

# M-ary Bi-orthogonal Modulation UWB with Narrowband Interference Suppression Capability

Weihua Zhang, Hanbing Shen, Jong Ok Joo, and Kyung Sup Kwak

**ABSTRACT**—An  $M$ -ary bi-orthogonal modulation scheme for ultra-wideband (UWB) systems capable of narrowband interference (NBI) suppression is proposed in this letter. We utilize a set of bi-orthogonal pulse series to achieve NBI suppression. Through analysis and simulation, we verify that the proposed scheme can suppress NBIs effectively.

**Keywords**— $M$ -ary bi-orthogonal modulation (M-BOM), ultra-wideband (UWB), narrowband interference (NBI).

## I. Introduction

Ultra-wideband (UWB) is considered a good candidate for next generation wireless personal area networks (WPAN) [1]. Due to low emission spectrum density, the performance of UWB systems is badly affected by high-level narrowband interference (NBI), which can even cause UWB receivers to be jammed [2].

Multiple  $M$ -ary modulation schemes for UWB have been discussed, including  $M$ -ary pulse amplitude modulation (MPAM),  $M$ -ary pulse position modulation (MPPM), and so on [3]. An  $M$ -ary bi-orthogonal modulation (M-BOM) signaling set comprises  $M/2$  orthogonal waveforms and their negatives. Compared with  $M$ -ary PPM, M-BOM has a simpler receiver structure because the number of correlators is reduced to half [4].

In next generation wireless communication systems, especially cognitive radio systems, the transmitter knows the in-band NBI frequencies before sending any signals [5]. Waveforms with NBI suppression have been proposed in [6]. We propose an M-BOM scheme for UWB systems, which is capable of NBI suppression by synthesizing pulse series.

## II. Proposed M-BOM UWB System

In an M-BOM system, the  $M$  signal waveforms are

$$w_i(t) \in \{w_0(t), w_1(t), \dots, w_{M/2-1}(t), -w_0(t), -w_1(t), \dots, -w_{M/2-1}(t)\}, \quad (1)$$

where the first  $M/2$  waveforms form an orthogonal set, and the latter  $M/2$  waveforms are the negatives of the former  $M/2$  waveforms. The orthogonal condition satisfies

$$\int_{-\infty}^{\infty} w_i(t) w_j(t) dt = \begin{cases} 0 & \text{if } i \neq j, \\ 1 & \text{if } i = j, \end{cases} \quad (2)$$

where  $i$  and  $j \in \{0, 1, \dots, M/2-1\}$ .

The transmission signal  $s(t)$  is given by

$$s(t) = \sum_{i=-\infty}^{\infty} \sqrt{E_s} \sum_{j=0}^{N_s-1} w_{d_i}(t - iN_sT_f - jT_f), \quad (3)$$

where  $i$  is the symbol sequence number,  $E_s$  is the symbol energy,  $N_s$  is the frame repetition number,  $d_i \in \{0, \dots, M-1\}$  is the  $i$ -th symbol,  $w_{d_i}(t)$  is the  $d_i$ -th symbol waveform in the  $M$ -ary signaling set, and  $T_f$  is the frame length.

With a basis pulse waveform  $g(t)$  for IR-UWB systems [7], we define a series of pulses as

$$\begin{aligned} w_0(t) &= g(t) \\ &\vdots \\ w_n(t) &= \begin{cases} w_n^{(+)}(t) = w_{n-1}(t + \delta_n^{(+)}), & \text{if } t \in [0, T_p - \delta_n^{(+)}] \\ w_n^{(-)}(t) = w_{n-1}(t + \delta_n^{(-)}), & \text{if } t \in [T_p - \delta_n^{(-)}, T_p] \end{cases} \\ &\vdots \end{aligned} \quad (4)$$

which are recursive expressions, where  $g(t)$  is the basis waveform with duration of  $T_p$ . The  $n$ -th pulse series  $w_n(t)$  is the bipolar combination of the early and late time shift of the  $(n-1)$ th pulse series  $w_{n-1}(t)$ . Due to the two expressions of each pulse series, the  $n$ -th pulse series is composed of  $2^n$  impulses.

The  $n$ -th pulse series can be expressed by the  $(n-1)$ th pulse

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Weihua Zhang (phone: +82 32 860 9189, email: zhweihua2000@hotmail.com), Hanbing Shen (email: shen\_ice@hotmail.com), Jong Ok Joo (email: joojoo@mic.go.kr), and Kyung Sup Kwak (email: kskwak@inha.ac.kr) are with the Graduate School of IT&T, Inha University, Incheon, Rep. of Korea.

series passing a linear, time-invariant system with impulse response as follows:

$$\begin{aligned} H_n(j2\pi f) \\ = \begin{cases} H_n^{(+)}(j2\pi f) = \exp(j2\pi f \delta_n^{(+)}) + \exp(-j2\pi f \delta_n^{(+)}) = 2\cos(2\pi f \delta_n^{(+)}) \\ H_n^{(-)}(j2\pi f) = \exp(j2\pi f \delta_n^{(-)}) - \exp(-j2\pi f \delta_n^{(-)}) = 2j\sin(2\pi f \delta_n^{(-)}) \end{cases} \end{aligned}$$

Let the power spectrum density (PSD) of  $g(t)$  be  $G(f)$ . Then the PSD of the pulse series is given by

$$\begin{aligned} W_0(f) &= G(f) \\ &\vdots \\ W_n(f) &= |H_n(j2\pi f)|^2 W_{n-1}(f) \\ &= \begin{cases} |H_n^{(+)}(j2\pi f)|^2 W_{n-1}(f) = 4W_{n-1}(f) \cos^2(2\pi f \delta_n^{(+)}) \\ |H_n^{(-)}(j2\pi f)|^2 W_{n-1}(f) = 4W_{n-1}(f) \sin^2(2\pi f \delta_n^{(-)}) \end{cases} \end{aligned} \quad (5)$$

Since  $\cos^2(2\pi f \delta_n^{(+)})$  equals zero when  $f = (k_n^{(+)} + 0.5)/(2\delta_n^{(+)})$  with some integers of  $k_n^{(+)}$ , and  $\sin^2(2\pi f \delta_n^{(-)})$  equals zero when  $f = k_n^{(-)}/(2\delta_n^{(-)})$  with some integers of  $k_n^{(-)}$ , there are at least  $N$  different zero points in  $W_n(f)$ , where  $N$  is the number of NBI frequencies. If  $z_n$  is the set of zero points of the  $n$ -th pulse series, it can be expressed as

$$\begin{aligned} z_0 &= \phi \\ &\vdots \\ z_n &= \begin{cases} z_{n-1} \cup \left\{ x \mid x = (k_n^{(+)} + 0.5) / (2\delta_n^{(+)}) \right\} \\ z_{n-1} \cup \left\{ x \mid x = k_n^{(-)} / (2\delta_n^{(-)}) \right\} \end{cases} \\ &\vdots \end{aligned} \quad (6)$$

Assuming we know the  $N$  different NBI frequencies,  $f_{c_1}, f_{c_2}, \dots, f_{c_N}$ , we can set

$$\delta_n^{(+)} = \frac{k_n^{(+)} + 0.5}{2f_{c_n}} \text{ or } \delta_n^{(-)} = \frac{k_n^{(-)}}{2f_{c_n}} \text{ for } n \in \{1, 2, \dots, N\}, \quad (7)$$

by which we obtain a series of pulses with  $N$  different zero points at the given frequencies.

According to (7), for the pulse series with PSD of  $N$  different zero points, there are  $2^N$  combinations of parameter  $\delta$ . By assuming that the basis waveform  $w_0(t) = g(t)$  is time-limited such that the pulse duration  $T_p$  is much less than the delay  $\delta$  of the pulse series, we can form  $2^N$  impulse series waveforms which are orthogonal to each other with these  $2^N$  combinations of parameter  $\delta$ . We denote these  $2^N$  impulse series waveforms as  $w_{N,1}(t), w_{N,2}(t), \dots, w_{N,2^N}(t)$ , which forms an orthogonal signal set. With these  $2^N$  orthogonal impulse series waveforms, we can construct a  $2^{N+1}$ -ary bi-orthogonal modulation system according to (1) with the ability to suppress  $N$  different NBIs.

### III. Performance Evaluation

According to FCC regulation, the main emission spectrum of UWB is from 3.1 GHz to 10.6 GHz [8]. We use a basis pulse of  $g(t) = [\cos(2\pi f_h t) - \cos(2\pi f_l t)]/\pi t$ , where  $f_h = 10.6$  GHz and  $f_l = 3.1$  GHz. The normalized PSD of  $g(t)$ ,  $G(f)$ , is 1 if  $3.1 \text{ GHz} \leq f \leq 10.6 \text{ GHz}$  and 0 otherwise.

Figure 1 exemplifies the construction of pulse series  $w_{2,1}(t)$ , which is

$$\begin{aligned} w_{2,1}(t) &= w_{1,1}(t + \delta_2^{(+)}) + w_{1,1}(t - \delta_2^{(+)}) \\ &= w_0(t + \delta_1^{(+)} + \delta_2^{(+)}) + w_0(t - \delta_1^{(+)} + \delta_2^{(+)}) \\ &\quad + w_0(t + \delta_1^{(+)} - \delta_2^{(+)}) + w_0(t - \delta_1^{(+)} - \delta_2^{(+)}). \end{aligned} \quad (8)$$

We construct  $w_{1,1}(t)$  first. Then, we construct  $w_{2,1}(t)$  based on  $w_{1,1}(t)$  according to (4), and  $w_{2,2}(t)$ ,  $w_{2,3}(t)$  and  $w_{2,4}(t)$  can be similarly constructed.

In our simulation, the transmission signal is (3). The frame duration  $T_f$  is 20 ns, and  $N_s$  is 10. We assume additive white Gaussian noise (AWGN) with S-V CM1 as the transmission channel model [9]. An ARake receiver is adopted. Two NBIs are presented with different frequencies of 4.4 GHz and 5.3 GHz, the same bandwidth of 20 MHz, and the same power.

We designed an 8-ary proposed pulse series system. Figure 2(a) shows its time-domain waveforms. The time shift parameters  $\delta$  are identified according to (7). Here, we choose  $\{k_1^{(+)}, k_1^{(-)}, k_2^{(+)}, k_2^{(-)}\} = \{1, 2, 4, 15\}$  to form an orthogonal signal set. Figure 2(b) shows the PSD of the basis impulse  $g(t)$  and the pulse series. All the eight pulse series have the same zero points at 4.4 GHz and 5.3 GHz.

The symbol error rate (SER) is evaluated by simulation. The proposed 8-ary bi-orthogonal scheme is compared with conventional 8-ary PAM and 8-ary orthogonal PPM schemes.

Figure 3 shows the SER vs.  $E_b/N_0$  performance, and Fig. 4

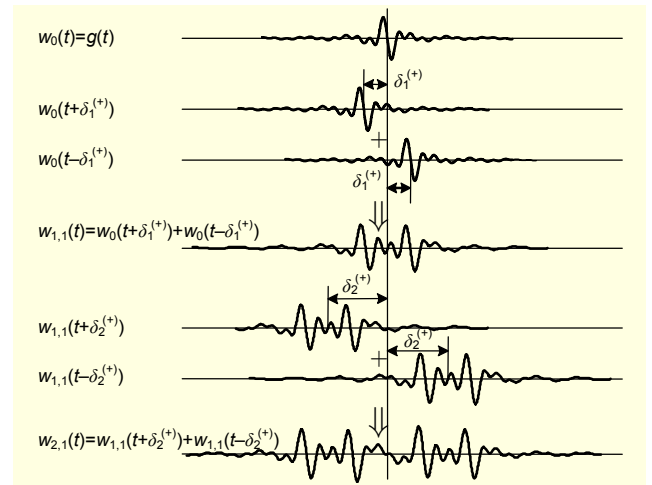


Fig. 1. Basis pulse  $g(t)$  and the construction of the  $w_{2,1}(t)$ .

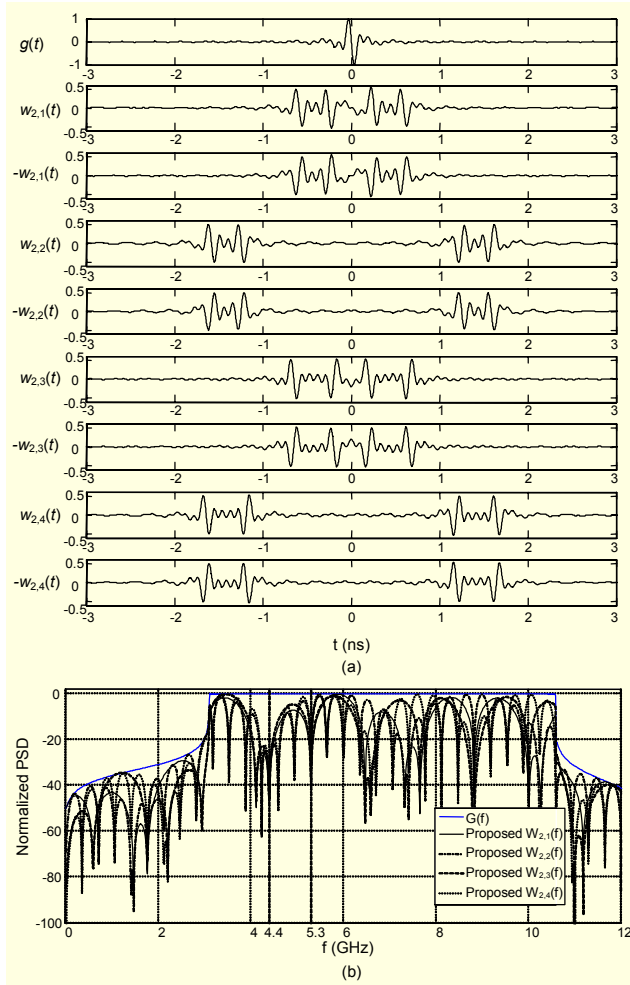


Fig. 2. (a) Time domain waveforms and (b) normalized PSD of the basis pulse  $g(t)$  and the proposed 8-ary bi-orthogonal pulse series.

shows the SER vs. signal-to-interference ratio (SIR) performance. The proposed scheme has a much lower SER than the other two schemes in terms of  $E_b/N_0$  and SIR scenarios. Compared with the orthogonal PPM scheme, when the SIR is  $-5$  dB, the proposed scheme has  $E_b/N_0$  gains of about  $6.7$  dB at an SER of  $2 \times 10^{-1}$ . By comparing the proposed scheme with the PAM system, more gains can be achieved. Moreover, when  $E_b/N_0$  is  $6$  dB, the proposed scheme has SIR gains of about  $30$  dB at an SER of  $10^{-1}$  compared to the orthogonal PPM scheme.

#### IV. Conclusion

In this letter, we propose a pulse-series-based M-BOM UWB system with NBI suppression ability. We compared the proposed scheme with impulse-based PAM and orthogonal PPM schemes when multi-tone NBI exists. Simulation results verified that the proposed scheme shows better performance.

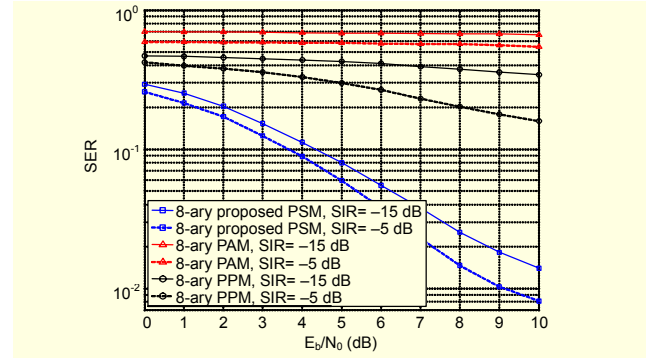


Fig. 3. SER vs.  $E_b/N_0$  performance of the proposed 8-ary pulse series,  $g(t)$  based 8-ary PAM, and orthogonal PPM system when NBIs with frequencies of  $4.4$  GHz and  $5.3$  GHz exist.

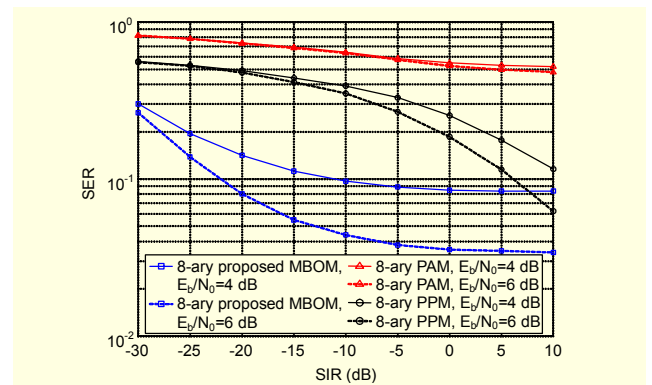


Fig. 4. SER vs. SIR performance of the proposed 8-ary pulse series,  $g(t)$  based 8-ary PAM, and orthogonal PPM system when NBIs with frequencies of  $4.4$  GHz and  $5.3$  GHz exist.

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