Spectrum Management Technique by using Adaptive Low Duty-Cycle UWB

Keisuke Sodeyama, Ryuji Kohno
Division of Physics, Electrical and Computer Engineering,
Graduate School of Engineering, Yokohama National University
79–5 Tokiwadai, Hodogaya, Yokohama, 240–8501, Japan.
Tel.: +81-45-339-4116 Fax: +81-45-338-1176
E–mail: sodeyama@kohnolab.dnj.ynu.ac.jp, kohno@ynu.ac.jp

***Abstract*—Low Duty Cycle (LDC) algorithm is interference mitigation technique, which can reduce the average interference to the existing radio systems by using lowering pulse repetition interval or pulse occupation time. In this paper, the coexistence environment between low data rate ultra wideband (UWB) communication system such as wireless sensor network, body area network (BAN) and the existing wideband system using orthogonal frequency division multiplexing (OFDM) such as 4th generation mobile cellular system (4G) is considered.**

In order to analyze the interference mitigation capability of LDC algorithm with impulse based UWB (LDC-UWB) system, the frame error rate (FER) of wideband OFDM system is examined for two types of LDC-UWB system: the signal with random polarity such as binary pole signals and without random polarity such as mono pole signals. We present that LDC algorithm is an efficient interference mitigation technique for low data rate UWB communication via computer simulations regardless of definitions of transmitted energy of UWB communication system, and also that the signal with random polarity is suitable for LDC-UWB system to mitigate interference to the other radio systems. We further investigate the adequate duty cycle of LDC-UWB system for each definitions of transmitted power of UWB communication.

Moreover, we propose the spectrum management techniques by using adaptive rate controlled LDC-UWB. The average interference from UWB to wideband OFDM systems is reduced by using LDC algorithm. Simultaneously, the frequency spectrally notching out the existing system operational bandwidth frequency avoidance technique can be formed by adaptively-changed duty cycle of LDC-UWB system. Therefore, we present that the interference mitigation capability of LDC-UWB system can be improved.

I. Introduction

The potential applications of UWB communication include high data rate wireless personal area network (WPAN) which can achieve more than 100 Mbps over short distance and wireless sensor networks such as IEEE 802.15.4a providing low data rate UWB communication over medium range combined with precise ranging and positioning capabilities. Thus, UWB communication is a promised technology to apply various application. While wireless local area network (WLAN) and Bluetooth coexist each other and also with the other unlicensed systems in the industry, science, and medical (ISM) band which is opened for some applications in Japan. UWB communication coexist with licensed system such as worldwide interoperability for microwave access (WiMAX), 4th generation mobile cellular systems (4G), and field pickup unit (FPU). Therefore, UWB communication may inherently degrade the performance of the existing other radio systems since the radio band of the UWB communication systems overlaps that of the other radio systems such as WiMAX and 4G. The technical conditions on the usage of UWB communication system were set up by the Ministry of Internal Affairs and Communications on March 2006, in Japan [1] and it is imperative for UWB communications to equip the interference mitigation techniques, *detect and avoid* (DAA) and *low duty-cycle* (LDC).

In general, DAA technique aims to mainly at high data rate UWB communication such as WPAN. On the other hand, LDC algorithm mainly aims to low data rate UWB communications such as IEEE 802.15.4a [2]. IEEE 802.15.4a standard for low data rate sensor networks is designed for long battery life, low cost, and low latency rather than maximizing the data rate. Thus, DAA technique may not be suited for low data rate UWB communication because of their strict constraints on energy consumption and device costs. Therefore, LDC algorithm can be an attractive candidate for interference mitigation in low data rate UWB communications.

The aim of LDC algorithm is to reduce the average interference to the existing radio systems by lowering pulse repetition interval or pulse occupation time. The features of LDC algorithm imposes low data rate but achieve low energy consumption since the pulse repetition interval is extended. Originally, LDC algorithm has been proposed to reduce energy consumption [3]. Moreover, in UWB ad-hoc network, LDC algorithm has been studied to improve the near/far power disparities or pulse-on-pulse interference of multiple access [4, 5]. Furthermore, in low power low rate UWB communication, LDC algorithm has been studied to improve the protocol design of medium access control (MAC) layer [6, 7].

However, the design of the duty-cycle of impulse-based UWB communication system with LDC algorithm (LDC-UWB) has not been presented. In addition, despite all the benefits inherent to LDC algorithm, UWB communication systems still interfere with the existing other radio systems. In this paper, we focus on the coexistence environment between LDC UWB system and wideband system based on OFDM such as 4G and WiMAX. This paper analyzes the performance of UWB system with LDC algorithm as the interference mitigation technique in the presence of coexistence environment. In order to analyze the interference mitigation capability of LDC-UWB, the performance of wideband OFDM systems based on the frame error rate (FER) over the coexistence environment is presented via computer simulations. Moreover, two types of LDC-UWB signal interference are considered: the signal with random polarity such as binary pole signals and without random polarity such as mono pole signals. We present that LDC algorithm is an efficient interference mitigation technique for low data rate UWB communication. In addition, the definition of UWB transmission power has been approached in two different manners: fixed power per pulse and fixed power per unit of time. The question that may arise at this point is how to design the duty-cycle of LDC-UWB system by each definition of UWB transmission power. Therefore, we further investigate the adequate duty-cycle of LDC-UWB system for each definition.

The rest of this paper is organized as follows. Section I describes the LDC-UWB system model considered throughout this paper. The wideband OFDM system model is presented in Section III. The simulation results are presented in Section IV. Finally, in Section V conclusions are given.

II. LDC-UWB System Model

The major parameters of LDC-UWB communication systems are given in Table I. In this paper, low data rate UWB communication system is considered such as wireless sensor network, and thus, its data rate is below 1 Mbps. Also, the pulse repetition frequency (PRF) is given as 3.9 MHz or 15.6 MHz, which is compliant with IEEE 802.15.4a. Also, PRF is defined as the number of the pulse in one frame of the transmit slot of LDC-UWB device.

Moreover, two types of LDC-UWB signal interference are considered: with random polarity such as binary pole signals and without random polarity such as mono pole signals. The reason for the later is the significant simplicity of the circuit design when using the signal without random polarity. We also consider two definitions of LDC-UWB transmission power: fixed power per pulse and fixed power per unit of time since these definitions have been discussed at the mutual interference between pulse-based UWB system and other radio system.

A. Specifications of LDC-UWB System

In this protocol, every UWB communication devices only wake up for short time to communicate with each other and timing schedule for communication is not available at each device. Thus, in order to establish a communication link, access controller (AC) is introduced. The wireless network based on LDC protocol must have one AC device, which may be allowed relatively high power consumption and high duty-cycle (HDC) compared with those of non-AC devices. AC can receive messages from all UWB devices belonging to its own network besides having AC has the timing schedule of every UWB devices. Note that this protocol is suitable for indoor applications since AC device should be connected to the power supply because of its high power consumption and high duty-cycle. Fig. 1 illustrates an example of the LDC protocol with UWB devices A and B, where, the duty-cycle is about 0.1 % with both UWB devices transmit (Tx) and receive (Rx) time slot length of 1 ms. AC has 2,002 ms receive time slot and the duty-cycle of LDC-UWB system is defined as

$$DC = \frac{2T_s}{T_f}, \tag{1}$$

where DC is the duty-cycle of LDC-UWB, T_s is the Tx+Rx slot length, T_f is the frame length of LDC-UWB (T_f is fixed 2,002 ms). As example, duty-cycle 0.1 % is defined that Tx and Rx of UWB communication devices are 1 ms, respectively, and total sleep period per frame is 2,000 ms, duty-cycle 50 % is defined that Tx and Rx are 500 ms and total sleep period per frame is 1002 ms.

The maximal number of interference pulse N_p is defined as

$$N_p = L_{Tx} \times DC \times f_{PRF}, \tag{2}$$

where L_{Tx} is the transmission frame length of LDC-UWB, DC is the duty-cycle of LDC-UWB system and f_{PRF} is the PRF of LDC-UWB system.

TABLE I
Major parameters of LDC-UWB systems

Type of UWB system	Impulse based UWB
Center Frequency: f_c	4.0 GHz
Bandwidth	2 GHz
Data rate	$>$ 1 Mbps
Pulse repetition frequency (PRF)	3.9 MHz, 15.6 MHz
Pulse width	0.5 ns
Duty-Cycle: DC	0.1, 0.5, 1, 10, 50, 100 %
Tx (or Rx) slot length	1 $-$ 1,001 ms
Sleep period after Tx (or Rx)	1,000 $-$ 0 ms
Frame length of LDC-UWB system	2,002 ms

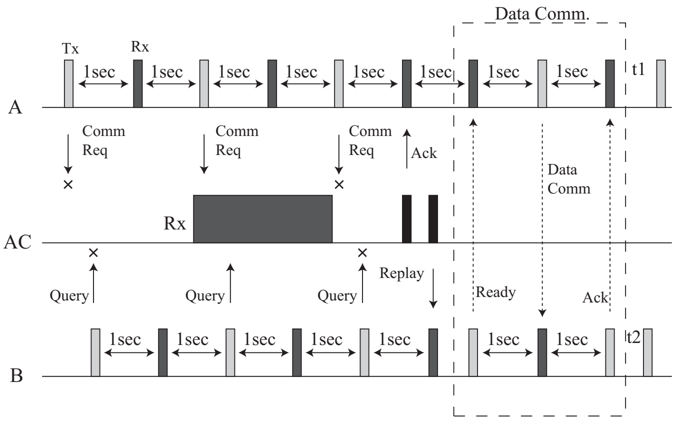

Fig. 1. an example of the LDC protocol with UWB communication devices A and B, where the duty-cycle is about 0.1 %.

TABLE II
MAJOR PARAMETERS OF THE WIDEBAND OFDM SYSTEMS

Bandwidth	101.5 MHz
Data rate objective	$>$ 100 Mbps
Number of sub-carriers: N_c	768
Sub-Carrier spacing: F_s	131.8 kHz
OFDM symbol duration: T_s	7.585 μs
Total OFDM symbols duration: T_s'	9.259 μs
Number of OFDM symbols per frame: N_s	54
OFDM frame length: T_{fr}	500 μs
Symbol mapping	QPSK

III. WIDEBAND OFDM SYSTEM MODEL

Wideband OFDM systems are considered among the most appropriate schemes for future high data rate communications systems due to their effective bandwidth utilization and the simplicity of the equalization strategies needed to compensate the channel frequency selective fading. The OFDM technique has been adopted in several standards, e.g., digital audio broadcasting (DAB), digital video broadcasting (DVB), multi-media mobile access communications (MMAC) and WLAN. It also has been proposed for cable TV, broadband radio access networks, multi-user communications via satellite link, WiMAX, 4G and FPU.

In this paper, we focus on the coexistence environment of UWB communication systems and wideband OFDM systems such as 4G and WiMAX. The basic idea of OFDM is to divide the available spectrum into several sub-channels (sub-carriers). By making all sub-channels narrower than the coherence bandwidth of the radio channels, they experience almost flat fading, simplifying the equalization process (one tap equalizer). In order to obtain a high spectral efficiency the sub-channels are overlapping, still keeping the orthogonality of their sub-carriers. This orthogonality is completely maintained, even when the signal passes through a time dispersive channel by introducing a cyclic prefix (the last part of the OFDM symbol is copied in front of the transmitted symbol). This of course introduces a loss in signal-to-noise ratio (SNR), but if the impulse response of channel is shorter than the cyclic prefix, then the inter-symbol interference (ISI) and inter-carrier interference (ICI) are completely removed at the output of the channel [8].

Fig. 2 shows the block diagram of the wideband OFDM system. Major parameters of the wideband OFDM systems are listed in Table II (c.f., [9]). In this paper, the bandwidth of the wideband OFDM system is about 100 MHz and, thus, its data rate is 100 MHz bps. The equivalent baseband model is employed, therefore, the interference of the UWB signals is introduced by adding the UWB signal to the transmitted OFDM signal (see Fig. 2). After that, the received signals are passed through the low pass filter (LPF) of the wideband OFDM system.

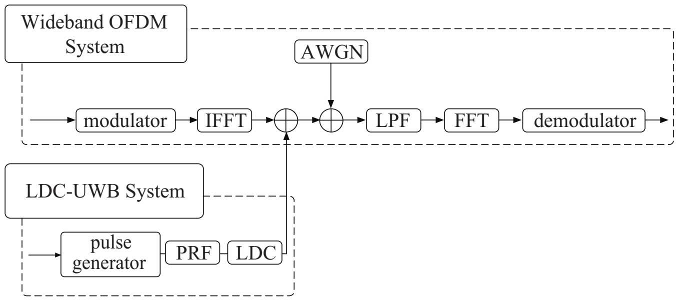

Fig. 2. The block diagram of the wideband OFDM system

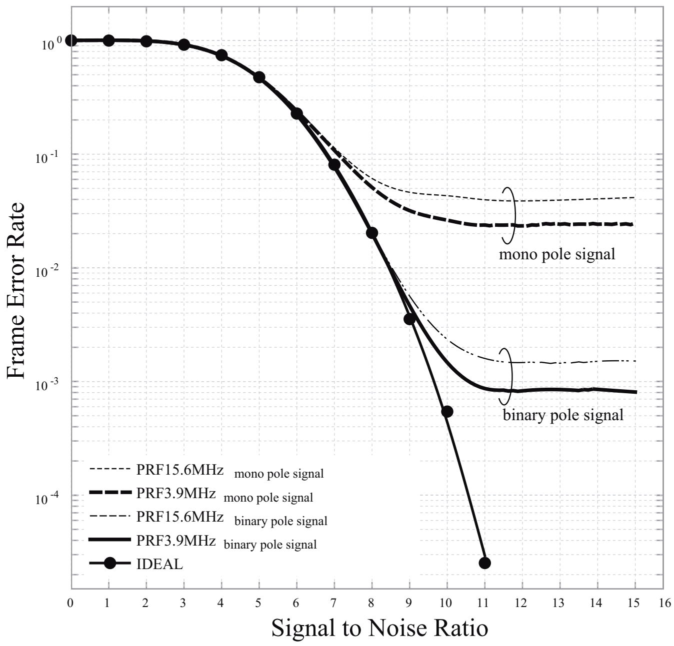

Fig. 3. The FER of the wideband OFDM system over AWGN channel with the interference by LDC-UWB system when SIR=10 dB and duty-cycle=0.1 %. The definition of UWB transmission power is fixed power per pulse.

IV. SIMULATION RESULTS

Although LDC protocol promises that the average interference to the wideband OFDM systems can be suppressed, LDC-UWB communication systems still interfere to wideband OFDM systems even with LDC protocol. Moreover, when UWB communication devices (or users) are increased, the interference to wideband OFDM system may be increased even applying lower duty-cycle.

First, the FER of the wideband OFDM systems over additive white Gaussian (AWGN) channel with the interference by the LDC-UWB system is analyzed. Fig. 3 shows the FER of the wideband OFDM system with the interference by LDC-UWB system when signal to interference ratio (SIR) = 10 dB, duty-cycle is 0.1 % and PRF is given as 3.9 MHz or 15.9 MHz. Also, SIR is defined as the wideband OFDM system transmission power to LDC-UWB interference transmission power ratio. LDC-UWB transmission power is fixed power per pulse.

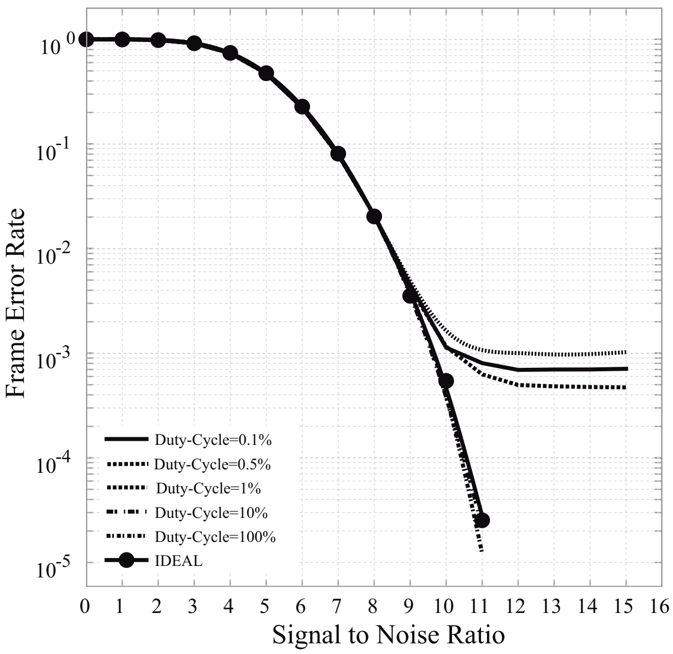

Fig. 4. The FER of the wideband OFDM systems over AWGN channel with the interference by LDC-UWB system when SIR=10 dB and PRF=3.9 MHz. The definition of UWB transmission power is fixed power per unit of time.

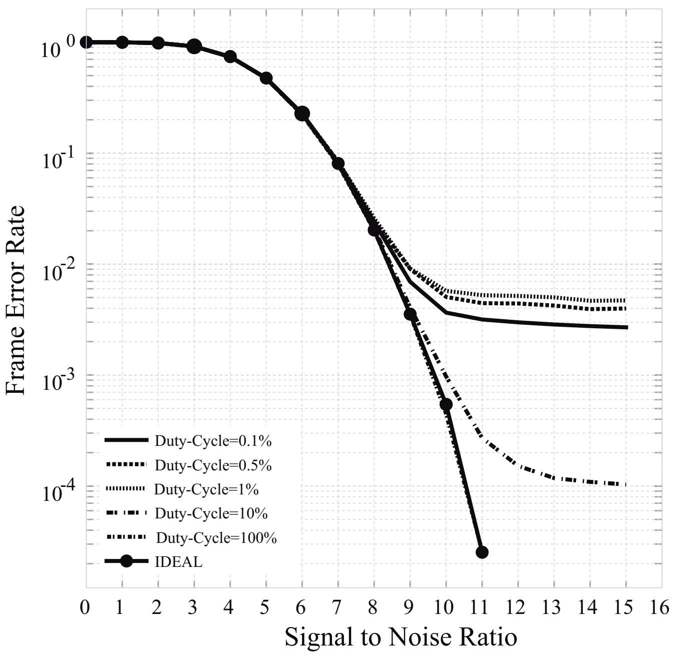

Fig. 5. The FER of the wideband OFDM systems over AWGN channel with the interference by LDC-UWB system when SIR=10 dB and PRF=15.6 MHz. The definition of UWB transmission power is fixed power per unit of time.

From Fig. 3, the FER of the wideband OFDM system with interference by binary pole signals is superior to the interference by mono pole signals. The reason for this to occur is that the LDC-UWB interference by mono pole signals amplifies the interference since the constant signal polarity

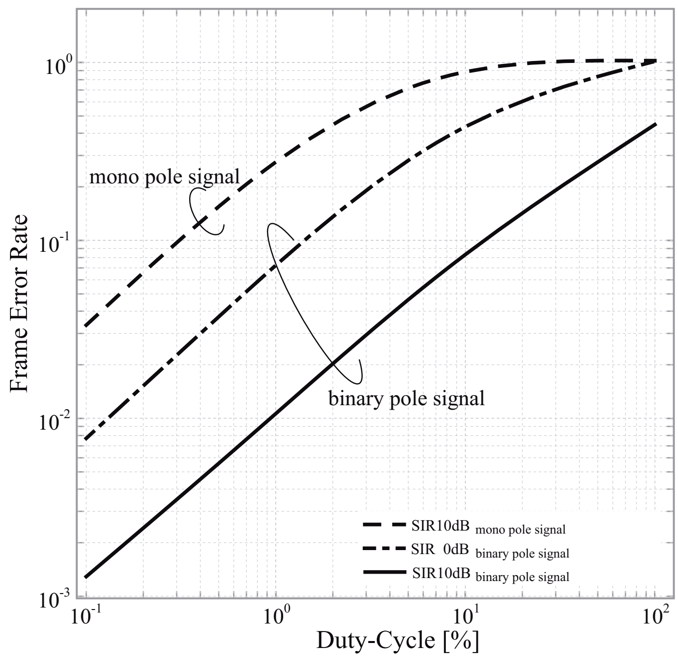

Fig. 6. The FER of the wideband OFDM system with the interference by the LDC-UWB communication devices, when SNR=10 dB and the PRF=3.9 MHz. The definition of UWB transmission power is fixed power per pulse.

adds to wideband OFDM system. Meanwhile, the interference by binary pole signal is reduced by the each random polarity of LDC-UWB signals. Therefore, LDC-UWB signal needs the random polarity such as binary pole signal. In other words, the binary pole signal is essential for LDC-UWB signal to reduce interference to wideband OFDM systems.

From another viewpoint, the FER of wideband OFDM systems are degraded by increasing PRF of LDC-UWB systems since the number of interference pulses are increased. Therefore, the PRF of LDC-UWB systems should be carefully chosen in consideration of the quality of performance required by wideband OFDM system and by each LDC-UWB application.

When the definition of LDC-UWB transmission power is fixed, the power per unit of time, the FER of wideband OFDM system with interference by LDC-UWB system with SIR = 10 dB, and PRF = 3.9 MHz is presented in Fig. 4. Fig. 5 shows the performance when PRF is changed to 15.6 MHz.

From Fig. 4 and Fig. 5, when the definition of UWB transmission power is fixed power per unit of time, the FER of wideband OFDM systems is superior to that of fixed power per pulse since the transmission power of each pulses is reduced. Therefore, the collision probability considered, the interference of LDC-UWB system is improved as longer as duty-cycle. However, the communication area of LDC-UWB devices is narrowed since the signal power is reduced by increasing duty-cycle. Thus, a trade-off between the communication area of LDC-UWB devices and duty-cycle of LDC-UWB system can be found. Moreover, the FER of wideband OFDM systems are degraded by decreasing PRF of LDC-

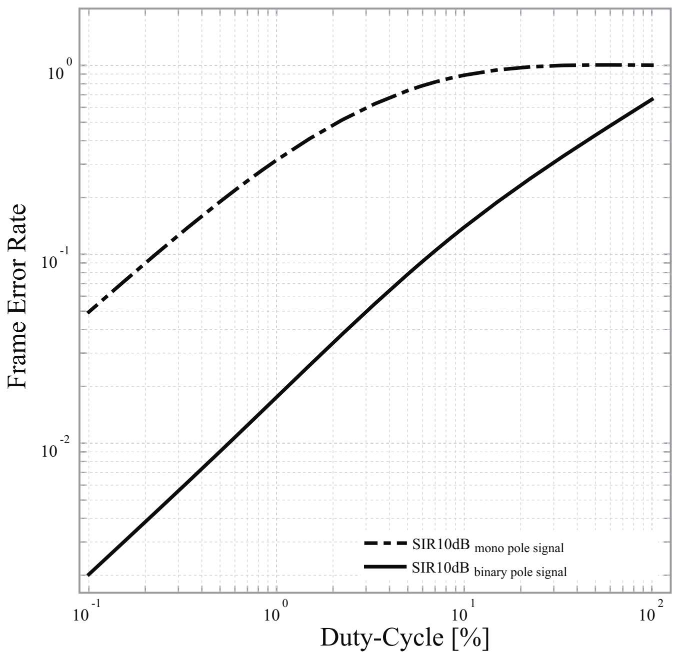

Fig. 7. The FER of the wideband OFDM system with the interference by the LDC-UWB communication devices, when SNR=10 dB and the PRF=15.6 MHz. The definition of UWB transmission power is fixed the power per the pulse.

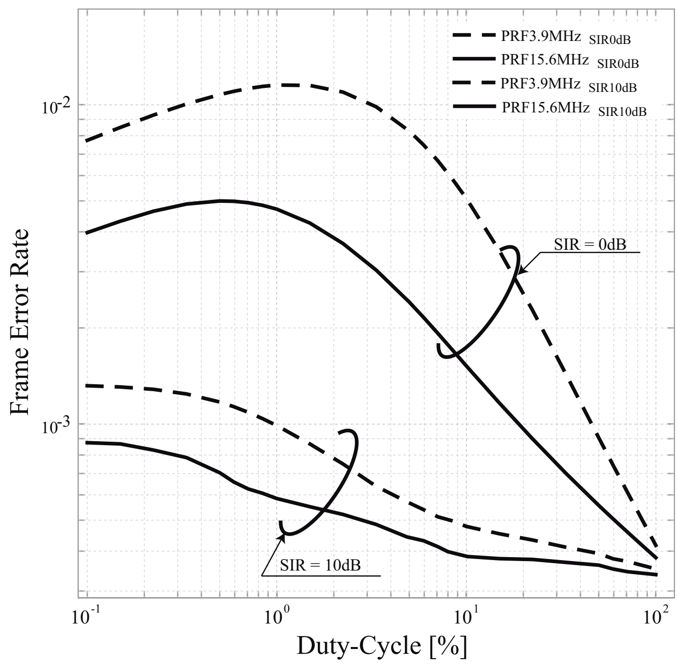

Fig. 8. The FER of the wideband OFDM system with the interference by the LDC-UWB communication devices with random polarity, when SNR=10 dB. The definition of UWB transmission power is fixed power per unit of time.

UWB systems since the power of each pulses are decreasing.

Secondly, the FER of wideband OFDM system over AWGN channel with the interference by LDC-UWB systems is presented when the duty-cycle of LDC-UWB system is changed. Here, SNR is fixed to 10 dB. The FER of the wideband OFDM systems with the interference by the LDC-UWB communication devices are shown in Figure 6, where PRF = 3.9 MHz. Fig. 7 shows the performance when PRF=15.6 MHz. Here, the definition of LDC-UWB transmission power is fixed power the pulse.

From Fig. 6 and Fig. 7, the FER of wideband OFDM systems are degraded by increasing of the duty-cycle of LDC-UWB systems. LDC cannot suppress interference to wideband OFDM systems completely. However it can be mitigated moderately without additional complexity such as DAA. Thus, the duty-cycle of LDC-UWB should be chosen carefully in consideration of the quality of the service required by the wideband OFDM system in the physical layer.

When the LDC-UWB signal power is fixed power per unit of time, the FER of wideband OFDM system with the interference by changing the duty-cycle of LDC-UWB system is presented. Here, SNR is fixed to 10 dB. Figure 8 shows the FER of the wideband OFDM systems with the interference by LDC-UWB communication devices.

In Fig.8, the FER of wideband OFDM system with interference by duty-cycle=100% is superior to that of duty-cycle = 0.1 %. For the reason that although the collision probability between wideband OFDM system and LDC-UWB system is increased, the pulse signal power becomes lower since the number of pulses is increased. However, when the duty-cycle of DC-UWB system is increased, simultaneously, the power consumption is also grown. Therefore, in IEEE 802.15.4a, such as wireless sensor network, using duty-cycle = 100 % is difficult. Therefore, the duty-cycle of LDC-UWB system should be set to distinctly low values of less than 0.1 %.

From these results, the duty-cycle of LDC-UWB system should be chosen carefully in consideration of the requirements of the each LDC-UWB applications. When the LDC-UWB signal power is fixed power per pulse, the interference to wideband OFDM is mitigated with reducing duty-cycle of LDC-UWB system. Therefore, when the LDC-UWB signal power is fixed power per pulse, the duty-cycle of LDC-UWB should be chosen low values of 0.1 % and using PRF = 3.9 MHz is absolutely essential. Meanwhile, when the LDC-UWB signal power is fixed power per unit of time, the duty-cycle of LDC-UWB system is depended on both the collision probability between wideband OFDM system and LDC-UWB system and the power of LDC-UWB pulse. In IEEE 802.15.4a such as wireless sensor network, using higher duty-cycle is difficult since the power consumption is also significantly high. Therefore, when the LDC-UWB signal power is fixed power per unit of time, the duty-cycle of LDC-UWB should be set to distinctly low values of less than 0.1 % and using PRF = 15.6 MHz is absolutely essential. Thus, the design issues of PRF and duty-cycle are different with each definition of LDC-UWB transmission power.

V. CONCLUSIONS

n this paper, we have focused on the coexistence environment between LDC-UWB system and wideband OFDM system and have analyzed the interference mitigation capability of LDC-UWB system in the presence of wideband OFDM system. The performance of wideband OFDM system based on FER over the coexistence environment has been presented via computer simulations. The signal with random polarity such as binary pole signal has been necessary to mitigate the interference for wideband OFDM system. Moreover, by the definition of the UWB transmission power, the duty-cycle of LDC-UWB system has been needed to establish in consideration of the request of the each LDC-UWB application. Moreover, we have presented the design issues of PRF and duty-cycle are different with each definition of LDC-UWB transmission power.

We can conclude that LDC algorithm is an efficient interference mitigation technique for low data rate UWB communication since the FER of wideband OFDM systems is improved with decreasing of the duty-cycle of LDC-UWB. However, LDC cannot suppress interference to wideband OFDM systems completely. Though, it can be mitigated moderately without additional complexity such as DAA. Thus, the duty-cycle of LDC-UWB should be chosen carefully in consideration of the quality of the service required by the wideband OFDM system in the physical layer. Moreover, the duty-cycle of LDC-UWB system should be chosen carefully in consideration of the requirements of the each LDC-UWB application.

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