A Simulation Comparison of Time-Hopping PAM and Interference Suppressing OFDM in Multiuser Ultra Wideband Communications Systems

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***Abstract*—In this paper we present a side-by-side comparison between time-hopping (TH) impulse radios (IR) based on pulse amplitude modulation (PAM) and interference suppressing (IS) OFDM-based ultra wideband (UWB) systems in multi-user scenarios. For both systems we use minimum mean squared error (MMSE) receivers, and look at the raw bit error rate (BER) at the physical layer as performance criterion. This is evaluated using simulations for various scenarios that include additive white Gaussian noise (AWGN), multipath and/or multiple access interference, and narrowband interference. Numerical results indicate that in the presence of AWGN only, the two systems display similar performance, while for multipath propagation the TH-PAM IR system outperforms the IS-OFDM system. However, in the presence of narrowband interference the IS-OFDM system outperforms the TH-PAM IR system which displays poor performance in this case.**

I. INTRODUCTION

UWB technology has been in use since the early 1960s, mostly in military radar applications requiring precision ranging and localization, high data throughput, as well as multipath immunity. Lately, research in UWB systems has gained new momentum in commercial applications involving wireless networking for consumer electronics, vehicle collision detection and avoidance systems, or warehouse inventory tracking, where operation is in a multiaccess/multiuser context.

Two main categories of UWB systems have been proposed for use in wireless networking applications: one based on transmission of extremely short carrierless pulses (also referred to as impulses or mono-pulses) which is known as IR, and an alternative one based on orthogonal frequency division multiplexing (OFDM).

In the category of IR we note the approach of Win and Scholtz [1], [2] in which information symbols are transmitted using pulse position modulation (PPM), as well as the approach proposed by Martret and Giannakis [3] in which information is transmitted using pulse amplitude modulation (PAM). The latter approach has been further investigated by Gezici et al. [4], [5] who analyzed linear receiver schemes for this type of IR.

In the category of OFDM-based UWB systems we note the interference suppressing OFDM (IS-OFDM) system proposed by Gerakoulis and Psalmi [6], as well as alternative multiband OFDM-based UWB systems investigated by Li et al. [7], Nakache et al. [8], and Batra et al. [9].

In our paper we consider the TH-PAM IR system in [5] and the IS-OFDM UWB system proposed originally in [6] for single-user (point-to-point) transmission and extended for use in multi-user scenarios in [10]–[12], and compare their performance for various wireless scenarios. The comparison is based on numerical results obtained from simulations in which we evaluate the raw BER at the physical layer for scenarios that include AWGN, multipath and/or multiple access interference, as well as narrowband interference.

II. SYSTEM DESCRIPTION

A. The TH-PAM IR System

The transmitted signal by a given user k in the TH-PAM IR system is expressed as

$$s_{tx}^{(k)}(t) = \sqrt{\frac{E_k}{N_f}} \sum_{j=-\infty}^{\infty} d_j^{(k)} b_{\lfloor j/N_f \rfloor} p_{tx}(t - jT_f - c_j^{(k)} T_c) \quad (1)$$

where $b_{\lfloor j/N_f \rfloor} \in \{-1, 1\}$ is the corresponding information symbol that changes only at multiples of N_f, $p_{tx}(t)$ is the transmitted pulse, E_k is the energy per bit of user k, T_f is the pulse repetition time, N_f is the number of pulses that are modulated by a given binary symbol, and $d_j^{(k)}$ are random polarity codes taking values ± 1 with equal probability [4]. The time-hopping sequence $c_j^{(k)}$ provides an additional time shift of $c_j^{(k)} T_c$ seconds to the j^{th} pulse in the pulse train, necessary to avoid collisions due to multiple access.

The transmitted signal by user k is received through a multipath channel with L paths spaced at time intervals of T_c characterized by discrete-time impulse response $\boldsymbol{\alpha}^{(k)} = [\alpha_1(k) \ldots \alpha_L(k)]$, where $\alpha_\ell(k)$ is the gain of path ℓ of user k. Assuming that there are K active users in the system, the received signal at the common receiver is

$$\begin{aligned} r(t) &= \sum_{k=1}^{K} \sqrt{\frac{E_k}{N_f}} \sum_{j=-\infty}^{\infty} \sum_{\ell=1}^{L} \Big[\alpha_\ell^{(k)} d_j^{(k)} b_{\lfloor j/N_f \rfloor} \times \\ &\quad \times\ p_{rx}(t - jT_f - c_j^{(k)} T_c - (\ell - 1) T_c) + \sigma_n n(t) \Big] \end{aligned} \quad (2)$$

where $p_{rx}(t)$ is the received pulse and $n(t)$ is the AWGN that corrupts the signal at the receiver.

An MMSE receiver is used to decode information symbols transmitted by users as described in [5], for which the received

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signal $r(t)$ is first passed through a filter matched to the received pulse $p_{rx}(t)$, and then sampled at the instances of multipath arrivals in each frame. For a given user k the sampled signal is despread by multiplying with the random polarity code $d_j^{(k)}$ corresponding to user k to obtain samples $r_{\ell,j}$, where $\ell = \ell_1, \ldots, \ell_M$ and $j = 0, 1, \ldots, N_f - 1$. These samples form a $N \times 1$ vector

$$\mathbf{r} = [r_{\ell_1, j_1^{(1)}} \ldots r_{\ell_1, j_{m_1}^{(1)}} \ldots r_{\ell_M, j_1^{(M)}} \ldots r_{\ell_M, j_{m_M}^{(M)}}] \quad (3)$$

where $\sum_{i=1}^{M} m_i = N$, with $N \leq MN_f$. Each element $r_{\ell,j}$ of the vector $\mathbf{r}$ will be affected by inter-frame interference (IFI) due to contributions from other frames carrying the same information symbol of the same user and by multiple access interference (MAI) due to contributions from frames belonging to other users. In order to minimize the effect IFI and MAI the elements of the vector $\mathbf{r}$ are combined using MMSE criterion to obtain the decision variable as described in [5].

B. The IS-OFDM UWB System

In the IS-OFDM system the available UWB bandwidth is divided into $\tilde{N}$ frequency bins, each corresponding to a different sub-carrier frequency, and information is transmitted in frames of $\tilde{N}$ symbols, as it is usually the case in OFDM-based systems. However, unlike usual OFDM, in the IS-OFDM system the $\tilde{N}$ symbols in a frame are divided into L sub-blocks of $\tilde{M}$ symbols each, and the power of each of the $\tilde{M}$ symbols in a sub-block is distributed over $\tilde{M}$ sub-carriers to provide better performance in the presence of narrowband interference as discussed in [6]. Thus, the $\tilde{N}$ frequency bins used for transmission by the IS-OFDM UWB system are divided into L groups with $\tilde{M}$ frequency bins (or sub-carriers) in each group. The $\tilde{M}$ symbols in each sub-block are multiplied by orthogonal Hadamard sequences in order to be easily separated at the receiver.

The multiple access capability needed in the case of multiuser scenarios is obtained by employing a multi-carrier code division multiple access (MC-CDMA) scheme [13], which assigns each user u a unique code $\mathbf{c}^{(u)}$ of length N_c that provides additional spreading of its transmitted symbols over the length N_c of the code, as discussed in [10]–[12].

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 $\widetilde{M}$ parallel streams each with rate $R/\widetilde{N}$. The $\widetilde{M}$ parallel streams in each group are multiplied by the orthogonal Hadamard sequences $\mathbf{w}$ of length $\tilde{M}$, $\{\mathbf{w}_q\}_0^{\widetilde{M}-1}$, so that after this operation the signal rate becomes R/L again, followed by S/P conversion back to $\widetilde{M}$ parallel streams each with rate $R/\widetilde{N}$. These are combined in an interference suppression scheme such that the power of each of the $\widetilde{M}$ symbols in the frame carried by a particular group of frequency bins is distributed over all $\widetilde{M}$ bins in the given group while symbols are separated by orthogonal Hadamard sequences. The symbols of a given user u are further multiplied by spreading sequence $\mathbf{c}^{(u)}$ of length N_c which generates N_c parallel sequences that are then encoded, processed by the IFFT block, converted from parallel to serial (P/S) and from digital to analog (D/A) for transmission over the air.

At the receiver for a the received signal is converted from analog to digital (A/D) and from serial to parallel (S/P), processed by the FFT block, and decoded/de-mapped. The resulting $\widetilde{N}$ parallel sequences of length N_c are despread using linear filters matched to the u^{th} user spreading sequence, followed by MMSE combining of the corresponding matched filter outputs [12], [14] to minimize interference coming from the other users in the system. We note that this implements a linear MMSE multiuser detector for the given user u, and is different from previous studies of the IS-OFDM UWB system with multiple users [10], [11], [15] which used the matched filter outputs directly to estimate the transmitted symbols at the receiver. The resulting data points at the output of the MMSE combiners are then P/S converted followed by separation of the data symbols in the IS-OFDM scheme using the $\widetilde{M}$ Hadamard sequences [6].

III. SIMULATIONS AND NUMERICAL RESULTS

In order to investigate the BER performance of the two UWB systems we have performed simulations for various scenarios that are characteristic to wireless systems consisting of AWGN along with multipath propagation and/or multiple users. In addition, we have also included a narrowband jamming signal to simulate performance also in the presence of narrowband interference. We note that narrowband interference is an important issue in UWB systems, which must be capable of operating in the presence of interfering signals coming from incumbent communication systems in the same frequency band. These occupy bandwidths that are considerably smaller relative to the bandwidth of UWB signals, and are usually regarded as narrowband interfering signals for the UWB signals.

A. Simulation Setup

The UWB system bandwidth considered in our simulations was of 528 MHz, which in the case of IS-OFDM UWB system is divided into $\tilde{N} = 512$ parallel channels that are split into $L = 8$ IS-OFDM groups, each group using $\tilde{M} = 64$ carriers. Pseudo-noise (PN) sequences of length 7 are used for providing multiple access, and MMSE multiuser detectors for each carrier are employed at the receiver.

For the TH-PAM IR we took the number of frames per symbol $N_f = 10$, and the number of chips per frame $N_c = 7$. The polarity codes took values of ± 1 with equal probability, and uniform random codes with cardinality $N_h = 7$ and periodicity of $P = 5000$ were used for the time-hopping sequences. The UWB system bandwidth of 528 MHz implies a pulse period of $T_p = 2.4566$ ns, and the time hopping interval T_c and the pulse repetition time of T_f were taken to be 3.0 ns and 27.0 ns respectively. In AWGN channel we used a correlation receiver as described in [1], while in the case of multipath and/or multiple users the MMSE receiver in [5] was used.

In order to simulate multipath propagation we used the channel model in [9], which is based on the Saleh-Valenzuela

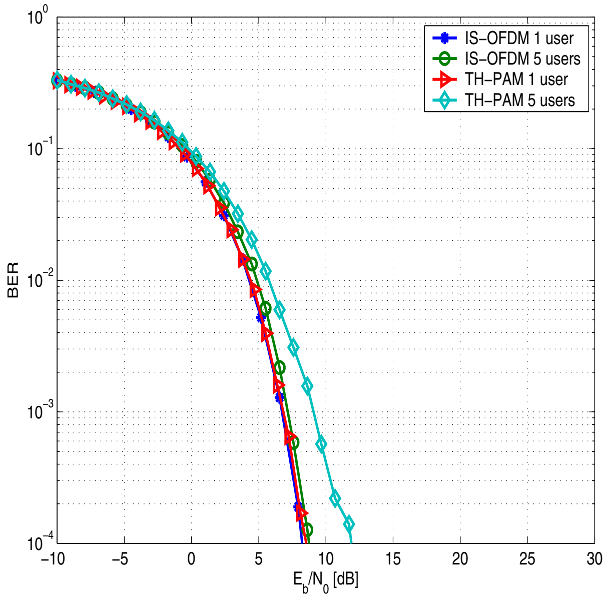

Fig. 1. IS-OFDM and TH-PAM performance with AWGN and different number of active users.

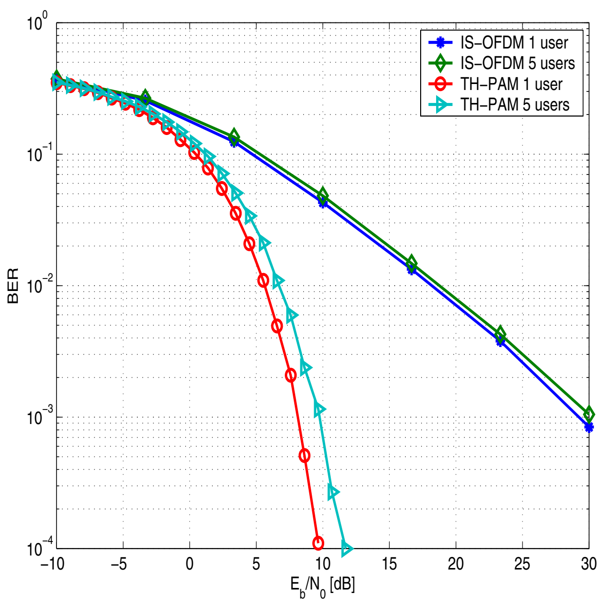

Fig. 2. IS-OFDM and TH-PAM performance with AWGN and multipath for different number of active users.

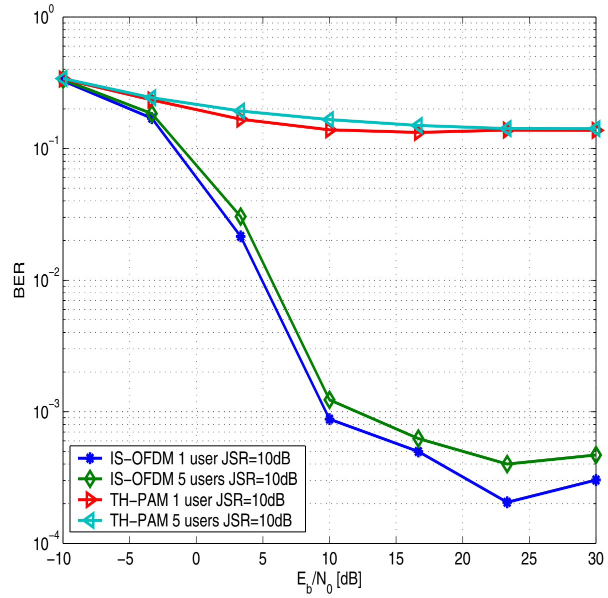

Fig. 3. IS-OFDM and TH-PAM performance with AWGN, narrowband jammer (JSR = 10 dB), and different number of active users.

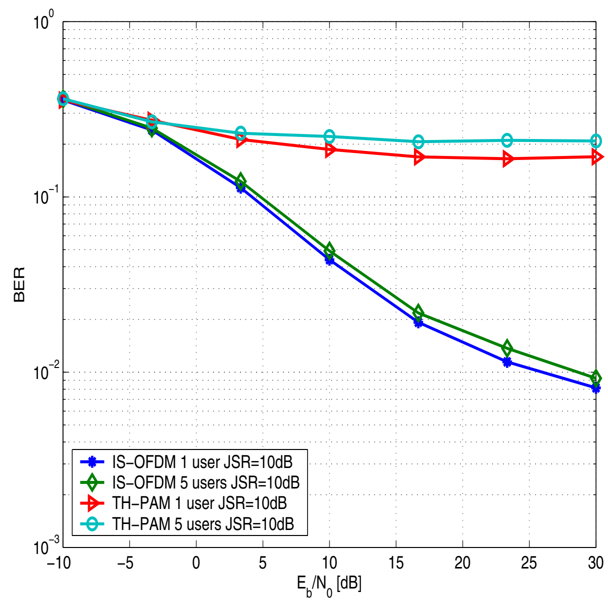

Fig. 4. IS-OFDM and TH-PAM performance with AWGN and multipath, narrowband jammer (JSR = 10 dB), and different number of active users.

model [16]. This model, which was selected for the IEEE 802.15.3a standard and was also used in other recent work dealing with UWB communication systems [17], consists of *clusters of multipath rays* with cluster arrival rates that have a Poisson distribution and rays within a cluster having ray arrival rates that are also Poisson distributed. By combining all rays that are within the multipath resolution time T_c an equivalent discrete-time channel impulse response is obtained, with L paths spaced at time intervals equal to T_c described by equivalent path gains. In our simulations we used the numerical values associated with the **CM 1** model in [9].

The narrowband interference signal used in simulations had a bandwidth of 5 MHz, and was generated using a linear bandpass FIR filter driven by white Gaussian noise with unit variance at the input.

B. Numerical Results

We have first looked at the BER performance of the TH-PAM IR and of the IS-OFDM UWB system in the presence of AWGN only for different number of active users, for which results are plotted in Figure 1. For a single user the BER curves for the two systems overlap, indicating that TH-PAM IR and IS-OFDM UWB systems have almost identical performance. With more active users the IS-OFDM UWB system displays better BER performance: its corresponding BER curve in Figure 1 is almost identical to the single-user curve, while the BER curve for the TH-PAM IR system is more distanced.

We looked next at the BER performance of the two systems with AWGN and multipath channel for different number of active users. The results of this experiment are plotted in Figure 2. We note that in this case the TH-PAM IR system outperforms the IS-OFDM UWB system as indicated by [18]. However, as can be observed from Figure 2, the BER curves for the IS-OFDM UWB system for 1 and 5 users come very close to each other as opposed to the corresponding curves for the TH-PAM IR system which are more distant, indicating that the IS-OFDM UWB system continues to be less sensitive to the presence of more users in the system.

We have also looked at the performance of the two systems in the presence of narrowband interference for different number of active users. The results of this experiment are plotted in Figure 3 for the case of AWGN only, and Figure 4 for the case of AWGN and multipath channel. A jammer-to-signal ratio (JSR) of 10 dB was assumed in both cases. In this case we note that for both systems the presence of narrowband interference introduces an error floor beyond which the BER can no longer be decreased by increasing E_b/N_0. However, the IS-OFDM UWB system outperforms the TH-PAM IR system in this case, as the error floor occurs at lower values in the case of the IS-OFDM UWB system compared to that for TH-PAM IR system.

IV. Discussions and Conclusions

In this paper we presented a side-by-side comparison between TH-PAM IR and IS-OFDM systems proposed for use in UWB wireless networking applications. The performance criterion used in our comparison is the raw BER at the physical layer after demodulation/detection, and was obtained from simulations in various scenarios that are include AWGN, multipath and/or multiple access interference, as well as narrowband interference.

Results of our analysis are mixed, and do not place one of the systems investigated at a clear advantage over the other. This is unlike our previous study [15] which has indicated that IS-OFDM UWB systems outperform TH-PPM IR UWB systems in all scenarios.

Overall, current results indicate that for AWGN only, the IS-OFDM and TH-PPM IR UWB systems with MMSE receivers have similar performance, with the TH-PPM IR system being more sensitive to increasing number of users than the IS-OFDM UWB system. However, in the case of AWGN and multipath the TH-PAM IR system outperforms the IS-OFDM UWB system, as suggested by [18]. This is explained by the fact that the MMSE receiver for TH-PAM IR incorporates optimal multipath combining in addition to mitigating multiple access interference (MAI) as discussed in [5], while the MMSE receiver for the IS-OFDM UWB system is designed to mitigate MAI only. In contrast, in the presence of narrowband interference the IS-OFDM system outperforms the TH-PAM IR system, which is explained by the inherent resistance against narrowband interference that is built in the IS-OFDM UWB system by the interference suppressing scheme in [6], and which is not present in the TH-PAM IR system. Furthermore, the IS-OFDM UWB system with MMSE receiver is less sensitive to the presence of more active users in the system in the case of both multipath and narrowband interference scenarios.

We conclude our study by noting that selection of the UWB system to be used in conjunction with a specific wireless networking application should explicitly take into account the operating environment and the presence of multipath versus narrowband interference, in addition to other factors like specific BER performance or implementation complexity.

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