MIMO-OFDM for Wireless Communications: Signal Detection With Enhanced Channel Estimation

Ye (Geoffrey) Li, *Senior Member, IEEE*, Jack H. Winters, *Fellow, IEEE*, and Nelson R. Sollenberger, *Fellow, IEEE*

***Abstract*—Multiple transmit and receive antennas can be used to form *multiple-input multiple-output* (MIMO) channels to increase the capacity by a factor of the minimum number of transmit and receive antennas. 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 prewhitening, followed by *minimum-Euclidean-distance* decoding based on successive interference cancellation. Computer simulation shows that for four-input and four-output systems transmitting data at 4 Mb/s over a 1.25 MHz channel, the required signal-to-noise ratios (SNRs) for 10% and 1% word error rates (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 (corresponding normalized frequency: 0.9%). Increasing the number of the receive antennas improves the system performance. When the number of receive antennas is increased from four to eight, the required SNRs for 10% and 1% WER are reduced to 4 dB and 6 dB, respectively. Therefore, MIMO-OFDM is a promising technique for highly spectrally efficient wideband transmission.**

***Index Terms*—Multiple-input multiple-output channels (MIMO), orthogonal frequency division multiplexing (OFDM), parameter estimation, wireless communications.**

I. INTRODUCTION

HIGH DATA-RATE 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.

Many researchers have studied using multiple transmit antennas for diversity in wireless systems. Transmit diversity may be based on linear transforms [1] or space–time coding [2]. In particular, space–time coding is characterized by high code efficiency and good performance; hence, it is a promising technique to improve the efficiency and performance of orthogonal frequency division multiplexing (OFDM) systems. On the other hand, the system capacity can be significantly improved if multiple transmit and receive antennas are used to form MIMO channels [3]–[6]. It is proven in [4] 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 number of transmit and receive antennas. For wideband transmission [7], space–time processing must be used to mitigate intersymbol interference (ISI). However, the complexity of the space–time processing increases with the bandwidth, and the performance substantially degrades when estimated channel parameters are used [8].

In OFDM [9]–[11], the entire channel is divided into many narrow parallel subchannels, thereby increasing the symbol duration and reducing or eliminating the ISI caused by the multipath. Therefore, OFDM has been used in digital audio and video broadcasting in Europe [12], and is a promising choice for future high-data-rate wireless systems. Multiple transmit and receive antennas can be used with OFDM to further improve system performance. We have studied OFDM systems with adaptive antenna arrays for co-channel interference suppression [13] and transmit diversity based on space–time coding, delayed transmission, and permutation [14]–[16]. In particular, a channel parameter estimator for OFDM systems with multiple transmit antennas was proposed in [14] and simplified in [16]. Optimum training sequences for OFDM with multiple transmit antennas were also proposed in [16].

In this paper, we study multiple transmit and receive antennas for OFDM to form MIMO channels (MIMO-OFDM). Our focus here is enhanced channel estimation and signal detection. The rest of this paper is organized as follows. In Section II, we introduce MIMO-OFDM systems based on space–time coding and briefly discuss wireless channel characteristics. We then present signal detection and decoding techniques for MIMO-OFDM systems in Section III. Next, in Section IV, we introduce an enhanced channel estimation technique and analyze its performance. Finally, we demonstrate the performance of MIMO-OFDM systems using our new techniques by computer simulation in Section V.

II. MIMO-OFDM OVER WIRELESS CHANNELS

Before introducing the signal detection and enhanced channel estimation technique, we briefly describe a MIMO-OFDM system and the statistics of mobile wireless channels.

Paper approved by C. Tellambura, the Editor for Modulation and Signal Design of the IEEE Communications Society. Manuscript received May 2, 2000; revised May 27, 2001. This paper was presented in part at ICC'01, Helsinki, Finland, June 2001.

Y. Li is with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250 USA (e-mail: liye@ece.gatech.edu).

J. H. Winters is with the AT&T Labs–Research, Middletown, NJ 07748-4801 USA (e-mail: jhw@research.att.com).

N. R. Sollenberger is with Mobilink Telecom, Inc., Middletown, NJ 07748 USA (e-mail: nsollenberger@mobilinktel.com).

Publisher Item Identifier 10.1109/TCOMM.2002.802566.

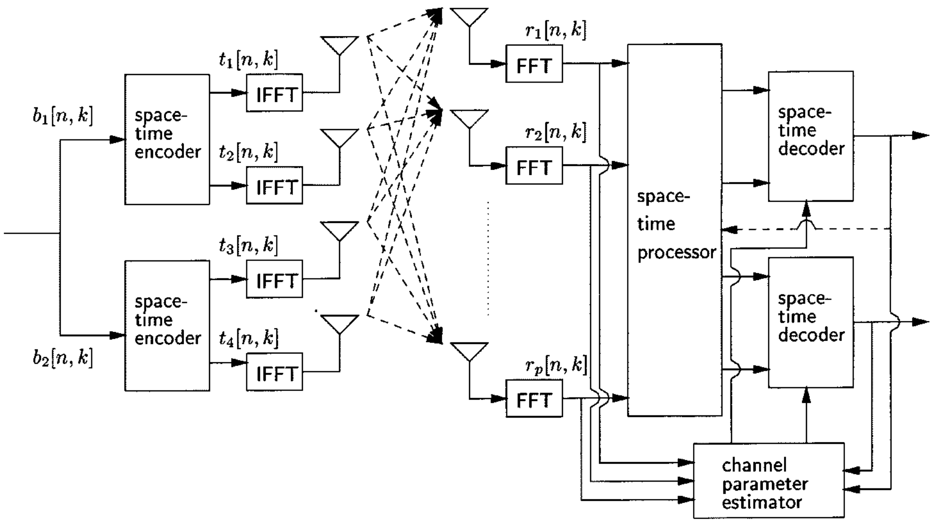


Fig. 1. MIMO-OFDM system.

A. MIMO-OFDM Systems

A MIMO-OFDM system with four transmit and $p (p \geq 4)$ receive antennas is shown in Fig. 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.

At time n, each of two data blocks, $\{b_i[n,k] : k = 0, 1, \ldots\}$ for i =1 and 2, is transformed into two different signals, $\{t_{2(i-1)+j}[n,k] : k = 0, 1, \ldots, j = 1, 2\}$ for i =1 and 2, respectively, through two space–time encoders. The OFDM signal for the ith transmit antenna is modulated by $t_i[n,k]$ at the kth tone of the nth OFDM block.

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

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

for $j = 1, \ldots, p$. $w_j[n,k]$ in (1) denotes the additive complex Gaussian noise at the jth 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 kth tone at time n, corresponding to the ith transmit and the jth receive antenna. The statistical characteristics of wireless channels are briefly described in Section II-B.

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

$$\mathbf{r}[n,k] = \mathbf{H}_1[n,k]\mathbf{t}_1[n,k] + \mathbf{H}_2[n,k]\mathbf{t}_2[n,k] + \mathbf{w}[n,k] \tag{2}$$

where

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

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

and

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

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.

B. Channel Statistics

From [20], the complex baseband representation of a mobile wireless channel impulse response can be described by

$$h(t,\tau) = \sum_k \gamma_k(t) c(\tau - \tau_k) \tag{3}$$

where τ_k is the delay of the kth path, $\gamma_k(t)$ is the corresponding complex amplitude, and $c(t)$ is the shaping pulse. Due to the motion of the vehicle, the $\gamma_k(t)$'s are wide-sense stationary (WSS), narrowband complex Gaussian processes, which are independent for each path. The average powers of the $\gamma_k(t)$'s depend on the channel delay profiles, which are determined by the environment. The channels corresponding to different transmit and receive antennas in MIMO systems usually have the same delay profiles.

From (3), the frequency response at time t is

$$\begin{aligned} H(t,f) &\triangleq \int_{-\infty}^{+\infty} h(t,\tau) e^{-j2\pi f \tau} d\tau \\ &= C(f) \sum_k \gamma_k(t) e^{-j2\pi f \tau_k} \end{aligned} \tag{4}$$

where

$$C(f) \triangleq \int_{-\infty}^{+\infty} c(\tau) e^{-j2\pi f \tau} d\tau.$$

For OFDM systems with proper cyclic extension and timing, it can be seen from discussions in [17] that, with tolerable leakage, the channel frequency response can be expressed as

$$H[n,k] \triangleq H(nT_f, k\Delta f) = \sum_{l=0}^{K_o-1} h[n,l] W_K^{kl}. \tag{5}$$

In (5), $h[n,l] \triangleq h(nT_f, kT_s/K)$, $W_K = \exp(-j2\pi/K)$, and K is the number of tones in an OFDM block. T_f and Δf are the block length and tone spacing, respectively, and T_s is the symbol duration of OFDM, which is related to Δf by $T_s = 1/\Delta f$. In (5), the $h[n,l]$'s, for $l = 0, 1, \ldots, K_o - 1$, are WSS, narrowband complex Gaussian processes. The average power of $h[n,l]$ and index $K_o (< K)$ depend on the delay profiles of the wireless channels.

III. Signal Detection

In this section, we will present techniques for signal detection, including spatial prewhitening and successive interference cancellation for *minimum Euclidean distance* (MED) decoding.

A. Spatial Prewhitening for MED 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. For example, if the two space–time codes in Fig. 1 have 16 states, then the complexity of the joint decoding is about 16 times that of of decoding the two space–time codes separately. In [18], we have studied the tradeoff between the complexity and performance of different space–time codes. Here we focus on spatial prewhitening for MED decoding for MIMO-OFDM to 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 $b_1[n,k]$. From (2), the received signal can be expressed as

$$\mathbf{r}[n,k] = \mathbf{H}_1[n,k]\mathbf{t}_1[n,k] + \mathbf{v}_1[n,k] \tag{6}$$

where $\mathbf{v}_1[n,k] = \mathbf{H}_2[n,k]\mathbf{t}_2[n,k] + \mathbf{w}[n,k]$ is spatially correlated; therefore, a prewhitening processor is required for the MED decoder.

Denote

$$\mathbf{R}_v[n,k] \triangleq E\left\{\mathbf{v}[n,k]\mathbf{v}^H[n,k]\right\} = \mathbf{H}_2[n,k]\mathbf{H}_2^H[n,k] + \sigma_n^2\mathbf{I}$$

which is obviously positive definite. Thus, there exists a nonsingular matrix, $\mathbf{L}_1[n,k]$, satisfying

$$\mathbf{L}_1[n,k]\mathbf{L}_1^H[n,k] = \mathbf{R}_v[n,k]$$

and then $\mathbf{L}_1^{-1}[n,k]$ can whiten $\mathbf{v}_1[n,k]$. Multiplying both sides of (6) by $\mathbf{L}_1^{-1}[n,k]$, we obtain

$$\tilde{\mathbf{r}}_1[n,k] = \tilde{\mathbf{H}}_1[n,k]\mathbf{t}_1[n,k] + \tilde{\mathbf{v}}_1[n,k] \tag{7}$$

where

$$\begin{aligned}\tilde{\mathbf{r}}_1[n,k] &= \mathbf{L}_1^{-1}[n,k]\mathbf{r}[n,k]\\ \tilde{\mathbf{H}}_1[n,k] &= \mathbf{L}_1^{-1}[n,k]\mathbf{H}_1[n,k]\\ \tilde{\mathbf{v}}_1[n,k] &= \mathbf{L}_1^{-1}[n,k]\mathbf{v}_1[n,k].\end{aligned}$$

Since $\tilde{\mathbf{v}}_1[n,k]$ is spatially and temporally white now, the decoding approach in [14] can be used here. It is equivalent to finding the transmitted data, $\{\hat{b}_1[n,k]\}$, that minimizes the following Euclidean distance:

$$\mathcal{C}(\{b_1[n,k]\}) = \sum_{k=1}^{K} \left\| \tilde{\mathbf{r}}_1[n,k] - \tilde{\mathbf{H}}_1[n,k]\mathbf{t}_1[n,k] \right\|^2. \tag{8}$$

Similar to [14] and [15], the Viterbi algorithm is used for the MED decoding.

Note that $\mathbf{L}_1^{-1}[n,k]$ can be also expressed as

$$\mathbf{L}_1^{-1}[n,k] = \left(\tilde{\mathbf{H}}_1^{-1}[n,k]\right)^H \mathbf{H}_1^H[n,k]\mathbf{R}_v^{-1}[n,k]. \tag{9}$$

From [21], $\mathbf{H}_1^H[n,k]\mathbf{R}_v^{-1}[n,k]$ 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

$$\begin{aligned}&E\left\{\mathbf{H}_1^H[n,k]\mathbf{R}_v^{-1}[n,k]\mathbf{v}[n,k]\left(\mathbf{H}_1^H[n,k]\mathbf{R}_v^{-1}[n,k]\mathbf{v}[n,k]\right)^H\right\}\\ &=\mathbf{H}_1^H[n,k]\mathbf{R}_v^{-1}[n,k]\mathbf{H}_1[n,k]\\ &=\tilde{\mathbf{H}}_1[n,k]\tilde{\mathbf{H}}_1^H[n,k].\end{aligned} \tag{10}$$

Hence, $(\tilde{\mathbf{H}}_1^{-1}[n,k])^H$ in (9) whitens the residual interferers and noise. Therefore, the prewhitening processing for the MED decoder is composed of MMSE restoration of the desired signals, followed by whitening of the residual interferers and noise.

Furthermore, if $t_3[n,k]$ and $t_4[n,k]$ are assumed to be uncorrelated and Gaussian, then $\mathbf{v}_1[n,k] = \mathbf{H}_2[n,k]\mathbf{t}_2[n,k] + \mathbf{w}[n,k]$ is also Gaussian. In this case, MED decoding is maximum-likelihood (ML) decoding.

B. Successive Interference Cancellation (SIC)

Previously, we have introduced prewhitening 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 SIC, as has been proposed for the code-division multiple-access (CDMA) or single-carrier systems, is used here, then system performance can be improved significantly. For MIMO-OFDM systems, SIC can be based on either *cyclic redundancy check* (CRC) codes or signal quality.

1) SIC Based on CRC: If CRC codes are used for *automatic request for repeat* (ARQ), then the same codes can be also used for SIC.

We first decode two data blocks, $b_i[n,k]$ for i =1, 2, using the prewhitening 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 redetect and decode the data block that had errors before, which will now have much better performance.

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.

The SIC approaches are slightly more complicated than the prewhitening MED decoding approach. However, the complexity increase of the SIC approaches is negligible, compared with the Viterbi decoder.

IV. ENHANCED CHANNEL ESTIMATION

In [14] and [16], we proposed a decision-directed channel parameter estimator and optimum training sequences for OFDM with multiple transmit antennas. These techniques can be directly used in MIMO-OFDM systems. Furthermore, for MIMO-OFDM systems where many independent channels with the same delay profile are involved, the channel delay profiles can be more accurately estimated. By exploiting this estimated channel delay profile, channel parameter estimation can be further improved.

From [14] and [16], $h_{ij}[n,l]$ in (5) can be estimated using the correlation of channel parameters in the time and frequency domains. With $\hat{h}_{ij}[n,l]$, the estimated $h_{ij}[n,l]$, the channel frequency response can be reconstructed by

$$\hat{H}_{ij}[n,k] = \sum_{l=0}^{K_o-1} \hat{h}_{ij}[n,l] W_K^{kl} \tag{11}$$

where $\hat{h}_{ij}[n,l]$ contains the true channel parameter, $h_{ij}[n,l]$, and an estimation error, $e_{ij}[n,l]$, that is

$$\hat{h}_{ij}[n,l] = h_{ij}[n,l] + e_{ij}[n,l]. \tag{12}$$

From [16], $e_{ij}[n,l]$ can be assumed to be Gaussian with zero-mean and variance σ^2, and independent for different i's, j's, n's, or l's. If we measure the parameter estimation quality by means of normalized mean-square error (NMSE) which is defined as

$$\text{NMSE} \triangleq \frac{E\left\|\hat{H}_{ij}[n,k] - H_{ij}[n,k]\right\|^2}{E\left\|H_{ij}[n,k]\right\|^2}$$

then it can be calculated directly that the NMSE for the estimation in (11) is

$$\text{NMSE}_r = K_o\sigma^2 \tag{13}$$

where we have used the assumption that

$$\sum_{l=0}^{K_o-1} E\left\|h_{ij}[n,l]\right\|^2 = \sum_{l=0}^{K_o-1} \sigma_l^2 = 1$$

with $\sigma_l^2 \triangleq E\|h_{ij}[n,l]\|^2$.

If the channel delay profile is known, that is, σ_l^2 for $l = 0, \ldots, K_o - 1$ is known and is used to reconstruct channel frequency response from $\hat{h}_{ij}[n,l]$, the mean-square error (MSE) of $\hat{H}_{ij}[n,k]$ can be significantly reduced. In this case, if the α_l's are selected to minimize the NMSE of

$$\hat{H}_{ij}[n,k] \triangleq \sum_{l=0}^{K_o-1} \alpha_l \hat{h}_{ij}[n,l] W_K^{kl} \tag{14}$$

then it can be proven by direct calculation that the optimal α_l is

$$\alpha_l = \frac{\frac{\sigma_l^2}{\sigma_l^2+\sigma^2}}{\sum\limits_{m=0}^{K_o-1} \frac{\sigma_m^4}{\sigma_m^2+\sigma^2}} \tag{15}$$

and the NMSE is

$$\text{NMSE}_o = \frac{\sigma^2 \sum\limits_{m=0}^{K_o-1} \frac{\sigma_m^2}{\sigma_m^2+\sigma^2}}{\sum\limits_{m=0}^{K_o-1} \frac{\sigma_m^4}{\sigma_m^2+\sigma^2}}. \tag{16}$$

As indicated in [19], channel delay profiles depend on the environment, and therefore are usually unknown to the users. However, for MIMO-OFDM systems, channels corresponding to different transmit or receive antennas should have the same delay profiles. Therefore, $\sigma_l^2 = E\|h_{ij}[n,l]\|^2$ can be estimated by

$$\hat{\sigma}_l^2 = \frac{1}{4p} \sum_{i=1}^{4} \sum_{j=1}^{p} \left|\hat{h}_{ij}[n,l]\right|^2.$$

With the estimated σ_l^2, enhanced channel frequency responses can be reconstructed by (14).

In the previous discussion, we have assumed that the additive noise is white with known variance. If the noise is colored, then noise whitening is required before the channel estimation. The performance of the enhanced estimator is not sensitive to the noise variance in (15); therefore, we usually just set σ^2 corresponding to a 10-dB signal-to-noise ratio (SNR).

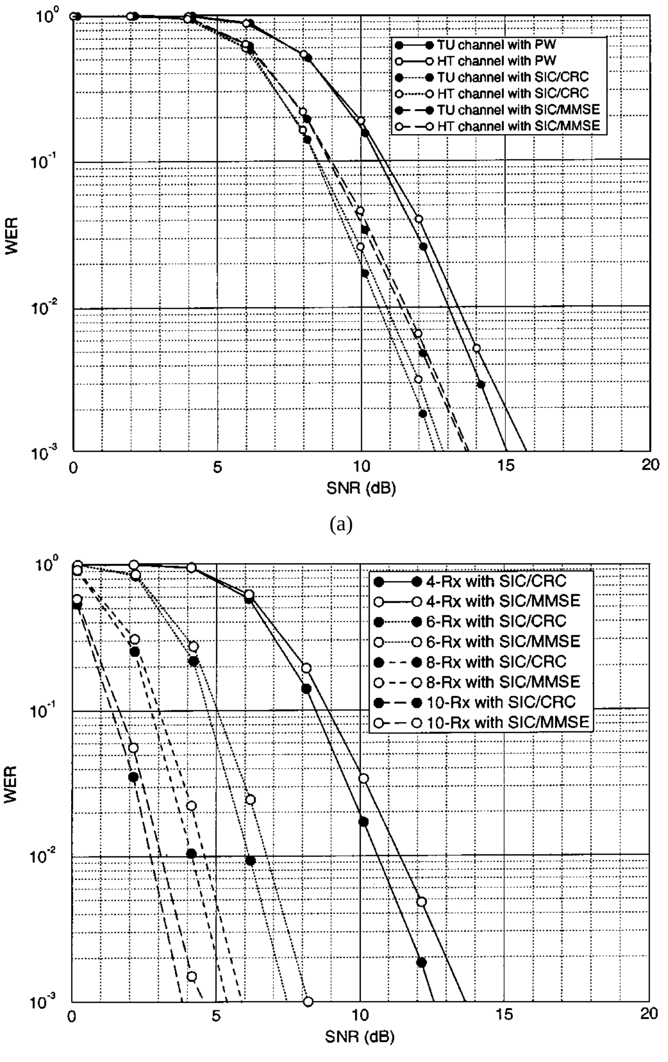
V. PERFORMANCE EVALUATION THROUGH SIMULATION

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 [14] with Doppler frequencies of 5, 40, 100, and 200 Hz, respectively. The additive channel noise is spatially and temporally white Gaussian with zero-mean, and the variance determined by the SNR. The channels corresponding to different transmit or receive antennas have the same statistics. Four transmit antennas and different numbers of receive antennas are used to form a four-input multiple-output OFDM system.

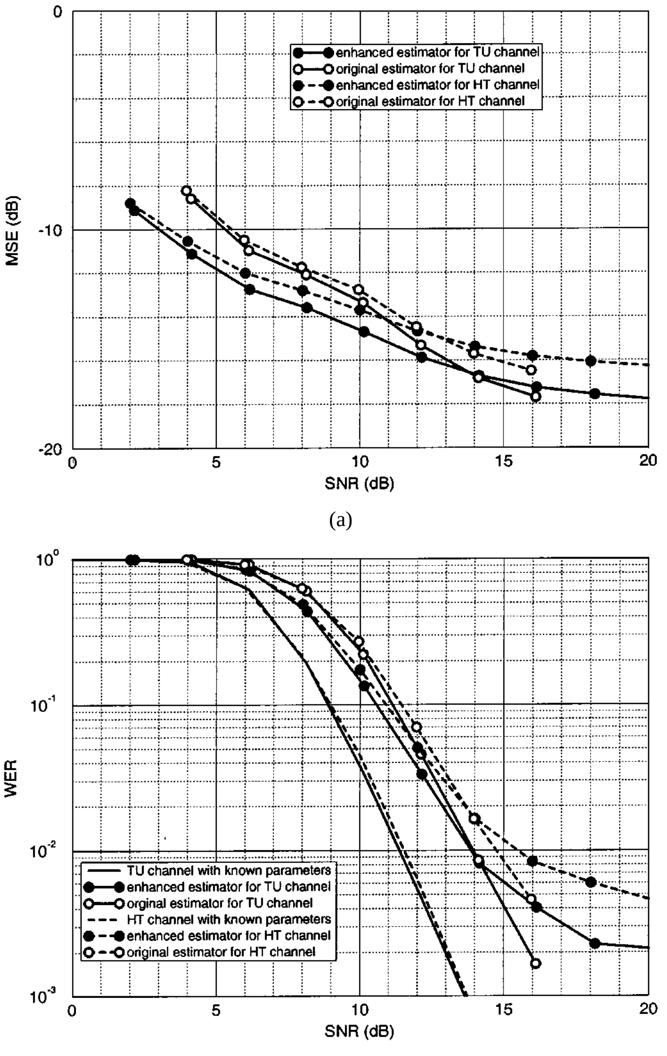
To construct an OFDM signal, we assume the entire channel bandwidth, 1.25 MHz, is divided into 256 subchannels. The two subchannels on each end are used as guard tones, and the rest (252 tones) are used to transmit data. To make the tones orthogonal to each other, the symbol duration is about 204.8 μ/s. An additional 20.2 μ/s guard interval is used to provide protection



(a)

(b)

Fig. 2. Performance comparison of MIMO-OFDM. (a) Different detection techniques. (b) Different numbers of receive antennas, when channel parameters are known.



(a)

(b)

Fig. 3. (a) MSE and (b) WER comparison of the original and the enhanced channel estimation techniques.

from ISI due to channel multipath delay spread. This results in a total block length $T_f = 225\ \mu$/s and a subchannel symbol rate $r_b = 4.44$ kBd.

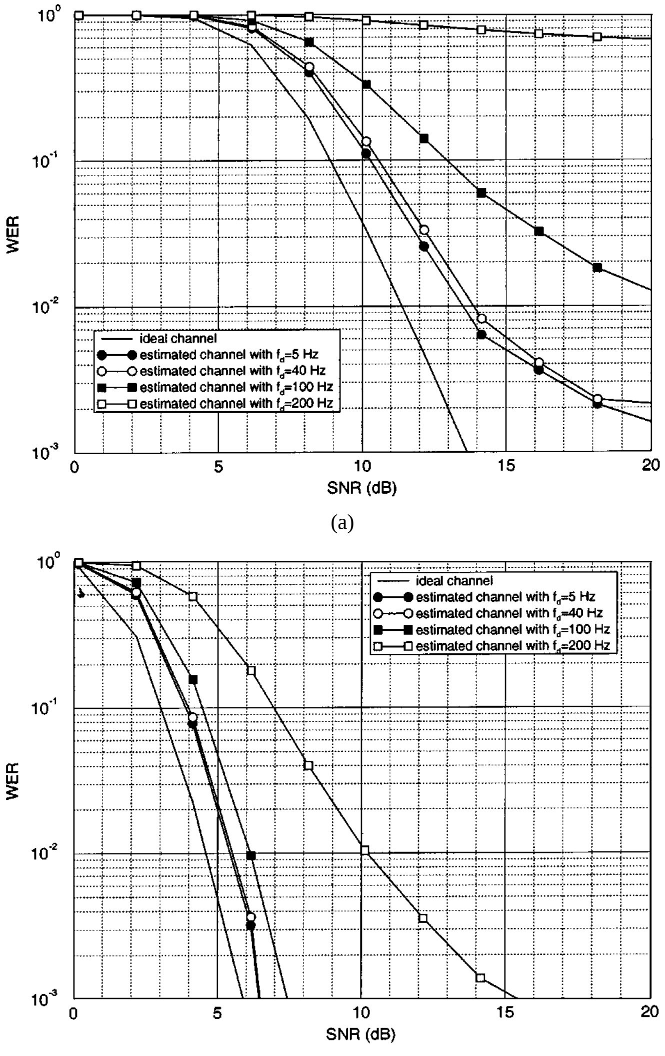
A 16-state space–time code with four-phase-shift keying (PSK) is used. Each data block, containing 500 information bits, is coded into two different blocks, each of which has exactly 252 symbols, to form an OFDM block. Therefore, the OFDM system with four transmit antennas can transmit two data blocks (1000 bits in total) in parallel. Each time slot consists of ten OFDM blocks, with the first block used for training and the following nine blocks used for data transmission. Consequently, the described system can transmit at 4 Mb/s over a 1.25 MHz channel, i.e., the transmission efficiency is 3.2 b/s/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. Fig. 2 shows the performance of MIMO-OFDM with different channel delay profiles, number of receive antennas, and detection techniques. Fig. 2(a) compares the WERs for different detection techniques. From the figure, SIC 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 Fig. 2(a) are for OFDM with four transmit and four receive antennas. With more receive antennas, the performance is improved, as shown in Fig. 2(b). In particular, if the number of receive antennas is increased from four to six, the OFDM system requires 4 dB lower SNR.

Fig. 3 compares the performance of MIMO-OFDM systems with ideal and estimated channel parameters for different channels with a 40–Hz Doppler frequency. From Fig. 3(a), the MSE of the enhanced channel estimator is about 1.5 dB better for the TU channels, and 1 dB better for the HT channels, than the original estimator introduced in [14]. Consequently, in Fig. 3(b), the required SNR for a 10% WER for the enhanced channel estimator is about 0.4 dB better than the original channel estimator. However, compared with the systems with ideal channel parameters, there is still a 1.6 dB gap.

Fig. 4 compares the performance of OFDM systems with different Doppler frequencies. With higher Doppler frequency, the channel estimation error increases. Therefore, the system suf-



(a)

(b)

Fig. 4. WER versus SNR with (a) four and (b) eight receive antennas using SIC/MMSE for the TU channel with different Doppler frequencies.

fers more degradation. For a MIMO-OFDM system with four transmit and four 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. However, with more receive antennas, the degradation is reduced. It is only about 0.4 dB with eight receive antennas.

VI. 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 MIMO system to increase system capacity. A prewhitening technique for MED decoding, and SIC techniques based on different rules, have been proposed. Using these techniques in a four-input, four-output OFDM system, the net data transmission rate can reach 4 Mb/s over a 1.25 MHz wireless channel, with a 10–11 dB SNR required for a 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, and developing a channel estimator for high mobility wireless communications.

ACKNOWLEDGMENT

The authors thank V. Tarokh and N. Seshadri for providing the space–time coding program.

REFERENCES

[1] A. Wittneben, “A new bandwidth efficient transmit antenna modulation diversity scheme for linear digital modulation,” in *Proc. IEEE Int. Communications Conf.*, Geneva, Switzerland, June 1993, pp. 1630–1634.

[2] V. Tarokh, N. Seshadri, and A. R. Calderbank, “Space–time codes for high data rate wireless communication: Performance analysis and code construction,” *IEEE Trans. Inform. Theory*, vol. 44, pp. 744–765, Mar. 1998.

[3] J. H. Winters, “On the capacity of radio communication systems with diversity in a Rayleigh fading environment,” *IEEE J. Select. Areas Commun.*, vol. SAC–5, pp. 871–878, June 1987.

[4] G. J. Foschini, “Layered space–time architecture for wireless communication in a fading environment when using multi-element antennas,” *Bell Labs Tech. J.*, pp. 41–59, Autumn 1996.

[5] G. J. Foschini and M. J. Gans, “On limits of wireless communications in a fading environment when using multiple antennas,” *Wireless Personal Commun.*, vol. 6, pp. 311–335, 1998.

[6] G. J. Foschini, G. D. Golden, R. A. Valenzuela, and P. W. Wolniansky, “Simplified processing for high spectral efficiency wireless communication employing multi-element arrays,” *IEEE J. Select. Areas Commun.*, vol. 17, pp. 1841–1852, Nov. 1999.

[7] A. Lozano and C. Papadias, “Space–time receiver for wideband BLAST in rich-scattering wireless channels,” in *Proc. VTC 2000*, Tokyo, Japan, May 2000, pp. 186–190.

[8] H. Zeng, Y. Li, and J. H. Winters, “Improved spatial-temporal equalization for EDGE: A fast MMSE timing recovery algorithm and two-stage soft-output equalizer,” *IEEE Trans. Commun.*, vol. 49, pp. 2124–2134, Dec. 2001.

[9] L. J. Cimini, Jr., “Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing,” *IEEE Trans. Commun.*, vol. COM-33, pp. 665–675, July 1985.

[10] V. Mignone and A. Morello, “CD3-OFDM: A novel demodulation scheme for fixed and mobile receivers,” *IEEE Trans. Commun.*, vol. 44, pp. 1144–1151, Sept. 1996.

[11] S. B. Weinstein and P. M. Ebert, “Data transmission by frequency-division multiplexing using the discrete Fourier transform,” *IEEE Trans. Commun. Tech.*, vol. COM-19, pp. 628–634, Oct. 1971.

[12] H. Rohling, T. May, K. Bruninghaus, and R. Grunheid, “Broadband OFDM radio transmission for multimedia applications,” *Proc. IEEE*, vol. 87, pp. 1778–1789, Oct. 1999.

[13] Y. Li and N. R. Sollenberger, “Adaptive antenna arrays for OFDM systems with co-channel interference,” *IEEE Trans. Commun.*, vol. 47, pp. 217–229, Feb. 1999.

[14] Y. Li, N. Seshadri, and S. Ariyavisitakul, “Channel estimation for OFDM systems with transmitter diversity in mobile wireless channels,” *IEEE J. Select. Areas Commun.*, vol. 17, pp. 461–471, Mar. 1999.

[15] Y. Li, J. Chuang, and N. R. Sollenberger, “Transmit diversity for OFDM systems and its impact on high-rate data wireless networks,” *IEEE J. Select. Areas Commun.*, vol. 17, pp. 1233–1243, July 1999.

[16] Y. Li, “Simplified channel estimation for OFDM systems with multiple transmit antennas,” *IEEE Trans. Wireless Commun.*, vol. 1, pp. 67–75, Jan. 2002.

[17] J.-J. van de Beek, O. Edfors, M. Sandell, S. K. Wilson, and P. O. Börjesson, “On channel estimation in OFDM systems,” in *Proc. 45th IEEE Vehicular Technology Conf.*, July 1995, pp. 815–819.

[18] R. S. Blum, Y. Li, J. H. Winters, and Q. Yan, “MIMO-OFDM for wireless communications: Capacity properties and space–time coding,” *IEEE Trans. Commun.* to be published.

[19] Y. Li, L. J. Cimini, Jr., and N. R. Sollenberger, “Robust channel estimation for OFDM systems with rapid dispersive fading channels,” *IEEE Trans. Commun.*, vol. 46, pp. 902–915, July 1998.

[20] R. Steele, *Mobile Radio Communications*. New York: IEEE Press, 1992.

[21] J. H. Winters, “Signal acquisition and tracking with adaptive arrays in the digital mobile radio system IS-136 with flat fading,” *IEEE Trans. Veh. Technol.*, vol. 42, pp. 377–384, Nov. 1993.

Ye Li (S'93–M'95–SM'97) received the B.S.E. and M.S.E. degrees in 1983 and 1986, respectively, from the Department of Wireless Engineering, Nanjing Institute of Technology, Nanjing, China, and the Ph.D. degree in 1994 from the Department of Electrical Engineering, Auburn University, Auburn, AL.

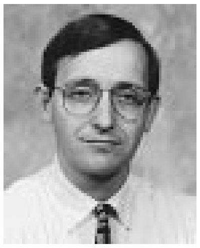
From 1986 to 1991, he was a Teaching Assistant and then a Lecturer with Southeast University, Nanjing. From 1991 to 1994, he was a Research and Teaching Assistant with Auburn University. From 1994 to 1996, he was a Postdoctoral Research Associate with the University of Maryland at College Park. From 1996 to 2000, he was with AT&T Labs–Research in Red Bank, NJ. Since August 2000, he has been with Georgia Institute of Technology, Atlanta, as an Associate Professor. He also currently serves as an editorial board member of *EURASIP Journal on Applied Signal Processing*.

Dr. Li's general research interests include statistical signal processing and wireless mobile systems. He once served as a guest editor for special issues on Signal Processing for Wireless Communications for the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, and is currently serving as an editor for Wireless Communication Theory for IEEE TRANSACTIONS ON COMMUNICATIONS.

Jack H. Winters (S'77–M'81–SM'88–F'96) received the B.S.E.E. degree from the University of Cincinnati, Cincinnati, OH, in 1977, and the M.S. and Ph.D. degrees in electrical engineering from The Ohio State University, Columbus, in 1978 and 1981, respectively.

From 1981 to early 2002, he was with AT&T Bell Laboratories, and then AT&T Labs-Research, Middletown, NJ, where he was Division Manager of the Wireless Systems Research Department. Since early 2002, he has been consulting for several wireless and optical communication companies. He has studied signal processing techniques for increasing the capacity and reducing signal distortion in fiber optic, mobile radio, and indoor radio systems, and is currently studying smart antennas, adaptive arrays, and equalization for indoor and mobile radio systems.

Dr. Winters is an IEEE Distinguished Lecturer for both the IEEE Communications and Vehicular Technology Societies, Area Editor for Transmission Systems for the IEEE TRANSACTIONS ON COMMUNICATIONS, and New Jersey Inventor of the Year for 2001.



Nelson R. Sollenberger (S'78–M'81–SM'90–F'96) received the B.S. degree in electrical engineering technology in 1979 from Messiah College, Grantham, PA, and the M.S. degree in electrical engineering in 1981 from Cornell University, Ithaca, NY.

He is the Vice President of R&D and General Manager for Mobilink Telecom Inc., Middletown, NJ. From May 1995 until January of 2001, Nelson was Department Head of Wireless Systems Research at AT&T Bell Labs Research (now AT&T Labs-Research), responsible for research on next-generation mobile radio systems, including smart antenna technology, EDGE technologies, and wireless OFDM techniques. From 1987 until 1995, he was with Bellcore's Radio Research Department, which he headed from 1993 through 1995. At Bellcore, he was a primary contributor to the PACS low-power wireless TDMA technology. Prior to joining Bellcore, he had been with Bell Lab's Cellular Development Department, starting in 1979, where he worked on SSB techniques for cellular systems and then digital cellular transmission techniques in the early 1980's. He has been awarded over 20 patents in wireless communications technologies, and has published papers on a variety of wireless communications techniques.

Mr. Sollenberger is an AT&T Fellow, an IEEE VEHICULAR TECHNOLOGY JOURNAL Associate Editor, and an IEEE Distinguished Lecturer.