Performance of IEEE 802.15.4a Systems in the Presence of Narrowband Interference

Çağlar Fındıklı,[1] Serhat Erküçük,[2] Mehmet Ertuğrul Çelebi[1]
[1]Department of Electronics and Communications, Istanbul Technical University, Istanbul, Turkey
[2]Department of Electronics Engineering, Kadir Has University, Istanbul, Turkey
E-mail: cfindikli@itu.edu.tr, serkucuk@khas.edu.tr, celebi@ehb.itu.edu.tr

***Abstract*—The regulatory agencies in Europe and Japan require the implementation of avoidance techniques in some bands to reduce interference to licensed systems. Accordingly, ultra-wideband impulse radio (UWB-IR) based Wireless Personal Area Network (WPAN) standard IEEE 802.15.4a has suggested using linear combination of pulses to reduce interference to coexisting primary systems. In this paper, we consider the implementation of linear combination of pulses for a peaceful coexistence, and assess the UWB-IR system performance in the presence of an active narrowband system. For that, we study the possible transmitter and receiver structures that can be adapted for the physical layer of the IEEE 802.15.4a standard. The study shows that while the bit-error rate (BER) performances of coherent and noncoherent receiving structures may be slightly degraded with the use of linear combination of pulses when there is no active primary system, the performances can be significantly improved with appropriate filtering techniques at the receiver when the primary system is active.**

I. INTRODUCTION

Ultra wideband (UWB) systems are designed as underlay systems to share the spectrum with existing licensed communications systems [1]. Despite the low transmission power of such underlay systems, regulatory agencies in Europe and Japan have made the implementation of detect-and-avoid (DAA) techniques mandatory in some bands to avoid interference to existing systems [2]. Hence, one of the major implementation issues to be addressed in UWB communications has become the coexistence of licensed systems and UWB systems.

In the coexistence literature, either UWB pulse design techniques or performance degradations of licensed and/or UWB systems have been studied. In the pulse design techniques considered, the pulses have been designed to utilize the desired spectrum mask with no restriction on the number of filter coefficients [3]–[5]. However, in the IEEE 802.15.4a standard [6], it is suggested to use linear combination of a few pulses, which is equivalent to using few filter coefficients, for spectrum shaping purposes. Recently in [7], the authors have addressed generating notches at the desired frequencies by conforming to the restrictions in the standard.

In parallel to pulse design techniques, the effects of licensed systems (also referred to as "interference" from the UWB communications perspective) on the UWB system performance have been studied [8]–[11]. In [8], jam resistance of UWB systems was investigated for interferences with various bandwidths. In [9], the effects of GSM900, UMTS and GPS systems on the UWB system performance (and vice versa) were studied. The authors evaluated the performance of UWB systems employing differential-Rake (D-Rake) receivers in the presence of narrowband interference in [10]. In order to suppress the narrowband interference, the authors employed a notch filter at the receiver and evaluated the improved system performance for UWB transmitted reference systems in [11]. The common approach in these studies is that the UWB systems employ pulses that do not take into account the interference level caused by UWB systems to the licensed systems. However, as mandated by the European and Japanese regulatory agencies, the UWB systems should transmit pulses with reduced power levels at the frequency bands occupied by licensed systems.

Motivated by this condition, we consider the implementation of the physical layer of the IEEE 802.15.4a standard in the presence of a narrowband interference. For that, we use linearly combined pulses (as suggested by the standard) that can generate notches at the desired frequencies, present coherent and noncoherent receiver structures that can suppress the narrowband interference, and study the UWB system performance for various practical scenarios. These scenarios include studying the effects of the interference level, the pulse type (standard pulse vs. linearly combined pulse) and the IEEE 802.15.4a channel models for coherent and noncoherent receivers. The results of this study are important as it demonstrates the alternative implementation of the IEEE 802.15.4a system complying with the regulatory agency mandates for coexistence, and yet achieving a reasonable system performance.

The rest of the paper is organized as follows. In Section II, the physical layer of the IEEE 802.15.4a standard is presented. In Section III, a modified transceiver structure that is suitable for coexistence is presented. In Section IV, simulation results are presented in order to assess the UWB system performance in the presence of a narrowband interference for various scenarios. Concluding remarks are given in Section V.

II. IEEE 802.15.4A SYSTEM MODEL

In this section, the system model of the IEEE 802.15.4a based UWB impulse radios is presented that can support

978-1-4577-1764-2/11/$26.00 ©2011 IEEE

both coherent and noncoherent data reception [6]. The IEEE 802.15.4a standard uses the combined binary phase shift keying (BPSK) / binary pulse position modulation (BPPM) for data transmission. While both the phase and position information can be detected by the coherent detection, only the position information can be detected by the noncoherent detection. The system model that supports both coherent and noncoherent data reception is explained as follows.

For reliable communications in a dense multipath environment, data transmission is achieved by burst of pulses, where each of the N_b consecutive pulses are transmitted within a chip time T_c and $T_b = N_b T_c$ is the burst duration. The symbol time $T_s = N_c T_c$, where N_c is the number of chips in a symbol, is much greater than the burst duration T_b ($T_s >> T_b$) in order to allow time hopping (TH) for multiple access (MA) and accommodate guard times to prevent intra- and inter-symbol interferences. With this symbol structure, the l^{th} symbol of the 1^{st} user that carries the position and phase information can be transmitted using the signal model

$$w_l^{(1)}(t) = \sum_{j=0}^{N_b-1} a_l^{(1)} s_j^{(1)} p\Big(t - lT_s - jT_c - d_l^{(1)}\delta_p - c_l^{(1)}T_b\Big) \quad (1)$$

where $w_l^{(1)}(t)$ is the waveform of the 1^{st} user's l^{th} transmitted symbol consisting of N_b consecutive pulses, $p(t)$ is the transmitted pulse with duration $T_p \leq T_c$, and $s_j^{(1)} \in \{\pm 1\}$ $\{j = 0, 1, \ldots, N_b - 1\}$ is a scrambling sequence specific to user-1 that is used to smooth the spectrum. $a_l^{(1)} \in \{\pm 1\}$ is the user phase information and can only be seen by the coherent receiver, whereas $d_l^{(1)} \in \{0, 1\}$ carries the user position information that can be seen by both coherent and noncoherent receivers, where $\delta_p = T_s/2$ is the position shift parameter. Accordingly, this combined modulation is regarded as BPSK/BPPM. $\{c_l^{(1)}\}$ are the TH integer values that scramble the position of the burst for multiuser interference suppression. The condition $c_{max}T_b + T_d \leq \delta_p$ should be satisfied in order to prevent inter-symbol interference, where c_{max} is the maximum TH shift integer value and T_d is the maximum channel delay spread.

In order to prevent inter-pulse interference and to specifically evaluate the effect of linear combination of pulses, we assume a single user scenario with a single pulse transmitted (i.e., $N_b = 1$) without loss of generality. Thus, the transmitted signal can be simplified to

$$w_l^{(1)}(t) = a_l^{(1)} p\Big(t - lT_s - d_l^{(1)}\delta_p\Big). \quad (2)$$

In the presence of an active narrowband system, the received signal can be modeled as

$$r(t) = \tilde{w}_l^{(1)}(t) + J(t) + n(t) \quad (3)$$

where $\tilde{w}_l^{(1)}(t)$ is the received waveform of the 1^{st} user's l^{th} symbol, $J(t) = \sqrt{2J_0}cos(2\pi f_j t + \theta_j)$ is a single tone narrowband interference with average power J_0, carrier frequency f_j and random phase θ_j uniformly distributed over $[0, 2\pi)$, and $n(t)$ is the additive white Gaussian noise (AWGN) with two-sided power spectral density $N_0/2$. The signal $\tilde{w}_l^{(1)}(t)$ is the waveform distorted by the channel $h(t)$ and is represented as

$$\tilde{w}_l^{(1)}(t) = w_l^{(1)}(t) * h(t) \quad (4)$$

where $*$ is the convolution operator. The equivalent channel model $h(t)$ can be given as

$$h(t) = \sum_{i=0}^{L-1} h_i \delta(t - \tau_i) \quad (5)$$

where h_i is the i^{th} multipath channel coefficient, τ_i is the delay of the i^{th} multipath component and $\delta(\cdot)$ is the Dirac delta function. Consistent with the earlier studies, it is assumed that the channel coefficients are normalized, i.e., $h(t) = \sum_{i=0}^{L-1} h_i^2 = 1$, to remove the path loss effect, and that the delays $\{\tau_i\}$ occur at the integer multiples of the chip time T_c.

At the receiver, the information of user-1 transmitted by BPSK/BPPM can be detected either coherently or noncoherently.

A. Coherent receiver

The coherent receiver is a Rake receiver implemented using the delayed versions of the reference signal. The output of the correlator corresponding to the i^{th} finger of the Rake receiver for the m^{th} PPM position can be given by

$$\begin{aligned} D_{i,m}^{(1)} &= \int_{-\infty}^{\infty} r(t) v_m(t - \tau_i) dt \\ &= \int_{-\infty}^{\infty} \Big(\tilde{w}_l^{(1)}(t) + J(t) + n(t)\Big) v_m(t - \tau_i) dt \quad (6) \end{aligned}$$

$i = 0, \ldots, L_0 - 1$ for $m = 0, 1$, where

$$v_m(t) = p(t - lT_s - m\delta_p) \quad (7)$$

is the reference signal and L_0 is the number of Rake fingers used. Assuming that the channel parameters can be predicted, a maximal-ratio combiner is used to combine the Rake receiver outputs as

$$D_m^{(1)} = \sum_{i=0}^{L_0-1} h_i D_{i,m}^{(1)} \quad (8)$$

to form the decision variables. Since $\{D_m^{(1)}\}$ carries the phase information as well, the data is recovered as

$$\begin{aligned} \max\Big\{|D_m^{(1)}|\Big\} = D_{d_l'}^{(1)} &\quad \Rightarrow \quad d_l' \\ \text{sign}\Big\{D_{d_l'}^{(1)}\Big\} &\quad \Rightarrow \quad a_l' \quad (9) \end{aligned}$$

where $|x|$ and sign$\{x\}$ denote the absolute value and the sign of x, respectively.

B. Noncoherent receiver

The noncoherent receiver is an energy detector with the decision variables $\{D_m^{(1)}\}$, where

$$\begin{aligned} D_m^{(1)} &= \int_{m\delta_p}^{m\delta_p+T_i} r^2(t)dt \\ &= \int_{m\delta_p}^{m\delta_p+T_i} \Big(\tilde{w}_l^{(1)}(t)+J(t)+n(t)\Big)^2 dt \end{aligned} \qquad (10)$$

with $m=0,1$, which integrates the received signal energy for the duration of T_i. The position information is recovered by finding the maximum decision variable as

$$\max\{D_m^{(1)}\} = D_{d_l'}^{(1)} \Rightarrow d_l' \qquad (11)$$

III. MODIFIED TRANSCEIVER STRUCTURE

In the case of an active primary system sharing the same frequency band, the UWB system has to take an action. The UWB system can either use DAA techniques, or use pulses that have low power spectra at the primary systems' frequency bands. If the primary system is active most of the time, using DAA techniques may decrease the operation time of UWB systems significantly. Hence, we will consider the implementation of the linear combination of pulses to reduce the power level at the desired frequency of a narrowband system, and will consider a front-end filter matched to the linearly combined pulse at the receiver before coherent or noncoherent receiver processing. The modified transceiver structure is shown in Fig.1.

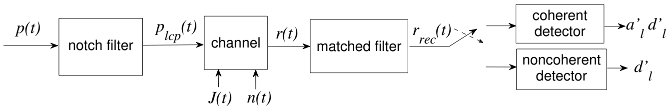

Fig. 1. Block diagram of the modified transceiver structure.

A. Linear Combination Of Pulses

The linear combination of pulses as defined in the IEEE 802.15.4a standard is

$$p_{lcp}(t) = \sum_{n=0}^{N-1} a_n \, p(t-\tau_n) \qquad (12)$$

where $p(t)$ is a standard pulse used in the data transmission, $a_n \in [-1,1]$ are the pulse coefficients, τ_n is the pulse delay, N is the number of pulses, and $p_{lcp}(t)$ is the new pulse shape. According to the standard [6], the maximum number of pulses is limited by 4, and the pulse delays are restricted to $0 \leq \tau_n \leq$ 4ns with $\tau_0 = 0$. The new pulse shape given in (12) has the frequency domain representation

$$\begin{aligned} P_{lcp}(f) &= \sum_{n=0}^{N-1} a_n \, e^{-j2\pi f \tau_n} P(f) \\ &= C(f) \cdot P(f) \end{aligned} \qquad (13)$$

where $C(f)$ is the code spectrum independent of the pulse spectrum $P(f)$. With the least number of pulse coefficients $\{a_n\}$, a notch at the frequency f_j (and also at the integer multiples of f_j) can be obtained by selecting $a_0 = 1$, $a_1 = -1$ and $\tau_1 = 1/f_j$ [7]. That is, if there is an active narrowband primary system at the frequency f_j, the UWB system can transmit the new pulse shape[1]

$$p_{lcp}(t) = p(t) - p(t - 1/f_j) \qquad (14)$$

without causing any interference. In Fig. 2, the magnitude spectra of a 2ns-duration root raised cosine pulse[2] and the linear combination of the root raised cosine pulses as in (14) with $f_j = 500$MHz are plotted. The notch frequencies can be observed at the integer multiples of f_j.

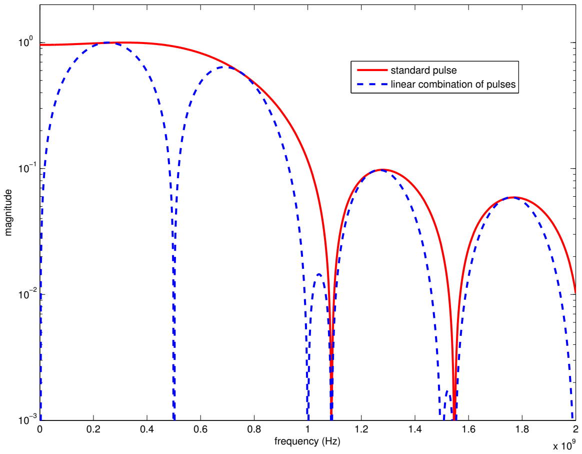

Fig. 2. Magnitude spectra of the standard and the linearly combined pulses.

B. Receiver Structures

Since the received signal contains the interference term $J(t)$, and the transmitted pulse shape is $p_{lcp}(t)$, the received signal should be matched filtered with $p_{lcp}(-t)$ before performing coherent or noncoherent detection. Accordingly, the signal at the output of the matched filter is

$$r_{rec}(t) = r(t) * p_{lcp}(-t). \qquad (15)$$

The useful signal component of $r_{rec}(t)$ can be obtained from (3), (4) and (15) as $\tilde{w}_l^{(1)}(t) * p_{lcp}(-t)$, where $\tilde{w}_l^{(1)}(t)$ consists of time-shifted pulses $p_{lcp}(t)$. Therefore, the correlation-based coherent receiver should use

$$v_{mrec}(t) = v_m(t) * p_{lcp}(-t) \qquad (16)$$

---

[1] Note that the energy of the linearly combined pulse, $p_{lcp}(t)$, should be normalized to the energy of the standard pulse, $p(t)$, under the same transmission power constraint.

[2] We refer to such monocycles as standard pulses in order to differentiate them from linearly combined pulses.

as the new reference signal to obtain the correlator outputs in (6). On the other hand, the matched filtered signal $r_{rec}(t)$ can be directly used in (10) for the noncoherent receiver.

In the following, the performances of the original IEEE 802.15.4a transceiver structure and the modified transceiver structure that allows for coexistence are compared for various practical scenarios.

IV. RESULTS

The system performances are evaluated in terms of the bit-error rate (BER) with respect to varying signal-to-noise-ratio (SNR) and signal-to-interference-ratio (SIR) values. The SNR and SIR are defined as E_b/N_0 and E_b/J_0, respectively, where E_b is the bit energy. It is assumed that the standard pulse used is a root raised cosine pulse with roll-off factor $\beta = 0.6$ and $T_p = 2$ns duration as given in [6]. The linearly combined pulse is obtained from (14) and generates a notch at $f_j = 500$MHz, where there is an active narrowband system. The channel models used are the standardized IEEE 802.15.4a channel models [12] with a channel resolution of $T_c = 2$ns.

Initially, the coherent receiver performance is assessed. In Fig. 3, the BER performances are plotted for various SIR values when SNR=15dB and 5-tap selective Rake receivers are used. When a standard pulse is used and there is no prefiltering (i.e., no matched filtering at the receiver front-end), the BER performance of the UWB system is poor for all SIR values and channel models. Note that this case is also unacceptable from the primary system's perspective (i.e., high UWB interference level). When a linearly combined pulse is used instead of the standard pulse, the corresponding correlator template at the receiver provides an inherent interference rejection capability although it is limited. When a prefilter is used as well, the narrowband interference is successfully suppressed at all SIR values. It should also be noted that the performances are better in the order of CM1, CM5 and CM8 as expected.

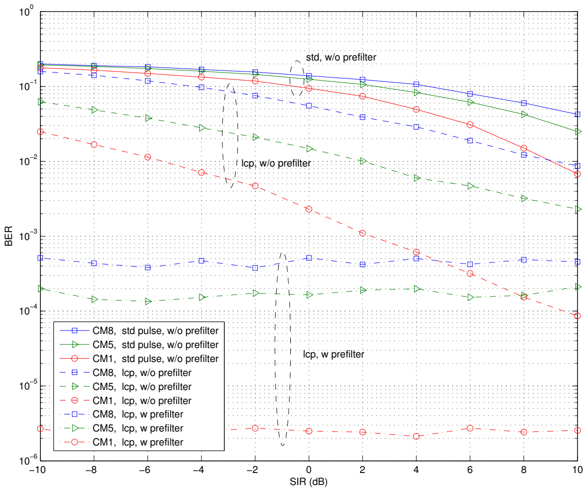

Fig. 3. BER performance of a 5-tap Rake receiver for various SIR values and transceiver structures when SNR=15dB.

In Fig. 4, the BER performances are plotted for various SNR values when 5-tap selective Rake receivers are used. When a standard pulse is used, the performances are the best. However, if a narrowband system becomes active the BER performances degrade drastically for both CM1 and CM8. When a linearly combined pulse is used, the performances are slightly worse than the standard pulse case (when there is no interference). This can be explained by the duration of the linearly combined pulse becoming longer than $T_p = 2$ns, which is also the assumed channel resolution. Hence, the performance degradation is due to the inter-pulse interference caused by the channel. If a narrowband system becomes active, while the linearly combined pulse with no prefiltering can provide some degree of interference suppression, including a front-end prefilter improves the performances close to the no interference case for CM1 and CM8.

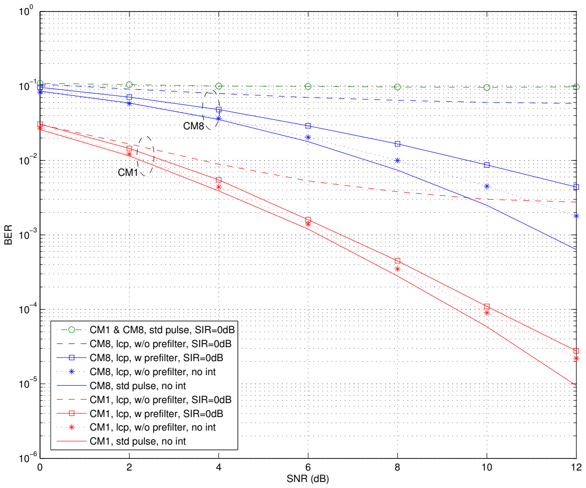

Fig. 4. BER performance of a 5-tap Rake receiver for various SNR values and transceiver structures.

Next, the noncoherent receiver performance is assessed in CM1. In Fig. 5, the BER performances are plotted for various SIR values when SNR=30dB and noncoherent receivers are used. When a standard pulse is used and there is no prefiltering, the BER performance of the UWB system is poor for all SIR values and integration durations. Similar to the coherent receiver case, using a linearly combined pulse improves the BER performance noticeably, whereas using also a prefilter at the front-end can suppress the interference independent from the SIR values. In Fig. 6, the BER performances are plotted for various SNR values when noncoherent receivers with different integration durations are used. Here, the performance of a standard pulse when there is no interference serves as a benchmark. When a linearly combined pulse is used for the same conditions, the performances are worse about 0.5–1dB compared to the standard pulse. This is also due to the linearly

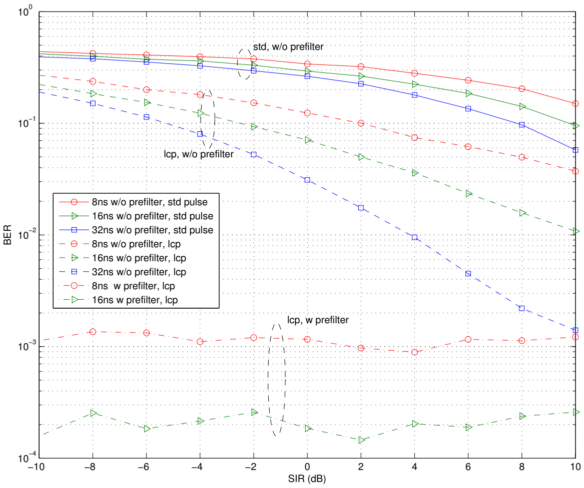

Fig. 5. BER performance of a noncoherent receiver in CM1 for various SIR values and transceiver structures when SNR=30dB.

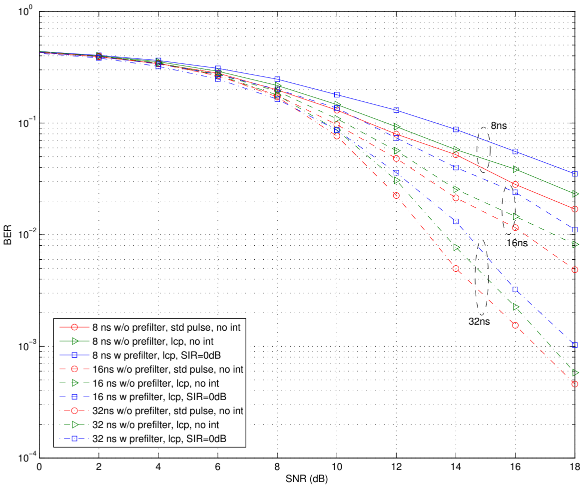

Fig. 6. BER performance of a noncoherent receiver in CM1 for various SNR values and transceiver structures.

combined pulse having a longer duration than the assumed channel resolution. If a narrowband system becomes active, the transceiver structure that uses the linearly combined pulse can activate the front-end prefilter and obtain 1–2dB worse performance compared to the standard pulse with no interference. It should also be noted that the performances improve with the increased integration durations at high SNR values.

While this study focused on the performance of the IEEE 802.15.4a based UWB systems in the presence of a single narrowband interference, future work will include the effects of multiple narrowband interferences and as well as wideband interferences on the system performance, when linear combination of UWB pulses is used.

V. CONCLUSION

In this paper, we investigated the possible implementations of linear combination of pulses and the corresponding receiver structures in order for an IEEE 802.15.4a based UWB system to be able to operate in the same frequency band with a licensed narrowband system. Accordingly, a modified transceiver structure that allows for coexistence was presented and the system performance was compared with the performance of a IEEE 802.15.4a system implemented according to the standard. The study showed that using a linearly combined pulse, the BER performances of coherent and noncoherent receiving structures may be slightly degraded when there is no active licensed system, however, the performances can be significantly improved with prefiltering at the receiver when the licensed system is active. The results presented are important as the modified transceiver structure can achieve a reasonable system performance while complying to the European and Japanese regulatory agency mandates.

ACKNOWLEDGMENT

This research was supported by a Marie Curie International Reintegration Grant within the 7th European Community Framework Programme.

REFERENCES

[1] M. Z. Win and R. A. Scholtz, “Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications,” *IEEE Trans. Commun.*, vol. 48, pp. 679–691, Apr. 2000.

[2] European Commission, “2009/343/EC: Commission Decision of 21 April 2009 amending Decision 2007/131/EC on allowing the use of the radio spectrum for equipment using ultra-wideband technology in a harmonised manner in the Community,” *Official Journal of European Union*, L 109, 9–13, Apr. 2009.

[3] X. Wu, Z. Tian, T. N. Davidson, and G. B. Giannakis, “Optimal waveform design for UWB radios,” *IEEE Trans. Signal Proc.*, vol. 54, pp. 2009–2021, June 2006.

[4] I. Dotlic and R. Kohno, “Design of the family of orthogonal and spectrally efficient UWB waveforms,” *IEEE Jour. Select. Topics Signal Proc.*, vol. 1, pp. 21–30, June 2007.

[5] Y. Wang, X. Dong, and I. J. Fair, “Spectrum shaping and NBI suppression in UWB Communications,” *IEEE Trans. Wireless Commun.*, vol. 6, pp. 1944–1952, May 2007.

[6] IEEE Std 802.15.4a-2007, “Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs),” 2007.

[7] S. Erküçük and B. A. Kaleli, “Linear combination of pulses for coexistence in the IEEE 802.15.4a standard,” *IEEE Proc. SIU*, pp. 620–623, Apr. 2009.

[8] L. Zhao and A. M. Haimovich, “Performance of ultra-wideband communications in the presence of interference,” *IEEE Jour. Select. Areas Commun.*, vol. 20, pp. 1684–1690, Dec. 2002.

[9] M. Hamalainen, V. Hovinen, R. Tesi, J. H. J. Iinatti, and M. Latva-aho, “On the UWB system coexistence with GSM900, UMTS/WCDMA, and GPS,” *IEEE Jour. Select. Areas Commun.*, vol. 20, pp. 1712–1721, Dec. 2002.

[10] M. Di Renzo, F. Tempesta, L. A. Annoni, F. Santucci, F. Graziosi, R. Minutolo, and M. Montanari, “Performance evaluation of IR-UWB D-Rake receivers over IEEE 802.15.4a multipath fading channels with narrow-band interference,” *IEEE Proc. ICUWB*, pp. 71–76, Sep. 2009.

[11] S. Cui, K. C. Teh, K. H. Li, Y. L. Guan, and C. L. Law, “Narrowband interference suppression in transmitted reference UWB systems with inter-pulse interference,” *IEEE Proc. ICUWB*, pp. 895–898, Sep. 2007.

[12] A. F. Molisch et. al., “A comprehensive standardized model for ultrawideband propagation channels,” *IEEE Trans. Antennas Propag.*, vol. 54, pp. 3151–3166, Nov. 2006.