. A hybrid of chase-combining and selection-combining is also considered. By using chase-combining for intra-site (with the p-cell) assisting cells and selection-combining for inter-site assisting cells, this hybrid-combining scheme is expected to achieve a URLLC capacity that is between that of chase-combining and selection-combining, while maintaining the backhaul throughput from selection-combining.

IV. MULTI-CELL AWARE RRM ENHANCEMENTS

Joint processing and combining from multiple cells, improves the signal to interference and noise ratio (SINR) compared to single-cell reception. This benefit from multi-cell reception lead to an improvement of reception reliability. When the experienced reliability is higher than the target, it leaves room for transmission parameter adjustments to relax the reliability and improve the URLLC capacity. Two proposals for multi-cell reception aware RRM enhancements are:

- Closed loop power control (CLPC), to reduce the receive power density target and hence reduce the transmit power P_u.
- MCS selection, to transmit the GF data with a higher order MCS based on the experienced improvement.

The aim with the proposed CLPC strategy is to reduce the generated interference by relaxing the UE receive power density target (P_0), when the SINR exceeds a predefined target. This target needs to account for a margin for transmission collisions and fading. The MCS selection strategy attempts to make use of the improved signal quality, to increase the MCS order and hence increase the spectral efficiency.

For sporadic GF transmissions, the p-cell cannot a-priori acquire uplink channel states and set the optimal transmission parameters. As an alternative, we use the post-combining experienced SINR as an indicator for adjusting the transmission parameters.

We propose to define the closed loop function $f(.)$ from (1) as

$$f(\Gamma_s)\ [dB] = \begin{cases} \Gamma_d - \Gamma_s, & \text{if } \Gamma_s > \Gamma_d \\ 0, & \text{otherwise} \end{cases}, \qquad (2)$$

where Γ_s is the experienced post-combining SINR and Γ_d is a predefined desired post-combining SINR. As the instantaneous post-combining SINR is subject to fading and sporadic interference, Γ_s is obtained by low-pass filtering the instantaneous SINR samples. Intentionally, this strategy does not allow an increase in transmission power, as it targets to effect UEs which systematically obtain SINR enhancements from multi-cell reception.

The MCS selection strategy is inspired from the study in [9] and the framework for resource allocations is already described in Section II. The idea is that UEs operating with higher order MCS options occupy a smaller bandwidth BW/k given their higher spectral efficiency. Further, such UEs have the option of selecting different sub-bands, hence reducing the probability of having fully overlaying GF transmissions. However, the usage of higher order MCS requires a higher SINR to maintain the transmission reliability.

The choice of using a default MCS_1 or a higher order MCS_k, is done by comparing Γ_s with a threshold Γ_t such that the chosen MCS is given by

$$\text{MCS} = \begin{cases} \text{MCS}_k, & \text{if } \Gamma_s > \Gamma_t \\ \text{MCS}_1, & \text{otherwise} \end{cases}. \qquad (3)$$

A too low Γ_t may jeopardize the future GF transmission reliability if the SINR cannot reach the transmission reliability with the higher order MCS. On the other hand, a too high Γ_t is a missed opportunity to increase the spectral efficiency and eventually a chance of increasing the URLLC capacity.

V. EVALUATION METHODOLOGY

The performance evaluation is designed to be of high practical relevance and is therefore based on extensive simulations using an advanced system level simulator designed for providing a high degree of realism. The simulations are based on widely recognized mathematical models, calibrated to industry standards. This simulator includes detailed models of the physical layer procedures, the transmitter and receiver chains, the MAC protocol, MCS selection, power control, UE measurements and cell selection. The simulation assumptions are aligned with 5G NR evaluation methodology for URLLC [18, p. 112] and are summarized in Table 1.

TABLE 1. Simulation assumptions.

Parameters	Assumption
Layout	Hexagonal grid with $C = 21$ cells distributed at 7 sites, world wrap-around
Inter-site distance	500 m
Carrier-bandwidth	4 GHz
Channel model	3D Urban Macro (UMa)
UE distribution	Uniformly distributed outdoor, 3 km/h quasi-static fading model
UE transmitter	23 dBm, 1 omni-directional transmit antenna
BS receiver	MMSE-IRC, single panel with 1 or 2 columns and two polarizations to acquire $M = 2$ or $M = 4$ receive antennas
Noise figure	5 dB
Thermal noise	-174 dBm/Hz
Bandwidth	10 MHz, FDD
PHY numerology	30 kHz sub-carrier spacing, 4 symbols/TTI, 12 sub-carriers/RB,
GF configuration	4 symbol periodicity, 24 RB
Traffic model	FTP Model 3 with 32 B packet and Poisson arrival rate of $\lambda = 10$ PPS per UE
Power control	Open loop power control (α=1), scheme and load optimized P_0 and $f(.)$ from (2)
MCS selection	MCS_1 = QPSK1/8 as baseline. Optional selection of MCS_4 = QPSK1/2 using (3)
Timing	In symbols; $t_{tti} = 4$ (0.143 ms), $t_{tx} = t_{tti}$, $t_{a1} = [0, t_{tti}]$, $t_{a2} = 1$, $t_{a3} = 0$, $t_{prep} = t_{pBS} = t_{pUE} = 3$
HARQ	Maximum of 4 retransmissions when enabled
Soft value	5 bit per coded bit

The simulated network consists of $C = 21$synchronized BSs distributed over 7 sites with an inter-site distance of 500 m. The BS directional antenna consists of a single antenna panel with one or two cross-polarized antennas to acquire a total of two or four receive antenna elements. The antenna gains is modeled according to [34]. The UEs are uniformly distributed outdoors within the network. Wrap-around is used to avoid world-edge effects. The channel model follows the 3D urban macro model [26, p. 12]. The UEs are semi-stationary with 3 km/h speed for fast fading calculations. The carrier frequency is 4 GHz with an uplink bandwidth of 10 MHz, using frequency division duplex (FDD). The sub-carrier spacing (SCS) is assumed to be 30 kHz ($\mu = 1$) which results in 24 RB with 12 sub-carriers per RB following 5G NR numerology [31, p. 9]. A mini-slot is assumed to consist of 4 OFDM symbols (0.143 ms). GF transmission opportunities are available in every mini-slot and denotes a TTI. Propagation delays are assumed to be negligible. However, it is noted that a longer cyclic prefix than the default 5G NR cyclic prefix of 2.38μs for 30 kHz SCS might be needed for assisting cells located further away than the second tier from the p-cell. The UEs are assumed to be time-aligned with the p-cell.

The BSs are configured to transmit a cell-specific reference sequence with a periodicity of 100 ms. The UEs estimates the wide-band RSRP measurement based on the reference sequences. The RSRP measurements are low-pass filtered using a moving average (MA) filter, averaging over the 20 most recent samples. These filtered RSRP value is signaled to the p-cell which configures the assisting cells.

Each URLLC UE generate a $P = 32$ B uplink packet according to a homogeneous Poisson Point Process with an average generation rate of $\lambda = 10$ packets per second (PPS) per UE. The load in the network is configured by adjusting the number of UEs U. Deployed UEs are ideally synchronized with the network and are configured with shared GF configurations. The UEs are configured with GF configurations which use either MCS_1 or MCS_4 when the MCS-selection scheme is used. We choose $MCS_1 =$ QPSK1/8 (QPSK with code rate 1/8) and $MCS_4 =$ QPSK1/2 (QPSK with code rate 1/2) as used in recent work [9]. The UEs are configured to use MCS_4 when the threshold $\Gamma_s > \Gamma_t$ according to 3. When this scheme is not enabled, MCS_1 is used.

The BSs are equipped with an MMSE-IRC receiver following the model presented in [28], [35]. BS c (a p-cell or an assisting cell) equipped with M receive antennas calculate the receiver filter g_c for a desired signal from UE u as

$$g_c = H_{u,c}^H R^{-1}, \tag{4}$$

where $(.)^H$ is the Hermitian operator, $H_{u,c} \in C^{M\times 1}$ is the channel matrix of the desired signal from UE u to BS c and R is the is the IRC interference covariance matrix given by

$$R = P_u H_{u,c} H_{u,c}^H + \sum_{i\in I} P_i H_{i,c} H_{i,c}^H + \sigma_{n,c}^2, \tag{5}$$

where $i \in I$ denotes interfering signals from the set of simultaneously transmitting UEs, $H_{i,c}$ is the channel matrix from UE i to BS c, P_u and P_i are the transmit powers from UE u and i respectively and $\sigma_{n,c}^2$ is the total background noise power received by BS c. All UEs are assumed to be uniquely identified based on its reference sequence, as a demodulation reference sequence (DMRS). The DMRS is also assumed to be used to acquire an ideal channel estimate from all simultaneously transmitting UEs when calculating the interference covariance matrix R.

The post-receiver instantaneous SINR from UE u to a receiving BS c can then be expressed as

$$\Psi_{u,c} = \frac{\Omega_{u,c} \left\| g_c H_{u,c} \right\|^2 P_u}{\sum_{i\in I} \Omega_{i,c} \left\| g_c H_{i,c} \right\|^2 P_i + \sigma_{n,c}^2}, \tag{6}$$

where $\Omega_{u,c}$ and $\Omega_{i,c}$ denotes the large scale fading from UE u and i respectively. The SINR value $\Psi_{u,c}$ is calculated for each sub-carrier and each symbol and then combined to an effective SINR in the mutual information domain, following the models presented in [36], [37]. The combining of soft bits which is used for the chase-combining multi-cell combining technique and for retransmissions follows the chase-combining principle [33]. Chase combining is modeled by a linear summation of the obtained effective SINRs and can be expressed as

$$\Phi_{u,E} = \sum_{s\in E} \Phi_{u,s} \eta^s, \tag{7}$$

where $\Phi_{u,s}$ denotes the effective SINR of transmission s for device u and $\eta \in \mathbb{R}_{0<x\leq 1}$ denotes the combining efficiency which is set to 1 in this work. The selection-combining is modeled as a selection of the maximum effective SINR which can be expressed as

$$\Phi_{u,E} = max_{s\in E} \left(\Phi_{u,s}\right). \tag{8}$$

A link-to-system model obtained through extensive link level simulations is then used to determine the error probability for the transmission depending on the $\Phi_{u,E}$ and the applied MCS.

Uplink power control with full path loss compensation ($\alpha = 1$) is used, based on the findings in [32]. The uplink power control parameter P_0 which leads to the maximum observed URLLC capacity is selected for each combination of M, multi-cell combining scheme, HARQ and the aggregated offered URLLC load L. Identifying the optimum uplink power control parameter values when interference is present, is a well-known NP-hard problem [38], and hence simulation based sensitivity studies are used to find the optimum values. A maximum interval of 2 dB is used for sensitivity studies of P_0 and a maximum interval of 5% is used when conducting a sensitivity study on the maximum L where the URLLC requirements can be satisfied.

The value of the SINR thresholds Γ_d and Γ_t from (2) and (3), depends on the used MCS, the reliability target, L and the experienced intra- and inter-cell interference. Sensitivity studies are conducted to determine the values of Γ_d or Γ_t that maximize the URLLC capacity. The filter chosen for Γ_s is a MA filter over the past 20 post-combining effective SINR samples ($\Phi_{u,E}$), collected with a periodicity of 100 ms.

Statistically reliable results are ensured by multiple Monte Carlo simulations drops. A total of 5 million samples (1 per generated GF packet) are collected to reliably determine the latency and outage probability relation. This gives a theoretical statistical confidence interval (assuming Gaussian residuals) of 27% around the 10^{-5} quantile with 95% confidence [39].

Assuming the UE and BS processing times from [40] and that the URLLC packet arrives at the worst time instance, the latency estimate for the initial GF transmission is 3.25 TTIs which corresponds to 0.6 ms. When adding a HARQ retransmission, the latency increases to 6.25 TTIs, corresponding to 0.9 ms. The additional delay from queuing is captured with the system level simulations, but the

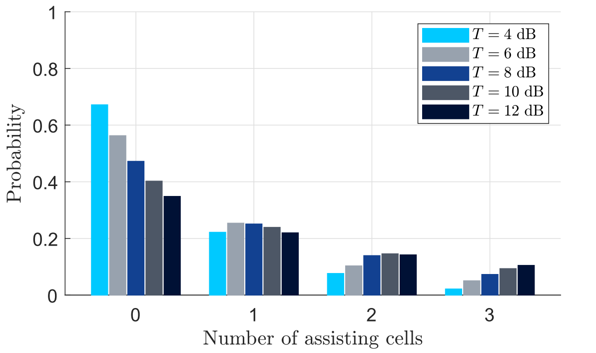

FIGURE 3. Probability distribution of the number of configured assisting cells per URLLC UE.

additional delays from backhaul and the multi-cell combining processing delays are omitted for simplicity.

Backhaul load calculations only account the exchanged data between sites. For chase-combining each receiving BS transfers 2 coded bits per OFDM symbol due to QPSK modulation. Each coded bit is represented by a soft value which is assumed to be 5 bits [16]. With MCS_1 this gives 11520 b per GF transmission. With selection and hybrid-combining, only the URLLC packet is exchanged, which is 32 B or 256 b.

VI. PERFORMANCE EVALUATION

The performance evaluation is structured into three parts. In the first part, we examine the trade-off between the achievable URLLC capacity and backhaul load using chase-, hybrid- and selection-combining for different choices of the RSRP window T and the maximum number of assisting cells C_{MAX}. Based on the findings from the first part, a T and C_{MAX} is selected and used for the remaining parts. In the second part the maximum achievable URLLC capacity with multi-cell reception is quantized when each BS is equipped with $M = \{2, 4\}$ receive antennas per BS and with the use of retransmissions. In the third part, the performance of the two proposed multi-cell aware RRM enhancement schemes based on either CLPC or MCS-selection is examined.

A. TRADE-OFF BETWEEN URLLC CAPACITY AND BACKHAUL LOAD

The probability distribution of a URLLC UE having either 0 (single-cell), 1, 2 or 3 configured assisting cells as a function of the RSRP threshold T is shown in Fig. 3. It is observed that when increasing T, cells with larger RSRP differences can be selected as assisting cells and the average number of configured assisting cells increases. It is also noticed that by increasing T, the probability of having 0 assisting cells decreases. These devices are typically located at the cell-center which are served only by their p-cell.

Fig. 4 shows the achievable URLLC capacity for the considered multi-cell reception combining schemes with parameters $C_{MAX} = \{1, 2, 3\}$ and $T = \{4, 6, 8, 10, 12\}$ dB. $M = 4$ receive antennas is used and retransmissions are not enabled. The corresponding empirically optimized power control parameters are selected using $T = 8$ dB and $C_{MAX} = 2$, which are found to be $P_0 = \{-101, -101, -98\}$ dB

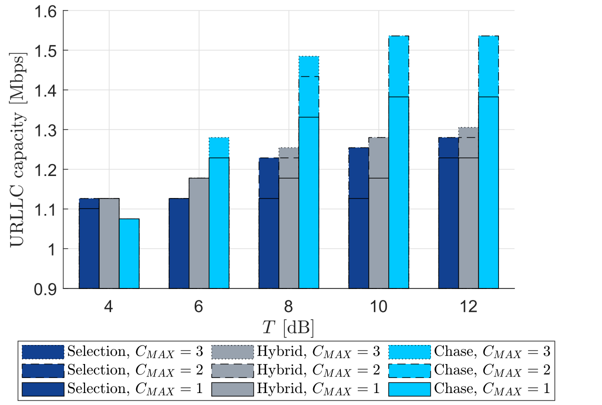

FIGURE 4. The maximum achievable URLLC capacity as a function multi-cell parameters T and C_{MAX}. Each BS is equipped with $M = 4$ receive antennas and retransmissions are not enabled.

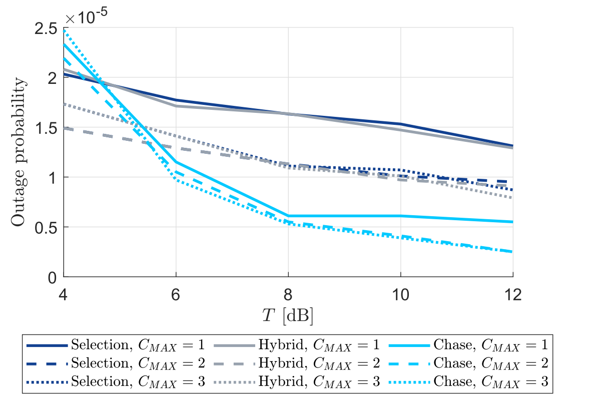

FIGURE 5. Outage probability with $L = 1.28$ Mbps aggregated URLLC load.

for selection-, hybrid-, and chase-combining respectively. The achievable URLLC capacity is observed to generally increase with T and C_{MAX} for all three combining schemes. The largest URLLC capacity enhancement by increasing C_{MAX} and T is observed when using chase-combining. The impact of increasing the maximum number of assisting cells is more evident at $T > 8$ dB, where changing C_{MAX} from 1 to 2 results in up to 10% increase in URLLC capacity. The impact of increasing C_{MAX} from 2 to 3 maximum assisting cells is almost indistinguishable.

Fig. 5 shows the outage probability for an aggregated URLLC load of $L = 1.28$ Mbps for the same parameter space used in Fig. 4. This further strengthens the observations drawn from Fig. 4. A clear reduction in the outage probability is observed when increasing T and C_{MAX}, and the largest reduction is observed for $C_{MAX} > 1$ and for chase-combining $T > 8$ dB. It is also worth to notice the similarities when using selection- and hybrid-combining, and their generally worse URLLC capacity compared to chase-combining. For $T = 4$ dB the outage probability for chase-combining is higher than for selection- and hybrid-combining. The reason for this is likely due to the different power control parameters.

Fig. 6 shows the corresponding backhaul load for the same parameter space used in Fig. 4 and Fig. 5. Firstly, it is

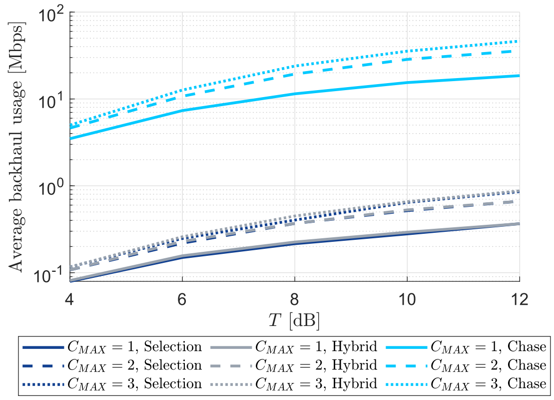

FIGURE 6. Backhaul load for the parameter space and URLLC capacity from Fig. 4.

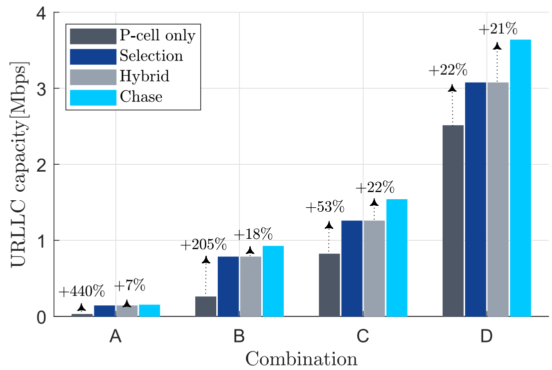

FIGURE 7. Achievable URLLC capacity for multi-cell reception combining options and parameter combinations given in Table 2.

TABLE 2. Combination labels.

Combination	Receive antennas	Retransmissions
A	$M = 2$	Disabled
B	$M = 2$	Enabled
C	$M = 4$	Disabled
D	$M = 4$	Enabled

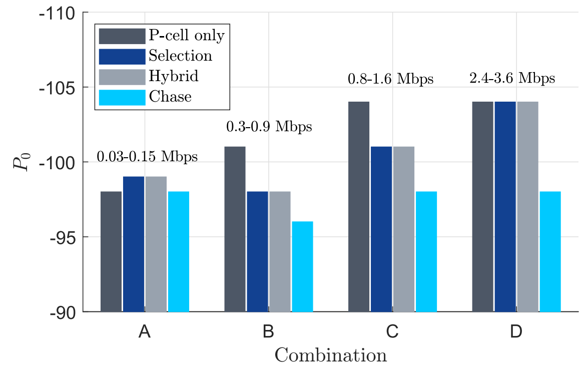

FIGURE 8. Corresponding empirically optimized P_0 value used to generate Fig. 7.

observed that the backhaul load difference between selection- or hybrid-combining and chase-combining is almost two orders of magnitude, where the corresponding URLLC capacity difference is in the order of 50%. Secondly, the backhaul load increases from $T = 4$ dB to $T = 12$ dB almost by a factor of 6 for all combining schemes, with a corresponding URLLC capacity increase of 16% for selection- or hybrid-combining and up to 43% for chase-combining. It is observed that the majority of the observed URLLC capacity gains (32% of maximum 43% for chase and 12% of 16% for selection- and hybrid-combining) is achieved with $T = 8$ dB and with $C_{MAX} = 2$ assisting cells. These parameters are used for the remaining two parts of the performance evaluation.

B. URLLC CAPACITY SUMMARY

Fig. 7 shows the achievable URLLC capacity with parameters $C_{MAX} = 2$ and $T = 8$ dB, for the three combining schemes and with four combinations of retransmissions and receive antennas per BS, labeled according to Table 2. For reference, a configuration where URLLC UEs are only served by a single-cell (the p-cell) is also included. Notice that combination B corresponds to the one used in the first part of the performance evaluation.

It is observed that multi-cell reception improve the URLLC with $M = 2$ receive antennas is used by 205% when retransmissions are enabled (combination B) and 440% when retransmissions are disabled (combination A). When $M = 4$ receive antennas are used, multi-cell reception is observed to improve the URLLC capacity by 22% when retransmissions are enabled (combination D) and 53% when retransmissions are disabled (combination C). The obtained gains indicate that, despite the use of retransmission and increased spatial diversity from multiple receive antennas, there is still room for significant enhancements by jointly receiving GF transmissions at multiple BS. Thirdly, it is observed that the additional improvement in terms of URLLC capacity by using chase-combining compared to selection- or hybrid-combining for combination B, C and D is in the range from 7% to 22%. The smallest improvement is observed for combination A, which also achieves the lowest URLLC capacity overall.

Fig. 8 includes the corresponding P_0 values as used in Fig. 7. When the UEs are served only by a single-cell (p-cell), the identified optimal P_0 decreases with the URLLC capacity, which is in line with related observations on the optimum choice of P_0 [32]. This tendency is also clear with multi-cell reception with hybrid- or selection-combining, but when chase-combining is used this tendency is not present. One explanation is the usefulness of the reception of transmissions in assisting cells. For selection- and hybrid-combining, these transmissions can be considered useful only if the transmission can be decoded by the assisting cell. With chase-combining, the received transmission at an assisting-cell is useful even if it cannot be decoded at the assisting cells alone. As a consequence, the highest URLLC capacity is observed with chase-combining and selection- and hybrid-combining is observed to perform indistinguishably, contrary the expectation.

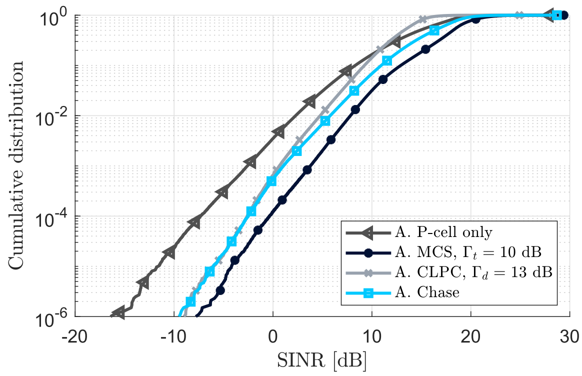

FIGURE 9. SINR CDF for the two proposed RRM enhancement schemes evaluated for combination A ($L = 0.03$ Mbps) defined in Table 2.

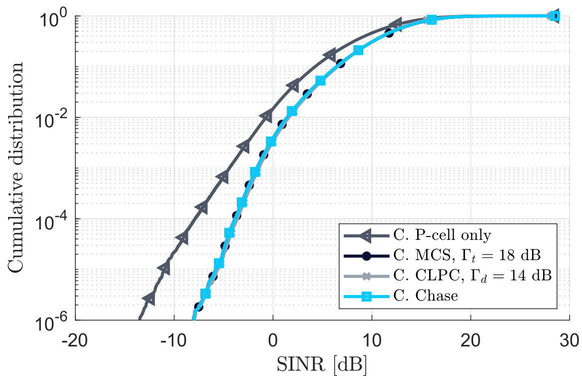

FIGURE 10. SINR CDF for the two proposed RRM enhancement schemes evaluated for combination C ($L = 0.8$ Mbps) defined in Table 2.

C. MULTI-CELL AWARE RRM ENHANCEMENTS

Finally, the performance of the two proposed multi-cell reception aware RRM enhancement schemes are evaluated. Fig. 9 and Fig. 10 show the cumulative distribution function (CDF) of the SINR for combinations A and C, respectively, with single-cell reception, multi-cell reception (chase-combining) and with the CLPC and MCS schemes on top. The loads for the combinations are chosen from Fig. 7, being $L = 0.03$ Mbps for combination A and $L = 0.8$ Mbps for combination C. The choices of Γ_d used in (2) and Γ_t used in (3) are those which is identified to provide the maximum URLLC capacity. A significant SINR enhancement is observed by enabling multi-cell reception with chase-combining, as also noticed in the initial part of the performance evaluation. Additionally, it is observed that for combination A, the MCS-selection scheme is capable of providing 2-3 dB SINR improvement. The CLPC based scheme, though reducing the probability of experiencing a high SINR ($>$ 3 dB), it slightly improves the SINR at low quantiles ($\leq 10^{-5}$). Based on these observations the two RRM enhancements schemes are expected to provide a URLLC capacity gain for combination A. For combination C, no obvious improvement in the SINR tail is observed for the two RRM enhancement schemes.

Fig. 11 shows the achieved URLLC capacity for combination A and C with single-cell reception, multi-cell

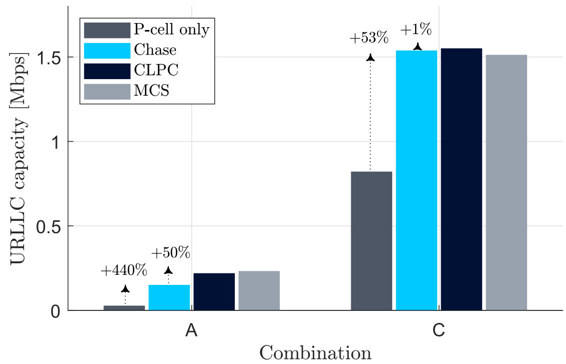

FIGURE 11. Achieved URLLC capacity with the two proposed RRM enhancement schemes evaluated for combination A and C defined in Table 2.

reception (chase-combining) and with the CLPC and MCS-selection scheme on top. We observe gains of CLPC and MCS in combination A, with up to 50% URLLC capacity increase. For combination C, using $M = 4$ receive antennas, the gains of the schemes are negligible. With $M = 4$, the RRM enhancement schemes intended for the $\approx 50\%$ deployed URLLC devices who are benefiting from multi-cell reception (from Fig. 3), are not giving a positive effect on the overall experienced URLLC reliability in the network. This indicates that the reliability bottleneck is to be found within the remaining 50% single-cell served UEs.

VII. CONCLUSION

In this study we have proposed and studied the potential of applying multi-cell reception as technique to improve the URLLC capacity for UL GF URLLC transmissions in a 5G NR scenario. Detailed insights into the sensitivity of multi-cell reception parameters and combining techniques are provided on the URLLC capacity and the backhaul throughput. On top, two multi-cell reception aware RRM schemes have been proposed. Performance evaluations are conducted with advanced system level simulations to provide a high level of realism in a multi-user multi-cell NR network. The main findings are summarized as:

- Multi-cell reception can provide substantial gains in URLLC capacity when compared to single-cell reception. Even the simplest multi-cell combining technique, referred to as selection-combining, is observed to provide capacity gains from 205% to 440% when BSs are equipped with two receive antennas and 53% to 22% when the BSs are equipped with four receive antennas and depending on whether HARQ retransmissions are used. Soft multi-cell combining gives additional capacity gains of +7% to +21%.
- A large improvement is observed by allowing 2 instead of 1 assisting cells per UE, but no benefit is found when increasing to 3 allowed assisting cells. The largest URLLC capacity gains are observed for RSRP thresholds of 8-10 dB.
- While soft combining may provide the largest URLLC capacity gains with multi-cell reception, it also requires

almost two orders of magnitude larger backhaul load and requires networks with high backhaul capacity.
- The full URLLC capacity gains can be achieved on top of soft combining with the proposed multi-cell aware RRM enhancements based on closed-loop power control or MCS-selection. The highest gains are observed in low diversity order configurations.

Future work will study the potential of multi-cell reception for GF in an indoor factory scenario where higher backhaul capacity can be assumed along with the use of even more receive antennas per cell. In this scenario, the IQ based multi-cell reception technique becomes interesting and should be studied. Additionally, the potential of increasing the SCS and the bandwidth to reduce the mini-slots duration and further reduce the latency should be studied. With shorter mini-slot durations, the use of dynamically scheduled transmissions can be studied as a technique to achieve even higher URLLC capacities for comparable URLLC latency and reliability requirements.

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