Error Performance of Ultrawideband MIMO Spatial Multiplexing Systems

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***Abstract*— Multiple-input multiple-output spatial multiplexing (MIMO-SM) ultrawideband (UWB) systems with orthogonal frequency division multiplexing (OFDM) signaling are developed. It is shown that the proposed linear and nonlinear receivers offer substantial spatial diversity beside data rate enhancement.**

I. Introduction

Ultrawideband (UWB) wireless systems offer very high throughput, reduced fading, and accurate positioning [1]. Extending conventional single-input single-output (SISO) UWB systems to the multiple-input multiple-output (MIMO) [2] regime, we develop a set of UWB spatial multiplexing (SM) receivers. As UWB systems cannot boost the transmit powers due to regulatory limits, MIMO is attractive for improving the throughput and robustness. Earlier work has analyzed the error performance of pulse-based UWB MIMO-SM systems [3]–[5]. In this paper, we adopt the multiband orthogonal frequency division multiplexing (MB-OFDM) UWB transmission scheme. We evaluate and compare the bit-error rate (BER) performance of optimal and suboptimal MIMO detectors via Monte-Carlo simulations using the statistical UWB channels in [1], [6].

II. System Model

Adopting the discrete frequency-domain matrix channel formulation of [7], we can represent the UWB MIMO channel by $\mathbf{H} \in \mathcal{C}^{N_R \times N_T \times N_F}$, where N_T, N_R, and N_F denote the number of transmit antennas, receive antennas, and frequency components, respectively. Here, $\mathbf{H} = [\mathbf{H}_f]_{f=f_l}^{f_h}$ can be perceived as a row vector, whose elements, $\mathbf{H}_f \in \mathcal{C}^{N_R \times N_T}$, are the flat MIMO matrices at frequency f, where f_l and f_h define the lower and upper-end frequencies. With MIMO-OFDM, we can reduce the UWB channel into N_F narrowband channels. At a given f, the $N_T \times N_R$ MIMO system model is given by

$$\mathbf{y}_f = \sqrt{E_x}\mathbf{H}_f\mathbf{x}_f + \mathbf{n}_f,$$

where $\mathbf{x}_f = [x_{1,f}, \ldots, x_{N_T,f}]^{\mathrm{T}}$ and $\mathbf{y}_f = [y_{1,f}, \ldots, y_{N_R,f}]^{\mathrm{T}}$ are the transmitted and received signal vectors, respectively, $\mathbf{n}_f = [n_{1,f}, \ldots, n_{N_R,f}]^{\mathrm{T}}$ is the zero-mean complex Gaussian noise vector with covariance $\sigma^2\mathbf{I}_{N_R}$, E_x is the energy of transmit symbol $x_{i,f}$, and $(.)^{\mathrm{T}}$ denotes the matrix transpose. The UWB channel matrix is normalized such that the squared Frobenius norm $\| \mathbf{H} \|_{\mathrm{F}}^2 = N_T N_R N_F$. We extend the IEEE 802.15.3a UWB SISO channel model to MIMO by generating $N_T \times N_R$ SISO subchannels and incorporate separable transmit and receive correlation using the fixed correlation model in [6].

A. Traditional Linear Receiver

The low complexity linear receiver is based on zero-forcing (ZF) or minimum mean-square error (MMSE) criteria [2]. At f, $\mathbf{y}_f$ is linearly transformed by the matrix equalizer, $\mathbf{G}_f$, and quantized to obtain the symbol estimate, $\hat{\mathbf{x}}_f = Q(\mathbf{G}_f\mathbf{y}_f)$. For ZF receivers, $\mathbf{G}_f = \mathbf{H}_f^{\dagger}$, where $(.)^{\dagger}$ denotes the Moore-Penrose matrix pseudo-inverse. In UWB systems with low SNR per dimension, ZF may suffer from noise enhancement, especially if $\mathbf{H}_f$ is rank deficient or ill conditioned. For MMSE receivers, $\mathbf{G}_f = \sigma^2\mathbf{H}_f^{\mathrm{H}}\left(\sigma^2\mathbf{H}_f\mathbf{H}_f^{\mathrm{H}} + \sigma^2\mathbf{I}_{N_R}\right)^{-1}$ minimizes the error due to noise and interference, with some additional complexity.

B. V-BLAST Receiver

V-BLAST achieves high spectral efficiency, realizing a good tradeoff between complexity and performance, by employing the ordered serial nulling and cancellation technique [2]. The nulling process may use the ZF or MMSE criteria, i.e., ZF-VBLAST and MMSE-VBLAST. We extend the narrowband V-BLAST detection algorithm to MB-OFDM UWB systems.

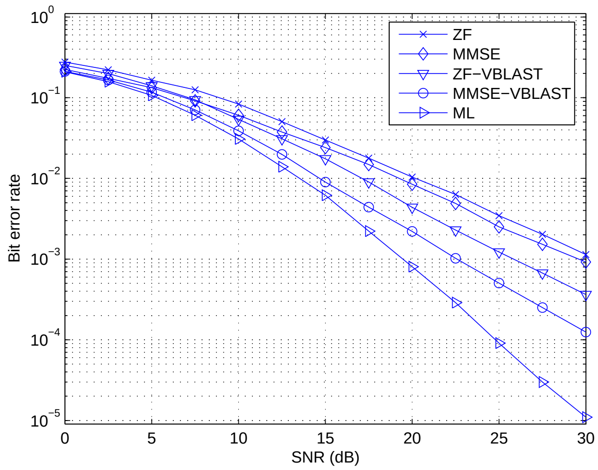
C. Maximum Likelihood (ML) Receiver

For a UWB system with large N_F, the ML scheme [2] is impractical as its complexity grows exponentially with N_T and linearly with N_F. However, our analysis of the ML receiver is insightful as it achieves the BER lower bound.

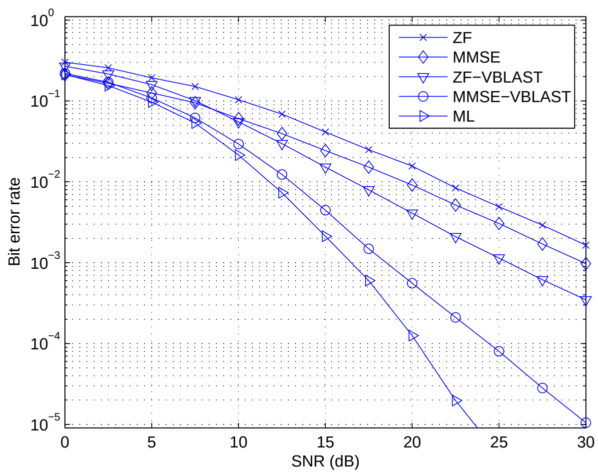
III. Simulation Results

We consider the CM1 channel [1] in the 3.1-10.6 GHz UWB band with $N_F = 1601$, QPSK modulation, OFDM cyclic prefix longer than the channel, no time-frequency interleaving or coding, and uniform MIMO transmit power allocation. All of the proposed SM systems achieve N_T-fold rate increase.

Fig. 1 shows that MMSE-VBLAST outperforms MMSE at BER $P_e = 10^{-3}$ by 7 and 11 dB when $N_T = N_R = N = 2$ and 3, respectively. The linear receivers achieve diversity order $d = 1$, whereas MMSE-VBLAST and ML achieve higher d. At larger N_R, the BER curves spread out, as the nonlinear receivers realize greater spatial diversity while the linear receivers suffer greater multistream interference that dominates over noise. As MMSE is more noise-resilient than



(a)



(b)

Fig. 1. BER performance of (a) 2×2 and (b) 3×3 UWB MIMO-SM systems for various detection algorithms based on the uncorrelated CM1 channel.

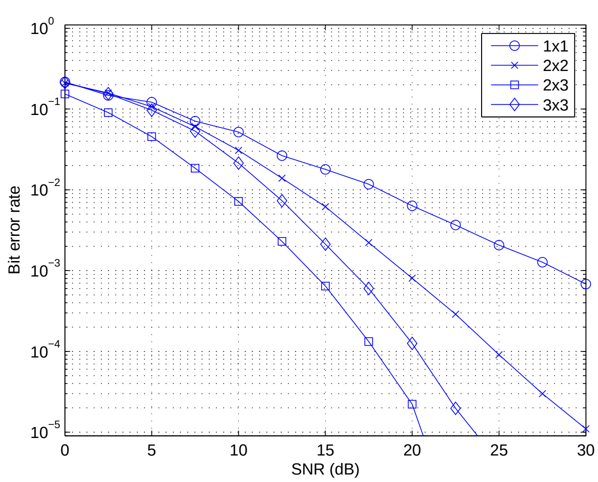


Fig. 2. BER performance of ML receiver in the uncorrelated CM1 channel.

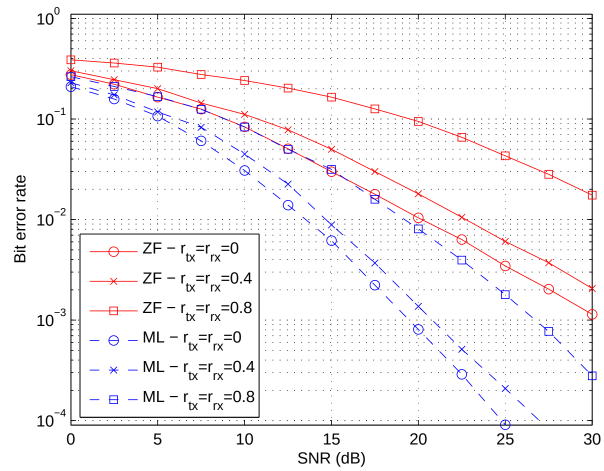


Fig. 3. BER performance of 2×2 MIMO-SM systems for various values of the transmit (r_{tx}) and receive (r_{rx}) correlation in the CM1 channel.

ZF, it performs better at larger N. From Fig. 2, MIMO diversity under ML increases with N_R for both symmetrical ($N_T = N_R$) and asymmetrical ($N_T < N_R$) arrays. Large arrays scale up the data-rate and also provide substantial diversity gain. Comparing 2×3 and 3×3 systems, the latter provides higher rate but requires 2.5 dB higher SNR than the former at $P_e = 10^{-3}$. Fig. 3 illustrates that the subchannel correlation affects UWB SM error performance significantly for all receivers, but the impact is small when $r_{tx} = r_{rx} \leq 0.4$, consistent with [2], [7]. From our results, UWB MIMO-SM improves both rate and BER under low channel correlation.

IV. Conclusion

We have extended narrowband MIMO-SM schemes to UWB systems and shown that suboptimum nonlinear detection techniques significantly outperform linear receivers. Our results show that with an appropriate detection scheme and low subchannel correlation, UWB MIMO systems not only provide higher data-rates but also improved diversity orders.

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