Dynamic Cooperation Link Selection for Network MIMO Systems with Limited Backhaul Capacity

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***Abstract*—Base-station (BS) cooperation in wireless cellular networks offers a promising approach for interference mitigation. However, the implementation of practical network multi-input multi-output (MIMO) system also faces the challenge of high capacity cost for sharing the user data over the backhaul connections. This paper considers a downlink multi-cell orthogonal frequency-division multiple-access (OFDMA) network where the capacities of the backhaul links between the BSs are limited, and extends the single-antenna BS multi-cell system model considered in our previous work to the multiple-antenna BS case. The BSs use zero-forcing precoding to spatially multiplex multiple users within each cell and to pre-subtract the interference from cooperating BSs that share user data with them. An iterative algorithm that maximizes the downlink network utility is proposed. The algorithm iteratively selects the cooperation links, schedules the users, and optimizes the precoding coefficients and the power spectra for each frequency tone. Numerical results suggest that the use of dynamic cooperation link selection can provide a better trade-off between the downlink sum-rate gain and the backhaul capacity than the earlier fixed link-selection algorithm.**

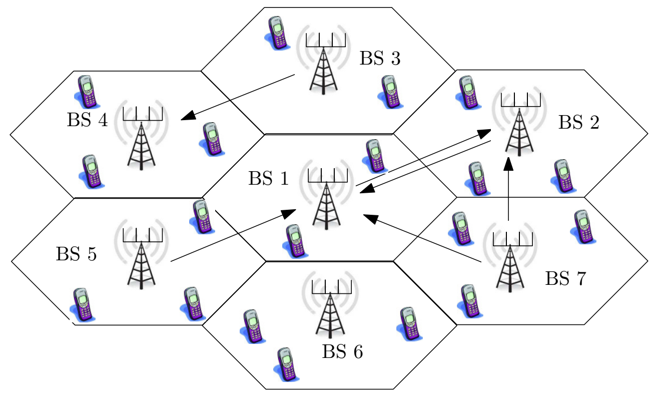

Figure 1. Wireless multi-antenna, multi-cell scenario with $Q = 4$ antennas per BS and each BS cooperating with only a subset of the neighboring BSs in the nth frequency tone.

I. Introduction

Network multiple-input multiple-output (MIMO), also known as coordinated multipoint (CoMP), promises to significantly improve the performance of wireless cellular networks by coordinating multiple base-stations (BSs), thereby effectively mitigating intercell interference [1]-[4]. The cooperation of BSs in a practical network MIMO system, however, can also involve high capacity cost in the backhaul, as the users' data streams need to be shared among all the cooperating BSs in order for them to jointly encode and transmit data to the users. This paper proposes a numerical optimization algorithm to quantify the benefit of network MIMO under limited backhaul-capacity constraints.

This paper builds upon and generalizes the study of network MIMO with backhaul-capacity constraints in [5]. In [5], the downlink of a wireless multicell orthogonal frequency-division multi-access (OFDMA) network is considered with single-antenna BSs. Neighboring BSs are coordinated so that they can jointly encode and transmit data signals to the users using zero-forcing (ZF) precoding, but only on a selected subset of frequency tones in order to reduce backhaul traffic. The heuristic optimization algorithm proposed in [5] maximizes the network-wide utility while satisfying the limited backhaul-capacity constraints and ensuring proportional fairness among the users. The resulting algorithm suggests a linear trade-off between the downlink sum rate and the backhaul capacity.

This paper extends the single-antenna BS system model of [5] to a multicell downlink scenario where each BS is equipped with multiple antennas and serves multiple users via spatial multiplexing. The multi-antenna BS uses ZF beamforming to eliminate not only intracell interference, but also intercell interference from cooperating neighboring BSs. In the limited backhaul-capacity case, in addition to choosing the tones over which cooperation links are active, each BS must also select which of the multiple user data streams should be shared with the neighboring BSs for interference cancellation; (see Fig. 1 for an example). The network-utility maximization algorithm proposed in this paper jointly selects the cooperation links, schedules users, and optimizes precoding coefficients and power spectra using an iterative approach to find a (local) optimal solution of the overall optimization problem. As compared to the approach of selecting a fixed set of cooperation links as in [5], the adaptive and dynamic link selection proposed in this paper is observed to provide higher gains in downlink sum rate under fixed backhaul-capacity constraints.

A. Related Work

Existing approaches in the literature for constraining backhaul-cooperation capacity in network MIMO systems include clustering and shared-private rate-splitting. The clustering approach groups cooperative BSs into clusters to cancel intra-cluster interference while inter-cluster interference persists. It has been proposed both for single-antenna systems [6]-[9], and multi-antenna systems [10], [11]. The cluster size regulates the required backhaul capacity and can be chosen statically [7], [8] or dynamically [6] in time. The shared-private rate-splitting approach has been studied from an information theoretical perspective in [12] and from an optimization perspective in [13] for a two-cell network with rate-limited cooperation between transmitters.

This paper differs from the above works in that we adopt a simple approach of selectively choosing a subset of cooperation links between the BSs across both the spatial and frequency dimensions in order to satisfy the limited backhaul-capacity constraint. This is done dynamically as different users are scheduled. On each cooperation link, either no message or the entire message is shared. Further, this paper considers a MIMO-OFDM network with proportionally-fair user scheduling, which is not always accounted for in previous studies.

It should be mentioned that backhaul capacity limit is by no means the only practical constraint for the implementation of large-scale network MIMO systems. The estimation and feedback of channel state information (CSI) and the delay and latency of data and CSI sharing are equally important factors, as have been analyzed in [14]. This paper, however, deals solely with the issue of backhaul capacity limit for data sharing, and in the interest of isolating its effect, assumes perfect and instantaneous CSI for the entire network.

II. System Model

The system model in this paper is similar to [5]: a downlink network MIMO system with L cells, K single-antenna users per cell, and an OFDMA multiplexing scheme with N tones over a fixed bandwidth. However, this paper extends the system model in [5] to multi-antenna BSs with Q antennas at each BS. Each BS may serve Q distinct users simultaneously on each frequency tone using ZF beamforming.

A planar deployment model is assumed (Fig. 1) where the backhaul links between the neighboring BSs allow them to share user data streams for interference pre-cancellation. This paper aims to investigate the effect of capacity-limited backhaul, and for simplicity assumes that the sum capacities of all the outgoing backhaul links from each BS is constrained to be some finite capacity. To utilize the limited backhaul capacity judiciously, each BS is allowed to choose a subset of frequency tones and a subset of beams for sharing its users' data streams with the neighboring BSs. The cooperation links are directional, and can be thought of as from a beam to a cell. Each BS employs a partial ZF precoding strategy whereby it computes the ZF precoding coefficients for every beam that is shared with it by its cooperating neighboring BSs, and in effect completely pre-subtracts the intercell interference caused by these beams. The interference caused by the beams not shared remains.

The scheduling of the users within each beam is denoted by the assignment function $f(m,b,n)$, which assigns a user k to the bth beam in the mth cell on the nth tone, i.e. $k = f(m,b,n)$. Let $u^n_{mk} \in \mathbb{C}$ denote the information signal for the kth user on the bth beam in the mth cell on the nth tone, which is assumed to have unit power, and let p^n_{mb} denote the power allocated by the mth base-station to transmit signal on the bth beam to its own scheduled user in its own cell on the nth tone. Since the mth BS needs to choose the precoding coefficients for transmitting its own data on different beams and to zero-force the interference of other users in neighboring cells that cooperate with it, the transmitted signal x^n_{mb} of the mth BS on the bth antenna in the nth tone is of the form

$$\begin{aligned} x^n_{mb} = \; & \textstyle\sum_{b'=1}^{Q} w^n_{mb,mb'} \sqrt{p^n_{mb'}} u^n_{mk'} + \\ & \textstyle\sum_{l'=1,l'\neq m}^{L} \sum_{q=1}^{Q} w^n_{mb,l'q} \sqrt{p^n_{l'q}} u^n_{l'k''}. \end{aligned} \quad (1)$$

Here the precoding coefficient $w^n_{mb,mb'}$ is used by the mth BS on the bth antenna for the b'th beam in the same cell, and the precoding coefficient $w^n_{mb,l'q}$ for $m \neq l'$ is used by the mth BS on the bth antenna to pre-subtract the intercell interference caused by the qth beam of the l'th cell to its own scheduled user k in the nth tone. By convention, $w^n_{mb,mb} = 1$. Here, the k'th user is scheduled at the mth base-station on the b'th beam, i.e. $k' = f(m,b',n)$, and the k''th user is scheduled at the l'th base-station on the qth beam, i.e. $k'' = f(l',q,n)$. Note that $w^n_{mb,l'q} = 0$ when there is no cooperation link from the qth beam of the l'th base-station to the mth base-station in the nth tone.

Let $h^n_{lq,mk}$ denote the complex channel response from the qth antenna of the lth base-station to the kth remote user in the mth cell on the nth tone for downlink. Let $\mathbf{h}^n_{l,mk}$ be a $Q \times 1$ column vector obtained by stacking the channel gains $\{h^n_{lq,mk} \; \forall 1 \leq q \leq Q\}$ of all the antennas on the lth base-station to the scheduled user k in the mth cell. Further, let $\mathbf{h}^n_{mk}$ be a $LQ \times 1$ column vector obtained by stacking the L column vectors $\{\mathbf{h}^n_{l,mk} \; \forall 1 \leq l \leq L\}$. Likewise, let the precoding vector $\mathbf{w}^n_{l,mb} \in \mathbb{C}^{Q\times 1}$ be obtained by stacking the precoder coefficients $\{w^n_{lq,mb} \; \forall 1 \leq q \leq Q\}$ used by all the antennas on the lth BS to zero-out the interference caused by the bth beam of the mth cell. Let $\mathbf{w}^n_{mb}$ be a $LQ \times 1$ column vector obtained by stacking the L column vectors $\{\mathbf{w}^n_{l,mb} \; \forall 1 \leq l \leq L\}$, Then, the received signal at the kth user in the mth cell scheduled on the bth beam in the nth tone can be written as

$$\begin{aligned} y^n_{mk} = \; & (\mathbf{h}^n_{mk})^H \mathbf{w}^n_{mb} \sqrt{p^n_{mb}} u^n_{mk} + \\ & \textstyle\sum_{b'=1,b'\neq b}^{Q} (\mathbf{h}^n_{mk})^H \mathbf{w}^n_{mb'} \sqrt{p^n_{mb'}} u^n_{mk'} + \\ & \textstyle\sum_{l'=1,l'\neq m}^{L} \sum_{q=1}^{Q} (\mathbf{h}^n_{mk})^H \mathbf{w}^n_{l'q} \sqrt{p^n_{l'q}} u^n_{l'k''} + z^n_{mk}. \end{aligned} \quad (2)$$

The second term on the right hand side of the above captures intracell interference and the third term captures intercell interference. Here, z^n_{mk} is the complex additive white Gaussian noise with variance $\sigma^2/2$ on each of its real and imaginary components. Further, $k = f(m,b,n)$, $k' = f(m,b',n)$, $k'' = f(l',q,n)$, and $(.)^H$ is the Hermitian operator.

Equation (2) can be used to obtain the following expression for signal-to-interference-and-noise ratio (SINR) of the kth user in the mth cell scheduled on the bth beam in the nth tone

$$\mathrm{SINR}^n_{mk} = \frac{|(\mathbf{h}^n_{mk})^H \mathbf{w}^n_{mb}|^2 p^n_{mb}}{\Gamma\left(\mathrm{Intra}^n_{mk} + \mathrm{Inter}^n_{mk} + \sigma^2\right)} \quad . \quad (3)$$

In the above expression, the intra-cell interference is given by $\text{Intra}^n_{mk} = \sum_{b' \neq b} |(\mathbf{h}^n_{mk})^H \mathbf{w}^n_{mb'}|^2 p^n_{mb'}$ and the inter-cell interference is given by $\text{Inter}^n_{mk} = \sum_{(l' \neq m, q)} |(\mathbf{h}^n_{mk})^H \mathbf{w}^n_{l'q}|^2 p^n_{l'q}$. Further, Γ is the SNR gap corresponding to the choice of modulation and coding schemes. Thus, the kth user in the mth cell achieves an instantaneous downlink user rate of $r^n_{mk} = \log_2(1 + \text{SINR}^n_{mk})$ on the nth tone and an instantaneous downlink user rate of $R_{mk} = \sum_{n \in \mathcal{D}_{mk}} r^n_{mk}$ over all frequency tones, where the summation is over all the frequency tones assigned to this kth user in the mth cell, i.e., $n \in \mathcal{D}_{mk}$, and $\mathcal{D}_{mk} = \{n | k = f(m, b, n)\}$.

Let the mth base-station send the data stream of the kth user scheduled on the bth beam to N^n_{mb} neighboring BSs in the nth tone, i.e., $N^n_{mb} = \text{cardinality}\{\ l \mid \exists q \text{ s.t. } w^n_{lq,mb} \neq 0\}$. Then, the amount of backhaul capacity required for cooperation is $N^n_{mb} r^n_{mk}$. Thus, $C_m = \sum_{n,b} N^n_{mb} r^n_{mk}$ gives the total cooperation rate of the mth base-station over all frequencies and over all beams. The objective of this paper is to characterize the tradeoff between the set of achievable rates $\{R_{mk}\}$ and the backhaul capacities $\{C_m\}$ in a realistic network MIMO deployment.

III. Problem Formulation

This paper adopts a network-utility maximization framework that ensures proportional fairness in user scheduling in a set up similar to [5]. However, differing from [5] and as a result of equipping the BSs with multiple antennas, this paper also considers the selection of cooperation links from each beam at a BS to its neighboring BSs, the scheduling of users on each of the Q beams in each frequency tone, and the optimization of the ZF precoder coefficients for mitigating both the intracell interference and the intercell interference between the cooperating BSs.

The joint optimization problem over cooperation-link selection, user scheduling, precoder-coefficient and power-spectrum adaptation can be expressed as

$$\begin{array}{lll} \max & & \sum_{m,k} \log(\bar{R}_{mk}) \\ \text{s.t} & \text{(A1):} & R_{mk} = \sum_{n \in \mathcal{D}_{mk}} \log_2(1 + \text{SINR}^n_{mk}) \quad \forall m, k \\ & \text{(A2):} & 0 \leq \sum_{l',q} |w^n_{mb,l'q}|^2 p^n_{l'q} \leq S^{\max} \quad \forall m, b, n \\ & \text{(A3):} & \bar{C}_m \leq C^{\max}_m \quad \forall m \end{array} . \tag{4}$$

The objective function maximizes the overall log network utility $\sum \log(\bar{R}_{mk})$ to ensure proportional fairness among all users in all cells, where $\bar{R}_{mk}$ is the time-averaged rate for the kth user in the mth cell. This is a mixed discrete and continuous optimization problem with cooperation-link selection and user-scheduling functions $f(m, b, n)$ as discrete variables, and precoder-coefficients $w^n_{mb,l'q}$ and power-spectra $p^n_{l'q}$ as continuous variables. The first constraint (A1) gives the instantaneous downlink rate R_{mk} for the kth user in the mth cell. The second constraint (A2) is the per-antenna transmit PSD constraint that requires the total transmit power of the bth antenna on the mth base-station in the nth tone to be less than the transmit PSD constraint $S^{\max}$. The third constraint (A3) requires the time-averaged backhaul capacity of the mth cell over all the frequencies and the beams, $\bar{C}_m$, to satisfy the backhaul-capacity constraint $C^{\max}_m$.

IV. Proposed Algorithm

Finding a true global network-wide optimal solution jointly across all BSs and tones is likely to be intractable for the complex mixed discrete and continuous optimization problem (4). This paper focuses on a heuristic approach for finding a practical and locally optimal solution.

As a first step, the optimization problem (4) is dualized with respect to the backhaul-capacity constraint (A3) at each base-station, resulting in

$$\begin{array}{ll} \max & \sum_{m,k} \log(\bar{R}_{mk}) - \sum_{m=1}^{L} \lambda_m \left(\bar{C}_m - C^{\max}_m\right) \\ \text{s.t} & \text{(A1), (A2)} \end{array} , \tag{5}$$

where λ_m is the Lagrange multiplier that ensures the backhaul-capacity constraints are met for the mth base-station.

In each time instance, the marginal increase in the log-utility $\log(\bar{R}_{mk})$ can be approximated by maximizing $\left(R_{mk}/\bar{R}_{mk}\right)$, and the marginal decrease in the time-averaged backhaul capacity $\bar{C}_m$ is just $\sum_{n,b} N^n_{mb} r^n_{mk}$. This transforms the objective of the optimization problem in (5) into a weighted rate-sum maximization problem for every frequency tone

$$\sum_{m,k} \alpha^n_{mk} r^n_{mk} \tag{6}$$

with the weights for r^n_{mk} set as $\alpha^n_{mk} = \left((1/\bar{R}_{mk}) - \lambda_m N^n_{mb}\right)$, where $k = f(m, b, n)$. The proposed dynamic cooperation link selection approach solves the above problem by iterating between selecting the cooperation links for each BS (Section IV-A), scheduling the users (Section IV-B), adapting the precoder coefficients and the power spectra (Section IV-C), while assuming that the quantities not being optimized are fixed.

A. Cooperation Link Selection

A cooperation link is added from a beam to a BS if the benefit of adding this link in terms of the data-rate increase for the destination BS exceeds the backhaul-capacity cost. However, the exact computation of cost and benefit of adding each cooperation link is a nontrivial task. This paper uses the following approximation to provide a good first-order estimate of such cost and benefits. It is assumed that adding a cooperation link from the qth beam of the lth base-station to the mth base-station in the nth tone completely eliminates the interference term from the qth beam of the lth base-station in the SINR expression of the scheduled users of the mth base-station in the nth tone. Further, to ease computation, only the intracell beamformers are used to approximate the rates.

More precisely, the initial set of achievable data rates are approximated as

$$\tilde{r}^n_{mk} = \log_2 \left(1 + \frac{|(\mathbf{h}^n_{m,mk})^H \mathbf{w}^n_{m,mb}|^2 p^n_{mb}}{\Gamma\left(\text{Intra}^n_{mk,\text{appr}} + \text{Inter}^n_{mk,\text{appr}} + \sigma^2\right)} \right) , \tag{7}$$

where the approximated intracell interference is

$$\text{Intra}^n_{mk,\text{appr}} = \sum_{b'=1, b'\neq b}^{Q} |(\mathbf{h}^n_{m,mk})^H \mathbf{w}^n_{m,mb'}|^2 p^n_{mb'}, \quad (8)$$

the approximated intercell interference is

$$\text{Inter}^n_{mk,\text{appr}} = \sum_{(l',q)\notin \mathcal{I}^n_m} |(\mathbf{h}^n_{l',mk})^H \mathbf{w}^n_{l',l'q}|^2 p^n_{l'q}, \quad (9)$$

and $\mathcal{I}^n_m$ represents the set of BS-beam pairs whose user data streams are zero-forced at the mth BS in the nth tone in the initial topology (i.e., the set of incoming cooperation links). Note that the SINR in the above expression is an approximation to the true SINR (3), but it has the advantage that the intercell interference term is decoupled from the beamformers in a way that allows the effect of cooperation to be estimated easily. The approximation is justified when the overall network MIMO channel is close to being block-diagonally dominant, i.e., the channel from a BS to users within its cell is much stronger than the interfering channels.

Now, suppose that a cooperation link is added from the q'th beam of the l'th BS to the mth BS in the nth tone. The new data rate can be approximated as:

$$\tilde{\tilde{r}}^n_{mk,l'q'} = \log_2\left(1+\frac{|(\mathbf{h}^n_{m,mk})^H \mathbf{w}^n_{m,mk}|^2 p^n_{mb}}{\Gamma\left(\text{Intra}^n_{mk,\text{appr}} + \text{Inter}^n_{mk,\text{appr}} - \Delta + \sigma^2\right)}\right), \quad (10)$$

where the interference from the q'th beam of the l'th BS to the the kth user assigned to the bth beam of the mth BS, denoted as $\Delta = |(\mathbf{h}^n_{l',mk})^H \mathbf{w}^n_{l',l'q'}|^2 p^n_{l'q'}$, is assumed to be completely eliminated after adding the cooperation link.

From a network utility point of view, the benefit of adding the above cooperation link is $(\tilde{\tilde{r}}^n_{mk,l'q'} - \tilde{r}^n_{mk})/\bar{R}_{mk}$. Since all Q beams at the mth BS benefit from the cooperation link at the same time, the collective benefit is therefore the sum $\sum_{b=1}^{Q}(\tilde{\tilde{r}}^n_{mk,l'q'} - \tilde{r}^n_{mk})/\bar{R}_{mk}$ where $k = f(m,b,n)$. Now, the backhaul-capacity cost of adding the above cooperation link is equal to the user data rate at the source BS l' on the q'th beam $\tilde{r}^n_{l'k''}$ for the k'' scheduled user, where $k'' = f(l',q',n)$. Thus, the algorithm should select the cooperation link from the q'th beam of the l'th BS to the mth BS in the nth tone if

$$\sum_{b=1}^{Q} \frac{1}{\bar{R}_{mk}}(\tilde{\tilde{r}}^n_{mk,l'q'} - \tilde{r}^n_{mk}) > \lambda_l \tilde{r}^n_{l'k''}, \quad (11)$$

where $k = f(m,b,n)$, $k'' = f(l',q',n)$, and λ_l accounts for the marginal cost of backhaul capacity. Otherwise, it should remove the cooperation link. If the above criterion is met, all Q beams of the mth BS will pre-subtract the interference from the q'th beam of the l'th BS and $\mathcal{I}^n_m$ is updated accordingly.

B. Proportionally Fair Scheduling with Backhaul-Capacity Penalty

This paper proposes the use of a proportionally fair scheduler to select the active user on each beam in each cell and in each frequency tone, but accounts for an additional penalty for the backhaul-capacity constraint. The user scheduling step assigns the kth user to the bth beam of the mth BS on the nth frequency tone according to

$$f(m,b,n) = \text{argmax}_k \left(\frac{1}{\bar{R}_{mk}} - \lambda_m N^n_{mb}\right)\tilde{r}^n_{mk} \;, \quad (12)$$

where $\tilde{r}^n_{mk}$ is the instantaneous approximate data rate of the kth user in the mth cell on the nth tone computed using (7).

C. Zero-Forcing Precoder Coefficient and Power Adaptation

When the cooperation links and the user schedules are assumed fixed, the network-wide ZF precoding coefficients can be computed on a beam-to-beam basis, and the power of each beam can then be optimized subject to the per-antenna power constraints.

1) Channel Inversion: The ZF precoding coefficients are chosen so that intracell interference between different beams within each cell is completely eliminated, and intercell interference caused by the qth beam in the lth BS is completely eliminated at the mth BS in nth tone if $(l,q) \in \mathcal{I}^n_m$, in other words, if its data is shared through the backhaul link. This is essentially a partial ZF precoding strategy in which the channel matrix is inverted only at selected entries.

In ZF precoding, to cancel intracell interference, the following condition must hold for the different beams within the mth base-station

$$(\mathbf{h}^n_{mk_b})^H \mathbf{w}^n_{mb'} = 0 \quad \forall b' \neq b \quad \text{where } k_b = f(m,b,n). \quad (13)$$

To cancel intercell interference corresponding to the cooperation link from the bth beam of the mth base-station to the qth beam of the lth base-station in the nth tone, the following condition must hold

$$(\mathbf{h}^n_{lk_q})^H \mathbf{w}^n_{mb} = 0 \quad \text{where } k_q = f(l,q,n). \quad (14)$$

Equations (13) and (14) result in a system of linear equations with the number of equations equal to the number of unknowns. This system of linear equations can now be solved to obtain all the non-zero ZF precoder coefficients.

2) Power Spectrum Adaptation: With the cooperation links and user schedules fixed and the precoder coefficients computed using (13) and (14), the power spectrum adaptation step proceeds to optimize the transmit power spectra by solving the network-utility maximization problem (5), or equivalently the per-tone problem

$$\begin{array}{lll} \max & & \sum_{m,b} \alpha^n_{mk} r^n_{mk} \\ \text{s.t} & (A4) & 0 \leq \sum_{l,q} |w^n_{mb,lq}|^2 p^n_{lq} \leq S^{\max} \quad \forall m,b \end{array}, \quad (15)$$

where the optimization is over the transmit power spectra $\{p^n_{lq}\}$ for each beam and k is the user scheduled on the bth beam of the mth cell in the nth tone, i.e. $k = f(m,b,n)$. Here, the inequality constraint (A4) is the per-antenna transmit PSD constraint $S^{\max}$. The optimization problem in (15) is non-convex in $\{p^n_{lq}\}$. The use of nonlinear optimization methods such as the interior-point method is required to find a local optimum of (15); (see [5] for details).

D. Summary

The overall algorithm involves iterating among the cooperation-link selection step using (11) with fixed user scheduling and beamforming, the user-scheduling step (12) with fixed cooperation links and beamforming, the ZF beamforming step using (13) and (14), and the power-spectra optimization step of solving (15) using interior-point method with fixed cooperation links and user schedules. This process is typically done for a fixed number of iterations; an outer loop then updates the proportional fairness weights and the Lagrangian multipliers corresponding to the backhaul capacity constraints.

V. Simulation Results and Discussions

To verify the proposed algorithm and to quantify the performance tradeoff between the sum-rate gain and the backhaul capacity on a reasonably sized network, we present a set of simulation results on a wireless cellular network with 7 cells and 40 users per cell, with maximal frequency reuse, where cells are wrapped around so that each cell has six neighboring cells. Standard cellular network parameters are used in simulation: the noise power spectral density is set to -162dBm/Hz; frequency-selective channel vectors over 64 frequency tones are chosen according to the multipath time delay profile of ITU-R M.1225 PedA and a distance-dependent path-loss model $L = 128.1 + 37.1 \log_{10}(d_0)$, where d_0 is the distance in km, with a Rayleigh fading component. The maximum PSD constraint is -27dBm/Hz on each antenna, so that over a 10MHz bandwidth the total transmit power at the BS is 49dBm per antenna. An antenna gain of 15dBi is assumed. The users are uniformly distributed within each cell. The initial user assignment is random, and the initial beamformers are also chosen randomly. For evaluation purposes, the channels are assumed to be fixed throughout and λ_m is assumed to be equal for all cells, which corresponds to a backhaul-capacity constraint on the sum of backhaul capacities of all BSs.

Figures 2 and 3 compare the improvement in downlink sum rates per cell as a function of the average backhaul capacity per BS for the case of one antenna per BS, and 4 antennas per BS, respectively. The distance between neighboring BSs d is 800m. The no-cooperation scenario is equivalent to the joint proportionally fair scheduling, ZF beamforming, and dynamic power-spectrum adaptation algorithm of [15]. Note that in the extreme scenario of the full-cooperation case, each BS uses ZF precoding to zero-out the interference of all the neighboring BSs, thus each BS shares its users' data streams on all beams with all the neighboring BSs on all tones. In this case, as each BS has six neighbors, the required total cooperative link capacity is six times the achieved sum rate at the BS.

This paper proposes the use of dynamic cooperation link selection in order to achieve a better tradeoff between the gain in achievable downlink sum rate and the average backhaul capacity per BS than the previous fixed cooperation-link selection scheme proposed in our previous work [5]. The difference between dynamic and fixed link selection is illustrated in Figs. 2 and 3 for the 1-antenna-per-BS case and the 4-antenna-per-BS case, respectively. It can be observed that at 50% of the cooperation rate, about 63% of the sum rate gains can be achieved for both the 1-antenna and the 4-antenna cases. It can also be observed that the concave tradeoff is slightly more pronounced at low backhaul rates, because fewer cooperation links are active at that point, providing more flexibility to the link-selection algorithm.

The network-utility maximization framework adopted in this paper ensures proportional fairness across the entire network. It in fact distributes the gains of network MIMO equitably among different users in a cell. The cumulative distribution functions of the downlink user rates shown in Fig. 4 illustrate this point. The successive curves from the left to the right correspond to increasing backhaul capacities (per BS) when each BS is equipped with 4 antennas.

Fig. 5 shows the convergence of the effective network

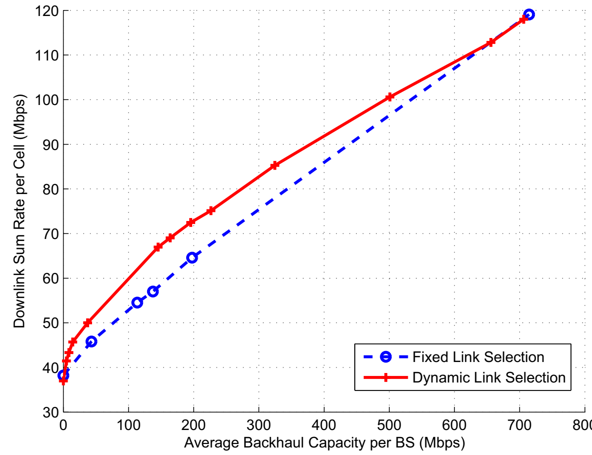

Figure 2. Downlink sum rate per cell vs. backhaul capacity for fixed cooperation link selection and dynamic cooperation link selection for $Q = 1$ antenna per BS with BS-to-BS distance $d = 800$m.

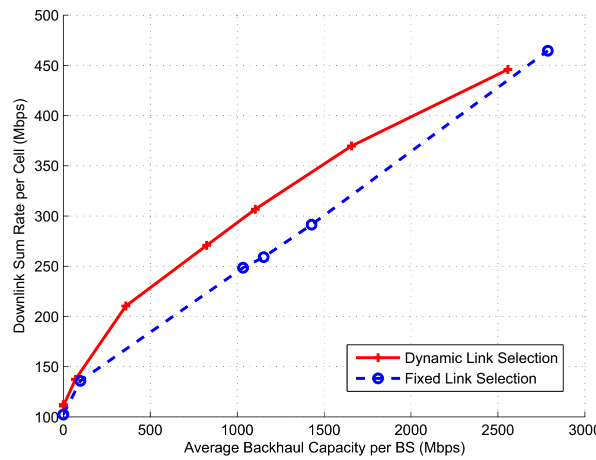

Figure 3. Downlink sum rate per cell vs. backhaul capacity for fixed cooperation link selection and dynamic cooperation link selection for $Q = 4$ antennas per BS with BS-to-BS distance $d = 800$m.

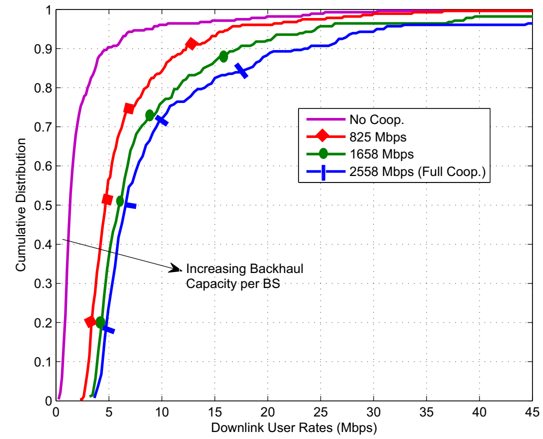

Figure 4. Cumulative distribution functions of downlink user rates for different backhaul capacities for the case of BS-to-BS distance of 800m with $Q = 4$ antennas per BS.

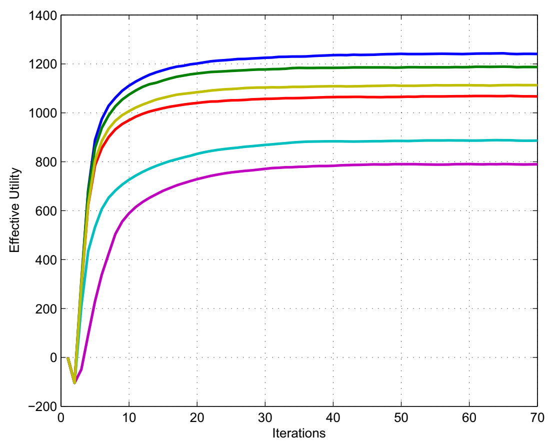

Figure 5. Convergence plot of $\sum \log(\bar{R}) - \lambda \bar{C}$ for the case of BS-to-BS distance of 800m with $Q = 4$ antennas per BS. Each line corresponds to a different λ_m.

utility (i.e., the log utility minus the backhaul-capacity cost) as a function of the number of iterations. Each iteration here corresponds to 20 iterations of cooperation-link selection, user scheduling, beamforming and power-spectra adaptation, followed by an update of the proportional fairness weights. The overall algorithm converges in roughly 30-40 iterations.

It should be mentioned that the proposed algorithm is iterative and heuristic in nature. For example, it involves the approximation of user rates (7) for cooperation link selection and scheduling, which may not be accurate when BS-to-BS distance is small. Future work is needed to assess the impact of the heuristics, especially in light of many local minima present in the optimization landscape. We observe that the algorithm can be sensitive to the initialization points. For example, simulation experiences indicate that it is necessary to initialize the cooperation link selection to be random (e.g. all-zero) at the beginning of each weighted rate-sum maximization.

VI. Conclusions

This paper presents an effort to numerically quantify the performance gain of a network MIMO system with limited backhaul capacity. It is shown that dynamic cooperation-link selection along with an iterative and heuristic optimization framework for user scheduling, ZF precoding, and power optimization can result in a better throughput-backhaul trade-off than the fixed cooperation-link selection scheme. It is observed that the benefit of network MIMO can be significant even with limited backhaul capacity. However, such benefit comes at a substantial cost in network optimization as well as the need for obtaining the CSI of the entire network.

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