# Multi-Band OFDM-Based UWB System with Multiple Users and Interference Mitigation

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***Abstract*—In this paper we present a multiuser multiband OFDM-based UWB system with interference mitigation capabilities. The proposed system combines the single band interference suppressing (IS) OFDM UWB system with time-frequency (TF) interleaving to enable symbol transmission in multiple bands along with multiaccess capabilities. Bit error rate (BER) performance of the proposed system is illustrated with numerical results obtained from simulations for various scenarios that include multiple users and narrowband interference.**

## I. INTRODUCTION

Ultra Wideband (UWB) technology has been used for over 40 years in military radar applications requiring precision ranging/localization, high data throughput, and multipath immunity. Recently, UWB systems have become of interest also for commercial applications in the areas of wireless networking for consumer electronics, vehicle collision detection and avoidance systems, or warehouse inventory tracking [1], [6]. In these emerging applications operation of the UWB radios is in a multiuser/multiaccess context and is subject also to interference coming from the existing narrowband systems like cellular telephones and wireless networks. Thus, an important challenge facing UWB system designers is mitigation of both multiaccess interference (MAI) and narrowband interference (NBI).

We note that two main approaches have been proposed in the literature for the design of UWB systems: one that is based on transmission of extremely short, carrierless pulses, and another that is based on Orthogonal Frequency Division Multiplexing (OFDM). In the former category we have the impulse radio (IR) systems [7], [13], [14], and in the latter we have the single band systems in [5], [10] as well as the multiband systems in [2], [8], [9].

According to the Multiband OFDM Alliance CITE the 7.5 GHz bandwidth available for UWB systems (3.1 to 10.6 GHz) is divided in 14 bands of 528 MHz each and is intended to enable selective implementation of bands at certain frequency ranges while leaving other parts of the spectrum unused in order to adapt to regulatory constraints imposed by different government agencies around the world.

In our paper we discuss extension of the single band IS-OFDM UWB system designed for single user (point-to-point) transmission in [5] to multiple bands and multiuser scenarios. This is done by employing a TF interleaving scheme that uses TF codes (TFCs) similar to those used in time-hopping (TH) impulse radio (IR) UWB systems [13], [14]. Performance of the proposed scheme is illustrated with numerical results obtained from simulations that display the raw BER at the physical layer observed after demodulation/detection of the UWB signal at the receiver.

The paper is organized as follows: in Section II we present the system model followed by a discussion of the TFCs for multiple access and interference mitigation in Section III. In Section IV we present numerical results obtained from simulations that illustrate the raw BER performance of the system for various scenarios and we conclude with final remarks in Section V.

## II. MULTI-BAND IS-OFDM UWB SYSTEM DESCRIPTION

The multiband IS-OFDM UWB system discussed here consists of a combination of the single band IS-OFDM UWB system [5] with a time-frequency interleaving scheme discussed in [2], [8], [9]. The corresponding block diagrams of the transmitter and receiver are shown schematically in Figures 1 and 2. At the transmitter QPSK modulation is used to map data bits into complex symbols, which are then serial-to-parallel (S/P) converted and modulated by the IS-OFDM transmitter block followed by addition of the cyclic prefix parallel-to-serial (P/S) and digital-to-analog (D/A) conversion to yield a UWB signal with 528 MHz bandwidth. Prior to transmission over the air the time-domain signal obtained is modulated to the center frequency that corresponds to the particular band in which the OFDM symbol is transmitted. The band changes for each OFDM symbol according to a specified TFC that is assigned to the user. At the receiver the TFC code is used in the reverse process performed to decode the transmitted data bits. For block diagrams of the IS-OFDM transmitter and receiver and more specific details we refer the reader to [5].

We note that the single band IS-OFDM UWB system provides improved performance in the presence of NBI by dividing the frame of bits that makes up the OFDM symbol into sub-blocks and transmitting all symbols in a sub-block over multiple sub-carriers. The IS-OFDM scheme outperforms the conventional OFDM scheme in the presence of NBI signals [5], [11] and was also used in single band multiuser scenarios in conjunction with a multicarrier CDMA scheme and multiuser receivers [10].

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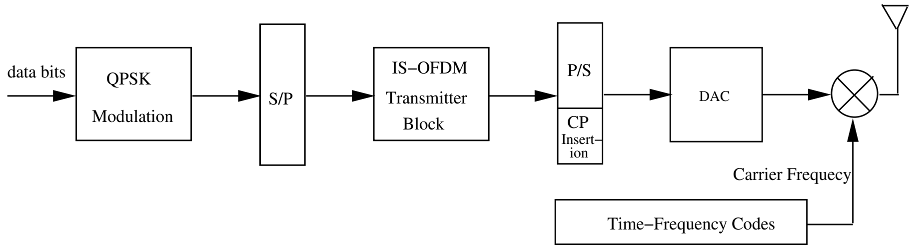


Fig. 1. MB-OFDM UWB Transmitter with IS-OFDM modulator.

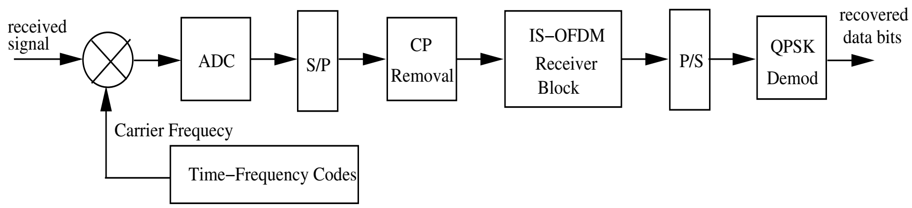


Fig. 2. MB-OFDM UWB Receiver with IS-OFDM demodulator.

## III. Time-Frequency Codes for Multiple Access and Interference Mitigation

The use of different TFCs for distinct users provides the multiple access capabilities needed to operate in a multiuser scenario, and the signal transmitted by a given user can only be decoded if its assigned TFC is known at the receiver so that the receiver is able to track the bands in which the desired signal is transmitted for demodulation/decoding. The TFCs determine also the probability of two or more users transmitting simultaneously in the same band. We note that this situation is similar to the case of UWB systems using TH IR based on pulse position modulation (PPM) [13], [14] where the TH sequences assigned to users determine the time instances when monopulses corresponding to different users occur. Since the use of TFCs which minimize the probability of two or more users' transmissions colliding in one band is desired we will use as TFCs in the proposed multiband IS-OFDM UWB system sequences similar to those used in TH-PPM UWB systems which have good multiacces properties. Among these we note the orthogonal Gold codes which have been shown to provide good performance in both TH-PPM and DS-BPSK UWB systems [3].

For a given TFC specified by a sequence of binary digits "0" and "1", the corresponding TF interleaving pattern is obtained by using a sliding window technique as discussed in [3] and shown schematically in Figure 3:

- **Step 1:** The TFC is selected from the set of available codes. We note that Gold codes are obtained using maximal length sequences (M-sequences) which are generated by linear shift registers. For a register of size $n$ the maximum possible period is $2^n - 1$. In Figure 3 and the numerical simulations we choose $n = 3$ which implies a total of 7 binary sequences of length 7.
- **Step 2:** A size $w$ for the sliding window is selected, the corresponding window elements are converted to decimal, and the window is shifted to the right by one bit.

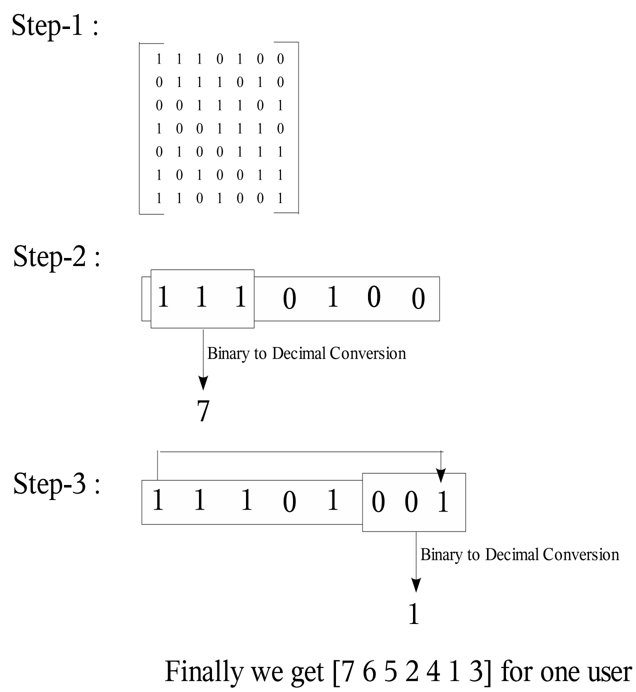


Fig. 3. Generation of the TF interleaving pattern from a binary TFC for the multiband IS-OFDM UWB system.

- **Step 3:** Once the end of the binary sequence is reached the shift is performed circularly and any missing bits in the window are taken from the begining of the sequence to complete the TF interleaving pattern corresponding to the chosen code. In Figure 3 and the numerical simulations we choose window length $w = 3$ resulting in length 7 decimal TF interleaving patterns.

## IV. Simulations and Numerical Results

In order to investigate performance of the proposed multi-band IS-OFDM UWB system we have performed numerical simulations for various scenarios and looked at the raw BER at the physical layer after demodulation/detection without considering any error correction techniques. We note that the use of error correction will only improve the raw BER observed after detection/demodulation.

### *A. Simulation Setup*

The UWB system bandwidth considered in our simulations was of 528 MHz and is divided into $\tilde{N} = 512$ parallel channels that are split into $L = 8$ IS-OFDM groups, each group using $\tilde{M} = 64$ carriers with correlation receivers (matched filters – MF) for each carrier as discussed in [5].

The TFC used are orthogonal Gold sequences of length 7 and the TF interleaving patterns are obtained using a sliding window of length 3 as discussed in the previous section.

In order to simulate multipath propagation we used the channel model in [2], which is based on the Saleh-Valenzuela model [12]. 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 [4], 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 [2]. This model describes short range (0 – 4 m) line-of-sight environments for local networking applications and was used in other recent studies of OFDM-based UWB systems [15].

The NBI signal used in simulations had a bandwidth of 10 MHz and was generated as in [5] using a linear bandpass FIR filter driven by white Gaussian noise with unit variance at the input. The NBI signal was assumed to be active only in band 1 of frequencies.

### *B. Multiuser Performance*

In this experiment we considered increasing number of users in the system and compared the performance of the proposed multiband IS-ODM UWB system with that of the single band IS-OFDM UWB system with multiuser detectors in [10]. Results of this experiment are presented in Figure 4 from which we note that for AWGN only the multi-band system with matched filters (MF) in the receiver has slightly better performance than the single band system with MMSE receivers. The BER for the multiband system is almost identical to the single user performance and is essentially insensitive to the increasing number of users in the system. This is due to the fact that even though multiple users are active they transmit their corresponding symbols in distinct frequency bands and the probability of colliding transmissions in a given band is very low.

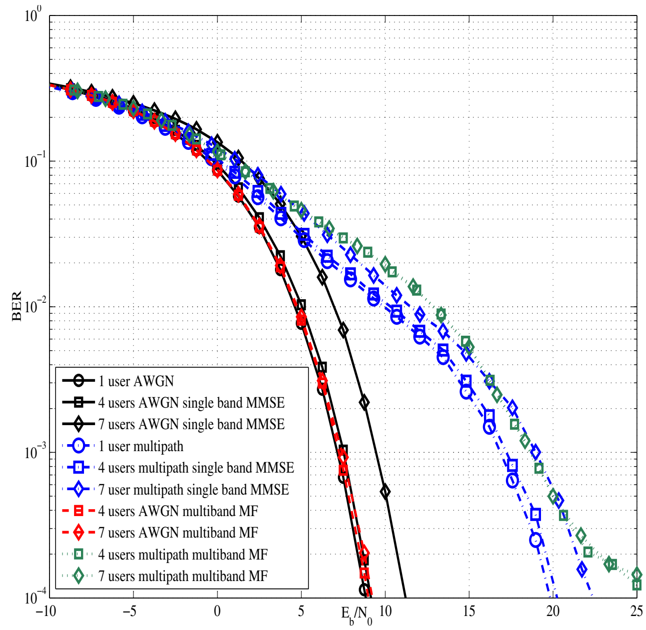


Fig. 4. BER vs. $E_b/N_0$ for the single- and multi-band IS-OFDM UWB system with AWGN and multipath channels.

However, in the case of multipath channels, the single band system with MMSE receivers has slightly better performance which is due to the fact that in this case the MMSE receiver uses channel information in deriving MMSE estimates of the transmitted symbols as discussed in [10].

### *C. Performance in the Presence of NBI*

In this experiment we consider that a narrowband jammer is active in band 1 and compare again the performance of the proposed multiband system with that of the similar single band system in [10] for different numbers of active users and Jammer-to-Signal-ratio (JSR) values. Results of this experiment are presented in Figure 5 for the 1 user case, respectively Figure 6 for the 4 user case, and we note that in the presence of NBI both systems display an error floor beyond which the BER can no longer be decreased by increasing $E_b/N_0$. However, the multiband system outperforms the single band one as the error floor occurs at lower values for the multiband system. For the examples in Figures 5 and 6 the BER floor for the multiband system is about 3 – 5 times lower than for the single band system. This was expected as for the multiband system the transmitted information is just occasionally corrupted by NBI (only when the TF interleaving pattern indicates that the band where NBI is active will be used) whereas for the single band system all transmitted symbols will be corrupted by NBI.

We also note that the multiband system appears to be less sensitive to the number of active users in the system as the BER values for the 1 and 4 user multiband systems in the corresponding plots in Figures 5 and 6 are very close to each other.

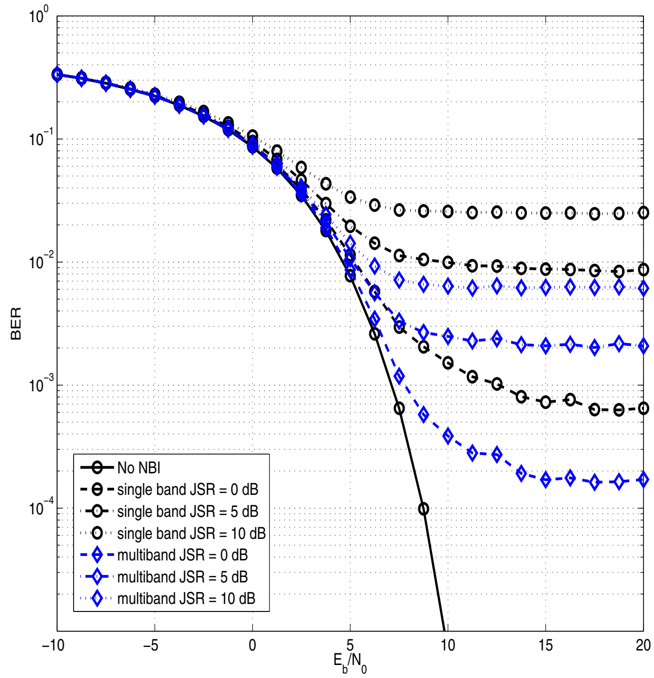


Fig. 5. BER vs. $E_b/N_0$ for a single user single- and multi-band IS-OFDM UWB system with AWGN and NBI.

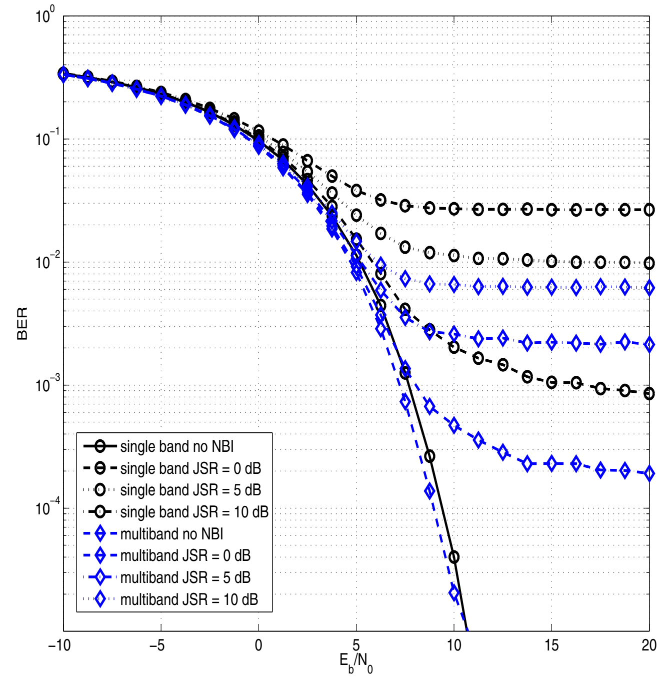


Fig. 6. BER vs. $E_b/N_0$ for a 4-user single- and multi-band IS-OFDM UWB system with AWGN and NBI.

## V. CONCLUSIONS

In this paper we discussed extension of the single band single user IS-OFDM UWB system in [5] to multiple bands multiuser scenarios. This is based on the use of a TF interleaving scheme which provides multiple access capabilities and reduces the effects of fixed NBI signals that occur in a single band as is the case with narrowband legacy systems such as cellular telephones or wireless LANs.

BER performance of the proposed system was illustrated with numerical results obtained from simulations and was also compared with that of the single band IS-OFDM UWB system with multple users and MMSE multiuser receivers.

Performance of the proposed system may be further improved by application the narrowband interference avoidance (NBIA) method discussed in [11] which will be the object of future research.

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