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Research Article

Analysis and Mitigation of the Narrowband Interference Impact on IR-UWB Communication Systems

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The impact of narrowband interference signals on impulse radio ultrawideband (UWB) communication systems has been investigated. A closed form expression for the bit error rate performance of UWB communication system in a Log-normal flat fading channel under such impact is evaluated. The actual UWB channel model is known as a multipath fading channel; however flat fading channel model can be considered with some of the UWB wireless applications such as UWB wireless sensor networks which are characterized by size and energy constraints. Thus, a simple and low-cost one-finger Rake receiver can be used with such wireless systems. It was proven that UWB systems unavoidably suffer from the interference caused by the coexisting systems due to the restraint on their transmission power levels. To this end, we propose an interference canceller scheme which is capable of suppressing the impact of such interference and enhancing the performance of UWB communication systems. The interference canceller scheme performance is also investigated in various scenarios of operation such as the presence of multiple narrowband interference signals, symbol timing error, and a comparison with a notch filter-based case.

1. Introduction

In comparison with some traditional communication technologies, UWB communication technologies have some advantages, such as higher multipath resolution, higher data throughput, low probability of detection, and low probability of intercept. So, it is very natural that the appeal of UWB signaling for communications has been more recent and has attracted a lot of attention globally [1].

In order to reduce the interference to existing narrowband systems, the Federal Communications Commission (FCC) also imposed a power restriction on UWB communication systems, where the power spectral density levels are limited to -41.3 dBm/MHz. However, its performance can suffer considerably in the presence of strong narrowband interferences [2, 3].

Previous work on performance analysis of UWB communication systems in the presence of NBI has been largely focused on different types of channel models. In [4] such performance has been investigated in additive white Gaussian noise (AWGN) channel model under the impact of IEEE802.11a narrowband interference, whereas in [5], such performance has been investigated in Nakagami flat and frequency-selective UWB fading channel models. The impact of NBI on the performance of UWB communication systems in Log-normal multipath fading channel has been investigated in [6].

In 2003, the IEEE802.15.3a model was developed by a standardization group for UWB communication systems in order to compare standardization proposals for high-data rate wireless personal area networks [7]. Although it is clear that the actual UWB channel model is a multipath fading channel, some wireless systems such as the wireless sensor networks are characterized by size and energy constraints. These constraints are imposed on each node that necessitate the use of simple devices. Thus, a one-finger Rake receiver can be considered as a suboptimal solution for simple and low-cost communication systems.

To this end, the goal of this paper is to investigate the performance of IR-UWB communication systems in the presence of NBI in a Log-normal flat fading channel. A closed form expression for the bit error rate (BER) performance of such systems in the presence of NBI by using a Gaussian Hermite quadrature expansion is derived. In addition, to propose the use of a NBI cancellation scheme that had been used previously with CDMA systems. It will be shown that such canceller scheme is capable of mitigating the impact of NBI signals on UWB communication systems. Its performance is also investigated in different scenarios of operation such as symbol timing error and the presence of multiple NBI signals. Finally, its performance will be compared with the performance obtained by using a notch filter.

The paper is organized as follows. The system model is described in Section 2. In Section 3 the UWB BER performance is analyzed. The idea of such canceller scheme is presented in Section 4. Section 5 presents the used simulation procedures for the proposed canceller scheme. Representative numerical and simulation results are presented in Section 6. Finally, Section 7 draws the conclusions.

2. System and Channel Models

A binary communication system in a single-user case is considered. For a matched filter (MF) reception, the transmitted UWB signal can be written in the form of a time hopping pulse position modulation (TH-PPM) as

$$S_{\text{PPM}}(t) = \sqrt{E_b} \sum_{j=-\infty}^{\infty} p\left(t - jT_f - c_j T_c - \delta d_{\lfloor j/N_s \rfloor}\right), \tag{1}$$

where $p(t)$ is the shape of the transmitted pulse with pulse width T_m, d_j is the transmitted jth binary data bit and composed of equally likely bits, and E_b is the bit energy. N_s is the number of pulses transmitted per bit, T_c is the hop width, and c_j is the TH code, $c_j \in \{0, 1, \ldots, N_h - 1\}$, such that an additional time shift of "$c_j T_c$" is introduced when the jth pulse is transmitted. T_f is the frame duration, satisfying $T_f = N_h T_c$; the bit duration can be represented as $T_b = T_f = N_c T_c$ and δ is the modulation index (the time shift added to a pulse with an optimal value of 20% of a pulse width [8]).

The NBI signal, $I(t)$, is modeled as the standard IEEE802.11a, which can be approximated as the sum of "N" tone interferers and it can be written as

$$I(t) = \sum_{n=1}^{N_i} \sqrt{2I_n} \cos(2\pi f_n t + \phi_n), \tag{2}$$

where "f_n" is the nth interference frequency and "ϕ_n" is the phase which can be considered as a random variable uniformly distributed over the interval $[0, 2\pi)$, "I_n" is the transmitted power of the nth tone signal.

Recent measurements indicate that the probability density function (pdf) of the received power in UWB channels is well approximated by Log-normal distribution [9]. Thus, the impulse response of the UWB system in a flat fading channel can be written as [10]

$$h_s(t) = a_s \delta(t - \tau_s), \tag{3}$$

where "a_s" is the channel gain coefficient, and "τ_s" is the associate channel time delay.

We will assume that the NBI signal is affected by Rayleigh fading, thus the NBI channel impulse response can be written as

$$h_i(t) = \alpha_{I_n} \delta(t - \tau_n), \tag{4}$$

where "α_{I_n}" is the Rayleigh distributed channel gain, and "τ_n" is the corresponding time delay, $n = 1, \ldots, N_i$.

The overall received signal, $r(t)$, can be written as

$$r(t) = s_d(t) + i_n(t) + n(t), \tag{5}$$

where, $n(t)$ is the AWGN with two-sided power spectral density "$N_o/2$". The UWB received signal, $s_d(t) = S_{\text{PPM}}(t) * h_s(t)$, can be written as

$$s_d(t) = \sum_{j=-\infty}^{\infty} a_s \sqrt{E_b}\, p\left(t - jT_f - c_j T_c - \delta d_{\lfloor j/N_s \rfloor} - \tau_s\right), \tag{6}$$

while the NBI received signal, $i_n(t) = I(t) * h_i(t)$, can be written as

$$i_n(t) = \sum_{n=1}^{N_i} \alpha_{I_n} \sqrt{2I_n} \cos(2\pi f_n (t - \tau_n) + \phi_n). \tag{7}$$

Without loss of generality, we will assume that the desired signal channel impulse response, $h_s(t)$, and the interferer channel gains, α_{I_n}, are normalized such that $E[a_s^2] = 1$, and $E[\alpha_{I_n}^2] = 1$, where $E[\cdot]$ denotes the expectation operator.

3. Performance Analysis

In this section, we evaluate the performance of a TH-PPM-UWB system in the presence of NBI in a Log-normal flat fading channel. It will be assumed that the channel is perfectly known at the MF receiver.

The correlation mask can be written as

$$\begin{aligned} m'(t) &= a_s \cdot m(t), \\ m(t) &= [p(t) - p(t - \delta)]. \end{aligned} \tag{8}$$

The transfer function of the MF receiver can be written as $|M(f)| = F.T.\{m(t)\}$, where $F.T.\{\cdot\}$ represents the Fourier Transform process; we can note that "$M(f)$" depends on the used pulse waveforms.

For a TH-PPM UWB system $M(f)$ can be written as

$$\begin{aligned} |M(f)| &= 2|P(f)||\sin(\pi f \delta)| \\ &\quad \times \sum_{k=0}^{N_s-1} \exp\left(j2\pi f\left(kT_f + c_k T_c\right)\right), \end{aligned} \tag{9}$$

where $P(f)$ is the Fourier Transform of the UWB pulse, $p(t)$, which can be modeled as the six derivative Gaussian pulse as suggested in [11]

$$p(t) = \sqrt{\frac{640}{231N_s\tau_p}} \times \left[1 - 12\pi\left(\frac{t}{\tau_p}\right)^2 + 16\pi^2\left(\frac{t}{\tau_p}\right)^4 - \frac{64}{15}\pi^3\left(\frac{t}{\tau_p}\right)^6\right] \times \exp\left[-2\pi\left(\frac{t}{\tau_p}\right)^2\right], \tag{10}$$

where τ_p is the pulse shaping factor, and the energy of $p(t)$ is $E_p = 1/N_s$.

$$P(f) = \frac{8\pi^3}{3\sqrt{1155N_s}}\tau_p^{13/2} f^6 e^{(-\pi/2)f^2\tau_p^2}. \tag{11}$$

With the consideration of perfect synchronization with the desired signal, the decision statistic can be written as

$$Z = \sum_{j=-\infty}^{\infty}\int_{jT_f}^{j(T_f+1)} r(t)\cdot m'(t)dt$$
$$Z = S_{\text{ppm}} + I_N + n, \tag{12}$$

where S_{ppm}, I_N, and n are the desired signal, interference, and noise components, respectively.

$$S_{\text{ppm}} = \sqrt{E_b}\left(1-\varrho\right)a_s^2, \tag{13}$$

where ϱ is the correlation coefficient between the two pulses $p(t)$ and $p(t-\delta)$, for bits 0 and 1, respectively, ϱ can be written as

$$\varrho = \int_{-\infty}^{\infty} p(t)p(t-\delta)dt, \quad \varrho \in [-1,1]. \tag{14}$$

The interference term, I_N can be written as

$$I_N = \sum_{n=1}^{N_i}\alpha_{I_n}\sqrt{2I_n}\,|M(f_n)|\cos(\phi_n). \tag{15}$$

Following the same approach as [11], the phase term $\{\arg[M(f_n)] + 2\pi f_n(t-\tau_n)\}$ is included within the random phase ϕ_n, conditioned on the r.v. $|M(f_n)|$. Also, each term $\alpha_{I_n}\cos(\phi_n)$ is a zero mean Gaussian r.v. with variance "1/2". Thus, the NBI term, "I_N" can be considered conditionally Gaussian with variance $[\sigma_i^2 = \sum_{n=1}^{N_i} I_n\cdot|M(f_n)|^2]$.

The variance of the noise can be written as

$$\sigma_N^2 = N_o\left(1-\varrho\right)a_s^2. \tag{16}$$

The total disturbance due to the NBI plus noise can be considered conditionally Gaussian with variance $[\sum_{n=1}^{N_i} I_n\cdot|M(f_n)|^2 + \sigma_N^2]$.

The conditional bit error probability (BEP), conditioned on (a_s) can be written as

$$P_{e|a_s} = Q\left(\sqrt{a_s^2\gamma}\right), \tag{17}$$

where

$$\gamma = \frac{1}{\left(N_o/E_b\left(1-\varrho\right)\right) + \left(\sum_{n=1}^{N_i}|M(f_n)|^2/\text{SIR}\cdot T_b\cdot\left(1-\varrho\right)^2\right)}, \tag{18}$$

where SIR is the signal to interference ratio.

Since "a_s" is Log-normally distributed, then "a_s^2" is Log-normally distributed as well. The BEP expression is obtained by averaging (17) over "a_s^2" as

$$P_e \simeq \int_0^{\infty} Q\left(\sqrt{a_s^2\gamma}\right)\cdot f(a_s)da_s, \tag{19}$$

where $f(a_s)$ is the pdf of (a_s), which is normally distributed with mean (μ_r) and variance (σ_r^2), and is given by

$$f(a_s) = \frac{1}{a_s\sigma_r\sqrt{2\pi}}\exp\left(\frac{-[\ln(a_s)-\mu_r]^2}{2\sigma_r^2}\right). \tag{20}$$

Parameters (μ_k,σ_k) are usually introduced to characterize a Log-normal distribution in wireless communications, where as presented in [12] $\mu_k = \lambda\mu_r$, $\sigma_k = \lambda\sigma_r$, and $\lambda = 10/\ln(10)$. The parameter "σ_k" is known as the dB spread, and its value ranges between 6 and 12 dB for most of the wireless communication systems [12], and between 2 and 5 dB for the UWB systems [13].

In order to calculate (19), the Q-function can be presented by the Craig's formula [14]

$$Q(x) = \frac{1}{\pi}\int_0^{\pi/2}\exp\left(-\frac{x^2}{2\sin^2(\phi)}\right)d\phi. \tag{21}$$

Then, by substituting in (19)

$$P_e = \frac{1}{\pi}\int_0^{\pi/2}\left[\int_0^{\infty}\exp\left(-\frac{a_s^2\gamma}{2\sin^2(\phi)}\right)\frac{1}{a_s\sigma_r\sqrt{2\pi}}\cdot\exp\left(\frac{[\ln(a_s)-\mu_r]^2}{2\sigma_r^2}\right)da_s\right]d\phi, \tag{22}$$

By letting $x = ((\ln(a_s)-\mu_r)/(\sqrt{2}\sigma_r))$, P_e will become

$$P_e = \frac{1}{\pi}\int_0^{\pi/2}\left[\frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty}e^{-x^2}\cdot\exp\left(-\frac{\gamma}{2\sin^2(\phi)}\cdot\exp\left[2\sqrt{2}x\sigma_r + 2\mu_r\right]\right)dx\right]d\phi. \tag{23}$$

The inner integral in (23) can be approximated by a Gauss-Hermite series expansion to become

$$= \frac{1}{\sqrt{\pi}}\sum_{i=1}^{N} w_i\exp\left(-\frac{\gamma}{2\sin^2(\phi)}\exp\left[2\sqrt{2}b_i\sigma_r + 2\mu_r\right]\right)d\phi, \tag{24}$$

where "w_i" and "b_i" are the weights and the associated roots of the Hermite polynomial, respectively. The values of "w_i"

and "b_i" can be found in [15]. "N" is the number of samples points used in this approximation.

By substituting (24) in (23) we will get

$$P_e = \frac{1}{\sqrt{\pi}} \sum_{i=1}^{N} w_i \times \left[\frac{1}{\pi} \int_0^{\pi/2} \cdot \exp\left(-\frac{\gamma}{2\sin^2(\phi)} \cdot \exp\left(2\sqrt{2} b_i \sigma_r + 2\mu_r\right) \right) \right] d\phi. \quad (25)$$

This equation can be rearranged, where a closed form expression of the BER performance of a UWB system in the presence of NBI signal can be finally evaluated as

$$P_e = \frac{1}{\sqrt{\pi}} \sum_{i=1}^{N} w_i \left[Q\left(\sqrt{\gamma \cdot \exp\left(2\sqrt{2} b_i \sigma_r + 2\mu_r\right)} \right) \right]. \quad (26)$$

4. ICS Performance Analysis

Assuming that the NBI signal is modeled as the standard orthogonal frequency division multiplexing (OFDM) IEEE802.11a signal and the UWB receiver is subjected to a single high power IEEE802.11a NBI signal; the idea of the ICS operates by (1) the incoming received signal will be split into two paths. In the first path an attempt to demodulate the NBI signal from the incoming received signal is done. (2) The output from the demodulation process will be used to regenerate the NBI signal. (3) The regenerated NBI signal will be multiplied by the NBI channel estimate prior to its subtraction from the incoming received signal at the input of the UWB receiver.

If the demodulation process is successful and the NBI channel model is perfectly known, the NBI signal can be perfectly suppressed from the incoming received signal and the reception of the UWB signal can be achieved as if there was no interference.

Figure 1 depicts a simplified schematic model of such canceller scheme. Note that, it has been shown in [5] that the assumption of sum of tone interferers is a good approximation for an OFDM signal. Thus, the OFDM-based IEEE802.11a NBI signal is approximated as "N" tone interferers (equal to the OFDM data subcarriers).

In order to analyze the performance of the ICS, the performance of the NBI receiver has to be initially investigated. The NBI receiver probability of symbol error can be summarized into one of the following cases.

Case 1: No Symbol Errors. If the NBI demodulator produces no errors, then the NBI receiver will be able to perfectly regenerate the NBI signal and the canceller scheme will efficiently suppress the NBI signal. In such case, the BER performance of the ICS is equivalent to the performance of a UWB system in the absence of interference.

Case 2: Multiple Symbol Errors. When the NBI demodulator produces multiple symbol errors, the BER of the ICS in this case can be written as

$$\begin{aligned} (P_e)_{\text{uwb}}^{\text{ics}} &= P_{e-\text{uwb}}^{\text{no int.}} \times \left(1 - P_{\text{ofdm}}^{e=1} - \cdots - P_{\text{ofdm}}^{e=e'}\right) \\ &\quad + P_{e-\text{uwb}}^{1} \times P_{\text{ofdm}}^{e=1} + \cdots + P_{e-\text{uwb}}^{e'} \times P_{\text{ofdm}}^{e=e'}, \end{aligned} \quad (27)$$

where $P_{e-\text{uwb}}^{\text{no int.}}$ is the BER performance of a UWB system in the absence of interference, $(P_{e-\text{uwb}}^{e'})$ is the probability of a UWB system in the presence of (e') tone interferers, while $(P_{\text{ofdm}}^{e=e'})$ is the probability of e' symbol errors occurring in a block of length "N" symbols.

Note that, the probability that the NBI receiver produces "e" symbol errors over a block of "N" symbols is given by [16]

$$P_{\text{ofdm}}^{e} = \frac{N!}{(N-e)! \times e!} P^e (1-P)^{N-e}, \quad (28)$$

where "N" can be interpreted for an OFDM NBI signal as the number of the OFDM data subcarriers, and "P" is the probability of symbol error.

It is worth mentioning that, the NBI receiver average probability of OFDM symbol error (av. Pse) can be considered as one of the main factors that control the performance of such canceller scheme. By manipulating this parameter we can evaluate the ICS performance.

5. Simulation of the ICS

Figure 2 depicts the simulation blocks of the ICS. The sampling rates of the UWB and IEEE802.11a NBI signals are "50 GHz" and "20 MHz," respectively. In simulation points "C and D", the IEEE802.11a NBI signal and the UWB signals are generated after adding the impact of their respective channel models.

Detection and noise level adjustment stages are used in order to generate the AWGN with the desired SNR ratio. It is worth mentioning that pilot symbols are inserted at the IEEE802.11a transmitter in all frequency domains at fixed time intervals (as in each subcarrier channel, the level of fluctuation is independent), where at the receiver the NBI channel is estimated with the aid of these pilot symbols.

6. Numerical Results

In this section, numerical examples are presented to investigate the performance of both a TH-PPM system and the ICS in Log-normal flat fading channels and validated with the aid of simulation. A six derivative Gaussian received pulse will be used with values: $\tau_p = 0.192$ ns, $\delta = 0.068$ ns, $T_f = 10$ ns, $N_s = 1$ pulse/bit, and $\varrho = -0.824$. The standard IEEE802.11a NBI signal will operate at the upper U-NII band with center frequency = 5.745 GHz, and the frequency spacing between the carriers $\Delta f = 0.3125$ MHz.

Figure 3 numerically evaluates the BER performance of TH-PPM UWB system in the presence of IEEE802.11a NBI at different SIRs. It can be seen that the performance of a UWB

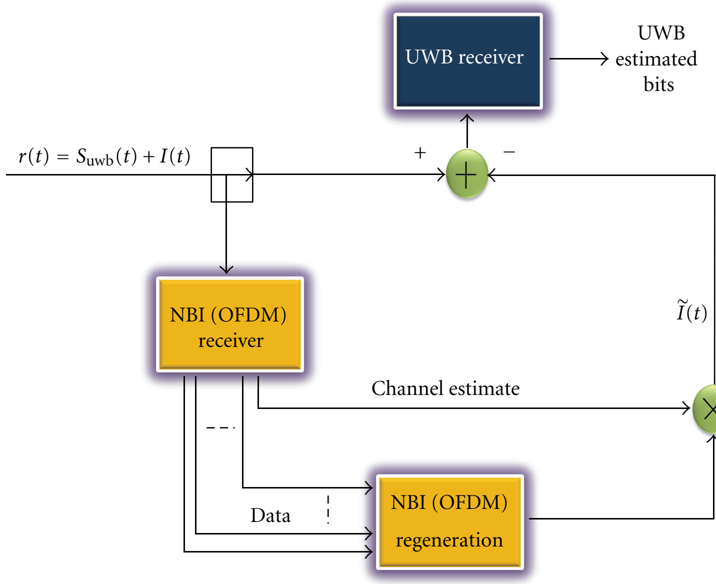

FIGURE 1: A simplified schematic model for the proposed canceller scheme.

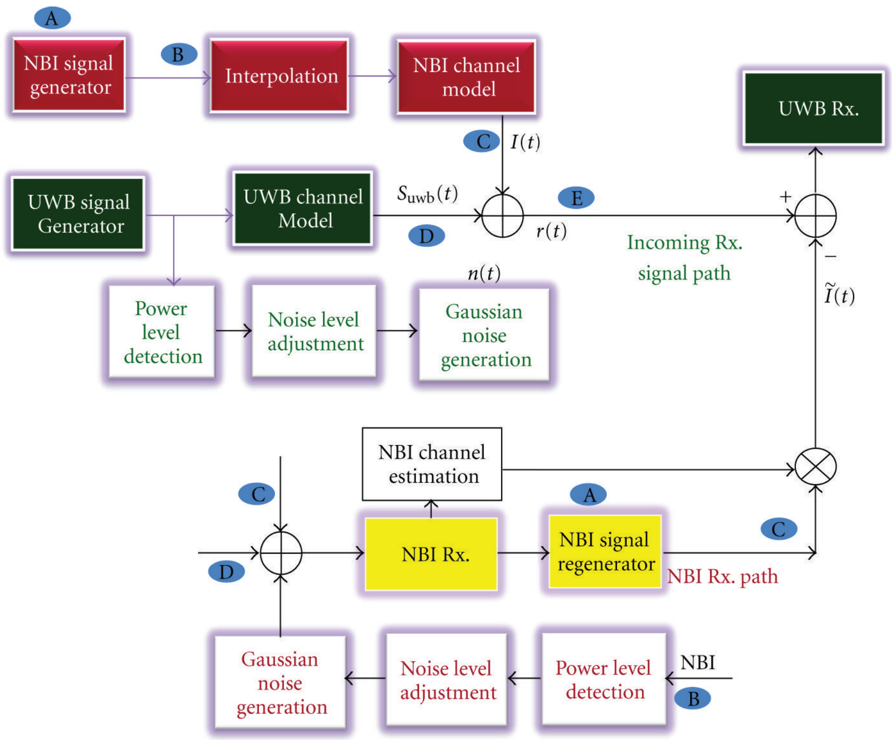

FIGURE 2: Simulation block diagram of the proposed canceller scheme.

system is deteriorated due to the presence of NBI. A SNR degradation is expected to be less than 2 dB and 12 dB for SIR = −5 and −10 dB, respectively, at BER = 1×10^{-2}.

Figure 4 depicts a comparison between the simulation and analytical performance of a TH-PPM UWB system with the aid of the ICS at SIR = −10 dB and dB-spread = 3 dB. It can be seen that the impact of NBI can be completely suppressed at an av. Pse = 1×10^{-3}, whereas for an av. Pse = 0.05, the SNR degradation is less than 2 dB at BER = 1×10^{-3}.

Also it can be seen that the simulation and the analytical results are in a good agreement, in which we can conclude the validation of the obtained analytical results.

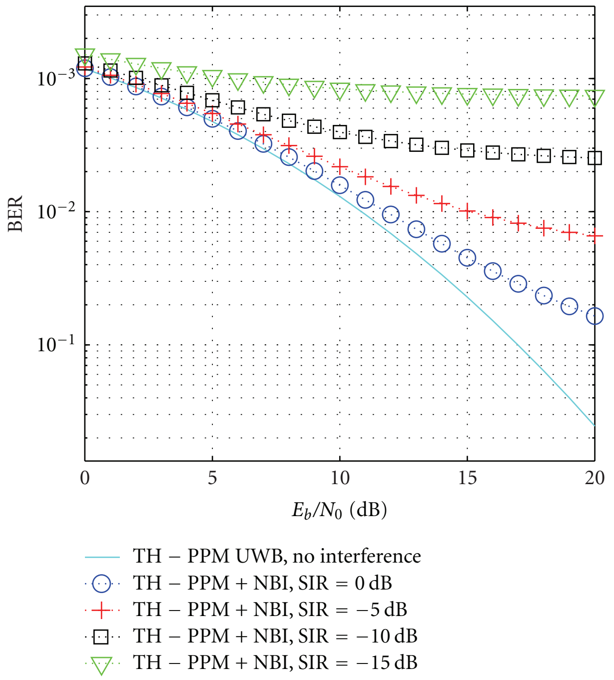

FIGURE 3: TH-PPM UWB performance in the presence of NBI.

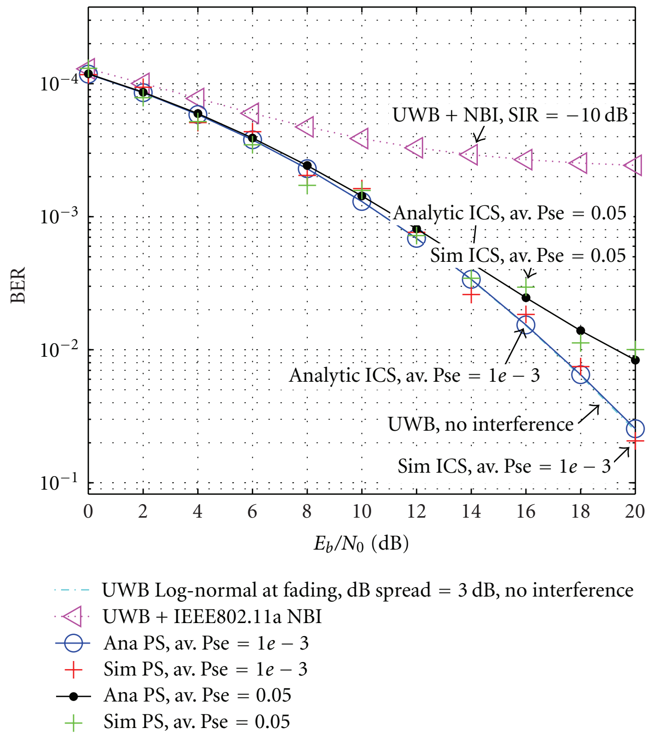

FIGURE 4: Simulation and analytical performance comparison of the ICS, dB-spread = 3 dB and SIR = −10 dB.

Now the performance of the ICS is investigated in various scenarios of operation as follows.

6.1. Symbol Timing Error. The first considered scenario is the presence of symbol timing errors (timing misalignment errors) between the regenerated NBI signal and the incoming received signal at the input of the subtraction process.

Figure 5 depicts the ICS performance in a Log-normal flat fading channel, the av. Pse = 0.1, dB-spread value = 2 dB and SIR = −15 dB. It can be seen that for a timing misalignment error equal to 0.5%, there is an additional SNR degradation equal to 2 dB at BER = 3×10^{-3}, whereas, for a timing misalignment error equals to 1% there is an additional SNR degradation equals to 4 dB at BER = 5×10^{-2}.

6.2. Multiple NBI Signals. The second considered scenario is the presence of two IEEE802.11a NBI signals. The ICS attempts to mitigate the impact of each NBI signal individually, where it regenerates and subtracts each NBI signal from the incoming received signal at the input of the UWB receiver. It is worth noting that the two used NBI signals have center frequencies 5.22 GHz and 5.745 GHz, respectively.

Figure 6 depicts a comparison between the BER performances of the canceller scheme in the presence of one and two NBI WLANs, the dB-spread value is 3 dB and the SIR = −10 dB.

It can be seen that an additional SNR degradation in the ICS performance is expected to be less than 2 dB at BER = 1×10^{-2}.

6.3. Notch Filter-Based Case. The performance effectiveness of the ICS is analyzed by making a comparison with the performance obtained by using a notch filter. The notch filter was simulated as a resonator with quality factor (Q = 35). The 3 dB bandwidth of the notch filter with the previous quality factors will be 165 MHz for a WLAN NBI signal with center frequency = 5.745 GHz.

The comparison is done in two scenarios: (1) the notch filter is assumed perfectly tuned to the center frequency of the NBI signal. (2) The notch filter is detuned and there is a shift between the center frequency of the NBI signal and the notch frequency.

Figure 7 depicts the BER performance comparison between a notch filter which is perfectly tuned to the center frequency of the NBI signal and the proposed ICS at SIR = −10 dB and dB-spread = 3 dB. It can be seen that the ICS with av. Pse = $1e-3$ and 0.01 outperforms the perfectly tuned notch filter. However, for an av. Pse = 0.05, the notch filter outperforms the ICS specially for large SNR.

Figure 8 depicts this comparison with a detuned notch filter with a notch frequency shift equal to 40 MHz. It can be seen that the ICS always outperform the detuned notch filter even with an av. Pse = 0.05, which means that the notch filter has to be perfectly tuned and has a prior knowledge about the center frequency of the NBI.

6.4. ICS Complexity. It can be seen from the previous discussion that the proposed canceller scheme is more complex than the use of a notch filter. Yet, the notch filter has to have a prior knowledge of the NBI signal. Also, the ICS is more agile than the notch filter based case in mitigating NBI

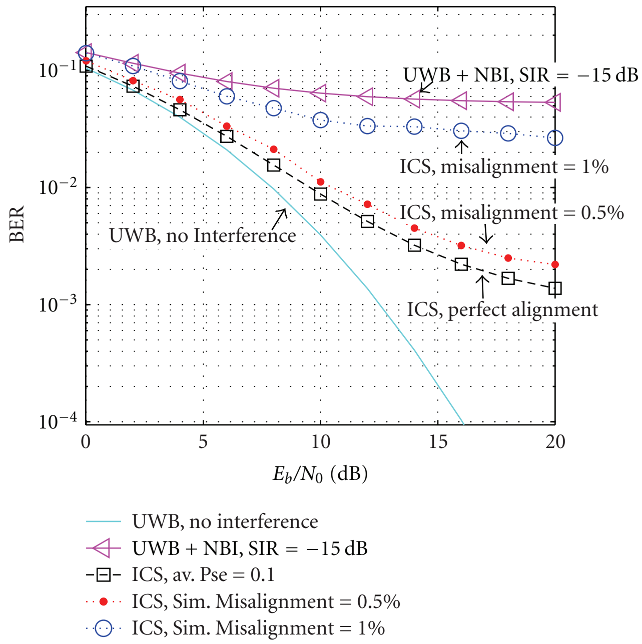

FIGURE 5: Timing error impact in the ICS performance, dB-spread = 2 dB and SIR = −15 dB.

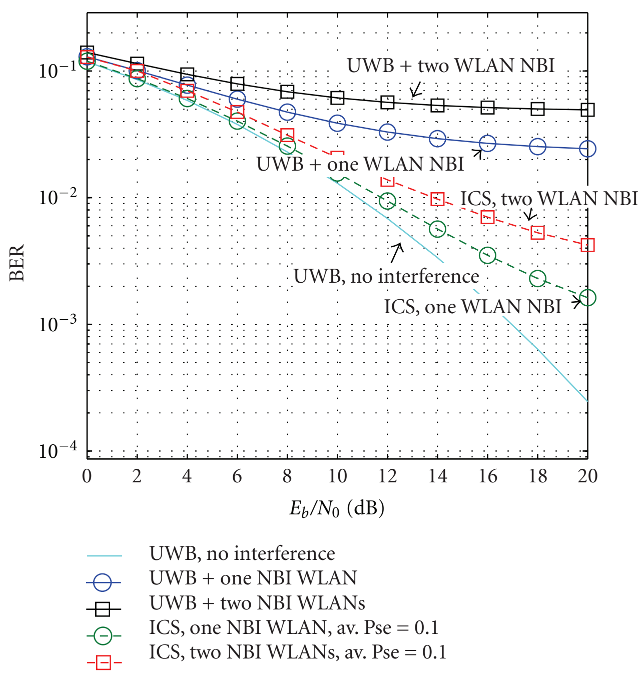

FIGURE 6: BER performance of the ICS in the presence of two NBI WLANs in a Log-normal flat fading channel, SIR = −10 dB.

signals as a detuned notch filter will not be able to mitigate the NBI impact on the UWB receiver. Such agility feature can compensate for the ICS's complexity drawback.

7. Conclusion

In this paper, the impact of IEEE802.11a NBI on the performance of a TH-PPM UWB system in a Log-normal

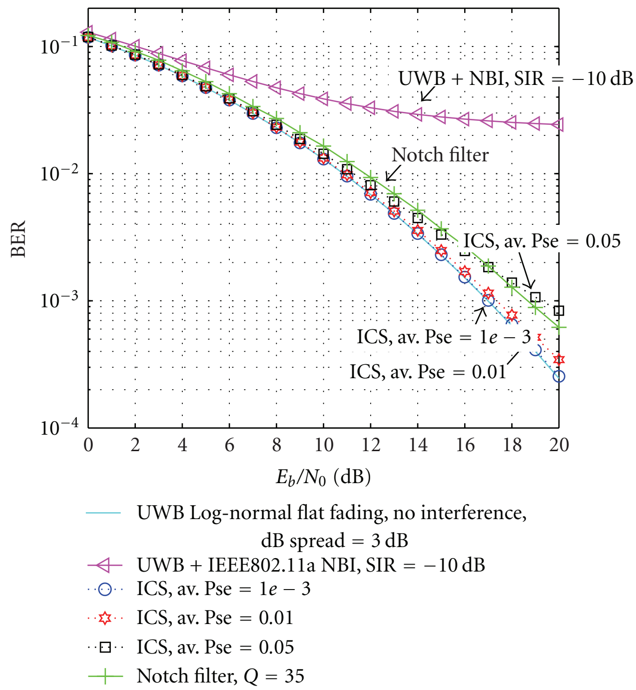

FIGURE 7: BER performance comparison of the ICS with a perfectly tuned Notch filter.

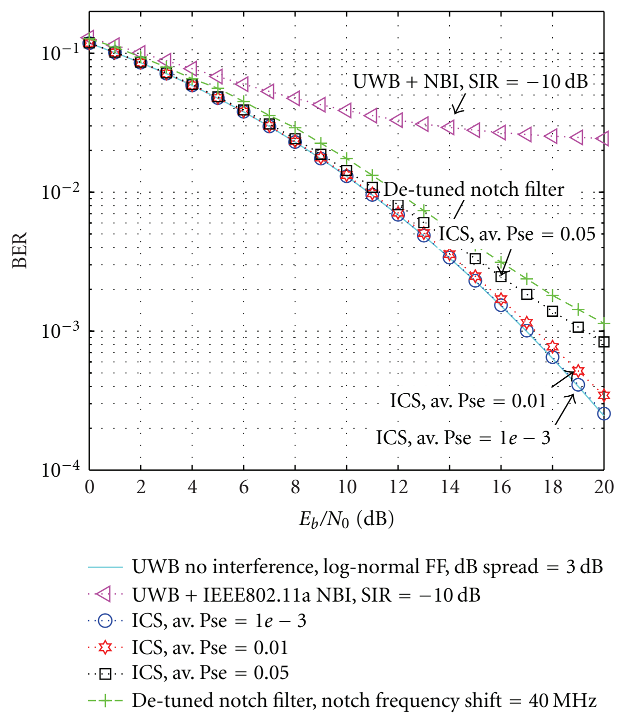

FIGURE 8: BER performance comparison of the ICS with a De-tuned Notch filter.

flat fading channel is investigated. Although, the considered channel is not the actual UWB channel, but this investigation is suitable for some wireless systems such as the wireless sensor networks. It has been shown that the impact of the IEEE802.11a NBI signal can severely degrade the UWB BER performance.

To this end, a canceller scheme that had been used with the CDMA systems is proposed to mitigate the impact of such interference on UWB communication systems. The ICS performance is analytically evaluated in Log-normal flat fading channels and validated with the aid of simulation.

The ICS performance is also investigated in various scenarios of operation such as the presence of symbol timing errors, the presence of two IEEE802.11a NBI signals, and a comparison with the performance obtained by using the conventional tuned and detuned notch filter. It was shown that such canceller scheme is capable of mitigating the impact of NBI signals on UWB communication systems and outperforming the notch filter based case.

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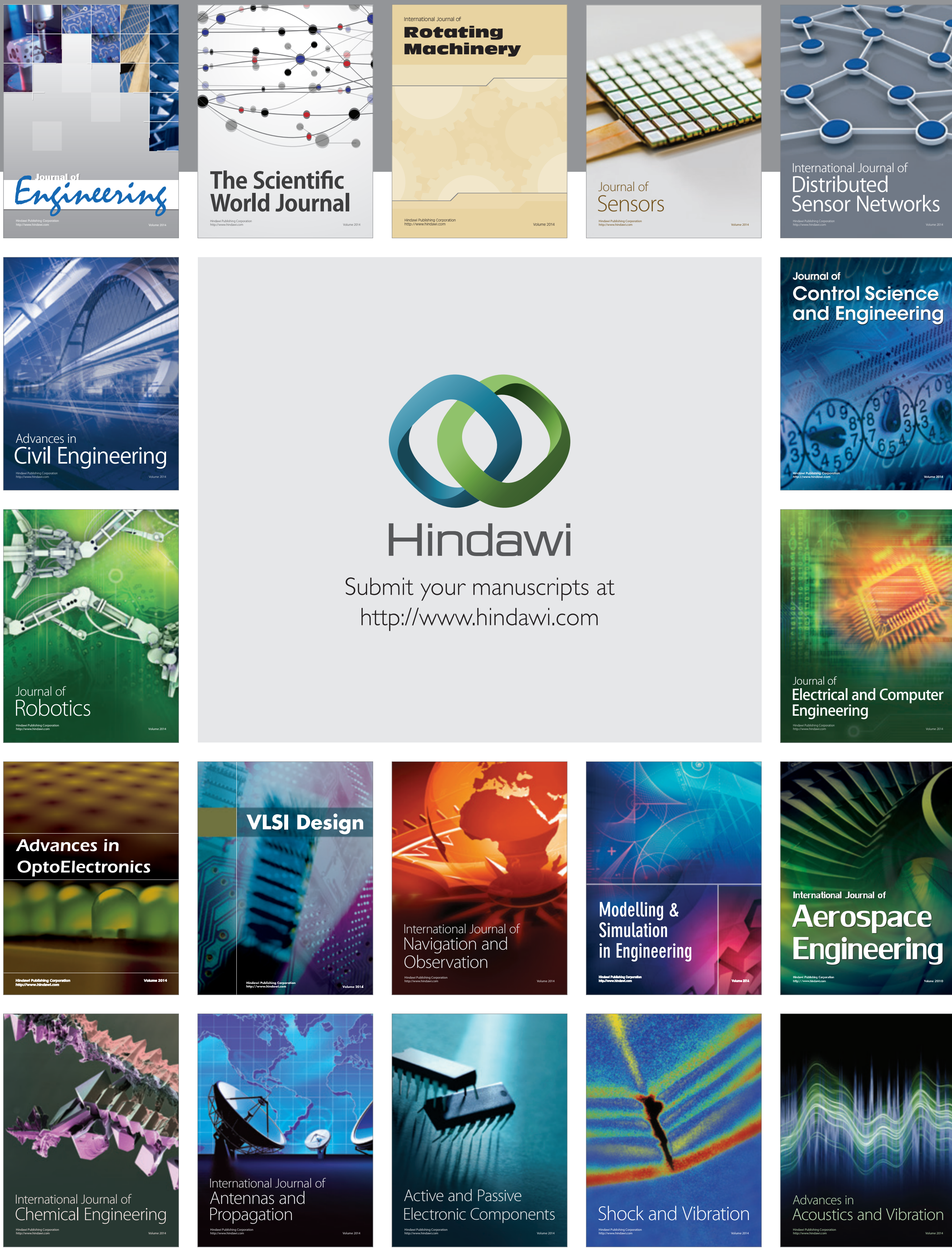
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