On Remote Radio Head Selection for the Downlink of Backhaul Constrained Network MIMO Systems

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***Abstract*—A relevant architecture to enable network MIMO in cellular systems consists of a central unit that is connected to remote radio heads (RRHs) via a shared wireless backhaul link. This letter studies the impact of RRH selection in this system under the two extreme scenarios of perfect and stale channel state information (CSI) at the central unit. It is shown that in both cases, RRH selection based on the instantaneous conditions or the long-term statistics of the backhaul links and of the access channels (i.e., from RRHs to mobile stations) significantly improves the sum-rate performance. The presented results also demonstrate that, in the presence of shared backhaul limitations, the classical precoding design based on the maximization of the number of degrees of freedom (DOFs) on the access channels leads to strictly suboptimal performance even when the access channels operate in the high SNR regime.**

***Index Terms*—Network MIMO, constrained backhaul, degrees of freedom, cloud radio access network, distributed antenna system.**

I. Introduction

Network MIMO [1] promises to increase the spectral efficiency of cellular systems by enabling cooperation among distributed remote radio heads (RRHs). The nomenclature "RRH" is used here to encompass a variety of infrastructural nodes such as femto/pico base stations, relay stations or distributed antennas (see, e.g., [2]-[6]). With network MIMO, the RRHs are jointly controlled by a central unit (CU) for the purpose of encoding in downlink and decoding in uplink. This can be enabled by an architecture whereby the RRHs are connected to the CU via a shared backhaul link (see Fig. 1). For instance, the backhaul link can be a wireless channel as illustrated in Fig. 1-(a) [7][8] or a wired backhaul link of sum-capacity constraint as sketched in Fig. 1-(b) [4, Sec. 6.2]. This set-up with a shared backhaul is especially relevant for scenarios in which it is not cost-efficient to deploy individual high-capacity backhaul connections from the CU to each RRH (e.g,. via fiber or microwave links) [7][8].

In order to maximize the performance gains from cooperation, it is generally beneficial for the CU to activate as many RRHs as possible. However, this conclusion does not account for the capacity limitations of the backhaul links between the CU and the RRHs. In this letter, we investigate the impact of RRH selection in the set-up illustrated in Fig. 1 with a shared backhaul from the CU to RRHs. We assume that the CU has full information about the capacity of the backhaul links, and we consider the two extreme scenarios of perfect and stale channel state information (CSI) (see [9]) concerning the access channels (i.e., from RRHs to mobile stations (MSs)) at the CU. It is shown via numerical results that in both cases, RRH selection significantly improves the sum-rate performance. Among the implications of the presented results is the fact that the classical precoding design criterion of maximizing the number of degrees of freedom (DOFs) on the access channel leads to strictly suboptimal performance even when the access channels operate in high SNR regime.

II. System Model

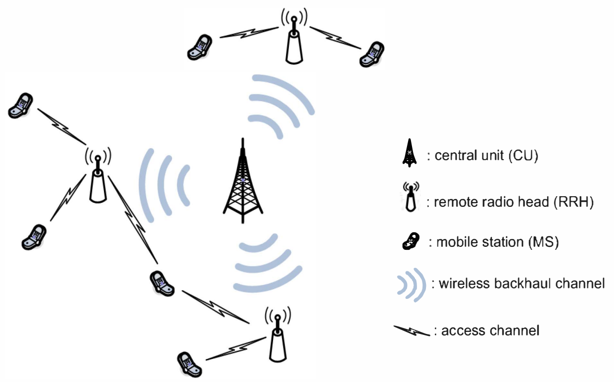
We consider a 2×2 downlink network MIMO system, in which two single-antenna MSs are served by two single-antenna RRHs. This is done for simplicity of exposition and the main conclusions apply to more general $M \times M$ systems with $M > 2$. For notational convenience, we denote the sets of RRHs and MSs by $\mathcal{M} = \{1, 2\}$ and $\mathcal{K} = \{1, 2\}$, respectively. The CU can communicate with the ith RRH on the backhaul in a given time-slot at a rate C_i bits/s/Hz. Moreover, the backhaul is shared among the RRHs via an orthogonal scheme such as time-division multiple access (TDMA) or frequency division multiple access (FDMA) [7][8]. As a result, the rate R_i is achievable from the CU to the ith RRH with $i \in \mathcal{M}$ if the condition

$$\sum_{i\in\mathcal{M}} \frac{R_i}{C_i} \leq 1 \tag{1}$$

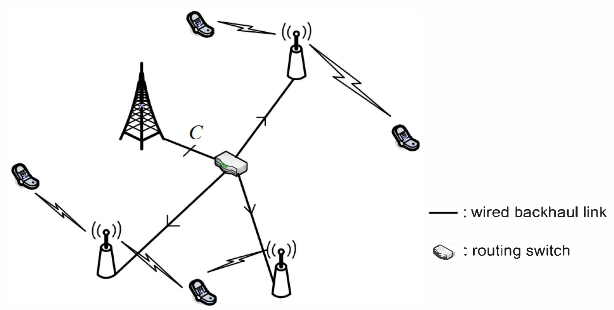
is satisfied. We assume that the values C_i, $i \in \mathcal{M}$, are known to the CU. We observe that this is a reasonable assumption considering that the CU is directly connected to the RRHs. For instance, if we assume a wireless backhaul channel as in Fig. 1-(a), the capacities $\{C_i\}_{i\in\mathcal{M}}$ are given by

$$C_i = \log_2(1 + |g_i|^2 P_{\mathrm{CU}}), \tag{2}$$

where g_i denotes the complex channel gain from CU to RRH i and P_{CU} represents the power constraint at the CU. Instead,



(a) Shared wireless backhaul channel



(b) Shared wired backhaul link

Figure 1: Illustration of the network MIMO system with the RRHs controlled by the CU over a shared backhaul link.

for a wired backhaul link of sum-capacity C as in Fig. 1-(b), we have $C_i = C$ for $i \in \mathcal{M}$.

As for the access channel between RRHs and MSs, we define the vector $\mathbf{x} = [x_1^\dagger, x_2^\dagger]^\dagger \in \mathbb{C}^{2\times 1}$, which collects signals transmitted by the RRHs in a channel use of a given time-slot, and the channel vector $\mathbf{h}_k = [h_{k,1}^\dagger, h_{k,2}^\dagger]^\dagger \in \mathbb{C}^{2\times 1}$, which describes the fading channels from the two RRHs to MS k within the time-slot. Overall, the received signal y_k by MS k is given as

$$y_k = \mathbf{h}_k^\dagger \mathbf{x} + z_k, \tag{3}$$

where $z_k \sim \mathcal{CN}(0,1)$ is white Gaussian noise. We assume that the channel vectors $\{\mathbf{h}_k\}_{k\in\mathcal{K}}$ remain constant during a time-slot and change independently from slot to slot (i.e., quasi-static fading). Moreover, $\mathbf{h}_k$ will be taken in the numerical results to be complex Gaussian with independent unit-power entries (i.e., Rayleigh fading). We have the per-RRH power constraints

$$\mathbb{E}|x_i|^2 \le P_{\mathrm{RRH}}. \tag{4}$$

As in a number of practical systems and theoretical studies [2]-[6], we will assume that RRHs operate as *oblivious relays*. As a result, the CU performs baseband modulation via precoding and then compresses the resulting baseband signal. The compressed signal is then transmitted to each RRH over the backhaul link. Each ith RRH then decompresses the baseband signal and transmits it to the MSs after passband modulation.

A. Precoding

We consider the two extreme scenarios of full CSI and stale CSI at the CU regarding the access channels between RRHs and MSs. With stale CSI, the CU has the information only about the channel responses corresponding to the previous time-slots. Instead, with full CSI, the CU knows also the current channels.

For the full CSI case, we fix a normalized beamforming vector $\mathbf{w}_k \in \mathbb{C}^{2\times 1}$ ($||\mathbf{w}_k|| = 1$) for each MS k. As a result, the precoded signal $\tilde{\mathbf{x}} \in \mathbb{C}^{2\times 1}$ in a channel use of a given time-slot is given as

$$\tilde{\mathbf{x}} = \sum_{k\in\mathcal{K}} \mathbf{w}_k \alpha_k s_k, \tag{5}$$

where $s_k \sim \mathcal{CN}(0,1)$ is the data symbol intended for MS k, and $\alpha_k \ge 0$ is a power scaling factor. A classical choice for the beamforming vectors follows the zero-forcing criterion (e.g., [10]), which is known to maximize the number of DOFs of the access channel, namely M DOFs for an $M \times M$ system, and generally requires the activation of all RRHs [11, Sec. IV].

Instead, with stale CSI, the precoded signals $\tilde{\mathbf{x}}$ are obtained based on space-time interference alignment as recently proposed in [9]. We refer to these approaches as *MAT schemes* following, e.g., [12]. MAT schemes achieve the maximum number of DOFs for $M \times M$ systems with stale CSI, namely $M/(\sum_{m\in\mathcal{M}} m^{-1})$ DOFs, by activating all RRHs (but not necessarily in all time-slots, see below and [9][12]).

B. Backhaul Compression

As mentioned, the precoded signals $\tilde{\mathbf{x}}$ are compressed prior to transmission on the backhaul link to the RRHs. We assume a standard Gaussian test channel for compression as in, e.g., [13][14] so that the compressed signal $\mathbf{x}$ is related to the precoded signal $\tilde{\mathbf{x}}$ as

$$\mathbf{x} = \tilde{\mathbf{x}} + \mathbf{q}, \tag{6}$$

where the compression noise $\mathbf{q} \in \mathbb{C}^{2\times 1}$ is independent of the precoded signal $\tilde{\mathbf{x}}$ and is distributed as $\mathbf{q} \sim \mathcal{CN}(\mathbf{0}, \mathrm{diag}(\sigma_1^2, \sigma_2^2))$. We note that the diagonal structure of the covariance matrix of $\mathbf{q}$ implies that the quantization noises in $\mathbf{q}$ for different RRHs are independent and hence compression of the signals intended for the RRHs can be done in parallel[1].

The noise powers $\{\sigma_i^2\}_{i\in\mathcal{M}}$ are chosen so that the resulting rates of the compressed streams to be communicated to the RRHs do not exceed the backhaul capacity. Using standard rate distortion theoretic arguments (see, e.g., [16, Ch. 3]), this condition is satisfied if the rates R_i, $i \in \mathcal{M}$, satisfy the inequality $R_i \ge I(\tilde{x}_i; x_i) = \log_2(1 + \mathbb{E}|\tilde{x}_i|^2/\sigma_i^2)$ with $\tilde{x}_i$ representing the ith element of the precoded signal $\tilde{\mathbf{x}}$, and hence, using (1), if the inequality

$$\sum_{i\in\mathcal{M}} \frac{1}{C_i} \log_2\left(1 + \frac{\mathbb{E}|\tilde{x}_i|^2}{\sigma_i^2}\right) \le 1 \tag{7}$$

[1] In general, better performance can be achieved by introducing the correlation among the elements of $\mathbf{q}$, as proposed in [15].

holds.

III. RRH Selection

In this section, we investigate the impact of RRH selection in the presence of backhaul constraints for a 2×2 system with full and stale CSI at the CU concerning the access channels.

A. Full CSI

In this subsection, full CSI is assumed at the CU concerning the access channels from RRHs to MSs. We compare the performance of strategies that select either one RRH ($\tilde{M}=1$) or both RRHs ($\tilde{M}=2$). Note that, when only RRH $i\in\mathcal{M}$ is selected, the beamforming vectors $\mathbf{w}_k$ are such that only the ith component is non-zero. In general, for given beamforming vectors $\{\mathbf{w}_k\}_{k\in\mathcal{K}}$, the power coefficients $\{\alpha_k\}_{k\in\mathcal{K}}$ and the quantization noise powers $\{\sigma_i^2\}_{i\in\mathcal{M}}$ can be jointly optimized so as to maximize the sum-rate $R_{\text{sum}}=\sum_{k\in\mathcal{K}}R_{\text{MS},k}$ subject to the constraints (4) and (7). This problem is stated as

$$\underset{\{\alpha_k\geq 0\}_{k\in\mathcal{K}},\{\sigma_i^2\geq 0\}_{i\in\mathcal{M}}}{\text{maximize}} \sum_{k\in\mathcal{K}} R_{\text{MS},k} \quad (8)$$
$$\text{s.t.}\quad [\mathbf{\Sigma}_{\tilde{\mathbf{x}}}]_{i,i}+\sigma_i^2\leq P_{\text{RRH}},\ \text{for } i\in\mathcal{M},$$
$$\sum_{i\in\mathcal{M}}\frac{1}{C_i}\log_2\left(1+\frac{1}{\sigma_i^2}[\mathbf{\Sigma}_{\tilde{\mathbf{x}}}]_{i,i}\right)\leq 1,$$

where we have defined the covariance $\mathbf{\Sigma}_{\tilde{\mathbf{x}}}=\sum_{k\in\mathcal{K}}\alpha_k^2\mathbf{w}_k\mathbf{w}_k^\dagger$, $[\mathbf{X}]_{i,i}$ represents the ith diagonal elements of the matrix $\mathbf{X}$, and the achievable rate $R_{\text{MS},k}$ for MS k is given as

$$R_{\text{MS},k}=\log_2\left(1+\frac{\alpha_k^2\left|\mathbf{h}_k^\dagger\mathbf{w}_k\right|^2}{\alpha_{\bar{k}}^2\left|\mathbf{h}_k^\dagger\mathbf{w}_{\bar{k}}\right|^2+\sum_{i\in\mathcal{M}}|h_{k,i}|\,\sigma_i^2+1}\right), \quad (9)$$

with $\{k,\bar{k}\}=\mathcal{K}$. The problem (8) can be seen to be an instance of the class of difference-of-convex problems [17]. Thus, the majorization minimization approach can used to derive an iterative algorithm that converges to a stationary point of the problem [17].

If only the ith RRH is selected, it is not hard to see that the optimal solution of problem (8) is given as $R_{\text{sum}}=\max_{k\in\mathcal{K}}R_{i,k}$ where

$$R_{i,k}=\log_2\left(1+\frac{|h_{k,i}|^2P_{\text{RRH}}\left(1-2^{-C_i}\right)}{|h_{k,i}|^2P_{\text{RRH}}2^{-C_i}+1}\right). \quad (10)$$

Moreover, the selection of the ith RRH can be either predetermined (i.e., *non-adaptive*) or selected adaptively depending on the current CSI of the backhaul and access channels (i.e., *adaptive*). In the latter case, the sum-rate (10) can be maximized also over $i\in\mathcal{M}$. When both RRHs are selected, one can use different criteria for the selection of the beamforming vectors, such as zero-forcing beamforming (which entails $\mathbf{h}_l^\dagger\mathbf{w}_k=0,\ l\neq k$) and maximum-ratio transmission (with $\mathbf{w}_k=\mathbf{h}_k/||\mathbf{h}_k||$).

Assuming a wireless backhaul (2) with g_i representing unit-power quasi-static Rayleigh fading, Fig. 2 plots the sum-rate versus the average SNR P_{CU} of the wireless backhaul link for average SNR value on the access channel $P_{\text{RRH}}=25\,\text{dB}$. It is observed that selecting both RRHs ($\tilde{M}=2$) is advantageous only when the SNRs P_{CU} and P_{RRH} of *both* the backhaul and access channels are large enough. In particular, for sufficiently small backhaul SNR, it is advantageous to devote the entire backhaul resource to one RRH via RRH selection, even when the RRH selection is done non-adaptively (i.e., based only on the average SNRs). Also, even at the considered high access SNR P_{RRH}, the DOF-maximizing zero-forcing beamforming is strictly suboptimal.

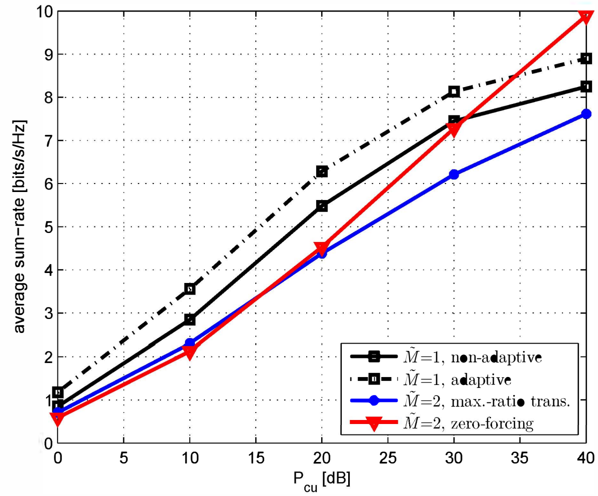


Figure 2: Average sum-rate versus the SNR P_{CU} of the wireless backhaul link with full CSI at the CU.

B. Stale CSI

In this subsection, we assume that the CU has stale CSI for the access channel from the RRHs to the MSs. As above, we compare schemes that select $\tilde{M}=1$ RRH and the DOF-optimal MAT schemes [9][12, Sec. III-B]. Specifically, the rate achievable by scheduling only RRH i is given as $R_{\text{sum}}=R_{i,k}$ with $R_{i,k}$ in (10). Note that, given the lack of CSI on the access channel, the MS index k is assumed to be predetermined. Moreover, the RRH index i can be either predetermined or selected adaptively based on the available CSI on the backhaul link. In this latter case, the ith RRH is selected as the one that maximizes the backhaul capacity C_i.

In the MAT scheme proposed in [9, Sec. III-A], the RRH transmits two independent data symbols $s_k(1), s_k(2)$ over three time-slots to each MS k, thus achieving the optimal number $4/3$ of DOFs. The transmission schedule along the three time-slots is summarized in Table I. As it can be seen, both RRHs are activated during the first two slots while only one RRH is active at the last slot. A variation of MAT was proposed in [12, Sec. III-B] that differs from MAT in that it applies linear precoding in the last time-slot using the stale CSIs corresponding to the previous two time-slots. We refer to this precoding method as generalized MAT (GMAT).

time-slot	RRH	MAT [9, Sec. III-A] and GMAT [12, Sec. III-B]	MNA [9, Sec. VII-A]
1	1	$s_1(1)$	$s_1(1) + s_2(1)$
	2	$s_1(2)$	$s_1(2) + s_2(2)$
2	1	$s_2(1)$	$\sum_{j=1}^{2} h_{2,j}(1)s_1(j)$
	2	$s_2(2)$	0
3	1	$\sum_{j=1}^{2} h_{2,j}(1)s_1(j)$ $+\sum_{j=1}^{2} h_{1,j}(2)s_2(j)$	$\sum_{j=1}^{2} h_{1,j}(1)s_2(j)$
	2	0	0

Table I: Illustration of the transmitted signals from each RRH at each time-slot for the MAT, GMAT and MNA: The coefficient $h_{k,i}(t)$ denotes the channel response between RRH i and MS k at time-slot t.

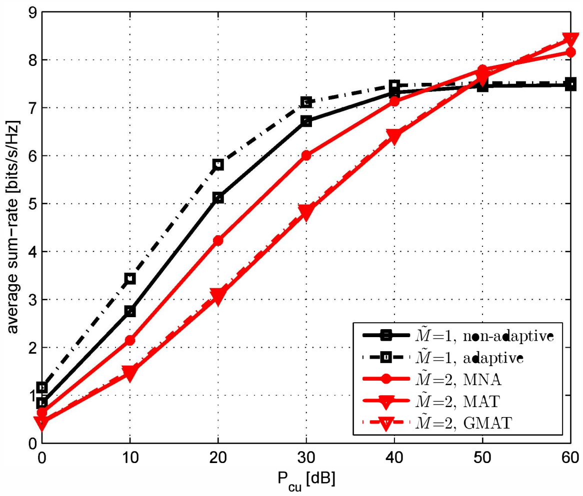


Figure 3: Average sum-rate versus the SNR P_{CU} of the wireless backhaul link with stale CSI at the CU.

Another variation of MAT was proposed in [9, Sec. VII-A], which was shown to obtain the optimal number of DOFs as MAT. As summarized in Table I, the scheme activates both RRHs only at the first slot and then uses only one RRH during the remaining two slots. Note that, overall, four antennas are activated along three slots to achieve $4/3$ DOFs. Therefore, this scheme activates the minimum possible number of antennas (i.e., RRHs) and is referred to as minimum number of antennas (MNA) scheme.

In order to allocate the backhaul resources and hence select the quantization noise powers based only on the backhaul CSI, we choose the criterion of minimizing the worst-case quantization noise power $\max_{i\in\mathcal{M}} \sigma_i^2$. This is accomplished by setting $R_i = \tilde{C}$ for $i \in \mathcal{M}$ with $\tilde{C} = (\sum_{j\in\mathcal{M}} C_j^{-1})^{-1}$. The sum-rates with MAT, GMAT and MNA schemes can be derived similar to Eq. (46) in [12, Sec. III-B] by adding the quantization noise to the noise variance.

In Fig. 3, we plot the average sum-rate versus the SNR P_{CU} of the wireless backhaul link in (2) and with access SNR $P_{\text{RRH}} = 25\,\text{dB}$. It is seen from the figure that, similar to the full CSI case, the DOF-optimal schemes MAT, GMAT and MNA, are advantageous only for sufficiently large SNRs of the backhaul and access channels. Moreover, comparing Fig. 2 and Fig. 3, it is seen that a larger backhaul SNR is required for the DOF-optimal schemes to outperform schemes that select only one RRH in the stale CSI case. This is due to the decreased advantage of stale CSI with respect to full CSI. Finally, among the DOF-maximizing schemes, when the backhaul link has enough capacity, MAT and GMAT outperform MNA since they consume more transmit power under the considered per-RRH power constraint (4). However, MNA provides better performance than MAT or GMAT for sufficiently small backhaul capacity due to the more efficient use of backhaul link.

IV. Conclusion

We have investigated the impact of RRH selection on the downlink of network MIMO systems, in which the RRHs are connected via a shared wireless backhaul link to the CU. The two extreme scenarios of perfect and stale CSI at the CU are considered. It was shown that in both cases, RRH selection significantly improves the sum-rate performance and DOF-optimal schemes show strictly suboptimal performance particularly when the backhaul links have limited capacity.

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