Quasi-Dynamic Frame Coordination For Ultra-Reliability and Low-Latency in 5G TDD Systems

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Abstract—The fifth generation (5G) mobile technology features the ultra-reliable and low-latency communications (URLLC) as a major service class. URLLC applications demand a tight radio latency with extreme link reliability. In 5G dynamic time division duplexing (TDD) systems, URLLC requirements become further challenging to achieve due to the severe and fast-varying cross link interference (CLI) and the switching time of the radio frame configurations (RFCs). In this work, we propose a quasi-dynamic inter-cell frame coordination algorithm using hybrid frame design and a cyclic-offset-based RFC code-book. The proposed solution adaptively updates the RFCs in time such that both the average CLI and the user-centric radio latency are minimized. Compared to state-of-the-art dynamic TDD studies, the proposed scheme shows a significant improvement in the URLLC outage performance, i.e., ~92% reduction gain, while boosting the cell-edge capacity by ~189% and with a greatly reduced coordination overhead space, limited to B-bit.

Index Terms— Dynamic TDD; 5G new radio; URLLC; Cross link interference (CLI); Traffic; UDP.

I. INTRODUCTION

Ultra-reliable low-latency communication (URLLC) is a key driver of the fifth generation (5G) mobile networks [1]. Various URLLC use cases require one-way radio latency of one or several milliseconds with an outage probability below 10⁻⁵ [2]. As most of the 5G URLLC deployments are envisioned over the 3.5 GHz band, the time division duplexing (TDD) becomes a vital candidate transmission mode due to its frame adaptation, in order to dynamically match the sporadic URLLC capacity in both downlink (DL) and uplink (UL) directions [3].

With the 5G new radio (NR), the agile frame structure with variable transmission time interval (TTI) duration is introduced [3, 4]. Thus, 5G-NR TDD offers more adaptation flexibility with much faster link-direction update periodicity, that is slot-dependent instead of being frame-based, i.e., ≤ 1 ms. However, the coexistence of different transmission directions in adjacent cells results in cross link interference (CLI) [5], i.e., base-station to base-station (BS-BS) and user-equipment to user-equipment (UE-UE) CLI, respectively. Hence, URLLC performance is highly impacted by the degraded decoding ability, due to the fast-varying CLI, and the waiting interval to the first DL/UL transmission opportunity.

To the best of our knowledge, no prior work has assessed the performance of the URLLC outage with the 5G-NR dynamic TDD technology. The state-of-the-art TDD proposals consider joint multi-cell scheduling, cell muting, and enhanced power control [6, 7] to minimize the average network CLI. Furthermore, advanced massive multi-antenna processing and beam-forming [8] are envisioned as vital to counteract the CLI by utilizing the channel hardening phenomenon. Opportunistic inter-cell coordination algorithms [9] are also proven attractive to boost the cell capacity of the dynamic TDD systems; however, at the expense of a sub-optimal URLLC outage performance.

In this work, we propose a hybrid-frame based coordination scheme (HFCS) for 5G-NR dynamic TDD systems. The proposed HFCS introduces a multi-objective and slot-dependent dynamic user scheduling. A hybrid radio frame structure and sliding radio frame configuration (RFC) code-book are designed to virtually extend the degrees of freedom of the TDD dynamicity. Thus, the URLLC users with the worst radio conditions always guarantee semi-preemptive, i.e., immediate scheduling over pre-set time slots, and CLI-free transmissions, leading to a significant reduction of the URLLC tail latency. The proposed coordination scheme shows a significant enhancement in the URLLC outage performance as well as maximizing the ergodic capacity, and with a confined coordination overhead span.

The performance of the proposed scheme is assessed by realistic system level simulations, due to the complexity of the 5G-NR and addressed problem herein. The major functionalities of the physical and media access control layers of the 5G-NR are incorporated and calibrated against latest 3GPP assumptions, including UL and DL channel modeling, hybrid automatic repeat request (ARQ), adaptive modulation and coding selection (MCS) and dynamic user scheduling.

This paper is organized as follows. Section II introduces the system modeling of this work while Section III presents the problem formulation. Section IV details the proposed solution and Section V discusses the numerical results of the proposed scheme. Finally, conclusions are drawn in Section VII.

II. SYSTEM MODELING

A macro 5G-NR TDD system is considered, with a single cluster of C cells, each with Nᵣ antennas. Each cell has an average of Kᵤ and Kᵰ uniformly-distributed DL and UL active UEs, respectively, each with Mᵣ antennas. We assume a URLLC dedicated network where the sporadic FTP3 traffic is adopted with finite packet sizes of fᵤ and fᵰ bits, and Poisson arrival processes λᵤ and λᵰ, in the DL and UL directions. Accordingly, the average offered load per cell in DL direction is: Kᵤ × fᵰ × λᵰ and in UL direction as: Kᵰ × fᵤ × λᵤ.

We assume an RFC of 10 sub-frames, each can be DL, UL or a special sub-frame. UEs are dynamically multiplexed
by the orthogonal frequency division multiple access with 15 kHz sub-carrier spacing. The smallest scheduling unit is the physical resource block (PRB) of 12 consecutive sub-carriers. Furthermore, we adopt a user scheduling per a mini-slot duration of 7-OFDM symbols for faster URLLC transmissions.

Furthermore, an arbitrary master cell is initially identified in each cluster, where other cells are considered as slaves. All slave cells within the cluster are bidirectionally inter-connected in each cluster, where other cells are considered as slaves. All slave cells within the cluster are bidirectionally inter-connected to the master cell through the Xn interface.

We define $B_d$, $B_u$, $K_d$, and $K_u$ as the inclusive sets of cells and UE with DL and UL transmission directions, respectively. Hence, the pre-decoding received signal at the $k$th UE, where $k \in K_d$, $c_k \in B_d$, is expressed by

$$y_{k,c_k}^d = \mathbf{H}_{k,c_k}^d v_k R_k + \sum_{c,d \in B_d \backslash k} \mathbf{H}_{k,c_d}^d v_{c_d} R_{c_d} + \sum_{j \in K_d} \mathbf{G}_{k,j} w_j s_j + n_{k,c_k}^d,$$  

where $\mathbf{H}_{k,c}^d \in \mathbb{C}^{M_r \times N_t}$ is the DL fading channel from the cell serving the $i$th UE, to the $k$th UE, $v_k \in \mathbb{C}^{N_t \times 1}$, $w_j \in \mathbb{C}^{M_r \times 1}$ and $s_d$ denote the single-stream zero-forcing precoding vector at the $c_d$ cell, precoding vector at the $j$th UE, and transmitted data symbol of the $k$th UE, respectively. $\mathbf{G}_{k,j} \in \mathbb{C}^{M_r \times M_t}$ represents the cross-link channel between the $k$th and $j$th UEs. $n_{k,c_k}^d$ denotes the additive white Gaussian noise at the $k$th UE in the UL direction, the received signal at the $c_k$th cell, where $c_k \in B_u$ from $k \in K_u$, is modeled by

$$y_{c_k,k}^u = \mathbf{H}_{c_k,k}^u w_k s_k + \sum_{j \in K_u \backslash k} \mathbf{H}_{c_k,j}^u w_j s_j + \sum_{i \in K_u \backslash k} \mathbf{Q}_{c_k,c_i}^u v_i s_i + n_{c_k,k}^u,$$

where $\mathbf{Q}_{c_i,c}^u \in \mathbb{C}^{N_i \times N_t}$ denotes the cross-link fading channel between the cells that serve the $k$th and $i$th UEs, respectively, $k \in K_u$ and $i \in K_d$. The pre-detection signal-to-interference-noise ratio (SINR) in the DL direction at the $k$th UE, $\gamma_k$, in the UL direction at the $c_k$th cell, $\gamma_{c_k}$, are given by

$$\gamma_k = \frac{\| \mathbf{H}_{c_k,k}^u v_k \|^2}{\sigma^2 + \sum_{i \in K_u \backslash k} p_{i,k}^u \| \mathbf{H}_{c_k,i}^u v_i \|^2 + \sum_{j \in K_d} p_{j,k}^u \| \mathbf{G}_{k,j} w_j \|^2},$$

$$\gamma_{c_k} = \frac{\| \mathbf{H}_{c_k,k}^u w_k \|^2}{\sigma^2 + \sum_{j \in K_u \backslash c_k} p_{j,k}^u \| \mathbf{H}_{c,k,j}^u w_j \|^2 + \sum_{i \in K_d} p_{i,k}^u \| \mathbf{Q}_{c_k,c_i}^u v_i \|^2},$$

where $p_{i,k}^u$ and $p_{j,k}^u$ denote the transmission powers of the $c_k$th cell and the $k$th UE, respectively. Finally, the received UL/DL signals are decoded by the linear minimum mean square error interference rejection combining receiver (LMMSE-IRC) [4] vector $\mathbf{a}$, expressed as: $s_k = (\mathbf{a}^H)^{-1} y_k^e$, $X^e, \kappa \in \{u,d\}$, with $(\ast)^H$ as the Hermitian operation.

III. PROBLEM FORMULATION

The URLLC latency and reliability requirements are further challenging to achieve in 5GNR dynamic TDD systems, mainly due to the link-direction switching time and the degraded URLLC decoding performance. The former is significantly minimized by the flexible 5G frame structure; however, the latter still remains an open issue.

In fully dynamic TDD macro networks, neighboring cells may have simultaneous cross-directional transmissions, leading to a strong CLI which varies per the link-direction update periodicity. With the 5G-NR, such periodicity is slot-based, i.e., $\leq 1$ ms, leading to highly varying CLI fluctuations. As a result, URLLC UEs inflict significantly degraded decoding performance. In particular, lower-power URLLC UL transmissions suffer from a strong CLI from adjacent higher-power DL transmissions, leading to several HARQ re-transmissions prior to a successful decoding, not satisfying the URLLC targets.

Let $u_c$ and $d_c$ present the estimated numbers of UL and DL slots during a given RFC while $u_c^{opt}$ and $d_c^{opt}$ are the respective optimal numbers. Hence, the proposed HFCS defines a programming optimization problem as:

$$R \triangleq \max_{\phi \in \mathcal{C}} \quad \sum_{c=1}^{C} \min \left( u_c, u_c^{opt} \right) f_u + \min \left( d_c, d_c^{opt} \right) f_d,$$

subject to:

$$\begin{align*}
\arg \min_{\phi \in \mathcal{C}} \quad & f_u \sum_{x \in L, x \neq c} \varphi_u(x, \eta_c, \eta_x), \\
& \forall k \in K_d \cup K_u : \arg \min \left( \psi_c, k \right), \quad \psi_c, k \leq \epsilon \text{ ms},
\end{align*}$$

where $R$ is total capacity of each cluster, $f_u$ and $f_d$ denote rate utility functions of the UL and DL transmissions, i.e., capacity gain due to an UL or DL transmission. $\phi_c$ and $\varphi_u(x, \eta_c, \eta_x)$ represent the average and actual slot misalignment of the requested RFC by the $c$th cell $\eta_c$ and between the RFCs of the $c$th and $x$th cells, i.e., $\eta_c$ and $\eta_x$, respectively, $\forall x \neq c$, and $\psi_c, k$ is the one-way radio latency of the $k$th UL or DL user which is confined by $\epsilon$ ms.

For best RFC adaptation and highest ergodic capacity, $u_c = u_c^{opt}$ and $d_c = d_c^{opt}$ should be arbitrarily set in (5). However, $u_c^{opt}$ and $d_c^{opt}$ may introduce a large inter-cell slot misalignment $\phi_c$, resulting in severe CLI within the cluster, and thus, a significant degradation of the overall capacity $R$ and URLLC latency performance. As such problem is non-convex, we propose a heuristic approach using complexity-efficient coordination with hybrid-frame design, multi-objective user scheduling and a sliding-based RFC code-book.

IV. PROPOSED HFCS COORDINATION

The proposed HFCS combines a hybrid RFC design, multi-objective distributed user scheduling, and a cyclic-offset-based RFC code-book. A pre-defined RFC code-book is constructed and presumed pre-known to all cells within the cluster, where all RFCs have a set combination of static and dynamic slots. At each RFC update instant, each slave cell selects the one RFC from the code-book that most satisfies its individual link-direction selection criterion. The slave cells signal the index of the selected RFC to the master cell where it seeks to improve the joint capacity. Thus, it may slightly change the RFCs requested by slave cells. Accordingly, the master cell feedback the updated RFC indices to the slave cells, to be adopted until the next RFC update. During each RFC period, each cell considers a dual-objective dynamic user scheduling.
A. Proposed Inter-Cell Coordination Scheme

Hybrid RFC design and sliding RFC code-book

A hybrid RFC design is adopted, where each RFC is divided into arbitrary static and dynamic slot sets (SSS, DSS). A SSS denotes the radio slots which are fixed across all RFCs in the code-book, i.e., static TDD slots with CLI-free transmissions. However, a DSS implies fully dynamic radio slots.

Accordingly, a pre-defined RFC code-book of $N$ unique RFCs is constructed such that it is divided into $L$ groups. The RFCs within each group share the same DL-UL slot ratio, i.e., $d_c : u_c$, though, with a different placement during the DSS. For instance, the DSS of each RFC is a cyclic-shift of the other RFCs, as depicted in Fig. 1. The structure of the SSS, DSS, and size of the RFC code-book are design parameters.

At slave cells – Traffic and latency adaptation

During each RFC update instant, each slave cell selects the one RFC from the code-book which best satisfies its link-direction selection criterion. Without loss of generality, we consider the DL/UL buffered traffic size including pending direction selection criterion. Without loss of generality, we one RFC from the code-book which best satisfies its link-direction selection criterion. Without loss of generality, we one RFC from the code-book which best satisfies its link-direction selection criterion. Without loss of generality, we one RFC from the code-book which best satisfies its link-direction selection criterion.

For an arbitrary cell, if the average CLI, experienced over the previous measurement cycle, is at maximum, e.g., $\psi_c(t) = 1$ slot. However, if such cell simultaneously inflicts a large HoLD, e.g., $\psi_c(t) = 10$ slots, in order not to allow the master cell to change the RFC of this cell, hence, having faster transmissions for the respective traffic. Without loss of generality, we apply a fair averaging of both misalignment thresholds, i.e., $\psi_c(t) = 5$ slots.

Finally, at each RFC update periodicity, slave cells signal the master cell with the requested RFC indices of $B = \log_2 (N)$.
bits on the Xn interface as well as the maximum allowable slot misalignment thresholds $\psi_c(t)$.

**At master cell - CLI minimization**

When the master cell receives all RFC information from slave cells, it first identifies a *common RFC*, which is requested by the majority of the slave cells. If not feasible, the master cell randomly selects any reported RFC as the common one, to which all other RFCs shall maintain the respective slot misalignment thresholds. Thus, for each RFC $\eta_c$ of the $c^{th}$ cell, master cell calculates the slot misalignment to the common RFC $\delta_c, \forall x \neq c$ as in (5). Then, the master cell does not alter such requested RFC if the following condition is fulfilled:

$$\varphi_{c,x}(t) \leq \psi_c(t).$$

Hence, the respective slave cell utilizes its best matching RFC to its latency and capacity outage. Otherwise, the master cell slides over all RFCs within the same group as the desired RFC of the $c^{th}$ cell $\eta_c$. Accordingly, it estimates the corresponding slot misalignment values and considers the one RFC with $\varphi_{c,x}(t)$ that has the closest linear distance to the requested $\psi_c(t)$. If the slot misalignment constraint in (10) is satisfied, master cell adopts such RFC as the updated RFC of the current cell. This way, an acceptable average CLI is guaranteed at the slave cells while still preserving the same requested traffic service ratio $d_c : u_c$, leading to a significant improvement of the capacity and outage latency performance.

If the slot misalignment constraint is not yet feasible across all RFCs from the same group as the requested one, master cell progressively slides to the other RFC groups from the Xn interface corresponding slot misalignment values and considers the one that is requested $\psi_c(t)$ of the current cell. Thus, cell randomly selects any reported RFC as the common one, and then, it signals all slave cells within the respective group according to (6). A sophisticated CFC-TDD algorithm, mainly for broadband services, to significantly reduce the average slot misalignment, based on a preset global misalignment threshold $\Omega$, and hence, the aggregate CLI, resulting in greatly improved ergodic capacity. Though, it has been demonstrated not suitable for URLLC transmissions due to the monotonic scheduling objective.

**Sliding code-book based coordinated TDD (SCC-TDD)** [9]: in our prior work, we introduced a simple inter-cell coordination algorithm, mainly for broadband services, to significantly reduce the average slot misalignment, based on a preset global misalignment threshold $\Omega$, and hence, the aggregate CLI, resulting in greatly improved ergodic capacity. Though, it has been demonstrated not suitable for URLLC transmissions due to the monotonic scheduling objective.

**CLI-free coordinated TDD (CFC-TDD)**: cells dynamically select their respective RFC according to (6). A sophisticated BS-BS and UE-UE coordination is artificially assumed. That is, BSs and UEs exchange PRB mapping, UE MCS and precoding information, for them to perfectly suppress the BS-BS and UE-UE CLI. However, such coordination introduces a significant control overhead over both the back-haul and radio interfaces, respectively. In [10], a 3GPP technical study introduces a sub-optimal CFC-TDD approach with a lower
Table I
SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>3GPP-UMA, one cluster, 21 cells</td>
</tr>
<tr>
<td>UL/DL channel bandwidth</td>
<td>10 MHz, SCS = 30 KHz, TDD</td>
</tr>
<tr>
<td>Antenna setup</td>
<td>$N_t = 8$ Tx, $M_r = 2$ Rx</td>
</tr>
<tr>
<td>UL power control</td>
<td>LTE-alike, $\alpha = 1$, $r_0 = -705$ dBm</td>
</tr>
<tr>
<td>Average user load per cell</td>
<td>$K^{dl} = K^{ul} = 10$ and $20$</td>
</tr>
<tr>
<td>TTI configuration</td>
<td>0.5 ms (7-OFDM symbols)</td>
</tr>
<tr>
<td>Traffic model</td>
<td>FTP3, $f^{dl} = f^{ul} = 400$ bits</td>
</tr>
<tr>
<td>Offered average load per cell</td>
<td>DL:UL = 1:2 (0.6:1.2) Mbps</td>
</tr>
<tr>
<td>Proposed HFCS setup</td>
<td>$N = 55$ RFCs, $L = 7$ groups, $B = 6$ bits</td>
</tr>
</tbody>
</table>

overhead space. However, CFC-TDD holds an optimal theoretical baseline, where both maximum TDD RFC flexibility and CLI-free transmissions are always guaranteed.

V. PERFORMANCE EVALUATION

The major simulation assumptions are presented in Table I. During each TTI, each cell dynamically multiplexes users over system PRBs using the PF metric, if it is within the DSS of the current RFC or by preemptive cell-edge user allocations when it is within the SSS. We consider a fully dynamic MCS selection and adaptive Chase-combining HARQ re-transmissions, where the HARQ feedback is always prioritized over new transmissions. The post-detection SINR levels are estimated by the LMMSE-IRC receiver, where the average interference is identified by its mean covariance. Finally, we assess the proposed solution under the latency-efficient user data-gram protocol for several offered cell loading conditions.

Fig. 3 depicts a comparison of the complementary cumulative distribution function (CCDF) of the URLLC outage latency in the UL direction for all TDD coordination schemes under assessment, for an average offered load of 2 Mbps/cell with a DL:UL traffic ratio of 1:2. Furthermore, we present the latency performance of the best static-TDD case where the static pattern is pre-selected to perfectly match the DL-to-UL average traffic ratio, i.e., 6 DL mini-slots, 12 UL mini-slots and 2 guard mini-slots. The optimal CFC-TDD achieves the best URLLC latency performance, i.e., 42 ms at $10^{-5}$ outage probability. However, it comes under the ideal assumption of perfect elimination of any experienced CLI, and with an infinite coordination overhead, which is infeasible in practice. The proposed HFCS clearly provides a significant improvement of the UL URLLC latency, approaching the optimal CFC-TDD; however, with greatly reduced overhead span, mainly limited to $\log_2 (N)$ bits. That is, it achieves 92% and 67% reduction gain in the UL outage latency compared to SCC-TDD and NC-TDD. The best static-TDD case outperforms proposed HFCS scheme, i.e., 9% reduction in the outage latency, due to the absence of the CLI, approaching CFC-TDD; though, this comes with the assumption that the static RFC pattern is pre-defined to perfectly align with the traffic demands.

The significant latency improvements of the proposed HFCS are attributed to the guaranteed preemptive cell-edge user scheduling with CLI-free transmissions, where these users majorly control the latency tail, i.e., outage, performance. Thus, less costly HARQ re-transmissions are experienced. The SCC-TDD latency performance depends on the preset misalignment threshold $\Omega$. For instance, with a tight $\Omega = 3$, the master cell may aggressively change the requested RFC of a given slave cell, in order to only allow for an average misalignment of three slots. As a result, slave cells may adopt RFCs that do not best match their current traffic demands, leading to a more queuing delay to the first transmission opportunity. Finally, the NC-TDD offers a fair URLLC latency performance since the maximum possible TDD RFC flexibility is utilized; however, with severe CLI levels.

Similar observations are obtained from the URLLC outage latency in the DL direction, as shown in Fig. 4. All considered TDD coordination schemes provide a decent DL latency, i.e.,
≤ 8 ms. This is due to the larger desired DL transmission power, i.e., compared to the interfering UL power, hence, less impactful CLI. However, static-TDD case inflicts a longer queuing delay due to the fixed DL and UL slot placement.

Fig. 5 shows the empirical CDF (ECDF) of the post-receiver UL interference performance in dBm, including both cross and same link inter-cell interference, respectively. Due to the absence of the CLI, CFC-TDD offers an attractive interference performance. However, due to the dual-scheduling metrics during the DSS and SSS periods, the proposed HFCS achieves the same interference suppression capability as the optimal CFC-TDD for the critical lower percentiles below 20%, i.e., cell-edge users. Furthermore, the proposed HFCS offers 39% and 45% reduction of the post-receiver interference at the 20th percentile, compared to SCC-TDD and NC-TDD, respectively. The SCC-TDD exhibits a monotonic interference suppression performance where cell-edge users get most impacted, while NC-TDD inflicts the worst interference performance due to the extreme slot misalignment, hence, the sever CLI levels.

Fig. 6 presents the average cell throughput per TTI in the UL direction, with an average total offered load per cell of 10 Mbps. As can be noted, proposed solution boosts the cell-edge capacity, e.g., 189% capacity gain is achieved against SCC-TDD at the 30th percentile. The change of the distribution slope of the proposed HFCS is due to the slot-based dual scheduling objectives, i.e., joint latency-capacity scheduling. However, the proposed HFCS still exhibits a capacity loss of 45% at the 95th percentile compared to ideal SCC-TDD, due to the preemptive scheduling of cell-edge users during the SSS of each RFC, despite that they may not be the best capacity/fairness maximizing set of users. The fully dynamic NC-TDD fails to offer an acceptable cell-edge capacity due to the extreme CLI, i.e., ~ 48% of the scheduling TTI instances have no sufficient capacity.

VI. CONCLUDING REMARKS

A quasi-dynamic coordination scheme has been introduced for ultra-reliable and low-latency communications (URLLC) in 5G TDD networks. The proposed solution combines hybrid radio frame design, distributed multi-objective user scheduling and a cyclic-offset-based radio frame code-book. Compared to the state-of-the-art coordinated TDD proposals from industry and academia, proposed scheme offers a significant improvement of the URLLC outage performance, e.g., 92% latency reduction gain, in addition to achieving aggregated cell capacity gain of 189%, and with a limited control overhead space, bounded to B-bit.

VII. ACKNOWLEDGMENTS

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