Signal Detection for MIMO-OFDM Wireless Communications

Ye (Geoffrey) Li‡, Jack H. Winters†, and Nelson R. Sollenberger†

‡ School of ECE
Georgia Institute of Technology
Atlanta, GA 30332-0250, USA

† AT&T Labs - Research
200 S. Laurel Avenue
Middletown, NJ 07748, USA

Abstract— **In this paper, orthogonal frequency division multiplexing (OFDM) for MIMO channels (MIMO-OFDM) is considered for wideband transmission to mitigate intersymbol interference and enhance system capacity. The MIMO-OFDM system uses two independent space-time codes for two sets of two transmit antennas. At the receiver, the independent space-time codes are decoded using pre-whitening followed by maximum-likelihood (ML) decoding or ML decoding based on successive interference cancellation. Computer simulation shows that for 4-input and 4-output systems transmitting data at 4 Mbits/sec over a 1.25 MHz channel, the required SNR's for a 10% and 1% WER are 10.5 dB and 13.8 dB, respectively, when each codeword contains 500 information bits and the channel's Doppler frequency is 40 Hz.**

I. Introduction

High data-rata wireless access is demanded by many applications. Traditionally, more bandwidth is required for higher data-rate transmission. However, due to spectral limitations, it is often impractical or sometimes very expensive to increase bandwidth. In this case, using multiple transmit and receive antennas for spectrally efficient transmission is an alternative solution. Multiple transmit antennas can be used either to obtain transmit diversity or to form multiple-input multiple-output (MIMO) channels. It is proven in [1] that, compared with a single-input single-output (SISO) system with flat Rayleigh fading or narrowband channels, a MIMO system can improve the capacity by a factor of the minimum of the number of transmit and receive antennas. For wideband transmission [2], space-time processing must be used to mitigate intersymbol interference. However, the complexity of the space-time processing increases with the bandwidth and the performance substantially degrades when estimated channel parameters are used [3].

In orthogonal frequency division multiplexing (OFDM) [4], [5], the entire channel is divided into many narrow parallel subchannels, thereby increasing the symbol duration and reducing or eliminating the intersymbol interference (ISI) caused by the multipath. Multiple transmit and receive antennas can be used with OFDM to further improve system performance. We have proposed optimum training sequences and a channel parameter estimator for OFDM systems with multiple transmit antennas in [6], [7]. In this paper, we will focus on signal detection for MIMO-OFDM.

II. MIMO-OFDM over Wireless Channels

A MIMO-OFDM system with four transmit and p ($p \geq 4$) receive antennas is shown in Figure 1. Though the figure shows MIMO-OFDM with four transmit antennas, the techniques developed in this paper can be directly applied to OFDM systems with any number of transmit antennas.

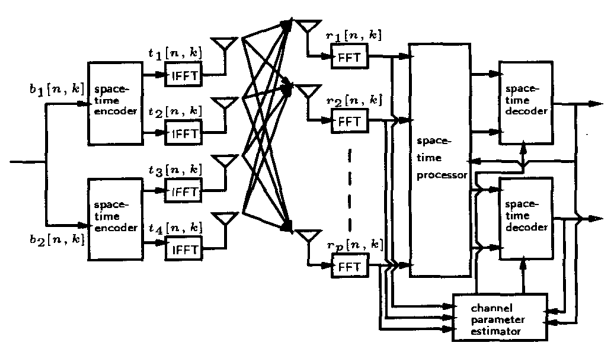

Fig. 1. Multiple-input multiple-output OFDM system.

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At time n, each of two data blocks, $\{b_i[n,k]: k = 0, 1, \cdots\}$ for $i = 1$ and 2, is transformed into two different signals, $\{t_{2i+j}[n,k]: k = 0, 1, \cdots, \& j = 1, 2\}$ for $i = 1$ and 2, respectively, through two space-time encoders. Each of these four signals forms an OFDM block. The transmit antennas simultaneously transmit OFDM signals modulated by $t_i[n,k]$ for $i = 1, \cdots, 4$.

From the figure, the received signal at each receive antenna is the superposition of four distorted transmitted signals, which can be expressed as

$$r_j[n,k] = \sum_{i=1}^{4} H_{ij}[n,k] t_i[n,k] + w_j[n,k], \qquad (1)$$

for $j = 1, \cdots, p$ $w_j[n,k]$ in (1) denotes the additive complex Gaussian noise on the j-th receive antenna and is assumed to be zero-mean with variance σ_n^2 and uncorrelated for different n's, k's, or j's. $H_{ij}[n,k]$ in (1) denotes the channel frequency response for the k-th tone at time n, corresponding to the i-th transmit and the j-th receive antenna. The statistical characteristics of wireless channels are briefly described in [6].

The input-output relation for OFDM can be also expressed in vector form as

$$\mathbf{r}[n,k] = \mathbf{H}_1[n,k]\mathbf{t}_1[n,k] + \mathbf{H}_2[n,k]\mathbf{t}_2[n,k] + \mathbf{w}[n,k],$$

where

$$\mathbf{r}[n,k] \triangleq \begin{pmatrix} r_1[n,k] \\ \vdots \\ r_4[n,k] \end{pmatrix}, \quad \mathbf{w}[n,k] \triangleq \begin{pmatrix} w_1[n,k] \\ \vdots \\ w_4[n,k] \end{pmatrix},$$

$$\mathbf{t}_i[n,k] \triangleq \begin{pmatrix} t_{2i+1}[n,k] \\ t_{2i+2}[n,k] \end{pmatrix},$$

and

$$\mathbf{H}_i[n,k] \triangleq \begin{pmatrix} H_{2i+1\ 1}[n,k] & H_{2i+2\ 1}[n,k] \\ \vdots & \vdots \\ H_{2i+1\ p}[n,k] & H_{2i+2\ p}[n,k] \end{pmatrix}.$$

To achieve transmit diversity gain and detect the transmitted signal, a space-time processor must extract the required signals for space-time decoders. Note that both the space-time processor and space-time decoding require channel state information.

In [6], [7], we proposed optimum training sequences and developed a channel estimator by exploiting the time- and frequency-domain correlations of the channel parameters for two-input two-output OFDM systems. These techniques can be directly used in MIMO-OFDM systems. Furthermore, with more transmit and receive antennas, channel delay profiles can be estimated, which can be used to enhance the channel estimation.

III. Signal Detection

In this section, we will present techniques for signal detection, including spatial pre-whitening and successive interference cancellation for maximum-likelihood (ML) decoding.

A. Spatial pre-whitening for ML decoding

When a system has multiple inputs or interferers, joint detection of the multiple inputs or users is optimal. However, joint detection is subject to forbidding computational complexity. Therefore, we introduce spatial pre-whitening for maximum-likelihood decoding for MIMO-OFDM, which can reduce detection complexity while maintaining reasonable performance.

Instead of the joint detection of the data blocks, $b_1[n,k]$ and $b_2[n,k]$, the coded signals for $b_2[n,k]$ are treated as interferers when detecting and decoding $b_1[n,k]$. Furthermore, to derive a ML decoding approach, we also assume that $t_3[n,k]$, and $t_4[n,k]$ are uncorrelated and Gaussian. Consequently, $\mathbf{v}[n,k] = \mathbf{H}_2[n,k]\mathbf{t}_2[n,k] + \mathbf{w}[n,k]$ is also Gaussian.

If $\mathbf{v}[n,k]$ is spatially and temporally white, then, as indicated in [6], [7], the minimum Euclidian distance decoder is equivalent to the ML decoder. However, if $\mathbf{v}[n,k]$ is spatially or temporally correlated, then a corresponding pre-whitening processor is required for the ML decoder. It can be shown directly from the ML criterion that ML decoding is equivalent to finding the $\{\hat{b}_1[n,k]\}$ that minimizes

$$\mathcal{C}(\{b_1[n,k]\}) = \sum_{k=1}^{K} \mathbf{e}^H[n,k]\mathbf{R}_v^{-1}[n,k]\mathbf{e}[n,k],$$

where

$$\mathbf{e}[n,k] \triangleq \mathbf{r}[n,k] - \mathbf{H}_1[n,k]\mathbf{t}_1[n,k],$$

and

$$\begin{aligned} \mathbf{R}_v[n,k] &\triangleq E\{\mathbf{v}[n,k]\mathbf{v}^H[n,k]\} \\ &= \mathbf{H}_2[n,k]\mathbf{H}_2^H[n,k] + \sigma_n^2\mathbf{I}. \end{aligned}$$

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Direct calculation yields that

$$\begin{aligned}&\mathcal{C}(\{b_1[n,k]\})\\ =\ &\sum_{k=1}^{K}\mathbf{r}^H[n,k]\mathbf{R}_v^{-1}[n,k]\mathbf{r}[n,k]-\tilde{\mathbf{r}}_1^H[n,k]\tilde{\mathbf{r}}_1[n,k]\\ &+\sum_{k=1}^{K}\left\|\tilde{\mathbf{r}}_1[n,k]-\tilde{\mathbf{H}}_1[n,k]\mathbf{t}_1[n,k]\right\|^2. \end{aligned}\tag{2}$$

where $\tilde{\mathbf{H}}_1[n,k]$ is a 2×2 matrix satisfying

$$\mathbf{H}_1^H[n,k]\mathbf{R}_v^{-1}[n,k]\mathbf{H}_1[n,k]\triangleq\tilde{\mathbf{H}}_1^H[n,k]\tilde{\mathbf{H}}_1[n,k],\tag{3}$$

$$\mathbf{L}_1[n,k]\triangleq(\mathbf{H}_1[n,k]\tilde{\mathbf{H}}_1^{-1}[n,k])^H\mathbf{R}_v^{-1}[n,k],$$

and

$$\tilde{\mathbf{r}}_1[n,k]\triangleq\mathbf{L}_1[n,k]\mathbf{r}[n,k].$$

When the Viterbi algorithm is used for the ML decoding of the space-time codes, the first term in (2) is independent of the detected data and only the second term is related to the detected data and affects the metric in the trellis search when the Viterbi algorithm is used. Consequently, ML Viterbi decoding is equivalent to finding the $\{\hat{b}_1[n,k]\}$ that minimizes

$$\tilde{\mathcal{C}}(\{b_1[n,k]\})=\sum_{k=1}^{K}\|\tilde{\mathbf{r}}_1[n,k]-\tilde{\mathbf{H}}_1[n,k]\mathbf{t}_1[n,k]\|^2.$$

Therefore, after pre-whitening, the space-time decoder for a 2-transmit and 2-receive antenna system in [6] can be used here.

Note that $\mathbf{L}_1[n,k]$ can be also rewritten as

$$\mathbf{L}_1[n,k]=(\tilde{\mathbf{H}}_1^{-1}[n,k])^H\mathbf{H}_1^H[n,k]\mathbf{R}_v^{-1}[n,k].\tag{4}$$

From [8], $\mathbf{H}_1^H[n,k]\mathbf{R}_v^{-1}[n,k]$ is the weight matrix for minimum mean-square error (MMSE) restoration of $\mathbf{t}_1[n,k]$, which can suppress the interferer $\mathbf{t}_2[n,k]$. After MMSE restoration, the correlation matrix of the residual interferers and noise is

$$\mathbf{H}_1^H[n,k]\mathbf{R}_v^{-1}[n,k]\mathbf{H}_1[n,k].$$

From (3), $(\tilde{\mathbf{H}}^{-1}[n,k])^H$ in (4) whitens the residual interferers and noise. Therefore, the pre-whitening processing for the ML decoder is composed of MMSE restoration of the desired signals followed by whitening of the residual interferers and noise.

B. *Successive interference cancellation*

Above, we have introduced pre-whitening for Viterbi decoding of the space-time codes for MIMO-OFDM. The coded signals, $t_3[n,k]$ and $t_4[n,k]$, for the second data block, $b_2[n,k]$, are treated as interference when decoding the first data block. If successive interference cancellation, as has been proposed for the CDMA or single-carrier systems, is used here, then system performance can be improved significantly. For MIMO-OFDM systems, successive interference cancellation can be based on either *cyclic redundancy check* (CRC) codes or signal quality.

B.1 SIC based on CRC

If CRC codes are used for *automatic request for repeat* (ARQ), then there the same codes can be also used for successive interference cancellation.

We first decode two data blocks, $b_i[n,k]$ for $i=1,\ 2$, using the pre-whitening approaches introduced before. If the CRC codes in the data blocks find decision errors in one data block and no errors in the other data block, then the coded signals for the correct data block can be regenerated at the receiver and removed from the received signal; consequently, cleaner signals (without interference from the correct signal) can be used to re-detect and decode the data block that had errors before, which will now have much better performance.

B.2 SIC based on signal quality

For systems without CRC codes, it is usually unknown if the decoded data block is correct. Similar to single-carrier MIMO systems, we can first detect and decode the data block corresponding to the signal with higher quality, *e.g.*, lower MMSE, and then remove it from the received signal for detection and decoding of the other data blocks.

IV. Performance Evaluation

In this section, we demonstrate the performance of MIMO-OFDM systems through computer simulation. First, we briefly describe the simulated OFDM system.

A. *System parameters*

In our simulation, we use the typical urban (TU) and the hilly terrain (HT) delay profiles [6] with Doppler frequencies of 5, 40, 100, and 200 Hz, respectively. The channels corresponding to different

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transmit or receive antennas have the same statistics. Four transmit antennas and different numbers of receive antennas are used to form a 4-input multiple-output OFDM system.

To construct an OFDM signal, we assume the entire channel bandwidth, 1.25 MHz, is divided into 256 subchannels. The 2 subchannels on each end are used as guard tones, and the rest (252 tones) are used to transmit data. To make the tones orthogonal to each other, the symbol duration is about 204.8 μsec. An additional 20.2 μsec guard interval is used to provide protection from intersymbol interference due to channel multipath delay spread. This results in a total block length $T_f = 225$ μsec and a subchannel symbol rate $r_b = 4.44$ kbaud.

A 16-state space-time code with 4-PSK is used. Each data block, containing 500 information bits, is coded into two different blocks, each of which has exactly 252 symbols, to form an OFDM block. Therefore, the OFDM system with 4 transmit antennas can transmit 2 data blocks (1000 bits in total) in parallel. Each time slot consists of 10 OFDM blocks with the first block used for training and the following 9 blocks used for data transmission. Consequently, the described system can transmit at 4 Mbits/sec over a 1.25 MHz channel, i.e., the transmission efficiency is 3.2 bits/sec/Hz.

B. Results

We first study the performance of a MIMO-OFDM system with ideal channel parameters using different techniques to improve the system performance.

Figure 2 compares the WER's of a system with interleaving for different detection techniques. From the figure, successive interference cancellation based on CRC and signal quality (MMSE) can reduce the required SNR for a 10% WER by 2.5 and 1.8 dB, respectively. All the performance curves in Figure 2 are for OFDM with 4 transmit and 4 receive antennas.

Figure 3 compares the performance of MIMO-OFDM systems with the ideal or the estimated channel parameters for different channels with a 40 Hz Doppler frequency. From Figure 3 (a), the required SNR's for a 10% WER are 10-11 dB for a MIMO-OFDM system with estimated channel parameters for successive interference suppression and space-time decoding, which is 1.5-2 dB higher that with ideal channel parameters for signal detection and decoding. With more the received antennas, the performance is improved, as shown in Fig. 3 (b). In particular, for a system with estimated channel parameters, the required SNR for a 10% WER is reduced by 4.5 dB and 2 dB when the number of receiver antennas is reduced from 4 to 6 and 6 to 8, respectively.

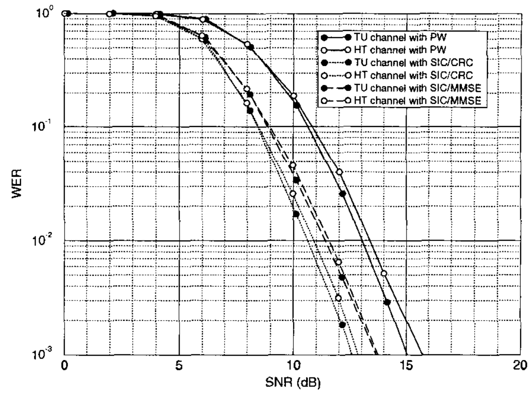

Fig. 2. Performance comparison of MIMO-OFDM with different detection techniques with ideal channel parameters.

Figure 4 compares the performance of OFDM systems with different Doppler frequencies. With higher the Doppler frequency, the channel estimation error increases. Therefore, the system suffers more degradation. For a MIMO-OFDM system with 4 transmit and 4 receive antennas, the required SNR for a 10% WER is degraded by 2.4 dB when the Doppler frequency is increased from 40 Hz to 100 Hz.

V. Conclusions

OFDM is an effective technique to combat multipath delay spread for wideband wireless transmission. In this paper, OFDM with multiple transmit and receive antennas has been used to form a multiple-input multiple-output (MIMO) system to increase system capacity. A pre-whitening technique for ML decoding and successive interference cancellation techniques based on different rules have been proposed. Using these techniques in a 4-input-4-output-OFDM system, the net data transmission rate can reach 4 Mbits/sec over a 1.25 MHz wireless channel, with a 10-11 dB SNR required for a

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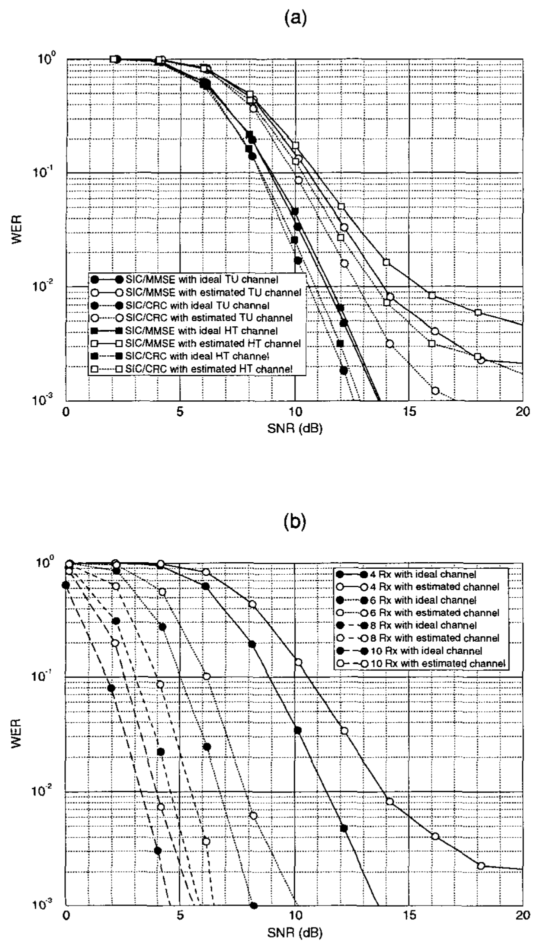

Fig. 3. Performance comparison of a MIMO-OFDM system with ideal and estimated channel parameters: (a) 4 receive antenna system with TU and HT channels, and (b) 4 to 10 receive antenna system with TU channels and $f_d = 40\ Hz$.

10% WER, depending on the radio environment and signal detection technique for word lengths up to 500 bits. Therefore, MIMO-OFDM can be effectively used in high data-rate wireless systems.

Future work will include a comparison of different MIMO-OFDM architectures with and without space-time coding.

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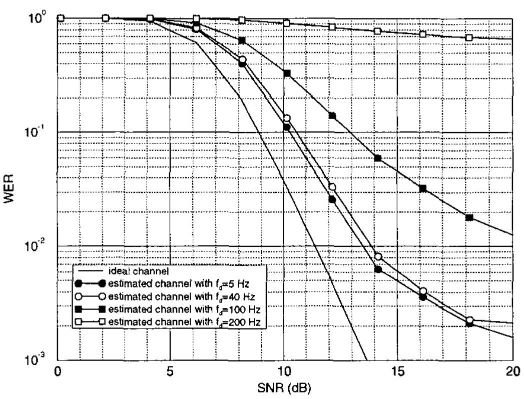

Fig. 4. WER versus SNR with 4 receive antennas using SIC/MMSE for the TU channel with different Doppler frequencies.

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