Experimental Demonstration of 2x2 MIMO Communications in a Reverberant Ventilation Duct Environment

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Abstract

In this work we demonstrate simultaneous communications using a 2x2 Multiple In Multiple Out (MIMO) antenna array inside an enclosed ventilation duct. We further demonstrate that MIMO coefficients applied to transmit and receive antennas can be computed at a single frequency and applied over a range of frequencies and still provide effective MIMO communications. We use this technique to demonstrate Bit Error Rates (BER) of $<10^{-5}$ using a 1 Mbps data rate and 2 MHz of radio frequency (RF) bandwidth.

Introduction

Significant prior work has shown that ventilation ducts are an attractive media for distributing RF communication signals indoors (See for example [1] and [2]). Further, in [3], the authors report a tremendous amount of potential bandwidth available if multielement array antennas are used inside ventilation ducts. However, actual MIMO communications have not yet been attempted. The goal of the work presented here is to demonstrate MIMO based communications using antenna arrays inside ventilation ducts. Further, we show that even when using antenna array coefficients calculated at a single frequency but applied across a range of frequencies, significant RF bandwidths can still be used for communications.

Experiments

The relevant experiments were performed in the 2.4 to 2.5 GHz band using a hollow, cylindrical, metal ventilation duct, 9.1 meters long and 0.3 meters in diameter with flat metal endcaps as the physical transmission environment. As illustrated in figure 1, the 2 by 2 MIMO setup was achieved using quarter wavelength monopoles tuned to 2.45 GHz. The antennas were connected to the duct and aligned longitudinally along the length of the duct. The transmit and receive antennas were separated individually by 1 wavelength and by 8.0 meters from one another. Since we will be applying complex coefficients to the transmitted and received RF waveforms, we used 8 digitally controlled vector modulators that operate at RF to apply the desired magnitude and phase shift directly to the test waveforms. The vector modulators are capable of repeatably setting complex coefficients ranging from to 0 to 40 dB of attenuation and any phase

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shift from 0 to 360 degrees across the frequency range of interest. The modulators can also provide a maximum attenuation with unknown phase shift of 70 dB. As seen in figure 1, two vector modulators are paired with each antenna. In this manner, any arbitrary combinations two input signals, T_1 and T_2 can be fed to both transmit antennas, and any arbitrary mix of signals at the two receive antennas can be fed to the two receive output ports, R_1 and R_2.

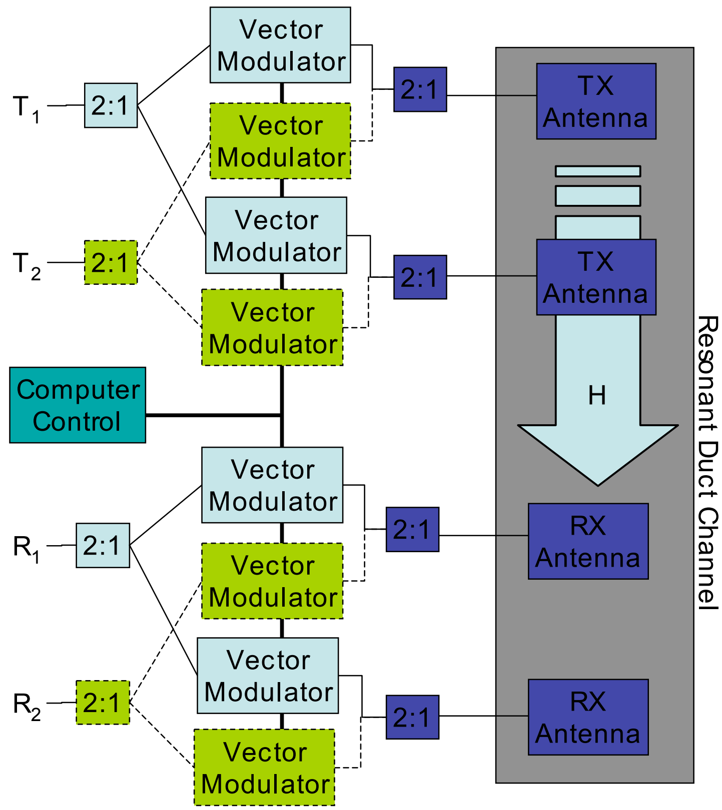

Figure 1: Setup of channel and equipment used in experiments.

The first step in the measurements was to characterize the channels between the transmit and receive antennas, $H_{mn}(f_q)$ using a Vector Network Analyzer (VNA). To do this, the transmit side of the VNA was connected through a power splitter to the two transmitter ports T_1 and T_2. Likewise, the receiver side was connected via power splitter to the two receiver powers R_1 and R_2. We then characterized the four H_{mn} channels between the transmit and receive antennas by selectively setting all but 1 transmit side and 1 receive side vector modulator to their maximum attenuation setting. In this way, $H(f_q)$ could be characterized without swapping cables. The measured channels are shown in figure 2.

After the $H(f_q)$ matrix was characterized, we could compute the transmit and receive coefficients that would create two virtual channels between the transmit and receive ends. However, the vector modulators provide a single coefficient at all frequencies, while the channel responses, as seen in figure 2, vary rapidly with frequency. We thus choose a single frequency bin, f_p of 2.45 GHz at which to create the MIMO channels.

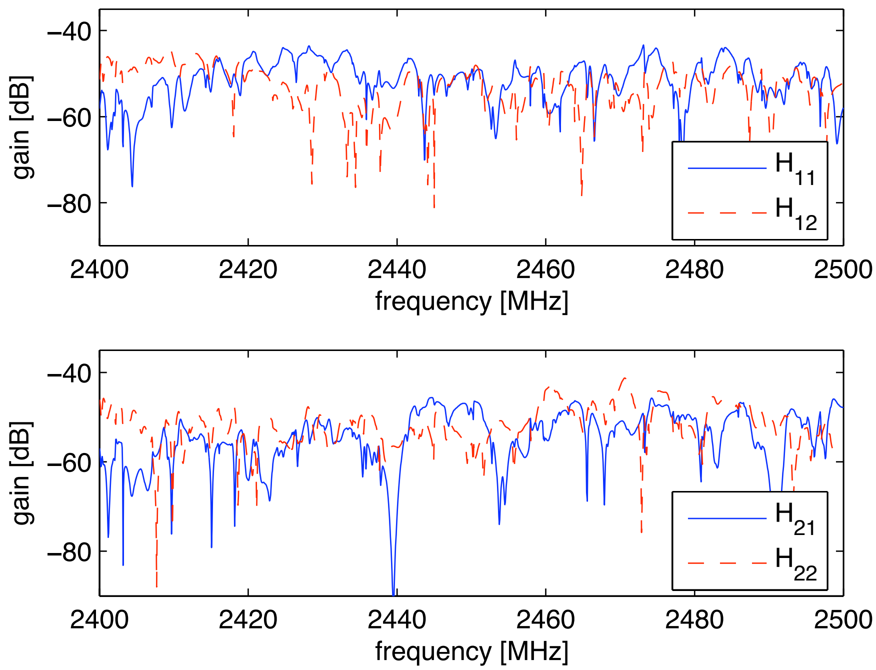

Figure 2: Measured channel responses forming the H matrix

It is a well know property of eigenvector bases that if we construct

$$D = X^{-1}HX \tag{1}$$

such that X is a matrix of the set of eigenvectors of H and X^{-1} is the matrix inverse of X, then D will be a diagonal matrix. In fact, the eigenvalues of H will make up the diagonal elements of D. equation 1 allows us to create two virtual channels between transmitter and receiver. This calculation was performed using the previously measured $H(f_p)$. The coefficients X and X^{-1} were applied to the appropriate vector modulators. We then utilized the same network analyzer measurement procedure to measure D across a range of frequencies around f_p. The resulting measured channels are shown in figure 3.

Next we wished to confirm that two virtual channels had been formed and that they could be used over a reasonable bandwidth, despite being created using a single frequency point, f_p. To do this we used two signal generators and a vector signal analyzer to perform bit error rate (BER) measurements. Specifically, a pseudo-noise (PN) sequence, encoded via 2 tone Frequency Shift Keying (FSK-2) was repeatedly transmitted at a 1 megabit per second (Mbps) rate into one transmit side port (i.e., T_1 or T_2). A 1 MHz, frequency modulated, square wave tone was transmitted at the same frequency on the other transmit side port. Both signals had a 1 MHz maximum frequency deviation and so occupied a nominal 2 MHz bandwidth about 2.45 GHz. The resulting BERs and the measured channel gains are shown in table 1. The BERs clearly indicate that two MIMO channels were successfully created and that reasonable communications could be performed even using imperfectly applied MIMO channel settings.

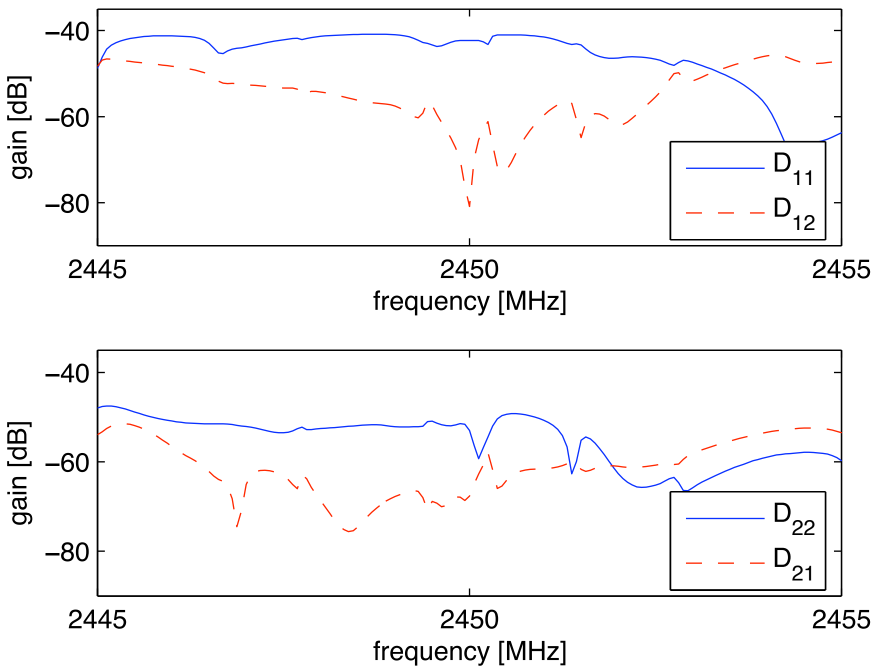

Figure 3: Measured MIMO based channel responses created using an eigenvector basis, X of $H(f_p)$.

Table 1: Measured gains and BERs of MIMO based channels.

Input	Output	MIMO Channel Gain, $\|D(f_p)\|$	Bit Error Rate
T_1	R_1	-42.4 dB	$< 10^{-5}$
T_1	R_2	-81.6 dB	$\sim 50\%$
T_2	R_1	-67.6 dB	$\sim 50\%$
T_2	R_2	-53.0 dB	2.3%

Conclusion

In this work we have successfully shown that a 2x2 MIMO communications channel can be created in a resonant environment. Even when channel variations are present across frequency, significant communication bandwidths can be achieved using MIMO coefficients applied based on measurements at a single frequency. The channel and BER measurements presented here confirm that MIMO techniques work well to create virtual communications channels even in the context of a reverberant ventilation duct environment.

References

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[3] A. G. Cepni, D. D. Stancil, A. E. Xhafa, B. E. Henty, P. V. Nikitin, O. K. Tonguz, and D. Brodtkorb, "Capacity of multi-antenna array systems for HVAC ducts," IEEE International Conference on Communications, 2004, vol. 5, pp. 2934-8.