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Research Article

Interference Mitigation Technique for Coexistence of Pulse-Based UWB and OFDM

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Ultra-wideband (UWB) is a useful radio technique for sharing frequency bands between radio systems. It uses very short pulses to spread spectrum. However, there is a potential for interference between systems using the same frequency bands at close range. In some regulatory systems, interference detection and avoidance (DAA) techniques are required to prevent interference with existing radio systems. In this paper, the effect of interference on orthogonal frequency division multiplexing (OFDM) signals from pulse-based UWB is discussed, and an interference mitigation technique is proposed. This technique focuses on the pulse repetition cycle of UWB. The pulse repetition interval is set the same or half the period of the OFDM symbol excluding the guard interval to mitigate interference. These proposals are also made for direct sequence (DS)-UWB. Bit error rate (BER) performance is illustrated through both simulation and theoretical approximations.

1. INTRODUCTION

Spectrum sharing technologies are attractive since there is a real lack of frequency bands for radio systems. Cognitive radio is one approach to coexisting radio systems. Ultra-wideband (UWB) is also able to share spectrum with other systems by spreading spectra extremely widely [1]. However, in UWB systems, a potential for interference exists when systems operate in the same frequency band. The Federal Communication Commission (FCC) allocated a frequency band for UWB from 3.1 GHz to 10.6 GHz and determined transmission power to be a maximum of −41.3 dBm/MHz in 2002 [2]. Detection and avoidance (DAA) techniques are required in both Japanese and European regulations to emit −41.3 dBm/MHz in the 4 GHz band [3, 4].

The effect of interference from UWB on narrow band systems has been evaluated by hardware experiments and computer simulations [5–7]. In multiband-orthogonal frequency division multiplexing (MB-OFDM) UWB systems, interference is detected using FFTs in the OFDM receiver. Null subcarriers are used for interfering bands [8]. Adaptive pulse waveform techniques are investigated as interference mitigation techniques in pulse-base UWB systems. UWB pulses consist of several narrow pulses that are combined to suppress an interfering band spectrum [9, 10]. Different interference characteristics are reported with changing the pulse repetition frequency and the center frequency of narrow band systems [7]. Low duty cycle (LDC)-UWB is recognized by European regulation as a DAA technique, since the average power is reduced by determining the maximum peak power [4]. Critical interference mitigation techniques are less favored. It is necessary to consider power consumption and transmitter-receiver hardware size for potential UWB system applications when DAA techniques are investigated.

The effect of interference from UWB on various kinds of systems is investigated, and a multicarrier type template wave to mitigate the influence of IEEE802.11a interference is proposed [11]. The proposed template is effective not only for narrowband interference such as that produced by existing wireless LAN systems, but also for wideband interference such as that produced by MB-OFDM. This is achieved using a multicarrier template and hopping band detection [12]. The technique can be also applied to the DAA technique [13].

In this paper, a technique to mitigate interference on OFDM signals from pulse-based UWB (p-UWB) is examined using a physical layer approach. The proposed system focuses on pulse repetition interval in UWB assuming a

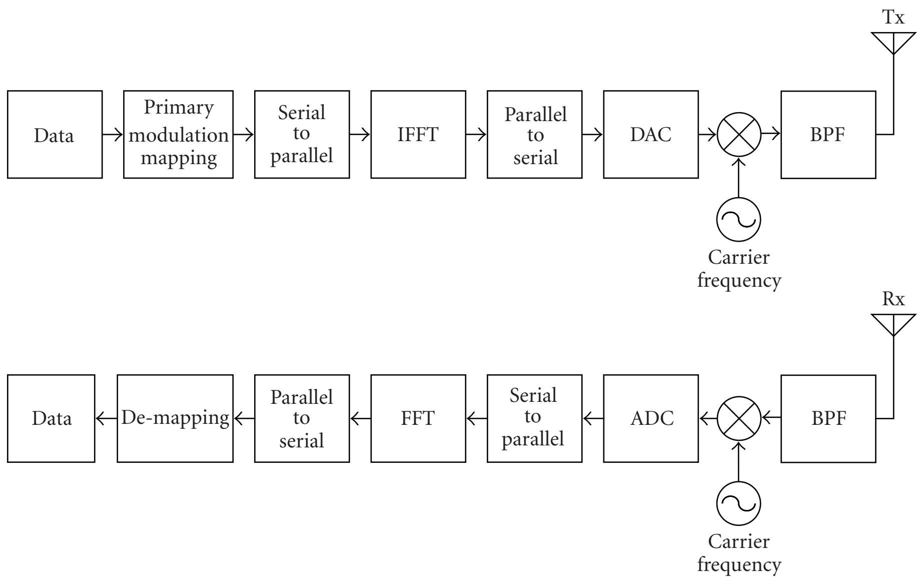


Figure 1: OFDM transmitter-receiver structure.

simple transmitter-receiver structure and a low-data rate personal area network (PAN) system. OFDM signals have a common modulation scheme for high-data rate wireless systems such as wireless LANs or mobile systems. In this paper, direct sequence (DS)-UWB is also discussed in relation to the effectiveness of the proposed mitigating methods.

This paper is organized as follows. In Section 2, the system models of UWB and OFDM are explained. In Section 3, Section 3.1, simulation results for the pulse repetition cycle are shown. The mechanism for the proposed interference mitigation technique and discussion of simulation results are considered in Section 3.2. In Section 4, the proposed interference mitigation technique is applied to a DS-UWB system.

2. SYSTEM MODEL

2.1. Pulse-based UWB

A pulse-based UWB (p-UWB) signal can be expressed:

$$s_{\text{uwb}}(t) = \sum_{i=0}^{\infty} d_i s_0(t - iT_r), \tag{1}$$

where T_r is the pulse repetition interval, i denotes ith pulse, d_i is modulated data, and $s_0(t)$ is the UWB pulse waveform, such as monocycle, sinusoidal wave enveloped with various waveforms, or differentials of Gaussian functions. Here, UWB pulse bandwidth is assumed to be wider than OFDM signals, and Bi-Phase modulation is adopted. Thus, d_i denotes +1 or −1.

2.2. OFDM

OFDM is a common modulation scheme. It is used for many wireless systems, for example, wireless local area networks (LANs). OFDM is also expected to be a next generation mobile and wireless metropolitan area network (MAN) system since it has many advantages in bandwidth, transmission rate, and antimultipath effect, and so forth.

A typical ODFM signal can be expressed:

$$s_{\text{ofdm}}(t) = \operatorname{Re}\left[\sum_{h=0}^{\infty} s_B(t - hT_{\text{SYM}}) \cdot w(t - hT_{\text{SYM}}) \cdot \exp(-j2\pi f_c t)\right],$$

$$w(t) = \begin{cases} 1 & (T_{\text{GI}} < t < T_{\text{FFT}} + T_{\text{GI}}), \\ 0 & (t < T_{\text{GI}},\ t > T_{\text{FFT}} + T_{\text{GI}}), \end{cases} \tag{2}$$

$$s_B\left(\frac{kT_{\text{FFT}}}{N}\right) = \sum_{l=0}^{N-1} (d_{c_l} + jd_{s_l}) \exp\left(\frac{j2\pi kl}{N}\right), \tag{3}$$

where, N is the number of subcarriers, f_c is a carrier frequency, and l and h are lth subcarriers in the hth symbol, respectively. d_{c_l} and d_{s_l} are transmitting data after primary modulation. T_{FFT} and T_{GI} are the IFFT/FFT period and guard interval duration, respectively. T_{SYM} is symbol duration including T_{FFT}, T_{GI}, and a cyclic prefix duration T_{cp}. $w(t)$ denotes a window function for IFFT. The window function is assumed to be rectangular, that is, “1” in the symbol and “0” elsewhere. The OFDM transmitter-receiver structure is shown in Figure 1 [14].

In this paper, OFDM systems are used unchanged in relation to interference mitigation, because it is difficult to change the specifications of existing systems after standardization. We can assume that it is impossible to synchronize the timing of the UWB and OFDM systems to mitigate interference.

Table 1: Simulation parameters for MB-OFDM and IEEE802.11a.

Parameter	MB-OFDM	IEEE802.11a
N: Number of FFT point	128	64
Band width: BW	528 MHz	20 MHz
D_F: Subcarrier frequency spacing	4.125 MHz (= BW/N)	312.5 kHz (= BW/N)
T_{FFT}: IFFT/FFT period	242.42 ns (1/D_F)	3.2 μ s (1/D_F)
T_{CP}: Cyclic prefix duration	60.61 ns (= 32/528 MHz)	—
T_{GI}: Guard interval duration	9.47 ns (= 5/528 MHz)	0.8 μ s (T_{FFT}/4)
T_{SYM}: Symbol interval	312.5 ns ($T_{\text{CP}} + T_{\text{FFT}} + T_{\text{GI}}$)	4.0 μ s ($T_{\text{FFT}} + T_{\text{GI}}$)
Frequency band (carrier frequency)	Lower Band: Band#1: 3.432 GHz, Band#2: 3.960 GHz, Band#3: 4.488 GHz Frequency hopping	5.2 GHz
Primary modulation	QPSK	16QAM

3. TECHNIQUE FOR THE MITIGATION OF p-UWB INTERFERENCE WITH OFDM

In this section, the effects of interference from UWB on OFDM signals are evaluated with specific focus on the pulse repetition cycle of UWB. It is proposed that adjusting the pulse repetition interval of UWB should mitigate the effect of interference with OFDM. The p-UWB interference signal is also derived from the OFDM receiver to demonstrate the mechanism of this interference mitigation technique.

3.1. Simulation evaluation

An MB-OFDM system and an IEEE 802.11a wireless LAN are used as the systems to coexist with p-UWB in this simulation. The parameters of the OFDM systems are shown in Table 1.

An MB-OFDM system is a type of UWB signal used for high-data rate systems such as wireless Universal Serial Bus (USB). It consists of 128 subcarriers at 4.125 MHz intervals and uses 3.1 to 10.6 GHz in 14 bands each of 528 MHz bandwidth. This simulation treats the lower-three bands (3.342, 3.960, 4.488 GHz). Every symbol of 312.5 nanoseconds is frequency hopped in these bands. The signal is paused in the cyclic prefix 60.6 nanoseconds [15, 16].

IEEE802.11a wireless LAN systems are narrow band OFDM systems in the 5 GHz band. The primary modulation is changed adaptively to transmission environments [17]. In this paper, Quadrature amplitude modulation 16(QAM) is used as the primary modulation scheme for simplicity.

The UWB pulses used in this study are Gaussian enveloped sinusoidal pulses as per (4). The pulses can be easily applied to various center frequencies and bandwidths:

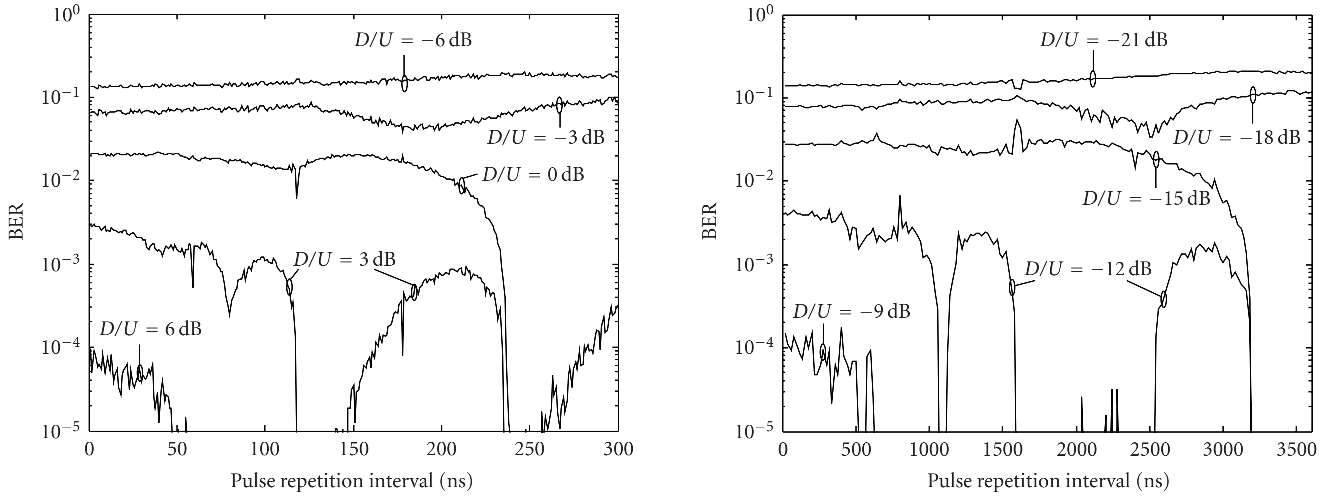
$$s_0(t) = \exp\left(-\frac{at^2}{\tau^2}\right)\sin\left(2\pi f_0 t\right), \tag{4}$$

where $a = \log_e 10$ is the amplitude of the -10 dB point to define the pulse width, τ is half the pulse width, and f_0 is the center frequency. The pulse width is set at 1 nanosecond, and the center frequency is 4.2 GHz in this simulation to use the lower-UWB band from 3.1 GHz to 5.3 GHz. Thus, the pulse bandwidth is wider than that of the MB-OFDM.

The proposed interference mitigation technique has an advantage that the average power of UWB is not reduced unlike the LDC-UWB. The evaluated result is shown by the desired to undesired signal power ratio (D/U ratio) defined as average power over time for each signal for the duration. Therefore, the peak power of the p-UWB is larger if the pulse repetition interval is longer.

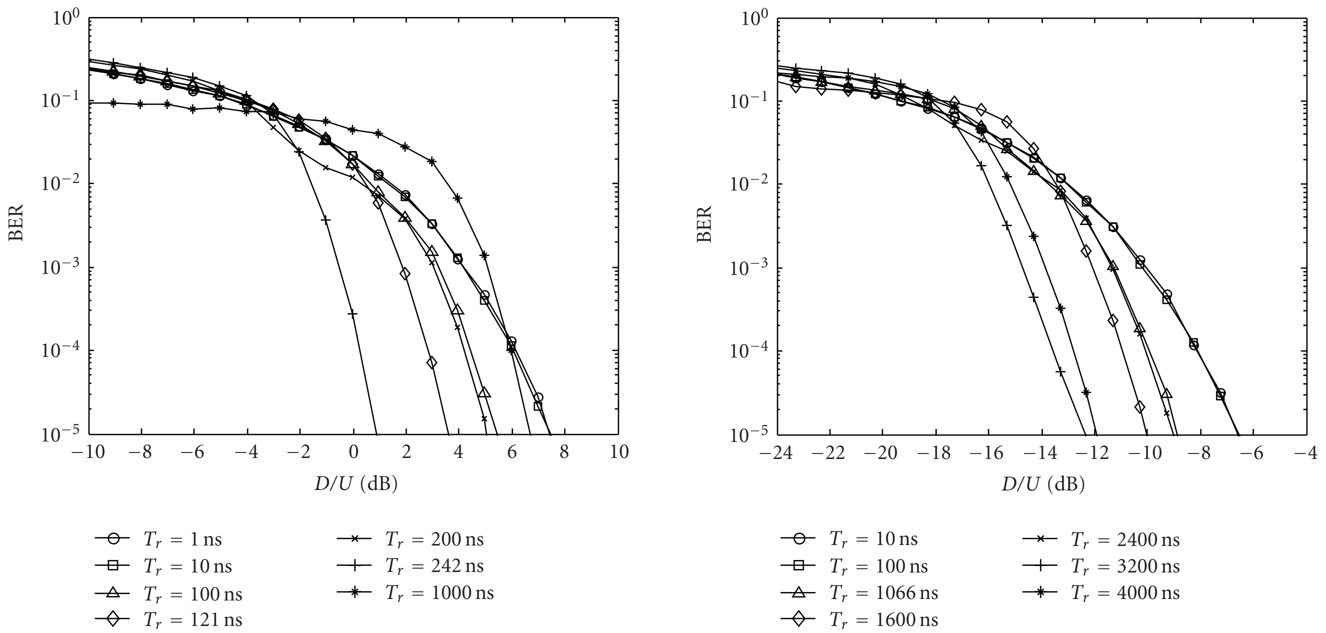
Bit error rate (BER) performance versus the pulse repetition interval T_r is shown in Figure 2. Notice that BER performances become better in both coexisting systems MB-OFDM and IEEE802.11a WLAN when the pulse repetition interval is equal to the OFDM IFFT/FFT duration or half that of the IFFT/FFT. The characteristics of the BER performance due to changing the pulse repetition interval are the same for MB-OFDM and IEEE802.11a systems.

BER performance is also shown for a D/U ratio in the AWGN channel where E_b/N_0 is equal to 20 dB in Figure 3. In the MB-OFDM system, the BER performance is the same for $T_r = 1$ nanosecond and $T_r = 10$ nanoseconds, that is, high-duty cycle UWB. The BER performance is improved by extending the pulse repetition interval. When the pulse repetition interval equals half the MB-OFDM IFFT/FFT duration, BER performance becomes better by about 3 dB over when it is affected by interference from a high-duty cycle UWB system. The BER deteriorated when interfered with by $T_r = 200$ nanoseconds p-UWB but is 6 dB better in comparison to when interfered with by high-duty cycle UWB with a repetition interval set to the same length as the MB-OFDM OFDM IFFT/FFT duration. When the pulse repetition interval is further increased, the BER performance deteriorates again. The BER performance of the IEEE802.11a WLAN shows the same characteristics as MB-OFDM when pulse repetition interval is normalized by the IFFT/FFT duration.



(a) MB-OFDM (b) IEEE802.11a

Figure 2: BER performance of OFDM interfered with by p-UWB for changing pulse repetition intervals (E_b/N_0 = inf.).

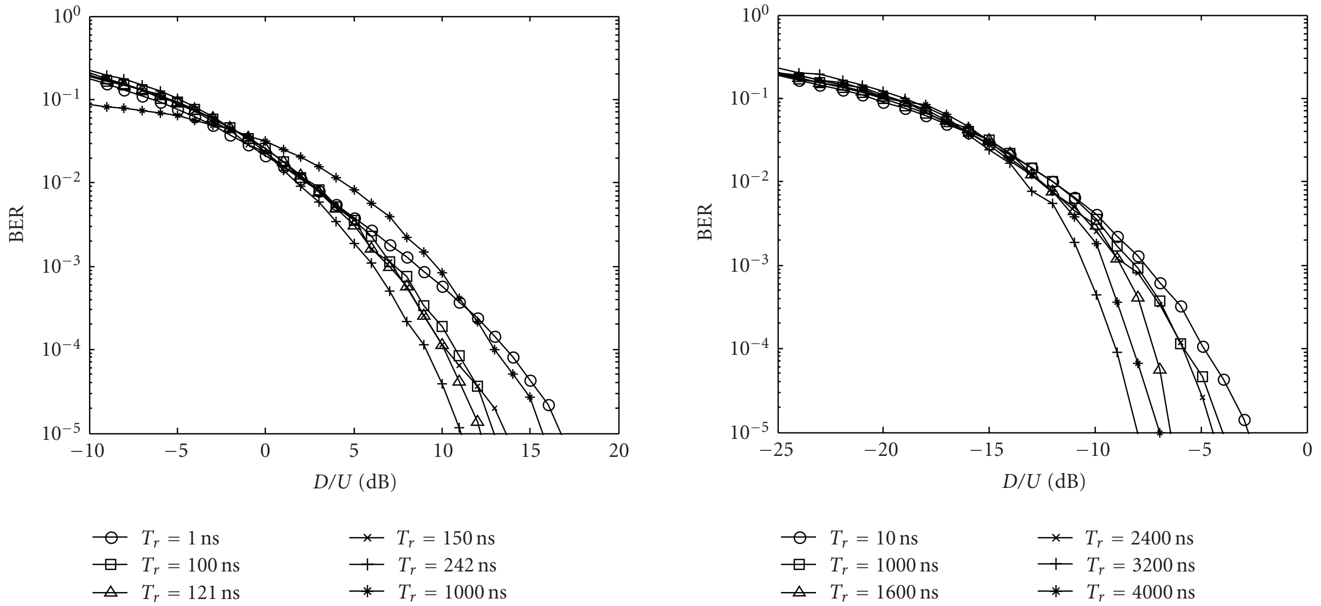


(a) MB-OFDM (b) IEEE802.11a

Figure 3: BER performance of OFDM interfered with by p-UWB (E_b/N_0 = 20 dB).

In Figure 4, BER performance is evaluated for a multipath channel. The channel model adopted is CM3 as set out by the IEEE802.15.4a working group [18]. IEEE802.15.4a is a standard for low-duty cycle PAN systems. Interference problems often occur when the victim transmitter is very close to the UWB transmitter. In most of cases, their positions are in line of sight (LOS). CM3 is designed for office LOS environments. It is assumed that OFDM receiver channel estimation and multipath compensation are perfect for the desired signal. The BER performance improves as the pulse repetition interval is set as per the proposal. The effectiveness of the proposed method is clearer for the IEEE802.11a WLAN system since the symbol duration is longer.

Pulse-based UWB should be transmitted at intervals of one half or one IFFT/FFT period to take the coexisting OFDM system into account. In UWB systems, the interference problem occurs when a UWB system terminal and a coexisting system terminal are used at close range, since the spectrum is extremely spread and has the suppressed the power spectrum density. The pulse repetition interval should be adjusted to minimize the effects of the most harmful coexisted OFDM system.



(a) MB-OFDM

(b) IEEE802.11a

Figure 4: BER performance of OFDM interfered with by p-UWB in CM3.

3.2. Analysis of the interfering signal in the OFDM receiver

In this section, a mechanism for determining the pulse repetition cycle in the proposed interference mitigation technique is illustrated.

The interfering signal is derived from OFDM signal demodulation in the receiver. The received interfering UWB pulse waveform is presumed to be

$$r(t) = \sum_{i=0}^{\infty} d_i a_0 \delta(t - iT_r), \tag{5}$$

where a_0 is the amplitude of the received UWB pulse. The received UWB interfering signal is passed through a band pass filter (BPF) for the OFDM signal and is down converted to the baseband as follows.

Filtering

$$\begin{aligned} r_{\text{filter}}(t) &= r(t) \otimes h_r(t) \exp\left(j2\pi f_c t\right) \\ &= \sum_{i=0}^{\infty} d_i a_0 h_r(t - iT_r) \exp\left\{j2\pi f_l(t - iT_r)\right\}. \end{aligned} \tag{6}$$

Down convert

$$\begin{aligned} r_{\text{dc}}(t) &= r_{\text{filter}}(t) \exp\left\{-j(2\pi f_c t + \phi)\right\} \\ &= \sum_{i=0}^{\infty} d_i a_0 h_r(t - iT_r) \exp\left\{-j(2\pi f_c iT_r + \phi)\right\} \\ &= \sum_{i=0}^{\infty} d_i a_0 h_r(t - iT_r)\left\{\cos(2\pi f_c iT_r + \phi) + j\sin(2\pi f_c iT_r + \phi)\right\}, \end{aligned} \tag{7}$$

where $h_r(t)$ denotes the impulse response of the BPF in the baseband. ϕ is the phase difference and is assumed to be a random value. The signal is delimited by a window interval and is converted from analog to digital. Quantization is ignored here. The signal is sampled at T_{FFT}/N. The signal duration of the filter impulse response is $2 \cdot T_{\text{FFT}}/N$, assuming that the filter has the same bandwidth as the OFDM signal. Therefore, the $h_r(t)$ is represented by one or two sampling points. Equation (8) shows the signal after analog to digital conversion (ADC) assuming one sampling point per pulse:

$$\begin{aligned} r_{\text{filter}}(n) = \sum_{i=0}^{I-1} d_i a_{in} \{&\cos(2\pi f_c iT_r + \phi)\delta(n - n_0 - in_r) \\ &- j\sin(2\pi f_c iT_r + \phi)\delta(n - n_0 - in_r)\}, \end{aligned} \tag{8}$$

where I is the number of pulses in a window interval, that is, T_{FFT}/T_r. a_{in} is amplitude of the each sampling point, n_0 is the first pulse position in a window interval, and n_r is pulse repetition cycle after sampling, thus $n_r = T_r N/T_{\text{FFT}}$, and is rounded off to an integer number.

The signal is processed using an FFT:

$$\begin{aligned} R_{\text{fft}}(k) &= \sum_{n=0}^{N-1} r_{\text{filter}}(n) \exp\left(-j2\pi \frac{nk}{N}\right) \\ &= \sum_{i=0}^{I-1} \sqrt{2}\, d_i a_{in} \left[\cos(2\pi f_c iT_r + \phi)\cos\left\{\frac{2\pi k}{N}(n_0 + in_r) + \frac{\pi}{4}\right\}\right. \\ &\qquad \left. + j\sin(2\pi f_c iT_r + \phi)\sin\left\{\frac{2\pi k}{N}(n_0 + in_r) + \frac{\pi}{4}\right\}\right]. \end{aligned} \tag{9}$$

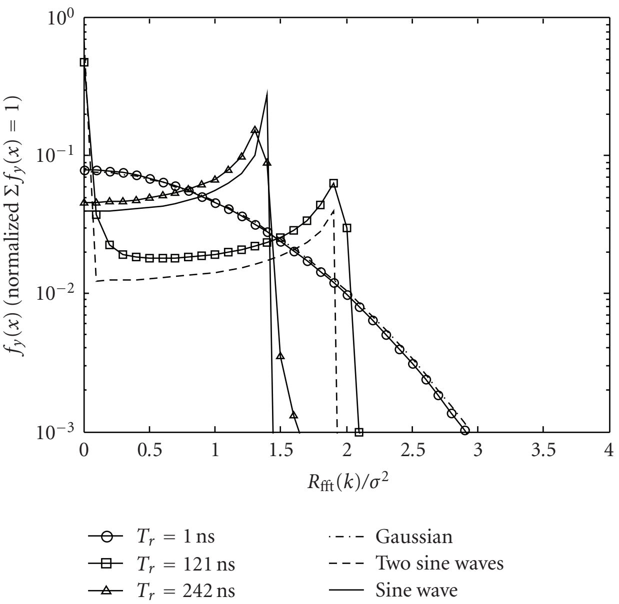


Figure 5: APD of the interfering signal after FFT in the OFDM receiver.

The real and imaginary parts of the $R_{fft}(k)$ interfere with the In-phase and Quadrature-phase components of the OFDM demodulation, respectively. Therefore, the interfering signal's contribution to the OFDM demapping can be expressed as the sum of sinusoidal waves. The number of sinusoidal waves is the number of interfering UWB pulses in a window interval. The effect of interference depends on the amplitude probability density (APD) of $R_{fft}(k)$. To mitigate the effect of the interference, the amplitude of the interfering signal should be constant. Conversely, if the $R_{fft}(k)$ has high-peak amplitude, like Gaussian distribution, the BER performance of the victim system deteriorates.

When the pulse repetition interval is equal to the OFDM IFFT/FFT duration, the effect of interference is approximated as interference from a sinusoidal wave. The normalized APD variation of the sinusoidal wave is expressed as (10) [19]. The APD of $R_{fft}(k)$ depends a great deal on the BER performance of the OFDM signal:

$$f_y(x) = \begin{cases} \dfrac{1}{\pi\sqrt{1 - x^2/2}} & (|x| < \sqrt{2}), \\ 0 & (|x| \geq \sqrt{2}). \end{cases} \tag{10}$$

Figure 5 shows the APD of $R_{fft}(k)$ including only the interferer. Here, the OFDM signal is assumed to be a MB-OFDM, and the band is fixed to avoid frequency hopping to the same band as the p-UWB signal. The p-UWB waveform is the same as Section 3.1 and is shown in (4). The pulse width is 1 nanosecond. The APD, where T_r equals T_{FFT}, is almost the same as the APD of a sinusoidal wave shown in (10).

The effect on interference of increasing the number of interfering pulses can be approximated to a Gaussian distribution by the central limit theorem. The APD is also confirmed to correspond to a Gaussian distribution in Figure 5 when the pulse repetition interval equals 1 nanosecond.

When the pulse repetition interval is equal to half the IFFT/FFT duration, the number of pulses in a window interval I becomes two, and real part of the $R_{fft}(k)$ is derived thus

$$\begin{aligned} \mathrm{Re}\left[R_{fft}(k)\right] &= d_0 a_{0n}\cos(\phi)\cos\left(\frac{2\pi k n_0}{N} + \frac{\pi}{4}\right) \\ &\quad + d_1 a_{1n}\cos(\pi f_l T_{FFT} + \phi)\cos\left(\frac{2\pi k n_0}{N} + \pi k + \frac{\pi}{4}\right). \end{aligned} \tag{11}$$

Equation (12) can be separated into two cases where k is either even or odd, since the phase difference between the first and second terms is $k\pi$.

k = even number

$$\begin{aligned} \mathrm{Re}\left[R_{fft}(k)\right] &= \{d_0 a_{0n}\cos(\phi) + d_1 a_{1n}\cos(\pi f_l T_{FFT} + \phi)\} \\ &\quad \times \cos\left(\frac{2\pi k n_0}{N} + \frac{\pi}{4}\right) \\ &= A_{even}\cos\left(\frac{2\pi k n_0}{N} + \frac{\pi}{4}\right), \end{aligned} \tag{12}$$

k = odd number

$$\begin{aligned} &\mathrm{Re}\left[R_{fft}(k)\right] \\ &= \{d_0 a_{0n}\cos(\phi) - d_1 a_{1n}\cos(\pi f_l T_{FFT} + \phi)\}\cos\left(\frac{2\pi k n_0}{N} + \frac{\pi}{4}\right) \\ &= A_{odd}\cos\left(\frac{2\pi k n_0}{N} + \frac{\pi}{4}\right). \end{aligned} \tag{13}$$

To simplify the equation, A_{even} and A_{odd} are set as per (12) and (13), respectively.

Normalized APD of the interfering signal is expressed as the sum of two sinusoidal wave distributions as follows:

$$f_y(x) = \frac{f_{y,even}(x) + f_{y,odd}(x)}{2}, \tag{14}$$

$$f_{y,even}(x) = \begin{cases} \dfrac{1}{\pi\sqrt{1 - (x/A_{even})^2}} & (|x| < A_{even}), \\ 0 & (|x| \geq A_{even}). \end{cases} \tag{15}$$

$f_{y,odd}(x)$ is expressed in the same way as A_{odd} in (16). $f_y(x)$ is normalized so that total power as 1. Thus

$$\frac{1}{2}\left(\frac{{A_{odd}}^2}{2} + \frac{{A_{even}}^2}{2}\right) = 1. \tag{16}$$

Therefore, the maximum amplitude of $R_{fft}(k)$ becomes two in the worst case, when either A_{even} or A_{odd} is equal to zero.

a_{0n} and a_{1n} become the same when the total number of subcarriers in the OFDM is an even number. For the MB-OFDM system, $\cos(\phi)$ and $\cos(\pi f_c T_{FFT} + \phi)$ become the

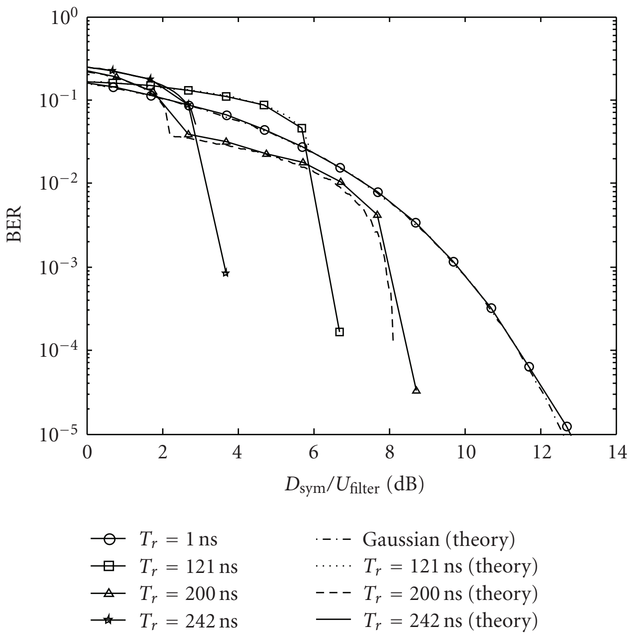


Figure 6: BER performance of OFDM signal compared to theoretical values.

same, since f_c is set multiple to 264 MHz (= 528/2), and T_{FFT} is $N/528$ MHz. The system operates a 528 MHz-based oscillator to reduce the hardware structure. d_i is modulated to ± 1. Thus, A_{even} or A_{odd} is equal to zero, and the APD of the interfering signal in the MB-OFDM receiver is expressed:

$$f_y(x) = \begin{cases} \dfrac{1}{2\pi\sqrt{1 - x^2/4}} & (|x| < 2,\ x \neq 0), \\ \displaystyle\sum_{x_i=-2}^{2} \frac{1}{2\pi\sqrt{1 - x_i^2/4}} + \frac{1}{2\pi} & (x = 0), \\ 0 & (|x| \geq 2). \end{cases} \quad (17)$$

The distribution also corresponds to the simulation results when the pulse repetition interval is 121 nanoseconds in Figure 5. The derivation is accurate, though the pulse waveform is assumed to have an impulse shape, and sampling points are omitted in ADC.

The BER performance for the OFDM interfered with by the p-UWB is calculated from the APD of the interfering signal. The D/U ratio is redefined as D_{sym}/U_{filter} here to compare the simulation and theory. The desired signal power D_{sym} is the average power per symbol duration (excluding the cyclic prefix duration). The undesired signal power U_{filter} is defined as the average power over time after the signal is passed through the BPF in the OFDM receiver and does not depend on the pulse waveform under the assumption that UWB bandwidth is wider than the OFDM system. The BER performance of OFDM interfered with by p-UWB is expressed in (18) when the number of the interfering pulses I can be considered large:

$$\text{BER}_{gauss}\left(\frac{D_{sym}}{U_{filter}}\right) = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{D_{sym}}{2U_{filter}}}\right). \quad (18)$$

The APD of the interference is assumed to be a Gaussian distribution. Thus, (18) is the same as the formula for BER performance by coherent detection in an AWGN channel. Equations (19) and (20) show BER performance in which the pulse repetition interval is the same as and half the OFDM IFFT/FFT duration, respectively:

$T_r = T_{FFT}(I = 1)$

$$\begin{aligned} &\text{BER}_{|I=1}\left(\frac{D_{sym}}{U_{filter}}\right) \\ &\quad = \int_{\sqrt{D_{sym}/2U_{filter}}}^{\infty} f_y(x)dx \\ &\quad = \begin{cases} \dfrac{1}{2} - \dfrac{1}{\pi}\arcsin\left(\sqrt{\dfrac{D_{sym}}{2U_{filter}}}\right) & \left(\dfrac{D_{sym}}{2U_{filter}} < 1\right), \\ 0 & \left(\dfrac{D_{sym}}{2U_{filter}} \geq 1\right), \end{cases} \end{aligned} \quad (19)$$

$T_r = T_{FFT}/2$

$$\begin{aligned} &\text{BER}_{|T_r=T_{FFT}/2}\left(\frac{D_{sym}}{U_{filter}}\right) \\ &\quad = \begin{cases} \dfrac{1}{4} - \dfrac{1}{2\pi}\arcsin\left(\sqrt{\dfrac{D_{sym}}{4U_{filter}}}\right) & \left(\dfrac{D_{sym}}{4U_{filter}} < 1\right), \\ 0 & \left(\dfrac{D_{sym}}{4U_{filter}} \geq 1\right). \end{cases} \end{aligned} \quad (20)$$

The BER of a signal interfered with by a sinusoidal wave is derived from the probability distribution function shown in (10) [19]. When the pulse repetition interval is half the IFFT/FFT period, the error rate converges by 1/4, because the interfering signal becomes zero at 1/2 probability from (17).

Theoretical and simulated BER performances are shown in Figure 6. Coexisting pulse UWB and MB-OFDM are simulated, and performance when the pulse repetition interval equals 1 nanosecond, 121 nanoseconds, and 242 nanoseconds corresponds to the theoretical values. Therefore, the number of interfering pulses in a window interval should be reduced to mitigate the effect of p-UWB interference on OFDM.

BER performance was investigated for varying numbers of interfering UWB pulses in each window interval as the IFFT/FFT duration cannot necessarily be a multiple of the pulse repetition interval. The number of UWB pulses in a window interval can fall into either of two cases: I_0 and $I_0 + 1$, since the pulse repetition cycle is constant. I_0 has a smaller number of pulses in a window interval. The probability of the number of interfering pulses is expressed:

$I = I_0$

$$P_{b,I_0} = \frac{(I_0 + 1)T_r - T_{FFT}}{T_r}, \quad (21)$$

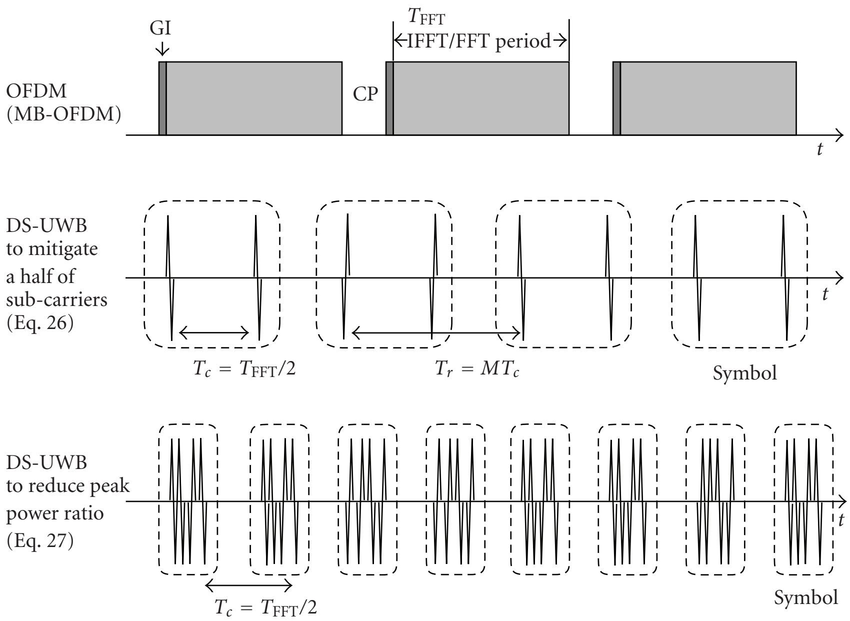


Figure 7: Time frames of proposed DS-UWB.

$I = I_0 + 1$

$$P_{b,I_0+1} = \frac{T_{\text{FFT}} - I_0 T_r}{T_r}. \quad (22)$$

The undesired power in each window interval also differs from the undesired power defined as the average across the duration U:

$I = I_0$

$$U_{I_0} = \frac{I_0 T_r}{T_{\text{FFT}}} \cdot U, \quad (23)$$

$I = I_0 + 1$

$$U_{I_0+1} = \frac{(I_0 + 1) T_r}{T_{\text{FFT}}} \cdot U, \quad (24)$$

and BER performance is expressed:

$$\text{BER}\left(\frac{D_{\text{sym}}}{U_{\text{filter}}}\right) = P_{b,I_0} \text{BER}_{|I=I_0}\left(\frac{D_{\text{sym}}}{U_{\text{filter}}} \cdot \frac{T_{\text{FFT}}}{I_0 T_r}\right) + P_{b,I_0+1} \text{BER}_{|I=I_0+1}\left(\frac{D_{\text{sym}}}{U_{\text{filter}}} \cdot \frac{T_{\text{FFT}}}{(I_0 + 1) T_r}\right). \quad (25)$$

The BER performance worsens because the interfering power is increased in the second term of (25). To mitigate the effect of the interference, the probability of the rebeing large numbers of interfering pulses P_{b,I_0+1} should be reduced to a satisfactory level or the undesired power in any window interval U_{I_0+1} should to be close to the average power U. For this purpose, it is necessary that $T_{\text{FFT}} = I_0 T_r$ or $T_{\text{FFT}} = (I_0 + 1) T_r$ from (22) and (24), respectively. Therefore, the number of interfering UWB pulses in a window interval should be constant over time to mitigate the effect of the interference.

For example, the BER performance of the MB-OFDM interfered with by the p-UWB is derived when T_r is equal to 200 nanoseconds. The number of UWB pulses in each window interval is one or two. The probabilities of a single pulse $P_{b,1}$ and two pulses $P_{b,2}$ occurring in a given window are 0.21 and 0.79, respectively. The BER is calculated from (19) when $I = 1$. When the number of interfering pulses is two, and the pulse repetition interval is not half the symbol duration, the BER must be derived from the APD of the interfering signal $R_{\text{fft}}(k)$. The interfering signal is the sum of two sinusoidal waves. Therefore, the APD is expressed as the convolution of the APD of the sinusoidal wave from (10). The BER performance is derived by integrating the APD and (19). The BER performance for $T_r = 200$ nanoseconds can be calculated using (25). BER performance is illustrated in Figure 6 and is almost identical to the simulated result. The performance is worse than for pulse repetition intervals equal to, and half of, the IFFT/FFT period.

There are, therefore, two main aspects of the proposed interference mitigation technique: the APD of the interfering signal after FFT process in the OFDM receiver and varying the interfering power for the window interval. To reduce high-peak amplitude of interfering signal, the number of interfering pulses in any window interval should be minimized to regulate the pulse repetition interval.

In conventional UWB systems, the pulse repetition cycle is decided from the p-UWB system requirements. Thus, in most cases, a shorter-pulse repetition interval is chosen without considering the effects of interference. Pulse repetition intervals effective in mitigating the effects of interference for the OFDM signal are investigated. When interfering signals exist in the UWB allocated band, the pulse repetition interval should be adjusted to IFFT/FFT duration of OFDM system.

4. A TECHNIQUE FOR THE MITIGATION OF DS-UWB INTERFERENCE ON OFDM

In this section, an interference mitigation technique focused on pulse repetition cycle is applied to direct sequence (DS)-UWB. Spreading codes and chip repetition cycles are proposed to mitigate the interference effects in OFDM subcarriers and to reduce the peak power of UWB signals.

4.1. Interference mitigation for individual subcarriers

To protect individual OFDM subcarriers, UWB pulse coding patterns and pulse repetition intervals are proposed. Important information can be transmitted on OFDM subcarriers resistant to interference from UWB signals.

When the pulse repetition interval is half the IFFT/FFT duration, in MB-OFDM and IEEE802.11a systems (f_c = 5.18–5.32 GHz), half of the subcarriers is not interfered with as per (17). If there are two interfering UWB pulses in a window interval that are modulated with the same codes, that is, [+1 +1] or [−1 −1], even numbered subcarriers are not interfered with. Odd numbered subcarriers are not interfered with, if the pulses are modulated with different codes, that is, [+1 −1] or [+1 −1].

If UWB is encoded as DS-UWB, the spreading codes are all either the same ([+1 +1]) or alternating ([+1 −1]). The proposed UWB signal is expressed:

$$s_{\text{uwb}}(t) = \sum_{i=0}^{\infty}\sum_{m=0}^{M-1} d_i c_m \cdot s_0\left(t - \frac{mT_{\text{FFT}}}{2} - \frac{iMT_{\text{FFT}}}{2}\right), \quad (26)$$

where M is the length of the spreading codes, c_m is the spreading code, and m is mth chip. The pulse repetition interval is constant at half the IFFT/FFT period of the OFDM. An example DS-UWB time frame is shown in Figure 7.

Simulation results are presented in Figure 8. The MB-OFDM parameter is used as the OFDM signal. The UWB pulse is the same as that in (4). When all codes are alike ([+1 +1] or [+1 +1 +1 +1 +1 +1 +1 +1]), the effects of interference on the even numbered subcarriers are improved when compared to the subcarriers in p-UWB. The mitigation effects are better, when the spreading code is longer, because the probability of two UWB pulses modulated by the same codes falling in the same window interval is increased; the error rate becomes $1/M$ better than ordinary p-UWB. However, the BER of the odd numbered subcarriers deteriorates by $2 - 1/M$, since the average BER is the same as for p-UWB. When the spreading code contains alternating codes like [+1 −1] or [+1 −1 +1 −1 +1 −1 +1 −1], the performance of the odd numbered subcarriers improves greatly. The error rate is the same as for the even numbered subcarriers using the same codes.

The total BER performance of the even subband pulses and the odd subband pulses is the same as the performance of uncoded p-UWB. However, it is important to protect individual subcarriers from UWB interference. Total BER performance is also better than for that interfered with by high-data rate p-UWB, because the pulse repetition interval is set to half the OFDM IFFT/FFT duration.

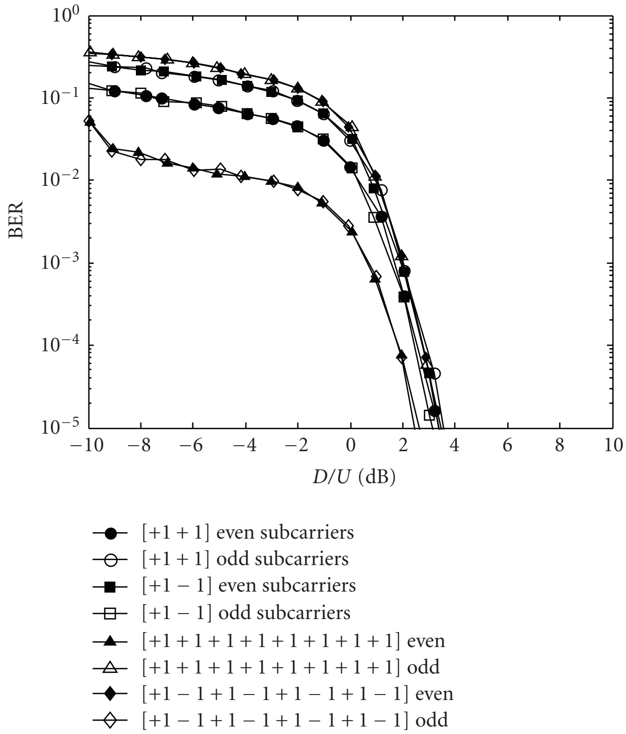


Figure 8: BER performance of OFDM for even and odd numbered subcarriers interfered with by DS-UWB.

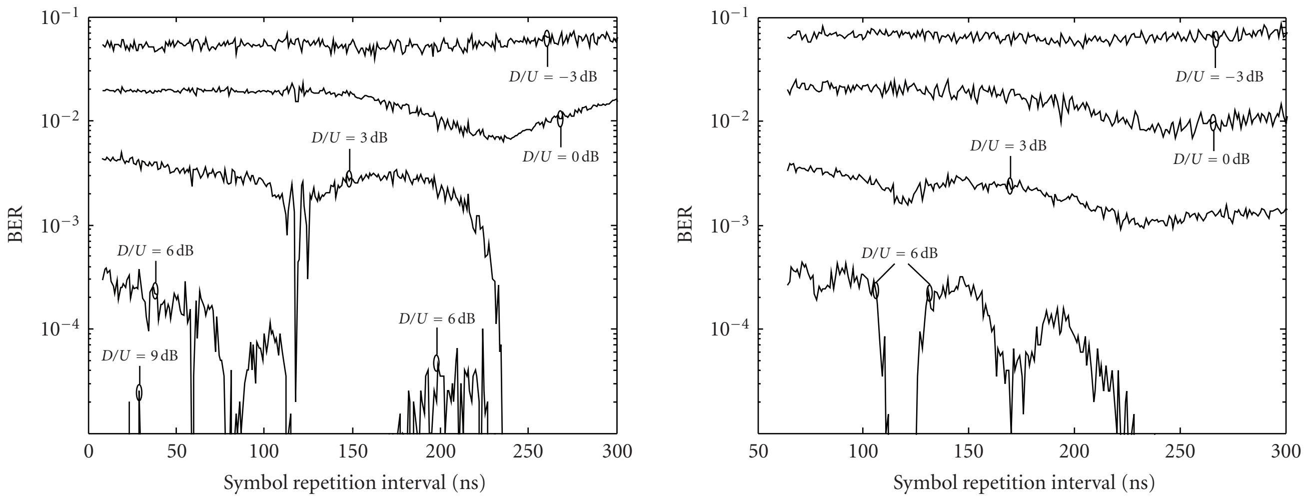
4.2. Using DS-UWB to reduce the peak power of UWB

UWB transmitting power is defined both as average power over a period sufficient for measurement, and the peak power output, by most regulations. Extending the pulse repetition interval should reduce UWB transmitting power as measured according to various regulations. Here, the UWB signal is spread as DS-UWB, and the symbol repetition cycle is controlled to mitigate the effects of interference. The DS-UWB is expressed:

$$s_{\text{uwb}}(t) = \sum_{i=0}^{\infty}\sum_{m=0}^{M-1} d_i c_m \cdot s_0(t - mT_c - iT_r), \quad (27)$$

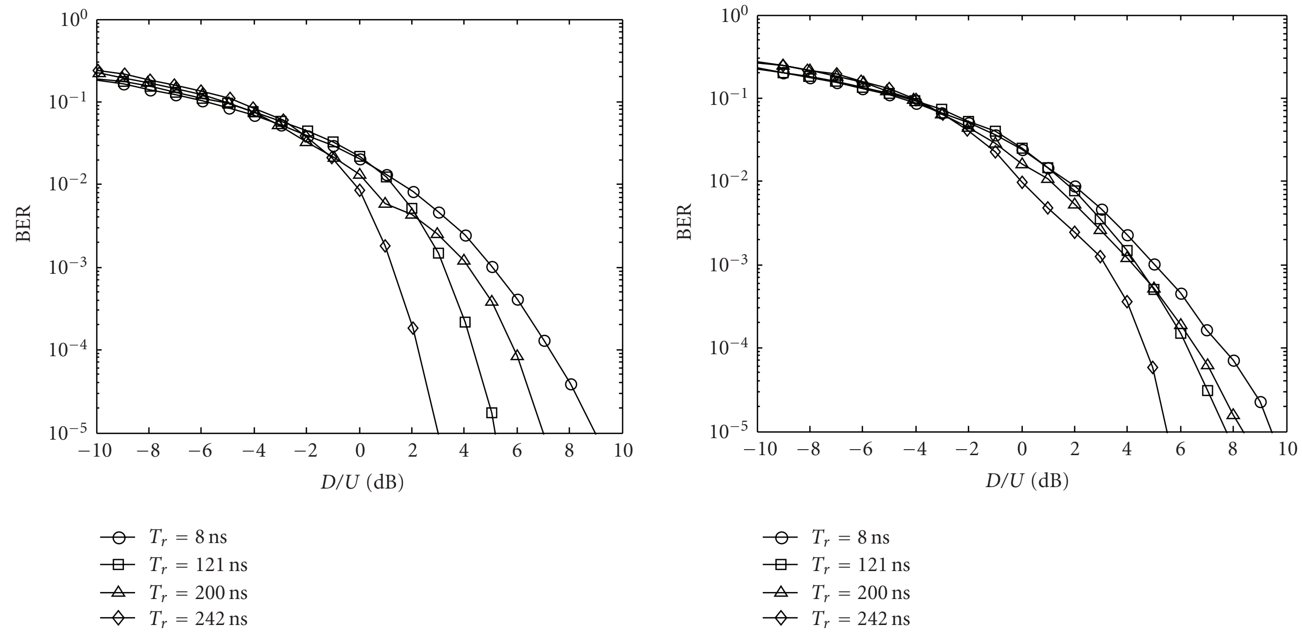
where T_c denotes the chip repetition cycle, which is set to match the UWB pulse width. An example of DS-UWB time frame is illustrated in Figure 7.

Figure 9 shows BER performance versus the symbol repetition cycle of DS-UWB. DS-UWB is spread over 8 and 64 chips, the spreading codes are M-sequence (maximum length sequence) and add "+1" to set the code length. The OFDM signal used is a MB-OFDM PAN system. The bandwidth of the MB-OFDM signal is wider than the gap that exists in the DS-UWB spectrum depending on the



(a) 8 chip spreading code (b) 64 chip spreading code

Figure 9: BER performance of OFDM signal interfered with by DS-UWB for changing symbol repetition intervals ($T_c = 1$ nanosecond).



(a) 8 chip spreading code (b) 64 chip spreading codes

Figure 10: BER performance of OFDM interfered with by DS-UWB ($E_b/N_0 = 20$ dB).

spreading codes. The characteristics of the BER performance are almost the same as Figure 2(a). When the symbol repetition interval is equal to or half of the OFDM IFFT/FFT period, the BER performance improves the same extent as the p-UWB paired with an OFDM signal.

In Figure 10, the BER performance is evaluated by changing the D/U ratio. The improvement in the BER performance drops as spreading code length increases, because the symbol duration of DS-UWB is also extended. In (8), the number of sampling points for each pulse is assumed to be one since the impulse response duration of the BPF is short. However, the number of sampling points for each symbol becomes larger than for p-UWB. Thus, the sinusoidal wave in (9) is also increased to extend symbol duration, and the effect of the interference becomes closer to a Gaussian distribution. Therefore, it is important that the symbol duration of DS-UWB should be shorter, and the symbol repetition interval should be set to equal to or half of the OFDM IFFT/FFT duration.

5. CONCLUSION

In this paper, an interference mitigation technique is proposed to set a pulse repetition cycle that does not reduce UWB average signal power. Coexistence issues among pulse-based UWB and OFDM signals are discussed. When the pulse repetition interval is set to the same as or half the OFDM IFFT/FFT duration, BER performance of the OFDM signal improves. Thus, it is important when deciding the pulse repetition interval for coexisting OFDM system parameters. This interference mitigation technique is expanded for DS-UWB systems. An explanation of how the symbol repetition interval in DS-UWB can be set to mitigate interference with individual subcarriers and to reduce the UWB peak power is provided.

The proposed interference mitigation techniques relate only to control the pulse repetition interval. This provides the advantage that they can be implemented in relatively simple UWB transmitter/receiver structures. Therefore, the system is suitable for simple hardware and low-data rate UWB systems.

REFERENCES

[1] M. Z. Win and R. A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Transactions on Communications*, vol. 48, no. 4, pp. 679–691, 2000.

[2] FCCET Docket 98–153, "FIRST REPORT AND ORDER: Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems," February 2002.

[3] Ministry of internal Affairs Communications, "The report of UWB radio system group," February 2005.

[4] Electronic Communications Committee, "ECC Decision of 1 Dec. 2006 on the harmonized conditions for devices using UWB technology with Low Duty Cycle in the frequency band 3.4GHz–4.8GHz," CEPT, December 2006.

[5] A. Tomiki, I. Pasya, and T. Kobayashi, "Simulation of interference effects from MB-OFDM and DS-UWB to a QPSK digital transmission system," *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, vol. E89-A, no. 11, pp. 3059–3065, 2006.

[6] M. Hamalainen, J. Saloranta, J.-P. Makela, I. Oppermann, and T. Patana, "UWB impact on IEEE802.11b wireless local area network," in *Proceedings of the 6th International Symposium on Wireless Personal Multimedia Communications (WPMC '03)*, pp. 278–282, Yokosuka, Japan, October 2003.

[7] S. Choi, S. Cho, and H. Lee, "UWB interference test in IEEE802.11b WLAN environment," in *Proceedings of the International Workshop on Ultra Wideband Systems (IWUWBS '03)*, Oulu, Finland, June 2003.

[8] H. Yamaguchi, "Active interference cancellation technique for MB-OFDM cognitive radio," in *Proceedings of the 34th European Microwave Conference*, vol. 2, pp. 1105–1108, London, UK, October 2004.

[9] H. Zhang and R. Kohno, "Re-configurable soft-spectrum UWB receiving scheme with multi-mode and multi-rate adaptation," in *Proceedings of the 6th International Symposium on Wireless Personal Multimedia Communications (WPMC '03)*, Yokosuka, Japan, October 2003.

[10] H. Zhang, X. Zhou, K. Y. Yazdandoost, and I. Chlamtac, "Multiple signal waveforms adaptation in cognitive ultra-wideband radio evolution," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 4, pp. 878–884, 2006.

[11] K. Ohno and T. Ikegami, "Interference mitigation study for UWB radio using template waveform processing," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 4, pp. 1782–1792, 2006.

[12] K. Ohno and T. Ikegami, "Interference detection and mitigation by using multi-carrier template wave for pulse based UWB," in *Proceedings of the 9th IEEE International Symposium on Spread Spectrum Techniques and Application (ISSSTA '06)*, pp. 183–187, Manaus, Brazil, August 2006.

[13] K. Ohno and T. Ikegami, "Interference DAA technique for coexisting UWB radio," in *Proceedings of the 65th Vehicular Technology Conference (VTC '07)*, pp. 2910–2914, Dublin, Ireland, April 2007.

[14] R. van Nee, *OFDM for Wireless Multimedia Communications*, Artech House, London, UK, 1999.

[15] A. Batra, "Multi-band OFDM Physical Layer Proposal," IEEE802.15-03/267r6, September 2003.

[16] A. Batra, "Physical Layer Submission to 802.15 Task Group 3a: Multi-band OFDM," IEEE802.15-03/268r3, March 2004.

[17] IEEE, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-speed Physical Layer in the 5 GHZ Band," IEEE Std 802.11a-1999, September 1999.

[18] A. F. Molisch, et al., "IEEE 802.15.4a channel model final report," IEEE P802.15-04/662r0-SG4a, November 2004.

[19] A. Papulis, *Probability, Random Variables, and Stochastic Process*, McGraw-Hill, New York, NY, USA, 1965.