A MULTICARRIER CHIP-INTERLEAVED MULTIUSER UWB SYSTEM

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ABSTRACT

We propose a multicarrier interleave-division multiple-access scheme for ultra-wideband wireless communications. A chip-level interleaving method at the transmitter with a simple turbo receiver is proposed to effectively suppress the frequency-selective fading and multiple-access interference. A soft frequency notching method is suggested to suppress the narrowband interference. The performance of the proposed system is evaluated by both theoretic analysis and simulations. It is seen the proposed system exhibits single-user performance even under over-loaded conditions.

1. INTRODUCTION

Ultra wideband (UWB) technologies for short-range high-throughput wireless communications have attracted considerable interests recently. Typically, a UWB system occupies a bandwidth that is greater than 25% of the central frequency. Similar to the conventional wideband communcation systems, UWB systems suffer from multipath frequency-selective fading and multiple-access interference (MAI). Furthermore, strong narrowband interference (NBI) from systems such as IEEE 802.11 will degrade the performance of UWB systems considerably.

To date, time-hopping pulse position modulation UWB (TH-UWB) and direct-sequence UWB (DS-UWB)are the two most popular UWB schemes. Recently, it has been demonstrated that multicarrier CDMA (MC-CDMA)-based UWB systems have a number of advantages over the TH-UWB and DS-UWB systems, such as better power spectral characteristic, frequency notching and robustness against NBI [1]. However, simple and effective techniques for combating frequency-selective fading and MAI still need to be developed. Here, we propose a multicarrier interleave-division multiple-access scheme (MC-IDMA) for the uplink UWB transmission. The chip-wise interleaving at the transmitter together with receiver iterative processing is proposed to mitigate the frequency-selective fading and suppress the MAI. Moreover, a soft frequency notching method is suggested to suppress the NBI. A variance evolution method is employed to assess the performance.

The remainder of this paper is organized as follows. In Section 2, the proposed MC-IDMA scheme for UWB transmission is presented, the soft NBI notching method is proposed. In Section 3, variance evolution analysis is employed to assess the system performance. Simulation results are given in Section 4. Section 5 contains the conclusions.

2. MULTICARRIER IDMA FOR UWB

2.1. Transmitter Structure

The transmitter structure for the system is shown in Fig. 1. Due to the timing errors (time delay between users) the base station will receive the data stream from each user asynchronously. Denote $\boldsymbol{D}_k(i) = [D_{k,1}(i), D_{k,2}(i), ..., D_{k,M}(i)]^T$ as the i^{th} symbol block of length M for the k^{th} user. For simplicity, the time index i is omitted hereafter. This symbol vector is spread by a spreading code to obtain the chip vector $\boldsymbol{C}_k$ of length N, which is then randomly interleaved to obtain the transmitted chip vector $\boldsymbol{P}_k$. Next, an inverse fast Fourier transform (IFFT) operation is applied to obtain $\boldsymbol{p}_k = \boldsymbol{F}^H \boldsymbol{P}_k$, where $\boldsymbol{F}$ is the $N \times N$ DFT matrix with $F(n,m) = e^{-j2\pi nm/N}$, $n, m = 0, 1, ..., N-1$. A cyclic prefix (CP) with length larger than the sum of the maximum timing error and the channel delay spread is appended to $\boldsymbol{p}_k$ before it is transmitted. Denote the k^{th} user's multipath channel response vector as $\boldsymbol{h}_k = [h_{k,0}, h_{k,1}, ..., h_{k,L-1}]^T$, where L is the number of paths. At the receiver, after removing the CP, a fast Fourier transform (FFT) is applied to obtain the received signal in the frequency-domain. A window operation is implemented at the base station to obtain the necessary data for detection. Without loss of generality, the data stream of user 1 is assumed to reach the base station first, followed by that of user 2, etc. The length of the window is the same as the length of the data block and it begins at the point where the data block of the first user arrives. Suppose the timing error (the timing delay between that user and the first user) for the k^{th} user is τ_k. After the window operation, the received signal vector for the k^{th} user is given by $\boldsymbol{R}_k = \boldsymbol{F}\boldsymbol{T}_k\tilde{\boldsymbol{H}}_k\boldsymbol{F}^H\boldsymbol{P}_k$, where $\tilde{\boldsymbol{H}}_k$ is an $N \times N$ circulant channel matrix with the first column as $[h_{k,0}, h_{k,1}, ..., h_{k,L-1}, 0..., 0]^T$; $\boldsymbol{T}_k$ is an $N \times N$ circulant time-shifting matrix with

$$T_k(p,q) = \begin{cases} 1, & p-q = \frac{\tau_k}{T_c} \text{ or } q-p = N - \frac{\tau_k}{T_c}, \\ 0, & \text{otherwise}, \end{cases} \quad (1)$$

where T_c is the sampling interval. Because both $\tilde{\boldsymbol{H}}_k$ and $\boldsymbol{T}_k$ are circulant matrices, they can be diagonalized by the Fourier transform matrix, that is

$$\boldsymbol{F}\boldsymbol{T}_k\boldsymbol{F}^H = \text{diag}(\boldsymbol{F}(:, \frac{\tau_k}{T_c}+1)), \quad \boldsymbol{F}\tilde{\boldsymbol{H}}_k\boldsymbol{F}^H = \text{diag}(\boldsymbol{F}_L\boldsymbol{h}_k), \quad (2)$$

where $\boldsymbol{F}_L$ denotes the submatrix of $\boldsymbol{F}$ consisting of its first L columns; and $\boldsymbol{A}(:,i)$ denotes i^{th} column of the matrix $\boldsymbol{A}$. Therefore we have

$$\boldsymbol{R}_k = \boldsymbol{F}\boldsymbol{T}_k\tilde{\boldsymbol{H}}_k\boldsymbol{F}^H\boldsymbol{P}_k = \underbrace{\text{diag}(\boldsymbol{F}_L\boldsymbol{h}_k)\text{diag}(\boldsymbol{F}(:, \frac{\tau_k}{T_c}+1))}_{\boldsymbol{H}_k}\boldsymbol{P}_k, \quad (3)$$

where $\boldsymbol{H}_k$ is a diagonal matrix corresponding to the k^{th} user's channel in the frequency-domain after some shifting in the time-domain. Finally, the received signal is the sum of all the users' signals plus the noise, given by

$$\boldsymbol{R} = \sum_{k=1}^{K} \boldsymbol{R}_k + \boldsymbol{N} = [\boldsymbol{H}_1, ..., \boldsymbol{H}_K][\boldsymbol{P}_1^T, ..., \boldsymbol{P}_K^T]^T + \boldsymbol{N}. \quad (4)$$

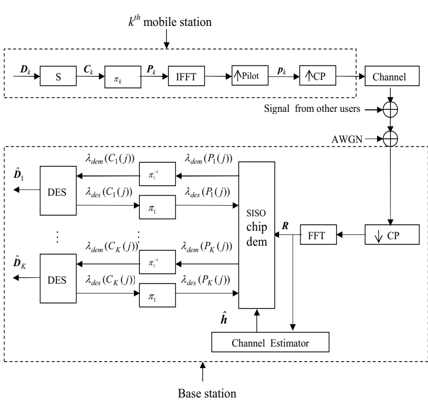

Fig. 1. Block diagram of the uplink MC-IDMA-UWB.

2.2. Receiver Structure

2.2.1. Chip-level Iterative Receiver

From (4) the received signal at the j^{th} subcarrier is given by

$$R(j) = \sum_{l=1}^{K} H_l(j)P_l(j) + N(j) = H_k(j)P_k(j) + V_k(j), \quad (5)$$

where $j = 1, ..., N$, $P_k(j) \in \{+1, -1\}$ and $H_k(j)$ are respectively the data chip over the j^{th} subcarrier and the corrresponding channel tap for the k^{th} user; $N(j)$ is the zero-mean additive white Gaussian noise (AWGN) with variance $\sigma_w^2 = N_0/2$; $V_k(j) = \Sigma_{l\neq k}H_l(j)P_l(j) + N(j)$ is the distortion term on the j^{th} subcarrier of the k^{th} user, which consists of the noise and the interference from other users.

Frequency-domain soft chip demodulator: As shown in Fig. 1, the iterative chip-by-chip receiver consists of a soft-input soft-output (SISO) chip demodulator and a bank of K single-user SISO de-spreaders working in a turbo manner. Considering the k^{th} user, $P_k(j)$ is treated as a random variable with mean $\mathbb{E}\{P_k(j)\}$ and variance $\text{Var}\{P_k(j)\}$ (initialized to 0 and 1 respectively). From (5), we have

$$\mathbb{E}\{R(j)\} = \sum_{k=1}^{K} H_k(j)\,\mathbb{E}\{P_k(j)\}, \quad (6)$$

$$\text{and} \quad \text{Var}\{R(j)\} = \sum_{k=1}^{K} H_k(j)\text{Var}\{P_k(j)\} + \sigma_w^2. \quad (7)$$

When K is large, $V_k(j)$ can be approximated by a Gaussian random variable with mean and variance given respectively by $\mathbb{E}\{V_k(j)\} = \mathbb{E}\{R(j)\} - H_k(j)\mathbb{E}\{P_k(j)\}$, and $\text{Var}\{V_k(j)\} = \text{Var}\{R(j)\} - |H_k(j)|^2\text{Var}\{P_k(j)\}$. Then, the demodulator computes the log-likelihood ratios (LLRs) of $P_k(j)$ as

$$\lambda_{dem}\{P_k(j)\} = \frac{2H_k(j)(R(j) - \mathbb{E}\{V_k(j)\})}{\text{Var}\{V_k(j)\}}. \quad (8)$$

The LLRs $\{\lambda_{dem}\{P_k(j)\}\}_{j=1}^N$ are fed to the de-interleaver to obtain the LLRs of $\{\lambda_{dem}\{C_k(j)\}\}_{j=1}^N$, where $C_k(j)$ is the j^{th} data chip of the k^{th} user before interleaving, and then sent to the single-user de-spreader as the *a priori* information for soft data de-spreading.

Frequency-domain de-spreader(DES): Without loss of generality, we consider the first data bit of the k^{th} user. The data bit $D_{k,1}$ is spread by the spreading sequence $\boldsymbol{S}_k = [S_k(1), ..., S_k(G)]^T$, where G is the processing gain. Because of the random interleaving, $\{\lambda_{dem}\{C_k(j)\}\}_{j=1}^N$ can be assumed approximately uncorrelated. We can derive the *a posterior* LLRs for $D_{k,1}$ as

$$\begin{aligned} \Lambda_{des}(D_{k,1}) &= \ln\Big(\frac{\prod_{j=1}^{G}\Pr(C_k(j) = S_k(j)|R(\pi(j)))}{\prod_{j=1}^{G}\Pr(C_k(j) = -S_k(j)|R(\pi(j)))}\Big) \\ &= \sum_{j=1}^{G} S_k(j)\lambda_{dem}(C_k(j)), \end{aligned} \quad (9)$$

where $\pi(j)$ is the index corresponding to *j* after interleaving. The extrinsic information for the chip $C_k(j)$ within $D_{k,1}\boldsymbol{S}_k$ is then given by $\lambda_{des}(C_k(j)) = \ln\Big(\frac{\Pr(C_k(j)=+1|\boldsymbol{R})}{\Pr(C_k(j)=-1|\boldsymbol{R})}\Big) -$

$\lambda_{dem}(C_k(j))$. Since $C_k(j) = +1$ if $S_k(j) = D_{k,1}$ and $C_k(j) = -1$ otherwise, then

$$\lambda_{des}(C_k(j)) = S_k(j)\,\Lambda_{des}(D_{k,1}) - \lambda_{dem}(C_k(j)). \quad (10)$$

The extrinsic LLRs will then be interleaved and fed back to the demodulator as the *a prior* information to update $\mathbb{E}\{P_k(j)\}$ and $\text{Var}\{P_k(j)\}$, $\mathbb{E}(P_k(j)) = \tanh\left(\frac{\lambda_{des}(P_k(j))}{2}\right)$, and $\text{Var}\{P_k(j)\} = 1 - \mathbb{E}\{P_k(j)\}^2$, which in turn are fed to the chip demodulator for the next iteration. The above procedure is repeated for a number of iterations. Final decision on symbol $D_{k,1}$ is obtained by making a hard decision based on (9) at the final iteration.

2.2.2. *Soft NBI Notching*

UWB systems are typically overlaid with other narrowband systems, and hence it may suffer from strong NBI. Suppose the NBI occupies the frequency subband $[F_L, F_H]$. Since the NBI signal is usually much stronger than the UWB signal, the overall received signal in this band will mainly consist of NBI, which renders the chips in this band useless. These corrupted chips will spread to other chips during the de-spreading process in (9) and eventually degrade the system performance. A soft notching method is proposed to mitigate the NBI. This method set the LLRs of the received signal corresponding to these subcarriers as zeros, i.e.,
$\lambda_{dem}(P_k(j)) = 0, \forall k, S_L \leq j \leq S_H$. $R(j) = 0, S_L \leq j \leq S_H$, where S_L and S_H denote the index of the subcarrier corresponding to frequency F_L and F_H respectively.

3. PERFORMANCE ANALYSIS BY VARIANCE EVOLUTION

From (5) and (8) we have

$$\begin{aligned}
&\lambda_{dem}(P_k(j)) \\
&= \frac{2H_k(j)(H_k(j)P_k(j) + V_k(j) - \mathbb{E}\{V_k(j)\})}{\text{Var}\{V_k(j)\}} \quad (11) \\
&\text{Var}\{V_k(j)\} = \sum_{l \neq k} |H_l(j)|^2 \text{Var}\{P_l(j)\} + \sigma_w^2, \quad (12) \\
&\text{Var}\{P_k(j)\} = 1 - \mathbb{E}\{\tanh(\lambda_{des}(P_k(j))/2)\}^2. \quad (13)
\end{aligned}$$

$H_k(j)P_k(j)$ and $V_k(j) - \mathbb{E}\{V_k(j)\}$ represent signal and distortion components respectively. Hence, the signal-to-noise ratio (SNR) at the j^{th} subcarrier of the k^{th} user is given by

$$\eta_k(j) = \frac{|H_k(j)|^2}{\sum_{l \neq k} |H_l(j)|^2 \text{Var}\{P_l(j)\} + \sigma_w^2}. \quad (14)$$

It is assumed that $\lambda_{dem}(P_k(j)), \forall j$, can be approximately regarded as LLRs generated from the observations of an AWGN channel with SNR equal to $\eta_k(j)$. This is based on the assumption that the distortion components among $\lambda_{dem}(P_k(j)), \forall j$, are uncorrelated, which is approximately true when long random interleavers are applied. Hence, from (11) we have

$$\begin{aligned}
&\mathbb{E}\{\lambda_{dem}(P_k(j) = \pm 1)\} = \pm 2\eta_k(j), \\
\text{and} \quad &\text{Var}\{\lambda_{dem}(P_k(j))\} = 4\eta_k(j). \quad (15)
\end{aligned}$$

The LLRs $\{\lambda_{dem}(P_k(j))\}_{j=1}^N$ are fed to the de-interleaver to obtain the LLRs of $\{\lambda_{dem}(C_k(j))\}_{j=1}^N$. Without loss of generality, we consider the first data bit of the k^{th} user. Using (9) and (10), we have

$$\lambda_{des}(C_k(j)) = S_k(j) \sum_{l \neq j} S_k(l) \lambda_{dem}(C_k(l)). \quad (16)$$

Because $\{\lambda_{dem}(C_k(j))\}_{j=1}^N$ are uncorrelated, we have

$$\mathbb{E}\{\lambda_{des}(C_k(j))\} = S_k(j) \sum_{l \neq j} S_k(l) \mathbb{E}\{\lambda_{dem}(C_k(l))\}, \quad (17)$$

$$\text{Var}\{\lambda_{des}\{C_k(j)\}\} = S_k(j) \sum_{l \neq j} S_k(l) \text{Var}\{\lambda_{dem}(C_k(l))\}. \quad (18)$$

The extrinsic LLRs $\{\lambda_{des}(C_k(j)\}_{j=1}^N$ will then be interleaved to obtain $\{\lambda_{des}(P_k(j)\}_{j=1}^N$. From (15),(17), and (18) we can get $\mathbb{E}\{\lambda_{des}(P_k(j) = \pm 1)\} = \pm 2 \sum_{l \neq j} \eta_k(l)$, and $\text{Var}\{\lambda_{des}(P_k(j))\} = 4 \sum_{l \neq j} \eta_k(l)$. Assuming the feedback extrinsic information is symmetric Gaussian [2], from (13) we have

$$\begin{aligned}
\text{Var}\{P_k(j)\} &= \mathbb{E}\{1 - \tanh^2(\lambda_{des}(P_k(j))/2)\} = g(\eta_k(j)) \\
&= \frac{\int_{-\infty}^{\infty} [1 - \tanh^2(y/2)] \exp\left(-\frac{[y - 2\sum_{l \neq j} \eta_k(l)]^2}{8 \sum_{l \neq j} \eta_k(l)}\right) dy}{\sqrt{8\pi \sum_{l \neq j} \eta_k(l)}} \quad (19)
\end{aligned}$$

Combining (14) and (19), we have

$$\eta_k^{new}(j) = \frac{|H_k(j)|^2}{\sum_{l \neq k} |H_l(j)|^2 g(\eta_l^{old}(j)) + \sigma_w^2}. \quad (20)$$

Initially, we set $g(\eta_k^{old}(j)) = 1, \forall k, j$, which corresponds to zero prior information. We can repeat (20) a number of times to obtain the final chip SNR $\eta_k^{final}(j)$. The SNR for the data bit is obtained by adding the SNR of corresponding data chips. Under BPSK modulation, the average bit-error-rate (BER) under a given channel $\boldsymbol{H}$ is then given by $\text{BER}(\boldsymbol{H}) = \frac{G}{NK} \Sigma_{k=1}^{K} \Sigma_{i=1}^{\frac{N}{G}} Q(\sqrt{\eta_{k,i}})$, where $\eta_{k,i}$ is the SNR for the i^{th} bit of the k^{th} user and $Q(x)$ is the Q function. It is seen from Table 1 that the two results match quite well. The detailed system set up is given in section 4.

4. SIMULATION RESULTS

We employ the channel model proposed by the IEEE 802.15.3a working group [3].We focus on channel model 2, which

	1 user		8 user		16 user	
SNR	Simu.	Anal.	Simu.	Anal.	Simu.	Anal.
0(dB)	0.08	0.08	0.10	0.11	0.13	0.15
4(dB)	0.016	0.015	0.02	0.02	0.03	0.05
8(dB)	5e-4	5e-4	6e-4	6e-4	7e-4	7e-4

Table 1. Simulated and analytical performance of proposed MC-IDMA-UWB system.

corresponds to a short-range indoor wireless environment. 1000 realizations of this stochastic channel model are generated by the MATLAB code provided in [3], leading to a channel model of mean delay spread of 9.57 ns and root mean-square delay of 8.50 ns. The final performance results are averaged over a large number of channel realizations. The system setup is as follows. The carrier frequency is assumed to be 6.46 GHz. The total available bandwidth 4.096 GHz is divided into 4096 subcarriers. This corresponds to a symbol duration of 1000 ns. An additional 100 ns guard interval is added to avoid the effect of inter-chip interference and timing offset errors, which results in a total block length of 1100 ns. Packet transmission is assumed. Each packet consists of 4 pilot symbol blocks and 60 data symbol blocks. Each symbol block has M=256 BPSK symbols and the processing gain is selected as G=16. Therefore, each user's data rate is $256/1100 \cdot (60/64) = 218.2$ Mbps. The maximum timing error between users is less than 50 ns, such that the sum of the timing error between users and the multipath delay are less than the length of the CP. The NBI generated in the simulation is an IEEE 802.11a OFDM system, which has 54 Mbps data rate at 5 GHz carrier frequency. For the MC-CDMA-UWB system, a length-16 spreading sequence is randomly generated for each user. For MC-IDMA-UWB system, a common length-16 spreading sequence, $[+1, -1, +1, ...]$ is assigned to all users, and a randomly generated chip interleaver is allocated to each user.

Fig. 2 shows the performance of the proposed MC-IDMA-UWB system and that of the corresponding MC-CDMA-UWB system. The MC-CDMA-UWB system has a similar structure to the MC-IDMA-UWB system shown in Fig. 1, except that there is no interleaver and de-interleaver in the transceiver. It is seen that the proposed system outperforms the MC-CDMA-UWB system significantly. It can approach the single-user performance under over-loaded conditions.

Fig. 3 shows the the performance of the MC-IDMA-UWB system with estimated channel and soft-notching method. The simple least-square channel estimator with proper training sequence is employed. It is seen that the soft NBI notching method can completely remove the effects of NBI. The proposed turbo receiver with soft-notching memthod is quite robust against the channel estimation error and the NBI.

5. CONCLUSION

We have proposed a multicarrier interleave-division multiple-access system for UWB communications. It is demonstrated that, when combined with soft narrowband interference notching method, the proposed system is quite robust against the multiple-access interference, frequency-selective fading and narrowband interference.

6. REFERENCES

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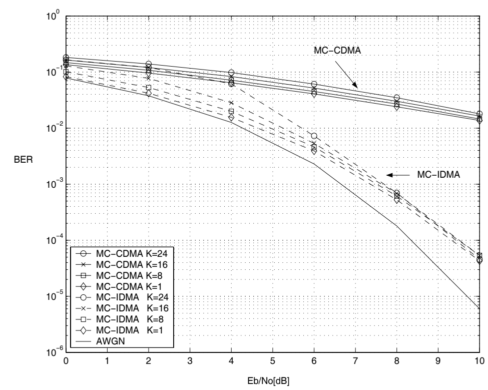

Fig. 2. BER performacne of MC-CDMA-UWB and MC-IDMA-UWB systems with random spreading and joint detection. G=16; 30 turbo iterations are performed.

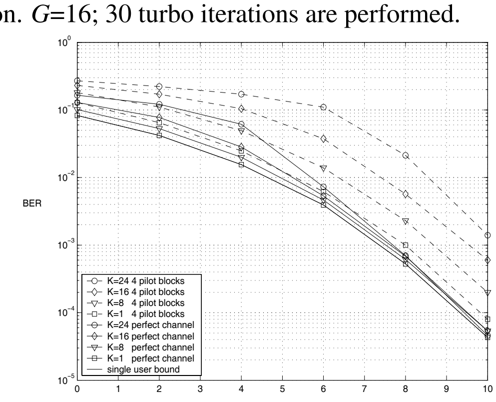

Fig. 3. BER performance of the MC-IDMA-UWB system in the presence of NBI (20dB) and channel estimation error.