Narrowband Jammer Resistance for MIMO OFDM.

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Abstract—Multi-input multi-output (MIMO) antenna systems provide the user with additional degrees of freedom over traditional single antenna (SISO) system to enable optimum transmission. This paper focuses on the use of multi-antenna techniques to compensate for in-band interference in scatter rich environments. We consider the effects of narrowband interference in a collection of typical channels with delay spreads and losses representative of both indoor and outdoor environments. We show the performance of a multi antenna technique that can be used to combat these types of interference. We present an analysis of the performance of this technique in channels with varying amounts of dispersion. Both simulation and experimental results will be discussed and presented. The experimental results are collected from testing performed on a highly versatile MIMO OFDM testbed developed at Silvus Technologies. The testbed uses a waveform similar to 802.11n. The chosen method will show up to 30dB rejection of the interfering signal, thereby allowing us to achieve roughly 50% of the unjammed throughput in the presence of strong jammer. We also show that this method is proven on real-time hardware, where we successfully received a 23Mbps stream of data with a signal to interference ratio of -20dB.

I. INTRODUCTION

The unlicensed nature of the ISM band has allowed for rapid development and deployment of various wireless technologies such as 802.11 and bluetooth. Since devices are allowed to operate in the same band without pre-determined frequency or spatial planning, they are bound to interfere with each other. There have been several attempts to mitigate this issue via higher layer protocols. Most of these involve some form of cooperative scheduling ([9],[4]). Some work has been done to show that time domain signal processing can be used to mitigate the effects of narrowband interference ([11],[8],[1],[10],[5],[2]). While these methods are effective, none of them have been proven to work on hardware. The primary oversight has been with respect to synchronization. Each of the proposed methods assume ideal OFDM symbol boundary information. None of these techniques explain how to filter the signal prior to detecting the packet. This paper will show how narrowband interference can be mitigated via multi antenna techniques at the receiver with imperfect channel state information(CSI) and no apriori knowledge of the OFDM symbol boundary.

Our original approach does not require the transmitter to have any knowledge of the existence or nature of the interference. We demonstrate the performance of this technique in an 802.11n communications system. The multi-antenna interference mitigation filter that we propose will filter the incoming signal before it is decoded by the existing receiver. This method is shown to not only provide significant jammer rejection in simulation, but also to provide a significant performance improvement in a real-time system.

Since the interference is narrowband it can also be filtered by an adaptive FIR filter. While this method can be very effective, the filter length will increase the effective dispersion of the signal seen by the demodulator. the cyclic prefix would need to be lengthened, in order to mitigate the potential inter-carrier interference that can be created from the extra dispersion. A longer cyclic prefix reduces the efficiency of the OFDM modulation. The single tap spatial filter will have an effective filter support of 1 sample and therefore will not increase the effective dispersion seen by the demodulator. This allows us to keep the same receiver structure, and maintain the same level of efficiency in our modulation.

Section II & III will describe the system model and simulation environment, as well as the techniques that will be used. Section IV will describe the performance results that were gathered from the simulation environment. Section V will describe the real-time hardware platform that was developed to test the algorithm. Section V-B will contain a discussion of the performance results that were witnessed on the hardware testbed. Section VI will conclude the paper with some final remarks.

II. SYSTEM MODEL

The simulation environment consists of a MATLAB model of a standard-compliant 802.11n transmitter, the standard channel models for 802.11, and a model of the receiver. The user data is encoded with a rate 1/2 convolutional code (133s,171s). If the transmission scheme calls for more than one spatial stream the encoded data is spread across the streams in a systematic manner to take advantage of spatial diversity. The coded data on each spatial stream is then interleaved over a single OFDM symbol and then mapped into QAM constellation points. The constellation used in our simulation is 16-QAM. These constellation points are used to modulate the 52 data subcarriers in our OFDM system. This modulation is done with a 64-point FFT, after which the resulting signal is extended with a 16 sample cyclic prefix. The cyclic prefix is a necessary part of OFDM modulation to combat the affects of a multipath channel and prevent inter-carrier interference. The resulting OFDM symbols are windowed and concatenated to generate the data payload of the transmitted packet.
The transmitted signal is a 4x4 20MHz MIMO OFDM signal. It uses the same training sequences for time and frequency synchronization as 802.11n. In our simulation we use the HT mixed mode packet format for all packets. Channel estimation is done using the HT long training sequences. The data payload of the packets is 100 bytes long.

III. SIMULATION ENVIRONMENT

In order to test the performance of our multi-antenna interference mitigation algorithms, we randomly place a single tone jammer in the band of interest. The power and frequency of the jamming tone are held constant for the duration of the packet. The jammer and transmitted packet are convolved with frequency selective spatial channels. The signals are combined at the receiver and passed through the multi-antenna interference mitigation filter. The filtered signal is then decoded using the software model of the receiver.

We use the inter-frame spacing before the packet to estimate the covariance matrix \( R \) of the interference + noise signal. We know the signal of interest will not be present during this time. The interfering tone is assumed to be present during this time so we can use this period to estimate the covariance of the interference and noise. Estimation is done using 1000 samples of the received signal. Since we have a 4-antenna receiver our covariance matrix will be a 4x4 matrix. Once the covariance matrix has been estimated we can generate a multi-antenna spatial filtering matrix. For generality we call this matrix \( W \).

The transmitted signal and the interfering source are convolved with randomly generated channels. These channels are modeled as the channels described in the TGn Draft proposal [7]. We used channel A, D for our simulations. Channel A is a signal-tap Rayleigh flat fading channel. Channel D is a frequency selective channel with 50ms rms delay spread. These channels are typical of what would be seen in a homeoffice environment. We will see that the amount of delay spread has a dramatic affect on the performance of the system.

We model the received signal as the desired signal passed through a 4x4 MIMO channel combined with interference and noise at the receiver. Equations 1 - 5 model the Signal to Interference+Noise ratio of the incoming signal. For convenience we will denote the covariance of the interference and noise as \( R_{\gamma+n} \) (eq. 3).

\[
E[yy^*] = E[(Hx + n + \gamma)(Hx + n + \gamma)^*] \tag{1}
\]

\[
E[yy] = HE[xx^*]H^* + R_{\gamma} + N_0I \tag{2}
\]

\[
R_{\gamma+n} = R_{\gamma} + N_0I \tag{3}
\]

\[
E[yy^*] = HH^*\|x\|^2 + R_{\gamma+n} \tag{4}
\]

\[
SINR = \frac{|HH^*\|x\|^2}{tr(R_{\gamma+n})} \tag{5}
\]

Equation 6 shows how the spatial filter affects the incoming signal. Since we assume that the interference is from a single source we assume that its covariance will be dominated by a single eigen-mode. Equation 7 shows the expected singular value decomposition of the covariance of the interference. The noise is modeled as AWGN whose covariance is shown in equation 8. The resulting SINR of the filtered signal can be modeled as 9.

\[
E[y_{clean}y_{clean}^*] = E[(WHx + Wn + W\gamma)(WHx + Wn + W\gamma)^*] \tag{6}
\]

\[
R_{\gamma} = U_{\gamma}\Sigma_{\gamma}V_{\gamma} \tag{7}
\]

\[
= \begin{bmatrix} u_1^* & u_2^* & u_3^* & u_4^* \end{bmatrix} \begin{bmatrix} \sigma_1 & \epsilon & \epsilon & \epsilon \\ \epsilon & \sigma_2 & \epsilon & \epsilon \\ \epsilon & \epsilon & \sigma_3 & \epsilon \\ \epsilon & \epsilon & \epsilon & \sigma_4 \end{bmatrix} \begin{bmatrix} v_1^* \\ v_2^* \\ v_3^* \\ v_4^* \end{bmatrix} \tag{8}
\]

\[
N_0I = U_n\Sigma_nV_n = \begin{bmatrix} \sigma_n & \epsilon & \epsilon & \epsilon \\ \epsilon & \sigma_n & \epsilon & \epsilon \\ \epsilon & \epsilon & \sigma_n & \epsilon \\ \epsilon & \epsilon & \epsilon & \sigma_n \end{bmatrix} \tag{9}
\]

A. Diagonal Loading

A simple technique for mitigating the interference is to invert the covariance matrix of the interference. However, it is not possible to estimate this matrix independently of the noise. As a result we invert the covariance of the interference+noise. Unfortunately, inadequate estimation of the covariance matrix can lead to large sidelobes and a distorted mainlobe in the receiver’s spatial gain pattern.

In order to mitigate these affects we apply diagonal loading to the estimated covariance matrix ([3],[6]). This method has been shown to improve the stability of the resulting inverse. Diagonal loading involves adding a value equal to a fraction of the noise power to each element on the main diagonal in the covariance matrix (eq. 10). This improves the rank of the covariance matrix and the spatial gain pattern of its inverse (eq. 11). We see the greatest benefit from this technique when the interference power is similar to the noise power. Diagonal loading reduces the depth of the nulls that are created, but when the interference power is low it’s better to have a weaker null than a randomly chosen one. We will show simulation results where the amount of diagonal loading was varied to find the best value.

\[
R_{DL} = R_{\gamma} + LN_0I \tag{10}
\]

\[
W_{DL} = R_{DL}^{-1} \tag{11}
\]

\[
W_{DL}W_{DL}^* = (R_{\gamma} + LN_0I)^{-2} \tag{12}
\]

IV. SIMULATION RESULTS

Diagonally loaded inversion was simulated for 16-QAM with a rate 1/2 code on 1, 2, and 3 spatial streams. 100 byte packets were simulated through channels with 10-20dB SNR. The signal to interference ratio(SIR) was swept from -20dB to 40dB. These simulations were done using channel A and D. Diagonal loading of -10dB and +10dB were evaluated for performance.
A. Packet Detection

Another major factor in the performance of a communications system is synchronization. In order to properly decode an OFDM waveform, the receiver must detect and synchronize in time with the OFDM symbol boundary. Figure 1 shows the packet detection performance of diagonal loading in channel A and D. Interestingly, packet detection has better performance with less diagonal loading. While diagonal loading reduces sidelobes of the nulling pattern it also reduces the intensity of the null in the direction of the interference. It is clear that excessive loading biases the covariance matrix too much and begins to hurt the performance. A small amount of loading provides enough stability to the inverse operation to maintain a good nulling pattern.

![Figure 1. Packet detection error rate](image)

B. Packet Error Rate for tested methods

The methods outlined in section 2 were all simulated for 16-QAM with a rate 1/2 convolutional code. The results for the 1TX antenna case are shown for channel A, and D in Figure 2[a,b]. We can see that the frequency diversity that we get from the multipath channel has a beneficial effect on the performance. We also find that when the interference power is sufficiently below the noise floor the performance of the filtered system tracks the performance of the non-filtered system. This shows that our interference mitigation filter does not adversely affect performance when the interference power is lower than the noise power.

Channel D provides us with the best performance. This is due to the nature of our OFDM modulation rather than the nature of the interference. This channel has a 50ns RMS delay spread which creates a frequency selective channel. This frequency diversity is exploited by the coding & interleaving that is performed over the data subcarriers. Channel A is a single tap Rayleigh flat fading channel. Since our OFDM modulation scheme cannot exploit frequency diversity in this channel, we see a much more dramatic affect when the packet is transmitted through a bad channel. The increase in performance is apparent when comparing the y-axis of Figure 2a with Figure 2b. For our system it is clear that diagonal loading of -10dB provides the best performance.

![Figure 2. Packet error rate for one transmit antenna](image)

The same simulations were run with two, and three transmit antennas, the PER curves have the same basic shape, the main difference is in the overall performance (See Figure 3 & Figure 4)

V. HARDWARE IMPLEMENTATION

This multi-antenna interference mitigation technique was implemented on the existing MIMO OFDM cognitive radio testbed developed at Silvus Technologies ([12]). The interfering tone was generated by a signal generated and randomly
placed in the signal band. Covariance was estimated during the inter-frame spacing between packets, and the diagonally loaded inverse was used to filter the incoming signal. The transmitter and receiver on this testbed operate in real-time and are contained in a single FPGA. This filter was added to the receive datapath so it could be used to filter the incoming signal and remove the interference before the receiver attempted to decode the packet.

A. System Overview

The Interference mitigation consisted of 4 major logical components. The first of which was the covariance estimation block. The second component was responsible for calculation of the spatial interference mitigation matrix. For practical reasons this operation was done on a microprocessor that was attached to the FPGA which contains the realtime MIMO OFDM transceiver. The third component performed the matrix vector multiplication required for the filtering operation. The final component was the control block which executed the finite state machine that controlled the operation of the entire interference mitigation subsystem.

B. Hardware Performance

The goal of the realtime system is to achieve the highest throughput possible in the presence of a jammer. The transmitter cycled through 32 different modulation and coding schemes(MCS) while the receiver counted the number of packets that were successfully received for each MCS. The modulation and coding scheme controlled the coding rate, constellation size and number of spatial streams. All packets were of the same length and had the same byte pattern. A CRC was performed on the data to determine if the packet had been decoded correctly.

Once the test had been completed the receiver calculated the PER for each MCS. The effective throughput was calculated as (1-PER)*[802.11n datarate]. This test was performed with a SNR of 12dB and an SIR of -20dB. Each trial consisted of 10,000 packets from each MCS. One hundred trials were performed with and without the interference. The baseline results without interference are shown in Figure 5. The throughput that was achieved in the presence of the narrowband interference are shown in Figure 6.

The baseline test without the interfering signal had a mean throughput of 39.8Mbps with a standard deviation of 8.5MBps. The experimental test with a -20dB SIR jammer had a mean of 21MBps with a standard deviation of 4.6MBps. No packets were received when the same test was run in the presence of interference with existing unmodified receiver developed in [12]. This is due to the inability of the receiver to detect packets in the presence of interference that we saw in Figure
The interference mitigation method tested during these trials had roughly 10dB diagonal loading applied to the covariance matrix. Due to hardware limitations we were not able to precisely characterize the receiver noise floor and adjust the loading for each packet.

VI. CONCLUSION

We have shown that multi-antenna techniques can be used to reject narrow band jammers in most channels. It is possible to sustain a high throughput communications link in the presence of a narrowband interference source. As the dispersion increased the performance of our system improved due to the ability of OFDM to exploit frequency diversity. The extra degrees of freedom provided by a MIMO communications system allowed us to cancel the interference signal without altering the underlying signaling scheme. We’ve shown that these methods not only work in simulation but can be proven on a real-time hardware system in real channels.

REFERENCES
