Feasibility of Closed Loop Operation for MIMO Links with MIMO Interference

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I. INTRODUCTION

Multiple-input multiple-output (MIMO) links provide high spectral efficiencies in rich multipath environments through the use of multiple spatial channels in the same system bandwidth [1-3]. In a network with several transmitting nodes, array antennas at both ends of the MIMO links can be exploited to have multiple links operate in the same channel. Depending on the network topology, each interfering link can transmit fewer modes than it would in an isolated environment, and use the remaining degrees of freedom to avoid or suppress interference.

This kind of spatial multiplexing is illustrated in Figure 1 over a simple network with 2 interfering links. With optimized array weights at both ends of each link [4,5] and stream control among the MIMO links [6], a network with interfering MIMO links can yield a higher throughput than if the links operated in a time-division multiple-access (TDMA) fashion.

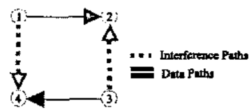

Fig. 1. A network with 4 nodes forming two interfering links.

With interference, the channel state information (CSI) must be fed back to the transmitter to reach the highest level of performance. Accordingly, the algorithms introduced in [4-6] require CSI feedback to the transmitter. In a mobile wireless network, CSI aging degrades closed-loop MIMO (CL-MIMO) performance over time. Hence, CSI aging effects the performance of the links and determines if the closed-loop operation is feasible.

For isolated MIMO links, the open- and closed-loop MIMO capacities can be close, thus, closed-loop operation may not be attractive. If CSI ages rapidly, the transmitter weights the power allocation will not match the channel realization at a later time. Channel mismatch can cause the transmit power to be concentrated in undesired directions, thereby, causing the performance to drop even below that of an OL-MIMO link.

However, we show that the difference between closed- and open-loop capacities when links interfere is usually much larger than with isolated links. This implies that less frequent CSI updates will be sufficient to keep CL-MIMO performance above open-loop MIMO (OL-MIMO).

We analyze the effect of CSI aging for MIMO links. To understand the effect of fading and study the feasibility of closed-loop operation in MIMO links, we utilize two models for the MIMO channels: In the next section, we use a Rayleigh fading model, and the filtered Gaussian noise method to simulate a fading channel [8]. In Section III, we consider a more realistic scenario, where we simulate propagation in a typical indoor environment using the finite-difference time-domain (FDTD) method. Section IV concludes the paper.

II. RAYLEIGH FADING CHANNELS

The Rayleigh channel model represents a multipath propagation environment with rich scattering and no line of sight. First, we use this statistical model to simulate MIMO channels with mobility.

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We assume that when the channel is estimated at the receiver at time $t = 0$, CSI feedback is sent instantaneously to the transmitter, and the transmitter weights are frozen.

II.1 Isolated MIMO Link

For an isolated link, the difference between closed-loop and open-loop capacities is not significant, especially at high signal-to-noise ratio (SNR) and in a rich scattering environment. Moreover, the autocorrelation of the optimum transmit weight vectors drops sooner than the autocorrelation of channel matrix coefficients [9]. Therefore, with Rayleigh channels, the performance with aged CSI at the transmitter falls below that of OL-MIMO quickly.

Consequently, the closed-loop operation of an isolated link is feasible only for channels with very low Doppler frequency. According to [9], at a Doppler frequency of 40Hz, the required channel update rate is 0.18ms.

Figure 2 shows the average capacity of an isolated MIMO link with 20dB noise-normalized total transmit power and 4 antenna elements at each node, as a function of $f_m T$ for three cases: CL-MIMO with perfect CSI at the transmitter at all times, OL-MIMO, and CL-MIMO with aged CSI at the transmitter. The capacity of CL-MIMO with aged CSI drops under the OL capacity at $f_m T = 0.006$, or in 0.15ms at 40Hz Doppler frequency, which supports the result of [9]. In other words, for mobile speeds up to 10km/h at a center frequency of 2.4GHz, which corresponds to 22Hz Doppler, CSI should be refreshed at least every 0.3ms. This is less than a typical packet transmission time (in the order of a ms) in the IEEE 802.11b standard.

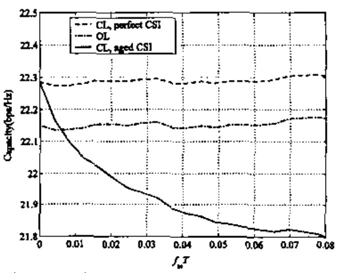


Fig. 2. The effect of mobility on the performance of an isolated CL-MIMO link.

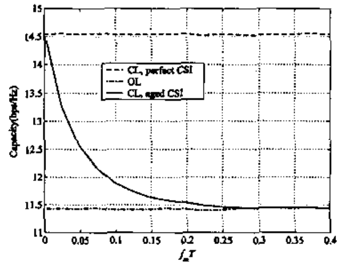
II.2 Interfering MIMO Links

With a set of co-channel MIMO links, the difference between closed- and open-loop capacities is larger than with isolated MIMO links. In addition, the use of CSI at the transmitter helps to null interference, as well as to decouple the streams. Therefore, the performance with aged CSI at the transmitter does not fall below OL-MIMO capacity as quickly as in the case of isolated links.

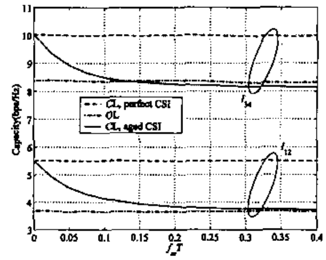
To illustrate this, we consider the two-link network of Figure 1 with equal node distances, 4 antennas at each node, and 20dB noise-normalized transmit power at each node. We assume that both links transmit simultaneously. The closed-loop capacities of the links are found using the iterative algorithm presented in [4, 6].

Figure 3(a) compares one link's capacity for the same three scenarios as in Figure 2, but with interference, assuming that each link uses 2 streams. With mobility, the channel matrices between each pair of nodes change. We observe that the closed-loop performance is better than open-loop for $f_m T < 0.3$. For 20Hz Doppler, this would correspond to 15ms. This allows for several packet transmissions between CSI updates if the IEEE 802.11b standard is taken as a baseline.

In Figure 3(a), the throughput with frozen weights degrades down to the OL-MIMO throughput. Figure 3(b) corresponds to an alternative scenario, which shows that this is not always the case. In this experiment, one of the links (l_{34}, the link from node 3 to node 4) uses 3 streams, and the other (l_{12}) uses 1 stream. In this case, the capacity of l_{34} drops below its open-loop capacity for $f_m T < 0.15$, whereas the capacity of l_{12} stays above the open-loop capacity for the time period considered. Notice that, since l_{12} uses a single stream, the closed-loop CSI aging causes an SNR loss because the optimum array weights change. However, with multiple streams, CSI aging causes inter-stream interference as well as SNR loss.



(a) Each link transmitting two streams.



(b) One link transmitting 3 streams and the other transmitting one stream.

Fig. 3. The effect of mobility on the performance of two interfering CL-MIMO links.

III. CHANNELS GENERATED USING THE FDTD ALGORITHM

In this section, we use the FDTD algorithm to generate more realistic fading MIMO channels and analyse the gain of CSI feedback and the effect of mobility in an indoor environment.

Figure 4 shows a typical floor-plan that is a part of an office building, modeled in the same way as in [10]. The size of the region is about 16m×16m ($125\lambda\times125\lambda$ at 2.4 GHz, where, λ is the transmission wavelength). Two fixed transmitter locations are marked, T1 and T2. The arrows represent the routes of three mobile receivers, R1 through R3. Each node is assumed to have a linear array antenna with 4 elements and half-wavelength spacing. Along each receiver route 151 points are taken, separated by half wavelength. The FDTD method is used to calculate 4×4 matrices of propagation coefficients from the transmitter to each point on the receiver routes. The matrices are all normalized so that each element of the channel matrix from T1 to R1 has unit average power when R1 is at its initial location.

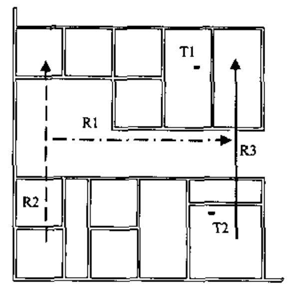
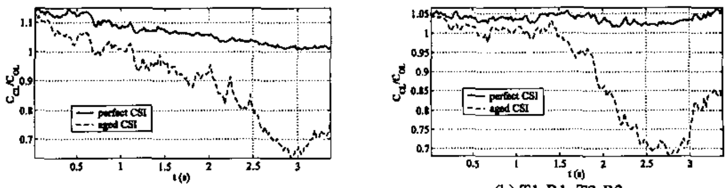


Fig. 4. Floor plan in an office building.

We will consider two network configurations, each with two interfering MIMO links: (T1-R3, T2-R1) and (T1-R1, T2-R2). Figure 5 shows the ratios of the closed- and open-loop capacities of the isolated links, averaged over the two links in each configuration, as the receivers move in the directions shown. Each plot carries two curves: for one of the curves, the closed-loop capacity is calculated assuming perfect knowledge of CSI at the transmitter at all times, and the other assuming a CSI feedback is sent to the transmitter only once, when the receivers are at the initial locations. The horizontal axis shows time, as each receiver goes through its 75λ-long route, assuming a speed of 10 km/h. For these configurations, the closed-loop capacity does not drop below open-loop capacity for about 0.68 and 0.57s, respectively.

Figure 6 shows the same curves in Figure 5 for the case of interfering links. As in the previous section, the gain of closed-loop operation is more significant with interference than for isolated links. With interference, the closed-loop capacities are always above the open-loop capacities for about 2.35 and 1.95s for the two configurations, respectively.

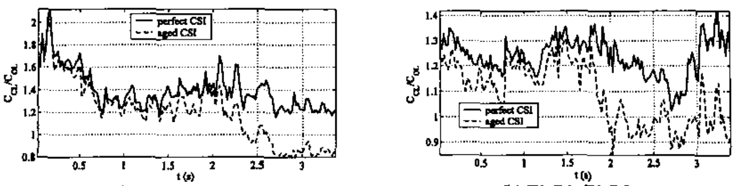
CSI feedback is more feasible with the real channels (even with no interference). This is because (1) the real channels have a less uniform singular value distribution, which enhances the advantage of closed-loop, and (2) the samples of the channels corresponding to different receiver



(a) T1-R3, T2-R1.

(b) T1-R1, T2-R2.

Fig. 5. Isolated links.



(a) T1-R3, T2-R1.

(b) T1-R1, T2-R2.

Fig. 6. Interfering links.

locations can be highly correlated even after the receiver moves from one side to the other side of a hallway, so the spatial characteristics of the channel does not change as much.

IV. CONCLUSION

The results especially with the realistic channels considered in Section III indicate that even with the overhead of CSI updates multiplied by the number of iterations, the proposed spatial multiplexing scheme may be attractive for static and low-mobility networks, such as in indoor environments.

REFERENCES

[1] G. J. Foschini, M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Comm.*, vol. 6, 1998.

[2] E. Telatar, "Capacity of multi-antenna gaussian channels," *Technical Report, AT&T Bell Labs*, June 1995.

[3] G. G. Raleigh, J. M. Cioffi, "Spatio-temporal coding for wireless communication," *IEEE Trans. on Comm.*, vol. 46, Mar. 1998.

[4] M. F. Demirkol, M. A. Ingram, "Power-controlled capacity for interfering MIMO links," *Proc. of the IEEE Vehicular Tech. Conf.*, vol. 1, pp. 187–191, Oct. 2001.

[5] M. F. Demirkol, 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. 1032–1036, Sep. 2002.

[6] M. F. Demirkol, M. A. Ingram, "Stream control in networks with interfering MIMO links," *Proc. of IEEE Wireless Comm. and Networking Conf.*, Mar. 2003.

[7] J.-S. Jiang, M. F. Demirkol, M. A. Ingram, "Measured capacities at 5.8 GHZ of indoor MIMO systems with interference," *Proc. of the IEEE Vehicular Tech. Conf.*, Oct. 2003.

[8] G. L. Stüber, *Principles of Mobile Comm.* Boston: Kluwer Acad. Pub., 2nd ed., 2001.

[9] G. Lebrun, T. Ying, M. Faulkner, "MIMO transmission over a timevarying TDD channel using SVD," *Electronic Letters*, vol. 37, pp. 1363– 1364, Oct. 2001.

[10] Z. Yun, M. F. Iskander, Z. Zhang , "Complex wall effect on fading and MIMO capacities for wireless communication environments," *Proc. of the IEEE Vehicular Tech. Conf.*, Oct. 2003.