Design and Implementation of Spectrally-Encoded Spread-Time CDMA Transceiver

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***Abstract*—In this paper, we present and discuss the physical implementation and testing of a Spectrally-Encoded Spread-Time Code Devision Multiple Access (SE/ST-CDMA) transceiver. The proposed design is suitable for multiple-access and anti jamming wireless communication systems. The design and implementation takes into account the ability to automatically detect and mitigate tone jammers by altering the corresponding Gold sequence codes assigned uniquely to each user and setting the corresponding code's chip to zero. A simple real-time anti jamming mechanism capable of dealing with frequency hopping jammers is also proposed. The simulation results are provided in terms of Bit Error Rate (BER) versus Signal to Noise Ratio (SNR) in one case and the number of multi tone jammers in another, both conditioned on the number of users. Finally, the experimental and simulation results are compared and we observe that they are in a very good agreement.**

***Index Terms*—Gold sequence, spectrally-encoded spread-time CDMA (SE/ST-CDMA), anti jamming, multi tone jammer.**

I. Introduction

THE usage of radio spectrum in wireless communication as a highly valued resource, has drawn the attention of many communication theorists and engineers for many years to maximize its utilization using spectrally efficient multiplexing techniques. In wireless communications, CDMA based systems enjoy many superior features when compared with systems based on other multiple access techniques.

Among various CDMA techniques, Spectrally-Encoded Spread-Time (SE/ST) is one of the most robust and spectrally efficient CDMA technique [1-7]. This technique is an alternative multiple access scheme to Direct-Sequence Spread-Spectrum (DS/SS)-CDMA and is considered as the time-frequency dual of DS/SS-CDMA. In SE/ST-CDMA, the signature sequence associated with each user is directly applied in the spectral domain of the transmitted pulse, whereas in DS/SS-CDMA it is applied in the time domain of the transmitted pulse. Using the spectral domain, pulse shaping can be applied easily and more flexibly by proper manipulation of the amplitudes and phases of various spectral components of the corresponding SE/ST signals. Consequently, in DS/SS-CDMA, the signal energy is spread in the frequency domain, whereas the SE/ST-CDMA spreads the energy of the corresponding data pulses in the time domain. In SE/ST-CDMA technique, the original spectrum of data pulse is multiplied by a Gold sequence in frequency domain followed by the inverse Fourier transform in such a way that the resulting pulse is spread in time domain. This noise-like signal in time domain would cause SE/ST technique to be unrecognizable with respect to devices such as edge detector.

At the receiver, the desired data is obtained by sampling the output of a filter matched to the user's pulse [2]. It has been shown in [2], [6] that the SE/ST-CDMA technique has a superior performance than the DS/SS-CDMA in Additive White Gaussian Noise (AWGN) and fading channels. It also has been pointed out in [6] that the SE/ST technique can be useful for Ultra Wide-Band (UWB) systems, because the spreading in time domain reduces the effective instantaneous power of the transmitted signal. This causes the RF system to work on linear regions of operational amplifiers, hence, decreasing its complexity and cost.

However, the main advantage of SE/ST is in its ability in matching the transmitted spectrum with the channel characteristic, such as when the channel is formed by disjoint frequency bands, which is rather difficult to achieve by the time domain pulse shaping in DS/SS-CDMA technique [2]. The direct application of SE/ST technique to the transmission channels with disjoint or non-contiguous frequency band allocation had been highlighted in [2], [6]. This feature is vital in UWB communication systems [8], [9], especially when encountering multiple interferences and disjoint spectrum allocation mask, which is typical in most UWB environments [7].

The inherent flexibility in the spectral shaping and spectrum management in the SE/ST technique is an efficient solution in alleviating Narrow Band Interference (NBI) which can severely degrade the performance of UWB communication systems [10], [11]. In the SE/ST-CDMA, it is possible to dynamically suppress strong NBIs by simply setting the relative chips amplitude in the corresponding user's spectral code to zero. In [7], the effect of imperfect channel estimation of UWB systems in the presences of the NBI for the SE/ST-CDMA and DS/SS-CDMA systems are analyzed. Furthermore, in [12] the authors have made comparisons with respect to the similarities and dissimilarities of multi carrier CDMA and the SE/ST-CDMA.

In this paper we present the implementation and the testing of the performance of an asynchronous SE/ST-CDMA system in the presence of multi access and multi tone jammer. Finally, BER performance is calculated and compared with respect to the experimental and simulation results versus SNR in one

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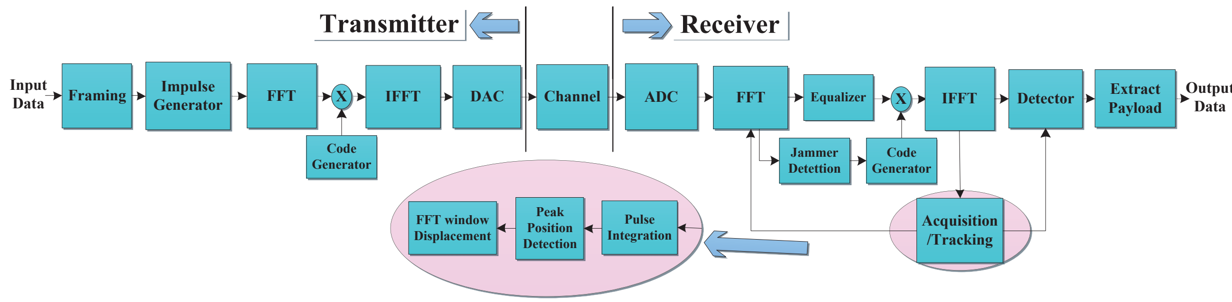


Fig. 1. Block diagram of the implemented SE/ST-CDMA system.

case and the number of multi tone jammers in another, both conditioned on the number of users.

The rest of the paper is organized as follows. In Section II, we describe the design details and experimental setup for the implementation of SE/ST-CDMA system. In Section III, the multiple-access and anti jamming performance of the system is discussed. Experimental and simulation results and discussions are presented in Section IV. Section V summarizes the paper and presents the conclusion.

II. Experimental Design Setup

The transmitter uses a 256-point Fast Fourier Transform (FFT) and Inverse FFT (IFFT). Each subcarrier occupies 400 kHz bandwidth, leading to the total bandwidth of 102.4 MHz. Considering Hermitian symmetry there will be 128 available subcarriers, one of which has zero value, thus, Gold sequences with length 127 are used for encoding and decoding.

The block diagram of the transmitter and receiver scheme for the implemented SE/ST-CDMA system is presented in Figure 1. At the transmitter side an impulse generator is used to generate the impulse signal, then using the FFT/IFFT modules the code is applied upon the pulse in frequency domain. The output of IFFT is followed by Digital to Analog Converter (DAC) and the analog output signal is transmitted through the channel. At the receiver side, the Analog to Digital Converter (ADC) brings the digital received signal to IFFT/FFT modules which are used to perform the decoding in the frequency domain and recover the desired signal. Prior to the code multiplier a frequency domain equalizer can be used to compensate the channel effects. As shown in Figure 1 an acquisition/tracking unit is used for FFT window synchronization. This block uses pulse integrator and peak detector to place FFT window in a position such that the peak is maximized. Finally, different headers (Cyclic Redundancy Check (CRC), Pilots, etc.) are dropped and the payload is extracted.

Figure 2 shows the time and frequency domain representations of the Gaussian shaped input pulse and the spectrally encoded signal at the transmitter. The signal is encoded by a Gold sequence, which is uniquely assigned to each user. As a result of this procedure, the input pulse is spread in the time domain and the output is a noise-like signal. Figure 2 (a) and (b) represent the time domain signal before and after spectral encoding, respectively. The frequency domain counterpart is shown in Figure 2 (c) and (d). At the receiver, by applying the complex conjugate of the same spectral code to signal in frequency domain the original ultra-short time domain pulse will be recovered, while the signals of other users, which are spread by different Gold sequence codes, will remain spread in time domain.

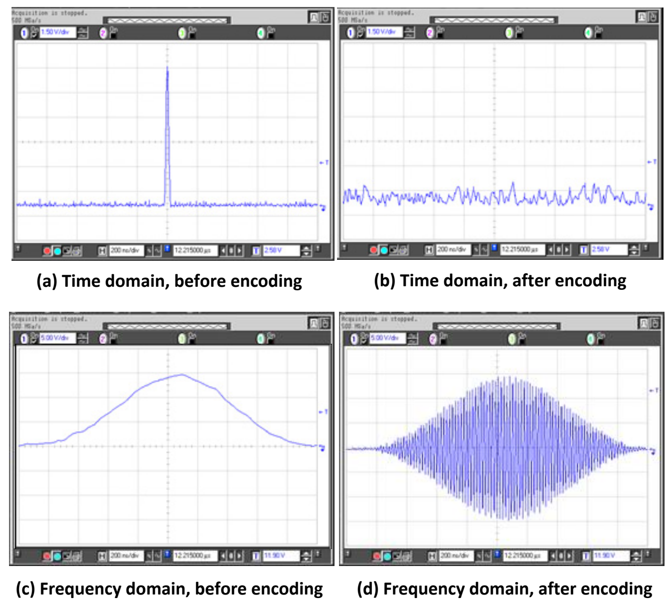


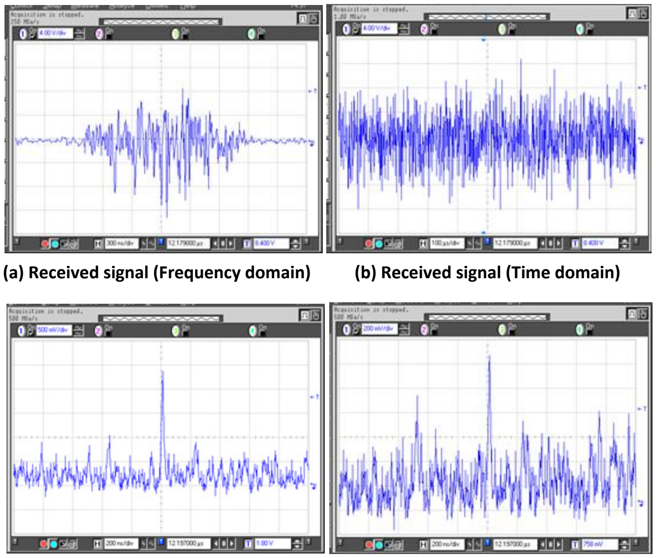
Fig. 2. Transmitted signal's time and frequency domain representation before and after the spectral encoder at the transmitter.

Another, essential block is the jammer detector block that uses the output of the FFT block at the receiver to detect any kind of NBI by a simple amplitude threshold on each frequency chip. The output of this block is used in the code generation block to reduce the corresponding chip level signal to zero in order to eliminate the NBI. Since this operation is implemented in real time, the system is capable of detecting and eliminating multi tone frequency hopping jammers, which is another very important advantage of the implemented SE/ST-CDMA system.

III. SE/ST Performance

A. *Multiple-access*

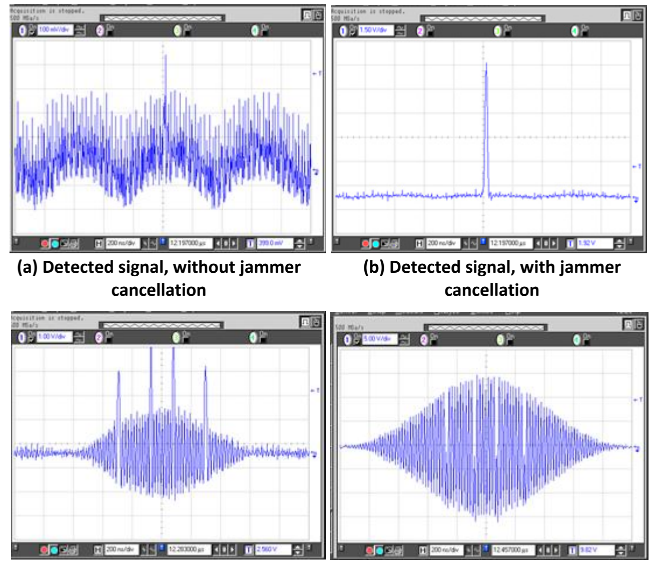
In this Subsection we discuss the performance of an SE/ST-CDMA system taking into account the multi access communications scenario. The frequency and time domain signal in a multi access scenario with 16 active interference users are illustrated in Figures 3 (a) and (b), respectively. As demonstrated in these figures the multi access effect causes the signal's spectrum to lose its soft shaping, and the power of the noise-like time domain signal is increased. Also, the output of the detector for 10 and 16 interfering users are shown in Figures 3 (c) and (d), respectively. In the detected signal,



(a) Received signal (Frequency domain) (b) Received signal (Time domain)

(c) Detected signal (10 active users) (d) Detected signal (16 active users)

Fig. 3. Signal representations showing the multi user performance of the implemented SE/ST-CDMA system.



(a) Detected signal, without jammer cancellation (b) Detected signal, with jammer cancellation

(c) Received spectrum, without jammer cancellation (d) Received spectrum, with jammer cancellation

Fig. 4. Signal representations showing the jammer cancellation performance in the implemented SE/ST-CDMA system.

the multi access effect appears as the background noise, the power of which increases as the number of users increases. It is apparent from this figure that in the 10 interference users scenario the main peak in the desired time domain signal is still detectable. However, in the 16 interference users scenario the detection is less likely compared to the previous case. The interference signals could easily lead to errors in the detection procedure. A detailed discussions and results of the system performance with different number of users is provided in Section IV.

B. Anti jamming

In this Subsection we examine the capability of the proposed SE/ST-CDMA system in eliminating the NBIs, such as tone jammers. The flexibility in spectrum shaping of the SE/ST technique makes it possible to dynamically suppress strong NBIs as soon as they are sensed. In such cases, the jammers could be detected using a thresholding mechanism at the output of the FFT block and their effects could be eliminated by setting the corresponding chips of the spectral codes to zero. Setting the amount of jammer detection threshold is a critical procedure. If the threshold is too high, the tone jammers get included, and if it is too low, many frequency chips are zeroed. Hence, the amplitude threshold in each chip is set at twice the expected value of the amplitude in that chip, as estimated from the adjacent frequency chips. This scheme competes against the more traditional DS/SS CDMA very well, since it is much more effective and easier to implement. In fact, in this way we essentially remove the jammer's influence, while in DS/SS CDMA we merely reduce it, by multiplying by a random code sequence.

Figure 4 illustrates the concept of jammer cancellation in the implemented SE/ST-CDMA system. Figures 4 (a) and (c) show the detected signal in the time domain, and the received signal's spectrum, in the presence of four tone jammers, respectively. From these figures it can be deduced that the tone jammers have caused the time domain signal to ride on a periodic function comprising of several sinusoid signals. However, in the frequency domain the spectrum is added with some impulses indicating the spectral positions of the tone jammers. The detected signal in the time domain and the received signal's spectrum after applying the software based anti jamming capabilities are shown in Figure 4 (b) and (d), respectively. From this figures we can observe that while in the frequency domain the chips with jammers are set to zero, in the time domain loosing a few chips power is barely recognizable. Undoubtedly, these figures, imply that the SE/ST technique shows robustness in performance when dealing with tone jammers. Furthermore, with the help of the real time software based anti jamming programming, also frequency hopping jammers can be easily detected and omitted as well.

IV. Experimental and Simulation Results

A. Simulation structure

In this Section we simulate the SE/ST-CDMA system performance in the presence of the multi user and multi tone jammers signals, taking into account the AWGN channel model in order to compare with the experimental results in the physical baseband implementation. It is necessary to mention that 10^7 symbols are simulated, which indicates that the BER levels higher than 10^{-5} are valid. The physical SNR used in the experimental implementation is about 35 dB, and to model various amount of E_b/N_0, an additive noise is added to the received signal in the receiver. In obtaining Figure 6, the SNR for this additive noise source is set to 10dB.

B. Results

Figure 5 represents the experimental and simulation results for the BER versus SNR for three different number of users. The solid lines represent simulation results and the dots stand for the experimentally obtained BER values under the same parameters. Various curves in the figure imply an excellent agreement between the experimental and simulation results. It is easily observed that, in general, increasing the number of users degrade the BER performance. Furthermore, the Forward

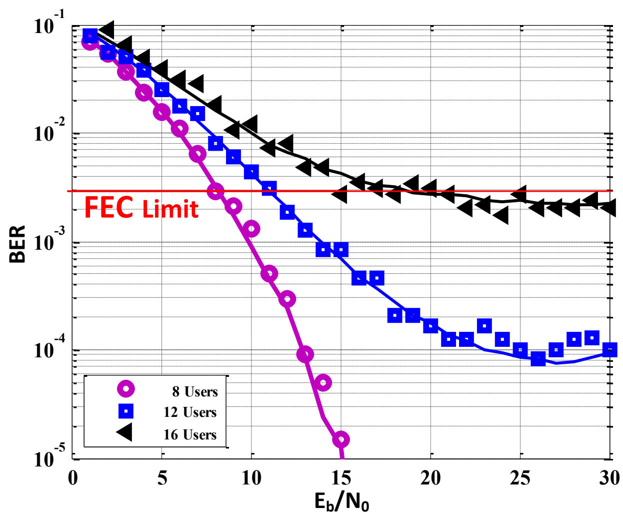


Fig. 5. BER performance versus E_b/N_0 with different number of users (solid lines: simulation, dots: experimental).

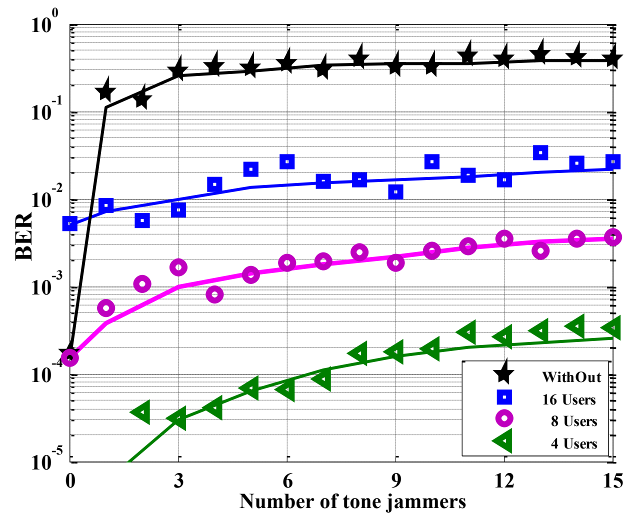


Fig. 6. BER versus the number of jammers for three different number of users, the performance of eight users scenario without jammer cancellation is also shown. (solid lines: simulation, dots: experimental).

Error Correction (FEC) limit, i.e, 3×10^{-3}, is shown by a horizontal line. Considering this limit one can see that in 8, 11 and 18 dB SNRs the system can support up to 8, 12 and 16 simultaneous users, respectively. In Figure 5, for the case of 12 and 16 users, the BER saturation is due to the fact that user interference is the main noise component in these BER-SNR range. Therefore, by increasing E_b/N_0, the BER does not improve any further.

Figure 6 represents the BER versus the number of multi tone jammer signals conditioned for three different number of users, with and without the automatic multi tone jammer cancellation module. In general, tone jammer effect depends on its fundamental frequency, bandwidth, and the power of the jammer. By applying the anti jammer mechanism, the corresponding chips, where the jammers occur, are set to zero, thus, the jammer's power is not the critical parameter. In our experimental demonstration the jammer bandwidth is less than the frequency chip length and the frequency of jammers is selected randomly. Thus, the only concerning parameter is the number of jammers. It is noteworthy to mention that in the scenario without jammer cancellation, the jammer power is set equal to the total symbol power and only the 8 user scenario is presented in Figure 6 in order to show and compare the significant performance improvement of the jammer cancellation unit. In addition to reveal the excellent agreement between the experimental and simulation results, this figure shows a significant performance improvement caused by the automatic jammer cancellation unit. When the number of jammers are higher, the system performance is slightly degraded which is a result of significant reduction in the desired signal energy.

V. Conclusion

In this paper, we present the physical baseband implementation and testing of an SE/ST-CDMA transceiver suitable for multi user and anti jamming wireless communication systems. The proposed system is able to automatically detect and mitigate the tone jammers influence by changing the Gold sequence codes and setting the chip level of the corresponding code to zero. Results indicate that the proposed system performs well in AWGN channels and in the presence of the multi tone jammers and multi user interference. A simple real-time mechanism capable of dealing with the frequency hopping jammers is also proposed. The simulation results were provided in showing BER versus E_b/N_0 and number of jammers, for different number of users. It was shown that it is in an excellent agreement with the experimentally obtained BERs.

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