Interfering MIMO Links with Stream Control and Optimal Antenna Selection

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Abstract—**Recent work has shown that multiple-input and multiple-output (MIMO) systems hold great promise to help achieve the high data rates required for next generation Wireless Local Area Networks (WLANs). This paper analyzes the advantages of using optimal antenna selection to aid the stream control process for the open-loop MIMO link with a limited-feedback channel. It is observed that stream control with optimal antenna selection renders significant throughput gain relative to stream control with deterministic selection for both simulated data and measured data. In high-interference zones, the gap between the open- and closed-loop MIMO throughput is significantly reduced if optimal antenna selection is used. Lastly, open-loop MIMO with optimal antenna selection provides better protection against correlated interference than open-loop MIMO with deterministic antenna selection.**

Index Terms—**MIMO, WLAN, stream control, antenna selection, co-channel interference, correlated interference**

I. INTRODUCTION

The current WLAN standard IEEE 802.11b is based on the carrier sense multiple access/collision avoidance (CSMA/CA) protocol, which does not permit simultaneous transmissions from two or more neighboring nodes that might cause interference to each other. The next generation WLAN standards allow nodes to have multiple antennas, which in turn provide additional degrees of freedom at the receiver to mitigate the deleterious effect of co-channel interference [1]-[3]. Thus MIMO capable nodes can transmit simultaneously, utilizing the precious resources optimally and improving the overall network throughput performance.

In this paper, we propose an efficient stream control strategy based on optimal antenna selection to jointly optimize the network throughput for open-loop MIMO systems (OL-MIMO) where only limited channel state information (CSI) is available at the transmitter. A number of authors have considered MIMO with antenna selection as a means of providing spatial diversity to the streams in an isolated (no interference) MIMO link [4]-[6]. However, achieving optimal throughput in the presence of co-channel interferers requires a mechanism to regulate the number of streams transmitted by each node, depending upon the strength and number of interfering streams. The authors of [7]-[8] suggested an optimal transmission scheme for OL-MIMO in an interference-free zone that puts independent data streams with equal power into the different antennas. However in an interference-limited environment, this may not be the best strategy. The author in [9] found that the system performance of OL-MIMO in presence of strong co-channel interferers is optimized when all power is put into a single antenna. The authors in [10]-[11] considered closed-loop MIMO (CL-MIMO) systems (i.e. when each link does waterfilling over its whitened channel) and proposed a distributed stream control mechanism wherein an additional stream is added if it leads to an increment in the network throughput. The authors show that MIMO nodes operating under this strategy greatly improve the overall network throughput compared to a time-division multiple access (TDMA) protocol, in which MIMO links operate in succession. In the sequel, we will refer to the transmission strategy with multiple antennas as SDMA, and its performance will be compared with the TDMA protocol.

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Although stream control works best with CL-SDMA, the overhead is significant, as the CSI for each pair of transmit-receive nodes has to be signaled back to the transmitters. Moreover, implementation of stream control for CL-SDMA is numerically intensive, involving matrix decompositions, thus real-time implementation would be a challenge as the channel matrix size grows. On the other hand, stream control for OL-SDMA has significantly less complexity. In [11], CL-SDMA was compared with OL-SDMA, where both used stream control, but the antenna selection in OL-SDMA was deterministic; in this case, OL-SDMA performed significantly worse relative to CL-SDMA when the interference was strong.

In this paper, we extend the analysis of [10]-[11] for OL-SDMA systems and show that a middle-path approach of having a limited feedback channel (used to convey the set of selected transmit antennas) provides a trade-off between the feedback signaling load and the network throughput performance. We show that for both simulated and measured channels, the performance gap between CL- and OL-SDMA with limited feedback can be substantially abridged if optimal antenna selection is combined with stream control.

The organization of the rest of the paper is as follows. In Section II we present the system model describing underlying assumptions. In Section III, we analyze optimal transmission strategies for different SDMA schemes including antenna selection assisted stream control for OL-SDMA with limited feedback. Sections IV and V present simulation and measured channel results, respectively. Finally, Section VI summarizes the main conclusions.

II. SYSTEM MODEL

We consider a system with L links (pairs of transmit and receive nodes) where each link is subjected to co-channel interference from the remaining L-1 links. The transmitting nodes are equipped with n_t antenna elements and receiver nodes use n_r antennas. The received baseband vector corresponding to the i^{th} link is given by

$$\mathbf{y}_i = \sqrt{\rho_{i,i}}\mathbf{H}_{i,i}\mathbf{x}_i + \sum_{j\neq i}^{L}\sqrt{\rho_{i,j}}\mathbf{H}_{i,j}\mathbf{x}_j + \mathbf{n} \qquad (1)$$

where $\{\mathbf{H}_{i,j}, \rho_{i,j}\}$denotes the channel gain matrix and noise normalized power corresponding to the transmitter of the j^{th} link and receiver of the i^{th} link, $\mathbf{x}_i$ denotes the transmit vector for the i^{th} link and $\mathbf{n}$ is the additive white Gaussian noise with zero mean and unit variance. The channel is assumed to be slowly varying, Rayleigh faded, and fixed for the duration of an entire burst. The entries of the channel matrix are independent Gaussian distributed complex random variables with zero mean and unit variance.

In the simulations presented in Section IV, we will analyze the performances of 2-link and 3-link network models. Figure 1 depicts the 2-link network model where R and D denote the receiver-transmitter separation for the interfering and the desired link respectively. Each node is assumed to have 4 antennas. The average signal-to-interference ratio (SIR) varies linearly as $n\log(R/D)$ on a logarithmic scale, where n denotes the path-loss exponent. In the 3-link network model, the links lie on every other edge of a hexagon as in [10].

III. MIMO CAPACITY AND STREAM CONTROL

In this section, we will briefly discuss the optimal transmission strategy with respect to system throughput for open-loop MIMO systems when no CSI is available to transmitter. Our goal is to maximize the network throughput (heretoafter referred to as "throughput"), which is defined as the sum of the link ergodic capacities. The ergodic capacity of i^{th} MIMO link in presence of cochannel interferers, when the interferers are treated as noise, is given by [12]

$$C(i) = \log_2 \det\left(\mathbf{I}_{n_r} + \tilde{\mathbf{H}}_i\mathbf{P}_{i,i}\tilde{\mathbf{H}}_i^{\dagger}\right) \qquad (2)$$

where, $\mathbf{I}_{nr}$ denotes the $n_r\times n_r$ identity matrix, $\mathbf{P}_{i,i}$ is the signal covariance matrix used by the transmitter of the i^{th} link and $\tilde{\mathbf{H}}_i$ denotes the spatially whitened channel matrix given as

$$\tilde{\mathbf{H}}_i = \left(\mathbf{I}_{n_r} + \sum_{j\neq i}^{L-1}\mathbf{H}_{i,j}\mathbf{P}_{i,j}\mathbf{H}_{i,j}^{\dagger}\right)^{-1/2}\mathbf{H}_{i,i} \qquad (3)$$

Since no CSI is available to the transmitter, all transmitted streams are allocated equal power, and an independent data stream is transmitted from each antenna [4],[8]. However, for optimal throughput, not all streams need to be transmitted (i.e. not all transmit antennas need to be excited). Here, "optimal" means that for a given number of streams per transmitter, the subset of streams/antennas among all possible combinations, for all links, that maximizes the throughput is chosen. We note that such a global optimization would not be reasonable in practice.

In the following, we discuss the optimal stream control strategy for the cases when the interference is either weak or strong. In absence of interference at the receiver and CSI at the transmitter, the capacity given by (2) is maximized when equal power is put into all antennas [4]-[8]. The transmit power correlation matrix in this case is simply a scaled identity matrix, $\mathbf{P}_{i,i} = (\rho_{i,i}/n_t)\mathbf{I}_{n_r}$. A similar strategy is followed in case of weak interference [9]. Thus in the case of weak interference, stream control is not that critical and close to optimal performance can be extracted by adopting OL-SDMA using all streams.

In the case of strong interference, the number of incident interfering streams becomes critical. When the number of interfering streams is greater than the number of receive antennas of the victim node, the optimal strategy is to excite just a single transmit antenna [9] as in this case the receiver is already overloaded. However, when the number of interfering streams is less than the number of receiver antennas, the victim node can suppress the interference using linear processing techniques [13]. In this case, the optimal strategy is to excite as many as n_r-n_i transmit antennas, where n_i denotes the number of incident interfering streams on the victim node [13]. The transmit power correlation matrix is given by

$$\mathbf{P}_{i,i} = \frac{\rho_{i,i}}{(n_r - n_i)}diag(\underbrace{1,1,..1}_{n_r-n_i},\underbrace{0,0,..0}_{n_t-n_r+n_i}) \qquad (4)$$

where $diag$(.) denotes the diagonal matrix formed by the elements in its argument. The optimal stream control approach requires the use of the subset of transmit antennas that gives best throughput performance. The transmit power correlation matrix is formed by reordering of diagonal elements in (4).

IV. SIMULATION RESULTS

In this section, we present simulation results for 2-link network as shown in Figure 1 and the 3-link network. The results are generated using Monte Carlo simulation of 1000 channel trials. For the CL-SDMA results, the algorithm of [10] was used. In [10], authors demonstrate the usefulness of stream control for various SDMA techniques with the exception of OL-SDMA with optimal antenna selection. This section mainly considers SDMA schemes with stream control and draws performance comparisons between OL-SDMA performance with deterministic antenna selection and optimal antenna selection. For more detail about the contents of this section, with the exception of optimal selection, the reader is referred to [14]. We consider a fair energy transmission approach, which requires both TDMA and SDMA networks use equal transmit powers, to allow for a fair performance comparison. The noise-normalized transmit power is fixed at P_T = 20dB for the TDMA scheme. For SDMA scheme, the total transmit power is divided equally among all the transmitting nodes, i.e. $P'_T = P_T/2$ = 17dB for the 2-link network and $P'_T = P_T/3$ = 15.2dB for the 3-link network.

A. Throughput Performance

Figure 1 shows the average percent throughput improvements for several SDMA schemes relative to TDMA for a 2-link network. The horizontal axis is $n\log(R/D)$, where n is the path loss exponent. As a reference, the 802.11 MAC is likely to enforce time multiplexing due to interference if $R/D < 2$. For $n = 3$, for example, $R/D < 2$ corresponds to $3\log(R/D) < 0.9$. Therefore, if an SDMA scheme has positive throughput improvement for $n\log(R/D) < 0.9$, then a MAC that exploits SDMA, such as the one in [1], would outperform the 802.11 MAC.

From Figure 1, we observe that CL-SDMA with stream control yields the best performance as expected. In [10], authors highlight the importance of stream control, which strikingly improves the throughput of OL-SDMA in strong interference regions. Yet, without optimal selection, stream control is not enough to make SDMA better than TDMA for $n\log(R/D) < ½$, when the interference is strong. However, when optimal antenna selection is used, the gap between CL-SDMA and OL-SDMA is reduced and in fact OL-SDMA outperforms TDMA even in high interference regions, offering an improvement of about 5%. For $n\log(R/D) > 1$, the interference from neighboring nodes is weak enough to allow the use of 4 data streams, thus explaining similar performances by various SDMA schemes. Thus stream control and optimal selection are the key factors in throughput performance when the interference is strong.

We also found that for a 3-link hexagonal network model, the average percent throughput improvement curves for different SDMA schemes follow similar trends. Again CL-SDMA with stream control yields the best performance with an improvement of about 20% over TDMA when the interference is strong. Also, OL-SDMA scheme with deterministic antenna selection performs poorly when $R \ll D$. With optimal antenna selection combined with stream control, OL-SDMA is able to provide an improvement of about 8% over TDMA. In the weak interference environment, all SDMA schemes exhibit superior performances against TDMA scheme with an improvement of about 122%.

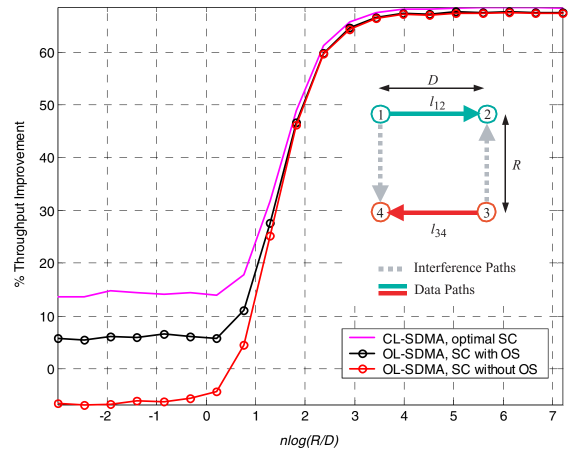
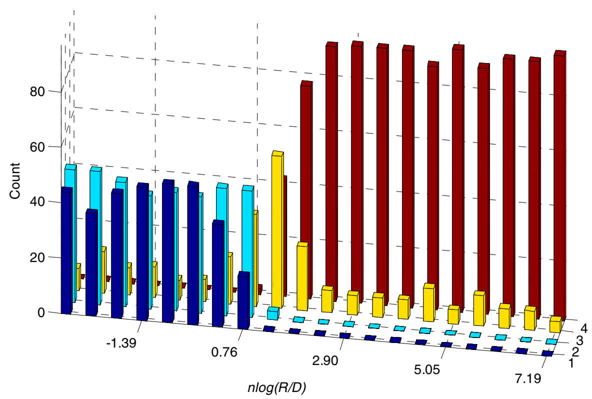


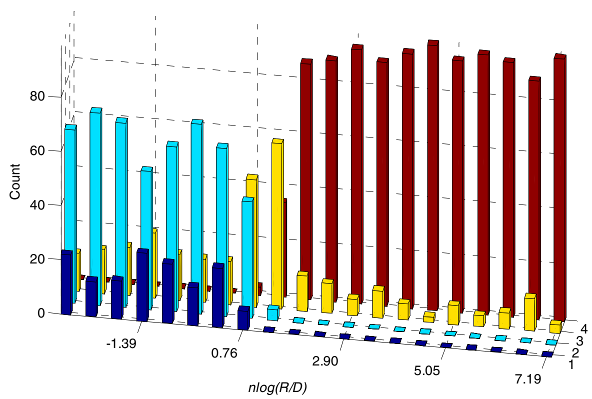
Figure 1. Average improvement in the network throughput relative to closed-loop TDMA, $(T - T_{TDMA})/T_{TDMA} \times 100\%$, fair energy approach. SC stands for stream control and OS stands for optimal antenna selection.

B. Number of Streams and Stream Control

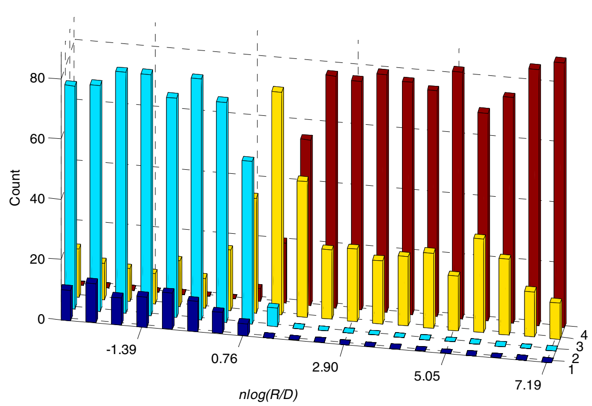
We shall consider the previous 2-link topology, assuming the noise-normalized total transmit power of each link is set to 17dB, and each node is assumed to have 4 antennas. 100 channel trials are generated, and the link parameters are found using the stream control method for 20 different values of $n\log(R/D)$. Figure 2 demonstrates the regulation of streams by different SDMA schemes as a function of the strength of interference, which varies with $n\log(R/D)$. We observe that, in accordance with [9], all the SDMA schemes mostly use 4 streams when interference is weak, thus greatly improving the throughput of the network. However, the similarity ends when the interference is significant ($R \ll D$). Figure 2(a) shows histograms of the number of streams used by link l_{12} with OL-SDMA with stream control but with deterministic antenna selection. It is apparent that when interference is strong, the link mostly uses either one or two streams with about equal probability. Figure 2(b) shows that with optimal antenna selection, OL-SDMA mostly uses 2 streams when the interference is strong. This is because if both the links use single stream, it would leave the victim receiver with two additional degrees of freedom, thus allowing each link to add another stream. It is apparent that optimal antenna selection aided stream control enables OL-SDMA to exploit spatial multiplexing better than the deterministic selection. The transition occurs when $n\log(R/D) \approx 0.9$ when both the schemes use mostly three streams. It is interesting to note that after this transition, both schemes perform almost identically. Finally, Figure 2(c) shows the optimal stream control that



(a) OL-SDMA, stream control with deterministic antenna selection



(b) OL-SDMA, stream control with optimal antenna selection



(c) CL-SDMA, stream control

Figure 2. Histograms of number of streams used by one link with different MIMO configurations for different $n\log(R/D)$ values. Each layer of bars is associated with a different number of streams used, as indicated on the y-axis.

could be achieved by CL-SDMA, the trends being very similar to those of [10]. Unlike OL-SDMA, with and without optimal antenna selection, CL-SDMA more often uses three streams when interference is relatively weak. Comparing different schemes, we see that optimal stream control, in consonance with [9] and [13], eliminates the use of excessive numbers of streams when interference is strong. In particular, the algorithm penalizes additional streams for $n\log(R/D) < 0.76$. However, when $n\log(R/D)$ exceeds 0.9, stream control has less influence.

C. Effect of Path-Loss Exponent

The average SIR varies as $n\log(R/D)$ on the logarithmic scale, where n denotes the path-loss exponent. Therefore, a change in path-loss exponent value reflects as a change in the received SIR at a given (R/D) location. Thus the value of n actually determines the transition region from strong interference to weak interference. A change in the value of n shifts this transition point (R/D) without affecting stream control before or after the transition point.

V. Performance over the Measured Channel

The experiments were conducted with our 3D MIMO measurement system at 5.8 GHz [15] in the Residential Laboratory (RL) at the Georgia Institute of Technology. As shown in Figure 3, there are two receive array (Rx) locations and eight transmit array (Tx) locations. For each Tx-Rx pair, measurements were sequentially performed to acquire the channel matrices for antenna spacing of 0.5λ, where λ is the wavelength. The matrices were measured at 51 frequencies (10MHz separation) to obtain $20\times51=1020$ realizations of (4,4) flat fading channel matrices. Four representative configurations will be considered Conf. I: (T2-R1, T7-R2), Conf. II: (T8-R1, T6-R2), Conf. III: (T3-R1, T4-R2), and Conf. IV: (T3-R1, T5-R2). The first two configurations represent channels with less correlated interference because the directions of data and interference paths are angularly separated for both links. For the last two configurations, the data and interference for both links are spatially more correlated because of the confinement of the hallway. In order to clearly illustrate the correlation between the links, the first and third configurations are shown in Figure 3 with solid and dashed arrows, respectively. All four links (data and interferences) are individually normalized such that the signal links have the same SNR, and the SIR is equal to 1. This approach maintains the angular spread of the multipaths, while removing the range-dependent effects [15]. Figure 4 illustrates the average throughput performance of different MIMO schemes with stream control for different network configurations. As expected, CL-SDMA with stream control provides the best throughput performance for all four network configurations. Next we note that OL-SDMA with deterministic antenna selection yields better performance than OL-TDMA for Confs. I and II, when interference is less

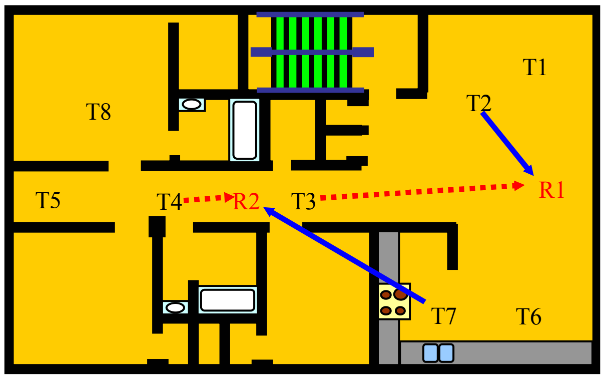


Figure 3. Layout of Residential Laboratory [15].

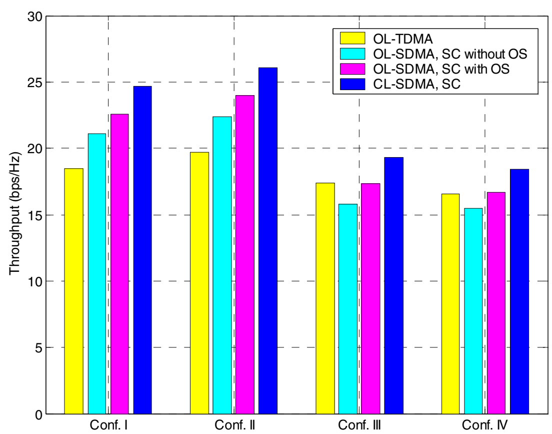


Figure 4. Average throughputs of various SDMA schemes for various network configurations. Equal-SNR normalization is assumed with SNR corresponding to 20dB noise-normalized total transmit power for TDMA and 17dB for schemes with interference.

correlated. However, for highly correlated interference, as in Confs. III and IV, the performance of OL-SDMA without optimal selection degrades and is inferior to OL-TDMA. In fact, the throughput performance for all schemes goes down for Confs III and IV, when interference is highly correlated. This is because the correlated interference reduces the rank of the whitened channel matrix (3), thereby decreasing the system capacity. Hence for highly correlated interference, antenna selection becomes even more critical. From Figure 4, we observe that with optimal antenna selection, the performance of OL-SDMA improves significantly for all four configurations. However, OL-SDMA with optimal selection gives only comparable performance to OL-TDMA when the interference is highly correlated. Since OL-SDMA with optimal selection requires some CSI feedback, and TDMA requires none, TDMA is preferable in the correlated interference environment. In the other environments, however OL-SDMA with optimal selection offers an attractive alternative to TDMA.

VI. CONCLUSIONS

We have analyzed the performance gains offered by the use of optimal transmit antenna selection to improve the effectiveness of the stream control algorithm for OL-MIMO for both simulated data and measured data. Although CL-MIMO with stream control offers the best throughput, it has substantial overhead of providing the CSI to the transmit nodes. Our results for two- and three-link network models indicate that OL-MIMO with optimal antenna selection is an attractive alternative to CL-MIMO with stream control as it incurs a minimal overhead of specifying the chosen antenna set.

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