OFDM Versus Time-Hopping in Multiuser Ultra Wideband Communication Systems

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Abstract—In this paper we present a comparison between OFDM-based radios and time-hopping impulse radios for ultra wideband (UWB) communication systems operating in a multiuser scenario, with additive white Gaussian noise and multipath channels, and narrowband interference. The comparison of the two different schemes for generating UWB signals is based on results obtained in numerical simulations, and is intended to assist the development of emerging UWB standards.

I. INTRODUCTION

UWB communication systems have generated increasing interest among researchers lately because of their potential for providing high data rates. One of the challenges in the design of UWB systems comes from the large bandwidth required for transmission of UWB signals which is in the Gigahertz range and is not available for exclusive use by UWB systems. Thus, the frequency range in which UWB systems operate will contain slices of bandwidth in which other existing communication systems operate, and under FCC regulations the UWB systems must appear as spurious interference to the already existing communication systems that operate in the frequency ranges below a few Gigahertz. Furthermore, UWB systems must be capable of operating in the presence of various interfering signals coming from the existing communication systems which may be considered as narrowband interfering signals for the UWB signal.

Two main approaches have been proposed in the literature for the design of UWB systems. One approach uses Orthogonal Frequency Division Multiplexing (OFDM), and is considered for the new IEEE 802.15 standard for generating UWB signals [3]. We note that OFDM is currently used in broadband wireless systems and has been incorporated in the IEEE 802.11 standard. The alternative approach is based on extremely short carrierless pulses (also referred to as impulses or mono-pulses) transmitted at random or pseudo-random time intervals by means of a time-hopping sequence, and is known as time-hopping impulse radio (TH-IR) [7], [8].

In our paper, we consider both OFDM-based radios and TH-IR for UWB systems that operate in a multiuser scenario, and investigate their bit error rate (BER) performance in the presence of additive white Gaussian noise, multipath channels, and narrowband interference. In the OFDM-based category we consider the system in [4], which was dubbed interference suppressing OFDM (IS-OFDM), which we extend for use in multiuser scenarios by using pseudo-random noise (PN) sequences and employing a technique similar to multicarrier CDMA (MC-CDMA) [5]. In TH-IR multiple users can communicate simultaneously by using distinct time-hopping sequences.

II. OFDM-BASED SYSTEM FOR UWB RADIOS

We consider the IS-OFDM system proposed for single-user UWB systems in [4] and extend it for simultaneous use by multiple users communicating with a single receiver as in the case of the uplink of a wireless system. To enable multiple access and allow multiple users to transmit information simultaneously we employ a technique similar to multicarrier CDMA (MC-CDMA) [5].

The available wide bandwidth is divided into L groups with \( M \) frequency bins (or carriers) in each group, which implies a total number of carriers \( N = LM \). The \( M \) carriers in each group are combined using the basic IS-OFDM and the \( L \) basic IS-OFDMs are combined using OFDM technique [4]. The input data stream of \( R \) bits/s enters a serial-to-parallel (S/P) converter which provides \( L \) data streams each with rate \( R/L \) bits/s. Each parallel stream of rate \( R/L \) corresponding to a given group of frequency bins enters a second S/P converter which provides \( M \) parallel streams each with rate \( R/N \). The \( M \) parallel streams in each group are spread using orthogonal Hadamard sequences \( w \) so that after this spreading operation the signal rate becomes \( R/L \) again, followed by S/P conversion back to \( M \) parallel streams each with rate \( R/N \). These are combined in an interference suppressing scheme such that the power of each of the \( M \) symbols in the frame carried by a particular group of frequency bins is distributed over all \( M \) bins in the given group while symbols are separated by orthogonal Hadamard sequences. Different groups of frequency bins are made orthogonal to each other as in an usual OFDM system. The orthogonally modulated symbols of the \( u \)th group are summed to form a set of \( M \) parallel symbols.

For a given user \( u \) these symbols are then spread using a spreading sequence \( c(u) \) of length \( N_c \). Thus, each group contains \( N_c \) parallel data sets. The corresponding parallel data sets of all \( L \) groups are combined to form a parallel sequence of length \( N = ML \). The \( N_c \) parallel sequences are applied to an IFFT block, and then fed to a parallel-to-serial (P/S)
converter to form the UWB IS-OFDM symbol. In a multiuser scenario distinct users transmitting simultaneously to the same receiver are assigned different spreading sequences as in [5]. The transmitter diagram is depicted schematically in Figure 1.

Mathematically, the operation of the transmitter is described as follows. The complex data points of the $q^{th}$ parallel stream of group $\ell$ of user $u$, $x_{q}^{(\ell,u)} = a_{q}^{(\ell,u)} + j\beta_{q}^{(\ell,u)}$, are spread by the orthogonal codes $w_{q} = [w_{q,0}, w_{q,1}, \ldots, w_{q,M}]$ yielding

$$ b_{k}^{(\ell,u)} = \sum_{q=0}^{M-1} x_{q}^{(\ell,u)} w_{q,k} \quad \text{for} \quad k = 0, \ldots, M - 1 \quad (1) $$

These are then spread by the user spreading sequence $c^{(u)}$ to yield

$$ b_{k}^{(\ell,u,m)} = \sum_{q=0}^{M-1} x_{q}^{(\ell,u)} w_{q,k} c^{(u)}_{m} \quad \text{for} \quad k = 0, \ldots, M - 1, \quad m = 0, \ldots, N_{c} - 1 \quad (2) $$

where $N = 2N$ and $m = 0, \ldots, N_{c} - 1$. Thus we have $N$ parallel data sets that are fed to the IFFT block whose output is given by

$$ s_{m}^{(u,m)} = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} a_{i}^{(u,m)} e^{j2\pi(iN/N)} \quad (3) $$

The $N_{c}$ parallel outputs of the IFFT block are then fed to a parallel to serial converter whose output sequence of length $NN_{c}$ forms the basic UWB IS-OFDM symbol.

At the receiver corresponding to the $u^{th}$ user, the received signal is serial to parallel converted and fed to an FFT block to obtain $N$ parallel data points $\tilde{x}_{k}^{(u,m)}$. These are then fed to a decoder where the data points are demapped, after which each of the $\tilde{N}$ parallel sequences of length $N_{c}$ are despread using the $u^{th}$ user spreading sequence. The output of the despread is given by

$$ z_{k}^{(\ell,u)} = \tilde{x}_{k}^{(\ell,u)} + \sum_{p=1, p \neq u}^{N_{u}} \sum_{m=0}^{N_{c}-1} c_{m}^{p} c_{m}^{u} \tilde{x}_{k}^{(\ell,u)} + w_{k}^{(u)} \quad (5) $$

for $k = 0, \ldots, M - 1$ and $\ell = 1, \ldots, L$, where the second term represents the multi-access interference and $w_{k}^{(u)}$ is the additive noise contribution. These points are then demapped, parallel to serial converted and despread by $\tilde{N}$ Hadamard sequences in parallel to obtain the original data symbols [4]. The receiver diagram is depicted schematically in Figure 2.

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Fig. 1. The Transmitter for the Multiuser UWB IS-OFDM system.

Fig. 2. The Receiver for the Multiuser UWB IS-OFDM system.
III. TIME-HOPPING IMPULSE RADIOS

The TH-IR is based on transmission of ultra short pulses [7], [8], and the transmitted signal by a given user \( u \) is

\[
S^{(u)}(t) = \sum_{i=-\infty}^{\infty} \sqrt{E_p} p(t - jT_f - c_j^{(u)}T_c - d_j^{(u)}/N_p) \delta
\]

where \( p(t) \) is the pulse (or monocyte) used, \( E_p \) is the energy per pulse, \( T_f \) is the pulse repetition interval, and \( N_p \) is the number of pulses that are modulated by a given binary symbol. The information symbols \( d_j^{(u)}/N_p \) change only at multiples of \( N_p \). The time-hopping sequence \( c_j^{(u)} \) provides an additional time shift of \( c_j^{(u)}T_c \) seconds to the \( j \)th monocyte in the pulse train, necessary to avoid collisions due to multiple access. Assuming that transmitted signals suffer only constant attenuation \( A_u \) and delay \( \tau_u \), \( \forall u \), the received signal for a multiuser system with \( K \) active users is

\[
R(t) = \sum_{u=1}^{K} A_u S^{(u)}(t - \tau_u) + N(t)
\]

where the \( u \)th user received signal is given by

\[
S^{(u)}(t - \tau_u) = \sum_{i=-\infty}^{\infty} \sqrt{E_p} p_{rec}(t - jT_f - c_j^{(u)}T_c - d_j^{(u)}/N_p) \delta
\]

where \( p_{rec}(t) \) being the second derivative of the monocyte used for transmission [8].

A single-user receiver using pulse correlation as described in [8] is employed to decode users. This forms the template signal \( v(t) = p_{rec}(t) - p_{rec}(t - \delta) \), and calculates the decision statistic by adding up the \( N_p \) correlations of \( v(t) \) with the received signal \( S^{(u)}(t - \tau_u) \) at various instances of time. In a multipath environment a selective Rake receiver [3, Sec. 8.2.4] with \( L_a \) fingers is used to select the \( L_a \) best components from all available paths.

Performance of this system for a single active user in the presence of narrowband interference has been analyzed in [9], where criteria like SIR, processing gain, and jam resistance are defined. An analysis of the multiaccess performance of this system with random time-hopping sequences can be found in [7]. In our paper we look at the BER performance of the system in a multiuser scenario when PN sequences are used.

IV. SIMULATION SETUP

We have performed simulations to investigate the BER performance of UWB systems using OFDM-based radios as well as TH-IR for a system with available bandwidth of 528 MHz.

For the OFDM-based system this implies a total of \( \tilde{N} = 256 \) parallel channels, split into \( L = 16 \) IS-OFDM groups, each group using \( M = 16 \) carriers. The \( L = 16 \) IS-OFDM groups are combined using ordinary OFDM as described in Section II. Single user matched filter detection was employed to decode users for this system.

For the TH-IR system we considered a pulse repetition time of 23.80 ns and a pulse duration of 2.1023 ns. One pulse per transmitted information symbol was used, \( N_p = 1 \), and the time hopping interval was taken to be 3.0 ns. A correlation receiver was used to decode users for this system. In the case of multipath channels a selective Rake receiver with \( L_p = 5 \) fingers was used.

The two systems were simulated in an additive white Gaussian noise (AWGN) channel and in a multipath channel, with and without a narrowband interferer present. The multipath channel model used in simulations is similar to the one in [1], and is based on the Saleh-Valenzuela (S-V) model [6]. The model, which was selected by the IEEE 802.15.3a standard and was also used in other recent work dealing with UWB communication systems [2] assumes that the multipaths arrive in clusters with arrival rate \( \Lambda \) given by a Poisson process, and the rays within a cluster also arrive as a Poisson process with arrival rate \( \lambda \). The impulse response of this multipath model is mathematically described by

\[
h(t) = x_1 \sum_{\ell=0}^{L_a} \sum_{k=0}^{K} A_k \delta(t - T_{\ell,k}^k - \tau_{\ell,k}^k)
\]

where

- \( \{ A_k \} \) represents the multipath gain for the \( k \)th ray within the \( \ell \)th cluster.
- \( \{ T_{\ell,k}^k \} \) is the delay of the \( k \)th cluster.
- \( \{ \tau_{\ell,k}^k \} \) is the delay of the \( k \)th multipath relative to the \( \ell \)th cluster arrival time.
- \( \{ x_1 \} \) is the log-normal shadowing.

The cluster and ray arrival time follow an exponential distribution given by

\[
p(T_{\ell} | T_{\ell-1}) = \Lambda \exp[-\Lambda(T_{\ell} - T_{\ell-1})]
\]

and we assumed that \( \tau_{0,\ell} = 0 \). The channel gains are defined as follows

\[
\alpha_{\ell,k} = p_{k,\ell} \xi_{\ell,k} \beta_{\ell,k}
\]

where

- \( p_{k,\ell} = \pm 1 \) with equal probability, and accounts for signal inversion due to reflections.
- \( \xi_{\ell} \) represents the fading associated with the \( \ell \)th cluster.
- \( \beta_{k,\ell} \) represents the fading associated with the \( k \)th ray of the \( \ell \)th cluster.

The small scale fading coefficients \( \xi_{\ell} \) and \( \beta_{k,\ell} \) are modeled as random variables with a log-normal distribution as given below

\[
20 \log_{10}(\xi_{\ell} \beta_{k,\ell}) \propto N(\mu_{k,\ell}, \sigma_1^2 + \sigma_2^2)
\]

The power delay profile is given as

\[
E[|\xi_{\ell} \beta_{k,\ell}|^2] = \Omega_0 e^{-\frac{c_{\ell,k} + b_{k,\ell}}{\gamma}}
\]

The mean \( \mu_{k,\ell} \) is given by

\[
\mu_{k,\ell} = \frac{10 \ln(\Omega_0) - 10 \gamma_{\ell} - 10 \gamma_{b,\ell}}{\ln(10)} - (\sigma_1^2 + \sigma_2^2) \ln(10)
\]

\[
\frac{20}{\mu_{k,\ell}}
\]
The large-scale fading coefficient is modeled also as a log-normal random variable and is given as

\[ 20 \log_{10}(\chi_4) \sim \mathcal{N}(0, \sigma^2_4) \]  

(14)

We used the parameters in Table II in [1] to obtain the channel model used in our numerical simulations.

The narrowband interference signal used in simulations was generated similar to [4] by using a linear bandpass FIR filter with 60 taps, passband equal to 10 MHz, and stopband attenuation of \(-35\) dB, driven by white Gaussian noise with unit variance at the input.

V. NUMERICAL RESULTS

We have first looked at the performance of the IS-OFDM UWB system in AWGN and multipath environment with one and two active users. Results of this experiment are presented in Figure 3. We note that, while in AWGN channel the BER curve has the typical “waterfall” shape, in the presence of multipath the BER performance of the IS-OFDM UWB system degrades, and the BER curve flattens. For the system under consideration increasing the ratio \(E_b/N_0\) beyond 10 dB implies almost no improvement in the BER. We also note that adding one active user in the system does not affect performance drastically.

We have also compared performance of the IS-OFDM UWB system with that of the TH-IR system with one active user in the system for both AWGN and multipath channels. Results of this experiment are presented in Figure 4. We note that the TH-IR displays similar performance degradation in the presence of multipath, and that its corresponding BER curve flattens as well. We also note that the IS-OFDM UWB system outperforms the TH-IR system in both cases. For the system under consideration, in AWGN the same BER requires a ratio \(E_b/N_0\) about 3-4 dB lower for the IS-OFDM UWB system, while for multipath the BER flattens at a lower BER value.

This experiment was followed by a similar one in which performance of IS-OFDM UWB and TH-IR systems was compared for multipath channels in the presence of a narrowband jamming signal with different values of the Jammer-to-Signal Ratio (JSR). Results of this experiment are presented in Figure 5. Similar BER curves for a comparable IS-OFDM UWB system can be found in [4]. We note again the flattening of the BER curve for both IS-OFDM UWB and TH-IR systems. We also note that IS-OFDM UWB system outperforms again the TH-IR system.

Finally, we have also looked at the performance of the two systems in a multiuser/multipath scenario. The BER curves that correspond to 2, respectively 5, active users in the system are presented in Figure 6. We note again the fact that the IS-OFDM UWB system displays better performance. We also note that the addition of active users into the system seems to have less impact in the IS-OFDM UWB system than in the TH-IR system. For the considered scenarios, the addition of 3 users in the IS-OFDM UWB system implies a smaller decrease in the BER than in the TH-IR system.

VI. CONCLUSIONS

In this paper we provided a performance comparison between OFDM-based radios and TH-IR for UWB systems. In the OFDM-based category we extended the IS-OFDM UWB system in [4] for use in multiuser scenarios. We extended also previous performance analysis for OFDM-based radios and TH-IR for UWB systems [4], [7], [9] to a multiuser scenario, with AWGN, multipath channels, and narrowband interference. Our numerical analysis showed that the IS-OFDM UWB system outperformed the TH-IR system in all cases.

Future work should include an analytical investigation of the BER for the two considered schemes for generating UWB signals to provide a theoretical basis for the experimental results obtained through simulations.

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REFERENCES

Fig. 3. BER vs. $E_b/N_0$ for an IS-OFDM UWB system with AWGN and multipath channels, and different number of active users.

Fig. 4. BER vs. $E_b/N_0$ for single user IS-OFDM UWB and TH-IR systems with AWGN and multipath channels

Fig. 5. BER vs. $E_b/N_0$ for single user IS-OFDM UWB and TH-IR systems with multipath channel and narrowband interferer with different powers.

Fig. 6. BER vs. $E_b/N_0$ for single user IS-OFDM UWB and TH-IR systems with multipath channels and different number of active users.