TURBO MULTI-USER RECEIVER FOR ASYNCHRONOUS MULTI-USER OFDM SYSTEMS

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ABSTRACT

This paper proposes a low complexity turbo multi-user receiver for the coded asynchronous multi-user orthogonal frequency division multiplexing (OFDM) signal over multipath fading channels. While asynchronous multi-user multiplexing with antenna diversity accommodates high speed applications and achieves the high spectral efficiency in communication systems, the multiple access interference deteriorates the quality of signal detection. In order to effectively suppress the interference and amplify a performance gain from channel coding, we employ a turbo equalization technique. Based on the asynchronous OFDM signal model and the corresponding linear minimum mean squared error (MMSE) estimator, an iterative space-time MMSE multi-user detector with a parallel soft interference canceller is developed. Simulation results demonstrate that iterative joint demodulation of the asynchronous multi-user OFDM signal achieves a significant performance gain even with a reduced complexity equalizer and a few iterations.

1. INTRODUCTION

A spatially multiplexed asynchronous multi-user OFDM system can be an appropriate approach to resolve the challenges in designing the future wireless communication systems. A space-time MMSE equalizer combined with a hard interference canceller has been proposed in [1] for asynchronous interference suppression. In order to enhance the performance of the space-time MMSE estimator, it is necessary to lower the interference level in the received signal by effectively estimating and cancelling the interfering signal.

It has been shown that turbo processing techniques, which exchange the extrinsic information between an equalizer and a channel decoder, can facilitate to obtain accurate interference estimates. [2] develops a turbo multi-user detection scheme for coded CDMA systems, and [3] and [4] study turbo equalization in inter-symbol interference (ISI) channels. Moreover, the turbo principle is applied to demodulation of zero padded OFDM [5] and equalization of the ISI corrupted OFDM signal due to large delay spread [6].

In this paper, we develop an iterative multi-user receiver for asynchronous OFDM. The proposed scheme employs a soft interference canceller, which exploits the outputs from both the MMSE equalizer without interference cancellation and the channel decoder for interference reconstruction. After subtracting the multiple access interference from the received signal synchronized to the desired user, space-time MMSE estimation is performed taking into account the residual interference statistics. It seems that the proposed multi-user receiver is similar to the one in [2]. However, in our system an instantaneous MMSE filter is replaced by a fixed MMSE filter over one OFDM baud since cyclic prefix in OFDM minimizes the inter-carrier interference (ICI). Furthermore, as cyclic prefix decorrelates the received signal at each subcarrier, there is little model mismatch error in approximating the MMSE filter output at each subcarrier to an independent random variable.

The rest of the paper proceeds as follows. Section 2 presents the signal model of asynchronous OFDM systems. In Section 3, the proposed iterative multi-user detection scheme is explained. Section 4 compares the bit error rate (BER) performance of various equalization algorithms via computer simulations and Section 5 concludes the paper. Finally, note that $(\cdot)^T$, $(\cdot)^H$, and $E\{\cdot\}$ denote the transpose, conjugate transpose, and expectation operator, respectively.

2. SYSTEM MODEL

Consider a U-user OFDM system employing antenna diversity at the receiver with M receive antennas. The information bit sequence $\{d^{(u)}\}$ for each user u, $u = 1, \ldots, U$, is encoded by a convolutional code encoder, and the coded bit sequence $\{b^{(u)}\}$ passes through an interleaver Π. After the interleaved bits are assigned to constellation points, the resulting signals are passed to the OFDM modulation block. OFDM modulation at each user's transmitter consists of serial-to-parallel conversion, an inverse discrete Fourier transform (DFT), and parallel-to-serial conversion. Suppose that an OFDM system processes a block of K symbols at a time. Then, the n_b^{th} OFDM block of user u is given by

$$\mathbf{X}^{(u)}(n_b) = \left[X^{(u)}(0, n_b), \ldots, X^{(u)}(K-1, n_b)\right]^T. \qquad (1)$$

In practice, OFDM systems have null side carriers as a frequency guard band. Thus, it is assumed that an N-point inverse DFT, where $N \geqslant K$, generates a time-domain sequence

$$\mathbf{x}^{(u)}[n_b] = \left[x^{(u)}[0, n_b], \ldots, x^{(u)}[N-1, n_b]\right]^T. \qquad (2)$$

To overcome multi-path fading, the cyclic prefix of length L_{cp}, which is greater than the maximum delay spread L, is appended to the beginning of vector $\mathbf{x}^{(u)}[n_b]$, and subsequent blocks of time-domain OFDM samples are transmitted over wireless channels.

At a receiver, let $\mathbf{y}_m^{(u)}[n_b]$ be an $N \times 1$ received signal vector at antenna m obtained by synchronizing the observation window with the n_b^{th} block of user u and removing first L_{cp} samples

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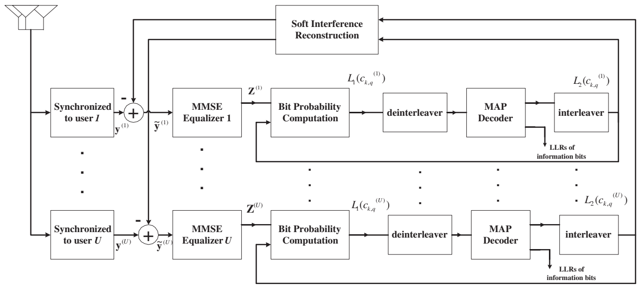

Fig. 1. Turbo multi-user receiver in asynchronous OFDM systems.

corresponding to the cyclic prefix. The different distances from each user to the receiver cause the signals to arrive asynchronously. Therefore, we denote the interfering user u's timing offset relative to the beginning of the desired user's cyclic prefix as $L_d^{(u)}$. Without loss of generality, user 1 is assumed to be the desired user, and $L_d^{(1)} \leqslant L_d^{(2)} \leqslant \cdots \leqslant L_d^{(U)}$ with $L_d^{(1)} = 0$. It is also assumed that there is no correlation among different channels in this multi-user OFDM system.

The set of OFDM signals, which are synchronized with respect to user 1's timing and measured at M receive antennas, is given as:

$$\mathbf{y}[n_b] = \mathbf{H}[n_b]\mathbf{F}\mathbf{X}(n_b) + \mathbf{v}[n_b], \tag{3}$$

where $\mathbf{X}(n_b)$ is $(2U-1)K \times 1$ block of transmitted data symbols in the frequency domain, $\mathbf{F}$ is the $U(N+L-1) \times (2U-1)K$ OFDM modulation matrix considering interferers' timing offsets, $\mathbf{H}[n_b]$ is a channel matrix with the size $MN \times U(N+L-1)$, and $\mathbf{v}[n_b]$ is an $MN \times 1$ vector of additive Gaussian noise with power σ_v^2. Specifically,

$$\begin{aligned}\mathbf{X}(n_b) = [\ & \mathbf{X}^{(1)}(n_b)^T \quad \mathbf{X}^{(2)}(n_b-1)^T \quad \mathbf{X}^{(2)}(n_b)^T \\ & \cdots \quad \mathbf{X}^{(U)}(n_b-1)^T \quad \mathbf{X}^{(U)}(n_b)^T\ \ ]^T,\end{aligned}$$

$$\mathbf{F} = \mathrm{diag}(\ \mathbf{F}^{(1)} \quad \mathbf{F}^{(2)} \quad \cdots \quad \mathbf{F}^{(U)}\ ),$$

$$\mathbf{H}[n_b] = \begin{bmatrix} \mathbf{H}_1^{(1)}[n_b] & \cdots & \mathbf{H}_1^{(U)}[n_b] \\ \mathbf{H}_2^{(1)}[n_b] & \cdots & \mathbf{H}_2^{(U)}[n_b] \\ \vdots & \vdots & \vdots \\ \mathbf{H}_M^{(1)}[n_b] & \cdots & \mathbf{H}_M^{(U)}[n_b] \end{bmatrix}, \tag{4}$$

and the channel impulse response is assumed to be invariant over one OFDM baud. Note that the superscript of $\mathbf{y}^{(1)}[n_b]$ is omitted in (3) for notational simplicity, and the OFDM block index, n_b, will be omitted from now on. More detailed description of the above asynchronous OFDM signal model can be found in [1].

3. MMSE-BASED TURBO MULTI-USER DETECTION

Fig. 1 depicts the proposed turbo multi-user receiver for asynchronous OFDM systems. Although a synchronization and channel estimation block is not shown explicitly in Fig. 1, the timing/frequency offset and channel information is assumed to be perfect. The proposed equalization scheme employs a space-time MMSE estimator combined with a soft interference canceller and a SISO channel decoder for joint detection and decoding. The following subsections will explain how each component of the turbo receiver performs cooperatively to improve the BER of the overall system.

3.1. Space-time MMSE Estimation with Soft Interference Cancellation

As shown in Fig. 1, the receiver makes use of the output LLR of the channel decoder to estimate the interference. However, the *a priori* information on the bits cannot yield useful interference estimates in the first step since it is set to be uniform in the initial stage. Hence, soft symbol estimates of interfering user u, $\hat{\mathbf{X}}^{(u)}$, are initially obtained from the received signal synchronized to user u's timing, $\mathbf{y}^{(u)}$, as follows:

$$\hat{\mathbf{X}}^{(u)} = \mathbf{W}^{(u)}\mathbf{y}^{(u)}, \tag{5}$$

where $\mathbf{W}^{(u)}$ is a $K \times MN$ space-time MMSE filter to extract user u's OFDM symbol $\mathbf{X}^{(u)}$ and is given by

$$\mathbf{W}^{(u)} = \mathbf{R}_{\mathbf{X}\mathbf{y}}^{(u)} \mathbf{R}_{\mathbf{y}\mathbf{y}}^{(u)\,-1}, \tag{6}$$

where $\mathbf{R}_{\mathbf{y}\mathbf{y}}^{(u)} = E\left\{\mathbf{y}^{(u)}\mathbf{y}^{(u)H}\right\}$ and $\mathbf{R}_{\mathbf{X}\mathbf{y}}^{(u)} = E\left\{\mathbf{X}^{(u)}\mathbf{y}^{(u)H}\right\}$. In the initial stage, the OFDM sub-symbols are assumed to be independent and identically distributed (i.i.d.) since the *a priori* information from the decoder is not available. In other words, the correlation matrix of $\mathbf{X}^{(u)}$ is set as $\mathbf{R}_{\mathbf{X}\mathbf{X}}^{(u)} = \sigma_s^2\mathbf{I}$, where σ_s^2 is the average signal energy and $\mathbf{I}_K$ represents the $K \times K$ identity matrix.

After soft interference cancellation, the resulting signal $\tilde{\mathbf{y}}$ is given by

$$\begin{aligned}\tilde{\mathbf{y}} &= \mathbf{y}^{(1)} - \sum_{u=2}^{U} \mathbf{H}^{(u)}\mathbf{F}^{(u)}\hat{\mathbf{X}}^{(u)} \\ &= \mathbf{H}^{(1)}\mathbf{F}^{(1)}\mathbf{X}^{(1)} + \sum_{u=2}^{U} \mathbf{H}^{(u)}\mathbf{F}^{(u)}\mathbf{e}^{(u)} + \mathbf{v},\end{aligned} \tag{7}$$

where $\mathbf{e}^{(u)} = [\mathbf{e}^{(u)}[n_b-1]^T\ \mathbf{e}^{(u)}[n_b]^T]^T = \mathbf{X}^{(u)} - \hat{\mathbf{X}}^{(u)}$. Note that in the above equation $\mathbf{X}^{(u)}$ and $\hat{\mathbf{X}}^{(u)}$ for $u = 2, \ldots, U$ are redefined as $2K \times 1$ vectors, which contain the previous and current OFDM baud. In order to detect the desired user signal $\mathbf{X}^{(1)}$, the soft space-time MMSE equalizer $\mathbf{W}_{soft}$ is applied to $\tilde{\mathbf{y}}$. Since correlation between $\mathbf{X}^{(1)}$ and $\mathbf{e}^{(u)}$ is negligible in (7), $\mathbf{W}_{soft}$ is given by

$$\mathbf{W}_{soft} = \left(\mathbf{R}_{\tilde{\mathbf{y}}\tilde{\mathbf{y}}}^{-1}\mathbf{H}^{(1)}\mathbf{F}^{(1)}\mathbf{R}_{\mathbf{X}\mathbf{X}}^{(1)}\right)^H. \tag{8}$$

When computing $\mathbf{R}_{\tilde{\mathbf{y}}\tilde{\mathbf{y}}}$, the correlation matrix of $\mathbf{e}^{(u)}$ is given by $\mathbf{R}_{\mathbf{ee}}^{(u)} = \mathrm{diag}(\mathbf{R}_{\mathbf{ee}}^{(u)}[n_b-1]\ \mathbf{R}_{\mathbf{ee}}^{(u)}[n_b])$, where the correlation matrix of $\mathbf{e}^{(u)}[n_b]$, $\mathbf{R}_{\mathbf{ee}}^{(u)}[n_b]$, is equal to $\sigma_s^2\mathbf{I}_K - \mathbf{W}^{(u)}\mathbf{R}_{\mathbf{y}\mathbf{X}}^{(u)}$ in the initial stage and is approximated to a diagonal matrix with the k-th diagonal element $Var\{X^{(u)}(k, n_b)\}$ in the following iteration. To reduce the computational complexity, the extrinsic information of the desired user is not used for soft MMSE estimation. That is, $\mathbf{R}_{\mathbf{X}\mathbf{X}}^{(1)}$ in (8) is set to be the identity matrix $\sigma_s^2\mathbf{I}_K$ in every stage. This low complexity MMSE approach does not make a considerable effect on the performance since the amount of inter-carrier interference (ICI) from the desired user is negligible in OFDM systems with cyclic prefix.

The output of the soft MMSE estimator, $\mathbf{Z}$, is given by

$$\mathbf{Z} = \mathbf{W}_{soft}\tilde{\mathbf{y}} = \mathbf{A}\mathbf{X}^{(1)} + \mathbf{b}, \quad (9)$$

where $\mathbf{A} = \mathbf{W}_{soft}\mathbf{H}^{(1)}\mathbf{F}^{(1)}$ and vector $\mathbf{b}$ represents the filtered residual interference plus noise such that the correlation matrix $\mathbf{R}_{\mathbf{bb}}$ is

$$\begin{aligned} \mathbf{R}_{\mathbf{bb}} &= \mathbf{R}_{\mathbf{ZZ}} - \sigma_s^2\mathbf{A}\mathbf{A}^H \\ &= \mathbf{W}_{soft}\mathbf{R}_{\tilde{\mathbf{y}}\tilde{\mathbf{y}}}\mathbf{W}_{soft}^H - \sigma_s^2\mathbf{A}\mathbf{A}^H \\ &= \sigma_s^2\mathbf{A} - \sigma_s^2\mathbf{A}\mathbf{A}^H. \end{aligned} \quad (10)$$

Due to the circular convolution property of cyclic prefix based OFDM systems, matrix $\mathbf{A}$ is diagonally dominant and off-diagonal elements of $\mathbf{A}$ are negligible. Thus, the k-th element of vector $\mathbf{Z}$, Z_k, can be approximated as

$$Z_k = a_k X^{(1)}(k) + b_k, \quad (11)$$

where a_k is the k-th diagonal element of $\mathbf{A}$ and the elements of $\mathbf{b}$, $\{b_k\}_{k=0}^{K-1}$, are assumed to be independent Gaussian random variables with zero mean and variance $\sigma_{b,k}^2 = \sigma_s^2(a_k - |a_k|^2)$.

3.2. Soft Input Soft Output Channel Decoding

Next, the MMSE equalizer outputs $\{Z_k\}$ are fed to the bit probability computation block, which generates the soft input of the SISO channel decoder. Let $\mathbf{c}^{(1)} \triangleq [\mathbf{c}_1^{(1)}, \ \ldots, \ \mathbf{c}_K^{(1)}]$ be a sequence of coded and interleaved binary bits over one OFDM baud of user 1 and $\mathbf{c}_k^{(1)} = [c_{k,1}^{(1)}, \ \ldots, \ c_{k,Q}^{(1)}]$ be a set of bits modulated into subcarrier k when 2^Q-ary signal constellation is employed. As mentioned before, $\{Z_k\}$ are assumed to be independent. Thus, the *a posteriori* LLR $L(c_{k,q}^{(1)}|\mathbf{Z})$ is approximated to $L(c_{k,q}^{(1)}|Z_k)$, and as in [4], the extrinsic information $L_1(c_{k,q}^{(1)})$ delivered by the MMSE equalizer is computed as follows:

$$\begin{aligned} L(c_{k,q}^{(1)}|Z_k) &\triangleq \ln\frac{P(c_{k,q}^{(1)}=0|Z_k)}{P(c_{k,q}^{(1)}=1|Z_k)} \quad (12) \\ &= \underbrace{\ln\frac{\sum_{\forall\mathbf{c}_k^{(1)};c_{k,q}^{(1)}=0} P(Z_k|\mathbf{c}_k^{(1)})\prod_{q'=1,q'\neq q}^{Q} P(c_{k,q'}^{(1)})}{\sum_{\forall\mathbf{c}_k^{(1)};c_{k,q}^{(1)}=1} P(Z_k|\mathbf{c}_k^{(1)})\prod_{q'=1,q'\neq q}^{Q} P(c_{k,q'}^{(1)})}}_{L_1(c_{k,q}^{(1)})} \\ &\quad + \ln\frac{P(c_{k,q}^{(1)}=0)}{P(c_{k,q}^{(1)}=1)}. \end{aligned}$$

Note that in (12) $P(\mathbf{c}_k^{(1)}) \approx \prod_{q'=1}^{Q} P(c_{k,q'}^{(1)})$ under the assumption of the large interleaver size. The probability $P(Z_k|\mathbf{c}_k^{(1)})$ is given by

$$P(Z_k|\mathbf{c}_k^{(1)}) \propto \exp\left(-\frac{1}{2\sigma_{b,k}^2}\left|Z_k - a_k S_k(\mathbf{c}_k^{(1)})\right|^2\right), \quad (13)$$

where $S_k(\mathbf{c}_k^{(1)})$ is a constellation point assigned by code bits $\mathbf{c}_k^{(1)}$. *A priori* LLRs for the channel decoder, $\{L_1(b_{k,q}^{(1)})\}$, are obtained by deinterleaving $\{L_1(c_{k,q}^{(1)})\}$. Finally, the SISO decoding algorithm [2] produces the *a posteriori probability* of the information bits and the extrinsic probability of the encoded bits, $\{L_2(b_{k,q}^{(1)})\}$.

3.3. Soft Interference Construction

The interleaved extrinsic probabilities $\{L_2(c_{k,q}^{(u)})\}$ are exploited for interference reconstruction since the soft interference estimate is given by the estimated mean of the modulation signal, that is, $\hat{X}^{(u)}(k) = E\{X^{(u)}(k)\}$. As for a Gray labeled 16-QAM constellation with right-most significant bit (msb) representation, the real part of $\hat{X}^{(u)}(k)$ is given by

$$\begin{aligned} \hat{X}_r^{(u)}(k) &= E\{X_r^{(u)}(k)\} \quad (14) \\ &= P(c_{k,1}^{(u)}=0,\ c_{k,3}^{(u)}=0) + 3P(c_{k,1}^{(u)}=0,\ c_{k,3}^{(u)}=1) \\ &\quad -P(c_{k,1}^{(u)}=1, c_{k,3}^{(u)}=0) - 3P(c_{k,1}^{(u)}=1, c_{k,3}^{(u)}=1) \\ &= \left(1 + \frac{e^{-L_2(c_{k,3}^{(u)})/2}}{\cosh(L_2(c_{k,3}^{(u)})/2)}\right)\tanh\left(\frac{L_2(c_{k,1}^{(u)})}{2}\right) \end{aligned}$$

and, similarly, the imaginary part of $\hat{X}^{(u)}(k)$ is

$$\hat{X}_i^{(u)}(k) = \left(1 + \frac{e^{-L_2(c_{k,4}^{(u)})/2}}{\cosh(L_2(c_{k,4}^{(u)})/2)}\right)\tanh\left(\frac{L_2(c_{k,2}^{(u)})}{2}\right). \quad (15)$$

Additionally, the estimated variance of $X^{(u)}(k)$, which is the diagonal element of $\mathbf{R}_{\mathbf{ee}}^{(u)}$, is given by

$$Var\{X^{(u)}(k)\} = E\{|X^{(u)}(k)|^2\} - |E\{X^{(u)}(k)\}|^2, \quad (16)$$

where $E\{|X^{(u)}(k)|^2\} = 2 + \frac{4e^{-L_2(c_{k,3}^{(u)})/2}}{\cosh(L_2(c_{k,3}^{(u)})/2)} + \frac{4e^{-L_2(c_{k,4}^{(u)})/2}}{\cosh(L_2(c_{k,4}^{(u)})/2)}$.

4. SIMULATION RESULTS

This section presents the performance of the proposed iterative demodulation technique for an asynchronous multi-user OFDM system. The OFDM system parameters used for simulation are as follows: The size of IDFT/DFT is $N = 64$, and the number of used subcarriers is $K = 49$. The multi-user OFDM system employs $M = 2$ receive antennas for two active users whose signals arrive at the receiver with the same strength. The cyclic prefix length is set as $L_{cp} = 16$, and the timing difference between two users is 16 samples. Simulations were performed over slowly time-varying Rayleigh fading channels specified as the channel model A in [7]. A channel code used in this paper is the half-rate, constraint length seven convolutional code with polynomial generators $(133)_8$ and $(171)_8$. Coding and interleaving is performed over each OFDM baud individually.

Fig. 2 shows a coded BER comparison of various equalization algorithms when 16-QAM signal constellation points are used. According to the results in Fig. 2 we will select an appropriate initialization method for turbo detection. ST-MMSE denotes the N-point space-time MMSE estimator using one OFDM baud without cyclic prefix. Hard-IC performs space-time MMSE estimation after hard interference cancellation, and soft-IC subtracts interfering user's MMSE equalizer output as soft interference estimates. MaxPwr method proposed in [8] shows the highest BER, and the performance of soft-IC is slightly better than that of hard-IC. Since soft-IC yields the lowest BER curve among the presented schemes, it is chosen as the initialization method of the proposed turbo multi-user receiver.

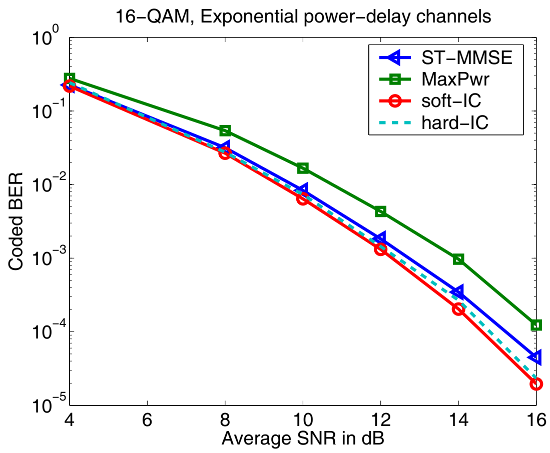

Fig. 2. Coded BER comparison of various equalization schemes using 16-QAM data symbols.

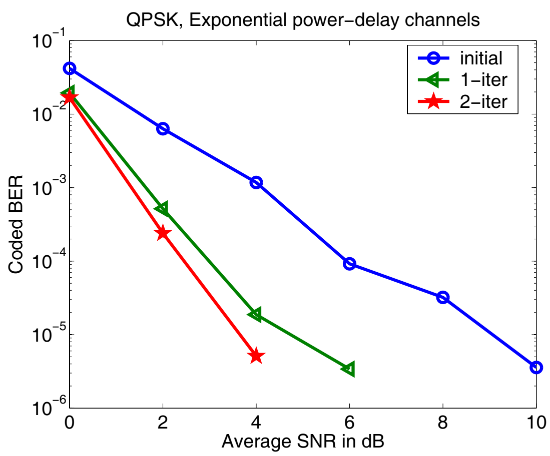

Fig. 3. Performance of turbo multi-user detection using QPSK data symbols.

Fig. 3 demonstrates the performance of turbo multi-user detection for QPSK data symbols. Even one iteration provides a 4 dB signal-to-noise ratio (SNR) gain at a BER of 10^{-5}, and two iterations yield a 5.3 dB SNR gain. Fig. 4 illustrates the performance for 16-QAM data symbols. In high-order modulation such as 16-QAM, performance improvement resulting from iterative processing is rather weakened compared to QPSK, and a performance gain is almost saturated after one iteration. However, it is shown that the turbo detection scheme is superior to any other equalization methods presented in Fig. 2 with a 2 dB or higher SNR gain at a BER of 10^{-5}.

5. CONCLUSION

This paper presents a space-time MMSE based low complexity turbo multi-user receiver for asynchronous multi-user OFDM systems. Iterative joint detection and decoding can produce reliable interference estimates and, accordingly, the overall coded BER performance is improved. Moreover, the complexity of the turbo

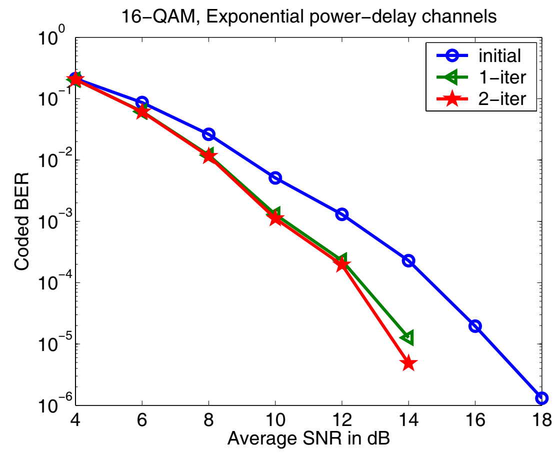

Fig. 4. Performance of turbo multi-user detection using 16-QAM data symbols.

equalizer and the required number of iterations can be significantly reduced due to the cyclic prefix appended to the OFDM signal.

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