An Ultra-Wide Band System with Chirp Spread Spectrum Transmission Technique

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***Abstract*-We consider a wireless Ultra-Wide Band (UWB) communication system using chirp spread spectrum (CSS) transmission technique. A system with high order modulation CSS technique is proposed. Our proposed system has inherited the advantages of CSS technique and common spread spectrum systems. It is immune to Doppler frequency offset and able to increase bit rate by the overlap technique. Existing CSS systems suffer intersymbol interference and high envelope variation caused by the overlap technique seriously while our proposed approach is able to overcome the above disadvantages without loss of the bit rate.**

I. INTRODUCTION

One of the most challenging topics in the area of transmitting data is wireless communication system, especially due to the requirements of mobility of users, flexibility, and creation of various communication services. The signals must be distributed over wide areas without loss despite the fact that the signal can be disturbed by other wireless systems and that multipath fading can affect the quality of the signal. In industrial environments these problems are even worse due to the larger dimension of rooms and halls, the often highly reflective walls and strong electromagnetic emission from e.g. power electronics for drives. For the realization of a robust wireless communication system under such difficult conditions a wideband (>50 MHz) spread spectrum system concept with a high processing gain is favorable. Chirp signals and the associated technique of pulse compression which is extensively used in radar systems are well suited for spread spectrum transmission [1]. Because of its advantages such as high processing gain, large bandwidth, low power, scalable bit rate, robustness to multipath interference, immunity to Doppler frequency offset, etc., Chirp Spread Spectrum (CSS) techniques have been applied to many areas. The IEEE 802.15.4a WPAN Task Group has selected the baseline specification without enacting their down-selection procedures, and confirmed the baseline with 100% approval. CSS (operating in unlicensed 2.4GHz spectrum) is one optional PHY of the baseline [2]. Chirp based RFID solutions have been proposed by Nanotron Technologies [3]. T. Doi and his group have proposed a chirp based inter-vehicle radar system [4].

CSS applications for communication were first proposed by Winkler [5]. In this work she infers the rudiments of a Binary Orthogonal Keyed (BOK) system, where data symbols can be represented by up and down linear chirps. J. Pinkley discussed many aspects of the CSS system in his PhD thesis [6], summarizing existing CSS systems into two basic schemes, BOK and Direct Modulation (DM). A. Springer and his group proposed a SAW-based WLAN using π / 4 Differential Quadrature Phase Shift Keying (DQPSK) CSS and showed its performance [7][8][9].

Overlap is a feature of CSS to increase bit rate. However, it causes serious intersymbol interference (ISI), even in the AWGN channel. In addition, the envelope of overlapped signals is very unstable and can result in very high amplitude variations (up to 15dB). In this paper, we propose a Quadrature Amplitude Modulation (QAM) CSS scheme combined with the overlap technique to increase bit rate and give some suggestions on selecting CSS parameters.

This paper is organized as follows. In section II, the basic CSS theory and the scheme of our proposed DM CSS system are presented. In section III, we give the system simulation result of our proposed QAM CSS system and discuss some issues on selecting CSS parameters. The conclusion is derived in section IV.

II. A DIRECT MODULATION CHIRP SPREAD SPECTRUM SYSTEM

A. Chirp Spread Spectrum Basics

CSS has its roots in the pulse compression theory in RADAR systems [1]. It uses chirp signals as PN codes to spread the spectrum, which is similar to Direct Spread Spectrum (DSS). However, chirp spreads in the time domain as well. This property enables chirp energy to be spread in time therefore chirp signals can maintain low power. The representation of a typical linear chirp waveform is given as

$$\begin{aligned} s(t) &= a(t)\cos\left(\omega_0 t + \frac{\mu t^2}{2}\right), -\frac{T}{2} < t < \frac{T}{2} \\ &= 0 \qquad elsewhere \end{aligned} \tag{1}$$

where T, $a(t)$, $f_0 = \omega_0 / (2\pi), \mu$ are chirp duration, envelope, center frequency and chirp rate, respectively. μ indicates the rate of change of instantaneous frequency. A chirp with positive μ is an "up-chirp", otherwise a "down-chirp". The impulse response of a filter matched to a chirp signal is also a chirp but with opposite sign of μ. If $a(t)$ is a rectangular function, the autocorrelation function of a linear chirp, or the output of a chirp passing a matched filter, can be written as:

$$g(t) = \sqrt{\frac{\mu}{2\pi}}\cos(\omega_0 t)\frac{\sin\left(\frac{\mu t(T-|t|)}{2}\right)}{\mu t}, -T < t < T \tag{2}$$

if the expression at $2\omega_0$ is neglected, which is reasonable for most cases of practical interest [1]. $g(t)$ is with the form of $(\sin x)/x$, a SINC function. SINC function has the property of high autocorrelation peak and low sidelobes. Due to this high autocorrelation peak, CSS has a very large processing gain. Furthermore, the output energy of other signals, such as noise, of the matched filter is spread in time.

It is easy to generate a linear chirp with Surface Acoustic Wave (SAW) devices [8] or Digital Chirp Generators (DCG) [11], both of which can be viewed as filters. Though both approaches have their own advantages and disadvantages [11], the basic process of generating a linear chirp is the same: a chirp signal is generated by exciting the filter with an intermediate frequency (IF) pulse.

It is possible to increase bit rate by overlap technique. If one chirp is generated before last one ends, the new and the previous chirp signals are added together, or overlapped in the time domain, as well as matched filter outputs. That is, chirp duration T is longer than IF pulse interval T_s, which determines the bit rate. We define the ratio of T and T_s, O_f, as the overlap factor, which represents the degree of the overlap process. For instance, if O_f = 2, two chirp signals are generated in the time duration T successively and the bit rate is twice as much as the non-overlap bit rate.

B. Direct Modulation

Basically, there are two types of systems to modulate chirp signals with information data. One is Binary Orthogonal Keying (BOK) [5], using up-chirps for bit "1"s while down-chirps for "0"s. The other is Direct Modulation (DM), in which modulation and demodulation are performed separately and independently from the chirping process, allowing many possible modulation methods to be employed. Modulated symbols are spread both in time and frequency by linear chirps.

Fig. 1 shows the block diagram of a DM CSS system. The modulation block can use various modulation schemes. References [9][12] proposed a π / 4 DQPSK CSS system. In their proposed system, the modulation/demodulation block in Fig. 1 is a π / 4 DQPSK modulator/demodulator. Though overlapping chirp signals can increase bit rate, the communication system suffers great ISI. Since matched filter outputs are added together, energy leakage from other symbols affects current information. Besides, large O_f results in high amplitude variations (up to 15 dB) which are subject to distortions due to nonlinear characteristics.

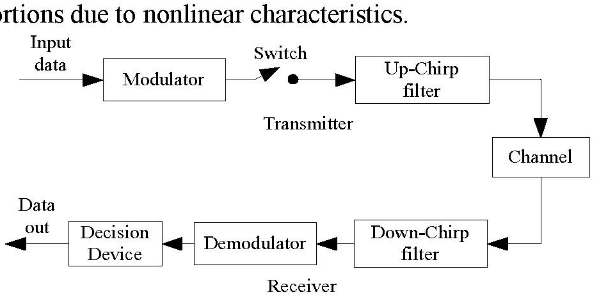

Figure 1. Block diagram of a DM CSS system

The problem of envelope variation caused by overlap technique is stated in [9]. Bit Error Rate (BER) performance will be much poorer (a loss more than 3dB in the BER performance) for O_f larger than 10.

C. Frequency Offset

It is widely accepted that CSS is immune to Doppler frequency offset [7]. Suppose a chirp signal with the form of (1) (where $a(t)$ is a rectangular function) has reached the receiver with a certain frequency offset $\varepsilon = \omega_d/(2\pi)$, then the received signal can be represented as:

$$f(t) = \cos\left[(\omega_0 + \omega_d)t + \frac{\mu t^2}{2}\right], -\frac{T}{2} < t < \frac{T}{2} \tag{3}$$

The output of the matched filter is:

$$G(t,\omega_d) = \sqrt{\frac{2\mu}{\pi}}\cos\left[\left(\omega_0 + \frac{\omega_d}{2}\right)t\right] \bullet \frac{\sin\left[\frac{\omega_d + \mu t}{2}\left(\frac{T}{2} - |t|\right)\right]}{\omega_d + \mu t}, -\frac{T}{2} < t < \frac{T}{2} \tag{4}$$

Comparing (4) with (2), we can see that the two outputs has the same form of a SINC function except for a timeshift of the autocorrelation peak, which can be represented as:

$$\delta_t = \frac{\varepsilon}{\mu} \tag{5}$$

For instance, a system with $\mu = 160\,\text{MHz}/\mu\text{s}$ and $\varepsilon = 10\,\text{kHz}$ would only result in a timeshift of 0.625 ns. However, we should be aware that in practice, Doppler frequency offset is much less than 10 kHz, which means that this timeshift is much less than 1 ns. Therefore, CSS is robust to Doppler frequency offset. If larger frequency offset is caused by other factors such as temperature difference and oscillator variation between the transmitter and receiver, it can be easily traced by a PLL [8].

D. Direct Modulation Using Quadrature Amplitude Modulation

In order to reduce the above imperfections caused by overlap while obtain the same bit rate, we propose a DM system with high order modulation scheme. N QAM can modulate $\log_2(n)$ bits in one data symbol. For example, one 16 QAM symbol contains 4 bits, twice as many as π / 4 DQPSK does.

Table I presents one example for the relationships of O_f, bit rate and different modulation schemes. In this table, the transmission bandwidth, chirp rate and the chirp duration are $80\,\text{MHz}, 160\,\text{MHz}/\mu\text{s}$ and $0.5\,\mu\text{s}$ respectively.

TABLE I
RELATIONSHIPS OF O_F, BIT RATE AND MODULATION SCHEMES

Modulation Scheme	Symbol Rate	O_f	Bit Rate
π / 4 DQPSK	2 M/s	1	4 Mbps
		10	40 Mbps
		25	100 Mbps
16 QAM		1	8 Mbps
		12.5	100 Mbps
64 QAM		1	12 Mbps
		8.33	100 Mbps

From Table I, we can see that in order to obtain a bit rate of 100 Mbps, O_f = 25 for π / 4 DQPSK, O_f = 12.5 for 16 QAM and O_f = 8.33 for 64 QAM. Obviously, under the same bit rate, the 64 QAM with small O_f suffers much less ISI and envelope variation than π / 4 DQPSK does. That is, in our proposed system, bit rate can be maintained with O_f less than 10.

III. Simulation Results

We performed the system simulation to show the feasibility of our proposed system with Matlab and Simulink. Where appropriate, the simulations were carried out in baseband. The linear chirp signals were generated by the Digital Filter Block with user defined chirp waveform in the time domain. The time span and time step were $0.5\,\mu s$ and 1 ns, respectively. To demonstrate the overlap effect in the π / 4 DQPSK simulation, we set chirp duration, transmission bandwidth and chirp rate to $0.5\,\mu s$, 80 MHz and $160 MHz/\mu s$ respectively, and the Time-Bandwidth Product (TB) is 40. We performed 10^6 bits per SNR point with a maximum error bit number of 100. The overlap parameters were set according to Table I. In order to reduce the ISI brought by overlapping, we use Hamming Window to lower the sidelobes of the matched filter output. Some tolerable errors may occur due to the limited number of bits during simulation.

We first performed the simulation to show the system performance under the effect of frequency offset. We used the "frequency/phase offset" block in Simulink to add frequency offset. Fig. 2 compares the matched filter outputs with a frequency offset of 4 MHz and 0 Hz. A timeshift caused by frequency offset can be seen clearly. Fig. 3 shows the BER performance with different frequency offset values without any frequency synchronization operation (however, time synchronization must be performed carefully in order to get decision data at the autocorrelation peak. Timing is supposed to be perfect in this paper). The BER performance remains the same as the theoretical one (no frequency offset) when the frequency offset is 10 kHz. For frequency offset more than 10 kHz, there exists a loss in BER.

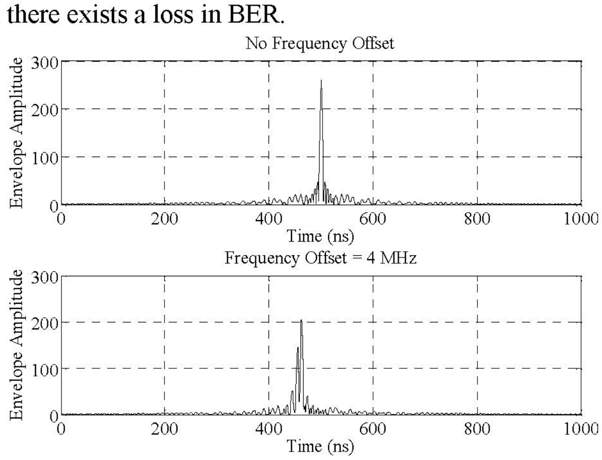

Figure 2. Matched filter outputs with different frequency offset values

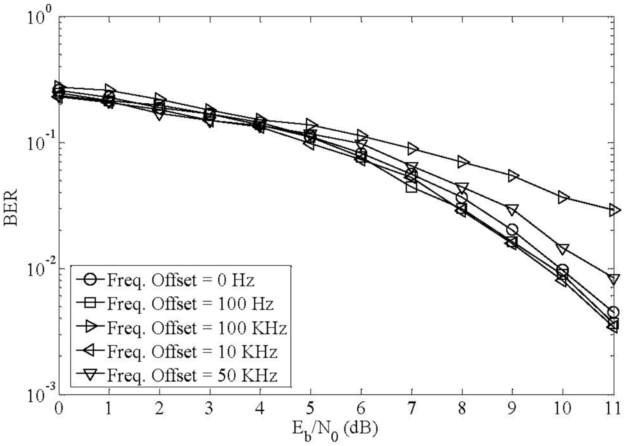

Figure 3. BER performance with different frequency offset values

We then performed the simulation with different O_f and modulation schemes. Fig. 4 depicts the BER plots of π / 4 DQPSK with different O_f. It is clear that Hamming Window tolerates a larger O_f without loss of BER. However, when O_f is 20, even Hamming Window suffers great ISI. Fig. 5 depicts the matched filter outputs from Hamming Window and Rectangular Window. It is obvious that with Hamming Window, though the mainlobe is widened, sidelobes are almost eliminated. This explains the ISI cancellation between adjacent symbols and the better BER performance with Hamming Window as shown in Fig. 4.

For QAM CSS system simulation, we used the same chirp parameters as previous ones. Relationships of O_f and bit rate were illustrated in Table I. BER plots of 16 QAM and 64 QAM were depicted in Fig. 6 and Fig. 7. From these figures, we found that system performance would suffer fewer ISI with O_f less than 10 while bit rate is maintained. For 64 QAM, when O_f = 8.33, the BER performance results in no loss when Hamming Window is applied.

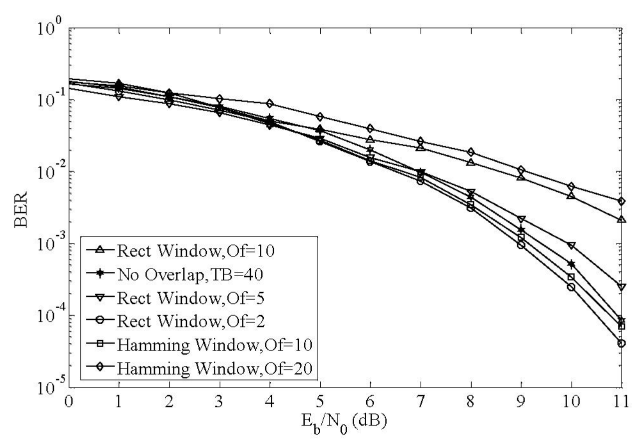

Figure 4. BER performance of π / 4 DQPSK with various O_f, Rectangular Window and Hamming Window

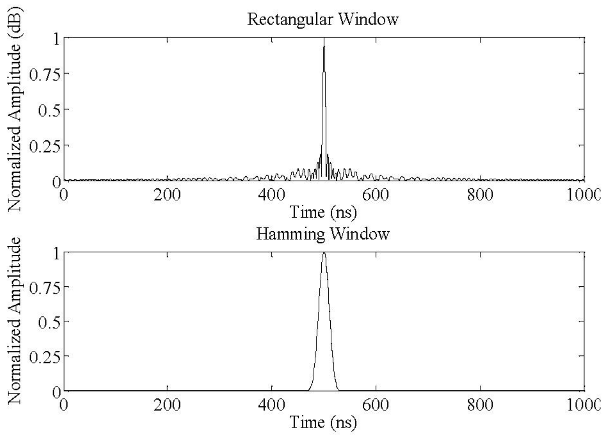

Figure 5.Matched filter outputs with Rectangular Window and Hamming Window.

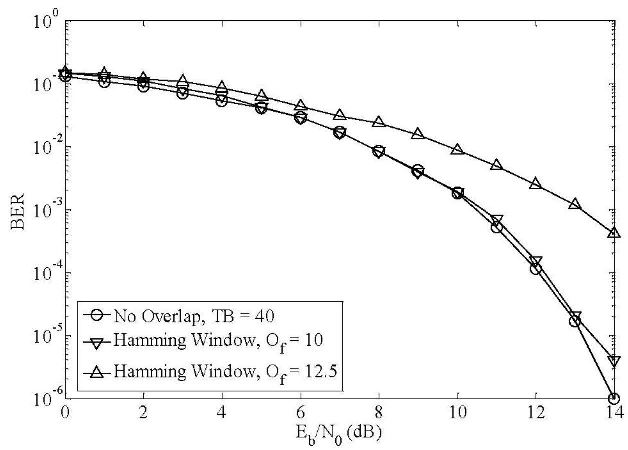

Figure 6. BER performance of 16 QAM with different O_f

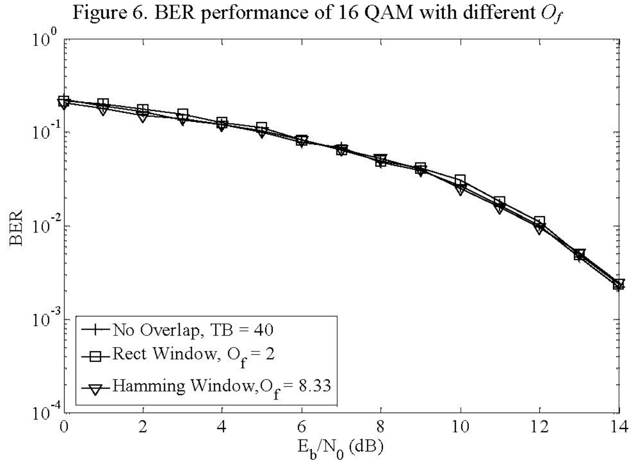

Figure 7. BER performance of 64 QAM with different O_f

IV. CONCLUSIONS

We consider a wireless UWB communication system using CSS transmission technique. In addition to the common advantages of spread spectrum systems, CSS is immune to Doppler frequency offset and able to increase bit rate by the overlap technique. However, overlap causes ISI and high envelope variation, all of which degrade the system performance seriously. We proposed a high order modulation scheme to reduce the negative effects caused by the overlap technique. Data rate is maintained while the overlap effects are reduced to a certain degree by our approach. However, there is a tradeoff between the system complexity and QAM order, since good channel estimation for QAM under multipath environment would inevitably increase the complexity of the system. Furthermore, the BER performance of high order QAM is not as good as the one of π / 4 DQPSK, though the latter one with large O_f suffers great envelope variation and ISI. To determine the balance between π / 4 DQPSK with large O_f and QAM with reasonable order and small O_f is our future work.

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