On the Performance of 5G Flexible TDD Systems with Coordinated Beamforming

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***Abstract*—5G systems are expected to utilize flexible time division duplex (TDD) to cater for instantaneous user traffic demands. 5G systems are also expected to benefit from user-specific beamforming using massive MIMO deployment. In this paper we study the performance of flexible TDD system with massive MIMO deployment and inter-cell coordination. We propose a centralized scheduling approach, where joint user scheduling and beamforming is performed taking into account interference cancellation receivers. Simulations results are shown in a multi-site scenario with multiple panels at each site. Results show that flexible TDD with per site standalone scheduling provides a significant 175% median uplink throughput gain over a fixed UL/DL TDD split. Advanced inter-site coordination based on IC receivers is seen to further improve uplink and downlink median throughput by around 85% and 65% respectively as compared to intra-site standalone scheduling.**

I. Introduction

5G mobile communication systems are envisioned to support diverse services and large number of subscribers by providing high data rates along with native support for lower latency. Flexible time division duplexing (TDD), also called dynamic TDD is one of the key enablers which aims to utilize radio resources flexibly for either uplink or downlink on individual cells. Flexible TDD can be used to increase the network capacity in dense networks by opportunistically switching the duplex direction based on the current user traffic demand.

Flexible TDD deployment per cell can however generate downlink-to-uplink and uplink-to-downlink cross-link interference between the neighboring cells. Cross-link interference management (CLIM) using inter-cell coordination and interference suppression receivers can be used to mitigate the interference [1]. The benefit of using advanced interference rejection combining (IRC) and successive interference cancellation (SIC) receivers has been investigated in prior works e.g [2], [3]. Interference coordination using coordinated MIMO rank adaptation has been studied in prior works such as [4]. Previously in [5], [6], we proposed a joint inter-cell MIMO rank coordination scheme which exploits SIC receivers for cross-link interference cancellation (IC). However the aforementioned works assume omni-directional antennas deployed at each cell.

Meanwhile 5G systems are expected to benefit from Massive multiple-input multiple-output (MIMO) deployment, where large number of antennas are used for beamforming to a specific user. The main use of beamforming is to increase the signal power to the user [7] which increases coverage to well shadowed locations. Beamforming has an effect on the inter-cell interference and cross-link interference between the neighbor cells because of the beam direction and the radiation pattern.

Interference coordination based on precoder design in beamformed cellular system is discussed for example as in [8],[9]. In [8] authors propose a scheme where a base station applies interference nulling based on the expected benefit for the cell edge users. In contrast to the precoder optimization approaches, in this paper we extend our prior work [6] and consider centralized user scheduling in a flexible TDD system with eigen-beamforming at each cell. The novelty of the scheme is to perform coordinated downlink and uplink eigen-beamforming to purposely benefit from cross-link strong interference cancellation using SIC receiver.

The main contribution of the paper is to answer the question to what extent we can benefit from flexible TDD and centralized scheduling with massive MIMO deployment. We compare two different scheduling approaches: a) standalone flexible TDD scheduling at each site with coordination only between the panels at that site, and b) fully centralized scheduling between all the sites which tries to achieve better performance at the cost of higher complexity. In the case of centralized scheduling, we further evaluate the extent to which we can benefit from interference cancellation receivers at each site. The throughput performance is evaluated using simulations in a muti-site scenario with multiple antenna arrays (panels) deployed at each site and with bursty traffic model. Each panel supports single user 4×4 MIMO along with eigen-beamforming, and the scenario consists of both outdoor and indoor shadowed users.

Results show that standalone fully flexible TDD scheduling provides a significant 175% throughput gain on the uplink as compared to fixed uplink-downlink TDD split. Centralized user scheduling without IC receivers improves the uplink and downlink throughput performance by around 25% as compared to standalone scheduling without IC receivers. Centralized scheduling with IC receivers achieves a further 47% throughput gain on the uplink and 36% throughput gain on the downlink as compared to centralized scheduling without IC receivers. The uplink spectral efficiency is seen to increase by around 30% with the use of IC receivers for cross-link interference mitigation.

II. SYSTEM MODEL

We consider flexible (dynamic) TDD where a given spectrum is flexibly used for uplink (UL) or downlink (DL) on a time slot in each site. We assume Orthogonal Frequency-Division Multiplexing (OFDM) air interface for all the links. Each base station site consists of multiple panels, with each panel supporting single-user MIMO (SU-MIMO) along with user-specific beamforming. We define a link as a unidirectional connection (either uplink or downlink) between the connected panel and the user. Thus for example index i may denote an uplink between a single UE and its connected panel, while j denote the downlink from the panel to that UE. The MIMO system consists of M_B antennas at each base station panel and M_U antennas at each UE, where $M_U \leq M_B$. The unit norm MIMO channel fading matrix of uplink i is represented by a matrix $\mathbf{G}_{ii}$ of dimension $M_B \times M_U$, and for downlink j is then its transpose matrix $\mathbf{G}_{jj}$ of dimension $M_U \times M_B$.

We apply transmit beamforming on each downlink using beamforming matrix $\mathbf{V}_j^{M_B \times M_U}$ and receive beamforming on the uplink using $\mathbf{V}_i^{M_U \times M_B}$. We further apply transmitter precoding weights $\mathbf{Q}_i$ and $\mathbf{Q}_j$ on uplink and downlink using the Singular Value Decomposition (SVD) of the beamformed channel. In a TDD system with perfect synchronization, the received uplink signal $\mathbf{y}_i$ of link i on a OFDM subcarrier is given by

$$\mathbf{y}_i = \sqrt{P_i \alpha_{ii}} \mathbf{H}_{ii} \mathbf{x}_i + \sum_{u \in \mathbf{I}_U} \sqrt{P_u \alpha_{iu}} \mathbf{H}_{iu} \mathbf{x}_u + \sum_{k \in \mathbf{I}_D} \sqrt{P_k \alpha_{ik}} \mathbf{\Phi}_{ik} \mathbf{x}_k + \mathbf{n}, \tag{1}$$

where,

$\mathbf{H}_{ii} = \mathbf{V}_i^{\tilde{N}_i \times M_B} \mathbf{G}_{ii}^{M_B \times M_U} \mathbf{Q}_i^{M_U \times \tilde{N}_i}$

$\mathbf{H}_{iu} = \mathbf{V}_i^{\tilde{N}_i \times M_B} \mathbf{G}_{iu}^{M_B \times M_U} \mathbf{Q}_u^{M_U \times \tilde{N}_u}$

$\mathbf{\Phi}_{ik} = \mathbf{V}_k^{\tilde{N}_i \times M_B} \mathbf{G}_{ik}^{M_B \times M_B} \mathbf{V}_k^{M_B \times M_U} \mathbf{Q}_k^{M_U \times \tilde{N}_k}$

In (1), $\mathbf{I}_U$ is the set of uplink interferers, $\mathbf{I}_D$ is the set of downlink interferers and $\mathbf{\Phi}_{ik}$ is the effective cross-link interference channel from a downlink k to uplink i. $\mathbf{G}_{ik}^{M_B \times M_B}$ is the cross-link channel between the transmitting panel of k^{th} downlink and the receiving panel of i^{th} uplink. $\tilde{N}_i \leq M_U$ is the number of transmitted streams on i^{th} link. The vector $\mathbf{x}_i$ denotes the $\tilde{N}_i$ modulated transmission symbols of uplink i.

Further in (1), $\mathbf{n}$ denotes the noise vector with variance N_o and α_{ki} is the pathloss between the transmitter of k^{th} link and the receiver of i^{th} link. P_k denotes the per-subcarrier transmit power of the k^{th} link transmitter. The downlink uses a constant power per-subcarrier, whereas the uplink is based on LTE-like open-loop power control.

Similarly, the received signal $\mathbf{y}_j$ at a downlink receiver of link j can be expressed as:

$$\mathbf{y}_j = \sqrt{P_j \alpha_{jj}} \mathbf{H}_{jj} \mathbf{x}_j + \sum_{k \in \mathbf{I}_D} \sqrt{P_k \alpha_{jk}} \mathbf{H}_{jk} \mathbf{x}_k + \sum_{u \in \mathbf{I}_U} \sqrt{P_u \alpha_{ju}} \mathbf{\Phi}_{ju} \mathbf{x}_u + \mathbf{n}, \tag{2}$$

where,

$\mathbf{H}_{jj} = \mathbf{W}_j^{\tilde{N}_j \times M_U} \mathbf{G}_{jj}^{M_U \times M_B} \mathbf{V}_j^{M_B \times M_U} \mathbf{Q}_j^{M_U \times \tilde{N}_j}$

$\mathbf{H}_{jk} = \mathbf{W}_j^{\tilde{N}_j \times M_U} \mathbf{G}_{jk}^{M_U \times M_B} \mathbf{V}_k^{M_B \times M_U} \mathbf{Q}_k^{M_U \times \tilde{N}_k}$

$\mathbf{\Phi}_{ju} = \mathbf{W}_j^{\tilde{N}_j \times M_U} \mathbf{G}_{ju}^{M_U \times M_U} \mathbf{Q}_u^{M_U \times \tilde{N}_u}$.

In the above $\mathbf{W}_j$ is the linear IRC receiver matrix for MIMO channel equalization [2].

As seen from the above system model, there are following types of interference : UL-to-UL, DL-to-DL interference as well as cross DL-to-UL and UL-to-DL interference. The cross-link interference can especially be severe on the uplink because of line of sight between the base stations. To suppress interference on the receiver side we consider successive interference cancellation (SIC) receiver, where the receiver first cancels the strong interference $\mathbf{x}_k$ in (1) and then decodes the intended signal $\mathbf{x}_i$ while treating $\mathbf{x}_u$ as noise. In the following sections we consider fully centralized user scheduling which performs coordinated user scheduling based on beamforming and interference cancellation.[6].

A. Channel state information

We assume multi-site channel knowledge at the scheduler of the MIMO matrices of all the links. The channel information at the scheduler is outdated and corrupted by estimation noise in time instance $[t]$ given as:

$$\hat{\mathbf{G}}_{ik}[t] = \frac{1}{\sqrt{1+\sigma_E^2}} (\mathbf{G}_{ik}[t-\delta] + \mathbf{E}), \tag{3}$$

where $\mathbf{G}_{ik}$ is the actual channel between the receiver of a link i and a transmitter of a link k. $[\delta]$ is the channel estimate outdate delay at the centralized scheduler. $\mathbf{E}$ is a noise matrix with complex-normal values e_{ik} with 0 mean power and σ_E^2 variance: $e_{ik} \sim CN(0, \sigma_E^2)$ [10]. $\sqrt{1+\sigma_E^2}$ is an average power normalization scaling factor. The error variance σ_E^2 is estimated with a LTE-like model using pilot signal to interference noise ratio (SINR) as in [10].

The centralized scheduler intends to perform scheduling decisions based on estimated performance of interference cancellation. The IC performance is impacted by quality of channel estimation which leads to interference leakage as well as SINR loss because of mismatch between the estimated channel and the actual channel realization. Thus for the purpose of the robust scheduling we generate an independent 'noise perturbed version' of the channel available at the scheduler as [6]: $\tilde{\mathbf{G}}_{ik} = \frac{1}{\sqrt{1+\sigma^2_{\Delta_{ik}}}} (\hat{\mathbf{G}}_{ik} + \mathbf{\Delta}_{ik})$

The perturbation noise $\mathbf{\Delta}_{ik}$ is a random noise process with channel estimation error variance modeled as seen at each receiver and calculated as in [10]. We now use $\tilde{\mathbf{G}}_{ik}$ and $\hat{\mathbf{G}}_{ik}$ at the scheduler to model the receiver filter mismatch and cancellation leakage as in [5].

III. CENTRALIZED SCHEDULING PROBLEM

We consider fully centralized scheduling which performs joint scheduling decisions for a set of coordinated sites on each scheduling slot. The centralized scheduling entity performs TDD switching decision for each cell on a time slot basis.The centralized scheduler further computes the beamforming matrices for the links and also allocates modulation and coding scheme (MCS) and MIMO rank to facilitate cross-link interference cancellation.

The quality-of-service aware resource allocation problem at the scheduler is given by :

$$\begin{aligned}&\underset{\mathbf{R},\mathbf{a},\tilde{\mathbf{N}},\tilde{\mathbf{V}}}{\text{argmax}} \sum_{s=1}^{|\mathbf{S}|} \sum_{p\in\mathbf{P}_s} \sum_{k\in\mathbf{K}_p} w_k a_k \sum_{n=1}^{\tilde{N}_k} r_{kn}(\mathbf{a},\tilde{\mathbf{N}},\tilde{\mathbf{V}}) \\ &s.t. \;\; a_k \in [0,1], \;\; \sum_{k\in\mathbf{K}_p} a_k \le 1, \forall_{p\in\mathbf{P}_s}, \; \forall_{s\in\mathbf{S}} \qquad (4) \\ &\Big(\sum_{p\in\mathbf{P}_s} \sum_{k\in\mathbf{K}_p^{DL}} a_k * \sum_{p\in\mathbf{P}_s} \sum_{k\in\mathbf{K}_p^{UL}} a_k\Big) = 0, \; \forall s \in \mathbf{S}\end{aligned}$$

The objective in (4) performs weighted sum rate maximization for all the panels in the coordinated sites. The constants in (4) are as follows. $\mathbf{S}$ is the set of sites coordinated by a central entity $\mathbf{P}_s$ is a set of panels co-located in the s^{th} site. Each panel $p \in \mathbf{P}_s$ comprises $\mathbf{K}_p$ links defined as unidirectional link (either uplink or downlink) between a transmitter and a receiver. The transmission direction is synchronized for panels at the same site and is flexible across different sites which is captured by a second constraint in (4), where $\mathbf{K}_p^{UL}$ and $\mathbf{K}_p^{DL}$ stand for the set of $uplink$ and $downlink$ links respectively. w_k represents the head of line packet delay of the k^{th} link. Thus delay weighted sum-rate maximization is used to prioritize the links experiencing higher packet delays.

The optimization variables in (4) are as follows. The binary scheduling decisions for all links are captured in vector $\mathbf{a}$ with entries $a_k \in [0,1]$. The beamforming matrices are represented by a matrix $\tilde{\mathbf{V}}$ with $\mathbf{V}_k$ being the beamforming matrix of link k.

The vector $\tilde{\mathbf{N}}$ captures MIMO rank decision for all of the links with scalar entries $\tilde{N}_k$ representing the number of spatial streams (SU-MIMO streams) assigned for link k. The transmission rate matrix is represented as $\mathbf{R}$ with entries r_{kn} denoting the assigned modulation and coding scheme (i.e transmission rate) of link k and MIMO stream n. We then apply the same MCS across the $\tilde{N}_k$ streams by averaging over the streams and resources.

The transmission rate r_{kn} of the k^{th} link should be less than the maximum achievable spectral efficiency of that link. The achievable spectral efficiency varies with scheduling decisions of other panels because of the interference. Thus r_{kn} depends on the scheduling decisions $\mathbf{a}$, the MIMO rank decisions $\tilde{\mathbf{N}}$ and beamforming matrices $\tilde{\mathbf{V}}$ of the serving link as well as interfering links. Furthermore, we perform joint rate coordination across the strong-interference links, to be able to fully decode the assigned MCS for cancellation at the victim receivers. We refer to [5] for description of the rate allocation algorithm.

One key issue for joint scheduling is the scheduling search space in case of multi-site multi-panel deployment. Assuming 3 panels per site, a brute-force joint scheduling will require a user scheduling search space of $2^{|\mathbf{S}|} \prod_{p=1}^{p=3|\mathbf{S}|} |\mathbf{K}_p|$. The beamformer optimisation to find $\mathbf{V}_k \, \forall k$ within each search will lead to prohibitive complexity. To realise coordinated beamforming with reasonable complexity, we propose a sequential user scheduling algorithm. The heuristic algorithm applies eigen-beamforming for each user [7] and then performs user scheduling in a current site based on the estimation of interference generated from previously scheduled sites. The steps are enumerated below.

1. Identify the set of links to users with active traffic to be served in that scheduling slot (called as active links). The base station sites with active links are arranged in a numerical order.

2. Flexible TDD In any s^{th} scheduling instance, the active links associated to a site $s \in \mathbf{S}$ are jointly scheduled. We go through all possible uplink combinations and downlink combinations in the s^{th} site with a half duplex constraint applied between the co-sited panels.

3. IC-aware sequential user scheduling While scheduling the s^{th} site, user specific transmit and receive beamforming matrices are computed for each link of the hypothesis. The scheduling decisions from previously scheduled sites $1..s-1$ are taken into account to compute the weighted sum-rate metric across all the sites. Thus the scheduler now makes use of interference knowledge. In particular, we decompose the uplink beamforming matrix as $\mathbf{V}_i = \mathbf{W}_i^{\tilde{N}_i \times M_U} \tilde{\mathbf{V}}_i^{M_U \times M_B}$, where $\tilde{\mathbf{V}}_i$ is first obtained from eigen-beamforming (EBF) [7] and then $\mathbf{W}_i$ is obtained using IRC receiver for MIMO equalization. The eigen-beamforming matrix for the i^{th} uplink is computed based on the received channel covariance matrix averaged over the C subcarriers:

$$\mathbf{D}_{ii} = \frac{1}{C} \sum_{c=1}^{C} \mathbf{G}_{ii}^{M_B \times M_U}(c) (\mathbf{G}_{ii}^{M_B \times M_U}(c))^H. \qquad (5)$$

where D_{ii} is the estimated covariance matrix of the channel. The beamforming eigenvectors $\mathbf{V}_i^{M_U \times M_B}$ corresponding to the M_U largest eigenvalues of D_{ii} are used. For the j^{th} downlink the EBF matrix $\mathbf{V}_j^{M_B \times M_U}$ is computed based on transmit covariance $(\mathbf{G}_{jj}^{M_B \times M_U})^H \mathbf{G}_{jj}^{M_B \times M_U}$.

4. MIMO rank and rate adaptation To perform IC (or IRC) efficiently we further search for best rate and MIMO rank allocation in the s^{th} scheduling instance as well as for scheduled links from instances $1..s-1$. For rank coordination, we use low complexity heuristic called SPARK [6] where the rank search to find $\tilde{N}_k \forall k$ is performed for the pairs of interferers based on successive decoding at a SIC receiver. For a given downlink MIMO rank $\tilde{N}_j$ for link j we thus obtain downlink transmit beamforming matrix $\mathbf{B}_j = \mathbf{V}_j^{M_B \times M_U} \mathbf{Q}_j^{M_U \times \tilde{N}_j}$

The achievable SINR for the uplink users already scheduled in sites $1..s-1$ is now estimated with the knowledge of the downlink transmit beamforming matrix $\mathbf{B}_j$ of a link j in the link hypothesis of the s^{th} site. In the case of SIC, the uplink SINR is estimated after canceling the strong interference, and modeling the leakage because of channel estimation errors. Similarly the achievable SINR of an uplink in the hypothesis of the s^{th} site is computed with the knowledge of the downlink beamforming decisions already made for sites $1..s-1$. Thus the scheduler can now purposely schedule a downlink j or an uplink i based on their corresponding beamforming matrices $\mathbf{B}_j$ and $\mathbf{V}_i$ to enhance the cancellation efficiency of the SIC receivers.

The achievable SINR is also estimated for each downlink user in the hypothesis. In the case of IC receivers, the scheduler further determines rate coordination (modulation and coding scheme) as in [5] based on the SINR of the cancellation links.

7. The weighted sum-rate metric is now calculated for each link hypothesis in the s^{th} scheduling instance based on the estimated SINR. The best set of links maximizing the metric in (4) is scheduled for the panels in s^{th} site and then we proceed to the next site.

8. The user scheduling decisions and associated beam scheduling decisions are now stored for the s^{th} site and taken as apriori information for the next instance. The outcome of the centralized scheduling is a set of scheduled users with assigned beams, MIMO ranks and MCS values for all the sites.

Assuming an equal number of links per each panel $|\mathbf{K}_p|$, the user scheduling search space of the above heuristic is $2|\mathbf{S}|\prod_{p=1}^{p=3}|\mathbf{K}_p|$. The worst case rank coordination complexity of the IC-aware scheme is $\frac{3|\mathbf{S}||\mathbf{K}_p|(M_U+1)^2}{2}$ as shown in [6], but with panels representing a cell. In the case of a system without SIC-receivers, the above steps are done assuming IRC receiver. The IC-aware scheme has an additional complexity to estimate the interferers' SINR for rate calculation [5]. The achievable spectral efficiency is calculated in a current transmission slot after applying the beamforming matrix and modeling interference in the current slot. If the transmission rate (i.e MCS with a MIMO rank) exceeds the achievable spectral efficiency in the current slot, a retransmission is done.

A. *Intra-site standalone scheduling*

In intra-site standalone scheduling, each site makes joint scheduling decisions only for the panels co-located within that site. A centralized scheduler is not used in this case. Each site uses the sum-weighted metric as in eq. (4) for the links within the same site. The eigen-beamforming weights are computed as above. The UL/DL switching decisions, UE scheduling, MCS and rank decisions are made independently by each site on a time slot basis without the instantaneous knowledge of interference generated by neighboring sites.

The throughput achieved in a current transmission slot is then calculated using SINR estimation after applying MIMO IRC receiver for interference suppression in a current time slot. The achievable MCS is updated for the next transmission slot based on the interference received from other sites on the current time slot.

B. *Fixed UL/DL TDD split*

The fixed UL/DL TDD split scheme completely avoids cross-link interference between the sites by synchronizing sites to either transmit or receive in a given time slot. In this scheme, the TDD uplink and downlink slot ratio is set to a fixed 1:4 split which corresponds to UL/DL packet size ratio in the simulation scenario. Intra-site coordinated user scheduling and rank coordination is performed as described for the above standalone scheme.

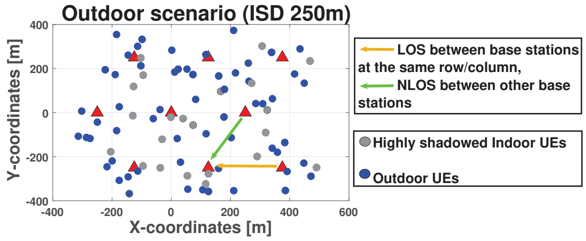

Fig. 1. Deployment scenario.

IV. Performance Evaluation

A. *Simulation setup*

We perform system level studies in a micro-cell outdoor scenario as shown in Fig. 1. The deployment scenario consists of 9 base station sites with inter-site distance of 250 m. Each site is equipped with 3 antenna panels with 120 degree steering range per panel. There are 81 users randomly dropped in the scene. We model 40 users as indoor users with outdoor-to-indoor building penetration low-loss model as in [11]. Based on the path-loss, we can thus divide the users into two groups, group A: these are the highly shadowed users, whose achievable signal to noise ratio (SNR) is below 5dB, and group B: these are the users with achievable SNR above 5dB. There are 16 users in group A and 65 users in group B. Each base station panel is equipped with 16 cross-polarized antenna elements while each user equipment (UE) has 4 cross-polarized antenna elements. Wideband eigen-beamforming is applied to each 4x4 MIMO link as described earlier.

The traffic is modeled independently for the uplink and the downlink as a Poisson distribution per user with fixed file sizes and 1 second mean inter-arrival time. The uplink packet size is 640 Kbytes and downlink packet size is 2560 Kbytes per user in 100 MHz bandwidth. A short description of simulation parameters is presented in Table I.

B. *Results discussion*

1) Interference statistics: We present the cross-link interference statistics in the simulation scenario. Fig.2 presents the achievable signal to interference ratio (SIR)

TABLE I
Table of Simulation Parameter

Parameter	**Default value**
Carrier frequency	3 GHz
Pathloss model	3GPP LOS-NLOS probability based model [11]. With 50% of outdoor-to-indoor users.
Channel model	3GPP Spatial Channel model for MIMO [11]
DL transmit power	33 dBm over 100 MHz
UL transmit power	Uplink SNR target of 14 dB after beamforming. Pathloss based slow power control with maximum transmit power 23 dBm over 100 MHz
Antenna configuration	4x4 MIMO based on cross-polarized beamforming antennas. 16 cross-polarised antennas (M_B) spaced 0.5λ at BS and 4 cross-polarised antennas (M_U) spaced 0.5λ at UE
BS deployment	9 base station sites, each equipped with 3 panels
UE deployment	81 users dropped randomly in the scene. UE speed 3 Kmph
Traffic	Poisson with 1 sec inter-arrival time and UL/DL packet size ratio of 1:4. Fixed packet size of UL=640 Kbytes & DL=2560 Kbytes

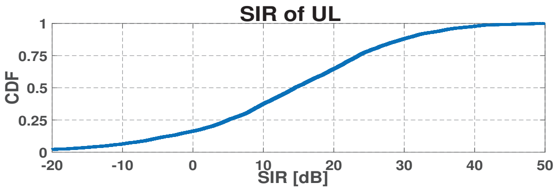

Fig. 2. Uplink signal to downlink interference ratio.

of uplink signal after beamforming when there is a single cross-link eigen-beamformed downlink interferer. The uplink signal has an average received SNR target of 14 dB after eigen-beamforming. The cross downlink interference is generated from the line of sight base stations in the same row and for all UEs associated with the base stations. We observe that a SIR of 14 dB is achieved in median. In around 17% of the uplink-dowlink combinations, the uplink sees a strong downlink interference above the target uplink signal power. The IC-aware scheduler can thus purposely schedule specific interference combinations for strong interference cancellation, while beam coordination between UL and DL can be used to minimize interference with linear receivers.
We now evaluate the following schemes: 1) Intra-site standalone scheduling with flexible TDD, 2) Inter-site coordinated scheduling with flexible TDD and without IC, 3) Inter-site IC-aware coordinated scheduling with flexible TDD and with IC, 4) Fixed 1:4 TDD split.

2) Throughput results: The end to end (E2E) user throughput is calculated as the ratio between transmitted packet size and the E2E packet serving delay which is the delay between packet arrival and packet fully delivered to the receiver. The numerical results are summarized in Table II for group A and group B users.

From Table II it can be seen that standalone flexible TDD per site provides significant throughput gain over fixed TDD on the uplink at the cost of the downlink. The uplink performance gain is particularly significant for the shadowed users, i.e group A users. The outdoor group B users also benefit by 200% on the uplink. The uplink gain comes at the cost of 27% throughput penalty on the downlink which overall achieves a better uplink-downlink throughput fairness. The throughput penalty on the downlink is because of the flexible TDD scheduler allocating a higher ratio of uplink slots as compared to the fixed 1:4 UL/DL ratio.

We further see that centralized inter-site coordination improves uplink median throughput for both group A and B users as compared to standalone flexible TDD. Inter-site coordination without IC improves $5^{th}\%$ uplink throughput by 118% and 32% for group A and group B users respectively as compared to the intra-site standalone scheme. The $5^{th}\%$ downlink throughput is improved by 51% for group A users and by 72% for group B users with inter-site coordination scheme.

Performance gain of IC: Results in Table II show that inter-site coordination with IC improves uplink throughput of the group A users (shadowed users) by 46% in the median as compared to inter-site coordination without IC. The median uplink throughput of group B users increases by 47% with IC. The median downlink performance is also improved by around 36% for group A and B users. The uplink throughput gain is a result of achieving a higher uplink spectral efficiency as tabulated in Table III. Furthermore, the gains of IC are also visible in case of intra-site standalone scheduling, where the strong inter-cell interference can be spontaneously cancelled. However, the gains are limited because of the lack of inter-cell interferers coordination and rank allocation.

TABLE II
E2E UPLINK AND DOWNLINK PER USER THROUGHPUT [MBPS]

Coordination scheme	uplink		downlink	
	$5^{th}\%$	$50^{th}\%$	$5^{th}\%$	$50^{th}\%$
Group A users				
Intra-site standalone with flexible TDD	2.31	10.58	28.41	71.36
Intra-site standalone with flexible TDD, with IC	4.57	12.51	35.95	79.37
Inter-site coordinated with flexible TDD without IC	5.06	11.58	43.00	85.33
Inter-site coordinated with flexible TDD with IC	6.78	16.95	58.58	112.53
Fixed 1:4 UL/DL TDD split	0.16	2.04	36.34	93.94
Group B users				
Intra-site standalone with flexible TDD	16.41	69.19	73.64	353.10
Intra-site standalone with flexible TDD, with IC	20.07	80.01	82.25	406.05
Inter-site coordinated with flexible TDD without IC	21.67	82.58	126.42	393.85
Inter-site coordinated with flexible TDD with IC	32.41	121.90	170.67	538.95
Fixed 1:4 UL/DL TDD split	4.29	23.71	126.42	487.62
Group A+B users				
Intra-site standalone with flexible TDD	6.66	53.34	49.94	249.76
Intra-site standalone with flexible TDD, with IC	9.81	60.95	55.47	302
Inter-site coordinated with flexible TDD without IC	9.25	67.37	62.05	301.18
Inter-site coordinated with flexible TDD with IC	13.71	98.46	85.12	409.60
Fixed 1:4 UL/DL TDD split	1.71	19.39	61.95	353.10

TABLE III
UPLINK AND DOWNLINK SPECTRAL EFFICIENCY [BITS/S/HZ]

Coordination scheme	uplink		downlink	
	$50^{th}\%$	mean	$50^{th}\%$	mean
Group A users				
Intra-site standalone with flexible TDD	0.602	0.653	2.352	2.400
Intra-site standalone with flexible TDD, with IC	0.602	0.672	2.352	2.426
Inter-site coordinated with flexible TDD without IC	0.602	0.623	2.053	2.166
Inter-site coordinated with flexible TDD with IC	0.602	0.694	2.352	2.470
Fixed 1:4 UL/DL TDD split	0.377	0.437	1.478	1.640
Group B users				
Intra-site standalone with flexible TDD	1.553	2.309	6.352	7.920
Intra-site standalone with flexible TDD, with IC	1.754	2.441	6.644	8.419
Inter-site coordinated with flexible TDD without IC	2.160	2.709	6.645	8.664
Inter-site coordinated with flexible TDD with IC	2.731	3.125	7.242	9.259
Fixed 1:4 UL/DL TDD split	2.352	2.493	5.137	6.786

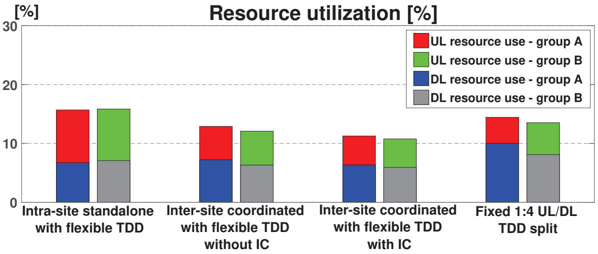

Fig. 3. Resource utilization results.

3) Spectral efficiency: Table III presents spectral efficiency results of the discussed schemes. The main observations from Tables II and III are as follows:

UL of group B: It can be recalled that group B users achieve the uplink SNR target of 14 dB after beamforming. These users may thus be served with more MIMO layers after cross-link interference cancellation. We thus see a significant median uplink spectral efficiency improvement of around 30% with IC using intra-site coordination. A corresponding median throughput gain of 50% is seen with inter-site coordination and IC in Table II.

UL of group A: Uplink mean spectral efficiency improvement of 10% is achieved with IC for the users with received uplink power below the target. The corresponding uplink median throughput gain with the IC scheme is a significant 46% because of spectral efficiency gain as well as the scheduling gain of serving group B users efficiently. The inter-site coordination scheme without IC improves the UL median throughput only marginally as compared to intra-site standalone scheme for group A users.

DL of group B: These users obtain a spectral efficiency benefit from downlink to downlink interference coordination. We also see a spectral efficiency benefit with IC as compared to coordination without IC because of reduced penalty for cross link interference mitigation. The combined benefit of spectral efficiency gain and flexible TDD scheduling gain obtained from serving uplink efficiently is seen in the downlink throughput results.

DL of group A: Inter-site coordination without IC achieves lower spectral efficiency as compared to intra-site standalone scheduling because of MIMO rank coordination. However, inter-site coordinated scheme achieves a higher throughput as compared to the intra-site standalone scheme. This result is because of the scheduling gain, where DL of group A users are prioritized in time scheduling to be preferably paired with the uplink of neighbor cell. In the case of IC, we observe that there is no spectral efficiency penalty for interference mitigation.

Fixed 1:4 UL/DL TDD split Fixed UL/DL TDD split offers higher uplink spectral efficiency for group B while being sub-optimal for uplink group A users. This result is because of a high probability of uplink-to-uplink interference associated to the co-sited panels. Furthermore, fixed UL/DL TDD split is seen to achieve significantly lower downlink spectral efficiency because of downlink-to-downlink interference.

The resource utilization of the discussed schemes is presented in Fig.3 and is seen to be around 30%. Flexible TDD schemes with better spectral efficiency are seen to be more resource-efficient. In case of fixed TDD split some of the pre-assigned slots may be unused when there is no active traffic. At higher loads, it can be expected that fixed TDD split may incur less wastage of resources. On the other hand, performance at higher loads can be expected to be more sensitive to wastages, and thus flexible TDD may provide good scheduling gains. The gain of coordination can also be expected to increase with the load because of a higher probability of cross-link interference.

V. Conclusions

In this paper we studied the performance of flexible TDD system with single user MIMO and eigen-beamforming. We evaluated the performance of centralized scheduling, where the user scheduling decisions are done based on the cross-link interference generated after beamforming. We further evaluated the performance gain achievable using centralized interference cancellation (IC)-aware beam scheduling. Simulation based results were obtained in a multi-site scenario with both outdoor and indoor users. Results show that centralized scheduling without IC improves the uplink and downlink throughput performance by around 25% for both outdoor and indoor users as compared to standalone scheduling per site. Centralized scheduling with IC receivers further improves the uplink and downlink performance by over 47% and 36% respectively as compared to centralized scheduling without IC.

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