Harnessing Receive Diversity in Distributed Multi-User MIMO Networks

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Abstract: In existing multiuser MIMO (MU-MIMO) MAC protocols, a multi-antenna node sends as many concurrent streams as possible once it wins the contention. Though such a scheme allows nodes to utilize the multiplex gain of a MIMO system, it however fails to leverage receive diversity gains provided by multiple receive antennas across nodes. We introduce Multiplex-Diversity Medium Access (MDMA), a MU-MIMO MAC protocol that achieves both the multiplex gain and the receive diversity gain at the same time. Instead of letting a node pair use all the available degrees of freedom, MDMA allows as many contending node pairs to communicate concurrently as possible and share all the degrees of freedom. It hence can exploit the antennas equipped on different receivers to further provide some of concurrent streams more receive diversity, without losing the achievable multiplex gain. We implement a prototype on software radios to demonstrate the throughput gain of MDMA.

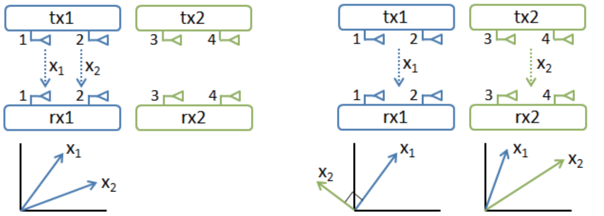
Categories and Subject Descriptors C.2.2 [**Computer Systems Organization**]: Computer-Communications Networks

General Terms Algorithms, Design, Performance

Keywords Multiuser MIMO, Diversity Gain

1. INTRODUCTION

The key idea behind our design is to enable multiple node pairs communicating concurrently to achieve more receive diversity on some streams. To illustrate why sharing all the degrees of freedom across node pairs can gain more receive diversity, let us consider an example shown in Fig. 1(a), where two 2-antenna nodes contend for transmission. In existing MU-MIMO MAC protocols. e.g., [1], tx1 delivers two streams once it wins the contention, while tx2 abstains from transmission. In this case, tx1 occupies the whole medium, and each stream tx1 transmits only has receive diversity of 1. In contrast, as shown in Fig. 1(b), if we make tx1 transmit one stream and tx2 transmit the second stream by using interference alignment, the stream from tx1 can obtain receive diversity of 2! This is because, when tx2 aligns its signal at rx1 along the direction orthogonal to tx1's signal, as shown in the bottom graph (below rx1) in Fig. 1(b), rx1 can decode the stream from tx1 using *maximal ratio combining (MRC)* as if the stream from tx2 does not exist.



(a) 2×2 multiplexing (b) 1×2 diversity+2×2 alignment

Figure 1: A 2-antenna node sending two streams, as shown in (a), only achieves the multiplex gain. Both nodes delivering one stream, as shown in (b), achieve both the multiplex and receive diversity gains.

Specifically, let h_{ij} be the channel from the i^{th} transmit antenna to the j^{th} receive antenna as shown in Fig. 1(b). If tx1 transmits x_1 alone from any of its antennas, say antenna 1, the two antennas at rx1 can receive the following signals

$$y_1 = h_{11}x_1 + n_1$$
$$y_2 = h_{12}x_1 + n_2$$

, where n_1 and n_2 are the noise observed at rx1's two antennas. To achieve the receive diversity gain, rx1 can recover the symbol x_1 by using the MRC technique as follows.

$$\hat{x}_1 = \frac{h_{11}^* y_1 + h_{12}^* y_2}{|h_{11}|^2 + |h_{12}|^2} \tag{1}$$

Since the recovered signal $\hat{x}_1$ is the weighted sum of two signals traversing two diverse paths, MRC can hence improve the SNR of the recovered signal.

Now lets assume that tx2 uses one of its antennas, e.g., antenna 3, to transmit concurrently without interference alignment. The received signals at rx1's two antennas become

$$y_1 = h_{11}x_1 + h_{31}x_2 + n_1$$
$$y_2 = h_{12}x_1 + h_{32}x_2 + n_2.$$

In this case, rx1 cannot use MRC in Eq. (1) to decode x_1 because tx2 creates interference at rx1. However, if tx2 performs interference alignment by transmitting the precoded symbols αx_2 and βx_2 from its two antennas, rx1 can now receive the following signals.

$$y_1 = h_{11}x_1 + (\alpha h_{31} + \beta h_{41})\, x_2 + n_1$$
$$y_2 = h_{12}x_1 + (\alpha h_{32} + \beta h_{42})\, x_2 + n_2.$$

To ensure rx1 to be able to use MRC to achieve the same SNR after tx2 joins concurrent transmission, we let tx2 align its signal x_2 at rx1 along the direction orthogonal to x_1, i.e., $(-h_{12}^*, h_{11}^*)$. That is, tx2 should ensure the precoding

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coefficients α and β to satisfy the following equations.

$$\frac{\alpha h_{31}+\beta h_{41}}{\alpha h_{32}+\beta h_{42}} = \frac{-h_{12}^*}{h_{11}^*}, \|(\alpha,\beta)\|^2 = 1$$

By performing the above interference alignment technique, tx2 can ensure not to interfere rx1 because rx1 can still use MRC in Eq. (1) to completely remove the interference from tx2. Note that rx2 in Fig. 1(b) can use the standard MIMO decoder, e.g., zero-forcing, to decode the second stream x_2. Therefore, this example shows that MDMA not only achieves the same multiplex gain, but also provides rx1 the receive diversity gain.

Numerical Analysis: We mathematically derive the SNR gain of the case shown in Fig. 1(b) over that in Fig. 1(a). Let P be the power constraint of both transmitters. In addition, we assume that n_i is white Gaussian noise with variance N_0. The received signals in Fig. 1(a) can be formulated as

$$\begin{aligned} y_1 &= \sqrt{P/2}[h_{11}x_1 + h_{21}x_2] + n_1 \\ y_2 &= \sqrt{P/2}[h_{12}x_1 + h_{22}x_2] + n_2. \end{aligned}$$

rx1 can decode x_1 and x_2 using zero-forcing and achieve the following SNR.

$$SNR_a(x_1) = \frac{P\left\|(h_{11},h_{12})\cdot(h_{22}^*,-h_{21}^*)\right\|^2}{2\left\|(h_{22}^*,-h_{21}^*)\right\|^2 N_0}$$

$$SNR_a(x_2) = \frac{P\left\|(h_{21},h_{22})\cdot(-h_{12}^*,h_{11}^*)\right\|^2}{2\left\|(-h_{12}^*,h_{11}^*)\right\|^2 N_0}$$

Similarly, the received signals in Fig. 1(b) are as follows.

$$\begin{aligned} y_1 &= \sqrt{P}[h_{11}x_1 + (\alpha h_{31}+\beta h_{41})\,x_2] + n_1 \\ y_2 &= \sqrt{P}[h_{12}x_1 + (\alpha h_{32}+\beta h_{42})\,x_2] + n_2 \\ y_3 &= \sqrt{P}[h_{13}x_1 + (\alpha h_{33}+\beta h_{43})\,x_2] + n_3 \\ y_4 &= \sqrt{P}[h_{14}x_1 + (\alpha h_{34}+\beta h_{44})\,x_2] + n_4 \end{aligned}$$

rx1 and rx2 use MRC and zero-forcing to decode x_1 and x_2, respectively, and achieve the following SNR.

$$\begin{aligned} SNR_b(x_1) &= \frac{P\left\|(h_{11},h_{12})\right\|^2}{N_0} \\ SNR_b(x_2) &= \frac{P\left\|(\alpha h_{33}+\beta h_{43},\alpha h_{34}+\beta h_{44})\cdot(-h_{14}^*,h_{13}^*)\right\|^2}{\left\|(-h_{14}^*,h_{13}^*)\right\|^2 N_0} \end{aligned}$$

Hence, the SNR gain of x_1 is

$$\frac{SNR_b(x_1)}{SNR_a(x_1)} = \frac{2\left\|(h_{11},h_{12})\right\|^2\left\|(h_{22}^*,-h_{21}^*)\right\|^2}{\left\|(h_{11},h_{12})\cdot(h_{22}^*,-h_{21}^*)\right\|^2} = \frac{2}{\sin^2\theta}$$

, which is always greater than 2. To derive the SNR gain of x_2, we assume that h_{ij} are i.i.d. complex Gaussian variables with zero mean and unit variance. Because of the unitary property of the precoding vector (α,β), $\alpha h_{33}+\beta h_{43}$ and $\alpha h_{34}+\beta h_{44}$ are also i.i.d. complex Gaussian variables with zero mean and unit variance. We can observe now that $SNR_b(x_2)$ and $2SNR_a(x_2)$ follow the same distribution. Thus, on average, $SNR_b(x_2)$ has a gain of 2.

2. PROTOCOL DESIGN

The goal of MDMA is to allow more node pairs to engage in concurrent transmission and achieve more receive diversity. Unlike existing protocols that allow each contention winner to send as many concurrent streams as possible [1], MDMA involves as many node pairs in concurrent transmission as possible. To achieve the receive diversity gain, we let multiple transmitters join concurrent transmission one after another, and use interference alignment to avoid affecting receive diversity of the ongoing transmissions. Consider a more general example shown in Fig. 2, where three transmitters contend for the medium. Unlike [1] that allows tx1 to transmit two streams and tx2 to transmit one stream, MDMA lets each of three transmitters send one stream, one after another. To provide rx1 and rx2 diversity gains, tx2 and tx3 align their signals orthogonal to the first stream at rx1, while tx3 further aligns its signal orthogonal to the projection of the second stream onto the subspace interference-free to the first stream at rx2. The main challenge of our design is how to allocate concurrent transmission opportunities and perform alignment across node pairs in a distributed way. To address these issues, we modify frequency-domain contention [2] to operate in a MU-MIMO WLAN. Due to space limit, we leave the details in our future work.

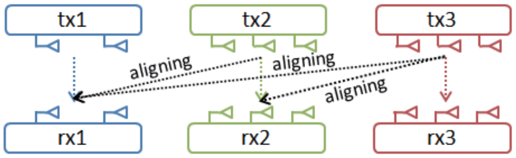

Figure 2: An example of three node pairs, each of which delivers one stream.

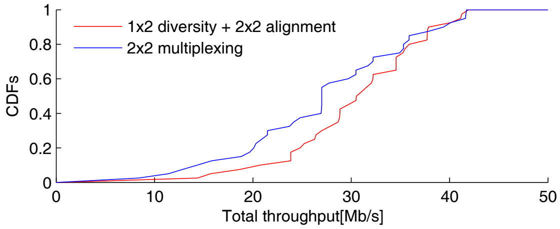

Figure 3: Throughput gain

3. PRELIMINARY RESULTS

We implement the scenario in Fig. 1 using USRP-N200 software radios, each of which is equipped with a RFX2400 daughterboard and communicates on a 10 MHz channel in the 2.4 GHz range. We repeat the experiment in randomly-selected locations in our testbed. Fig. 3 plots the CDFs of the total throughput of both scenarios in Fig. 1. It shows that MDMA leverages both the diversity and power gains, and hence outperforms the single-pair MIMO scenario.

4. CONCLUSION

We propose MDMA, which enables as many node pairs to involve in concurrent transmission as possible in order to utilize receive diversity gains and power gains. We analytically derive the theoretical SNR gain and empirically demonstrate the throughput gain of a toy example in MDMA. While more work needs to be done, we believe that MDMA can be generalized to any scenarios and better utilize MIMO capability than the examples explored in this work.

5. REFERENCES

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