Chirp-Based Cognitive Ultra-wideband Radio

Hanbing Shen, Weihua Zhang, and Kyung Sup Kwak

ABSTRACT—In this letter, we propose a cognitive ultra-wideband radio scheme which is based on a modified chirp waveform. Therefore, it requires only time domain processing in the cognitive radio systems and reduces system complexity and power consumption.

Keywords—Cognitive radio (CR), chirp waveform (CW), ultra-wideband (UWB).

I. Introduction

Cognitive radio (CR) is viewed as a novel spectrum sharing approach. It uses the spectrum hole introduced in [1] to improve spectrum utilization. Orthogonal frequency-division multiplexing (OFDM) and transform-domain communication system (TDCS) have been proposed as CR candidates [2]. The computation of the time-frequency transform is required, though these techniques have the ability to use spectrum holes flexibly. The time-frequency transform method increases system complexity, power consumption, and processing delay.

Chirp waveform (CW) is one of the main modulation schemes in ultra-wideband (UWB) systems. Compared with the impulse radio (IR) UWB system, CW has the advantages of low-cost hardware and low complexity. Non-linear chirp waveforms with narrowband interference (NBI) suppression abilities have been proposed as modulation waveforms in UWB DS-PAM communication system [3] and ranging systems [4]. We propose a modified CW modulation scheme for the cognitive UWB system. Compared with OFDM and TDCS technologies, the proposed CW scheme can utilize spectrum holes with simple time domain processing.

II. Technology Background

1. Interference Issues

A licensed application can be expressed as a stochastic band-limited signal, which is a zero-mean Gaussian random process with power spectral density (PSD) [5]:

$$A_i(f) = \begin{cases} P_i & \text{if } f_i - \dfrac{B_i}{2} \le |f| \le f_i + \dfrac{B_i}{2}, \\ 0 & \text{otherwise,} \end{cases} \quad (1)$$

where f_i, B_i, and P_i are the center frequency, bandwidth, and PSD of the i-th application, respectively. The sum of N_a interference applications can be expressed as:

$$A(f) = \sum_{i=1}^{N_a} A_i(f), \quad (2)$$

2. UWB Chirp Waveforms

A linear CW can be expressed as given in [6] by

$$w(t) = \sqrt{2P}\cos(2\pi f_0 t + \pi \mu t^2 + \varphi_0) \text{ for } |t| \le \frac{T_s}{2}, \quad (3)$$

where P is the average power of the chirp signal, T_s is the chirp duration, f_0 is the center frequency, μ is the chirp rate, and φ_0 is the initial phase of $w(t)$.

From (3), the instantaneous frequency of $w(t)$ is given by

$$f_w(t) = \frac{1}{2\pi}\frac{d\left(2\pi f_0 t + \pi \mu t^2 + \varphi_0\right)}{dt} = f_0 + \mu t. \quad (4)$$

The chirp rate μ remains constant.

III. The Proposed CW-Based CR Scheme

The instantaneous frequency $f_w(t)$ of the linear CW varies linearly with time. This can be used to modify the signal spectrum
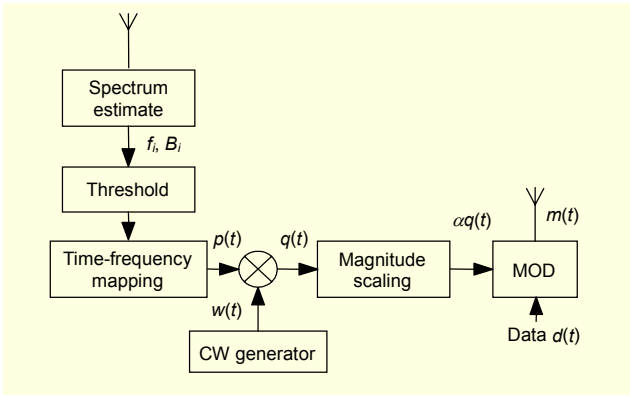
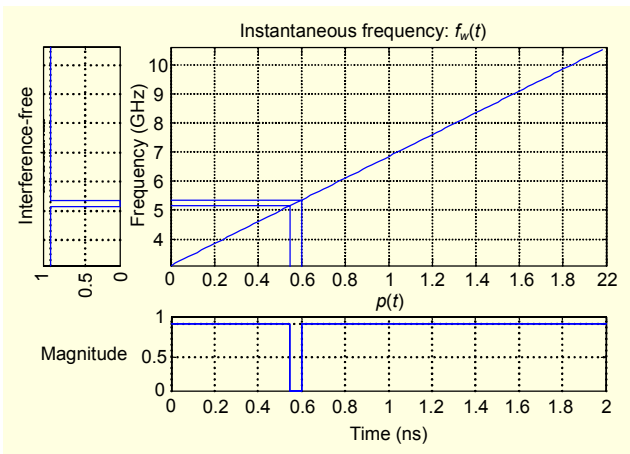Fig. 1. Block diagram of the proposed transmitter.

Fig. 2. Time-frequency relationship of the proposed CW notched window with the estimated spectrum hole.

neatly. By applying this in the proposed system, we can construct a modified CW waveform based on the spectrum holes detected by the radio environment estimation component of CR.

Figure 1 shows a block diagram of the proposed system. The spectrum estimation module is to estimate the spectral content of the environment, and the threshold module is applied to the estimated spectrum and generates an interference free spectrum.

After the spectrum hole is estimated, a time-frequency mapping processing, shown in Fig. 2, is required to produce a proper notched window $p(t)$ in the time domain. We assume that the FCC regulated UWB spectrum is the frequency band (f_l, f_h), where we let f_l=3.1 GHz and f_h=10.6 GHz. We assume that there are N_a licensed applications and they can be expressed as in (2). If the i-th licensed application with center frequency f_i and width B_i is detected, according to the chirp time-frequency relationship, we can map the frequency domain of the i-th application onto a time domain expression:

$$\text{mapping: } A_i(f) \rightarrow s_i(t),$$

that is, $\quad$ mapping: $(f_i, B_i) \rightarrow (\alpha_i, \beta_i)$

with the rectangle function of

$$s_i(t) = \text{rect}\big((t-\alpha_i)/\beta_i\big), \tag{5}$$

where

$$\alpha_i = T_s(f_i - f_l)/(f_h - f_l), \qquad \beta_i = T_s B_i/(f_h - f_l),$$

$$\text{rect}\big((t-\alpha_i)/\beta_i\big) = \begin{cases} 1 & \text{if } \alpha_i - \beta_i/2 \le t \le \alpha_i + \beta_i/2, \\ 0 & \text{otherwise.} \end{cases}$$

If N_a licensed applications are detected, the whole notched window $p(t)$ can be given by

$$p(t) = 1 - \sum_{i=1}^{N_a} s_i(t). \tag{6}$$

Thus, the spectrum notch for the licensed application can be realized in the time domain.

Next, we combine a linear CW with the notched window $p(t)$ by time domain multiplication:

$$\begin{aligned} q(t) &= w(t) \cdot p(t) \\ &= \sqrt{2P} \cos\big(2\pi f_0 t + \pi \mu t^2 + \varphi_0\big)\left(1 - \sum_{i=1}^{N_a} \text{rect}\left(\frac{t-\alpha_i}{\beta_i}\right)\right). \end{aligned} \tag{7}$$

We assume a narrowband application with center frequency f_i=5.3 GHz and width B_i=200 MHz. The time domain proposed CW is shown in Fig. 3(a). The spectrum magnitude of the proposed waveform is given by

$$\begin{aligned} |Q(f)| &= \sqrt{\frac{\pi P}{2}} \sin\left(\frac{\pi}{\mu}(f-f_0)^2\right) \\ &\times \left(\text{erf}\left(\sqrt{\frac{\pi}{2\mu}}(f-f_0)\right) - \text{erf}\left(\sqrt{\frac{\pi}{8\mu}}(2f-2f_0-2\mu\alpha+\mu\beta)\right)\right. \\ &\left. + \text{erf}\left(\sqrt{\frac{\pi}{8\mu}}(2f-2f_0-2\mu\alpha-\mu\beta)\right) - \text{erf}\left(\sqrt{\frac{\pi}{2\mu}}(f-f_0-\mu T_s)\right)\right), \end{aligned} \tag{8}$$
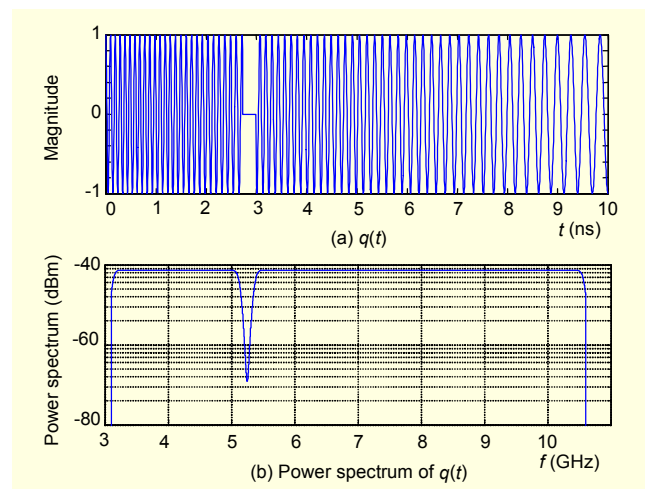

Fig. 3. Power spectrum and $q(t)$ of the proposed scheme.

where $\operatorname{erf}(x) = \dfrac{2}{\sqrt{\pi}} \displaystyle\int_0^x e^{-x^2}\, dx$ is the error function encountered in integrating the normal distribution.

The power spectrum is shown in Fig. 3(b). The notch in the time-domain maps directly onto the frequency domain. To achieve the desired transmission energy, $q(t)$ must be scaled appropriately. The magnitude-scaling module shown in Fig. 1 handles this task.

We consider a UWB direct sequence (DS) pulse amplitude modulation (PAM) system for performance evaluation. The transmitted DS-PAM signal is given by

$$m(t) = \alpha \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_s-1} d(i)\, c(j)\, q\big(t - iT_b - jT_s\big), \qquad (9)$$

where α is the amplitude of each CW, N_s is the number of signal waveforms in one transmitted bit, $c(j) \in \{-1,+1\}$ is the j-th DS code with the length of N_s, $d(i) \in \{-1,+1\}$ is the i-th transmitted data bit, T_b is the time duration occupied by one bit, and T_s is the time duration of one signal waveform. Generally, we have $T_b = N_s T_s$.

By notching frequency bands where licensed primary applications exist, the proposed CW avoids interference to and from the primary applications. Because there is no frequency domain processing, the processing delay is low in the proposed scheme.
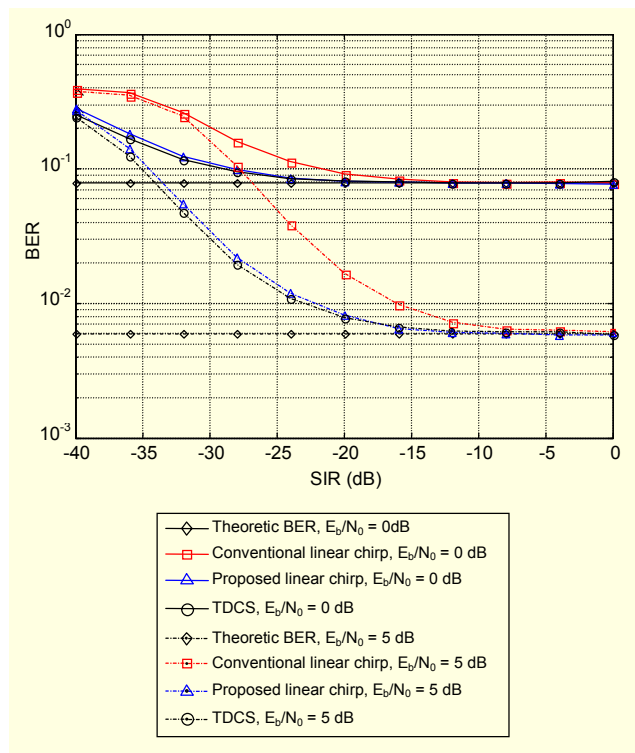
IV. Simulation Results

We compare the bit error rate (BER) of the proposed scheme to that of a conventional linear scheme [7] and a binary antipodal TDCS scheme [2]. The conventional linear scheme adopts linear CW with no NBI rejection abilities. The fundamental modulation waveform of the binary antipodal TDCS system is generated by the conventional inverse Fourier transform processing.

The chirp duration is 10 ns. The available bandwidth is 3.1 to 10.6 GHz. The interference source is a NB signal with the central frequency of 5.3 GHz and bandwidth of 200 MHz. All the simulations are based on AWGN channel. A matched filter is used at the receiver side for demodulation. We assume one primary application in the simulation.

Figure 4 shows the evaluation result of the BER versus signal to interference ratio (SIR) performance. The proposed scheme achieves obvious performance gains compared to the conventional linear chirp system without NBI rejection abilities: For instance, when $E_b/N_0 = 0$ dB, the proposed scheme has SIR gains of about 6 dB at an SIR of 10^{-1}. When $E_b/N_0 = 5$ dB, the proposed scheme has SIR gains of about 7 dB at an SIR of 10^{-2}. For any SIR, the proposed scheme is superior to the conventional linear chirp scheme without NBI suppression abilities. Moreover, the performance of the proposed scheme is similar to that of the binary antipodal TDCS scheme because they both utilize the spectrum notch in the system. The main advantage of our scheme is its lower complexity compared with TDCS.

Fig. 4. BER of the proposed CW, traditional one, and TDCS.

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