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計畫主持人：許大山

計畫參與人員：許大山 蘇耿毅 蔡隆盛 謝佳辰 施凱挺 黃笙瑜 張永煌

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A pragmatic channel-adaptive scheduling approach in multiuser MIMO downlink

Da-shan Shiu

Graduate Institute of Communication Engineering
Department of Electrical Engineering
National Taiwan University
dsshui@cc.ee.ntu.edu.tw

Abstract—In the downlink of a multiuser multiple-input, multiple-output (MIMO) network, one can take advantage of multiuser diversity by employing channel-adaptive user scheduling. During a given slot, a base station can dedicate all the spatial resources to a single user with the best channel condition. On the other hand, it can distribute them among several users which together have an advantageous channel condition combination. We refer to these two approaches as MIMO single-cast and MIMO multi-cast, respectively. In this paper, we show that MIMO multi-cast significantly outperforms MIMO single-cast. Optimal MIMO multi-cast scheduling requires substantial computation complexity. In light of this, we propose a pragmatic scheduling approach which offers good performance while greatly reduces the computation load and the scheduling overhead. Our simulation results indicate that, given four transmit and receive antennas, the average capacity achieved by MIMO multi-cast with the proposed scheduler exceeds that by MIMO single-cast by 2 and 4 bits per channel use at 0 and 10 dB SNR, respectively.

scheduling is sometimes called the *multiuser gain* [6].

The channel-adaptive user scheduling technique was first introduced for a single-input, single-output (SISO) or a signal-input, multiple-output (SIMO) cellular downlink. In this paper, we investigate how this concept can be extended to a MIMO cellular downlink. A straightforward evolution from SISO to MIMO is to grant the channel - defined as a unit of time slot - to the user with the best MIMO channel. Although this offers substantial performance enhancement over SISO, by utilizing the spatial resource at the transmitter more intelligently, even higher spectral efficiencies can be achieved. For example, due to the size constraint of a mobile receiver, in many deployment situations a base station (BS) can have more antennas than a mobile. Given this imbalance, the BS should simultaneously transmit to several users to take full advantage of capacity scaling [2] [3].

I. INTRODUCTION

Multiple-input, multiple-output (MIMO) signaling has the potential to greatly enhance the spectral efficiency for wireless communications. It is now a well-known fact that, if the transmitter and the receiver are equipped with N_T and N_R antenna elements, respectively, the channel capacity scales linearly with $\min(N_T, N_R)$ in high SNR regime. For a comprehensive summary, see [1]. The MIMO concept was further generalized to scenarios in which those N_R receiving antennas do not belong to one single receiver. Even though the nice property of linear scaling of total channel capacity is still valid, the actual transmit and receive strategies are quite different due to the fact that the receivers cannot collaborate with each other [2] [3].

In modern cellular networks such as 1xEV-DO and DV, Release 5 and 6 of WCDMA(HSDPA and EUL), and IEEE 802.16 OFDMA, channel-adaptive user scheduling is employed to enhance both uplink and downlink network performance, particularly for data applications with relaxed rate jitter requirements. Loosely speaking, the network attempts to match transmissions with good instantaneous channel conditions in time (or frequency) [4]. The modulation order, coding format, and beamforming coefficients for a particular transmission can be adjusted in accordance to the instantaneous channel realization [5]. The gain due to such

In this paper, we consider a cellular network in which both the base station and the mobile stations (MSs) are equipped with multiple antenna elements. We will show that, as long as the number of MSs in the network is not too low, by simultaneously transmitting to several MSs which together have a favorable instantaneous channel combination, one can achieve a significantly higher channel capacity than by transmitting to only the single MS with the best instantaneous channel condition. We refer to these two strategies as MIMO multi-cast and MIMO single-cast, respectively. Conceptually, the capacity gain of MIMO multi-cast comes from the statistical independence among downlink channels. When the number of MSs is sufficiently large, the channels of some $N \leq N_T$ MSs allow the base station to spatially multiplex the downlink signals to these MSs together while only incurring a low multiple access interference (MAI) penalty. In addition to yielding a higher spectral efficiency, due to the inherently low MAI, such spatial multiplexing technique can be supported with a very simple receiver implementation.

A MIMO multi-cast scheduler must obtain the channel state information (CSI) and search for an appropriate group of MSs for transmission in real-time for each time slot. In order to evaluate the data rate supportable to a particular candidate MS group, the scheduler must compute the corresponding transmit weights and the power allocation [7][8]. For certain optimality

criteria such as maximizing the sum capacity, deriving the optimal scheduling decisions involves time-consuming iterative computations [2][9][10]. Therefore, for practical reasons, one must employ a reduced complexity scheduler. In this paper, we propose a pragmatic scheduling approach. This approach provides good scheduling performance and also significantly reduces both the scheduling complexity and the amount of auxiliary information exchange, such as CSI feedback and transmit vector notification.

We show that with the pragmatic scheduling approach MIMO multi-cast achieves a substantially higher channel capacity over MIMO single-cast. Our results also show that, when the number of MSs in a network is not too low, the performance degradation due to the use of suboptimal transmit and receive vectors produced by the pragmatic scheduler is no more than 5% at 10 dB signal-to-noise ratio (SNR).

The rest of this paper is organized as follows. In Section II, we give the channel models and our notations. We also provide a brief summary of known results. In Section III, we introduce the notions of MIMO single-cast and MIMO multi-cast downlinks. In Section IV, we propose a pragmatic scheduler approach. The intuition behind the algorithm and the performance bounds are given. In Section V, we give our simulation results. The summary remarks are given in Section VI.

II. DEFINITIONS

A. Channel models

In this paper we focus on the downlink, or the forward link, direction in a cellular network. In the downlink direction, the BS assumes the role of the transmitter. It is equipped with an N_T -element antenna. Multiple MSs are connected to one BS to receive information. For simplicity, we assume that each MS is equipped with an N_R -element antenna. This is referred to as an (N_T, N_R) downlink.

In order to keep our notation simple and to accentuate the key concepts, we consider only narrowband quasi-static channels. Our results can be extended to wideband channels using multi-carrier modulation techniques [11] [12]. A narrowband MIMO channel between the BS and MS k at a given moment of interest is modeled as a matrix $\mathbf{H}_k$. The i -th row, j -th column entry of $\mathbf{H}_k$, $\mathbf{H}_k(i, j)$, is the path gain from the j -th transmitting antenna to the i -th receiving antenna. At the receiver, additive white Gaussian noise is added to each receiving antenna. The discrete-time BS-to-MS k MIMO link can be modeled as

$$\mathbf{r}_k = \mathbf{H}_k \mathbf{s} + \mathbf{n}_k, \quad (1)$$

where $\mathbf{r}_k$ is the received vector signal by MS k , $\mathbf{s}$ is the transmitted vector signal, and $\mathbf{n}_k$ represents additive noise. The components of $\mathbf{n}_k$ are modeled as identical and independently distributed (i.i.d.) circularly symmetric Gaussian random variables with variance σ_k^2 . If the BS

transmits simultaneously to N MSs, $\mathbf{s}$ can be the sum of individual downlink signals: $\mathbf{s} = \sum_{k \in \{k_1, k_2, \dots, k_N\}} \mathbf{s}_k$. The base should construct $\mathbf{s}$ in a way to assist MS k to recover $\mathbf{s}_k$ from $\mathbf{r}_k$.

To model the propagation environment in dense urban environments, the entries of $\mathbf{H}_k$ are modeled as identical circular symmetric Gaussian random variables with common variance g_k^2 . When there is sufficient multipath and antenna separation, $\mathbf{H}_k(i, j)$ can be modeled as independent. On the other hand, if only a few multipath dominates, or if the angle of arrival at the BS is quite narrow, the entries of $\mathbf{H}_k$ can be correlated [13]. Under this situation, the statistics of the channel matrix can be approximated by [13]:

$$\mathbf{H}_k = \Psi_{R,k}^{1/2} \mathbf{H}_{w,k} \Psi_{T,k}^{1/2}, \quad (2)$$

where $\mathbf{H}_{w,k}$ consists of i.i.d. complex Gaussian entries with common variance of g_k^2 , and $\Psi_{R,k}$ and $\Psi_{T,k}$ are transmit and receive antenna correlation matrices, respectively. $\Psi_{R,k}$ and $\Psi_{T,k}$ are semi-positive-definite matrices whose traces are N_R and N_T , respectively.

B. Statically-scheduled multiuser MIMO downlink

In this section, we summarize published results concerning statically-scheduled multiuser MIMO downlink. In this conventional channel allocation approach, a pre-determined, usually quite simple, rule selects the MS or the subset of MSs to transmit to during a time slot. Such a user-selection rule does not take the instantaneous channel conditions into account.

Let us consider the case in which the BS transmits to only one MS, say MS k , during a time slot. We refer to such a practice as MIMO single-cast downlink. In MIMO single-cast, $\mathbf{s} = \mathbf{s}_k$. Let $\Sigma_k = E(\mathbf{s}\mathbf{s}^\dagger) = E(\mathbf{s}_k\mathbf{s}_k^\dagger)$ be the spatial autocorrelation matrix for the transmit vector signal $\mathbf{s}$ when transmitting to MS k . Given Σ_k , the instantaneous channel capacity with CSI at the transmitter is [14]:

$$C_k^{SC}(\Sigma_k) = \log_2(\det(\mathbf{I}_{N_R} + \frac{1}{\sigma_k^2} \mathbf{H}_k \Sigma_k \mathbf{H}_k^\dagger)) \text{ bits/channel use.} \quad (3)$$

In (3), $\mathbf{I}_{N_R}$ is an N_R -by- N_R identity matrix. The overall transmit power constraint requires $tr(\Sigma_k) \leq P_0$.

Consider the singular value decomposition of $\mathbf{H}_k$: $\mathbf{H}_k = \mathbf{U}_k \mathbf{D}_k \mathbf{V}_k^\dagger$. It can be shown that if the transmit autocorrelation matrix $\Sigma_k = \mathbf{V}_k \mathbf{P} \mathbf{V}_k^\dagger$, where $\mathbf{P}$ is a diagonal matrix with nonnegative diagonal elements, the MIMO channel can be decomposed into parallel SISO channels with no mutual interference among them. Henceforth in this paper we refer to these SISO channels as the spatial eigenmodes of the channel matrix. The SISO channel that corresponds to the largest singular value is of particular interest. We shall refer to this SISO channel as the dominant spatial eigenmode. A water-filling solution on $\mathbf{P}$ under the constraint that $tr(\mathbf{P}) \leq P_0$ maximizes $C_k^{SC}(\Sigma_k)$ over the

space of all Σ_k that satisfies the average power constraint [15].

Instead of transmitting to only one MS in a time slot, a BS may transmit to multiple MSs simultaneously. Spatial processing at the receivers must isolate out the intended signal from the interfering ones. We refer to this practice as MIMO downlink multi-cast. For simplicity, we assume that each MS is to receive one data stream, even though it may be able to receive multiple data streams.

Specifically, suppose that the BS is to transmit to $N = N_T$ MSs indexed by 1, 2, ..., N . From its knowledge of $\mathbf{H}_1, \mathbf{H}_2, \dots, \mathbf{H}_N$, the BS computes an N_T -by- N transmit matrix $\mathbf{M}$. The k -th column of $\mathbf{M}$, denoted as $\mathbf{m}_k$, represents the unmodulated vector signal for MS k . Sometimes $\mathbf{m}_k/|\mathbf{m}_k|$ is called the spatial signature, or the spatial precoding vector, for MS k . The overall transmitted signal vector $\mathbf{s}$ is the vector sum of modulated vector signals:

$$\mathbf{s} = \sum_{k=1}^N \mathbf{m}_k x_k = \mathbf{M}\mathbf{x}, \quad (4)$$

where x_k is the symbol intended for MS k , and $\mathbf{x} = (x_1, x_2, \dots, x_N)^t$ denotes the vector of transmit symbols. In our notation, $E[|x_k|^2] = 1$ for all k . The average transmit power for the transmission to MS k is hence $|\mathbf{m}_k|^2$. The total average power constraint translates to $\text{tr}(\mathbf{M}^\dagger \mathbf{M}) \leq P_0$.

At the receiving end, we assume that interference is suppressed using linear spatial processing only. Nonlinear techniques such as successive interference cancellation will not be considered in this paper [16]. Specifically, MS k forms an estimate for the symbol intended for it from its antenna inputs:

$$\begin{aligned} \hat{x}_k &= \mathbf{w}_k^\dagger \mathbf{r}_k = \mathbf{w}_k^\dagger (\mathbf{H}_k \mathbf{s} + \mathbf{n}_k) \\ &= (\mathbf{w}_k^\dagger \mathbf{H}_k \mathbf{m}_k) x_k + \sum_{i \neq k} (\mathbf{w}_k^\dagger \mathbf{H}_k \mathbf{m}_i) x_i + \mathbf{w}_k^\dagger \mathbf{n}_k. \end{aligned} \quad (5)$$

In (5), $\mathbf{w}_k$ is a properly chosen N_R -by-1 column vector. Given $\mathbf{w}_k$ and $\mathbf{m}_k$, $\mathbf{w}_k^\dagger \mathbf{H}_k \mathbf{m}_k$ can be considered as the SISO virtual channel from the BS to MS k .

Recent studies have investigated the issue of the construction of $\mathbf{M}$ and $\mathbf{w}_k$ given the knowledge of $\mathbf{H}_k, k = 1, 2, \dots, N$. A few examples are summarized as follows.

- 1) The easiest and most traditional way is to use the $\mathbf{m}_k$ that maximizes the signal strength at MS k , ignoring the consequences at the other receivers. According to this criterion, $\mathbf{m}_k$ is a scaled version of the dominant right singular vector of $\mathbf{H}_k$. Except for certain extreme situations, this strategy does not perform well.
- 2) In [7] the generalized zero forcing solution was studied. The criterion used to select $\mathbf{M}$ and $\mathbf{w}_k$ is such that the multiuser interference term in (5) is exactly zero. Even though zero-forcing precoding does not introduce noise enhancement, it could suppress the desired signal.
- 3) In [10], the matrix $\mathbf{M}$ is chosen to maximize the signal-to-leakage ratio. Such a scheme can be effective

in high signal-to-noise and high signal-to-adjacent cell interference ratio regimes.

- 4) In [3], a generalized interference balancing scheme is proposed. Although reaching maximum sum capacity, the solution requires a computation-intensive iterative calculation.

III. SCHEDULED MULTIUSER MIMO DOWNLINK

In a channel adaptive rapid user scheduling network, downlink is partitioned into time slots. Each time slot lasts for only a very short duration such that the wireless channel can be considered essentially time-invariant within a slot. In a SISO or SIMO downlink, in order to achieve the highest network throughput, according to information theory, a time slot shall be dedicated to the MS which is experiencing the most advantageous channel. The modulation format, coding scheme, and power allocation used for that slot can all be dynamically adjusted to best suit the instantaneous channel realization. The gain due to scheduling is sometimes called *multiuser gain*.

For each slot, the network scheduler computes a score for each MS, and then selects the MS with the highest score. Explicitly or implicitly, the score typically contains two parts: a data rate score and a fairness score [4] [17]. The data rate score reflects the data rate that can be supported by the current channel condition. The fairness score, on the other hand, conveys how urgent the network must grant the slot to the MS in order to ensure that the MS receives adequate quality of service.

The channel adaptive scheduling concept can be extended beyond SISO and SIMO. This extension is straightforward in the case of MIMO single-cast. In such a downlink, the rate score shall be formulated to reflect the data rate achievable over a MIMO link. Note that the supportable data rate is not only a function of the instantaneous channel realization but also of the transmit and receive schemes employed over the MIMO link. There are a wealth of MIMO single-cast transceiving schemes in the literature such as the famous BLAST algorithm [18].

However, over a MIMO downlink, unlike in the case of SISO and SIMO, it is actually not optimal to dedicate a slot to a single MS in terms of maximizing network throughput. According to the “writing on a dirty paper” concept [19], it is possible to construct a transmit signal that leads to zero multiple access interference at the receivers if CSI is available at the BS. Should this be done, significant throughput increase can be achieved over MIMO single-cast. However, such a method is very complicated and is not compatible with existing communication systems and protocols.

Instead, in this paper we focus on a downlink described by (5). In this downlink network, the overall transmit vector signal is formed as a linear combination of individual signal vectors. At the opposite end, the receivers can only suppress

interference by means of linear spatial processing. As we will demonstrate later, this practice can still improve throughput significantly over MIMO single-cast if the BS transmits to an appropriately chosen subset of MSs.

A MIMO multi-cast scheduler must determine the achieved data rate if it is to transmit to a given group of N MSs. The achieved data rate is not only a function of the instantaneous channels but also the transmit and receive vectors. Consider a group of N MSs. Denote the set of MS indices for this group as $\mathcal{K}$. Given the transmit vectors $\mathbf{m}_k$ and the receive vectors $\mathbf{w}_k$, the total channel capacity for this group of MSs, which we use as the data rate score in this paper, is

$$C^{\text{MC}}(\mathcal{K}, \mathbf{M}, \{\mathbf{w}_k\}) = \sum_{k \in \mathcal{K}} \log_2 \left(1 + \frac{|\mathbf{w}_k^\dagger \mathbf{H}_k \mathbf{m}_k|^2}{|\mathbf{w}_k|^2 \sigma_k^2 + \sum_{i \in \mathcal{K}, i \neq k} |\mathbf{w}_k^\dagger \mathbf{H}_k \mathbf{m}_i|^2} \right) \quad (6)$$

bits/channel use.

In (6), we assume that the multiple access interference can be modeled as complex Gaussian.

IV. A PRAGMATIC SCHEDULING APPROACH

A. The need for a pragmatic scheduler

As we mentioned above, the complexity of scheduling in a downlink MIMO multicast network is much higher compared to its counterpart in a SISO network. In a network with N_U MSs, the scheduler must consider $\binom{N_U}{N}$ groups of N MSs instead of just N_U individual MSs. Furthermore, for each candidate group, the scheduler must complete the signal design in order to evaluate the corresponding data rate score.

In general, one would like to minimize the scheduling delay, which is the time lag between the instant of channel measurement and the instant of the corresponding downlink transmission. During this time, the scheduler computes the winning group and the transmit/receive vectors. The longer it takes for this computation, the longer the delay must be. Unfortunately, in general a long delay results in poor scheduler performance due to the time varying nature of the radio channel. In light of this preference for small scheduling delay, a high-performance, fast scheduling algorithm is highly desirable in practice.

Another practical concern is the amount of auxiliary information exchange. To perform scheduling, a BS must acquire necessary CSI. Typically, an MS measures the CSI and transmits it to the BS over the uplink. Over the downlink, the BS announces the scheduling decision. The BS may also transmit other assistance information (e.g. to assist in producing receiving weights). To reduce overhead and to improve robustness against errors, it is desirable to employ a scheduling algorithm which inherently demands a low amount of auxiliary overhead.

B. Pragmatic scheduler

In this subsection, we describe the proposed pragmatic scheduling algorithm. The most important step to a pragmatic scheduler is to simplify the process of transmit and receive vector design. To understand the motivation of our approach, consider for the moment the following particularly fortunate situation. Suppose that there exists N downlink MIMO channel matrices $\mathbf{H}_1, \mathbf{H}_2, \dots, \mathbf{H}_N$ whose dominant right singular vectors are orthogonal to each other. In this case, the base station can simply use these dominant right singular vectors as the spatial signatures for MS 1, 2, ..., N . At MS k , the optimal receive weight is the dominant left singular vector of $\mathbf{H}_k$. With such transmit and receive basis vectors, all MSs receive their respective signals through their respective dominant spatial modes without any MAI. To maximize the aggregate channel capacity, a standard water-pouring procedure is used to determine the optimal transmit power allocation.

Certainly one cannot design a scheduler relying on such a rare scenario. Nevertheless, if the number of MSs is much greater than the number of transmit antennas, due to the independence among channel fades, there exist a large number of groups of N MSs whose channels are approximately *mutually orthogonal* in the sense that the dominant right singular vectors of their channel matrices are approximately mutually orthogonal.

The proposed pragmatic scheduler for MIMO multi-cast is formulated as follows. The scheduler first assumes that the receive weight for MS k is the dominant left singular vector of $\mathbf{H}_k$. Furthermore, it imposes a zero-forcing requirement, i.e., the transmit vectors must be chosen such that there is no MAI at any MS given such receive weights. Specifically, say the scheduler is considering MSs 1, 2, ..., N , $N \leq N_T$. Let $\mathbf{w}_k$ denote the dominant left singular vector of $\mathbf{H}_k$. Define $\tilde{\mathbf{H}}_{\mathcal{K}} = (\mathbf{H}_1^\dagger \mathbf{w}_1, \mathbf{H}_2^\dagger \mathbf{w}_2, \dots, \mathbf{H}_N^\dagger \mathbf{w}_N)^\dagger$. The N -by- N_T matrix $\tilde{\mathbf{H}}_{\mathcal{K}}$ is the collection of the N_T -in, 1-out virtual channels between the BS and MS 1, 2, ..., N . The transmit matrix $\mathbf{M}$ is constructed by $\mathbf{M} = \tilde{\mathbf{H}}_{\mathcal{K}}^{-1} \mathbf{G}$, where $\tilde{\mathbf{H}}_{\mathcal{K}}^{-1}$ is the pseudoinverse of $\tilde{\mathbf{H}}_{\mathcal{K}}$ and $\mathbf{G}$ is some appropriately chosen nonnegative diagonal matrix such that $\mathbf{M}$ satisfies the power constraint. Given this choice of transmit and receive weights, the signal-to-noise ratio at the output of the virtual channel $\hat{x}_k = \mathbf{w}_k^\dagger \mathbf{H}_k \mathbf{m}_k x_k + \mathbf{w}_k^\dagger \mathbf{n}_k$ is

$$\rho_k = |\mathbf{v}_k^\dagger \mathbf{m}_k|^2 \frac{d_{1,k}^2}{\sigma_k^2}, \quad (7)$$

where $d_{1,k}$ and $\mathbf{v}_k$ are the dominant singular value and the dominant right singular vector of $\mathbf{H}_k$, respectively. Note that, in this construction, $\mathbf{m}_k$ are not necessarily orthogonal to each other.

Equation (7) provides an intuitive explanation as to why MIMO multi-cast is superior to MIMO single-cast. If the dominant right singular vectors of the channel matrices are approximately mutually orthogonal, then $\mathbf{m}_k$ can be chosen to be almost parallel to $\mathbf{v}_k$. As a result, almost all of the

transmit power reaches MS k . Furthermore, the amplitude gain for the virtual SISO channel is close to the dominant singular value of $\mathbf{H}_k$. In the case of MIMO single-cast, the achieved channel capacity is the sum of channel capacities for individual SISO channels whose channel amplitude gains are the singular values of the channel matrix [14]. In contrast, the aggregate channel capacity for MIMO multi-cast is the sum of channel capacities for individual SISO channels whose channel gains are nearly the dominant singular values for the corresponding channel matrices. Clearly, the channel capacity achieved by MIMO multi-cast is higher due to higher channel gains.

The observation above predicts an interesting and somewhat surprising phenomenon. It is generally believed that spatial channel correlation depresses the channel capacity for a MIMO link. When there is spatial fading correlation, the distributions of the singular values of the channel matrix deteriorate, except that of the dominant mode [13]. The weakened minor spatial modes become ineffective for information transport, especially when SNR is low. However, in a MIMO multi-cast downlink, the intended signals are transported primarily through the individual dominant modes. Hence, spatial fading correlation can potentially improve the throughput of such downlink.

Finally, we summarize our pragmatic scheduling scheme.

- 1) Acquire necessary CSI. Only the dominant right singular vectors, $\mathbf{v}_k$, and the normalized dominant virtual channel gains, $(d_{1,k}/\sigma_k)^2$, are required.
- 2) For each group of N MS, compute the transmit matrix $\mathbf{M} = \hat{\mathbf{H}}_{\mathcal{K}}^{-1}\mathbf{G}$. A reasonable heuristic, such as equal norm for all m_k , can be used for the selection of $\mathbf{G}$ to satisfy the average power constraint. Compute the sum of individual channel capacities as the data rate score for this group using (7).
- 3) Adjust the data rate score with the fairness score. Select the candidate with the largest composite score.

This scheduling algorithm has the following advantages. The primary computation complexity is in computing the inverse of a small matrix for each candidate group. This is much less complicated when compared to many algorithms such as those in [3]. As far as overhead is concerned, over the uplink, a MS only transmits the dominant right singular vector and the normalized dominant singular value. The scheduler does not need to know the full channel matrix. Finally, the BS does not need to transmit any information to assist the MS to construct the receive vector. As a matter of fact, since the receiving weight is independent of the scheduling decision, a MS can listen to the base station using the default receive weight and unilaterally detects whether a transmission to it takes place. In this case, downlink overhead can be completely eliminated.

Before we conclude this section, we note that for some candidate group whose dominant eigenmodes are not nearly mutually orthogonal, the algorithm above can seriously un-

derestimate the supportable data rate for the candidate. Nevertheless, when there are many MSs in a network, we expect that it is rare for such a candidate group to be elected as the winner group even if its actual channel capacity can be properly computed at the scheduler. The reason is that MIMO multi-cast to such a group inevitably makes use of minor spatial eigenmodes to mitigate MAI. Thus such a candidate group stands at a natural disadvantage compared to groups whose dominant eigenmodes are nearly mutually orthogonal.

C. Performance upperbound for further optimization of the transmit and receive vectors

In the scheduling process, in order to calculate the supported data rate, the proposed pragmatic scheduler must first construct a set of assumed transmit and receive weights for each candidate group. Once the winning group is determined, however, the transmit and receive weights to actually be used can be further improved. For instance, given the transmit vector, an MS can utilize an MMSE receive weight instead of the ZF weight to achieve a higher received SNR. Other potential improvements, such as those in [2], can be found in the literature.

To estimate the benefit of further transmit and receive vector optimization, we consider the following simple upper bound. Assume that the MSs can somehow perfectly eliminate MAI without sacrificing the intended signal. Under this assumption, the BS shall transmit to the selected MSs via individual dominant spatial eigenmodes. Specifically, the optimal transmit and receive weights applied for MS k are the dominant right and left singular vectors of $\mathbf{H}_k$, respectively. The SNR at MS k is

$$\rho'_k = p_k \frac{d_{1,k}^2}{\sigma_k^2}, \quad (8)$$

where p_k is the power allocated to MS k .

As the number of MSs in the network grows, we expect that the scheduler can find correspondingly more MS groups whose members momentarily experience a low level of MAI due to the near orthogonality among the dominant eigenmodes. Hence, as the number of MSs increases, the achieved capacity by the pragmatic scheduler shall gradually trend toward this upper bound.

V. SIMULATION RESULTS

In this section, the simulation results are presented. We compare scheduled SISO, SIMO, MIMO single-cast, and MIMO multi-cast configurations. We intend to study the following issues through simulation: the performance gain of MIMO multi-cast over the rest of the configurations; the required number of MSs in the network for the performance gain to be significant; and the room for improvement due to further weight optimization after the winner MS group is chosen.

A. Simulation setup

Five thousand runs were conducted to collect the channel capacity histograms. During each run of a simulation, we generate N_U downlink channels, select the winner MS or the winner group of MSs, and record the resulting channel capacity. We assume that all the MSs experience the same path loss and noise power. The channel matrices are randomly generated according to the model in Section II-A. Channel matrices corresponding to different MSs are modeled as independent and identically distributed. For simplicity, in the MIMO configurations, the transmit power is divided evenly among the MSs.

Due to the fact that the channel matrices for all the MSs share the same underlying distribution, all MSs experience the same long term data rate. Hence, this set of result can be viewed as the performance of a downlink supporting an application whose jitter requirement is not stringent.

B. Simulation results

In Figure 1 and 2, we show the average downlink channel capacity for SISO, (1, 2) SIMO, (2, 2) MIMO single-cast, and (2, 2) MIMO multi-cast. Figure 1 and Figure 2 represent low SNR and high SNR scenarios, respectively. As can be seen from Figure 1, with just two transmit and two receive antennas, the performance gain of MIMO single-cast over SIMO when operating in a low SNR (0 dB) environment is marginal at best. It is likely that this gain can be lost in a real-world implementation due to other practical considerations. In contrast, using the MIMO multi-cast configuration with the proposed scheduler, a capacity gain of over 1 bit/channel use over the (1, 2) SIMO configuration can be obtained. At a higher SNR of 10 dB, as is shown in Figure 2, MIMO single-cast provides a 2 bits/channel use improvement over SIMO. MIMO multi-cast provides a further 1.7 bits/channel use advantage over MIMO single-cast.

From Figures 1 and 2, we observe that a (2, 2) MIMO multi-cast downlink outperforms a (2, 2) MIMO single-cast one even with as few as four MSs. The capacity gap continues to widen as N_U grows until N_U reaches about 12. After that, the capacity gap remains approximately constant.

Comparing the average channel capacity achieved by the proposed scheduler and its upper bound, one finds that when N_U is 10 or higher, the difference between these two is quite small. The interpretation for this phenomenon is that, as the number of users in the network reaches 10 or higher, the dominant spatial eigenmodes of the two MSs chosen by the scheduler are almost mutually orthogonal. Under this condition, the use of zero-forcing transmit and receive weights entails only a very small penalty. Further optimizing the transmit and receive vectors produces comparatively insignificant benefits.

In Figures 3 and 4, we show the average downlink channel capacity for each configuration at 0 and 10 dB

SNR, respectively. When applicable, the number of transmit and receive antenna elements is 4. Due to the use of more antenna elements than the cases above, the differences in average channel capacity among these configurations become more substantial. Similar to the two-antenna configuration above, the gap in achieved average channel capacity between MIMO multi-cast and MIMO single-cast continues to grow as N_U increases. Given a modest number of MSs, MIMO multi-cast achieves an average channel capacity that is 2 and 4 dB higher than its counterpart by MIMO single-cast at 0 and 10 SNR, respectively. Note that MIMO multi-cast does not outperform MIMO single-cast unless N_U is greater than 6. We also note that, after N_U reaches 20, the performance of the proposed pragmatic scheduler and its upper bound are quite close.

In Figures 5 and 6, we show the average downlink channel capacity with spatially correlated fading. The number of transmit and receive antenna elements is 2. The transmit and receive antenna fading correlation coefficient in our simulation is chosen at 0.5 and 0, respectively. This choice is consistent with an outdoor cellular setup. A transmit correlation coefficient of 0.5 represents a moderate level of fading correlation. When Figures 5 and 6 and Figures 1 and 2 are compared, it is evident that fading correlation does suppress the achieved channel capacity in a MIMO single-cast downlink. However, as predicted in Section IV, in a MIMO multi-cast downlink, the transmit fading correlation actually enhances the achieved aggregate channel capacity.

VI. SUMMARY

In this paper, we investigated algorithmic and performance aspects of a scheduled multiuser MIMO downlink. For every downlink time slot, a scheduler determines a small group of MSs for transmission based on the instantaneous channel conditions. The downlink transmit signal is a linear spatial multiplexing of signals intended for individual users. At the receiving end, the received signals from multiple receive antennas are linearly combined to extract the intended signal.

Although more complicated, we showed that scheduled MIMO multi-cast offers significant performance enhancement over scheduled MIMO single-cast. Our intuitive explanation is that, given sufficient number of users in a network, due to the independence among channel fades, there exist many groups of MSs whose associated channel matrices allow simultaneous downlink transports using their dominant spatial eigenmodes with inherently very low level of MAI.

Unfortunately, due to the need to schedule multiple MSs in one time slot, the amount of computation involved in MIMO multi-cast scheduling can be enormous. In this paper, we proposed a pragmatic scheduling approach. This approach provides good scheduling performance and also significantly reduces both the scheduling complexity and the amount of auxiliary information exchange, such as CSI feedback and transmit vector notification.

Our simulation results indicate that, when there are two transmit antennas at the base station and two receive antennas at each mobile station, the average channel capacity achieved by MIMO multi-cast is higher than its counterpart by MIMO single-cast by more than 1 and 2 bits per channel use at 0 and 10 dB SNR, respectively. If the number of antenna elements is four, the difference in achieved channel capacity increases to slightly more than 2 and 4 bits per channel use at 0 and 10 dB SNR, respectively. This performance gain can actually be realized with a very limited number of users in a network.

In general, spatial fading correlation improves the dominant spatial eigenmode but degrades the other minor eigenmodes. Consequently, we predicted that MIMO multi-cast could perform better in an environment with a reasonable level of fading correlation. Our simulation results confirmed this prediction.

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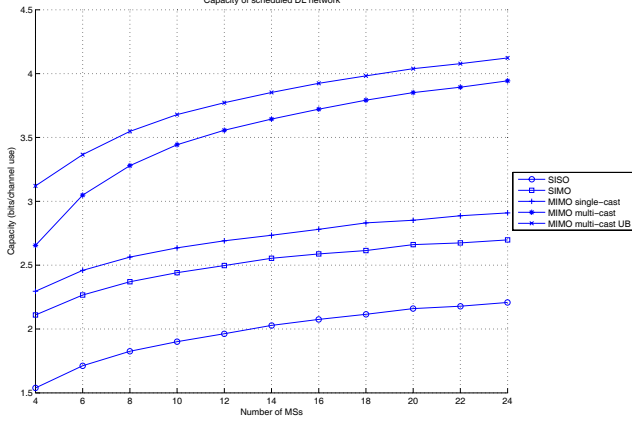


Fig. 1. Average aggregate channel capacity for SISO, (1,2) SIMO, and (2,2) MIMO configurations at 0 dB SNR.

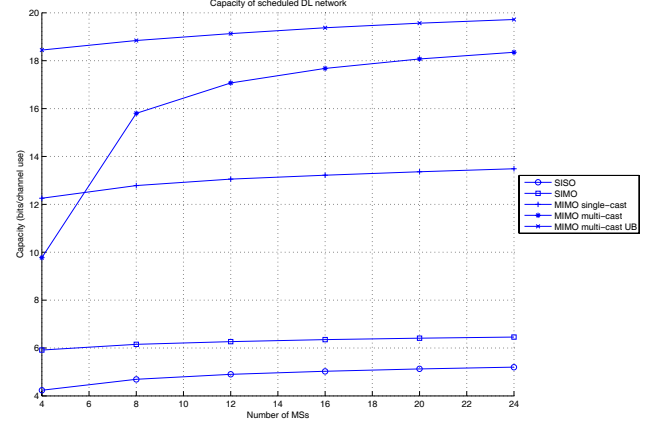


Fig. 4. Average aggregate channel capacity for SISO, (1,4) SIMO, and (4,4) MIMO configurations at 10 dB SNR.

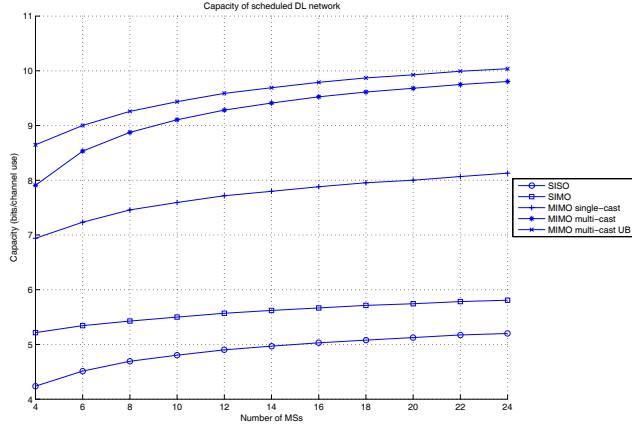


Fig. 2. Average aggregate channel capacity for SISO, (1,2) SIMO, and (2,2) MIMO configurations at 10 dB SNR.

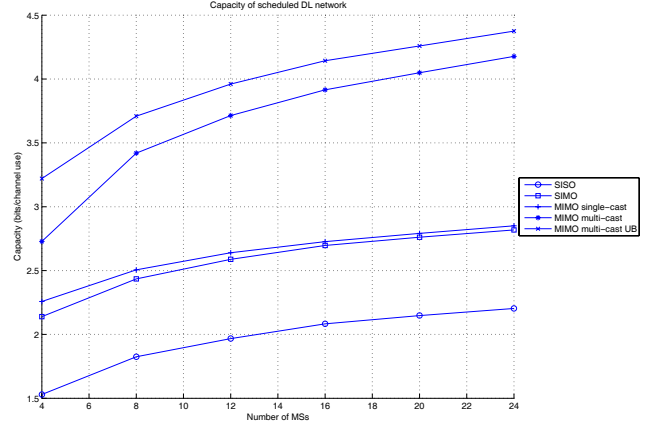


Fig. 5. Average aggregate channel capacity for SISO, (1,2) SIMO, and (2,2) MIMO configurations at 0 dB SNR under correlated fading. The transmit and receive fading correlation coefficients are 0.5 and 0, respectively.

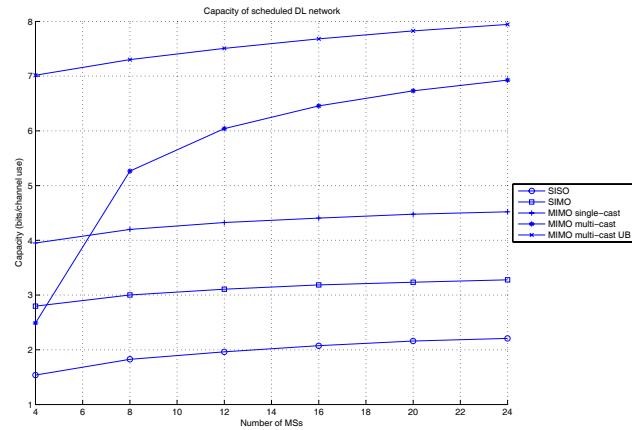


Fig. 3. Average aggregate channel capacity for SISO, (1,4) SIMO, and (4,4) MIMO configurations at 0 dB SNR.

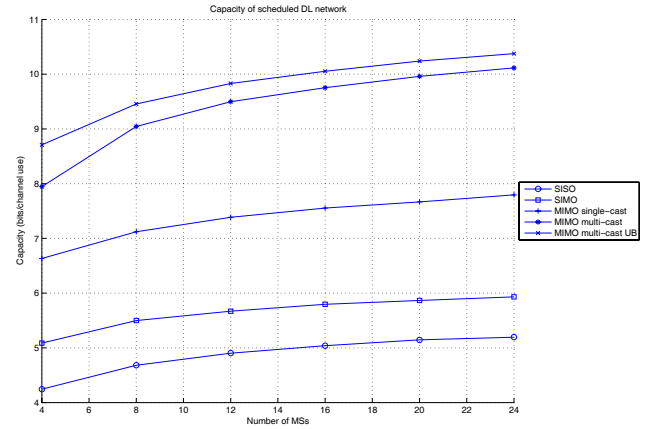


Fig. 6. Average aggregate channel capacity for SISO, (1,2) SIMO, and (2,2) MIMO configurations at 10 dB SNR under correlated fading. The transmit and receive fading correlation coefficients are 0.5 and 0, respectively.