LETTER *Special Section on Wide Band Systems*

Impact of Chip Duty Factor in DS-UWB Systems over Indoor Multipath Environment

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SUMMARY This paper investigates the impact of chip duty factor (DF) in DS-UWB system with Rake receiver over AWGN and UWB indoor multipath environment corresponding to system parameters such as spreading bandwidth and chip length. Manipulating DF in DS-UWB system offers several advantages over multipath channel and thus, capable of improving system performance for better quality of communication. Although employing lower DF generally improves performance, in some exceptional cases on the other hand, degradation can be observed despite decreasing DF. Therefore, the objective of this paper is to clarify the relationship between DF and DS-UWB system performance. We discovered that with constant processing gain and spreading bandwidth, performance improvement can be observed at DF lower than 0.17. Additionally, with spreading bandwidth as tradeoff parameter, significant performance improvement can only be observed below DF of 0.85.
key words: *chip duty factor, DS-UWB, UWB indoor multipath channel, bit error rate (BER), spreading bandwidth*

1. Introduction

Ultra wideband (UWB) technology has emerged to be one of the most promising technologies in wireless communications. By occupying wide bandwidth from 500 MHz [1] and low power spectral density (PSD) of −41.3 dBm/MHz [1], UWB system is able to offer advantages such as high data rate and spectral coexistence with existing narrowband systems.

The use of UWB signal with low chip duty factor (DF) is extensive in conventional time hopping (TH) UWB systems [2], [3], where the low DF signal is modulated by user-dependent time shifting sequences. Besides TH-UWB system, low DF signals can also be employed in direct sequence (DS) UWB system to increase multipath resolvability, and thus to improve system performance. DF can be varied by manipulating parameters such as pulse repetition frequency and pulse duration. Changing either parameter results in different impact to the system performance, and also consumes different system resources. Therefore, with different DF, we can design the DS-UWB system to achieve various design options and demands.

DS-UWB system has received a lot of attention in recent literatures [4]–[6]. An overall performance evaluation on DS-UWB system in various propagation channels based on simulation is conducted in [4]. Works in [5] investigates on the differences between conventional impulse radio and DS-UWB systems, whereas [6] compares the differences between DS and time hopping (TH) modulation methods. Recently, the significance of DF in UWB signal design becomes more pronounced as low duty cycle (LDC) signal [7] receives intensed attention in the detection and avoidance (DAA) technology [8]. Therefore, signal design employing low DF is bound to be an essential part in performance improvement and interference mitigation for UWB systems.

However, to the best knowledge of the authors, the impact of DF in DS-UWB systems has not been explored in existing literatures. The technical advantage in multipath resolvability offered by low DF DS-UWB systems should be of interest to the UWB community. In this paper, we investigate the achievable performance improvement and tradeoff parameters employing low DF signal in DS-UWB systems.

The organization of this paper is as follows. Section 2 presents the system model. Next, Sect. 3 describes the simulation parameters, discusses the system performance and tradeoff parameters. Finally, Sect. 4 provides concluding remarks and potential future works.

2. Signal and System Models

A binary phase shift keying (BPSK) DS-UWB system as shown in Fig. 1 is considered. The representation of the transmitted signal can be given by:

$$s(t) = \sqrt{E_p} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_s-1} d_i c_j p(t - iT_s - jT_c) \qquad 0 \le t \le T_s \quad (1)$$

where
d_i = the i-th BPSK data bit uniform over {+1,−1}.
c_j = the j-th chip of the user dependent DS code of a random sequence over {+1,−1}.

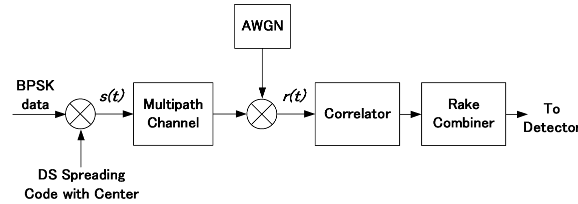

Fig. 1 System diagram of DS-UWB system.

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N_s = number of DS chips per bit.
T_s = bit duration.
T_c = chip duration.
E_p = pulse energy.
$p(t)$ = unit energy pulse waveform with center frequency f_c.

Here, Note that the chip duty factor (DF) δ is T_p/T_c where T_p is the pulse duration, $T_c \geq T_p$ and $0 < \delta \leq 1$. Spreading bandwidth BW can be approximated by $2/T_p$. The system pulse repetition frequency (PRF) can be defined as $1/T_c$ and system data rate R_b can be defined as $1/T_s$. The system processing gain PG is defined as N_s/δ.

Additionally, δ can be decreased by applying two methods. Method one is by fixing T_c to constant and reduce T_p. This increases BW as δ decreases. Method two is by fixing T_p to constant and increase T_c. This on the other hand, reduces PRF and R_b as δ decreases.

The received signal over multipath channel can be given by:

$$
\begin{aligned}
r(t) &= s(t) * h(t) + \eta(t) \qquad (2)\\
&= \sqrt{E_p} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_s-1} d_i c_j m(t - iT_s - jT_c) + \eta(t)
\end{aligned}
$$

where
$h(t)$ = the channel impulse response.
$\eta(t)$ = white Gaussian noise.
$m(t)$ = channel response of the signal, $m(t) = p(t) * h(t)$.
$*$ = convolution process.

We assume that the channel remains constant for the entire bit duration. Note that the transmitted pulse $p(t)$ has unit energy, channel response $m(t)$ of the pulse has energy $E_d = \int_0^{T_d} m^2(t)dt$, and $E_d \leq 1$ 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 $L = T_d/T_p$.

By employing a Rake receiver, the Rake fingers correlate $r(t)$ by using template signal $\psi(t) = \frac{1}{\sqrt{N_s}} \sum_{j=0}^{N_s-1} c_j p(t - jT_c)$ at delays of multiple T_p [9]. The correlation between $r(t)$ at the l-th Rake finger with delay τ_l and $\psi(t)$ can be described as:

$$
Z_l = \int_0^{T_s} r(t)\psi(t-\tau_l)dt = \sqrt{E_p N_s E_d}\chi_l \alpha(\tau_l) + \eta_l \qquad (3)
$$

$$
l = 0, 1, ..., L-1
$$

where
$\alpha(\tau_l)$ = $\int_{-\infty}^{\infty} m(t)p(t-\tau_l)dt$ 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.
η_l = $\int_0^{T_s} \eta(t)\psi(t)dt$.

Note that the signal amplitudes χ_l are assumed to be lognormally distributed based on the recommendation by [10] that it better fits the data obtained from the experimental measurement. Also, $\alpha(\tau) = 0$ if $\tau \leq 0$ or $\tau \geq T_d$. We employ Rake receivers with maximal ratio combining (MRC) method [9] for energy capture, assuming both magnitude and phase of the channel response are known.

Next, the Rake combiner combines the total resolvable L paths to form the decision statistics:

$$
\begin{aligned}
Z &= \sqrt{E_p N_s E_d} \sum_{l=0}^{L-1} \chi_l \alpha(\tau_l) Z_l\\
&= E_p N_s E_d \sum_{l=0}^{L-1} \chi_l \alpha(\tau_l)\alpha(\tau_l) + \eta \qquad (4)
\end{aligned}
$$

where $\eta = \sum_{l=0}^{L-1} \sqrt{E_p N_s E_m}\alpha(\tau_l)\eta_l$.

Next, we describe the signal to noise ratio (SNR) to be SNR=$E[Z]^2/Var[Z]$, where $E[Z]$ and $Var[Z]$ denote the mean and variance of the decision statistic respectively. Then, the system performance is quantified as bit error rate (BER) which can be described as:

$$
\begin{aligned}
BER &= P(d_i = +1)P(Z_i < 0|d_i = +1)\\
&\quad + P(d_i = -1)P(Z_i > 0|d_i = -1) \qquad (5)
\end{aligned}
$$

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

Here, note that the total resolvable paths is described as:

$$
L = \frac{T_d}{T_p} = \frac{T_d}{\delta T_c} = \frac{T_d N_s}{\delta T_s} \qquad (6)
$$

Equation (6) shows that L is dependent on δ, T_p, T_c, T_s and N_s. The multipaths in the received signal can be resolved by template signal in the multiples of T_p, depending on δ. In other words, multipath resolvability can be manipulated by the value of δ. Additionally, in UWB systems, instead of an all Rake receiver that combine all resolvable paths, normally a selective Rake receiver that selects and combines a total of $L_c \leq L$ best resolvable paths is employed to reduce system complexity.

3. Simulation Results and Discussions

Based on the system model described in the previous section, the system performance is determined by using computer simulations. The DS-UWB system transmits modulated Gaussian pulses with center frequency f_c over UWB indoor multipath channels.

In this paper, we consider two types of multipath channel models proposed by the IEEE P802.15.3a Working Group for wireless personal area network (WPAN) [10]. Firstly, we consider a line of sight (LOS) channel (called CM1) within the range of 4 m. CM1 has root mean square (RMS) delay of 5 ns. Secondly, we also consider the case of a non LOS (NLOS) (called CM2), also within the range of 4 m. The RMS delay is 8 ns. More detailed specifications of the channel models can be obtained from [10]. Note that the channel models are proposed according to the technical specifications of UWB systems and propagation, and is therefore valid for the range of spreading bandwidth and center frequency applied in this paper.

The impact of varying DF in system performance is evaluated corresponding to different system parameters. Firstly, performance of DS-UWB system with varying DF and fixed processing gain is evaluated. Then, system performance with varying DF corresponding to varying spreading bandwidth is investigated.

3.1 Impact of DF with Constant Processing Gain

In this section, we investigate the impact of DF on BER performance of systems with constant processing gain PG. The spreading bandwidth BW is also designed to be constant for fair comparison. As shown in the summary of system parameters in Table 1, each DF is paired up with a distinctive N_s. As DF becomes lower, less N_s is employed to maintain the PG. These different pairs of DF and N_s are each matched to systems A, B and C as shown in Table 2. Also, systems A, B and C supports different data rate R_b respectively as shown in Table 2. Here, constant T_p indicates that the BW is constant for varying δ. Other parameters such as SNR, L_c and f_c are set to 20 dB, 8 and 4 GHz. Then, by applying (5), computer simulation is performed to determine the BER performance.

Figure 2 shows the impact of employing different DF

Table 1 Simulation parameters 1.

DF	0.04	0.08	0.13	0.17	0.25	0.5	1
N_s	1	2	3	4	6	12	24

Table 2 Simulation parameters 2.

	System A	System B	System C
T_p(ns)	0.25	0.5	1
T_s(ns)	6	12	24
BW(GHz)	8	4	2
R_b(Mbps)	166	83	41
PG	24	24	24

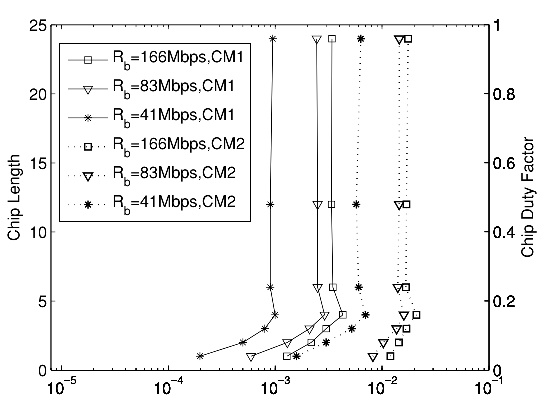

Fig. 2 BER performance vs. DF and chip length for DS-UWB system. SNR=20 dB, L_c=8, f_c=4 GHz.

(right ordinate) paired up with the respective N_s (left ordinate) in systems with different R_b. Both multipath channel LOS (CM1) and non-LOS (CM2) are investigated.

As a general observation, system with lower R_b outperforms that of higher R_b. We found that as DF decreases from δ=1 to 0.17, the BER performance does not display significant degradation until δ=0.25. At DF=0.17, slight performance degradation can be observed as compared to DF=0.25. This can be explained that as DF decreases, interchip interference (ICI) is reduced because the distance between adjacent chips becomes farther apart. On the other hand, simultaneously as DF decreases, shorter N_s is employed (refer to Table 1) in order to maintain PG. Shorter N_s indicates that less number of chips are used to spread one data bit. In other words, the same amount of bit SNR is distributed to lesser number of chips. This increases the energy per pulse and therefore also increases the amount of 'ICI per pulse.' Lower DF paired up with shorter N_s causes two opposing factors: (1) decreasing DF decreases ICI thus improves BER performance and, (2) decreasing N_s increases energy per pulse and 'ICI per pulse,' thus degrades BER performance. The combination of these two factors decides the improvement or degradation of performance, depending which is more dominant. If the positive factor of decreasing DF is more dominant, BER performance improves. On the other hand, if the negative factor of shorter N_s is more dominant, BER performance degrades.

By changing DF and N_s, the number of selected and combined paths L_c and total resolvable paths L can be manipulated as shown in (6) and thus determine the BER performance. At $0.25 \leq \delta \leq 1$, both factors are equally strong, causing the BER performance to remain constant. However, as DF decreases from δ=0.25 to 0.17, BER performance becomes noticeably worse due to the factor of shorter N_s (increasing ICI per pulse) becoming more dominant over the factor of decreasing DF (decreasing ICI).

Next, as DF continues to decrease below δ=0.17, BER performance is found to improve significantly. This is because the lower DF becomes, the more ICI can be mitigated. In this range, the decreasing DF is dominant over the factor of shorter N_s. This indicates that the mitigation of ICI becomes effective at lower range of DF (DF less than 0.17) despite increasing 'ICI per pulse.' This observation is valid for both CM1 and CM2 multipath channels, and also for different system data rate R_b.

From the discussions above, we can conclude that the advantage of BER improvement in DS-UWB system by employing lower DF can only be achieved in δ approximately less than 0.17. Additionally, by manipulating DF and N_s, a worst case for BER performance can be observed, where decreasing DF results in degraded BER. The avoidance of this 'worst case' value is essential in system designs with different demands and tradeoff.

3.2 Impact of DF with Different Spreading Bandwidth

In this section, we present the impact of varying DF on BER

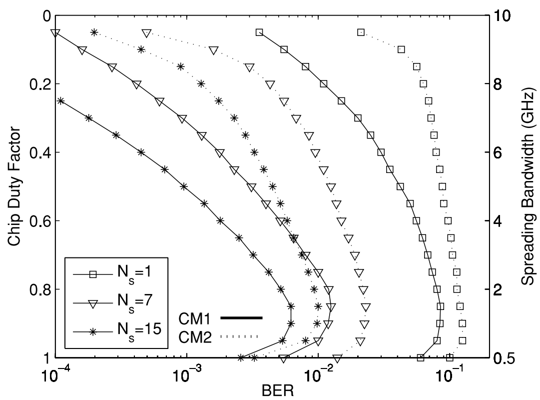

Fig. 3 BER performance vs. DF for DS-UWB system. T_c is set to constant 4 ns with 0.04 ns≤ T_p ≤4 ns. SNR=20 dB, L_c=8, f_c=4 GHz.

performance with spreading bandwidth BW as a tradeoff parameter. To design δ from 0.01 to 1, T_c is set to constant 4 ns and T_p is varied from 0.04 ns to 4 ns. By reducing T_p the BW becomes wider. Other system parameters such as system SNR, L_c and f_c are set to 20 dB, 8 and 4 GHz respectively. Then, by applying (5) in computer simulations, BER performance for each δ with N_s=1,7 and 15 are plotted in Fig. 3. DF is placed at the left ordinate and BW is placed at the right ordinate in Fig. 3.

Firstly, it is observed that BER performance in multipath channel CM1 is better than that in CM2. This is due to the greater degradation of signal over non-LOS environment in CM2. Furthermore, as δ falls below 0.4, more BER improvement is observed in CM1 as compared to CM2. This suggests that the use of lower DF signal is more effective in LOS channel.

Next, the observation can be divided into two parts for discussion. Firstly, for 0.85≤ δ ≤1, system performance degrades. Secondly, for δ <0.85, system performance improves considerably. At 0.85≤ δ ≤1, pulse duration T_p is decreased to the range of $0.85T_c \leq T_p \leq T_c$. Note that Rake receivers increase multipath resolvability by placing template signals in multiples of T_p to capture energy from receiving signal in multiples of T_c. However, in the range of $0.85T_c \leq T_p \leq T_c$, the template signals are constantly placed between two adjacent multipaths, and are therefore subjected to partial correlation from these adjacent multipaths. This degrades the amount of energy able to be captured by the template signals, especially when the adjacent multipaths consist of opposing polarities. This factor contributes mainly to the BER degradation taking place in the region 0.85≤ δ ≤1.

Secondly, as DF continues to decrease below 0.85, performance improvement is observed. This is because at δ <0.85, T_p becomes notably shorter and thus the possibility of the template signal being placed between two adjacent multipaths becomes lower. This results in the effect of partial correlation becoming less significant and energy capture more efficient. Besides, decreasing DF reduces ICI by separating the adjacent pulses farther apart. Furthermore, referring to (6), with shorter T_p, more paths L can be resolved and less channel fading is experienced, thus increasing the energy capture of Rake receivers. All these factors contribute to the improvement of BER performance at δ <0.85 when L_c paths is selected and combined.

The discussions above conclude that in order to obtain significant performance improvement from employing lower DF, the signal has to be designed to have DF lower than 0.85.

The discussion of BW as a tradeoff parameter as DF decreases can also be referred to the right ordinate in Fig. 3. At 0.6 GHz ≤ BW ≤ 9 GHz, BER performance can be improved by increasing BW. This is reasonable because wider BW enables system to experience less channel fading. However, at BW ≤ 0.6 GHz. the contrary is observed, where increasing BW from 0.5 to 0.6 GHz on the other hand, degrades BER performance. This result suggests that there exist a ‘worst case’ for DS-UWB system employing wider BW. This ‘worst case’ normally takes place in lower BW, with δ in the range of 0.9 to 1.

4. Conclusion

This paper investigates the impact of DF on DS-UWB systems corresponding different system parameters. As DF decreases, system performance can be improved by maintaining the same system processing gain and spreading bandwidth. Alternatively, system performance can also be improved by increasing spreading bandwidth as a tradeoff parameter. Optimum performance improvement can be achieved with careful system design. Future works include impact of DF on hybrid DS time hopping UWB systems, in both single user and multiple access systems.

Acknowledgments

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