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Inter-Cell Radio Frame Coordination Scheme Based on Sliding Codebook for 5G TDD Systems

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Abstract*—The fifth generation (5G) of the wireless communication networks supports wide diversity of service classes, leading to a highly dynamic uplink (UL) and downlink (DL) traffic asymmetry. Thus, dynamic time division duplexing (TDD) technology has become of a significant importance, due to its radio frame flexibility. However, fully dynamic TDD systems suffer from potentially severe inter-cell cross link interference (CLI). In this paper, we propose a novel inter-cell radio frame coordination (RFC) scheme based on sliding codebook for fully dynamic TDD 5G networks. Proposed coordination scheme simultaneously addresses two optimization objectives of minimizing the average CLI while reliably maximizing the achievable DL/UL capacity, by virtually extending the RFC degrees of freedom through a sliding phase-offset RFC codebook design. Compared to the state-of-the-art TDD studies, the proposed scheme shows significantly improved ergodic capacity, i.e., at least $\sim 140\%$ gain under both the TCP and UDP protocols, and with much less signaling overhead, limited to B-bit. The paper offers valuable insights about how to most efficiently pre-mitigate potential CLI in Macro TDD systems.

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

I. Introduction

Time division duplexing (TDD) technology has drawn a major research attention since day-one of the long term evolution (LTE) development. The 3rd generation partnership project (3GPP) LTE-Advanced Rel-12 introduces an enhanced interference mitigation and traffic adaptation (eIMTA) [1, 2] to offer a more flexible TDD adaptation. eIMTA supports seven different TDD radio frame configuration (RFC) patterns with different downlink (DL) to uplink (UL) traffic ratios, where each cell dynamically in time adapts its radio frame based on its own link direction selection criteria, e.g., aggregated traffic demand [3]. Though, the fastest possible RFC adaptation periodicity of eIMTA is the LTE radio frame, i.e., 10 ms.

With the agile frame structure of the 5G new radio (5G-NR) [4], e.g., the flexible TDD slot formats and the variable transmission time interval (TTI) duration, a fully dynamic TDD with much faster and flexible adaptation becomes feasible. Accordingly, the link direction switching periodicity can be slot-based, i.e., $\leq$ 1 ms, instead of being RFC-based. Thus, 5G-NR TDD systems significantly improve the spectrum utilization and the ergodic capacity for services with fast-varying and asymmetric DL and uplink UL traffic [5]. However, the coexistence of different link directions over same frequency resources in adjacent cells results in potential cross link interference (CLI), i.e., user-to-user (UE-UE), and base-station to base-station (BS-BS) interference [6]. In Macro deployments, the CLI, especially the BS-BS interference, is a critical problem due to the UL and DL power imbalance. Consequently, the gains of the adaptive RFCs in TDD may completely vanish due to severe CLI [7].

The state-of-the-art CLI suppression proposals from the open literature consider either CLI avoidance or post-cancellation. In [8], the combination of cell muting, liquid clustering and enhanced UL power control is suggested to minimize the average UE-UE and BS-BS CLI. Additionally, joint UE scheduling and advanced beam-forming techniques [9, 10] are envisioned as beneficial to counteract the CLI. Furthermore, a performance case study on the interaction of the transmission control protocol (TCP) with the 5G-NR TDD systems is presented [11]. In [12], a recent proposal introduces perfect CLI cancellation using full packet exchange, where DL-heavy cells signal neighboring UL-heavy cells with their respective DL UE transmission information for the UL-heavy cells to optimally cancel the critical BS-BS CLI.

Compared to the state-of-the-art coordinated TDD studies, significant inter-cell control signaling overhead and/or ideal periodic UE CLI measurements are usually assumed, which are infeasible in practice. Consequently, the overall capacity gains from the TDD RFC flexibility can be greatly limited due to cell muting or the abrupt changes in the joint scheduling decisions. Needless to say, an efficient and flexible coordination scheme is vital for macro TDD systems, to simultaneously improve the overall ergodic capacity in both UL and DL directions and with limited signaling overhead.

In this work, we propose an RFC based sliding codebook (RFCbCB) coordination scheme for 5G TDD systems. The proposed scheme effectively boosts the TDD system degrees of freedom, coming from its frame flexibility, with the size of a specially pre-designed RFC codebook. Consequently, the maximum possible ergodic capacity is achieved while simultaneously guaranteeing acceptable CLI levels and with a significantly reduced inter-cell control signaling overhead, limited to B-bit. Extensive system level simulations show that the proposed RFCbCB scheme significantly improves the ergodic capacity by the efficient CLI avoidance in both DL and UL directions simultaneously. Moreover, as various applications require different link reliability levels, e.g., TCP is commonly used with the 5G-NR enhanced mobile broadband service class and user data-gram protocol (UDP) with latency critical traffic, we evaluate the proposed scheme performance over both transport protocols to study the effect of the CLI on the TCP flow and congestion controls, respectively.

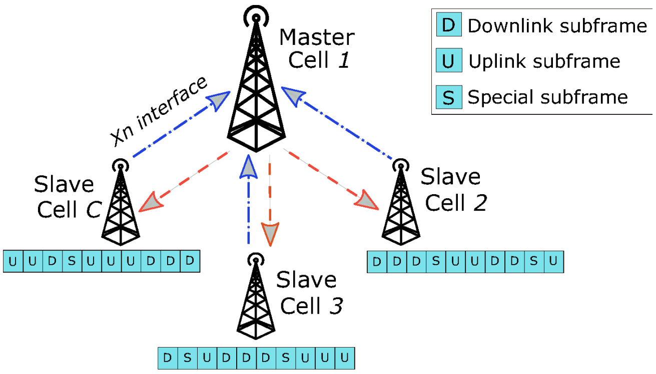

Fig. 1. Proposed RFCbCB: system model.

Due to the complexity of the 5G-NR [4] and addressed problem herein, we evaluate the performance by extensive system simulations, where the main TDD functionalities are calibrated against the 3GPP 5G-NR assumptions. This includes UL and DL channel modeling, dynamic modulation and coding schemes (MCS), dynamic hybrid automatic repeat request (HARQ), and dynamic UE scheduling.

This paper is organized as follows. Section II presents the system model of this work. Section III introduces the problem formulation while Section IV details the proposed RFCbCB coordination scheme and the reference studies to compare against. Section V discusses the performance evaluation results and paper is finally concluded in Section VI.

II. System Model

We consider a 5G-NR TDD system with a single cluster of C cells, each with N_t antennas. Each cell serves an average of K^{dl} and K^{ul} uniformly-distributed DL and UL UEs, each with M_r antennas. Without loss of generality, we assume the FTP3 traffic modeling with finite payload sizes f^{dl} and f^{ul} bits, and Poisson point arrival processes λ^{dl} and λ^{ul}, in the DL and UL directions, respectively. Thus, the total offered traffic load per cell in DL direction is: $K^{\text{dl}} \times f^{dl} \times \lambda^{\text{dl}}$ and in UL direction: $K^{\text{ul}} \times f^{ul} \times \lambda^{\text{ul}}$, respectively.

In the time domain, we assume an RFC of 10 sub-frames, each is 1-ms and can be either a DL, UL or special sub-frame. In the frequency domain, UEs are dynamically multiplexed by the orthogonal frequency division multiple access (OFDMA), with the smallest schedulable unit as the physical resource block (PRB) of 12-subcarriers, each is 15 kHz. Thus, a sub-frame is one slot of 14-OFDM symbols. Nonetheless, the proposed solution is also valid with different numerologies of the 5G-NR sub-carrier spacing, TTI duration, and number of TDD slots per sub-frame, respectively.

Within each cluster, an arbitrary master cell is declared where other cells act as slaves. Such master cell can be manually pre-configured since it is independent from time and the coordination technology. All cells within each cluster are assumed to be bi-bidirectionally inter-connected to the master cell through the *Xn interface*, as shown in Fig. 1.

Let $\mathfrak{B}_{\text{dl}}$, $\mathfrak{B}_{\text{ul}}$, $\mathcal{K}_{\text{dl}}$ and $\mathcal{K}_{\text{ul}}$ indicate the sets of cells and UEs in the DL and UL transmission modes, respectively. Then, the received signal at the k^{th} UE, where $k \in \mathcal{K}_{\text{dl}}$, $c_k \in \mathfrak{B}_{\text{dl}}$, is

$$\mathrm{y}^{\text{dl}}_{k,c_k} = \underbrace{\mathbf{H}^{\text{dl}}_{k,c_k}\mathbf{v}_k s_k}_{\text{Useful signal}} + \underbrace{\sum_{i\in\mathcal{K}_{\text{dl}}\backslash k} \mathbf{H}^{\text{dl}}_{k,c_i}\mathbf{v}_i s_i}_{\text{BS to UE interference}} + \underbrace{\sum_{j\in\mathcal{K}_{\text{ul}}} \mathbf{G}_{k,j}\mathbf{w}_j s_j}_{\text{UE to UE interference}} + \mathbf{n}^{\text{dl}}_k, \tag{1}$$

where $\mathbf{H}^{\text{dl}}_{k,c_i} \in \mathcal{C}^{M_r \times N_t}$ denotes the DL channel from the cell, serving the i^{th} UE, to the k^{th} UE, $\mathbf{v}_k \in \mathcal{C}^{N_t \times 1}$ and s_k are the single-stream precoding vector at the c_k^{th} cell and data symbol of the k^{th} UE, respectively, $\mathbf{G}_{k,j} \in \mathcal{C}^{M_r \times M_r}$ is the channel between the k^{th} and j^{th} UEs. $\mathbf{w}_j \in \mathcal{C}^{M_r \times 1}$ is the single-stream precoding vector at the j^{th} UE, and $\mathbf{n}^{\text{dl}}_k$ is the additive white Gaussian noise at the k^{th} UE. The first summation denotes the DL-to-DL inter-cell interference while the second summation represents the inter-cell UE-UE CLI. Similarly, the received signal at the c_k^{th} cell, where $c_k \in \mathfrak{B}_{\text{ul}}$ from $k \in \mathcal{K}_{\text{ul}}$, is

$$\mathrm{y}^{\text{ul}}_{c_k,k} = \underbrace{\mathbf{H}^{\text{ul}}_{c_k,k}\mathbf{w}_k s_k}_{\text{Useful signal}} + \underbrace{\sum_{j\in\mathcal{K}_{\text{ul}}\backslash k} \mathbf{H}^{\text{dl}}_{c_k,j}\mathbf{w}_j s_j}_{\text{UE to BS interference}} + \underbrace{\sum_{i\in\mathcal{K}_{\text{dl}}} \mathbf{Q}_{c_k,c_i}\mathbf{v}_i s_i}_{\text{BS to BS interference}} + \mathbf{n}^{\text{ul}}_{c_k}, \tag{2}$$

where $\mathbf{Q}_{c_k,c_i} \in \mathcal{C}^{N_t \times N_t}$ is the channel between the cells that serve the k^{th} and i^{th} UEs, respectively, where $k \in \mathcal{K}_{\text{ul}}$ and $i \in \mathcal{K}_{\text{dl}}$. The first summation implies the UL-to-UL inter-cell interference while the second summation denotes the inter-cell BS-BS CLI. Then, the received signal is decoded using the linear minimum mean square error interference rejection combining receiver (LMMSE-IRC) [4] matrix **a** as

$$\hat{s}^{\kappa}_k = \left(\mathbf{a}^{\kappa}_k\right)^{\text{H}} \mathrm{y}^{\kappa}_k, \tag{3}$$

where $\mathcal{X}^{\kappa}, \kappa\in\{\text{ul}, \text{dl}\}$, and $(\bullet)^{\text{H}}$ denotes the Hermitian operation. Finally, the received signal-to-interference-noise-ratio (SINR) levels in the DL direction at the k^{th} UE and in the UL direction at the c_k^{th} cell, respectively, are expressed by

$$\gamma^{\text{dl}}_k = \frac{p^{\text{dl}}_{c_k} \left\|\mathbf{H}^{\text{dl}}_{k,c_k}\mathbf{v}_k\right\|^2}{\sigma^2 + \sum\limits_{i\in\mathcal{K}_{\text{dl}}\backslash k} p^{\text{dl}}_{c_i} \left\|\mathbf{H}^{\text{dl}}_{k,c_i}\mathbf{v}_i\right\|^2 + \sum\limits_{j\in\mathcal{K}_{\text{ul}}} p^{\text{ul}}_j \left\|\mathbf{G}_{k,j}\mathbf{w}_j\right\|^2}, \tag{4}$$

$$\gamma^{\text{ul}}_{c_k} = \frac{p^{\text{ul}}_k \left\|\mathbf{H}^{\text{ul}}_{c_k,k}\mathbf{w}_k\right\|^2}{\sigma^2 + \sum\limits_{j\in\mathcal{K}_{\text{ul}}\backslash k} p^{\text{ul}}_j \left\|\mathbf{H}^{\text{dl}}_{c_k,j}\mathbf{w}_j\right\|^2 + \sum\limits_{i\in\mathcal{K}_{\text{dl}}} p^{\text{dl}}_{c_i} \left\|\mathbf{Q}_{c_k,c_i}\mathbf{v}_i\right\|^2}, \tag{5}$$

where $p^{\text{dl}}_{c_k}$ and p^{ul}_k are the transmission power of the c_k^{th} cell in the DL direction and the k^{th} UE in the UL direction, respectively. As can be observed from (5), the BS-BS CLI can significantly degrade the perceived UL SINR level due to the DL and UL power imbalance, i.e., $p^{\text{dl}}_{c_i} \gg p^{\text{ul}}_k$.

III. Problem Formulation - CLI Mitigation

In fully TDD systems, cells may not adopt exactly the same RFC. Thus, neighboring cells experience different transmission directions over several sub-frames, causing severe BS-BS and UE-UE CLI. Accordingly, the lower-power UL transmissions are severely degraded due to the strong CLI resulting from adjacent larger-power DL transmissions. As a result, the achievable UL capacity exhibits a significant loss,

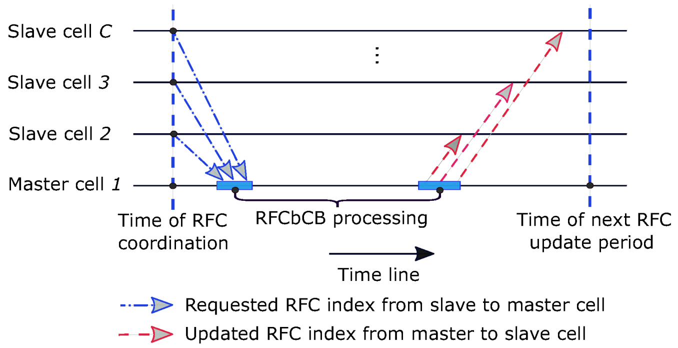

Fig. 2. Timing diagram of the inter-cell RFC coordination.

leading to more buffered UL traffic in those victim cells. Hence, these cells will be dictated by new and buffered UL traffic leading to a limited DL capacity and a highly degraded overall spectral efficiency as a consequence.

To address this problem, the proposed RFCbCB seeks to maximize the long-term ergodic capacity while simultaneously preserving limited inter-cell sub-frame misalignment, thus, an acceptable average CLI. Let u_c and d_c denote the estimated numbers of UL and DL sub-frames in an arbitrary RFC while $u_c^{\text{opt.}}$ and $d_c^{\text{opt.}}$ indicate the corresponding optimal numbers. Thus, we define a heuristic optimization problem as

$$R \triangleq \arg\max_{c} \sum_{c=1}^{C} \min\left(u_c, u_c^{\text{opt.}}\right) \digamma_c^u + \min\left(d_c, d_c^{\text{opt.}}\right) \digamma_c^d, \quad (6)$$

$$\phi_c\left(\eta_c\right) = \arg\min_{x} \frac{1}{C} \sum_{x=1, x\neq c}^{C} \varphi_{c,x}\left(\eta_c, \eta_x\right), \quad (7)$$

where R is the aggregate capacity of the cluster, $\digamma_c^u$ and $\digamma_c^d$ are the rate utility functions of the UL and DL transmissions in the c^{th} cell, i.e., the achievable capacity gain from having either UL or DL transmission. $\phi_c\left(\eta_c\right)$ and $\varphi_{c,x}\left(\eta_c, \eta_x\right)$ are the average and actual sub-frame misalignment of the RFC requested by the c^{th} cell η_c and between the RFCs of the c^{th} and x^{th} cells, i.e., η_c and η_x, respectively, $\forall x \neq c$. To maximize (6), $u_c = u_c^{\text{opt.}}$ and $d_c = d_c^{\text{opt.}}$ should be preserved; however, $u_c^{\text{opt.}}$ and $d_c^{\text{opt.}}$ may result in a large sub-frame misalignment, leading to severe CLI in the cluster and the overall capacity R shall be significantly degraded accordingly.

IV. Proposed RFCbCB Coordination

A specially designed RFC CB is pre-defined and assumed pre-known to all cells in each cluster. Slightly before each RFC update periodicity, each slave cell identifies its desired upcoming RFC from the CB that satisfies its link direction selection objectives. Next, it signals the master cell with the index of its desired RFC from the CB over *Xn interface*. The master BS then seeks to simultaneously satisfy both (6) and (7). Hence, the master cell may slightly change the RFC indices, which were requested by slave cells. Finally, it signals the updated RFC indices back to the slave cells, which should be used during the next RFC update period. Fig. 2 depicts the generic timing diagram of the proposed solution.

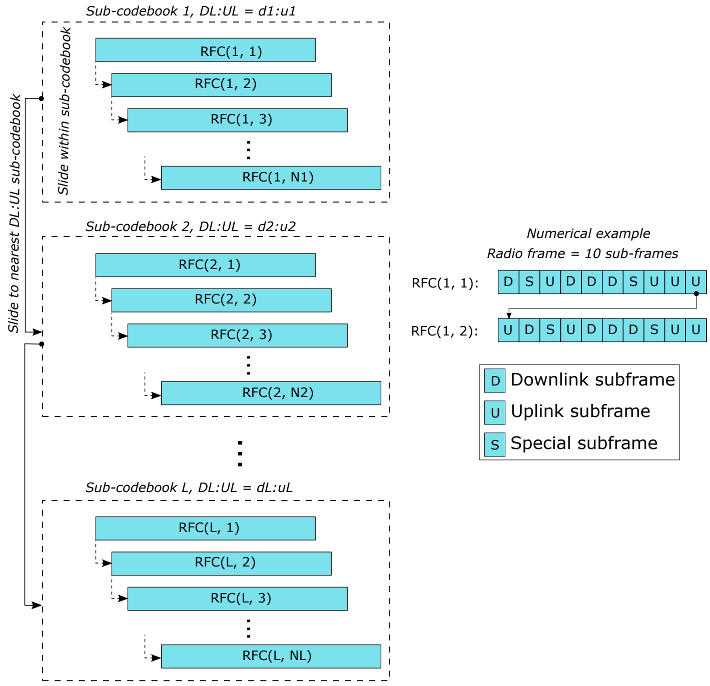

Fig. 3. Proposed RFCbCB: RFC sliding CB design.

A. *Proposed Inter-Cell Coordination Scheme*

The design of the RFC sliding codebook:

A pre-defined RFC CB of size $\mathcal{N}$ unique RFCs is constructed, where it is divided into L different sub-CBs. Each sub-CB contains RFCs with the same DL:UL sub-frame ratio in a radio frame, i.e., $d_c : u_c$; however, with a different DL and UL sub-frame placement as depicted in Fig. 3, where each RFC is cyclic-shift of the other RFCs in the same sub-CB. The total number of RFCs, sub-CBs, and cyclic-shift in the CB are arbitrary design parameters.

At the slave cells within a cluster:

At each RFC update period, each slave cell selects an RFC from the CB that most meets its own link direction selection criteria. Without loss of generality, we consider the buffered traffic including pending re-transmissions as the main criterion with which each cell determines its required $d_c : u_c$ ratio. Let β_c implies the traffic load threshold of the c_k^{th} cell, as

$$\beta_c \leq \frac{\sum Z_c^{\text{dl}}}{\sum Z_c^{\text{dl}} + \sum Z_c^{\text{ul}}}, \quad (8)$$

where $\sum Z_c^{\text{dl}}$ and $\sum Z_c^{\text{ul}}$ are the total buffered traffic in the DL and UL directions, respectively. The traffic load threshold β_c is used to bias the link direction selection to either DL or UL. For an instance, with fair $\beta_c = 0.5$, if $\sum Z_c^{\text{dl}} \geq \sum Z_c^{\text{ul}}$, a cell decides a DL-heavy RFC. Finally, slave cells feedback the master cell with $\text{B} = \log_2\left(\mathcal{N}\right)$ bits on the *Xn interface* to indicate the index of the desired RFC from the CB.

At the master cell within a cluster:

The master cell first identifies the *common RFC*, as the most requested RFC by the majority of the slave cells in the cluster. If not possible, the master cell considers any requested RFC as the common RFC of this cluster, and to which other requested

RFCs from other slave cells must satisfy the minimum possible sub-frame misalignment with.

Then, for each requested RFC η_c of the c_k^{th} cell, the master cell calculates the sub-frame misalignment to the common RFC $\delta_x, \forall x \neq c$ as: $\varphi_{c,x}\left(\eta_c\left(u_c, d_c\right), \delta_x\left(u_x, d_x\right)\right)$. If $\varphi_{c,x} \leq \psi$, with ψ as a pre-defined sub-frame misalignment threshold, the master cell skips updating such requested RFC, i.e., does not change it, since it originally drives a limited CLI. Otherwise, the master cell slides over all RFCs within the same sub-CB of the requested RFC η_c. It calculates the corresponding misalignment values $\varphi_{c,x}$ and selects the RFC with the minimum sub-frame misalignment. Finally, it performs two variations:

- **Option-1**: if the sub-frame misalignment of the selected RFC is below ψ, the master cell considers such RFC as the updated RFC of this cell. Hence, an acceptable average CLI level is guaranteed across the upcoming RFC update period while still preserving the same required traffic service ratio $d_c : u_c$, improving both the slave cells and overall cluster capacity, respectively.
- **Option-2**: if $\varphi_{c,x} \leq \psi$ is not feasible with all RFCs in the same sub-CB, the master cell slides to a different sub-CB in the CB, with the nearest $d_c : u_c$ ratio to the requested ratio, e.g., $d_c : u_c = 2:6 \underset{\text{slide to}}{\rightarrow} d_c^{'} : u_c^{'} = 3:5$, and repeats the same operation. Herein, the master cell slightly sacrifices part of the full TDD RFC flexibility, due to the change in the requested $d_c : u_c$. However, such capacity loss is bounded over only a limited number of sub-frames and is reversibly proportional to the size of the CB, since the master cell slides only to the nearest $d_c : u_c$ sub-CB. As will be discussed in Section V, this capacity loss is fully recovered on the long-term statistics due to the significantly reduced CLI.

As a last resort, if the sub-frame misalignment threshold can not be further satisfied, the master cell considers the RFC with the minimum misalignment $\varphi_{c,x}$, from either the same or different sub-CB as the requested one, as the updated RFC of this slave cell even it does not satisfy $\varphi_{c,x} \leq \psi$. Finally, the master cell feeds-back all slave cells back with B-bit indices over the *Xn interface* to indicate their respective updated RFCs to be used over the next RFC update period.

B. Comparison to the state-of-the-art TDD studies

We compare the performance of the proposed solution against the following state-of-the-art TDD proposals as:

Fully-uncoordinated TDD (FUC): all cells in the cluster independently select their respective RFCs from the CB based on the traffic criterion in (8). No inter-cell RFC coordination is assumed. Thus, a large inter-cell sub-frame misalignment and hence, severe CLI levels can be exhibited.

Ideal-UL interference coordination TDD (IUIC) [12]: within a cluster, cells independently select respective RFCs based on (8). Then, the DL-heavy cells feedback their respective DL payload, PRB mapping, UE MCS and precoding information to UL-heavy cells over the *Xn interface*. Accordingly, the UL-heavy cells are perfectly able to fully suppress the BS-BS CLI, i.e., BS-BS CLI = 0. Therefore, the IUIC is an UL-optimal TDD coordination scheme; however, with a significant signaling overhead over the back-haul links.

Table I
SIMULATION PARAMETERS.

Parameter	Value
Environment	3GPP-UMA, one cluster, 21 cells
UL/DL channel bandwidth	10 MHz, TDD
TDD mode	Synchronized
Antenna setup	$N_t = 8$ Tx, $M_r = 2$ Rx
Average user load	$K^{\text{dl}} = K^{\text{ul}} = 10$ users per cell
UL/DL receiver	LMMSE-IRC
TTI configuration	1 ms (14-OFDM symbols)
HARQ	Chase combining
Link adaptation	Dynamic MCS
Traffic model	FTP3, f^{dl} = f^{ul} = 4000 bits λ^{dl} = 500, 375, and 250 pkts/sec λ^{ul} = 500, 375, and 250 pkts/sec
User scheduler	Proportional fair
Offered average load per cell DL:UL	DL:UL = 2:1 (20:10) Mbps DL:UL = 1:1 (15:15) Mbps DL:UL = 1:2 (10:20) Mbps
Proposed RFCbCB setup	ψ = 3 sub-frames $\mathcal{N}$ = 55 RFCs L = 7 sub-CBs B = 6 bits
Transport layer setup	TCP/UDP max PDU: 1500 Bytes Congestion control: CUBIC Slow start threshold: 35 MSS

V. PERFORMANCE EVALUATION

The performance assessment of the proposed coordination scheme is based on highly dynamic system level simulations, where the main 3GPP assumptions are followed [4]. The major simulation setup parameters are listed in Table I. At each TTI, each cell dynamically and independently schedules UEs over system PRBs according to the proportional fair criterion. Herein, we assume fully dynamic link adaptation and Chase combining HARQ, respectively, where the DL/UL HARQ feedback is sent with a higher priority during the first available transmission opportunity of the adopted RFC. The sub-carrier SINR level is calculated using the LMMSE-IRC receiver. For MCS selection, sub-carrier SINR levels are combined using the effective exponential SNR mapping algorithm to obtain an effective wide-band SINR. Finally, we evaluate the performance of the proposed RFCbCB scheme under both TCP and UDP, with different offered traffic loads per cell and for the two proposed options.

Table II shows the achievable DL and UL throughput per cluster under TCP of the FUC, proposed RFCbCB (option-1), and IUIC, for different DL:UL traffic ratios. As can be clearly observed, with all traffic load variations, the proposed RFCbCB (option-1) provides a significant capacity improvement in both the DL and UL directions, compared to the FUC. It also approaches the optimal IUIC, due to the significantly reduced average CLI. For instance, with a BS-BS CLI extreme case, i.e., DL:UL = 2:1, proposed RFCbCB (option-1) achieves $\sim +144.41\%$ gain in the UL capacity than the FUC. The optimal IUIC offers the best DL and UL throughput since the BS-BS CLI is assumed perfectly suppressed. Thus, UL traffic gets transmitted faster with zero CLI, i.e., UL PRBs become of higher capacity, leaving more time and resources for DL

Table II
PROPOSED RFCBCB (OPTION-1): ACHIEVABLE DL AND UL THROUGHPUT (MBPS) PER CLUSTER, WITH TCP.

Traffic Ratio	Offered load per cell (Mbps)	FUC		Proposed RFCbCB (option-1)		IUIC	
		DL	UL	DL	UL	DL	UL
DL:UL = 2:1	DL:UL = 20:10	131.52 0.0%	17.63 0.0%	167.87 +24.2%	109.23 +144.41%	228.38 +53.82%	158.61 +159.98%
DL:UL = 1:1	DL:UL = 15:15	117.73 0.0%	26.12 0.0%	149.53 +23.79%	154.39 +142.12%	191.09 +47.50%	195.16 +152.78%
DL:UL = 1:2	DL:UL = 10:20	106.07 0.0%	138.24 0.0%	113.10 +6.41%	198.65 +35.86%	139.79 +27.43%	264.6 +62.73%

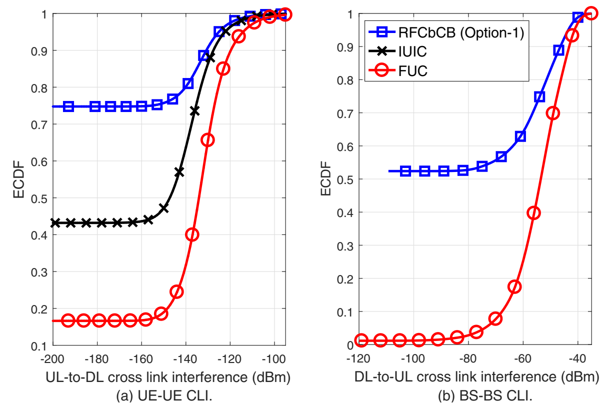

Fig. 4. Cross link interference performance (dBm), with TCP.

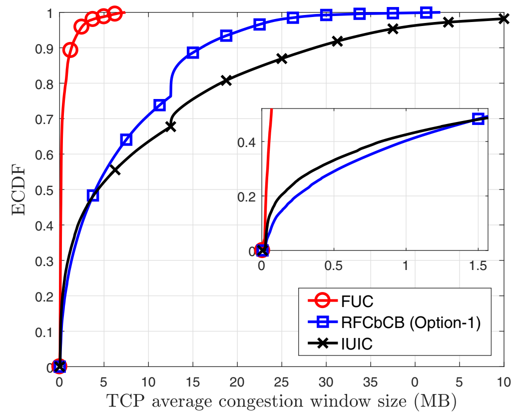

Fig. 5. TCP average congestion control performance.

traffic. Accordingly, both UL and DL capacity are improved. The FUC exploits the full TDD RFC flexibility; however, the aggregated capacity is severely degraded due to the exhibited strong CLI levels.

The RFCbCB performance gain is mainly due to the significant reduction of the average CLI. Hence, Figs. 4.a and 4.b show the empirical cumulative distribution function (ECDF) of the BS-BS and UE-UE CLI, respectively, averaged over all system PRBs with DL:UL = 2:1. The proposed RFCbCB offers a highly improved CLI performance, i.e., more than 70% and 50% of the simulation time are UE-UE and BS-BS CLI-free, respectively. Compared to the optimal IUIC, the RFCbCB shows a further reduced UE-UE CLI since IUIC is only UL-optimal with no BS-BS CLI (no ECDF of the BS-BS CLI with IUIC in Fig. 4.b). However, the proposed RFCbCB non-biasedly seeks for minimizing both BS-BS and UE-UE CLI, respectively.

Looking at the TCP performance, Fig. 5 depicts the ECDF of the average UL and DL TCP congestion window (CWND) in MB. The TCP CWND is a congestion control measure, applied at the transmitter side, to counteract network congestion. It defines the maximum rate bound that a transmitter can use towards a receiver such that it is exponentially increased when a successful TCP acknowledgment (ACK) is received, otherwise, it is decreased. Hence, the TCP transmission rate is restricted by either the transmitter CWND or the receiver advertised maximum window. Accordingly, the TCP CWND performance is highly correlated to the exhibited CLI in TDD systems. As shown in Fig. 5, the FUC inflicts an extremely small CWND size, due to the exhibited severe CLI. The proposed RFCbCB achieves $\sim +168.25$ gain in the 90 percentile CWND size compared to the FUC. However, the optimal IUIC offers the best average CWND performance, despite that it exhibits a larger average UE-UE CLI than the proposed RFCbCB, as shown in Fig. 4.a. This consolidates the fact that the BS-BS CLI has a stronger impact on overall capacity than the UE-UE CLI due to the power imbalance between UL and DL transmissions. Though, the proposed RFCbCB achieves an average $\sim +58.1\%$ gain in the CWND size than IUIC for the percentiles below 40%, due to the achievable $\sim -52.1\%$ reduction in the UE-UE CLI as in Fig. 4.a. Thus, with the proposed RFCbCB, cell-edge DL UEs inflict much less CLI from adjacent inter-cell-edge UL UEs.

Furthermore, the proposed RFCbCB scheme is demonstrated as best effort since the minimum sub-frame misalignment threshold may not be satisfied over all RFCs within the same requested $d_c : u_c$ sub-CB. Thus, we investigate cases where the master cell slides to the nearest $d_c : u_c$ sub-CB to the requested one, i.e., RFCbCB (option-2), sacrificing part of the TDD RFC flexibility due to the $d_c : u_c$ change. Fig. 6 introduces the post-detection UL SINR, after the IRC decoding as in eq. (3), of the RFCbCB (option-1) (slide only within requested sub-CB), RFCbCB (option-2) (if applicable, slide to nearest sub-CB), FUC, and IUIC, with UDP on top for DL:UL = 2:1. The RFCbCB (option-1) provides substantial improvements in the UL SINR compared to the FUC, i.e., an average of $+7.9$ dB increase. Moreover, RFCbCB (option-2) further improves the perceived UL SINR level by an average of $+2.9$ dBs than RFCbCB (option-1), and with a bounded average loss of -2.7 dB to the optimal IUIC.

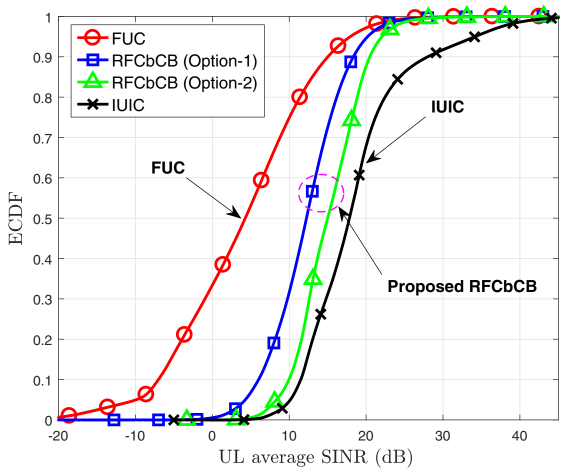

Fig. 6. UL average SINR performance (dB), with UDP.

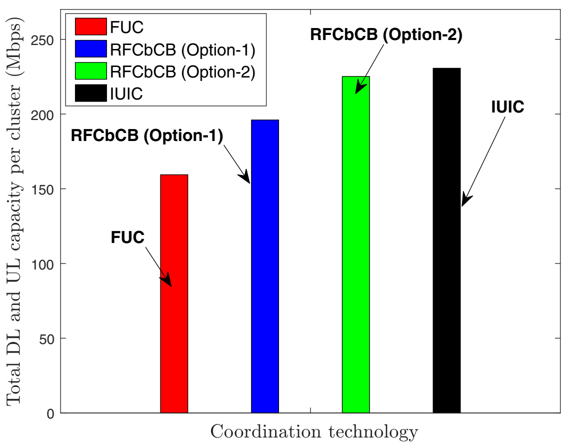

Fig. 7. Total DL and UL capacity per cluster (Mbps), with UDP.

Interestingly, the proposed RFCbCB (option-2) further improves the overall DL and UL capacity per cluster, as depicted in Fig. 7, closely approaching the UL-optimal IUIC. The RFCbCB (option-2) further significantly reduces the probability of the CLI occurrence than RFCbCB (option-1) by sliding to other RFC sub-CBs, at the expense of slightly changing the traffic service ratio $d_c : u_c$, requested by slave cells. Thus, the instantaneous UE rates may inflict a capacity loss, though, being limited due to the conservative $d_c : u_c$ change. However, on the average traffic statistics, the UL and DL traffic gets scheduled and successfully decoded faster due to limited CLI, and thus, an enhanced decoding ability, leaving more time and resources for incoming traffic. As a result, the total UL and DL capacity per cell is further improved.

VI. Concluding Remarks

In this work, a radio frame configuration based on sliding codebook coordination scheme has been proposed for dynamic TDD 5G macro systems. The proposed solution, with its introduced variations, offer a significant capacity improvement, i.e., more than $\sim 140.0\%$ gain, under both TCP and UDP, and with a highly reduced inter-cell signaling overhead size, limited to B-bit. Compared to the state-of-the-art TDD solutions from industry and academia, the proposed scheme has been demonstrated as a flexible, high-performance and low-complexity way to control the critical cross link interference (CLI) in dynamic TDD networks.

The main insights brought by this work are summarized as: (1) the achievable capacity gains from the frame direction flexibility in dynamic TDD macro systems can fully vanish or revert to a capacity loss due to severe CLI, (2) the majority of the state-of-the-art dynamic TDD coordination schemes assumes sophisticated inter-cell communications to share the scheduling decisions, and transmission information. This leads to a significant amount of control overhead, which is infeasible in practice, and (3) proposed solution demonstrates a flexible coordination scheme that dynamically exploits the fully dynamic TDD frame flexibility when moderate levels of CLI are accepted. Otherwise, it slightly relaxes the requirement of the fully flexible frame configuration, trading-off an intended small capacity loss in the UE instantaneous rates for the sake of a significant improvement in the overall capacity. A further study with an analytical demonstration on the radio latency optimization of the proposed solution will be conducted in a future work.

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