Transmission Strategies for High Throughput MIMO OFDM Communication

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Abstract — This paper presents two transmission techniques for MIMO OFDM communication, referred to as spatial spreading and eigenvector steering. Spatial spreading is used when the transmitting station is not presumed to have sufficient channel state information to compute optimum steering vectors. This situation may occur for a variety of reasons, including poor or aged channel estimates or lack of calibration between the transmit and receive antenna chains. Eigenvector steering is used in cases where the transmitting station has sufficient information about the channel to compute optimum transmit steering vectors. Simulation results showing throughput and range achieved by the two transmission strategies are provided.

Keywords: eigenvector steering, spatial spreading, cyclic transmit diversity, MIMO, OFDM, WLAN, 802.11n.

I. INTRODUCTION

Tremendous consumer interest in multimedia applications is driving the need for successively higher data rates in wireless networks. The emerging IEEE 802.11n standard for high throughput Wireless Local Area Networks (WLANs) seeks to improve significantly upon the data rates experienced by end users of current WLAN systems, e.g., 802.11a, b, g. Specifically, 802.11n has set out to create a standard in which the data throughput, as measured at the top of the medium access control (MAC) layer, exceeds 100 Mbps [1]. Qualcomm’s 802.11n proposal [2], consisting of both MAC layer and physical layer enhancements, includes a high throughput multiple-input multiple-out (MIMO) based physical layer which employs orthogonal frequency division multiplexing (OFDM) and up to four antennas at each end of the link. Many of the proposal details may also be found in [3].

This paper proposes transmission techniques applicable to data communication between stations with multiple antennas operating in a MIMO OFDM system. These spatial processing techniques provide high throughput and high-range coverage for WLAN operation. The two modes of operation are referred to as spatial spreading and eigenvector steering.

The organization of the paper is as follows. Section II presents an overview of a MIMO OFDM system. Section III describes spatial spreading and Section IV presents a detailed overview of eigenvector steering. In Section V, the two transmission techniques are compared, and simulation results are provided in Section VI. Conclusions are drawn in section VII.

II. MIMO OFDM OVERVIEW

In a MIMO communication system, the transmitter and receiver are equipped with multiple antennas, thus allowing multiple data streams to be transmitted over parallel channels [4]. In a MIMO OFDM system with \( N_T \) transmit antennas and \( N_R \) receive antennas, the wideband channel can be characterized at discrete frequencies \( \ell \Delta f, \ell_1 \leq \ell \leq \ell_2 \), by a set of \( N_R \times N_T \) channel matrices, \( \mathbf{H}(\ell) \), where \( \Delta f \) is chosen to be much less than the coherence bandwidth of the channel.

The received waveform in subcarrier \( \ell \) of a MIMO OFDM communication system with \( N_T \) transmit antennas and \( N_R \) receive antennas may be expressed as

\[
\mathbf{y}(\ell) = \mathbf{H}(\ell) \mathbf{x}(\ell) + \mathbf{n}(\ell)
\]

where \( \mathbf{y}(\ell) \) is the \( N_R \)-element received vector, \( \mathbf{x}(\ell) \) is the \( N_T \)-element transmit vector, \( \mathbf{H}(\ell) \) is the \( N_R \times N_T \) channel matrix whose elements represent the complex gains of the channel coupling between individual transmit and receive antennas, and \( \mathbf{n}(\ell) \) is the additive white Gaussian noise (AWGN) vector.

In a MIMO system with \( N_T \) transmit antennas and \( N_R \) receive antennas, up to \( N_m = \min(N_T, N_R) \) parallel channels may be synthesized. The number of spatial streams transmitted is denoted by \( N_S \), where \( N_S \) is upper bounded by \( N_m \). Letting \( \mathbf{s}(\ell) \) be the \( N_S \)-element vector of modulation symbols to be transmitted, one element for each spatial stream, the \( N_T \)-element transmit vector may be expressed by

\[
\mathbf{x}(\ell) = T[\mathbf{s}(\ell)]
\]

where \( T[\cdot] \) is a transformation on \( \mathbf{s}(\ell) \) dependent on the transmission scheme employed.

In this paper, we consider a \( W=20 \) MHz bandwidth base-band channel that is divided into 64 subcarriers, with \( \Delta f = 312.5 \) kHz and \( -32 \leq \ell \leq 31 \). Each of the \( N_S \) streams undergoes separate encoding, interleaving, and modulation. The 4.0 \( \mu s \) time-domain symbol on each transmit antenna is obtained by taking a 64-point inverse FFT of \( \mathbf{x}(\ell) \) and prepending the 3.2 \( \mu s \) symbol with a 0.8 \( \mu s \) circular extension or cyclic prefix. The cyclic prefix is necessary to maintain orthogonality among the subcarriers in the presence of delay spread in the channel.

III. SPATIAL SPREADING FOR MIMO OFDM

Spatial spreading is used when full characterization of the channel is not available at the transmitter. In this mode, the receiver spatial processing is solely responsible for isolating the independent transmitted data streams and demodulating them. The spatial spreading MIMO techniques described in

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this paper are an extension of the work found in [5], which is the original idea as applied to multiple-input single-output (MISO) systems.

A Signal Model

In the spatial spreading mode, the transmitted vector, \( \mathbf{x}(\ell) \), is formed by transforming the vector of modulation symbols to be transmitted, \( \mathbf{s}(\ell) \), by the \( N_T \times N_S \) matrix, \( \mathbf{W}(\ell) \). The transmitted vector at frequency \( \ell \Delta_f \) may be expressed as

\[
\mathbf{x}(\ell) = \mathbf{W}(\ell)\mathbf{s}(\ell)
\]  

where \( \mathbf{W}(\ell) \) consists of the first \( N_S \) columns of the orthonormal spatial spreading matrix, and the \( N_S \)-element vector \( \mathbf{s}(\ell) \) consists of the modulation symbols to be transmitted on each of the \( N_S \) spatial channels. The received signal is then given by

\[
\mathbf{y}(\ell) = \mathbf{H}(\ell)\mathbf{s}(\ell) + \mathbf{n}(\ell)
\]  

where \( \mathbf{H}(\ell) = \mathbf{H}(\ell)\mathbf{W}(\ell) \) is the effective channel observed at the receiver. As before, \( \mathbf{n}(\ell) \) is a column vector of complex Gaussian noise elements each with zero mean and variance, \( N_0 \).

The spatial spreading matrix, \( \mathbf{W}(\ell) \), varies with subcarrier frequency, \( \ell \Delta_f \), in order to maximize the transmit diversity and to provide many independent “looks” at the channel over the set of OFDM subcarriers. A very simple and effective construction uses a single fixed unitary spreading matrix \( \mathbf{W} \) in combination with a linear phase shift across the OFDM subcarriers per transmitted stream. The resulting spatial spreading matrix may be expressed as

\[
\mathbf{W}(\ell) = \mathbf{C}(\ell)\mathbf{W}
\]  

where \( \mathbf{W} \) consists of the first \( N_S \) columns of a unitary matrix, which can be a Hadamard matrix or a Fourier matrix, for example.

The linear phase shift may be implemented as cyclic transmit diversity (CTD) by introducing a different fixed cyclic time shift per transmit antenna, which is represented in the frequency domain by the \( N_T \times N_T \) matrix

\[
\mathbf{C}(\ell) = \text{diag}\{1, e^{-j2\pi h_1\ell \Delta_f}, \ldots, e^{-j2\pi h_{N_T} \ell \Delta_f}\}
\]  

where \( h_i \) is the cyclic shift on antenna \( i, 0 \leq i \leq N_T - 1 \) (typically a multiple of \( 1/W \)). One must be careful with the amount of cyclic shift that is introduced, as it may impact the channel estimation if smoothing is taking place at the receiver. The receiver can then estimate the transmitted symbols, \( \mathbf{s}(\ell) \), by spatially filtering the received vector, \( \mathbf{y}(\ell) \), based on the estimate of the effective channel, \( \mathbf{H}(\ell) \).

B Channel Estimation and Rate Adaptation

In order for the receiving station to obtain an estimate of the channel, \( \mathbf{H}(\ell) \), or the effective channel, \( \mathbf{H}_e(\ell) \), the transmitting station must send reference to the receiving station. The receiver can estimate the channel from the known MIMO training sequence sent by the transmitting station. The effective channel can be estimated by the receiver when the MIMO training sequence is transmitted using spatial spreading.

The MIMO training sequences may be used by the receiving station to determine the number of active spatial streams and data rates that may be supported. The rate recommendations can be fed back to the transmitting station.

IV. Eigenvector Steering for MIMO OFDM

A Wideband Eigenmodes

With eigenvector steering, the MIMO channel associated with a single OFDM subcarrier can be decomposed into orthogonal spatial channels commonly referred to as eigenmodes [6]. The channel matrix for each subcarrier can be diagonalized by means of the singular value decomposition (SVD), as follows:

\[
\mathbf{H}(\ell) = \mathbf{U}(\ell)\mathbf{D}(\ell)\mathbf{V}^H(\ell)
\]  

where \( \mathbf{U}(\ell) \) (\( N_R \times N_R \)) and \( \mathbf{V}(\ell) \) (\( N_T \times N_T \)) are the matrices of left and right singular vectors, respectively, of the channel at frequency \( \ell \Delta_f \), and \( \mathbf{D}(\ell) \) is a diagonal matrix of dimension \( N_R \times N_T \) whose diagonal elements are the singular values of the channel at the discrete frequency [7]. The diagonal elements of \( \mathbf{D}(\ell) \) are the ordered singular values \( \lambda_0(\ell), \lambda_1(\ell), \ldots, \lambda_{N_m-1}(\ell) \), where \( \lambda_1(\ell) \) is an eigenvalue and \( N_m = \min( N_T, N_R ) \). The notation \( \mathbf{A}^H \) denotes the complex conjugate transpose of the matrix \( \mathbf{A} \).

The largest eigenvalue is sometimes referred to as the principal eigenvalue, and the associated eigenmode is referred to as the principal eigenmode. We can synthesize a set of wideband eigenmodes consisting of the eigenmodes associated with an eigenvalue of a specific rank across the entire set of frequencies, \( \ell \Delta_f, \ell_1 \leq \ell \leq \ell_2 \). Thus, the principal wideband eigenmode consists of the collection of principal eigenmodes at each frequency \( \ell \Delta_f \).

The resulting wideband eigenmodes exhibit interesting properties that make them particularly suitable for communicating over frequency selective channels and that reflect the underlying statistics of the individual single-frequency eigenmodes. The most important of these is that the largest wideband eigenmodes exhibit relatively little frequency selectivity, while the smallest tends to reflect the frequency selectivity of the underlying single-input single-output (SISO) channel.

B Eigenvector Steering

The optimum transmit and receive steering vectors may be obtained from the SVD of the channel, and when the columns of \( \mathbf{V}(\ell) \) are used as transmit steering vectors and the rows of \( \mathbf{U}^H(\ell) \) are used as receiving steering vectors, up to \( N_m \) parallel channels can be synthesized [6].

The transmitted signal vector may be formed by transforming the vector of modulation symbols to be transmitted by the matrix of right singular vectors, as follows:

\[
\mathbf{x}(\ell) = \mathbf{V}(\ell)\mathbf{s}(\ell).
\]

The received signal vector is

\[
\mathbf{y}(\ell) = \mathbf{H}(\ell)\mathbf{x}(\ell) + \mathbf{n}(\ell) = \mathbf{U}(\ell)\mathbf{D}(\ell)\mathbf{V}(\ell)\mathbf{s}(\ell) + \mathbf{n}(\ell)
\]  

where \( \mathbf{n}(\ell) \) is a column vector of complex Gaussian noise elements each with zero mean and variance, \( N_0 \). Processing the received vector with the matrix of left singular vectors results in an estimate of the transmitted modulation symbol vector:

\[
\hat{\mathbf{s}}(\ell) = \mathbf{U}^H(\ell)\mathbf{y}(\ell) = \mathbf{D}(\ell)\mathbf{s}(\ell) + \hat{\mathbf{n}}(\ell).
\]  

The advantage of this approach is that \( \mathbf{D}(\ell) \) is diagonal so that there is no cross talk between the symbols in the estimate at the receiver. Thus, the elements of \( \hat{\mathbf{s}}(\ell) \) are received as though coming from \( N_S \) parallel channels. Up to
$N_s$ spatial streams may be created and each spatial stream may have independent coding and modulation; thus, the coding and modulation may vary over the spatial streams, but are fixed across frequency for a given spatial stream.

C Steering Vectors

For a communication link between two stations, the reverse link channel may be expressed as

$$H_{R}(\ell) = U(\ell)D(\ell)V^{H}(\ell),$$  \hspace{1cm} (11)

and assuming reciprocity in the time division duplexed (TDD) channel, the forward link may be expressed as

$$H_{F}(\ell) = H_{R}^{*}(\ell) = V^{*}(\ell)D(\ell)U^{T}(\ell),$$  \hspace{1cm} (12)

where the notations $A^{T}$ and $A^{*}$ denote the transpose and the complex conjugate of the matrix $A$, respectively.

Define station $A$ to be the station that is transmitting on the reverse link and receiving on the forward link, and define station $B$ to be the station that is transmitting on the forward link and receiving on the reverse link. The optimum transmit and receive steering vectors for station $A$ are $V(\ell)$ and $V^{T}(\ell)$, respectively, and the optimum transmit and receive steering vectors for station $B$ are $U^{*}(\ell)$ and $U^{H}(\ell)$, respectively. Thus, once a station has its receive vectors, it may derive the transmit steering vectors by conjugating the receive vectors.

D Channel Estimation in the Eigenvector Steering mode

The MIMO training sequence allows a receiving station to estimate the channel over which the training sequence was transmitted, as described in subsection B of section III. From the channel estimate, the station may derive the receive and transmit steering vectors by means of the SVD. Transmitting a MIMO training sequence using transmit steering vectors allows a receiving station to directly estimate receive steering vectors without the intermediate steps of estimating the channel and performing an SVD calculation. Due to the reciprocity of the TDD channel, the receiving station can then calculate transmit steering vectors from the estimate of the receive vectors.

The eigenvector steering mode of operation functions under the assumption of channel reciprocity. In order to assure reciprocal channels, calibration of transmit and receive chains of the two stations must be performed before eigenvector steering may take place. Furthermore, a station may derive a valid set of steering vectors regardless of whether it has an estimate of the channel or a unitary transformation of the channel.

As is the case for spatial spreading, the MIMO training sequences allow the receiver to perform rate adaptation. The rate information can be fed back to the transmitting station on the next transmission.

V. COMPARISON OF EIGENVECTOR STEERING AND SPATIAL SPREADING

The primary difference between spatial spreading and eigenvector steering is how the SNR is distributed per spatial channel at the receiver. With eigenvector steering, the SNR per spatial stream in a given subcarrier is directly proportional to the eigenvalue in the subcarrier. The principal wideband eigenmode exhibits the lowest variance while lower eigenmodes have a higher variance. Fig. 1 shows SNRs achieved across the frequency band for a single channel realization. In the figure, eigenvector steering and spatial spreading are used with a minimum mean-square error (MMSE) receiver in a $2 \times 2$ configuration with an average SNR per receiver of 30 dB. The difference in the SNR variance between the principal eigenmode (SNR$_{\text{max}}$) and the lower eigenmode (SNR$_{\text{min}}$) is evident.

With eigenvector steering, the larger eigenmodes contribute a larger fraction of the total capacity. The lower SNR variation exhibited by the larger eigenmodes permits lower redundancy forward error correction (FEC) codes to be used in this case. For example, punctured convolutional codes can be used without incurring a substantial loss due to the low SNR variance. With a strong code, such as a turbo code, performance is less influenced by SNR variations.

With spatial spreading, the received SNR is determined in part by the cross talk among the symbol streams transmitted over the spatial channels. As a result, all spatial channels have statistically similar SNR distributions, with a variance that can be significantly greater than that on the larger eigenmodes, as shown in Fig. 1. Spatial spreading creates diversity across the band by exploiting the spatial dimensionality of the channel. Compared to no steering or fixed steering across subcarriers, spatial spreading can increase the SNR variation across the band, which may degrade the average throughput when using weak codes. However, spatial spreading reduces the outage probability.

Fig. 2 shows the cumulative probability distributions of the power gain obtained by performing various transmission techniques in a $2 \times 2$ flat channel whose elements are random complex Gaussian quantities with unity average power. For eigenvector steering, the distributions of the maximum and minimum eigenvalues, $\lambda_{\text{max}}$ and $\lambda_{\text{min}}$, respectively, are shown. The maximum eigenvalue follows the fourth-order maximum ratio diversity distribution with a mean value of 3.5 while the minimum eigenvalue is Rayleigh distributed with a mean of 0.5 [6].

In Fig. 2, the distribution of power gains achieved with spatial spreading is compared to that achieved with a fixed steering scheme. The distribution of power gains achieved with spatial spreading is closer to that of the principal eigen-
Figure 2: Cumulative probability distributions of gains obtained with various transmission techniques.

value, while that of fixed steering is better than Rayleigh, but not quite as good as fourth-order diversity. As a result of varying the transmission matrix across subcarriers, the outage probability is reduced.

VI. SIMULATION RESULTS

A Simulation Setup

Simulation results are presented for a 20 MHz OFDM system with 64 subcarriers, 48 of which are used for data and four as pilot. The DC subcarrier is unused, and the remaining subcarriers are used as guard subcarriers. Table 1 shows the code rate and modulation allowed for each spatial stream. The base code is a constraint length 7, rate-1/2 convolutional code. Each 3.2 µs OFDM symbol is prefixed with a cyclic extension of duration 0.8 µs, resulting in the 4.0 µs transmitted OFDM symbol. The throughput values shown in the results below are the average physical layer data rates, taking into account the overhead of unpopulated subcarriers and cyclic prefix added to each OFDM symbol. Furthermore, the signal-to-noise ratio is given in terms of total $E_s/N_0$ per receiver, where $E_s$ reflects the captured energy in the 3.2 µs OFDM symbol, exclusive of the cyclic prefix.

The communication system was simulated with the added impairments of phase noise at the transmitter and receiver, power amplifier non-linearity, carrier frequency offset, and symbol clock offset. Acquisition was performed for each packet transmitted. The simulation results are presented for IEEE 802.11n channel model B, which has an rms delay spread of 15 ns, a total delay spread of 80 ns, two clusters, and a 6 Hz Doppler component at the carrier frequency of 5.25 GHz [8].

On the forward link portion, station A transmits MIMO training sequences, which are received by station B and used to perform channel estimation. From the channel estimate, station B determines the data rate that can be received reliably on each forward link spatial channel. The channel estimate is also used to determine the MMSE matrix used at the receiver. If eigenvector steering mode is used, transmit steering vectors are obtained using the SVD of the MIMO channel estimate or can be derived directly from the MIMO training sequences if they are transmitted using eigenvector steering.

The forward link rates obtained by station B are fed back to station A on the reverse link. Station A then uses the rates on the next forward link transmission; thus, there is a delay from the time the rates are computed to the time that they are used.

B Simulation Results

Fig. 3 shows the average physical layer data rate as a function of SNR per receiver for eigenvector steering and spatial spreading in 2×2 and 4×4 configurations. The target packet error rate of the adaptive rate selection was 0.01.

The difference between eigenvector steering and spatial spreading is highly visible in the 4×4 configuration. Eigenvector steering results in medium to high power gain and low variance on the highest three eigenmodes [6]. The power gains resulting from spatial spreading have variance comparable to that of the lowest eigenmode, with a slightly higher average SNR.

In the 2×2 case, the difference between spatial spreading and eigenvector steering is much smaller. While the power gains achieved on the principal eigenmode tend toward fourth-order diversity, the lower eigenmode power gains have a lower mean and higher variance, thus limiting performance.

Fig. 4 shows the average physical layer data rate as a function of distance for eigenvector steering and spatial spreading for the 2×2 and 4×4 configurations, assuming a total transmit power of 17 dBm and a noise figure of 10 dB. The path loss model consists of the free space loss with slope of 2 up to the breakpoint distance of 5 m and slope of 3.5 after the breakpoint distance [8].

Eigenvector steering achieves a noticeable improvement in range over spatial spreading for a given data rate. The difference is especially evident in the 4×4 configuration, where a marked improvement over the 802.11a standard is achieved.

VII. Conclusion

In this paper, two transmission techniques were discussed and compared. Eigenvector steering results in a small SNR variance on the larger eigenmodes, a property that is highly beneficial to a weak code whose performance degrades with high variance in the SNR. The use of a varying transmit steering matrix in spatial spreading introduces variance, which can degrade throughput when using weak codes. However, by providing diversity through many different looks at the channel, spatial spreading significantly reduces the outage probability.

| Table 1: Data rates                                                                 |
|--------------------------------|---------|---------|-----------|
| Efficiency (bps/Hz) | Code rate | Modulation |
| 0.5                 | 1/2      | BPSK     |
| 1.00                | 1/2      | QPSK     |
| 1.50                | 3/4      | QPSK     |
| 2.0                 | 1/2      | 16-QAM   |
| 2.5                 | 5/8      | 16-QAM   |
| 3.0                 | 3/4      | 16-QAM   |
| 3.5                 | 7/12     | 64-QAM   |
| 4.0                 | 2/3      | 64-QAM   |
| 4.5                 | 3/4      | 64-QAM   |
| 5.0                 | 5/8      | 256-QAM  |
| 6.0                 | 3/4      | 256-QAM  |
| 7.0                 | 7/8      | 256-QAM  |
Simulation results, which included several channel impairments, showed the highest average physical layer data rate, achieved with 4\times4 eigenvector steering, in excess of 250 Mbps. In comparison with the 802.11a WLAN standard, where the throughput saturates at 54 Mbps, the system proposed here achieves a throughput improvement factor of 4.75. With insufficient channel state information at the transmitter, the spatial spreading mode in 4\times4 configuration achieves an improvement by a factor of 3.83 over 802.11a.

Because the lowest eigenmode in a 2\times2 configuration has a very high variance and low average power, most of the capacity is derived from the principal eigenmode. The spatial spreading streams have lower average power but higher variance than that on the principal eigenmode. As a result, the performance of the two techniques is similar.

Improvements in implementation would decrease effects of channel impairments, such as power amplifier non-linearity, phase noise, and noise figure of the transceiver, and allow the physical layer throughput to approach the saturation value of 336 Mbps. Additional throughput is possible by shortening the cyclic prefix and using more than 48 subcarriers for data. In the case of a 0.4\mu s cyclic prefix and 52 data subcarriers, physical layer data rates up to 404 Mbps may be achieved.

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