MIMO Space-Time Coding for Diffuse Optical Point to Point Communication

Matt Garfield, Chao Liang, Timothy P. Kurzweg, and Kapil R. Dandekar,

Abstract: A Multiple Input, Multiple Output (MIMO) diffuse optical communications link is implemented and evaluated in this letter. We have adapted a 2x2 Alamouti-type space-time coding (STC) scheme to increase link performance beyond that of Single Input, Single Output (SISO), and Multiple Input, Single Output (MISO) systems. Using our experimental testbed and indoor field measurements, we present a representative profile of received power versus distance, as well as comparative SISO, MISO, and MIMO bit error probability performance.

Introduction: Modern office environments have expanding demand for wireless local area networks (LANs). Traditionally, these networks have been implemented using radio frequency (RF) communication methods. RF networks provide a wide coverage area, supporting mobile users at data rates up to hundreds of Mbps. However, the broad coverage of RF networks presents security risks and significant interference concerns. Due to these limitations, the use of RF radiation is strictly regulated, severely restricting the available bandwidth. In this letter, we present the use of infrared (IR) diffuse optical signaling to overcome the inherent limitations of RF communications. While IR-based communication systems are not typically employed due to received signal power limitations, alignment issues, and low data rates, we propose the use of MIMO signal processing techniques to overcome these limitations and enable high performance diffuse optical links. Using IR light as the transmission medium, we create a picocellular coverage area within an indoor office-type environment using a standard ceiling as a diffusing surface. IR light is constrained by the physical boundaries of a room, creating a tightly contained coverage area that presents a significant security and frequency/network planning advantage over RF-based networks. This IR system also reduces interference concerns that allow the IR band to be unregulated worldwide, creating the potential for virtually unlimited bandwidth [1]. By incorporating multiple transceiver elements and MIMO STC techniques, we hope to achieve data rates that meet or exceed current RF LANs with significantly improved security and ease of deployment.

MIMO Optical Space-Time Coding: Transmitting IR light onto a diffusing surface, such as an office ceiling, causes it to scatter, creating various multipath components. Previous diffuse optical MIMO link research has incorporated multi-spot diffusion methods to reduce the reception of multipath components [2]. Our work is unique in that we have employed MIMO STC techniques to productively utilize the “cross-talk” and multipath signal environment that generally limit conventional optical communication systems. Adapting the 2x1 Alamouti-type encoding method presented in [3], we have derived a maximum-likelihood decision rule for a 2x2 diffuse optical MIMO configuration. Specifically, for $i \in \{1,2\}$, we can choose $x_i = \hat{x}_i$ iff:

$$(\tilde{x}_i - \hat{x}_i)^2 + (h_{1,1}^2 + h_{2,1}^2 + h_{1,2}^2 + h_{2,2}^2 - 1)\hat{x}_i^2 \leq (\tilde{x}_i - x_i)^2 + (h_{1,1}^2 + h_{2,1}^2 + h_{1,2}^2 + h_{2,2}^2 - 1)x_i^2 \qquad (1)$$

where, x_i is the transmitted on-off keyed symbol, $\tilde{x}_i$ is the maximum likelihood decision statistic from [3], and $\hat{x}_i$ is the estimated transmitted signal at the receiver. The propagation channel coefficient from the bth transmitter to the ath receiver is given by $h_{a,b}$. In contrast to RF-MIMO systems, the channel coefficients for an IR-MIMO system are real, non-negative values.

Our method uses a training period to characterize the communications channel and calculate the instantaneous channel coefficients ($h_{a,b}$) with each packet transmission. During the training period, each transmitter element is driven individually. These alternating pilot signals allow the receiver array to estimate all of the channel coefficients used in equation (1). After the training sequence, the Alamouti encoded payload [3] is simultaneously sent by both independent and spatially separated transmitters. The transmitted signals utilize unique, but correlated, paths to each of the spatially separated receiver elements. Bit values are decoded by applying the channel coefficients determined during the training period and received signal to the decision rule in equation (1).

To evaluate bit error rate performance, we have derived the bit error probability conditioned on channel knowledge (CBEP) obtained during the training interval for the maximum likelihood receiver from equation (1):

$$\text{CBEP} = Q\left(\sqrt{\frac{E_b}{2N_0}\mathbf{h}^T\mathbf{h}}\right) \qquad (2)$$

where, Q(x) is the Gaussian Q-function, E_b/N_0 is the total bit energy to noise ratio [3], and $\mathbf{h} = [h_{1,1}, h_{1,2}, h_{2,1}, h_{2,2}]^T$.

We can evaluate the potential of differing levels of transmit diversity by considering a variable number of channel coefficients in the decision rule in equation (1) and the CBEP in equation (2). For example, a conventional SISO architecture can be evaluated using only the $h_{1,1}$ terms of the two equations. Similarly, the $h_{1,1}$ and $h_{2,1}$ terms can be used to consider a MISO architecture. To provide a fair comparison between SISO and MISO/MIMO configurations, power normalization was performed by scaling E_b to ensure that total transmit power was constant for both single and multiple transmitter configurations.

Experimental Testbed: We have developed a flexible experimental diffuse optical MIMO testbed with which we can test the performance of the MIMO STC. The baseband of our system is a software-defined radio making use of high speed arbitrary waveform generators and digitizers from National Instruments. Infrared emitting diodes (Vishay TSHF5400) and photodetectors (Vishay TESP5700) were used to implement the transmitter and receiver arrays respectively. We have performed several channel sounding experiments to characterize the diffuse optical MIMO channel and evaluate the performance of the testbed, implementing the methods described above. Figure 1 shows a plot of the received power vs. transmitter-to-receiver distance. In Figure 2, we compare the CBEP for several test cases: a 1x1 SISO link, a 2x1 MISO link as in [3], and a 2x2 MIMO link. Experiments were conducted in an indoor laboratory environment with no special preparation or treatment on the walls or ceilings to enhance the propagation of multipath signal components. Although the results presented in this letter were conducted without the presence of ambient lighting, the qualitative results remain unchanged when ambient is introduced. The results are discussed below.

Results: The coverage area plot shown in Figure 1 shows that we can maintain sufficient received power levels to reliably detect a pilot signal from a transmitter with an output power of 120mW at a distance of 7 feet. Beyond the 7 foot threshold, the receiver was no longer able to detect a pilot signal over the ambient noise. This is consistent with our notion of a secure picocellular coverage area. The size of the coverage area could be increased by increasing transmitter power or through the use of better amplification at the receiver. Current research is focused on the construction of more sophisticated transceiver electronics to allow for larger (and adjustable) access point coverage areas. In the relatively short-range indoor office environment in which experiments were conducted, we observed that the measured channel coefficients, **h,** could be modeled as correlated Gaussian random variables.

In Figure 2, we observe the effects of transmitter-to-receiver distance on the CBEP over the range of E_b/N_0 measured during field experiments. We also compare the CBEP performance of the diffuse optical link under SISO, MISO, and MIMO configurations to quantify the benefits of additional levels of system complexity. As expected, when transmitter-to-receiver distance is fixed, there is increased CBEP performance when switching from SISO to MISO to MIMO configurations. However, the benefit of using MISO over SISO is relatively small. This result can be explained by noting that total transmit power was held constant for single and multiple transmitter configurations. Furthermore, these results show that diffuse optical space-time coding with transmit diversity alone is not enough to yield an appreciable performance increase. The use of both transmit and receive diversity in a MIMO configuration, however, improves CBEP performance given equal levels of transmitted signal power. As Figure 2 shows, MIMO processing allows the larger transmitter-to-receiver link to outperform a conventional SISO link of a smaller distance. Thus, MIMO techniques can significantly increase the effective range of a diffuse optical access point without the need for additional signal power.

Conclusions: Diffuse optical links provide a more secure alternative to traditional RF systems by providing a tightly contained wireless coverage area. By applying MIMO space-time coding to diffuse optical communication links, we can utilize the various multipath components to reduce the CBEP, thereby increasing the achievable data rate. Using our experimental testbed, we verified our MIMO space-time code to show a proof-of-concept diffuse optical MIMO wireless link providing a secure picocellular coverage area with a 7 foot radius. We have demonstrated that the application of our 2x2 MIMO STC outperforms both the SISO and MISO configurations. Further research in this area will consider the impact of different transceiver array geometries (spacing, orientation, etc.), error correcting codes, and adaptive power control on the performance of the MIMO free space optical link.

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References:

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Figure Captions:

Figure 1: Plot of received power vs. distance using 120mW per transmitter element

Figure 2: Comparison of bit error performance with different transmitter-to-receiver distances and variable levels of transmit and receive diversity

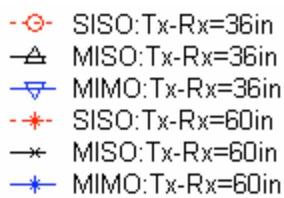
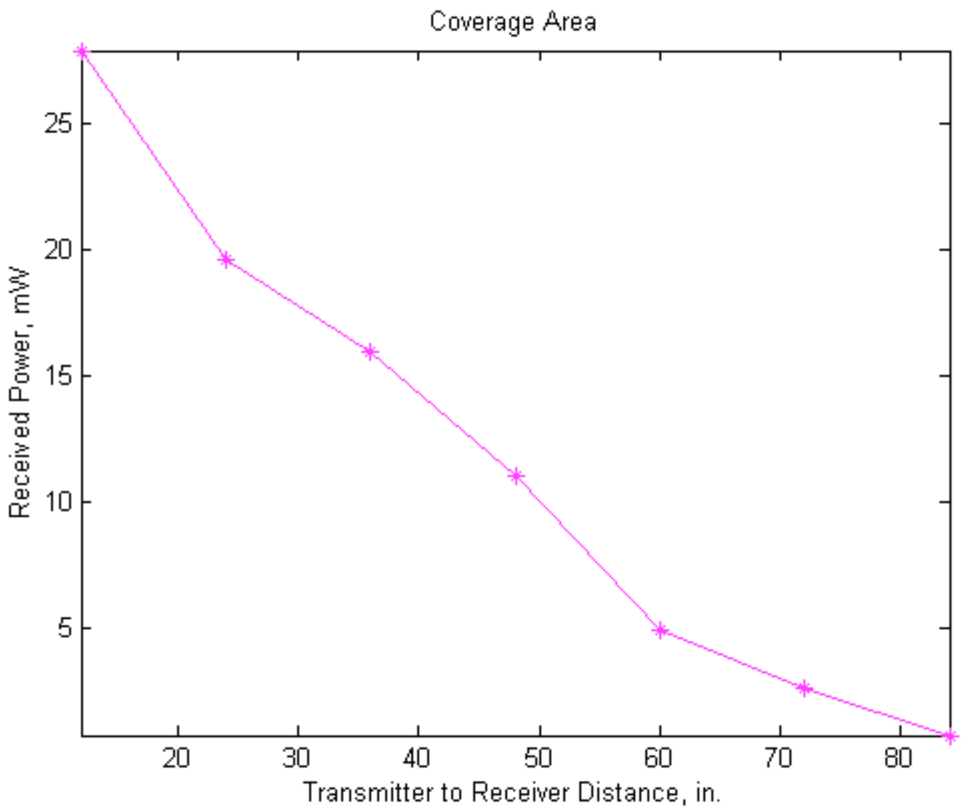
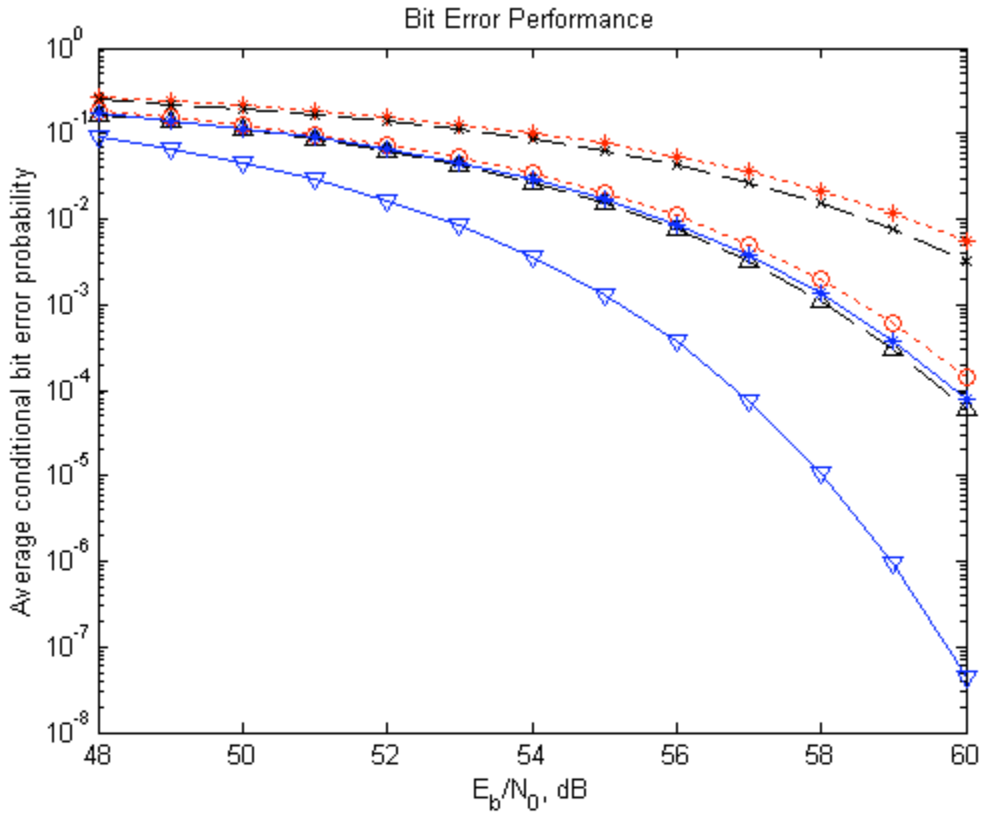


Figure 1:



Coverage Area
Received Power, mW
25
20
15
10
5
20
30
40
50
60
70
80
Transmitter to Receiver Distance, in.

Figure 2:



Bit Error Performance
Average conditional bit error probability
E_b/N_0, dB
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
48
50
52
54
56
58
60