DS-PAM UWB System Using Non-linear Chirp Waveform

Hanbing Shen, Weihua Zhang, Xizhi An, and Kyung Sup Kwak

We propose a direct-sequence pulse-amplitude modulation (DS-PAM) ultra-wideband (UWB) system which employs a non-linear chirp waveform instead of the conventional Gaussian monocycle in this paper. In the approved frequency for UWB, there exist myriad narrowband interferers. Specifically, we focus on the mutual interference between UWB systems and 802.11a WLAN. This paper offers a method to suppress this in-band narrowband interference by introducing a kind of non-linear chirp waveform. Using the proposed non-linear chirp waveform, the effects of one or more narrowband interference sources with different frequencies can be suppressed. System performance of UWB systems in the narrowband interference environment can be improved. Computer simulations with additive white Gaussian noise successfully demonstrate an increase in performance with the proposed system as compared to traditional linear chirp systems.

Keywords: Ultra-wideband (UWB), non-linear chirp, narrowband interference (NBI).

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I. Introduction

Recently, ultra-wideband (UWB) has gained considerable research interest since the FCC approved a frequency limit for UWB technology. The FCC allows occupation of an ultra-wide frequency band from 3.1 GHz to 10.6 GHz with a power spectral density of less than -41.3 dBm/MHz [1].

Existing UWB systems are based on two main kinds of waveform modulation schemes: pulsed waveform and chirp. Both schemes have their own advantages and shortcomings. Different waveforms have been previously studied in pulsed UWB schemes, including Gaussian pulse series [2], [3] and Hermite pulse series [4], [5]. The pulsed scheme can be operated by simple transmitter with rich resolvable multipath components for multipath diversity reception in communication systems and fine time resolution for accurate position location in radar applications. However, pulsed UWB using extremely short time duration of time pulses with an extremely high peak-to-average ratio causes many hardware implementation problems. These include power amplifier nonlinearity when the system is designed to operate at low data rates but with a large frequency bandwidth. It also requires an extremely fast power rise time and low-noise amplifiers (LNA), which incur high costs at present [6]. Chirp waveform schemes have historically been used extensively in radar applications. Compared with pulsed schemes, chirp schemes can overcome their shortcomings. Using a long time duration modulation waveform without a high peak-to-average ratio, power amplifier nonlinearity in the system can be avoided. Low-cost and low-complexity hardware can be used in the LNA parts of an apparatus. Sometimes chirp wave signals are called continuous-waveform (CW) signals.

Because of the very short time windowing at the receiver and the high correlation of narrowband signals over a short time interval, UWB systems have inherent immunity to narrowband interference (NBI). Due to the low power spectral density, however, a high level of NBIs, as when there is an IEEE 802.11a wireless local area network (WLAN) device operating nearby, can still badly affect the system performance of UWB systems. It can even cause the UWB receiver be jammed if the interference is not properly suppressed [7].

Chirps have many desirable properties and are used in many applications, such as sonar and radar [8]. Chirp signals are spread spectrum signals [9]. The interference rejection property of chirp signals is inherently good. The utility of linear frequency chirp is superior to PSK and FSK in partially coherent and fading cases [10]. Chirp modulation in the high frequency (HF) band was introduced in an experimental communication system in [11]. Linear FM chirp signals have been proposed for UWB ranging systems, where chirp signals have the same time duration and different frequency bands [12].

This paper proposes a new non-linear chirp modulation system for UWB systems. Using non-linear chirp modulation, system performance under high level NBIs improves compared with linear chirp systems. The design of this NBI resistible non-linear chirp is described. The system performance, especially the bit error rate (BER) of linear chirps and the proposed non-linear ones are compared by computer simulation. The simulation results confirm that the proposed scheme outperforms the traditional linear schemes.

II. Background Introduction

1. Chirp Theory

A chirp waveform, as presented in [13], can be written as

$$c(t) = a(t)\cos[\Theta(t)], \tag{1}$$

where $\Theta(t)$ is the phase, and $a(t)$ is the envelope of the chirp signal, which is zero outside a time interval of length T_s. The instantaneous frequency is defined as

$$f_c(t) = \frac{1}{2\pi}\frac{d\Theta(t)}{dt}. \tag{2}$$

Chirp rate, an important parameter in chirp systems, is defined by

$$\mu(t) = \frac{df_c(t)}{dt} = \frac{1}{2\pi}\frac{d^2\Theta(t)}{dt^2}. \tag{3}$$

It represents the rate of change of the instantaneous frequency. The chirp waveforms with $\mu(t) > 0$ are called up-chirps and those with $\mu(t) < 0$ are called down-chirps.

For a linear chirp system, $\mu(t)$ is constant; hence, $f_c(t)$ is a linear function of t, and $\Theta(t)$ is a quadratic function. If we define the linear chirp waveform to be centered at $t = 0$, it can be written as

$$c(t) = a(t)\cos(2\pi f_0 t + \pi\mu t^2 + \varphi_0), \tag{4}$$

where f_0 is the center frequency and $a(t) = 0$ for $|t| > T_s/2$.

The bandwidth B is conveniently defined as the range of the instantaneous frequency so that

$$B = |\mu| \cdot T_s. \tag{5}$$

On the receiver side, a matched filter is used to demodulate the chirp waves, whose impulse response, $h_m(t)$, is given by

$$h_m(t) = c^*(-t), \tag{6}$$

where * denotes the complex conjugate. The envelope of the chirp signal $a(t)$ is often a constant value when $|t| \le T_s/2$. Without loss of generality, we can set $a(t)=1$ in the analysis. The output waveform $g(t)$ of the matched filter is given by

$$g(t) = h_m(t) * c(t) = T\frac{\sin\left[\pi Bt\left(1 - \frac{|t|}{T_s}\right)\right]}{\pi Bt}\cos(2\pi f_0 t) \tag{7}$$

for $|t| \le T_s$.

2. Narrowband Interference (NBI)

In the approved frequency for UWB, there exist myriad potential interferers (licensed and unlicensed) operating in the spectrum allotted to UWB. Compared with the ultra-wide bandwidth of UWB systems (3.1 GHz to 10.6 GHz of the main spectrum band), all these interferers can be treated as narrowband interference sources. For example, WLAN devices using the IEEE 802.11a standard operate in the 5 GHz Unlicensed National Information Infrastructure (U-NII) frequency bands. Three 100-MHz-wide frequency bands (5.15 to 5.25, 5.25 to 5.35, and 5.725 to 5.825 GHz with the maximum ERP set to 2.5, 12.5, and 50 mW/MHz, respectively) exist in the spectrum of IEEE 802.11a WLAN. It is the main interference source in the spectrum of UWB.

Generally, an NBI with a single tone can be modeled as

$$i(t) = a\sqrt{2P}\cos(2\pi f_i t + \phi), \tag{8}$$

where P and f_i are the average power and frequency of the sinusoids, respectively. Correspondingly, NBI with more tones can be modeled as

$$i(t) = \sum_{n=1}^{N} a_n\sqrt{2P_n}\cos(2\pi f_{in} t + \phi_n), \tag{9}$$

where $i(t)$ is the sum of different single tone NBIs.

3. UWB DS-PAM System

In this paper, a UWB direct-sequence (DS) pulse-amplitude modulation (PAM) system is considered. The transmitted DS-PAM signal is given by

$$m(t) = \sum_{i=-\infty}^{\infty}\sum_{j=0}^{N_s-1} d(i)c(j)p(t-iT_b-jT_s), \tag{10}$$

where N_s is also the number of frames in one transmitted bit, $c(j)$ is the j-th DS code with a length of N_s, $d(i)$ is the i-th transmitted data bit, $d(i)$ and $c(j)$ are positive and negative binary valued data, and $p(t)$ is the transmitted waveforms; T_b is the time duration occupied by one bit, and T_s is the time duration of one signal waveform. Generally, we have $T_b = N_s T_s$.

In our analysis and simulation, we assume that an additive white Gaussian noise (AWGN) channel with only one single tone NBI and no multi-user UWB interference is present in the system. The received signal is given by

$$\begin{aligned} m_{rec}(t) &= \beta m(t) + i(t) + n(t) \\ &= \beta \sum_{i=-\infty}^{\infty}\sum_{j=0}^{N_s-1} d(i)c(j)p(t-iT_b-jT_s) \\ &\quad + i(t) + n(t), \end{aligned} \tag{11}$$

where β is the path loss parameter and $n(t) \sim N(0, \sigma^2)$.

A template will be generated in the matched filter in the receiver and is given by

$$v(t) = \sum_{j=0}^{N_s-1} c(j)p(t-jT_s). \tag{12}$$

If we assume that the DS code $c(j)$ and pulse shape $p(t)$ are known to the receiver, when appropriate synchronization is fulfilled, the correlation output over a symbol interval is given by

$$\begin{aligned} m_{out}(t) &= \int_{iT_b}^{iT_b+N_sT_s} m_{rec}(t)v(t)dt \\ &= \int_0^{N_sT_s}\left(\beta \sum_{i=-\infty}^{\infty}\sum_{j=0}^{N_s-1} d(i)c(j)p(t-jT_s) + i(t) + n(t)\right) \\ &\quad \cdot \left(\sum_{j=0}^{N_s-1} c(j)p(t-jT_s)\right)dt \\ &= d(i)\beta N_s^2 m_p(\delta) + \tilde{i} + \tilde{n}, \end{aligned} \tag{13}$$

where $d(i)\beta N_s m_p(\delta)$, $\tilde{i}$, and $\tilde{n}$ are the useful signal, interference, and noise outputs from the matched filter, respectively. The final system BER is given by

$$BER = Q\left(\sqrt{\frac{2E_b}{N_0 + I}}\right). \tag{14}$$

III. Proposed Non-linear Chirp Scheme

1. Non-linear Chirp Waveform

As we have discussed in section II, when $\mu(t)$ is a constant value, we consider this kind of chirp to be linear. "Linear chirp" means that all frequency sections in the frequency bands have the same weights, thus in the receiver matched filter, the interference frequency bands will be treated the same as the other bands which have no interference.

Based on this principle, we propose a novel non-linear chirp waveform. Unlike the linear chirp waveform, the non-linear chirp waveform is defined as a chirp function whose chirp rate $\mu(t)$ is not a constant value but a variable function. From the conception, we can understand that there is not only one kind of non-linear chirp at present.

In this paper, we use a sinusoidal chirp waveform, with which better NBI rejection capabilities can be achieved. As previously mentioned, the main NBI source is the IEEE 802.11a WLAN application with three 100-MHz bandwidths. Compared with the ultra-wide transmission band of UWB (3.1 to 10.6 GHz), IEEE 802.11a WLAN can be considered a single tone with a frequency of f_c=5.3 GHz.

Our scheme can suppress a single tone interference with a frequency of f_c. The instantaneous frequency is defined as

$$f_c(t) = \frac{1}{2\pi}\frac{d\Theta(t)}{dt} = f_c + a\cos(bt). \tag{15}$$

We set the frequency f_c to be the same as the center frequency of the NBI; thus, the chirp rate $\mu(t)$ is given by

$$\mu(t) = \frac{df_c(t)}{dt} = -ab\sin(bt). \tag{16}$$

During the waveform transmission duration, the whole spectrum (3.1 to 10.6 GHz) should be used in the chirp. Moreover, a and b will have different values depening on whether the interference f_c is higher or lower than the central frequency (6.85 GHz) of the UWB spectrum; therefore, a and b are given by

$$\begin{aligned} a &= \begin{cases} 10.6 - f_c & \text{if } f_c \le 6.85 \text{ GHz}, \\ 3.1 - f_c & \text{if } f_c > 6.85 \text{ GHz}, \end{cases} \\ b &= \begin{cases} \dfrac{1}{T_s}\arccos\left(\dfrac{3.1 - f_c}{10.6 - f_c}\right) & \text{if } f_c \le 6.85 \text{GHz}, \\ \dfrac{1}{T_s}\arccos\left(\dfrac{10.6 - f_c}{3.1 - f_c}\right) & \text{if } f_c > 6.85 \text{GHz}. \end{cases} \end{aligned} \tag{17}$$

The sinusoidal chirp waveform is given by

$$c(t)=\cos[\Theta(t)]=\cos\left[2\pi f_c t+2\pi\frac{a}{b}\sin(bt)+\varphi_0\right], \quad (18)$$

where $|t|\leq T_s/2$. Based on the same definition mentioned before, we can obtain the output $g(t)$ of the matched filter. For analysis purposes, we take for granted the complex envelope of the sinusoidal chirp:

$$s(t)=\text{rect}\left(\frac{t}{T_s}\right)\exp\left(i(2\pi f_c t+2\pi\frac{a}{b}\sin(bt)+\varphi_0)\right).$$

The output of the matched filter is

$$g_{\text{complex}}(t)=h_m(t)*s(t)$$
$$=\exp(i2\pi f_c t)\int_{-T_s/2}^{T_s/2}\text{rect}\left(\frac{t-\tau}{T_s}\right)$$
$$\cdot\exp\left(i4\pi\frac{a}{b}\sin\left(\frac{bt}{2}\right)\cos\left(\frac{2b\tau-bt}{2}\right)\right)d\tau. \quad (19)$$

Utilizing the Jacobi-Anger identity expressed by $\exp(iz\cos(\varphi))=\sum_{n=-\infty}^{\infty}i^n J_n(z)\exp(in\varphi)$, we obtain

$$g(t)=\text{real}\left(e^{i2\pi f_c t}\sum_{n=-\infty}^{\infty}i^n J_n\left[4\pi\frac{a}{b}\sin\left(\frac{bt}{2}\right)\right]\frac{2*\sin\left(\frac{1}{2}nb(T_s-|t|)\right)}{nb}\right), \quad (20)$$

where $J_n(z)$ denotes Bessel functions of the first kind. Comparing the outputs of the linear chirp matched filter from (7) and (19), when $t=0$, both outputs equal T_s. This means that the two chirps have the same energy if the chirp time durations are the same.

For the NBI of the IEEE 802.11a WLAN with a center frequency of 5.3 GHz, the instantaneous frequency is given in Figs.1, 2, and 3. Figure 1 shows the traditional linear chirp waveform and our proposed one. The proposed waveform is designed according to the method above. The interference to be suppressed is f_i = 5.3 GHz, which is equal to the design parameter f_c in (18). The initial phase parameter φ_0 is set to 0.

The design method is illustrated in Fig. 2. We use a sinusoidal curve as the instantaneous frequency function of the non-linear chirp. At the point where the sinusoidal curve crosses zero, the instantaneous frequency should be the central frequency of the narrowband interference because, at this point, the slope of the sinusoidal curve is the maximum value. The maximum slope of the sinusoidal curve means that in the chirp waveform, the frequency which matches the interference frequency occupies the minimum time duration. It also means that in the output signals of the receiver correlator, the narrowband interference has a minimal effect on system performance compared with linear chirp waveforms.

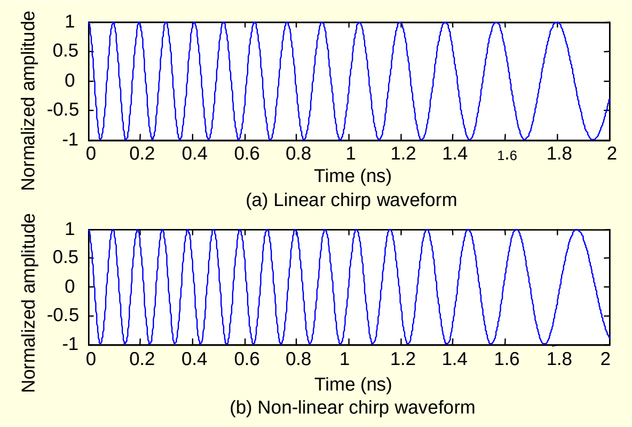

Fig. 1. Comparison of the linear chirp waveform and proposed NBI suppressing non-linear chirp waveform. Waveform duration T_s = 2 ns and the interference frequency f_i = 5.3 GHz.

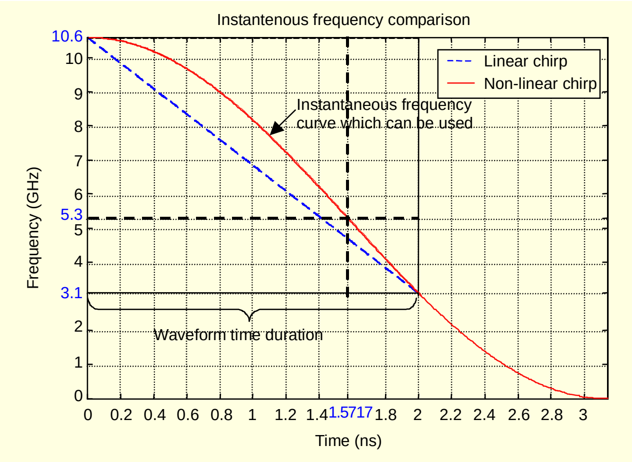

Fig. 2. Illustration of how to design proposed NBI suppressing non-linear chirp. The proposed waveform is portion of a whole sinusoidal curve.

The central frequency of the UWB main transmission spectrum (3.1 GHz to 10.6 GHz) is 6.85 GHz. As Fig. 2 demonstrates, if the NBI frequency is the same as the central frequency of UWB, a whole π phase sinusoidal curve can be used as the instantaneous frequency function, whereas when the central frequencies of NBI are not generally allocated the same as the central frequency of UWB, only a portion of a sinusoidal curve can be used. Figure 2 shows that, for the interference frequency of 5.3 GHz, only two-thirds of the sinusoidal curve can be used. The zero crossing point is set at $f=f_i$ = 5.3 GHz.

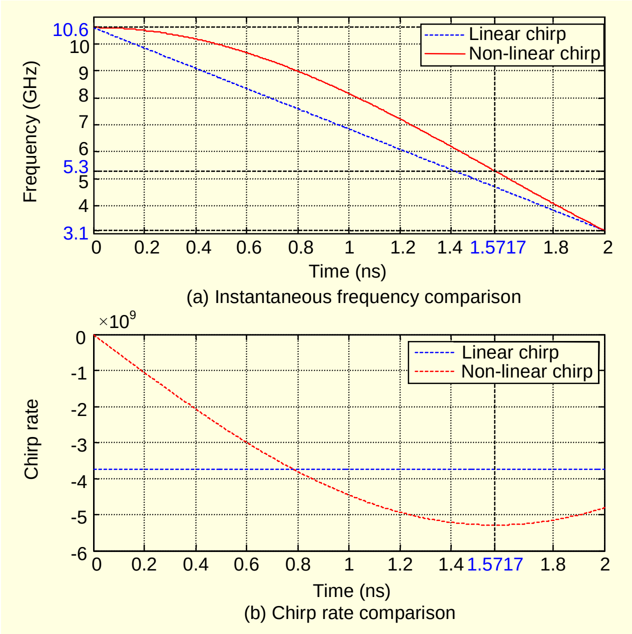

Fig. 3. Comparison of the instantaneous frequency and the chirp rate of the traditional linear chirp and proposed NBI suppressing non-linear chirp waveforms. Waveform duration T_s=2 ns. The interference frequency f_i=5.3 GHz.

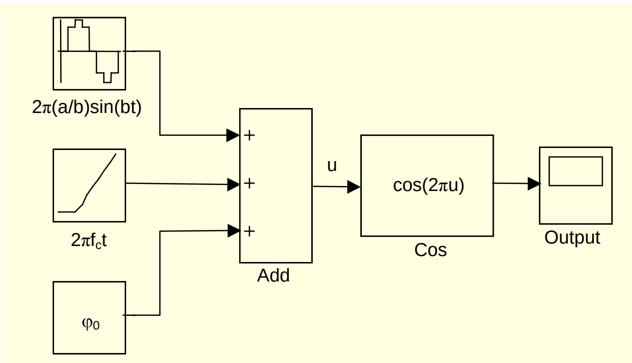

Fig. 4. Non-linear chirp generation method.

The instantaneous frequency and chirp rate of the two chirps are given in Fig. 3. At the corresponding time point of zero crossing in the instantaneous frequency (t = 1.5717 ns), the chirp rate of the proposed chirp achieves the minimum value. This also confirms that the proposed non-linear chirp passes the interference frequency with the maximum speed and will achieve the best NBI suppressing performance in the receiver.

Figure 4 illustrates the non-linear chirp generation method. Compared with the generation method for linear chirp, the proposed non-linear chirp generation method avoids the hardware operating t^2 and replaces it with a sinusoidal operation. Therefore, our proposed non-linear chirp can be generated without incurring too much hardware complexity as compared with linear chirp.

IV. Results of Computer Simulation

Our simulation was performed for both the linear and proposed non-linear chirp waveforms. Simulation parameters are shown in Table 1. As previously mentioned, for all the simulations we assumed an AWGN channel with single-tone interference and no multi-user UWB interference present in the system.

The system performance (BER) of the traditional linear chirp and the proposed non-linear chirp are compared in Fig. 5 with different E_b/N_0 values. We compare the results of SIR = -30 dB and -20 dB. The results show that a higher SIR decreases the BER. In both SIR environments, the proposed non-linear chirp system outperforms the traditional linear ones.

In addition, the BERs of traditional linear chirp methods and the proposed non-linear chirp method are compared in different SIRs. We compared the results of E_b/N_0=0 dB and 5 dB. The results are shown in Fig. 6. When the interference power maintains a high level, both systems may reach the BER ceiling of 50%. When the interference power level is low, both systems come close to the ideal BER value. In any cases, a lower BER can be achieved with the proposed non-linear chirp system.

Table 1. Parameters of simulation.

Number of measurements	100,000
Length of one chirp waveform (T_s)	10 ns
Number of chirp waveforms / bit (N_s)	8
Available bandwidth	3.1–10.6 GHz
Central frequency of the NBI (f_i)	5.3 GHz
Signal to interference ratio (SIR)	-20, -10 dB
Channel model	AWGN

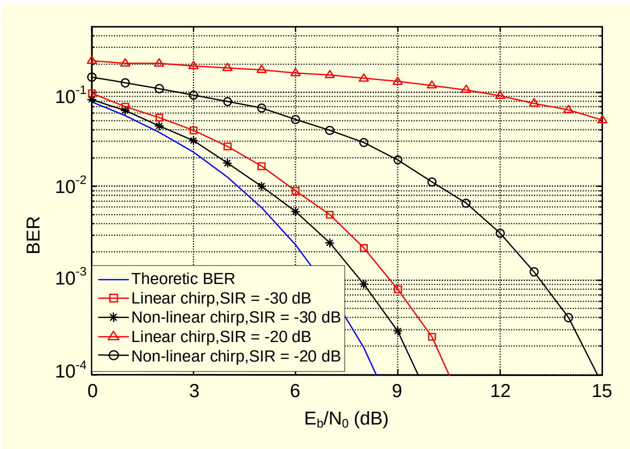

Fig. 5. System performance of linear chirp and proposed non-linear chirp in different E_b/N_0 values, SIR= -30 dB and -20 dB.

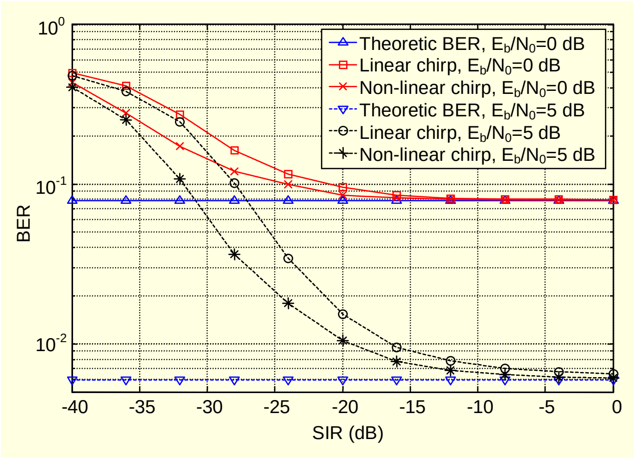

Fig. 6. System performance of linear chirp and proposed non-linear chirp in different SIRs, E_b/N_0= 0 dB and 5 dB.

V. Conclusion

In the main allowable spectrum band of UWB, some high power level NBIs exist. They can cause serious problems for UWB transmission and sometimes jam UWB systems. We proposed a novel chirp waveform modulated UWB system to resist these NBIs to some extent. By locating the minimum chirp rate exactly at the frequency of the narrowband interference, the component of the chirp signal at that frequency at the output of the matched filter is less important. Thus, a non-linear chirp with better NBI suppression performance is proposed. Performance analysis and computer simulation results confirm that the proposed scheme outperforms traditional linear schemes in the absence of multi-user UWB interference. Other forms of non-linear chirp such as the arc tangent chirp will be studied in the future works.

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