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Impact of Chip Duty Factor on DS, TH and DS-TH UWB Systems in Realistic Environment

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SUMMARY In this paper, the impact of chip duty factor (DF) on direct sequence (DS), time hopping (TH) and hybrid DS-TH ultra wideband (UWB) systems is investigated in realistic environments. Rake receivers are designed to perform energy capture (EC) on received UWB signals over multipath and multi-user environment in the presence of narrowband interference. It is found that by applying lower DF in the signal design, multipath resolvability can be increased and system performance can be improved. However, in contrary to the common belief, lower DF does not always contribute to performance improvement. On the other hand, it is observed that at extremely low DF, EC capability may be compromised, causing performance degradation. The optimum DF values for respective systems are determined and discussed in this paper. Additionally, the strength and tradeoff for DS, TH and DS-TH UWB systems employing varying DF are investigated and compared over multipath and multi-user environment. In a multipath environment, a selective Rake receiver with less than 10 fingers is found to be sufficient for energy capture. In a single user environment, DS-UWB system has the most superior performance, followed by DS-TH-UWB and TH-UWB systems. And in a multi-user environment, DS-TH-UWB is found to outperform the rest, followed by DS-UWB and TH-UWB systems.
key words: *UWB, chip duty factor, DS, TH, DS-TH, energy capture*

1. Introduction

Ultra wideband (UWB) is a wireless technology that focuses on offering high data rate by transmitting very short pulses to increase spreading bandwidth at a fixed low power spectral density (PSD). These technical features enable UWB technology to obtain several advantages such as higher multipath resolvability and low power low complexity operation. The momentum that UWB technology gathered is becoming more significant that several major communication related institutions have drawn specifications to assist its research, development and implementation [1]–[3].

UWB technology has inherited several technical characteristics from the conventional spread spectrum (SS) technology, except for a few differences. UWB intends to increase data rate by increasing spreading bandwidth at a fixed PSD, whereas SS commonly decreases the PSD by increasing spreading bandwidth at a fixed data rate. Particularly, one unique UWB feature is to employ signal with low chip duty factor (DF) for the purpose of bandwidth spreading. In fact, DF is a major parameter that contributes most of the attractive advantages that UWB technology is capable of offering. Despite its importance, this issue is not receiving essential attention it deserves. Up to date, besides some of our recent works in [4], [5], investigation on DF in UWB systems are hardly found in current literatures.

From the conventional impulse radio, UWB technology has gradually evolved into coupling with various spreading schemes to further utilize its potentials. Some of the commonly applied spreading techniques are the time hopping (TH), direct sequence (DS) and hybrid DS-TH methods. Investigations for these works can be found separately in [6]–[10]. In [6], the classical idea of impulse radio is proposed and [7] further explores its multiple access potentials by applying TH spreading. Then, DS-UWB system performance in various propagation channel is analyzed via computer simulation in [8] and analytical approach in [9]. Next, work in [10] combines both modulation methods into a hybrid DS-TH-UWB system, and discusses its performance.

The main limitation of the existing literatures is twofold: (a) no investigation on DF as an essential UWB system design parameter over realistic channel and, (b) no comparative studies among the DS, TH and DS-TH systems on a fair platform with similar system resources. Therefore, the first contribution of this paper is to investigate the impact of the rarely explored parameter DF in UWB systems. We describe how signal with different DF behave in the energy capturing process of the Rake receivers, and how it affects the system performance. The idea of energy capture (EC) for impulse radio is initially proposed in [11] and later applied to characterize system performance in multipath environment [12]. Our previous work [5] addressed the impact of DF in a single user DS-UWB environment. In this paper, we have extended the analysis of EC to very low DF UWB signals over realistic environment based on actual UWB signal measurements. Secondly, we have also analyzed and compared the impact of DF in DS, TH and DS-TH UWB systems under similar system resources. Thirdly, we have enhanced the analytical environment to multipath, multi-user environment in the presence of narrowband interference. These findings should be of practical interest to system designers looking to achieve higher performance with the lowest possible resources.

The rest of this paper is organized as follow. Section 2 describes system model and various signal schemes. Section 3 characterizes the EC and system performance in the

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receiver. Section 4 presents and discusses the simulation results. Section 5 summarizes the overview of the DS, TH and DS-TH UWB systems. Finally Sect. 6 concludes with potential future works.

2. System Model

The system is considered to have a binary phase shift keying (BPSK) data input. The top diagram for a general UWB system is shown in Fig. 1. Signal models for DS, TH and DS-TH are as shown respectively as follows.

2.1 DS-TH-UWB Signal

The DS-TH-UWB signal of the k-th user is described as:

$$s^{(k)}(t) = \sqrt{E_p} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_s-1} d_i c_j^{(k)} p\left(t - iT_b - j\frac{T_p}{\delta} - v_j^{(k)} T_p\right) \cdot \cos(2\pi f_c t) \quad (1)$$

where d_i and c_j, both with random uniform values of $\{+1, -1\}$, are the i-th BPSK data and j-th user-dependent DS spreading code respectively, N_s is the number of chips (each with duration T_c) per bit, T_p is the pulse duration with pulse energy E_p, $\delta = T_p/T_c$ is the chip duty factor DF and $0 < \delta \leq 1$, T_b is the bit duration with bit energy $E_b = N_s E_p$, $v_j = \{0, 1, 2, ..., N_c\}$ is the user-dependent TH sequence that provides an additional time shift of $v_j T_p$ to the j-th pulse, $N_c = T_c/T_p = 1/\delta$ is the total number of time slots available for the time hopping pulse, f_c is the pulse center frequency and $p(t)$ is the transmitted pulse waveform. Note that spreading bandwidth W can be approximated by $2/T_p$. The system data rate R_b and processing gain PG are defined as $1/T_b$ and $N_s/\delta = N_s N_c$, respectively. Signaling diagram for DS-TH-UWB can be referred to Fig. 2(a), where pulses with different polarity are placed in different time slots in every T_c.

2.2 DS-UWB Signal

Next, (1) can be modified easily to obtain the DS-UWB signal of the k-th user, by simply setting the TH sequence v_j to constant 0, as below:

$$s^{(k)}(t) = \sqrt{E_p} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_s-1} d_i c_j^{(k)} p\left(t - iT_b - j\frac{T_p}{\delta}\right) \cdot \cos(2\pi f_c t) \quad (2)$$

Here, the PG is defined as N_s/δ. Signaling diagram for DS-UWB is shown in Fig. 2(b), where pulses with different polarity are placed in the first time slot in every T_c.

2.3 TH-UWB Signal

Likewise, modifying (1), the TH-UWB signal of the k-th user can be obtained by setting DS code c_j to constant 1, as below:

$$s^{(k)}(t) = \sqrt{E_p} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_s-1} d_i p\left(t - iT_b - j\frac{T_p}{\delta} - v_j^{(k)} T_p\right) \cdot \cos(2\pi f_c t) \quad (3)$$

where the PG is defined as $N_s N_c$. Here, signaling diagram for TH-UWB is shown in Fig. 2(c), where pulses with similar polarity are placed in different time slots in every T_c.

2.4 Chip Duty Factor

In this paper, the design of signal with different DF is achieved by pairing up lower DF with shorter N_s, meanwhile maintaining the PG, W and R_b. The definition of DF is given as $\delta = T_p/T_c$ in (1). Here, we can further describe DF as:

$$\delta = \frac{N_s}{PG} \quad (4)$$

From (4) we know that by setting PG constant, if δ decreases, N_s will decrease accordingly. In other words, to maintain PG, as DF becomes lower, number of chips for data spreading should also decrease. In this case, T_p and T_b remain constant despite changing DF. The illustration of such signal design can be shown in Fig. 3.

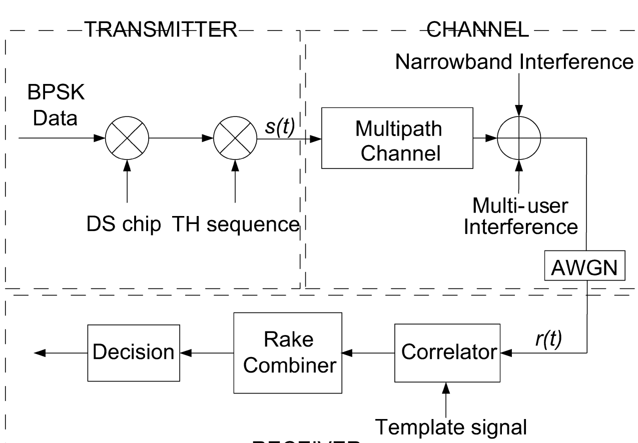

Fig. 1 Top diagram of UWB system.

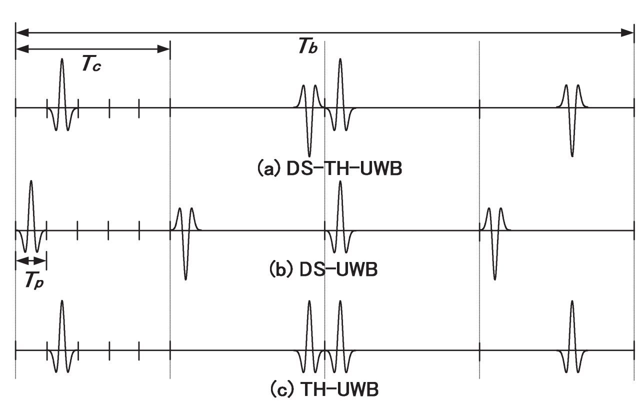

Fig. 2 Illustrations for (a) DS-TH-UWB, (b) DS-UWB and (c) TH-UWB signal. In this example, N_s=4 and N_c=5.

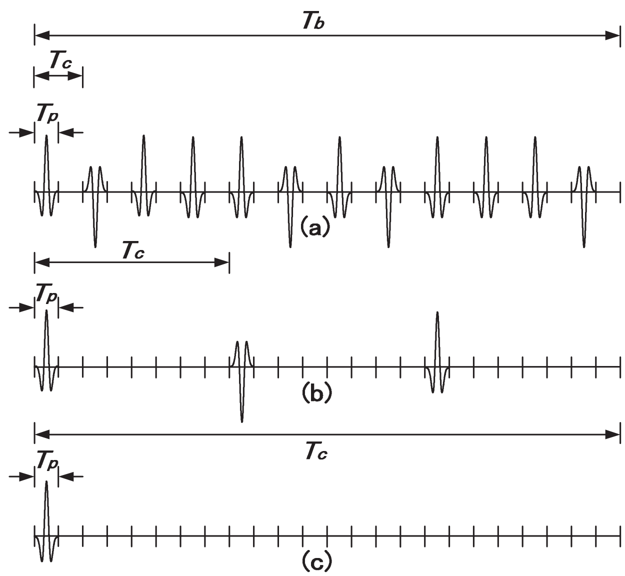

Fig. 3 Illustration of signal with different pairs of DF and N_s, and with constant PG, W and R_b. (a) δ=0.5, N_s=12, (b) δ=0.125, N_s=3, (c) δ=0.04, N_s=1.

2.5 Received Signal

Next, the received signal over multipath channel for the k-th user can be described as:

$$\begin{aligned} r^{(k)}(t) &= s^{(k)}(t) * h(t) + \eta(t) + \epsilon(t) \\ &= \sqrt{E_p} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_s-1} d_i c_j^{(k)} m\left(t - iT_b - j\frac{T_p}{\delta} - v_j^{(k)} T_p\right) \\ &\quad \cdot \cos(2\pi f_c t) + \eta(t) + \epsilon(t) \end{aligned} \tag{5}$$

where $h(t)$ is the channel impulse response, $\eta(t)$ is the white Gaussian noise, $\epsilon(t)$ is the narrowband interference, * denotes the convolution process and $m(t) = p(t) * h(t)$ is the channel response.

It is assumed that the channel remains constant for the entire bit duration. Note that $p(t)$ is a unit energy pulse, the channel response $m(t)$ of the pulse has energy $E_d = \int_0^{T_d} m^2(t)dt$, and $E_d \le N_s E_p$ due to fading. Here, T_d is the maximum delay spread with respect to the first arriving path. The total number of resolvable multipath is therefore given by $L = T_d/T_p$.

Next, the narrowband interference $\epsilon(t)$ in (5) can be further described as:

$$\epsilon(t) = \sqrt{2P_j} \sum_{x=-\infty}^{\infty} v_x g(t - xT_j) \cos(2\pi f_{nrb} t) \tag{6}$$

where v_x represents the x-th BPSK phase randomly uniform on $\{+1, -1\}$, T_j is the data duration, f_{nrb} is the center frequency, $g(t)$ is the signal waveform with signal power P_j and bandwidth $W_j = 2/T_j$.

Here, we also define the signal to noise ratio (SNR) and signal to interference ratio (SIR) to be E_b/N_0 and $E_bT_b/2P_j$, where N_0 is the one-sided AWGN PSD.

Then, in a multi-user channel, the received signal can be given by:

$$r(t) = \sum_{k=0}^{K-1} r^{(k)}(t - \phi_k) \tag{7}$$

where K is the total number of simultaneous users sharing the same propagation channel, ϕ_k represents the time delays of the interfering signals from other asynchronous users received by the k-th user and $0 \le \phi_k < T_b$.

2.6 Signal Correlation

By employing a Rake receiver, the template signal (*i.e.* the transmitted-signal-equivalent reference signal) as described below is generated:

$$\psi^{(k)}(t) = \frac{1}{\sqrt{N_s}} \sum_{j=0}^{N_s-1} c_j^{(k)} p\left(t - j\frac{T_p}{\delta} - v_j^{(k)} T_p\right) \cos(2\pi f_c t) \tag{8}$$

Note that the receiver is assumed to obtain knowledge of the sequence and spreading codes of the transmitted signal. This is a path-by-path correlator receiver and is equivalent to a match filter in the frequency domain. Here $\psi^{(k)}(t)$ is used to correlate with $r(t)$ at delays of multiple T_p [13]. This is where multipath resolvability can be increased as low DF signal in the multiples of T_c being resolved in multiples of T_p. Since it is well understood that we are modeling the receiver of the k-th user, here on the superscript k will be left out from the template signal $\psi^{(k)}(t)$. The correlation between $\psi(t)$ and $r(t)$ at the l-th Rake finger with delay τ_l can be described as:

$$Z_l = \int_{-\infty}^{+\infty} r(t)\psi(t - \tau_l)dt = \sqrt{E_p N_s E_d}\chi_l \alpha(\tau_l) + \eta_l + \epsilon_l \qquad l = 0, 1, ..., L-1 \tag{9}$$

with

$\alpha(\tau_l) = \int_{-\infty}^{\infty} m(t)p(t - \tau_l)dt$ is the correlation between channel response m(t) and unit energy pulse p(t) at delay τ_l.

χ_l = signal amplitude at delay τ_l.

$\eta_l = \int_0^{T_b} \eta(t)\psi(t)dt.$

$\epsilon_l = \int_0^{T_b} \epsilon(t)\psi(t)dt.$

Note that $\alpha(\tau) = 0$ if $\tau \le 0$ or $\tau \ge T_d$. In this paper, we employ Rake receivers with maximal ratio combining (MRC) method [13] for EC, assuming both magnitude and phase of the channel response are known.

Next the Rake combiner combines the resolvable paths. If all L paths are combined the receiver is known as an all

Rake receiver, whereas if $L_c < L$ paths are combined, the receiver is known as a selective Rake receiver. A selective Rake receiver has a compromised EC capability, with lower system complexity [13], [14].

3. System Performance

In this section, the idea of EC proposed in [11] is extended for analysis in UWB signals with different spreading schemes over multipath environment. The energy able to be captured by the Rake receiver in a total number of L_c paths are given as:

$$E_{cap} = E_p N_s E_d \sum_{l=0}^{L_c-1} |\chi_l \alpha(\tau_l)|^2 \tag{10}$$

It is important to note that E_{cap} is the energy captured by matching the template signal to the channel response, and $E_{cap} < E_d$ due to fading and self interference. Similar analysis in EC for impulse radio has been reported in [14], without the presence of self interference.

Next, making use of the captured energy, the combined resolvable paths are used to form the decision statistics, described as:

$$\begin{aligned} Z &= \sqrt{E_p N_s E_d} \sum_{l=0}^{L_c-1} |\chi_l| \alpha(\tau_l) Z_l \\ &= E_p N_s E_d \sum_{l=0}^{L_c-1} |\chi_l| \chi_l \alpha(\tau_l) \alpha(\tau_l) + \eta + \epsilon \end{aligned} \tag{11}$$

where

$$\eta = \sum_{l=0}^{L_c-1} \sqrt{E_p N_s E_d} \chi_l \alpha(\tau_l) \eta_l.$$

$$\epsilon = \sum_{l=0}^{L_c-1} \sqrt{E_p N_s E_d} \chi_l \alpha(\tau_l) \epsilon_l.$$

Finally, the system performance is quantified as bit error rate (BER) which can be described as:

$$\begin{aligned} \text{BER} = & P(d_i = +1) P(Z_i < 0 | d_i = +1) \\ & + P(d_i = -1) P(Z_i > 0 | d_i = -1) \end{aligned} \tag{12}$$

where $P(\cdot)$ denotes probability and Z_i is the decision statistic of the i-th data d_i.

4. Results and Discussions

Based on the model developed in the previous section, the EC capability and performance of DS, TH and DS-TH UWB system is investigated through computer simulations. This section presents the simulation setup and parameters, results on EC and results on system performance sequentially.

4.1 Simulation Setup

All three systems transmit modulated Gaussian pulse at f_c=6 GHz over two UWB indoor multipath channel models [15], both line of sight (LOS) and non-LOS channels. The parameters of the channel models can be given in Table 1.

Table 1 Multipath channel models based on actual measurements. LOS-line of sight. CM-channel model. RMS-root mean square.

Model	**LOS/Non-LOS**	**Range**	RMS delay
CM1	LOS	0–4 m	5 ns
CM2	Non-LOS	0–4 m	8 ns

As mentioned in Sect. 2.4, in order to design low DF signals while maintaining PG and R_b, each DF value is paired up with respective N_s, as shown in Table 2. To ensure fair comparison, the system is designed with constant PG=48. The illustration of such signal design can be shown in Fig. 3.

Table 2 Pairs of DF and N_s. (Figures are rounded up for simplicity)

δ	0.02	0.04	0.08	0.13	0.17	0.25	0.5
N_s	1	2	4	6	8	12	24

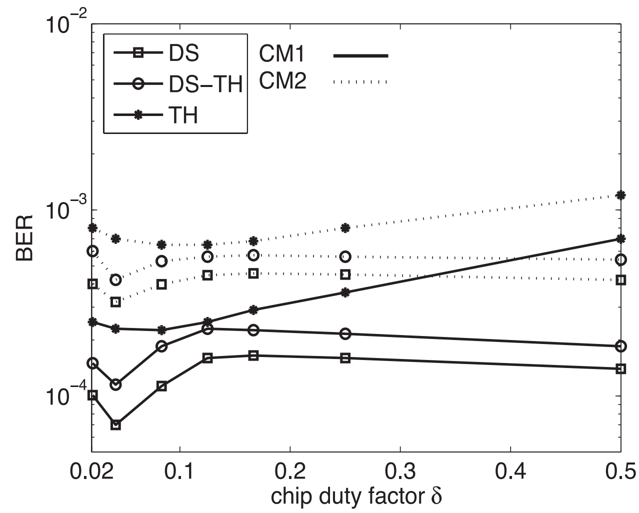

Fig. 4 BER performance vs. chip duty factor for DS, TH and DS-TH UWB systems. SNR=20 dB, L_c=8, W=2 GHz, f_c=6 GHz.

4.2 System Performance

The amount of EC by the Rake receiver determines the system performance. The relationship between the two parameters can be described in (10) to (12). In this section, by applying these equations, we present and discuss the BER performance of the DS, TH and DS-TH UWB systems in multipath environment. Besides, we also explore the effects of multi-user and narrowband interference in these systems. Take note that as δ decreases, N_s is also reduced accordingly (refer Table 2) so that PG and R_b remain constant.

4.2.1 Chip Duty Factor

In Fig. 4, we present the BER performance corresponding to varying DF for DS, TH and DS-TH UWB systems. System parameters such as L_c, f_c and W are set to 8, 6 GHz and 2 GHz respectively. SNR is set at 20 dB, with the scenario of a single user occupying the propagation channel.

Firstly, for DS and DS-TH systems in CM1, we can see that both BER performance follows similar pattern as DF decreases, with DS constantly outperforming DS-TH. It is known that the additional time shift of the pulses in accordance to the time hopping sequence causes stronger ICI in the received signal, and thus degrades the capability of EC in the Rake receiver. From (11) we show that the decision statistic is formed based on the amount of EC in the receiver. This becomes the major factor of why DS-TH system has worse BER performance than DS system.

In the range $0.13 \leq \delta \leq 0.5$, no significant improvement can be observed in both DS and DS-TH systems. This is because EC remains unchanged due to both decreasing total ICI (positive factor) and increasing 'ICI per pulse' (negative factor) canceling out each other. Then as δ decreases from 0.13 to 0.04, total ICI can be mitigated effectively, thus increasing amount of EC, and thus improves BER performance. On the other hand, as δ decreases below 0.04, BER performance degrades because EC is compromised due to the insufficient DS spreading.

Secondly, for TH system, BER performance drops to the worst in δ=0.5 due to the decreasing hoppable time slots. Then as δ decreases to 0.13, BER performance improves significantly. We can explain this observation by stating that the EC capability improves as DF decreases and so, more energy can be captured from the received signal while total ICI reduces. However, at δ lower than 0.13, EC declines due to increasing 'ICI per pulse' and as a result, BER performance degrades significantly.

Thirdly, all systems perform better in multipath CM1, owing to the strong direct path of LOS propagation channel and stronger ISI in CM2. The only exception is the performance of TH system at high duty of δ=0.5. Generally, besides offset in BER value, the characteristics of system performance (graphical curvature) in CM2 does not differ much from those in CM1.

We discovered that there is an optimum DF for each DS, TH and DS-TH system, where the best performance can be obtained, where also, beyond or below which results in degradation of performance. This optimum DF is important in system designs attempting to optimize system resources. Also, under fair system resources, DS is found have best BER performance, followed by DS-TH system and TH system.

4.2.2 Selected and Combined Paths

Figure 5 presents the BER performance vs. number of selected and combined paths in the selective Rake receiver of DS, TH and DS-TH UWB systems. System parameters such as SNR, W and f_c are set to 20 dB, 2 GHz and 6 GHz respectively. Here, single user environment is assumed in CM1 and CM2.

We found that for all DS, TH and DS-TH systems, BER performance for δ=0.04 outperform those with δ=0.5. This statement is valid for all range of L_c. Among all, DS system has the best BER performance, and TH system performs relatively the worst.

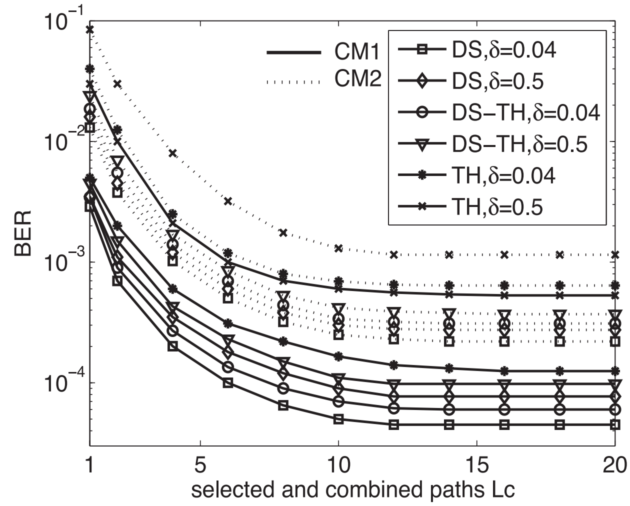

Fig. 5 BER performance vs. selected and combined paths L_c for DS, TH and DS-TH UWB systems. SNR=20 dB, W=2 GHz, f_c=6 GHz.

As shown in Fig. 5, we can identify the 'saturated L_c' at around L_c=10, where beyond, no significant BER improvement is detectable. This is due to the decreasing energy able to be captured beyond the 10-th multipath. This also suggests that a selective Rake receiver with L_c=10 is not significantly inferior as compared to an all Rake receiver, but the former has the advantage of lower system complexity.

The less effective EC in CM2 is also observable in Fig. 5 that most systems have degraded BER performance as compared to those in CM1.

4.2.3 Pulse Duration

So far, we have only considered systems with constant pulse duration T_p=1ns, which gives the spreading bandwidth W of 2 GHz. In this section, we will examine the effects of T_p in system performance for DS, TH and DS-TH UWB systems. The modulated Gaussian pulse center frequency remains at f_c=6 GHz, with SNR and L_c set at 20 dB and 8 respectively.

Figure 6 shows the effects of employing pulses with different durations. We will comment on the system characteristics collectively since all systems follow similar pattern as T_p decreases from 4 ns (equivalent W=0.5 GHz) to 0.267 ns (equivalent W=7.5 GHz). As T_p decreases from 4 ns to 2 ns, BER improvement can be observed easily. This is because as shorter pulse is employed, less channel fading is experienced by the signal. In other words, when a shorter pulse is transmitted, and correlated in the receiver by similar template signals, the amount of EC is higher because shorter template signal tends to match the the channel response more accurately during correlation process. This is the main factor contributing to the improvement of BER as T_p decreases.

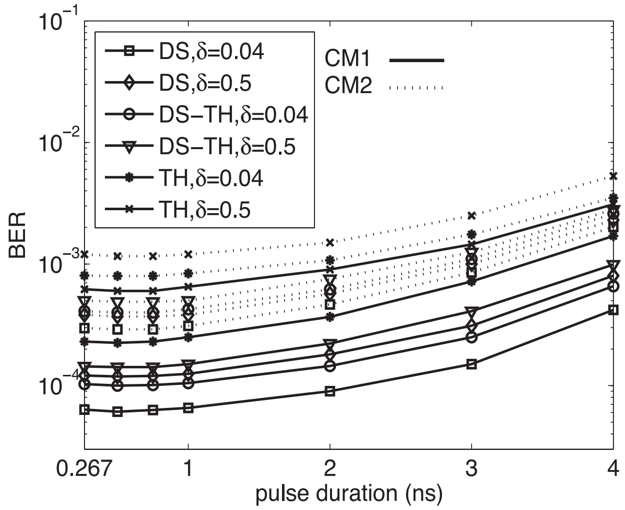

Fig. 6 BER performance vs. pulse duration T_p for DS, TH and DS-TH UWB systems. SNR=20 dB, L_c=8, f_c=6 GHz.

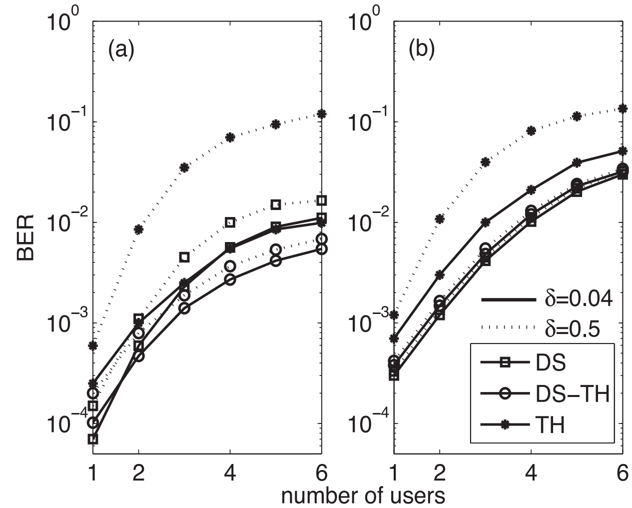

Fig. 7 BER performance vs. number of users for DS, TH and DS-TH UWB systems. (a) CM1, (b) CM2. SNR=20 dB, L_c=8, f_c=6 GHz.

On the other hand, as T_p continues to decrease below 2 ns, less improvement can be observed in BER performance. Furthermore, as T_p decreases towards 0.267 ns, slight degradation can be detected. This can be explained that as T_p becoming considerably short, the number of total resolvable paths $L=T_d/T_p$ becomes correspondingly large. With L increasing continuously and L_c remains at 8, the amount of energy able to be captured by the receiver decreases. Moreover, as T_p becomes very short, the effect of AWGN also becomes relatively strong. Both of these factors causes the BER performance to display slight degradation despite less channel fading due to decreasing T_p.

4.2.4 Multi-User Channel

Discussion so far has been focused on BER performance of DS, TH and DS-TH UWB systems under the assumption of single user environment. In this section, we review the results of BER performance of these UWB systems when more than one user are sharing the propagation channel. System parameters such as SNR, L_c and f_c are set to be 20 dB, 8 and 6 GHz. Here, we consider the transmission of multiple users to be asynchronous in time and all users transmit signal with similar power. Figure 7 is divided into (a) CM1 and (b) CM2 for a more comprehensible discussion.

In single user environment, we know that DS system outperforms DS-TH system. In Fig. 7(a) for CM1 communication, at number of users U=1, we can verify that DS system with δ=0.04 performs the best, followed by DS-TH systems with δ=0.04. However, as U increases, it is worth noting that DS-TH system outperforms DS system starting from U=2, and beyond $U > 3$, significant difference can be observed between DS-TH system and DS system. In DS systems, all pulses are placed at the first time slot in every T_c as described in (2), therefore the possibility for catastrophic collision [16] (where large number of pulses from two or more signals are received simultaneously) to occur is high. Catastrophic collision severely degrades the system performance. This is the reason of DS systems becoming inferior as U increases beyond 1. And as DF increases, the possibility of catastrophic collision also increases correspondingly, degrading performance even more seriously.

On the other hand, for DS-TH and TH systems, although suffering the cause of increasing ICI due to the time hopping feature in single user environment, here in multi-user environment, catastrophic collision can be avoided effectively. The non-uniform spacing of the pulses results in less collision among signals from different users. This explains why BER performance for TH system with δ=0.04 is almost similar to that of the DS system with δ=0.04 at U=3 and beyond. Moreover, with the random polarity pulses in DS-TH system, BER performance in channel with higher U becomes even more superior.

It is noted that TH system with δ=0.5 has severely degraded BER performance. This is due to the high DF that compromises the ability to avoid catastrophic collision.

Referring to Fig. 7(b), we can see that TH system performance in CM2 is not very different from that in CM1. As for DS and DS-TH systems in CM2, the difference in respective BER performance is also found to be less distinguishable. This can be explained that with stronger ICI and furthermore ISI in CM2 propagation, the EC capability of the receivers degrades collectively regardless of DF and modulation methods, thus compromising system performance in an overall manner.

4.2.5 Narrowband Interference

Since UWB system occupies a large bandwidth and is likely to coexist with other existing narrowband systems, it is also of practical interest to investigate the impact of DF on BER performance for DS, TH and DS-TH UWB systems in the presence of narrowband interference. Here, SNR, L_c and f_c

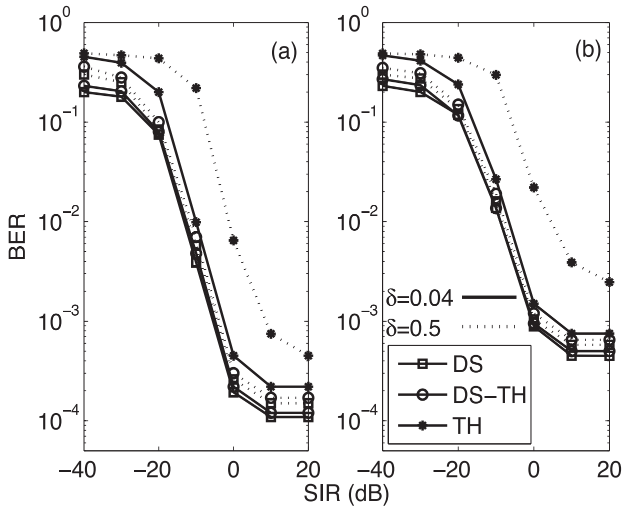

Fig. 8 BER Performance vs. SIR for DS, TH and DS-TH UWB Systems. (a) CM1, (b) CM2. SNR=20 dB, L_c=8, f_c=6 GHz, f_{nrb}=6 GHz, W_j=10 MHz, U=1.

are set to be 20 dB, 8 and 6 GHz. The narrowband interference described in (6) is assumed to have f_{nrb}=6 GHz and W_j=10 MHz. Also, single user environment is assumed. In this section, we also divide Fig. 8 into (a) CM1 and (b) CM2 for more comprehensible discussion.

Figure 8(a) presents the relationship between SIR and BER performance for DS, TH and DS-TH UWB systems in different DF for CM1. Generally, as SIR increases, BER performance for all systems improves. Particularly, BER performance improvement is observed to be more rapid in the range of $-20\,\text{dB} \leq \text{SIR} \leq 0\,\text{dB}$ for DS and DS-TH systems, and in the range of $-10\,\text{dB} \leq \text{SIR} \leq 10\,\text{dB}$ for TH system. In these ranges, increasing SIR to improve system performance is found to be the most effective.

For DS and DS-TH systems employing different DF, slight performance advantages can be observed at lower δ. Among all, TH system performs relatively the worst in all range of SIR regardless of DF value.

Also, for non LOS channel CM2, the achievable BER improvement due to increasing SIR is less significant. This can be observed in Fig. 8(b) that as SIR increases to 20 dB, BER values reaches below 10^{-3}, whereas for CM1 at SIR approaching 20 dB, BER values as low as around 10^{-4} can be achieved. Apart from that, the patterns of BER graphical curvature as SIR increases are similar for both CM1 and CM2.

5. DS-UWB vs. DS-TH-UWB vs. TH-UWB

This section provides an overview on the performance of DS, TH and DS-TH UWB systems. The DS-UWB system outperforms TH and DS-TH UWB systems in most of the environments, except for multi-user environment with high number of users. In a single user multipath channel, DS-UWB has the best performance due to the constant but milder ICI among the pulses as compared to TH and DS-TH UWB systems with ICI dependent on placement of the pulses. On the other hand, in multi-user environment, the advantage of DS-TH-UWB system is more pronounced since the dominant interference is the multi-user interference from coexisting users.

6. Conclusion

In this paper, we have investigated the impact of DF on DS, TH and DS-TH UWB systems from the perspective of EC in multipath environment. The impact of DF was also investigated in other environments such as multi-user channel and channel in the presence of narrowband interference. We found that performance for these systems depend greatly on the energy capture capability of the Rake receivers in multipath and multi-user channel. And DF plays a vital role in increasing EC capability to improve system performance. Rake receivers with less than 10 fingers are sufficient for energy capture. In single user environment, DS-UWB is found to have the best performance, whereas in multi-user environment, DS-TH-UWB takes over to obtain the most superior performance.

Future works include transmission not only in single band systems but also multi band systems. Additionally, the peak power of UWB system is a critical design parameter and will be investigated corresponding to regulations such as spectral mask and other constraints.

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