Coordinated Single-Cell vs Multi-Cell Transmission with Limited-Capacity Backhaul

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***Abstract*—Base station coordination is an efficient technique to transcend the limits on spectral efficiency imposed by inter-cell interference. In this paper, we compare the performance of different coordination strategies with different amount of channel state information (CSI) and data sharing among the coordinating base stations. We focus on the effect of limited backhaul capacity in a two-cell network. Contrary to the common belief, we show that coordination strategies with no data and only limited CSI sharing is preferred to those with full data and CSI sharing when the backhaul capacity is relatively low and the edge SNR is high.**

I. INTRODUCTION

Base station coordination has been proposed in emerging cellular wireless standards, such as 3GPP LTE-Advanced, as an efficient way to improve the spectral efficiency for the cell edge users. Different base station coordination strategies have been proposed. They can be classified into two main categories based on the amount of information shared between base stations, namely coordinated multi-cell transmission and coordinated single-cell transmission [1]. In coordinated multi-cell transmission, the data to each user is transmitted from multiple base stations. This requires a substantial amount of signaling to make the channel state information (CSI) and the data of all users available at all the coordinating base stations. In coordinated single-cell transmission, however, the data for each user is transmitted only from one base station (i.e., its *serving* base station), so no inter-base station data exchange is required. Furthermore, each user needs to feed back the CSI only to some of the coordinating base stations, which results in much lower signaling overhead with respect to multi-cell transmission strategies.

One fundamental limitation in deploying coordinated multi-cell transmission is the limited capacity of backhaul links. Recently, the effect of limited backhaul capacity on the performance of multi-cell processing has been studied in [2–5]. The authors in [2] investigate different transmission strategies using joint encoding in the downlink of a cellular system, where base stations are connected to a central unit via finite capacity backhaul links. In this study, it is shown that joint encoding with oblivious base stations, in which only the quantized version of the transmit signal is sent from the central unit to the base station, achieves a good trade-off between performance and complexity. The authors in [3] study the central cell encoding with oblivious cells scheme in [2] with a more realistic system model, where they propose an optimization framework for signal quantization. A more information theoretic approach, which consider both the impact of limited-capacity backhaul and the imperfect CSI, with transmission strategies based on superposition coding is studied in [4]. Recently, a framework for the optimization of the amount of user data sharing between the base stations was studied in [5]. In this study, the authors have proposed to divide each user message into a common part transmitted jointly by all the base stations and a private part transmitted only from the serving base station of the user. All the aforementioned work, however, have considered single-antenna users.

In this paper, we consider different single-/multi-cell transmission strategies with limited backhaul capacity and multiple-antenna users. We compare the performance of these strategies under the practical linear precoding framework to transmit independent data streams to each user. To share the available backhaul capacity and power between the data streams of both users, we formulate an optimization problem to maximize the sum rate subject to backhaul capacity constraints and per-base station power constraints. It is shown that, opposite to the prevailing views, the coordination strategies with no data and only limited CSI sharing outperforms those with full data and CSI sharing when the backhaul capacity is relatively low and the edge SNR is high. A comparison for the CSI requirement of different schemes is also presented.

Notations: Scalars are denoted by lower-case letters. Vectors and matrices are denoted by bold-face lower- and upper-case letters, respectively. $(\cdot)^{\mathsf{H}}$ and $(\cdot)^{\dagger}$ denote complex conjugate transpose and pseudo inverse of a matrix, respectively. The distribution of a random vector with zero mean complex Gaussian elements and covariance matrix Φ is denoted by $\mathcal{CN}(\mathbf{0}, \Phi)$.

II. SYSTEM MODEL

We consider a two-cell setup with two base stations and two users, as shown in Fig. 1. We assume each base station is

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equipped with 4 antennas while each user has only 2 antennas. A backhaul capacity of C_i (in bps/Hz) is assumed between the backbone network and the base station i, for $i = 1, 2$. To focus on data sharing, we assume the necessary CSI for each coordination strategy is available at both base stations. Subsequently, all the precoding design and power allocation are done independently (and redundantly in case of multi-cell transmission) at each base station without the need for any CSI exchange. Therefore, the backhaul capacity will solely be used to distribute users' data from the backbone to the base stations. Furthermore, we only consider linear precoding to transmit independent data streams (so no joint encoding like superposition coding or dirty paper coding is done here). A narrowband frequency-flat fading and downlink transmission is considered. Let $\bar{i} = \mod(i, 2) + 1$, for $i = 1, 2$ denote the other base station/user depending on the context. Note that in this setup, each base station/user may transmit/receive multiple data streams simultaneously, i.e., spatial multiplexing (SM). Define μ_{ji} as the number of data streams for user j from base station i such that

$$\begin{aligned} &0 \le \mu_{ji} \le 2 \\ &0 \le \mu_{ji} + \mu_{j\bar{i}} \le 2. \end{aligned} \tag{1}$$

for $i, j \in \{1, 2\}$. The received signal at user i can be written as a combination of the contributions from its serving base station i and the other base station $\bar{i}$ as

$$\boldsymbol{y}_i = \boldsymbol{H}_{ii} \sum_{j=1}^{2} \boldsymbol{T}_{ji} \boldsymbol{u}_{ji} + \boldsymbol{H}_{i\bar{i}} \sum_{j=1}^{2} \boldsymbol{T}_{ji} \boldsymbol{u}_{ji} + \boldsymbol{n}_i, \tag{2}$$

where $\boldsymbol{H}_{ji} \in \mathbb{C}^{2\times 4}$ denotes the channel matrix between user j and base station i, $\boldsymbol{T}_{ji} \in \mathbb{U}(4 \times \mu_{ji})$ is the precoding matrix for user j at base station i, $\boldsymbol{u}_{ji}$ denotes the $\mu_{ji} \times 1$ data symbol vector transmitted by base station i toward user j, and $\boldsymbol{n}_i$ denotes the 2×1 additive white Gaussian noise at user i with entries that are *i.i.d* $\mathcal{CN}(0, 1)$. We let $\boldsymbol{H}_{ii} \sim \mathcal{CN}(0, \boldsymbol{I}_{2\times 4})$ and $\boldsymbol{H}_{i\bar{i}} \sim \mathcal{CN}(0, \epsilon \boldsymbol{I}_{2\times 4})$, where ϵ captures the interference power from the other cell. This model is the two-cell downlink version of the Wyner's model [6], which though simple, provides useful insight [7].

To cancel the inter-user interference at the transmit side (when necessary), we adopt block diagonalization (BD) precoding [8]. Other non-linear multi-user MIMO precoding algorithms such as dirty paper coding [9] and Tomlinson-Harashima precoding [10] can also be chosen, but we prefer to choose BD for its low implementation complexity. On the receive side, each user can perform detection in a conventional single-user MIMO manner, such as zero-forcing (ZF), minimum mean-squared error, successive interference cancelation, etc. Note that SM considered here is only advantageous in high SNR regime where ZF is near optimal. Therefore, without loss of generality and for simplicity ZF decoding is adopted. With these choices of precoder and decoder, the channel of each user is decomposed into parallel interference-free scalar sub-channels. The power allocation over all sub-channels is then optimized to maximize the sum-rate of two users under a per base station power constraint. This method of separating the precoder/decoder design and power allocation is in general suboptimal [11]. The optimal joint design of precoder/decoder and power allocation under limited backhaul capacity is, however, beyond the scope of this paper and is left as our future work.

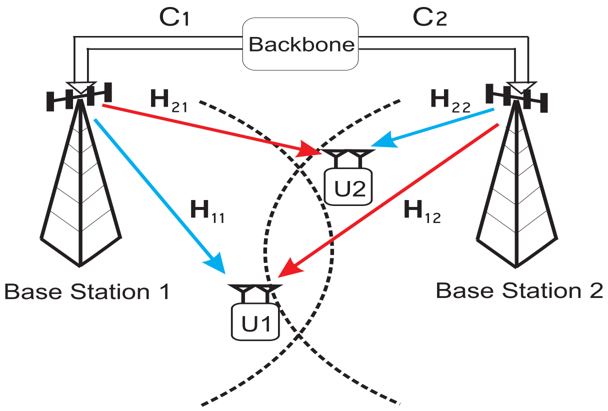

Fig. 1. A two-cell network with limited-capacity backhaul links.

III. SINGLE-CELL TRANSMISSION STRATEGIES

In the following, we present two classes of single-cell transmission (SCT) strategies with different levels of coordination and CSI requirements.

A. Conventional SCT

This is the conventional case where each cell operates as an isolated cell (i.e., no coordination) and each base station serves only its own user. Hence, there is no intra-cell interuser interference. The interference from the other base station at each user is treated as noise. Furthermore, base station i only needs to know the channel between itself and its home user, i.e., $\boldsymbol{H}_{ii}$. With this CSI knowledge, the optimal single-user MIMO precoder is obtained using right singular vectors of the channel matrix [12]. In this case, $\boldsymbol{T}_{i\bar{i}} = \boldsymbol{0}$, $\boldsymbol{u}_{i\bar{i}} = \boldsymbol{0}$, and $\mu_{ii} = 2$. The received signal at user i after applying the decoder can be written as

$$\boldsymbol{r}_i = \boldsymbol{W}_i \boldsymbol{H}_{ii} \boldsymbol{T}_{ii} \boldsymbol{u}_{ii} + \boldsymbol{W}_i \boldsymbol{z}_i, \tag{3}$$

where $\boldsymbol{z}_i$ denotes the inter-cell interference plus noise given by

$$\boldsymbol{z}_i = \boldsymbol{H}_{i\bar{i}} \boldsymbol{T}_{\bar{i}\bar{i}} \boldsymbol{u}_{\bar{i}\bar{i}} + \boldsymbol{n}_i, \tag{4}$$

and $\boldsymbol{W}_i = (\boldsymbol{H}_{ii} \boldsymbol{T}_{ii})^{\dagger}$ is the ZF decoder. The inter-cell interference plus noise covariance matrix, $\boldsymbol{K}_{\boldsymbol{z}_i}$, for user i is given by

$$\boldsymbol{K}_{\boldsymbol{z}_i} = \boldsymbol{H}_{i\bar{i}} \boldsymbol{Q}_{\bar{i}} \boldsymbol{H}_{i\bar{i}}^{\mathsf{H}} + \boldsymbol{I}_2, \tag{5}$$

where $\boldsymbol{Q}_{\bar{i}}$ is the transmit covariance matrix of the $\bar{i}$-th base station. Since each cell operates independently in this strategy, the maximization of the sum rate of both users is equivalent to the maximization of each user's rate in each cell. Furthermore, the other-cell interference information is not available in advance, therefore the power allocation optimization to maximize the rate of user i is performed only based on the knowledge of the receiver noise. The power allocation optimization problem at base station i can be formulated as

$$\begin{aligned}(p_{i1}^*, p_{i2}^*) = &\arg\max_{p_{i1},p_{i2}} \sum_{l=1}^{2}\log(1+p_{il}),\\ \text{s.t.}: &\sum_{l=1}^{2} p_{il} < P,\\ &\sum_{l=1}^{2} \log(1+p_{il}) < C_i,\end{aligned} \tag{6}$$

where p_{il} is the allocated power to the l-th data stream of user i. The achieved rate of user i, R_i, can then be written as

$$R_i = \sum_{l=1}^{2}\log\left(1+\frac{p_{il}^*}{\boldsymbol{w}_{il}\boldsymbol{K}_{\boldsymbol{z}_i}\boldsymbol{w}_{il}^{\mathsf{H}}}\right), \tag{7}$$

where $\boldsymbol{w}_{il}$ is the l-th row of $\boldsymbol{W}_i$.

B. Coordinated SCT

In this coordination strategy, similar to the conventional SCT the data for each user comes from its serving base station. The coordination is, however, done in the form of inter-cell interference cancelation (IC) [1]. To perform IC, base station i needs to know the channels between itself and both users, i.e., $\boldsymbol{H}_{ii}$ and $\boldsymbol{H}_{\bar{i}i}$. The block diagonalization (BD) [8] is then used to design the precoder $\boldsymbol{T}_{ii}$ such that $\boldsymbol{H}_{\bar{i}i}\boldsymbol{T}_{ii} = \boldsymbol{0}$. This cancels the interference base station i causes to user $\bar{i}$ when transmitting to user i. Similar to the conventional case we have $\boldsymbol{T}_{i\bar{i}} = \boldsymbol{0}$, $\boldsymbol{u}_{i\bar{i}} = \boldsymbol{0}$, $\mu_{ii} = 2$. The received signal at user i after decoding can be written as

$$\boldsymbol{r}_i = \boldsymbol{W}_i\boldsymbol{H}_{ii}\boldsymbol{T}_{ii}\boldsymbol{u}_{ii} + \boldsymbol{W}_i\boldsymbol{n}_i, \tag{8}$$

where $\boldsymbol{W}_i = (\boldsymbol{H}_{ii}\boldsymbol{T}_{ii})^\dagger$ is the zero-forcing (ZF) decoder. Similar to the conventional case, the power allocation optimization to maximize the sum rate of both users can be decoupled into optimization of each user's rate as given in (6). The achievable rate of user i is, however, given by

$$R_i = \sum_{l=1}^{2}\log\left(1+\frac{p_{il}^*}{\boldsymbol{w}_{il}\boldsymbol{w}_{il}^{\mathsf{H}}}\right). \tag{9}$$

IV. MULTI-CELL TRANSMISSION STRATEGIES

In multi-cell transmission, the data for each user is transmitted from both base stations. We consider two different types of coordinated multi-cell transmission, namely distributed SM and network MIMO, which are explained next.

A. Distributed SM

In distributed SM, each user receives a different data stream from each base station. The data of each user is divided into two streams and each stream is forwarded to one of the base stations. Therefore, the backhauling overhead is similar to SCT techniques. It has been shown in [13] that under low spatial channel correlation, high edge SNR, and no limitation on the backhaul capacity, this mode of operation outperforms the other distributed transmission schemes such as fractional frequency reuse [13], joint transmission single-user SM [13]. In this case, we have $\mu_{i\bar{i}} = 1$ and $\mu_{ii} = 1$. Furthermore, we index the data streams of user i from base stations i and $\bar{i}$ as i and $\bar{i}$, respectively. To cancel inter-user interference at base station i, it requires to know the channel between itself and both users, i.e., $\boldsymbol{H}_{ii}$ and $\boldsymbol{H}_{\bar{i}i}$. The precoders $\boldsymbol{T}_{ii}$ and $\boldsymbol{T}_{\bar{i}i}$ are then designed such that $\boldsymbol{H}_{ii}\boldsymbol{T}_{\bar{i}i} = \boldsymbol{H}_{\bar{i}i}\boldsymbol{T}_{ii} = \boldsymbol{0}$. The received signal after decoding at user i can be written as

$$\boldsymbol{r}_i = \boldsymbol{W}_i[\boldsymbol{H}_{ii}\boldsymbol{T}_{ii}\ \boldsymbol{H}_{i\bar{i}}\boldsymbol{T}_{i\bar{i}}]\begin{bmatrix}\boldsymbol{u}_{ii}\\ \boldsymbol{u}_{i\bar{i}}\end{bmatrix} + \boldsymbol{W}_i\boldsymbol{n}_i, \tag{10}$$

where $\boldsymbol{W}_i = [\boldsymbol{H}_{ii}\boldsymbol{T}_{ii}\ \boldsymbol{H}_{i\bar{i}}\boldsymbol{T}_{i\bar{i}}]^\dagger$ is the ZF decoder. Note that the ZF decoder at each user depends on the precoded channels from both base stations. To perform power allocation centrally, the knowledge of the noise power on both data streams of each user after applying the decoder is required at both base stations. Here, it is assumed that these powers are measured at each user and sent back to both base stations. The power allocation optimization is then done redundantly at both base stations to maximize the sum rate of both users. The power allocation optimization problem can be formulated as

$$\begin{aligned}\boldsymbol{p}^* = &\arg\max_{\boldsymbol{p}} \sum_{i=1}^{2}\sum_{l=1}^{2}\log\left(1+\frac{p_{il}}{\boldsymbol{w}_{il}\boldsymbol{w}_{il}^{\mathsf{H}}}\right),\\ \text{subject to}: &\sum_{j=1}^{2}\log\left(1+\frac{p_{ji}}{\boldsymbol{w}_{ji}\boldsymbol{w}_{ji}^{\mathsf{H}}}\right) < C_i,\ \text{for } i=1,2,\\ &\sum_{j=1}^{2} p_{ji} < P,\ \text{for } i=1,2,\end{aligned} \tag{11}$$

where $\boldsymbol{p} = [p_{11}\ p_{12}\ p_{21}\ p_{22}]$. The achievable rate of user i is obtained as in (9).

B. Network MIMO

In network MIMO, each user receives the same data from both base stations coherently. The CSI and data of both users needs to be available at both base stations completely. Furthermore, we have $\mu_{i\bar{i}} = 2$, $\mu_{ii} = 2$, and $\boldsymbol{u}_{ii} = \boldsymbol{u}_{i\bar{i}}$. Let the aggregate channel matrix and precoder for user i be defined as

$$\boldsymbol{H}_i = [\boldsymbol{H}_{ii}\ \boldsymbol{H}_{i\bar{i}}], \tag{12}$$

and

$$\boldsymbol{T}_i = [\boldsymbol{T}_{ii}^{\mathsf{H}}\ \boldsymbol{T}_{i\bar{i}}^{\mathsf{H}}]^{\mathsf{H}}, \tag{13}$$

respectively. The received signal after decoding at user i can be written as

$$\boldsymbol{r}_i = \boldsymbol{W}_i\boldsymbol{H}_i\boldsymbol{T}_i\boldsymbol{u}_{ii} + \boldsymbol{W}_i\boldsymbol{n}_i, \tag{14}$$

where we have used the fact that $\boldsymbol{H}_i\boldsymbol{T}_{\bar{i}} = \boldsymbol{0}$ due to BD. Using zero-forcing (ZF) decoder, $\boldsymbol{W}_i = (\boldsymbol{H}_i\boldsymbol{T}_i)^\dagger$, the power

TABLE I
CSI REQUIREMENT COMPARISONS

	Conventional SCT	Coordinated SCT	Distributed Spatial Multiplexing	Network MIMO
Base Station 1	$\boldsymbol{H}_{11}$	$\boldsymbol{H}_{11},\ \boldsymbol{H}_{21}$	$\boldsymbol{H}_{11},\ \boldsymbol{H}_{21}$	$\boldsymbol{H}_{11},\ \boldsymbol{H}_{21},\ \boldsymbol{H}_{12},\ \boldsymbol{H}_{22}$
Base Station 2	$\boldsymbol{H}_{22}$	$\boldsymbol{H}_{22},\ \boldsymbol{H}_{12}$	$\boldsymbol{H}_{22},\ \boldsymbol{H}_{12}$	$\boldsymbol{H}_{11},\ \boldsymbol{H}_{21},\ \boldsymbol{H}_{12},\ \boldsymbol{H}_{22}$
User 1	$\boldsymbol{H}_{11}\boldsymbol{T}_{11}$	$\boldsymbol{H}_{11}\boldsymbol{T}_{11}$	$\boldsymbol{H}_{11}\boldsymbol{T}_{11},\ \boldsymbol{H}_{12}\boldsymbol{T}_{12}$	$\boldsymbol{H}_{11}\boldsymbol{T}_{11},\ \boldsymbol{H}_{12}\boldsymbol{T}_{12}$
User 2	$\boldsymbol{H}_{22}\boldsymbol{T}_{22}$	$\boldsymbol{H}_{22}\boldsymbol{T}_{22}$	$\boldsymbol{H}_{22}\boldsymbol{T}_{22},\ \boldsymbol{H}_{21}\boldsymbol{T}_{21}$	$\boldsymbol{H}_{22}\boldsymbol{T}_{22},\ \boldsymbol{H}_{21}\boldsymbol{T}_{21}$

allocation optimization problem to be solved is given by

$$\begin{aligned} \boldsymbol{p}^* &= \arg\max_{\boldsymbol{p}} \sum_{i=1}^{2}\sum_{l=1}^{2} \log(1+\frac{p_{il}}{\boldsymbol{w}_{il}\boldsymbol{w}_{il}^{\mathsf{H}}}), \\ \text{s.t.}: &\sum_{i=1}^{2}\sum_{l=1}^{2} \log\left(1+\frac{p_{il}}{\boldsymbol{w}_{il}\boldsymbol{w}_{il}^{\mathsf{H}}}\right) < \min(C_1, C_2), \\ &\sum_{j=1}^{2} ||\boldsymbol{t}_{ji}||^2 p_{ji} < P, \ \text{for } i = 1, 2, \end{aligned} \tag{15}$$

where $\boldsymbol{p} = [p_{11}\ p_{12}\ p_{21}\ p_{22}]$. Note that in this case p_{il} is the power allocated to the l-th data stream of the i-th user. This data stream, however, is transmitted from both base station. The achievable rate of user i is obtained as in (9).

V. PERFORMANCE EVALUATION

In this section, we present some numerical result to compare the performance of the different strategies. We assume similar backhaul capacity between each of the base stations and the backbone, i.e., $C_1 = C_2 = C$. The power allocation optimization problems in (6), (11), and (15) contain a non-convex constraint related to backhaul capacity. We use the optimization routine `fmincon` in Matlab software to solve these problems.

A. Numerical Results

In Fig. 2, the mean sum rate versus backhaul capacity is compared for different strategies where $\epsilon = 1$. This can be thought of as the case where both users are at the edge of the cell and experience the same pathlosses from both base stations. Since noise is distributed as $\mathcal{CN}(0, 1)$, the transmit power P represents the cell-edge SNR. It is observed that coordinated SCT and distributed SM have approximately the same performance. Furthermore, these two strategies outperform the conventional SCT and network MIMO when the backhaul capacity is less than 12 bps/Hz. Network MIMO strategy, however, provides better performance when C is large enough.

In Fig. 3, the mean sum rate versus the power P is compared for different strategies when $C = 7$ bps/Hz and $\epsilon = 1$. It can be observed that for small to moderate values of P network MIMO outperforms the other strategies. The mean sum rate increase of network MIMO is, however, stopped when the achieved mean sum rate reaches C. In coordinated SCT and distributed SM the sum rate will continue to increase since in these two strategies the maximum sum rate limit is $2C$. It is also observed that coordinated SCT and distributed SM have almost the same performance over the whole range of P.

In Fig. 4, the mean sum rate versus the interference power ϵ is compared for different strategies for $C = 7$ bps/Hz and $P = 10$ dB. Here, the performance of network MIMO does not depend on ϵ, since network MIMO is designed to cancel the interference completely. The performance of the conventional SCT is shown to outperform the other strategies for small values of ϵ ($\epsilon < 0.2$) and decreases as ϵ increases. The performance of coordinated SCT and distributed SM, however, is approximately the same only at the cell edge. Distributed SM is inferior to coordinated SCT at other positions of the cell.

B. CSI Requirement Comparisons

In Table I, we address the CSI requirement at the base station/user to compute the precoder/decoder. It is observed in Table I that the conventional single-cell transmission scheme requires the least CSI at the base stations among the four schemes. Network MIMO, however, is the most demanding in terms of the CSI at the base station. This could place a huge amount of burden on the feedback channel and easily occupies the available uplink resources in realistic systems with more users and coordinating base stations. In distributed SM and coordinated SCT, each base station i needs only the channel between it self and both users, i.e., $\boldsymbol{H}_{ii}$ and $\boldsymbol{H}_{\bar{i}i}$. The CSI at the base station can be obtained for example by using the sounding reference signal transmitted by both users [13]. On the receive side, it can be seen that each user needs to know the precoded channel matrix from its serving base stations to perform decoding in all the considered transmission strategies. Note that in distributed SM both $\boldsymbol{H}_{ii}\boldsymbol{T}_{ii}$ and $\boldsymbol{H}_{i\bar{i}}\boldsymbol{T}_{i\bar{i}}$ are 4×1 vectors, while in coordinated SCT and conventional SCT and $\boldsymbol{H}_{ii}\boldsymbol{T}_{ii}$ is a 4×2 matrix. In network MIMO, both $\boldsymbol{H}_{ii}\boldsymbol{T}_{ii}$ and $\boldsymbol{H}_{i\bar{i}}\boldsymbol{T}_{i\bar{i}}$ are 4×2 matrices. Therefore, the number of channel coefficients that need to be estimated at the receiver in network MIMO is as twice as the other three strategies. To estimate the precoded channel matrix in distributed SM and network MIMO, however, we need two sets of orthogonal dedicated reference signal for both base stations which is challenging to design [13].

VI. CONCLUSION

In this paper, we investigated the performance of different single-/multi-cell transmission strategies under limited-

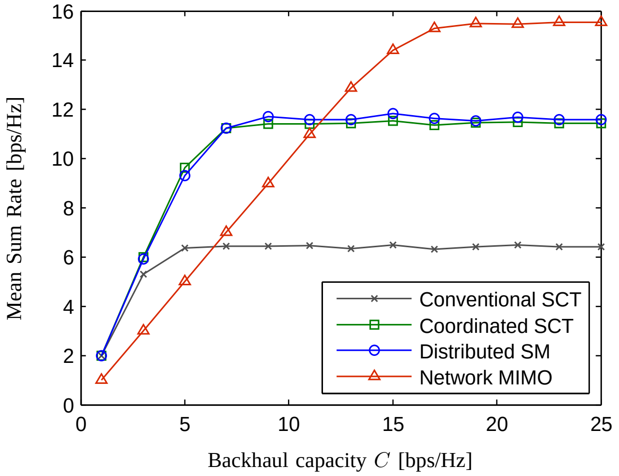

Fig. 2. Comparison of mean sum rate versus backhaul capacity for different strategies with $P = 10$ dB and $\epsilon = 1$.

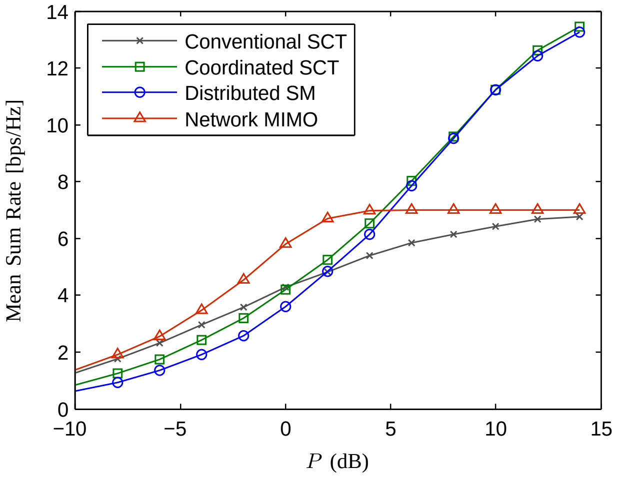

Fig. 3. Comparison of mean sum rate versus transmit power for different strategies with backhaul capacity $C = 7$ bps/Hz and $\epsilon = 1$.

backhaul capacity. Two single-cell and two multi-cell transmission strategies have been studied. The optimization problem for power and backhaul capacity allocation to data streams of each user was formulated for each transmission strategy. It was shown through simulation that the low complexity coordinated SCT with interference cancelation have approximately the same performance at the cell edge as distributed SM over backhaul capacity. The distributed SM has, however, higher receiver complexity. Furthermore, it was shown that coordinated SCT outperforms the high complexity network at low to moderate backhaul capacity and high cell edge SNR. As a future work, one can study the effect of limited feedback and limited backhaul capacity at the same time. Furthermore, an adaptive single-/multi-cell transmission strategy is to be investigated.

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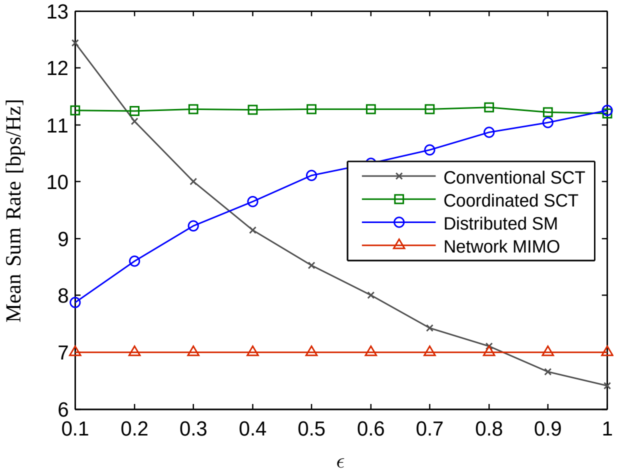

Fig. 4. Comparison of mean sum rate versus ϵ for different strategies with $P = 10$ dB and backhaul capacity $C = 7$ bps/Hz.

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