On the Potential of Broadcast CSI for Opportunistic Coordinated Multi-Point Transmission

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***Abstract*—Coordinated Multi-Point transmission is a promising technique to improve the performance of the users at the cell-edge. To achieve this, in case of a centralized approach, users need to unicast the quantized channel state information (CSI), typically to the anchor base station (BS), and then each BS forwards this information to a central coordination node for precoding and scheduling. In the case of a decentralized approach, users broadcast the quantized CSI such that the coordinating BSs could simultaneously receive the CSI. The advantage of a decentralized approach is that it does not require a central coordination node, thereby not imposing stringent latency constraints on the backhaul. The CSI transmission over the erroneous feedback channel in the uplink gives rise to precoding loss and scheduling loss. In the decentralized framework, the feedback errors could result in BSs receiving a different version of the CSI. In this work, we propose a decentralized opportunistic scheduling approach, which only requires a minimal sharing of scheduling information between BSs. The results show that the sum rate achieved with the proposed method is comparable to that of the centralized approach even when there is a high bit error probability introduced by the feedback channel. We also show that when the bit error probabilities in the feedback channel are less than 10^{-4}, the decentralized approach achieves the sum rate of the centralized approach.**

***Index Terms*—Broadcast CSI, CoMP, Decentralized Architecture, Scheduling**

I. Introduction

In cellular systems, Coordinated Multi-Point (CoMP) transmission is a promising technique to improve the user experience, especially at the cell-edge as the user throughput is limited primarily due to intercell interference [1]-[3]. To harvest these gains in a frequency division duplex system, the User Equipments (UEs) need to feedback the Channel State Information (CSI) to their anchor Base Stations[1] (BSs). This information is then forwarded to a Central Coordination Node (CCN) where user scheduling and data transmission are designed. This approach is called *Centralized Joint Processing* (CJP) with unicast CSI[2] [3], [4]. Fig. 1 shows the centralized architecture. The main drawback of the centralized architecture is the backhaul latency introduced due to the forwarding of CSI and precoding weights, to and from the CCN.

To avoid the stringent latency constraints in the backhaul, a novel feedback approach is proposed in [4], [5] where the CSI is broadcasted by the UE to the coordinated BSs. We define this approach as *Decentralized Joint Processing* (DJP) with broadcast CSI [4]. Fig. 2 captures the decentralized architecture (without any information exchange between BSs). In [6], it is shown that the CSI distribution over the air (without backhaul) outperforms the CSI distribution over the backhaul in terms of the user rate even with backhaul latency of 4 ms. One of the main benefits of a DJP approach is that it does not need the backhaul for CSI exchange. In a real system, the performance of Joint Processing (JP) is severely affected by errors in the CSI feedback due to quantization and delays in the backhaul. With CJP, the CSI needs to undergo two hops to reach the CCN via its anchor BS, for every UE involved in JP. Similarly, the precoding weights need to traverse the path of CSI in the backhaul, taking one hop from the CCN to the corresponding BS. With DJP, the backhaul is not used, and hence, it reduces the total latency related to the CSI and the precoding weights per scheduled UE by two hops.

The CSI that needs to be fed back always suffers from quantization loss [7]. The errors in the CSI due to the feedback channel gives rise to precoding loss and scheduling loss. Quantization, precoding and scheduling play an important role in harnessing the gains of CoMP. Building on the ideas based on [5], [6] as described above; in this work, we propose an opportunistic scheduling (UEs that result in the best sum rate are served) and sharing minimal scheduling information between BSs for a decentralized architecture where the UEs broadcast the CSI. This is shown in Fig. 2. We show that minimal exchange of scheduling information between the coordinating BSs following DJP with a broadcast CSI approach can realize the gains of CJP with unicast CSI. These gains are valid for a range of bit error probabilities experienced by the collaborating BSs. Unlike [8], where the CSI delay is considered based on the feedback rate, and each BS broadcasts the selected user index and the CSI to other BSs, under equal power allocation. To position our work in comparison to [8], we consider the quantization loss in the CSI feedback and a BS shares only the scheduled user index to the BSs involved in JP under optimal power allocation. The iterative broadcasting of CSI from each BS to other BSs are avoided in our proposal.

The paper is organized as follows: Section II discusses the signal and system model. The proposed decentralized opportunistic CoMP and various network architectures are presented in Section III. In Section IV, the potential gains and open issues of the network architectures are discussed. Finally, the main conclusions of this work are summarized in

[1]We define anchor BS for a specific UE as the BS that provides the best average channel gain.

[2]Here unicasting refers to the transmission of the CSI from a UE to an anchor (single) BS.

Section V.

The following notation is used in this paper: boldface upper-case letters denote matrices, $\mathbf{X}$, boldface lower-case letters denote vectors, $\mathbf{x}$, and italics denote scalars, x. The absolute value of the elements in a vector $\mathbf{x}$ is denoted as $|\mathbf{x}|$. The $\mathbb{C}^{m\times n}$ is a complex valued matrix of size $m\times n$. The $(\cdot)^T$ and $(\cdot)^H$ is the transpose and the conjugate transpose, respectively. $\mathbf{E}_x\{\cdot\}$ is the expectation with respect to x. The $||\mathbf{x}||_2$ is the 2-norm of $\mathbf{x}$. $\mathbf{X}(i,j)$ is the (i,j)th element of matrix $\mathbf{X}$. The ith row of a matrix $\mathbf{X}$ is $\mathbf{X}(i,:)$. The sets are indicated in calligraphic letters and $|\mathcal{X}|$ denotes the cardinality of the set $\mathcal{X}$. The $<\mathbf{x},\mathbf{y}>$ represents the inner product between $\mathbf{x}$ and $\mathbf{y}$. The operator $\otimes$ is the modulo-2 addition.

II. Signal and System Model

Consider K single antenna BSs that need to serve $M=|\mathcal{M}|$ single antenna UEs, where $\mathcal{M}$ is the set of all the active UEs requiring service. In this regard, two different architectures are considered. They are centralized and decentralized architectures. $\mathcal{U}$ is the set of UEs selected for JP such that $\mathcal{U}\subseteq\mathcal{M}$ and $|\mathcal{U}|\leq K$, so that orthogonality can be maintained under a linear precoding assumption [9]. These UEs need to feed back the quantized CSI. For simplicity, the channel norm, g_m, is assumed not to be corrupted by errors and it is available at the BS from the mth UE as

$$g_m=||\mathbf{h}_m||_2, \tag{1}$$

where $\mathbf{h}_m=[h_{m,1},h_{m,2},...,h_{m,K}]$ is the CSI of the links from the K BSs to the mth UE. In other words, g_m is well protected with suitable channel coding, and being a scalar the overhead of feeding back g_m can be considered negligible compared to the CSI. The discrete time signal received at $|\mathcal{U}|$ UEs, $\mathbf{y}\in\mathbb{C}^{|\mathcal{U}|\times 1}$ is

$$\mathbf{y}=\mathbf{H}\overline{\mathbf{W}}\mathbf{x}+\mathbf{n}. \tag{2}$$

In a centralized approach, the channel matrix serving $|\mathcal{U}|$ UEs is $\mathbf{H}\in\mathbb{C}^{|\mathcal{U}|\times K}$, $\overline{\mathbf{W}}\in\mathbb{C}^{K\times|\mathcal{U}|}$ is the precoding matrix and $\mathbf{n}$ is the receiver noise at the UEs, which are spatially and temporally white with variance σ^2. Random vector quantization [10]-[12] is used to quantize the direction of the CSI after normalizing it with the channel norm such that the generated codebook vectors are on a unit sphere and is represented as $\widetilde{\mathbf{h}}_m$ for the normalized CSI from the mth UE. This approach simplifies the codebook, $\mathbf{B}\in\mathbb{C}^{2^N\times K}$, required at the UEs and the BSs, where N is the number of bits required to represented the quantized CSI. Random vector quantization mainly aligns the channel vector to that of the codebook and can be summarized as follows:

$$\begin{aligned}\widetilde{\mathbf{h}}_m &= \mathbf{h}_m/g_m &(3)\\ b' &= \arg\max_b|<\mathbf{B}(b,:),\widetilde{\mathbf{h}}_m>|, &(4)\end{aligned}$$

where $\mathbf{B}(b,:)\in\mathbb{C}^{1\times K}$ such that the elements of $\mathbf{B}(b,:)$ are iid circularly symmetric complex Gaussian distributed as $\mathcal{CN}(0,1)$, b' is the codebook index which can be represented as a vector, $\mathbf{v}$, of length N bits and is fed back by the mth UE. These bits are independently flipped with a probability depending on the bit error probability, P_e, of the feedback channel. An error is declared on the nth bit of $\mathbf{v}$ as

$$\begin{aligned}e &= \begin{cases}1, & \text{if } P_e>r,\\ 0, & \text{otherwise no error}\end{cases} &(5)\\ \hat{\mathbf{v}}(n) &= \mathbf{v}(n)\otimes e, &(6)\end{aligned}$$

where r is a random number chosen from a uniform distribution in the interval $[0,1]$. The BSs perform the reverse processing in extracting the CSI of the mth UE as $\hat{\mathbf{h}}_m$. The errors in feedback channel affect the CSI feedback vector $\mathbf{h}_m$ to have a different value from what was transmitted. This is due to the decoding of the codebook vector based on an incorrect codebook index. If the decoded codebook index is $\hat{b}'$, then the decoded CSI for the mth UE can be written as

$$\hat{\mathbf{h}}_m = g_m\mathbf{B}(\hat{b}',:) \tag{7}$$

When the feedback channel is error free, the quantization error is the difference between $\hat{\mathbf{h}}_m$ and $\mathbf{h}_m$. It should be noted that in this work, we do not aim to optimize quantization.

As the main focus of this study is on the network architecture, a linear zero forcing beamformer (BF) is considered in this work. The BF is calculated as

$$\mathbf{W}=\hat{\mathbf{H}}^H(\hat{\mathbf{H}}\hat{\mathbf{H}}^H)^{-1}, \tag{8}$$

which is the Moore-Penrose pseudoinverse and $\hat{\mathbf{H}}\in\mathbb{C}^{|\mathcal{U}|\times K}$ is the estimated CSI available for beamforming. The optimization problem that jointly optimizes the user scheduling and power allocation is formulated as

$$\begin{aligned}&\text{maximize} \quad \left\{\sum_{m\in\mathcal{U}}\log_2\left(1+\tfrac{p_m}{\sigma^2}\right)\right\} &(9)\\ &\text{subject to}\\ &\quad |\mathbf{W}(k,:)|^2\mathbf{p} \preceq P_{\max}\mathbf{1}_{|\mathcal{U}|\times 1}\\ &\quad \mathbf{p} \succeq \mathbf{0}_{|\mathcal{U}|\times 1}\end{aligned}$$

where $\mathbf{p}=\left[p_1,\ldots,p_{|\mathcal{U}|}\right]^T\in\mathbb{R}^{|\mathcal{U}|\times 1}$ is the power transmitted to the selected $|\mathcal{U}|$ UEs. Note that for each fixed user set, the optimization problem is a convex problem and the optimal solution can be obtained in a water filling fashion [13]. Finally, the power allocated to each UE is absorbed into the BF giving a precoding vector to the mth UE as

$$\overline{\mathbf{W}}(:,m)=\mathbf{W}(:,m)\sqrt{p_m} \tag{10}$$

The Signal to Interference plus Noise Ratio (SINR) for the mth UE is given as

$$\text{SINR}_m=\frac{||\mathbf{h}_m\overline{\mathbf{W}}(:,m)||^2}{\sum\limits_{\substack{j=1,j\neq m\\ j,m\in\mathcal{U}}}^{|\mathcal{U}|}||\mathbf{h}_m\overline{\mathbf{W}}(:,j)||^2+\sigma^2}, \tag{11}$$

The average sum rate per cell in bps/Hz/cell for scheduling $|\mathcal{U}|$ different UEs on the same frequency/time resource is

$$\overline{R}_{tot}=\frac{1}{K}\mathbb{E}_{\mathbf{h}}\left\{\sum_{m\in\mathcal{U}}\log_2\left(1+\text{SINR}_m\right)\right\}. \tag{12}$$

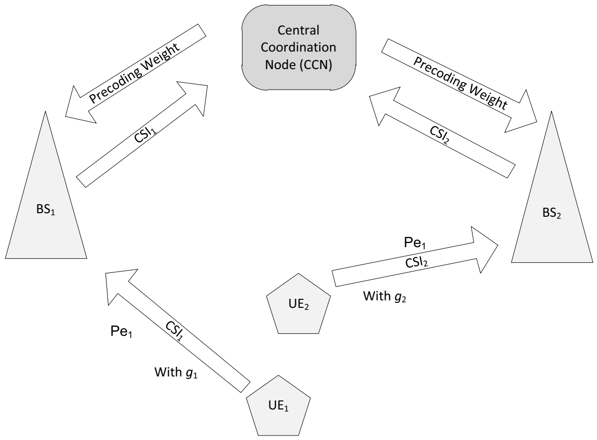

Fig. 1. Joint processing Architecture: Centralized. Here g_1 and g_2 are assumed not to be corrupted by errors.

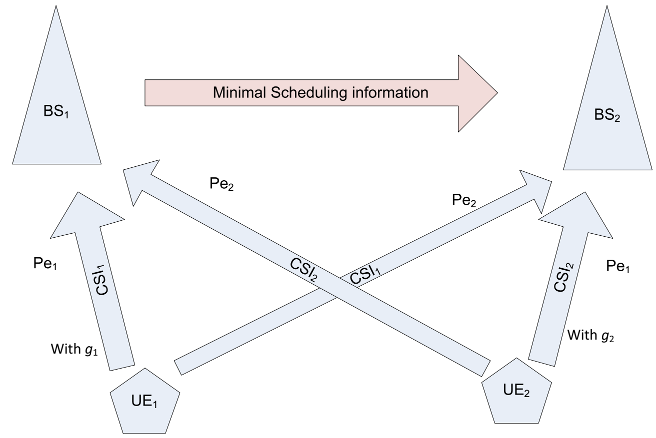

Fig. 2. Joint processing Architecture: Decentralized with minimal exchange of scheduling information. Here g_1 and g_2 are assumed not to be corrupted by errors.

Scheduling: There are two types of scheduling approaches considered in this paper,i.e., random scheduling and opportunistic scheduling. Random scheduling involves arbitrarily choosing $\mathcal{U}$ UEs for JP while the opportunistic scheduling picks $\mathcal{U}$ UEs based on the combination of UEs that produces the best sum rate, i.e.,

$$\mathcal{U}^* = \arg\max_{\mathcal{U}} \sum_{m\in\mathcal{U}} \log_2(1+\widehat{\mathrm{SINR}}_m) \quad (13)$$

$$\widehat{\mathrm{SINR}}_m = \frac{||\hat{\mathbf{h}}_m \overline{\mathbf{W}}(:,m)||^2}{\sum\limits_{\substack{j=1, j\neq m\\ j,m\in\mathcal{U}}}^{|\mathcal{U}|} ||\hat{\mathbf{h}}_m \overline{\mathbf{W}}(:,j)||^2 + \sigma^2}. \quad (14)$$

III. Decentralized Opportunistic CoMP

In this section, different network architectures are discussed. The potential of using a decentralized opportunistic CoMP transmission is investigated.

A. Centralized joint processing with Unicast CSI

Each UE feed back or unicasts the CSI to its anchor BS. The UEs quantize the CSI and feed it back to their anchor BS with a bit error probability of P_{e1}. The BSs decode the CSI based on the codebook mapping and then forward this CSI to the CCN. In this setup, the backhaul is assumed to be error free. The CCN performs precoding and sends back the precoding weights to the BSs. This is illustrated in Fig. 1.

B. Decentralized Opportunistic CoMP with Broadcast CSI

A decentralized approach aims to avoid the stringent latency constraints on the backhaul unlike the centralized approach. In the decentralized architecture, the UEs broadcast the CSI such that the BSs receive a version of the CSI that undergoes a different probability of error. For simplicity, considering two BSs, the anchor BS to the UE undergoes P_{e1} and the other BS experiences P_{e2}. This is as shown in Fig. 2. Each BS could potentially have a different version of the CSI estimated by the UE. This implies that each BS will potentially generate different precoding vectors depending on the UEs being scheduled. In our proposed method, the BS_1 losslessly shares the scheduling information with BS_2, such that joint transmission is made possible. This implies an extra hop but the amount of this information required to be shared is negligible compared to sharing the CSI. This is illustrated in Fig. 2. It should be noted that in the CJP approach, the scheduling information is also needed to be passed on from the CCN to the BSs. The scheduling information is merely an index consisting of the UEs being scheduled. BS_1 may decide this based on the scheduling algorithm, e.g., opportunistic scheduling. Then, BS_2 selects the same UEs as those selected by BS_1. The index values are integers, thus lossless compression can be applied when sharing this information between BSs. It should be noted that the best UEs selected by BS_1 via opportunistic scheduling may not be the best UEs to be served by BS_2.

C. Decentralized Joint Processing with Broadcast CSI exploiting diversity

A potential alternative architecture would be a hybrid architecture where the system is decentralized as shown in Fig. 2 and the CCN is introduced. The broadcasted CSI undergoing different feedback errors are received by different BSs and forwarded to the CCN where the CSI can be coherently combined to exploit diversity. This architecture could be useful when there is high uncertainty in the CSI obtained at the BSs. But, these potential diversity gains could diminish due to the latency involved in the two hops required for the CSI to be available at the CCN. This hybrid architecture combines the CJP and DJP approaches but this causes additional increase in the backhaul traffic as different variations of the same CSI reaches the CCN. Hence, this hybrid architecture is more of an overhead and this architecture does not motivate further study. However, if the backhaul is unconstrained and there is a need for a better quality of the CSI then this hybrid architecture could be considered.

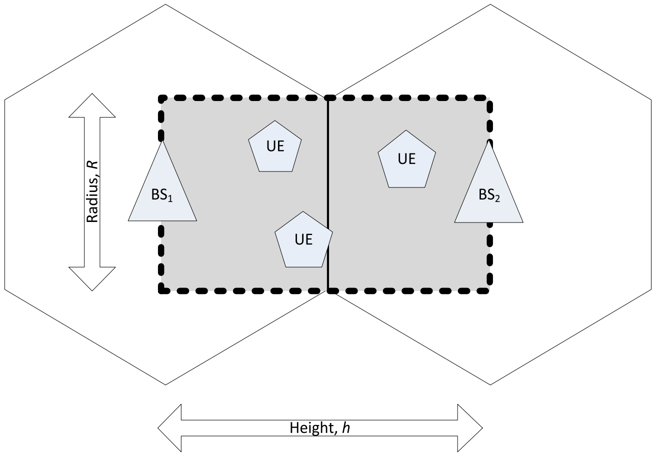

Fig. 3. Serving area where the M UEs are dropped.

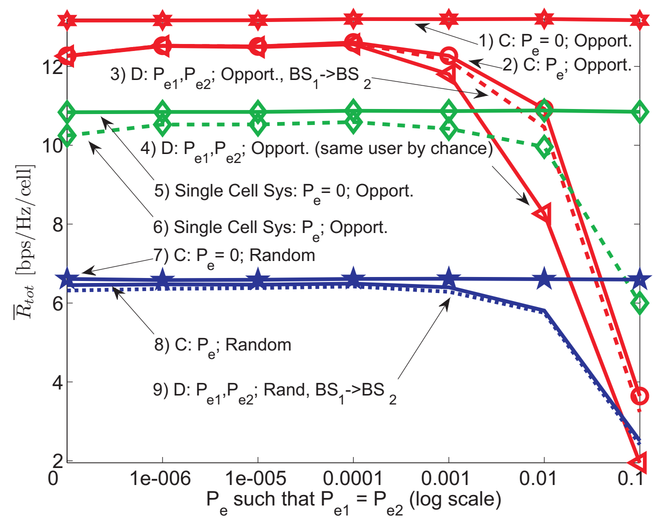

Fig. 4. Average sum rate with $P_{e1} = P_{e2}$ simulating a cell-edge scenario for CSI feedback at both BSs, where $M = 10$, and $N = 16$.

IV. Performance Evaluation

Consider $K = 2$ single antenna BSs located at the center of two hexagonal cells, as shown in Fig. 3. The distance separating the BSs is the height of the hexagon, h. The length of any side of the hexagon is the same as the cell radius, $R = 1$ km. Hence, the rectangular area of concern is h by R, where M UEs are dropped. This is illustrated as the shaded region in Fig. 3. In every instance $\mathcal{U}$ UEs are scheduled, where $|\mathcal{U}| = 2$. The scheduling is based on the CSI fed back from the M UEs, based on which random or opportunistic scheduling is performed. Initially, the codebook is generated and shared between the UEs and the BSs. The number of bits (or size), $N = 16$, required for the feedback is chosen for a given set of K BSs. This was chosen based on the simulations and [5]. In a real system, the CSI feedback data would be encapsulated as a packet and suitably protected. In these simulations, the size of the packet can be considered to be N and the packet is never discarded even if they contain errors. It is assumed that the CSI feedback is not protected for any error correction. Instead, the UEs are still served based on the erroneous CSI feedback. Also, as the errors are introduced at the bit level, the results are presented in terms of the bit error probabilities instead of block errors. This gives an intuitive feel for the potential benefits with the decentralized architecture when there are errors in the CSI feedback.

The maximum power, $P_{\max}$, at which the BS can transmit is determined based on cell-edge signal to noise ratio of 15 dB. Water filling based power allocation as formulated in (9) is implemented using CVX [14]. A Rayleigh fading component, Γ, is simulated as a circularly symmetric complex Gaussian random variable as $\mathcal{CN}(0,1)$. The channel between the kth BS and the mth UE is calculated as

$$\mathbf{h} = \Gamma\sqrt{\gamma_{\text{SF}} \cdot \gamma_{\text{PL}}}, \tag{15}$$

where shadow fading is $\gamma_{\text{SF}} \sim \mathcal{CN}\left(0, 8\,\text{dB}\right)$ and γ_{PL} is based on the 3GPP pathloss model [15] as

$$\gamma_{\text{PL}}(\text{dB}) = 128.1 + 37.6\log_{10}R. \tag{16}$$

In Fig. 4, the average sum rate as determined by (12) is evaluated for various centralized and decentralized architectures with equal error probabilities. In the legend of Fig. 4, 1) C: $P_e = 0$; Opport. represents that it is a centralized architecture without any errors in the feedback and opportunistic scheduling is applied. Similarly, 7) involves random scheduling and 5) is the single cell system which does not perform any precoding but only considers the unicast of the channel strength and is affected by interference due to the transmission to the other UE. It should be noted that quantization is not considered for the curves that appear flat in Fig. 4. This is to provide an upper bound for the corresponding scenarios undergoing bit errors. Scenarios 2) and 8) are the centralized approaches with opportunistic and random scheduling. Their counterparts in the decentralized approach are 3) and 9), where the scheduling information is shared by BS_1 to BS_2. It can be observed that the centralized and the decentralized curves nearly overlap. The decentralized approach performs marginally below the centralized approach due to the broadcasted CSI undergoing different errors. More importantly, the UEs selected at BS_1 with opportunistic approach might not be appropriate to be opportunistically scheduled at BS_2. This loss is more at high bit error probabilities. Hence, diversity could be exploited to overcome this loss, as explained in Section III-C. Finally, scenario 4) shows the typical DJP approach without sharing any scheduling information. In this case, the UEs are scheduled by each BS running the same opportunistic scheduler. For a given bit error rate of 0.01, the DJP (scenario 4) has a loss of 2.94 bps/Hz/cell compared to the CJP approach (scenario 2) while the DJP with sharing the scheduling information (scenario 3) only loses out by 0.56 bps/Hz/cell. Also, when the feedback bit errors are less than 10^{-4}, even sharing the scheduling information can be avoided. The single cell system with perfect CSI is shown in scenario 5) and those with errors are shown in scenario 6). A random scheduler being a dummy approach performs the worst.

Fig. 5 captures the average sum rate for different bit errors experienced at different BSs, for scenarios 3) and 4),

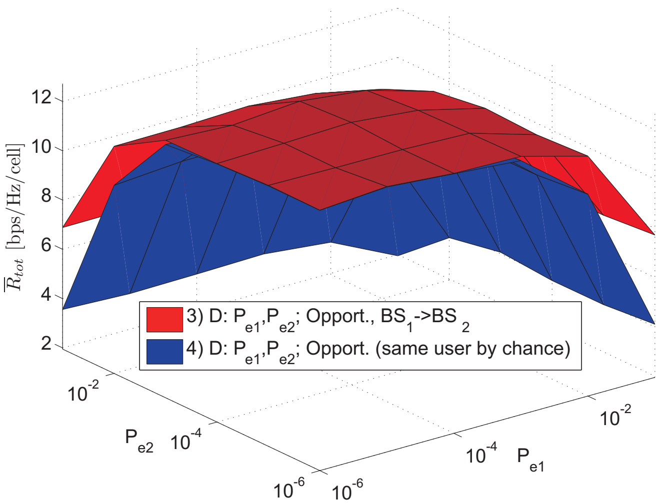

Fig. 5. Decentralized opportunistic scheduling where the BS is sharing the scheduling information, and the decentralized scheduling where the BSs do not share any information. The variation in the average sum rate for different error probabilities at both BSs, where $M = 10$, and $N = 16$.

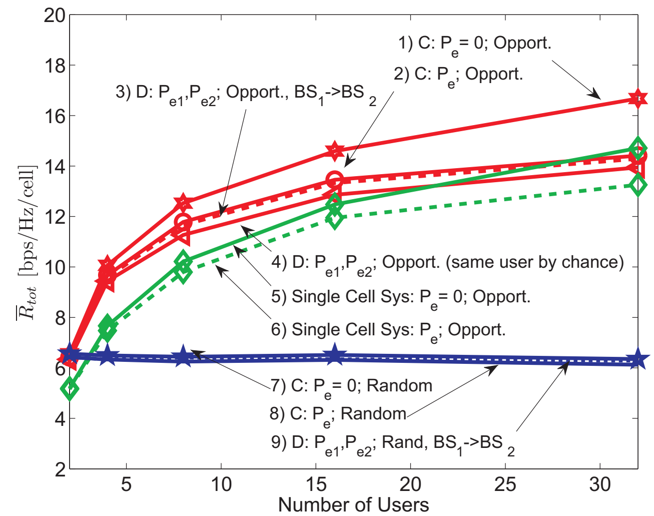

Fig. 6. Average sum rate increases logarithmically with the number of UEs with opportunistic scheduling undergoing a bit error probability, $P_{e1} = P_{e2} = 0.001$.

where BSs share and not share the scheduling information, respectively. It captures the scenarios for values of P_{e1} and P_{e2}. It can be observed that if the feedback channel has low bit error probabilities then one can even avoid sharing the scheduling information between BSs. This implies that the performance of the decentralized approach in terms of sum rate would be comparable to the centralized approach. Fig. 6 shows the effect of the number of UEs on the average sum rate, for a given bit error probability $P_{e1} = P_{e2} = 0.001$. The increase in the average sum rate with the increase in the number of users is due to the multiuser diversity gains, as opportunistic scheduling comes into play. The average sum rate with the decentralized approach without cooperation of BSs is much smaller compared to CJP. While the decentralized approach with sharing the scheduling information, i.e., 3) D : P_{e1}, P_{e2}; Opport., $BS_1 \rightarrow BS_2$, always catches up CJP, i.e., 2) C: P_e; Opport. It should be noted that if errors are considered in the backhaul links, then the gains with CJP would reduce. Hence, the decentralized approach is an attractive alternative. It is interesting to note that the single cell system with no feedback errors performs better than the CJP with feedback errors. This performance loss can be attributed to the precoding loss due to the ZF approach while given a large set of UEs, the single cell system favors those UEs close to the BS.

Table I summarizes the differences with the architectures considered in this work. The CSI is unicast in case of the centralized approach while it is broadcast in the case of the decentralized approach. The CCN is required in the centralized while this logical entity can be omitted with the decentralized approach. A high capacity backhauling link is needed with the centralized architecture while none is required for signaling

Table I
Comparison of centralized and decentralized architectures, with minimal scheduling information exchange

Parameters	Centralized	Decent. w/ Sched.†	Decent.‡
CSI	Unicast	Broadcast	Broadcast
CCN	Req.	Not req.	Not req.
Backhaul (BH)	High	Low	None
BH Latency	2 hops/UE	1 hop/JP UEs	None
Scheduling	Centralized	Semi-decent.	Decent.
Quantization Loss	CSI & BF*	CSI only	CSI only

† Corresponds to scenario 3) D: P_{e1},P_{e2}; Opport., $BS_1 \rightarrow BS_2$
‡ Corresponds to scenario 4) D: P_{e1}, P_{e2}; Opport. (same user by chance)
* The BF weights with quantization loss is not studied here.

the CSI or precoding weights in case of the decentralized architecture. However, the decentralized architecture where minimal scheduling information needs to be shared only requires a low capacity link. The backhaul latency in case of the centralized architecture is two hops, as every UE needs to feedback the CSI to its anchor BS and the same needs to be forwarded to the CCN. These hops are avoided in case of a decentralized architecture. However, sharing scheduling information requires one hop per JP UEs. Scheduling the UEs is decided at the CCN in case of the centralized architecture while in the case of the decentralized architecture sharing the scheduling information can be treated as semi-decentralized due to the extra hop required for sharing. Some performance loss in terms of the average sum rate can be expected with completely decentralized scheduling, as observed in scenario 4) where the BSs do not share the scheduling informatoin. The quantization loss when feeding back the CSI can be expected in the architectures discussed here. However, the centralized architecture has an additional quantization loss due to the BF weights that need to be transported from the CCN to the corresponding BSs.

Sharing the scheduling information between BSs can happen harmoniously within the cooperating BSs, i.e., without the need of a master-slave relationship between the cooperating BSs. As the UEs about to be scheduled can be losslessly exchanged, and each BS is at liberty to choose what the other BS has planned to schedule. Alternatively, the BSs receiving the scheduling information can choose the best UEs that should be scheduled given this new information.

V. Conclusion

Scheduling is an important function that should be exercised to harness the gains in CoMP. In this work, we proposed a decentralized approach with broadcasting channel state information with opportunistic scheduling and sharing minimal scheduling information between cooperating base stations. The proposed approach yields a sum rate comparable to the centralized joint processing. A purely decentralized approach yields poorer performance when the bit errors in the feedback channel occur with high probability. The main advantage of using a decentralized approach is that the stringent latency constraints on the backhaul imposed by the centralized approach can be circumvented. The decentralized approach should be preferred when the bit error probability in the feedback channel are less than 10^{-4}, otherwise the precoding loss would diminish these gains. Without sharing the scheduling information, the decentralized approach still performs well when the bit error probability is low but the scheduling loss kicks in when the BSs do not cooperate and the bit errors are high. However, when both BSs apply the same opportunistic algorithm, the performance is reasonable under low bit error conditions.

The results in this paper were obtained using single-antenna nodes, and a relevant question is how they generalize for multi-antenna BSs and UEs. The minimal scheduling exchange could potentially be avoided if a given BS can predict what other BSs are about to schedule, based on the location information of the UEs. Then there would be no need to exchange the scheduling information between BSs. Also, a joint opportunistic scheduling could further improve the sum rate. These research items are considered as part of our future work.

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