New Trends Towards Speedy IR-UWB Techniques

Marwa M.El-Gamal*, Shawki Shaaban**, Moustafa H. Aly***

* College of Engineering and Technology, Arab Academy for Science & Technology & Maritime Transport
** Faculty of Engineering, University of Alexandria

Abstract

Wireless communications have been dominated by transmission schemes based on conventional narrowband technology. Therefore, narrowband systems are unable to increase higher data-rates in wireless communication applications, which cause Inter Symbol Interference (ISI) due to multipath fading phenomenon that can be resolved at the receivers. Several implementation schemes for Impulse-Radio (IR) Ultra-Wide Band (UWB) systems have been presented. These include methods such as Transmit Reference (TR) and Frequency-Shifted Reference (FSR), which can overcome the complexity of channel estimation by transmitting reference pulses separated by a shift in time and frequency, respectively. Code-Shifted Reference (CSR) has been proposed for IR-UWB transmission. The CSR scheme with UWB systems has been found to achieve a better performance than the previous schemes. In order to improve system performance, the CSR scheme was extended to the Differential CSR (DSCR) to reduce the power used to transmit the reference pulse sequence. This Paper includes the methods of Rake Receiver, TR, Frequency-Shift Reference (FSR), emerging CSR and DCSR. A brief discussion is given for each method followed by a performance comparison between DCSR and CSR, TR and FSR Rake methods.

I. INTRODUCTION

In the world of wireless communications, UWB is considered an attractive technology for its high capacity, high data rates, low fading, low interference to and from other wireless systems, easier wall-and floor penetration, and inherent security, low power consumption, low cost and low-complexity devices. In spite of all the benefits of UWB, the extremely wide frequency bands (at least greater than 500 MHz) and exceptionally narrow pulses (in the range of few hundred picoseconds) make it difficult to apply conventional narrowband modulation techniques into UWB systems [1]. Wireless communications have different transmission schemes based on narrowband technology. The challenge faced by narrowband transmission results from its limited bandwidth, which has the direct effect of limiting the transmission capacity. Therefore, narrowband systems are unable to accommodate the increasing need of higher data-rates in wireless communications applications. Providing a solution to the problem of bandwidth limitation, UWB technology has recently received a significant amount of attention in the field of wireless communications. Although UWB is not a new concept, having been used for several years for military applications, the Federal Communications Commission’s (FCC) approval of an unlicensed UWB spectrum for wireless communications has opened up new potentials in this field, sparking the interest of both industry and academia. In comparison to narrowband transmission, UWB technology spreads the signal over a very wide range of frequencies by means of transmitting ultra-short duration pulses on the order of nanoseconds. This enables transmission speeds of several hundred Mbps, accommodating the high data-rate demands of current and future wireless systems. In addition to the advantage of higher data-rates, the reason for UWB of popularity in the wireless field lies in the many other benefits it offers, including low-cost, low transmit power, low complexity, low power consumption, and low probability of detection and interference.

UWB systems can be characterized as an extension of traditional spread spectrum (SS) systems. One of the major differences between UWB systems and traditional SS systems is the radio channel which they use. The UWB channel is extremely multipath rich. The multipath components that are combined increase the total signal power. The multipath components that are not combined lead to interference. The significantly greater number of resolvable multipath components associated with UWB system’s much greater bandwidth means that many more receiver elements need to be considered. There are some of the more popular receiver structures for UWB systems, particularly the rake and modifications of the rake [2].

Over the years, several implementation schemes for IR-UWB systems have been presented. Most notably, these include methods such as Transmit Reference (TR) and Frequency-Shifted Reference (FSR), which have overcome the complexity of channel estimation by transmitting reference pulses to be used as a template for
extracting the data pulse. In these methods, this reference pulse is separated from the data pulse by a shift in time and frequency, respectively [3].

Recently, the scheme of Code-Shifted Reference (CSR) has been proposed for IR-UWB transmission. In the proposed CSR scheme, rather than being separated by time (TR) or by frequency (FSR), the reference and data pulse sequences are separated by codes [3]. The CSR scheme overcomes the technical challenges encountered by other UWB systems, given that it does not require explicit channel estimation, a wideband delay element, or separation of reference and data pulse by analog carriers. As a result, it has reduced system complexity and has been found to achieve a better performance than the previous schemes [4].

II. IMPLEMENTATION SCHEMES FOR IR-UWB

1. Rake Receiver Types

1.1 All-rake (A-rake) or Ideal rake (I-rake)

A common receiver structure is that of the Rake Receiver, also called the all-rake (A-rake) [5]. The Rake Receiver is able to combine the received signal energy in all of the multipath components (MPCs) of the signal, which in turn will increase the signal-to-noise ratio (SNR) and improve the performance of the system. The general structure of the Rake Receiver, Fig. 1, requires that a detecting finger be available for each resolvable MPC. Each of these detecting fingers requires channel estimation, multipath acquisition, and tracking operations in order to match the amplitude, phase and delay of each MPC [3].

![Fig.1 General Rake receiver structure (with 2 MPCs) [6].](image)

1.2 The Selective Rake Receiver (S-rake)

A more practical implementation of the Rake Receiver is known as the Selective Rake Receiver (S-rake) [5], which only combines those MPCs with the strongest energies. This is far less complex than the A-rake receiver, as less detecting fingers are required, due to the reduced number of MPCs to capture. However, the S-rake receiver trades off complexity for performance [5].

One of the main advantages of UWB signals is their immunity to multipath fading. Within a multipath environment, the received IR-UWB signal may consist of a large number of resolvable MPCs. Therefore, even when the S-rake receiver is considered for UWB transmission, the complexity and cost needed to resolve these MPCs may be high due to the large number of detecting fingers, and the channel estimation, multipath acquisition, and tracking operations required for each finger.

1.3 A practical rake receiver (P-rake)

The partial-rake receiver, P-rake, is a simplified approximation to the S-rake. The P-rake involves combining the first propagation paths. The principle behind this approach is that, the first multipath components will typically be the strongest and contains the most of the received signal power. The disadvantage is that, the multipath components that the P-rake receiver combines are not necessarily the strongest multipath components. So, optimum performance will not be achieved. These are illustrated in Figs. 2-4 [2].
Comparison

Under ideal conditions, the A-rake outperforms the S-rake, which typically outperforms the P-rake. However, if the strongest propagation paths are at the beginning of the channel impulse response, the S-rake and P-rake will give the same performance [2]. The energy collected by the P-rake is tens of decibels less than the energy collected by the S-rake, which uses the strongest paths. The single-path S-rake uses the strongest path, so, it has significantly a better performance than the single-path P-rake. The system performance of A-rake is not as good as the ideal system performance in the AWGN channel because of the limited delay resolution of the A-rake receiver [2].

Figure 5 displays the difference between types of rake receiver by using Matlab.

2. Transmit Reference Receiver (TR)

In order to eliminate the need for channel estimation, a method known as the Transmit Reference (TR) Receiver is used. This method simultaneously transmits a modulated data pulse and an un-modulated reference pulse, which are separated by a delay, D, known by both the transmitter and receiver. Transmission is organized into frames, where each frame is of duration $T_f$ and consists of a reference pulse followed by a data pulse. As long as the delay between these two pulses is significantly smaller than the channel coherence time (i.e. the minimum time before the channel will become uncorrelated with its previous state), the two pulses can be assumed to suffer the same distortion and multipath fading as they pass through the wireless channel [7]. The general structure of the TR receiver is illustrated in Fig. 6. The received signal is delayed by the known delay element, D. In this way, the reference pulse is used as a template to extract the data pulse.
3. Frequency Shifted Reference (FSR)

Another scheme that has arisen for UWB transmission is Frequency-Shifted Reference (FSR), which aims to separate the data pulse and reference pulse in the frequency domain rather than the time domain. The motivation behind FSR is that, implementation of a frequency shift for a wideband signal is simpler to achieve than the implementation of a wideband delay for the same signal [8]. We recall from the TR method that, in order to effectively use the reference pulse as a template for the data pulse, both pulses must undergo the same channel distortion and fading; i.e. the delay time between the two pulses must be significantly less than the coherence time of the channel. For the FSR scheme, this constraint becomes that, the frequency offset, $f_0$, between the reference and data pulse must be much smaller than the coherent bandwidth of the channel [8]. The method of FSR Receiver is suggested to satisfy the above constraint. To explain this method, transmission can be considered to be in the terms of frames and symbols:

$$T_s = N_f T_f$$  \hspace{1cm} (1)

where $T_s$ is the time period per symbol, $N_f$ is the number of frames where there is one pulse per frame, and $T_f$ is the time period per frame. A reference pulse sequence and one or more data pulse sequences are simultaneously transmitted; where each data pulse sequence is shifted by a specific frequency offset [8]. In order to ensure orthogonality between the reference pulse sequence and the data pulse sequences, the orthogonality is ensured over each symbol period, rather than by frame period. Therefore [8]:

$$f_{offset} = \frac{1}{N_f T_f} = \frac{1}{T_s}$$  \hspace{1cm} (2)

The general structure of the FSR receiver when only one data sequence is transmitted is shown in Fig. 7. The frequency offset, $f_0$, is the same offset that was used to shift the data sequences before transmission. On the receiver side, this offset will shift the reference pulse sequence so that it may be used as a template to extract the information from the data pulse sequences.

Due to the analog frequency offsets employed in the FSR scheme, the performance of the system can be affected by frequency errors caused by oscillator mismatch, phase errors caused by multipath fading, and amplitude errors caused by nonlinear amplifiers [3]. Therefore, the reference pulse sequence may not provide a perfect template for the data pulse sequence.
4. CODE-SHIFTED REFERENCE (CSR)

Recently proposed is that of the Code-Shifted Reference (CSR) scheme for the IR-UWB Receiver. In the CSR scheme, rather than being separated by time (TR) or by frequency (FSR), the reference and data pulse sequences are separated by codes [3].

![Diagram of General CSR receiver structure [3]](image)

On the receiver of the CSR systems, \( M = (2^{N-1}) \) orthogonal detecting codes of length \( 2^N \) are used to extract the information from the data sequence. The general structure of the CSR receiver is illustrated in Fig. 8. Referring to Fig. 8, filtering is performed to remove any noise and interference beyond the desired signal band, followed by a square unit and then integrated from \((jN_f + i)T_f\) to \((jN_f + i)T_f + T_M\) to obtain \( r_{ij} \). The value of \( T_M \) varies from \( T_p \) in an additive white Gaussian noise (AWGN) channel to \( T_f \) in a multipath channel with severe delay spread. Although a larger value of \( T_M \) will result in the collection of more signal energy distributed in different MPCs, this also results in added noise and interference [3].


The CSR scheme is able to eliminate some of the issues regarding the complexity of the TR scheme and the performance degradation of the FSR scheme. But, the CSR system, like the TR system, spends half of its power transmitting the reference pulse sequence [4]. Therefore, the CSR system, although having reduced implementation complexity when compared to the TR system, cannot achieve a better BER performance than the TR system. In order to improve system performance, the CSR scheme was extended to the differential CSR (DSCR). This performance improvement is achieved by reducing the amount of power used to transmit the reference pulse sequence [9].

The DSCR method makes use of the fact that the CSR scheme can transmit multiple data pulse sequences simultaneously, where each data pulse sequence bears one information bit. In the DCSR scheme, the information bits are differentially encoded so that one data pulse sequence can be used as a reference for another data pulse sequence. Therefore, when \( M \) bits are transmitted simultaneously, the amount of power used to transmit the reference pulse sequence can be reduced from \( \frac{1}{2} \) to \( \frac{1}{M+1} \) [9].
Fig. 9 General DCSR receiver structure [9].

The front end of the receiver for the DCSR scheme, as shown in Fig. 9, is the same as that for CSR: a BPF to remove noise and interference beyond the desired signal band, followed by a square unit and then integration from \((jN_f+i)T_f\) to \((jN_f+i)T_f+T_M\) to obtain \(r_j\). The only difference is that, in the DCSR scheme, for \(M+1\) shifting codes, since the multiplication of these codes can have \(M(M+1)/2\) combinations, \(M(M+1)/2\) orthogonal detection codes are required in order to detect the transmitted information bits [9].

PERFORMANCE COMPARISON

The CSR scheme offers advantages over the TR and FSR schemes. Since the data pulses and reference pulse are shifted by means of code rather than time, a wideband delay element is not required. Therefore, system complexity is reduced when compared with the TR system. Also, since digital codes are employed rather than analog carriers to provide the separation between the reference and data pulse sequences, the CSR scheme is able to avoid most of the performance degradation that occurs in the FSR scheme due to errors in frequency, amplitude and phase [3].

The performance comparison between the DCSR and the CSR/TR/FSR schemes was presented in [4]. It should be noted that in this paper, a comparison on the performance of the systems was made assuming that no inter-pulse interference existed.

The bit error rate (BER) of the CSR receiver in a multipath environment was found as [4]:

\[
BER_{CSR} = Q\left(\frac{\sqrt{M \alpha E_b}}{2 \alpha E_b N_0 + N_0^2 (f_H - f_L) N_f T_M}\right)
\]

(3)

where \(E_b\) is the received energy per information bit, \(N_0\) is the single-side power spectral density of AWGN, \(M\) is the number of information bits transmitted, \((f_H-f_L)\) is the bandwidth of the UWB signal, \(N_f\) is the number of frames transmitted, and \(T_M\) is a time value used in receiver integration [10].

As was the case with CSR, it can be seen that for a fixed number of frames of fixed duration, as the number of bits transmitted simultaneously increases the performance of the DCSR system improves.

The performance comparison of the DCSR and CSR systems with the FSR and TR systems [4], provided the following equations for the BER of the FSR system (under AWGN environment) and the TR system (under multipath environment):

\[
BER_{TR} = Q\left(\frac{\alpha E_b}{\sqrt{2 \alpha E_b N_0 + 2 N_0^2 (f_H - f_L) T_M}}\right)
\]

(4)
Using these equations and the BER equations derived for DCSR and CSR, a comparison was performed between the systems for instances where \( M=2 \) and \( M=3 \) as shown in Figs. 10 and 11, respectively.

For \( N_f=6 \), as shown in Figure.10, there are only two analog carriers available, and \( M \) can only be “1” or “2” [4]. Therefore the highest achievable bit-to-pulse ratio \( (M/N_f) \) for the FSR system when \( N_f=6 \) is \( 1/3 \) [10]. Comparing this result to the other systems shown in Figure.11, their highest achievable bit-to-pulse ratio is \( M/N_f=1/2 \). When \( M=3 \), the FSR system requires \( N_f=10 \), while the TR system requires \( N_f=6 \).

III. CONCLUSION

Referring to the cases presented in the previous figures 10 &11. The FSR system has the worst performance, while the DCSR system has the best performance. For the FSR system, the number of bits that can be transmitted simultaneously is limited by the number of analog carriers available [4]. In general, the FSR system will achieve a bit-to-pulse ratio of less than \( 1/2 \), while the TR system will achieve a bit-to-pulse ratio equal to \( 1/2 \). For the CSR and DCSR systems, the bit-to-pulse ratio can be up to \( 1/2 \) and has the flexibility to transmit less than \( 1/2 \) as shown in Fig. 11.

From Fig. 10, it can be seen that for \( M/N_f=1/2 \), the CSR system can achieve the same performance as the TR system and no better. Both schemes use half of the available power to transmit the reference pulses. Recall that, the DCSR scheme was proposed as an extension of the CSR scheme in order to improve system performance by reducing the power to transmit the reference pulses from \( 1/2 \) to \( 1/(M+1) \) [9].

In terms of sensitivity to noise and interference, the FSR scheme is more sensitive than TR, CSR and DSCR [4]. Although more signal energy can be collected from the resolvable MPCs, it will also add more noise and interference [3].

REFERENCES