Measured Capacities at 5.8 GHz of Indoor MIMO Systems with MIMO Interference

by

Jeng-Shiann Jiang, M. Fatih Demirkol, and Mary Ann Ingram

{jsjiang, demirkol, mai}@ece.gatech.edu

School of Electrical and Computer Engineering
Georgia Institute of Technology

Measured Capacities at 5.8 GHz of Indoor MIMO Systems with MIMO Interference

Jeng-Shiann Jiang, M. Fatih Demirkol, and Mary Ann Ingram
School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, GA 30332-0250, USA
jsjiang@ece.gatech.edu, demirkol@ece.gatech.edu, and mai@ece.gatech.edu

Abstract— **The capacity performances of two interfering flat-fading MIMO links are determined based on measured channels. Time-multiplexing of the links (TDMA), that is, when the MIMO links take turns operating without interference, serves as our baseline case. To this, we compare the spatial-multiplexed case (SDMA), which allows both MIMO links to operate simultaneously. Under SDMA, both open-loop (no channel state information (CSI) is used at the transmitter) and closed-loop (CSI is used at the transmitter) operation are considered. Using data measured by virtual arrays, we explore the effects of line-of-sight (LOS), element spacing, correlated fading, and interference that has various levels of spatial correlation with intended signal. Results show the benefit of wider element spacing in the channels without interference, especially when LOS is available, and with correlated interference if stream control is employed. However, wider spacing is hurtful if stream control is lacking.**

Keywords- MIMO; channel measurement; wireless communications; spatial multiplexing; virtual antenna array; correlated fading; correlated interference.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) links are well known to provide extremely high spectral efficiency in rich multipath environments [1]. However, some factors, such as correlated fading and interference, are known to significantly degrade the performance in simulated channels [2,3]. Furthermore, when the array response vector (i.e. the spatial signature) of interference is nearly co-linear with the array response vector of the desired signal, the signal-to-interference-and-noise ratio (SINR) of a linear array processor is degraded [4]. This is the "correlated interference" problem. This paper addresses interference and both kinds of correlation based on measured MIMO channels. To the best of our knowledge, this paper presents the first measurement results devoted to exploring the effect of interference on MIMO channels.

We present Shannon capacities for interfering MIMO channels which were measured in a home-like environment with virtual arrays at both ends. The results show significant effects of correlated fading, interference, and antenna separation. We also use the measured channels to compare open-loop MIMO (OL-MIMO), which operates without channel state information (CSI) at the transmitter, with closed-loop MIMO (CL-MIMO), which requires CSI at the transmitter. In an independent fading environment and for high signal-to-noise ratio (SNR), OL- and CL-MIMO approaches yield nearly equal capacities [5]. However, CL-MIMO is known to outperform OL-MIMO in the presence of interference [3,6,7], or in correlated fading [9]. Based on our measured data we show that CL-MIMO yields a higher throughput than OL-MIMO. Furthermore, we show that when two links interfere, spatial-division multiple-access (SDMA) MIMO with stream control [6,7] yields improvements over time-division multiple-access (TDMA) MIMO of up to about 65%.

We note that Blum and Winters have some related work [8]. While their focus was mainly on antenna selection, they also examined the OL capacity of a whitened channel as a function of the number of desired signal streams and the number of interference signal streams. They analyzed and simulated independently identically distributed (i.i.d.) channels and considered how the capacity changes as SNR increases, holding interference-to-noise ratio (INR) constant. They also found that stream control is desirable when interference is strong. The OL results in this paper are distinct from theirs in that we let the SNRs of both links grow together, we consider antenna spacing, and we use measured channels.

The paper is organized as follows: In Section II, we describe the measurement environment and the system settings. Section III demonstrates MIMO capacities of the channels without interference and explores the effects of element spacing and line of sight (LOS). Section IV is devoted to the introduction of network model used in the subsequent sections. The influence of element spacing on the channels with interference is discussed in Section V. Section VI compares the throughputs of SDMA and TDMA. A brief conclusion is provided in Section VII.

II. MEASUREMENT SYSTEM AND SETTINGS

The experiments were conducted with our 3D MIMO measurement system [10] in the Residential Laboratory at the Georgia Institute of Technology. As shown in Figure 1, there are two receive array (Rx) locations and eight transmit array (Tx) locations. The transmitter was a virtual 25-element square array and the receiver was a virtual 5-element uniform linear array. For each pair of transmit and receive array locations, five measurements were sequentially performed to acquire the channel matrices for five antenna spacings: 0.25λ, 0.5λ, 1λ, 2λ, and 3λ, where λ is the wavelength. From each (5×5,5) channel matrix, we extract 20 (4,4) channel matrices of uniform linear arrays. Each component of the channel matrix is in fact the

This research was supported in part by the National Science Foundation under Grant No. CCR-0121565, and in part by the Georgia Tech Broadband Institute (GTBI).

wideband frequency response with bandwidth 500 MHz centered at 5.8 GHz. The abundant frequency samples are utilized to increase the number of outcomes in the calculation of ergodic narrowband channel capacity. The matrices were measured at 51 frequencies (10MHz separation) to obtain 20×51=1020 realizations of (4,4) flat fading channel matrices.

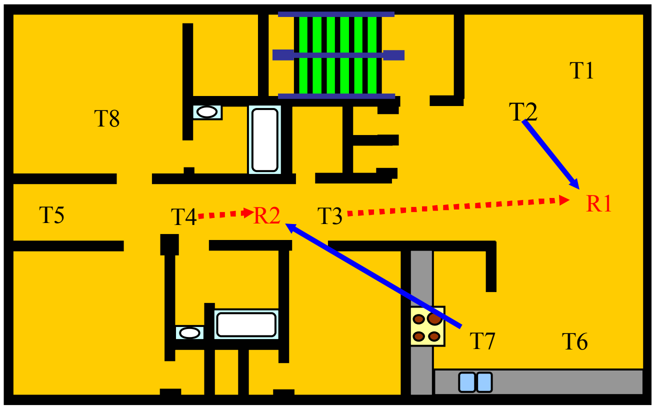

Figure 1: Layout of Residential Laboratory (RL).

III. MIMO Channels without Interference

First, we consider the channels with no interference. In Figure 2, Link T2–R1, where LOS is available, and T7–R2, where LOS is obstructed, are considered. All four antennas are used at each end, and the (4,4) channel matrix is noise-normalized before being applied to the calculation of its open-loop capacity.

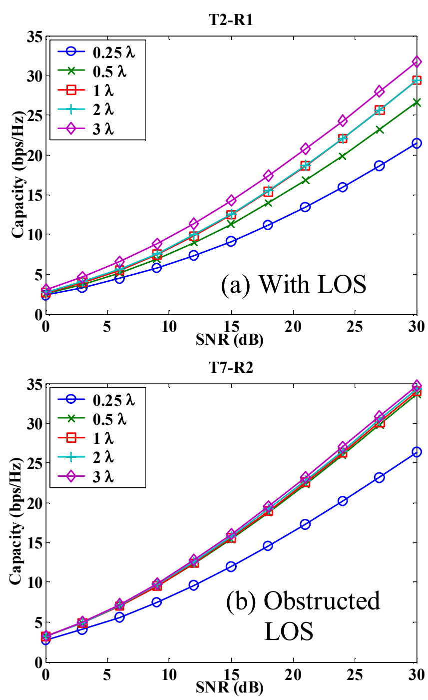

Figure 2: No interference. (a) LOS (b) Obstructed LOS.

For the channel with LOS, we find that the capacity grows with increasing element spacing. This is a special feature of the LOS for short range MIMO [11]. At 20 bits/s/Hz, 4 dB SNR improvement is obtained by increasing the spacing from 0.5λ to 3λ. For the obstructed LOS channel, T7–R2, the capacity tends to saturate while the spacing approaches 0.5λ.

In order to realize the strong impact of the element spacing on the capacity of MIMO systems in the indoor environment, we show the capacity improvement by increasing the spacing from 0.5 to 3λ for all 16 measured Tx-Rx locations in Figure 3. Overall, the improvement ranges from 8% to 70%. Therefore, the results indicate that half wavelength is not sufficient to decorrelate the signals of MIMO channels even though the multipath is rich in the indoor environment, especially when the performance is dominated by LOS or a few strong paths.

Improvement

$$= \frac{C_{3\lambda} - C_{0.5\lambda}}{C_{0.5\lambda}} \times 100\%$$

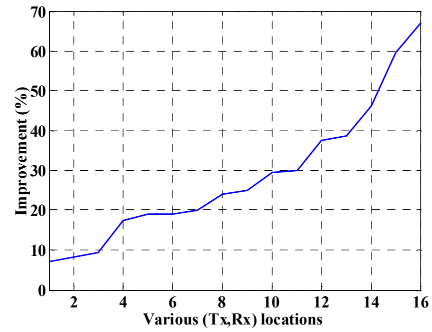

Figure 3: Capacity improvement by increasing spacing from 0.5λ to 3λ for all 16 locations.

IV. MIMO Channels with Interference

Next, we will consider pairs of co-channel MIMO links. The network will be represented as (node 1 – node 2, node 3 – node 4). Four representative configurations will be considered in the following sections, including 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.

We use two kinds of normalizations to demonstrate the performances of each scheme and the effect of the network topology. In the first approach, we keep the effects of the network topology (i.e. node distances). For each configuration, we scale the data link for Link 1 so that each element of the channel matrix between T1 and R1 has unit variance. Then we use the same scaling factor for the other data channel and the interference channels. Assuming the transmit power of both data links are the same, the average link SNRs are generally not equal because of varying node distances. With this approach, we can better observe the effects of LOS and node distances among different configurations. This approach will be called the distance-preserving normalization in the following discussion.

The second approach, denoted as equal-SNR normalization, normalizes the data channel (i.e. the channel from the transmitter to the desired receiver) so that each coefficient of the channel matrix has unit variance, and uses the same normalization factor to normalize the channel from the transmitter to the unintended receiver. Assuming again that both links have the same transmit power, it follows that the links have equal average SNRs in each configuration. However, the link average INR will not generally be equal, so some of the effects of the network topology will be evident.

To illustrate the difference of the two approaches and to better understand the advantage of LOS, consider Conf. I. The channel of Link 1 (T2-R1) has a LOS, and the transmitter-receiver distance is short, while the channel gain for Link 2 (T7-R2) is lower because it is longer and goes through a wall. The gain of the channel (as indicated by the Frobenius norm of the channel matrix) for Link 2 is lower than Link 1 by a factor of 24dB. However, with the equal-SNR approach, we assume Link 2 can use more power to achieve the desired SNR.

V. OPEN-LOOP SDMA

In this section, we will demonstrate the effect of antenna spacing and stream control on OL-SDMA, where no CSI is used at the transmitters. The distance-preserving normalization is performed before the calculation of the capacity. The throughput is the summation of the OL capacities of the two links. For one link, let P be the total noise-normalized transmit power, n_T be the number of transmit antennas, and $\tilde{\mathbf{H}}$ be the whitened channel matrix. Then the capacity of one link is given by [12]

$$C = \log_2 \left| \mathbf{I}_{n_R} + \tilde{\mathbf{H}}\mathbf{P}\tilde{\mathbf{H}}' \right|, \quad (1)$$

where $\mathbf{P} = (P/n_T)\mathbf{I}_{n_T}$.

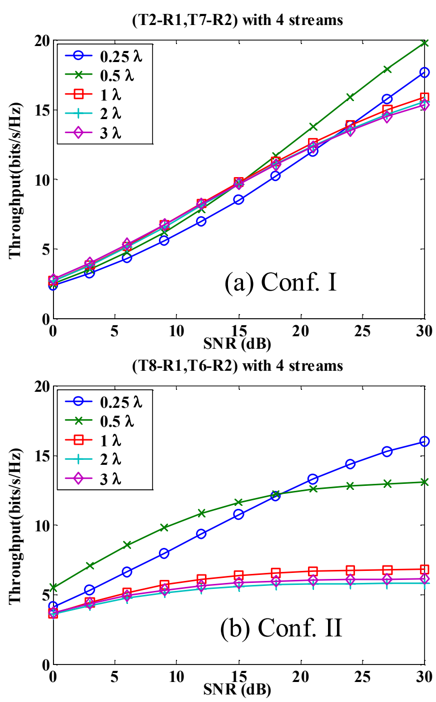

Figure 4: Less correlated interference. No stream control: (a) Conf. I (b) Conf. II.

Figure 4 shows the throughput of the channels with less correlated interference without stream control. It is important to note that each array receiver is overwhelmed without the stream control because there are 8 independent data streams impinging on each 4-element receive array. Increasing the spacing tends to reduce the slope of the curve at high SNR.

The explanation for the phenomenon is that wider antenna spacing increases the effective rank of the channel matrix in MIMO system [11] and hence the signal-to-interference ratio decreases for every transmitted stream. For Conf. I, the performance at 0.5λ surpasses all the other spacings when the SNR exceeds 15 dB. For Conf. II, because Link T8-R1, a link with weak signal, is normalized to achieve the intended SNR, distance-preserving normalization causes strong interferences. In this case, the throughput at 0.25λ surpasses the other spacings when SNR is over 15dB and reaches 3 times of the throughput of 3λ at 30dB.

Stream control avoids the situation that total number of streams exceeds the number of receive antennas [7]. The throughput with stream control is illustrated in Figure 5. Comparing to Figure 4, the overall throughput is improved, especially in Conf. II. For both configurations, the throughput tends to saturate when the spacing is over 0.5λ.

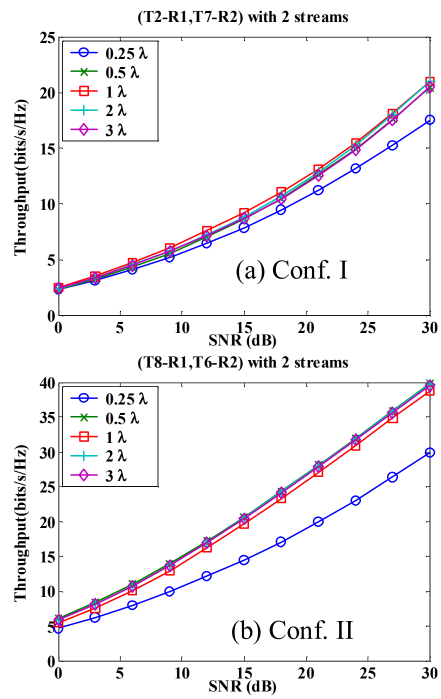

Figure 5: Less correlated interference. With stream control: (a). Conf. I (b) Conf II.

Next, we consider the channels with highly correlated interference. Similar to the less correlated interference, capacity drops with wider spacing if there is no stream control. As shown in Figure 6, the slopes of 2 and 3λ drop drastically when the SNR is over 15 dB. However, when the stream control is applied, the benefit of wide antenna spacing becomes apparent as shown in Figure 7. For Conf. III, the throughput improves as much as 50% when the antenna spacing is increased from 0.5λ to 2λ. In addition, the maximum achievable throughput is about two times of the throughput without stream control.

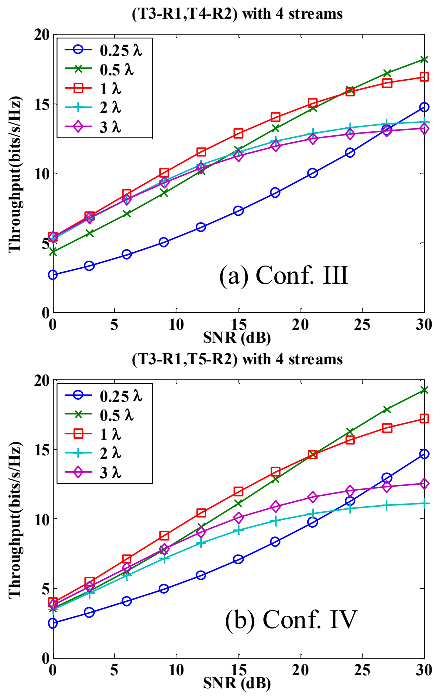

Figure 6: Highly-correlated interference. No stream control: (a) Conf. III (b) Conf. IV.

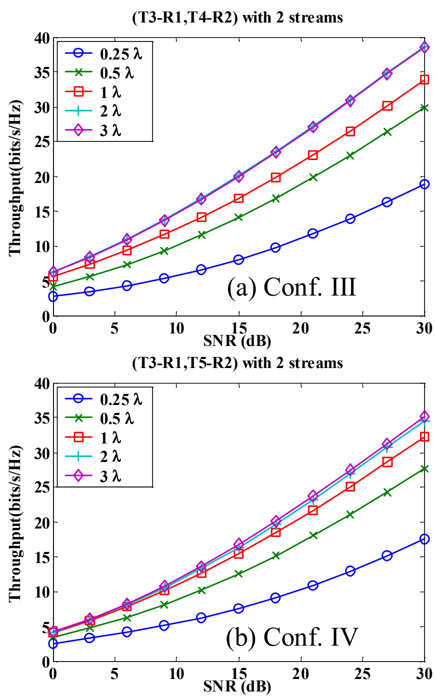

Figure 7: Highly-correlated interference. With stream control: (a). Conf. III (b) Conf. IV.

VI. SDMA VS. TDMA

In this section, we consider an SDMA scheme that allows multiple interfering CL-MIMO links, and compare its throughput to MIMO with conventional TDMA. The CL-MIMO capacity is given by (1) where **P** is determined by the water-filling solution. In [6,7,13,14], distributed link adaptation and stream control methods are given for interfering CL-MIMO links. By using the number of parallel streams for each link and the total transmit powers or target capacities as control parameters, these methods allow us to manage each link's capacity.

In [7], the throughput of an SDMA scheme using these algorithms is demonstrated with simulated channels. Here, the performances of the MIMO links and the distributed link adaptation algorithms are demonstrated for measured channels. We use only the measured channels with 0.5λ and focus on the effects of spatial correlation between data and interference streams, presence of LOS, different path losses, and different scattering characteristics on the links' performance.

A. Results with the Distance-Preserving Normalization

Figure 8 shows the average throughputs of each network configuration for several MIMO schemes. We assume the two links use equal transmit powers in each configuration. We also assume that the schemes with interfering links have half the transmit power (17dB) of the TDMA schemes (20dB) so that all schemes use the same energy. Note that in the TDMA schemes, the links transmit half of the time (assuming equal priorities). Therefore, for the TDMA schemes, the throughput values shown for "both links" are half of the link capacities computed based on the peak total power per link.

Even though channels of Link 1 in all configurations are normalized to have the same total gain, the capacities of these links are not the same. Link 1 of Conf. II (T8-R1) has the highest capacity. Link 1 of Confs. I, III, and IV have a LOS, whereas the Link 1 of Conf. II does not. Normally, the LOS links would have higher capacities because they have higher SNR. However, after normalization, the capacity of the NLOS link is higher because the channel gain is not concentrated in just one mode. The capacities of the LOS links with normalized path loss gains (Link 1 in Conf. I, III, and IV) are close to each other.

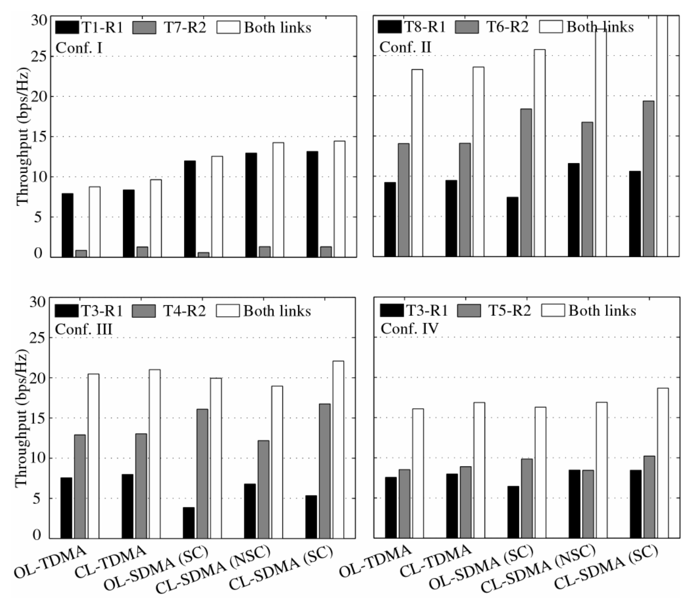

Figure 8: Average throughputs in bps/Hz of different MIMO schemes and network configurations assuming the distance-preserving normalization. SC stands for stream control. NSC means that no explicit stream control is used.

For each configuration, one link has more path loss than the other, resulting in lower capacity for the link with more loss. When there is interference, that is, when both links operate simultaneously, we observe that the switch from OL to CL gives the weaker link a much larger percentage increase in capacity than it gives the stronger link. For example, in Conf. III "with stream control" cases, the improvement that CL-SDMA gives over OL-SDMA is 53% for the weaker link (Link1, T3-R1), but only 4.1% for the stronger link (Link 2, T4-R2).

Some insight to this can be gained by looking also at the TDMA or no-interference cases. In those cases, the change from OL to CL usually does not make a big improvement for the weaker link. The exception is Conf. I, Link 2 (T7-R2). We expect a big difference between OL-TDMA and CL-TDMA only when the SNR is low, which must be the case for Conf. I, Link 2 (T7-R2). Therefore, in this particular case, the difference between OL-SDMA and CL-SDMA is attributable mostly to low SNR, and not so much to better control of the interference.

On the other hand, in the weaker links where OL-TDMA and CL-TDMA give about the same performance, we can conclude that their SNRs must be high, and the other link in each configuration has an even higher SNR. However, because there is a big difference between OL-SDMA and CL-SDMA, we may conclude that under OL-SDMA, the weaker link has a lower signal-to-interference ratio (SIR), and the improvement from CL-SDMA is attributable to the spatial filtering doing a good job of interference management.

It is also interesting to compare CL-TDMA to CL-SDMA with stream control. In the first two configurations, the strong link gets a large improvement and the weak link gets a small improvement. These configurations have interference that is not highly spatially correlated with the desired signal, so jointly optimized spatial filtering is effective at managing the interference. The later two configurations have spatially correlated interference. This leads to minimal improvements in throughputs from SDMA. In Conf. III, the interference seen by the weak link (T3-R1) is so correlated and strong that the capacity of the link actually degrades in CL-SDMA. We conclude that when the interference is spatially correlated with the desired signal, spatial filtering does not provide good interference management.

B. Results with Equal-SNR Normalization

Assuming that the two links have equal SNRs in each configuration, we compare the throughputs of the schemes considered in the previous section.

Normalizing each transmitter's total power to obtain equal SNRs may not be practical in all configurations. For instance, in Conf. I, Link 2's trasmit power has to be 24 dB higher than Link 1. However, we follow this approach to give the links comparable capacities in our throughput comparisons.

Again, we constrain the total transmit energies to be equal for TDMA and spatial multiplexing with interfering links. The results are shown for two power settings: high-SNR, and low-SNR. With the high-SNR setting, the noise-normalized transmit power for TDMA links is 20 dB, while for the schemes with interfering links, it is 17 dB because of the equal-energy argument. With the low-SNR setting, the noise-normalized transmit power for TDMA inks is 10dB, and for the schemes with interfering links, it is 7dB.

Figure 9 shows the network throughputs for each configuration obtained by several schemes for two different power settings. Since the links have comparable channel gains with the equal-SNR approach, the network throughputs are shown for each configuration, rather than individual link capacities.

The improvement of closed-loop operation over open-loop is not very large for the high-SNR TDMA case. CL-TDMA gives only 1.8–4.5% improvement at 20dB SNR over OL-TDMA. At 10dB, the improvement ranges from 7% to 14.7%. However, with interference, the difference between OL and CL is more significant. With stream control, CL-SDMA is 13.9% to 20.6% better than OL-SDMA at high SNR, and 24% to 28.6% better at low SNR. Therefore, closed-loop operation becomes rewarding with low SNR or interference.

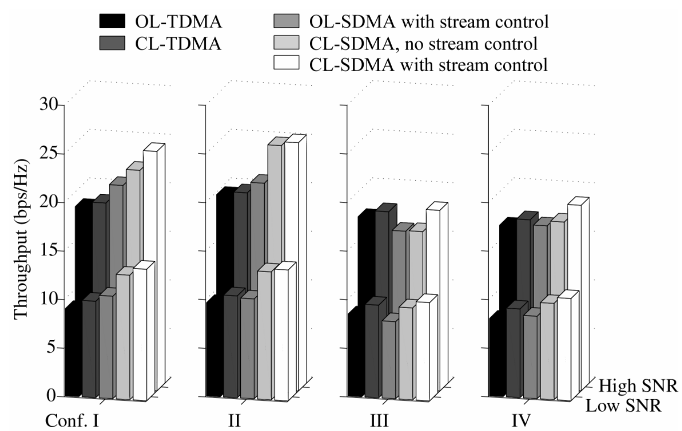

Figure 9: Average throughputs of different MIMO schemes and network configurations assuming equal-SNR normalization.

The high-SNR throughputs in this section can be compared with the throughputs calculated from Figure 8, for the topology-preserving normalization. From Figure 8, the throughput improvements for OL- to CL-TDMA are 10.04%, 1.28%, 2.67%, and 4.83%, by order of configuration. The only noteworthy difference between these values and the improvements of Figure 9 is for Conf. I, which has a LOS link (T1-R1), and a low-SNR link (T7-R2). With the topology-preserving normalization, both links in this configuration benefit from CL-TDMA. In the high-SNR setting of Figure 9, the SNR of T7-R2 is more (by 24dB), and since the channel of this link does not have a LOS, the open- and closed-loop capacities are closer to each other.

In Figure 8, the improvements for OL-SDMA to CL-SDMA with stream control are 15.10%, 16.40%, 10.72%, 14.49%, in order of configuration. These numbers are lower than the improvements for Figure 9, for equal SNR. This is because in the topology-preserving case, the biggest percentage capacity improvements occur for the weaker link. When the capacity improvements of the weak and strong links are added to get the improvement, the percentages are not as high as in the equal-SNR case.

Conf. III is the only configuration where OL-SDMA with stream control yields lower throughputs that OL-TDMA. In Conf. IV, the other correlated interference configuration, OL-TDMA and OL-SDMA throughputs are nearly equal. In Confs. I and II, OL-SDMA throughputs are higher by 7% to 43% than OL-TDMA.

Of course, the most dramatic differences in throughput are between CL-SDMA with stream control and OL-TDMA. Of these, the low-SNR cases in Figure 9 yield the highest improvements as a group: 51.02%, 40.33%, 20.11%, and 32.33%, in order of configuration. However, the single highest improvement in throughput, for Conf. I with the topology-preserving normalization, is 64.90%.

VII. Conclusion

Interference is generally present in the practical environment for the wireless communications. Using the measured data obtained in a home-like environment, we have shown the impact of interference on the performance of MIMO channels. The measurement results show that wider antenna spacing is beneficial to the MIMO capacity of the channel without interference, but not for the channel with interference unless proper stream control is applied. For the less correlated interference, the throughput of the two-link network with stream control tends to saturate at 0.5λ, while for the highly-correlated interference, the throughput is sensitive to the antenna spacing and up to 50% of improvement can be achieved by increasing the spacing from 0.5 to 2λ.

The performance of the link adaptation algorithms in [6,7] was demonstrated by measured channels. The most important comparison may be between CL-SDMA with stream control and OL-TDMA, since OL-TDMA could be achieved with current MAC layer protocols. In this comparison, CL-SDMA improved the throughput relative to TDMA by 20% to 65%, even when the interfering and desired signal paths are near in angle.

Power and stream control both play key roles in the fair utilization of the wireless resources. The power control is essential both among the links and the streams of each link. Although all measurements were taken in the same building, different LOS and path loss characteristics of the links produced disparities as high as 24dB in the channel gains. Stream control is required to reach the highest network throughputs. In all cases considered, CL-SDMA with stream control gave the best performance, with the largest difference when the desired and interfering signal paths are resolvable by the receiver arrays.

CL-SDMA has the overhead of providing channel state information (CSI) to the transmitter, and this overhead was not taken into account in this paper. However, the performance margin is perhaps high enough to warrant further consideration of CL-SDMA. The results show that CL-SDMA outperformed OL-SDMA (which does not have the CSI overhead) by 25%-35% in ideal simulated channels and by 10.7%-28.6% in the measured channels. Therefore, in slowly varying environments, where CSI might be accumulated slowly in the transmitter, without incurring a large overhead, CL-SDMA may be practical.

Interestingly, OL-SDMA with stream control was not always better than OL-TDMA. This happened in simulated channels, when the MIMO links were in close proximity, and in one of the measured channels, when the desired and interfering signals both emerged out of a hallway into a living room where the receiver was located.

References

[1] G.J. Foschini and M.J. Gans, “On limits of wireless communications in a fading environment when using multiple antennas,” *Wireless Personal Communications*, pp. 311-335, 1998.

[2] D. Shiu, G.J., Foschini, M.J. Gans, and J.M. Kahn, “Fading correlation and its effect on the capacity of multielement antenna systems,” *IEEE Trans. Communications*, vol. 48, pp. 502-513, Mar. 2000.

[3] S. Catreux, P.F. Driessen, and L.J. Greenstein, “Simulation results for an interference-limited multiple-input multiple output cellular system,” *IEEE Communications Letters*, vol. 4, Nov. 2000.

[4] R. Janaswamy, Radiowave *Propagation and Smart Antennas for Wireless Communications*, Kluwer Academic Publishers, 2000.

[5] A.M. Sengupta, and P.P. Mitra,, “Capacity of multivariate channels with multiplicative noise: I. random matrix techniques and large-n expansions for full transfer matrices,” *Bell Labs Technical Report*, Apr. 2001.

[6] M.F. Demirkol, and M.A. Ingram, “Control using capacity constraints for interfering MIMO links,” *IEEE Personal, Indoor, and Mobile Radio Communications*, vol.3, pp. 1032-1036, 2002.

[7] M.F. Demirkol and M.A. Ingram, “Stream control in networks with interfering MIMO links,” *Proc. of IEEE Wireless Communications and Networking Conference*, Mar. 2003.

[8] R.S. Blum and J.H. Winters, “On optimum MIMO with Antenna Selection,” *IEEE Conference on Communications*, vol. 1, pp. 386-390, Apr. 2002.

[9] F. Rashid-Farrokhi, K.J.R. Liu, and L. Tassiulas, “Transmit beamforming and power control for cellular wireless systems,” *IEEE Journal on Selected Areas in Communications*, vol. 16, pp. 1437–1450, Oct. 1998.

[10] J-S. Jiang and M.A. Ingram, “Enhancing measured MIMO capacity by adapting the locations of the antenna elements,” *IEEE Personal, Indoor, and Mobile Radio Communications*, vol.3, pp. 1027-1031, 2002.

[11] J-S. Jiang and M.A. Ingram, “Distributed source model for short range MIMO,” *IEEE Vehicular Technology Conference*, Fall 2003.

[12] D.W. Bliss, K.W. Forsythe, A.O. Hero, and A.F. Yegulalp “Environmental issues for MIMO capacity,” *IEEE Trans. on Signal Processing*, pp.2128-2142, Sep. 2002.

[13] M. F. Demirkol and M. A. Ingram, “Control using capacity constraints for interfering MIMO links,” *Proc. of the Int. Symp. on Personal, Indoor and Mobile Radio Comm.*, vol. 3, pp. 1032-36, Sep. 2002.

[14] M.F. Demirkol, *Resource Allocation for Interfering MIMO Links*, Ph.D. Dissertation, School of Electrical and Computer Engineering, Georgia Institute of technology, May, 2003.