On the Performance of Multi-User 2PPM-TH-UWB SIMO Systems in Multipath Channels

Sun-Young Baek, Yun-Jeong Kang, Sang-Choon Kim, *Member, KIMICS*

Abstract—In this paper, the performance of ultra-wideband (UWB) single input multiple output (SIMO) systems to achieve high data rate communications is studied in dense multipath environments. The effects of spatial and temporal diversities on the performance of multi-user time-hopping UWB systems using binary pulse position modulation (2PPM) are analyzed. The reduced-complexity Rake receivers based on the selective combining (called SRake) and partial combining (called PRake) are considered. The theoretical and simulation results show that the BER performance of the UWB system can be enhanced as the number of array elements and/or Rake fingers increases. Moreover, we observe that SRake is more effective for the IR-UWB systems to achieve a good BER performance, as compared with PRake.

Index Terms—Ultra-Wideband (UWB), Impulse Radio (IR), Rake Receiver, Multi-User Interference (MUI), Pulse Position Modulation (PPM)

I. INTRODUCTION

Ultra-wideband (UWB) is based on the transmission of very short pulses called impulse radio (IR) with typically no radio frequency modulation. It has received enormous attention as an appealing transmission technique due to its promising capability to provide high data rate over short distances with relatively low power consumption [1].

In [2], the performance of time-hopping (TH) spread-spectrum IR systems when there is only a single path between the transmitter and receiver has been studied. In realistic scenarios, the performance of IR multiple access system is significantly affected by multi-user interference (MUI) and multipath fading. This is particularly true for in indoor environments, where propagation is perturbed by a number of interfering objects. The presence of multipaths with different time delay places fundamental limitations on the performance of the receiver [1]. In order to take advantage of multipath propagation, the Rake receiver can be employed by combining a very large number of different multipath components in IR-UWB systems [8]. The multipath characteristics of UWB systems with single receive antenna have been examined in [3]. In dense multipath environments, multiple receive antennas can be used to exploit spatial and temporal diversities in conjunction with Rake receiver in order to reduce the effects of multipath fading and MUI. In [4], [5], and [9], the BER performance of IR-UWB systems with antenna array has been analyzed in the presence of multipaths and MUI.

In this paper, we evaluate the performance of multi-user binary pulse position modulation (2PPM)-TH-UWB single input multiple output (SIMO) systems with multiple receive antennas in a typical IEEE 802.15 multiplath channel with line-of-sight (LOS) and non-LOS (NLOS). Here, two rake diversity combining techniques, including Selective Rake (SRake) and Partial Rake (PRake), for UWB systems are employed at the receiver. From the numerical results, it is observed that the bit error rate (BER) performance of the TH-UWB system can be greatly improved as the number of multiple receive antennas increases. The performance can be further improved when more multipaths are selected at the Rake receiver. In addition, we show that SRake is superior to that of PRake since it achieves higher SNR at the output of the combiner.

II. SYSTEM MODEL

In 2PPM-TH-UWB systems, the stream of bits to be conveyed is composed of the information bits, “0” and

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"1" with bit interval T_b. Each bit of the binary stream is repeated N_s times by using a code repetition coder at a rate of $R_b = N_s / T_b = 1/T_s$ bits/s. The binary PPM-TH UWB signal transmitted from user u can be expressed as

$$s_{tx}^{(u)}(t) = \sum_{j=-\infty}^{+\infty} \sqrt{E_{tp}^{(u)}}\, w\left(t - jT_s - c_j^{(u)} T_c - a_j^{(u)} \varepsilon\right) \qquad (1)$$

where $E_{tp}^{(u)}$ indicates the energy transmitted over each single pulse. The notation of T_s corresponds to frame time and $c_j^{(u)} T_c$ represents the time shift introduced by the TH code. The $c_j^{(u)}$ term is the j-th coefficient of the TH sequence used by user u and T_c is the chip duration. Each TH code is a pseudorandom sequence with a period N_p, that is, consists of N_p integer values randomly selected with uniform distribution on the range $[0,\ N_h - 1]$. The $a_j^{(u)} \varepsilon$ term denotes the time shift introduced by modulation, where $a_j^{(u)}$ is the binary value transmitted by j-th pulse of user u and ε is the PPM shift. The energy-normalized pulse waveform $w(t)$ of width T_p at the nanosecond scale is modeled as the second derivative Gaussian pulse with α shape factor and is given by

$$w(t) = \left(1 - \frac{4\pi t^2}{\alpha^2}\right) \exp\left(-\frac{2\pi t^2}{\alpha^2}\right) \qquad (2)$$

In this work, we use the UWB channel model proposed by the IEEE 802.15.3a [1], which is similar to the Saleh and Valenzuela (S-V) channel model [6] with slight modifications [7]. S-V channel model is based on the observation that multipath contributions (rays) created by the same pulse arrive at the receiver grouped into clusters.

III. UWB SIMO RAKE RECEIVER

A uniform linear array with N multiple antenna elements is considered. Two temporal diversity combiners such as the Selective Rake (SRake) and Partial Rake (PRake) are employed at the receiver for IR UWB systems. The SRake consists of selecting the L_f best path components among the L_T available at the receiver input and PRake combines the first arriving L_f paths without operating any selection among all available. We use the Maximal Ratio Combining (MRC) strategy to exploit path diversity.

The receiver is assumed to be perfectly synchronized to the first transmitter corresponding to the desired user (user 1). In addition, we also assume that the channel coefficients and time delays of the selected paths by the Rake receiver are known at the receiver, and the receiver selects $L_f^{(u=1)}$ dominant paths of user 1. With soft decision at the receiver, the analysis focuses on a bit time interval of duration T_b by considering all N_s pulses composing each bit. The received signal can thus be written as

$$\begin{aligned} &r(t) \\ &= \sum_{u=1}^{N_u} \sum_{n=0}^{N-1} \sum_{l=0}^{L_T^{(u)}-1} \sum_{j=0}^{N_s-1} \sqrt{E_{rp,n}^{(u)}}\, \alpha_{l,n}^{(u)} w\left(t - jT_s - c_j^{(u)} T_c - a_j^{(u)} \varepsilon - \tau_{l,n}^{(u)}\right) \\ &\quad + \sum_{n=0}^{N-1} \eta_n(t) \end{aligned} \qquad (3)$$

where $E_{rp,n}^{(u)} = (X_n^{(u)})^2 E_{tp}^{(u)}$ is the total received energy for one transmitted pulse at the n-th antenna element. The parameter $X_n^{(u)}$ is the amplitude gain of the channel at the n-th antenna element, which is modeled as a log-normal random variable. $\eta_n(t)$ is the additive white Gaussian noise (AWGN) at the n-th antenna element with bilateral PSD $N_0/2$. The terms $\alpha_{l,n}^{(u)}$ and $\tau_{l,n}^{(u)}$ are the channel coefficient and time delay of the l-th path at the n-th antenna element for the u-th user, respectively. Without loss of generality, it is assumed that $\tau_{0,n}^{(1)} = 0$.

Then the received signal is multiplied by the correlation mask at each finger of every antenna element. Furthermore, the outputs of the correlator to exploit the spatial diversity are equally combined. Thus, the decision statistic can be given by

$$Z = \sum_{n=0}^{N-1} \sum_{l_f=0}^{L_f-1} \int_0^{T_b} r_{l_f,n}(t)\, \alpha_{l_f,n}^{(1)} m(t)\, dt \qquad (4)$$

where $m(t)$ is the correlation mask for one bit duration and is defined as

$$m(t) = \sum_{j=0}^{N_s-1} v\left(t - jT_s - c_j^{(1)} T_c - \tau_{l_f,n}^{(1)}\right) \qquad (5)$$

$$v(t) = w(t) - w(t - \varepsilon) \qquad (6)$$

The decision statistic in (4) can be decomposed into four components as

$$Z = Z_u + Z_{si} + Z_{mui} + Z_\eta \tag{7}$$

where Z_u , Z_{si} , Z_{mui} and Z_η , respectively, represent the component of a desired signal, self-interference (SI), multi-user interference (MUI), and thermal noise at the receiver output. The receiver makes a decision based on the decision statistic as

$$\begin{aligned} Z > 0 &\Rightarrow \hat{b} = 0 \\ Z < 0 &\Rightarrow \hat{b} = 1 \end{aligned} \tag{8}$$

where $\hat{b}$ denotes the estimated bit.

IV. ANALYSIS OF BER PERFORMANCE

In this section, the BER expression for 2PPM-TH-UWB systems with multiple receive antennas is derived on the basis of Gaussian approximation. In order to develop the BER formula, we calculate the energy of the desired signal and the variances of thermal and interference noise contributions. For the derivation of those variances, we extend the analysis used in [1] for single input single output (SISO) systems on the multipath-free channels to the SIMO case on the multipath channels. Thus those computed results are differently developed from [4] and presented in more details than in [4].

The energy of the desired signal contribution E_{rxb} at the output of the receiver can be obtained as

$$\begin{aligned} &E_{rxb} \\ &= (Z_u)^2 \\ &= \left(\sum_{n=0}^{N-1} \sum_{l_f=0}^{L_f^{(1)}-1} \sqrt{E_{rp,n}^{(1)}} \sum_{j=0}^{N_s-1} \int_{jT_s + c_j^{(1)}T_c + \tau_{l_f,n}^{(1)}}^{jT_s + c_j^{(1)}T_c + \tau_{l_f,n}^{(1)} + T_c} \left(\alpha_{l_f,n}^{(1)} \right)^2 \right. \\ &\quad \left. \times w\left(t - jT_s - c_j^{(1)}T_c - \tau_{l_f,n}^{(1)}\right) v\left(t - jT_s - c_j^{(1)}T_c - \tau_{l_f,n}^{(1)}\right) dt \right)^2 \\ &= \left(N_s \sum_{n=0}^{N-1} \sum_{l_f=0}^{L_f^{(1)}-1} \sqrt{E_{rp,n}^{(1)}} \left(\alpha_{l_f,n}^{(1)} \right)^2 \right)^2 \left(1 - R(\varepsilon)\right)^2 \end{aligned} \tag{9}$$

The variance, σ_η^2, of the total thermal noise at the 2PPM receiver output is given by

$$\sigma_\eta^2 = N_s N_0 \left(1 - R(\varepsilon)\right) \sum_{n=0}^{N-1} \sum_{l_f=0}^{L_f^{(1)}-1} \left(\alpha_{l_f,n}^{(1)} \right)^2 \tag{10}$$

The MUI contribution generated by the presence of one alien pulse from the *l*-th path of the *u*-th transmitter at the *n*-th antenna element can be written as

$$m_{l,n}^{(u)} = \sqrt{E_{rp,n}^{(u)}} \int_0^{2T_p} \alpha_{l,n}^{(u)} w\left(t - \tau_{l,n}^{(u)}\right) \alpha_{l_f,n}^{(1)} v(t)\, dt \tag{11}$$

We assume that time delay $\tau_{l,n}^{(u)}$ is uniformly distributed over the interval $[0, T_s)$. The variance of the MUI component by the presence of this alien pulse can thus be expressed as

$$\begin{aligned} &\sigma^2_{m_{l,n}^{(u)}} \\ &= \frac{1}{T_s} \int_0^{T_s} \left(\sqrt{E_{rp,n}^{(u)}} \int_0^{2T_p} \alpha_{l,n}^{(u)} w\left(t - \tau_{l,n}^{(u)}\right) \alpha_{l_f,n}^{(1)} v(t)\, dt \right)^2 d\tau_{l,n}^{(u)} \\ &= \frac{E_{rp,n}^{(u)}}{T_s} \left(\alpha_{l,n}^{(u)} \alpha_{l_f,n}^{(1)} \right)^2 \int_0^{T_s} \left(\int_0^{2T_p} w\left(t - \tau_{l,n}^{(u)}\right) v(t) dt \right)^2 d\tau_{l,n}^{(u)} \end{aligned} \tag{12}$$

The total interfering MUI energy on the bit, that is, on N_s pulses in all selected paths from all antenna elements, can be obtained as

$$\begin{aligned} \sigma_m^2 = &\sum_{n=0}^{N-1} \sum_{l_f=0}^{L_f^{(1)}-1} \sum_{u=2}^{N_u} \sum_{l=0}^{L_T^{(u)}-1} \frac{N_s E_{rp,n}^{(u)}}{T_s} \left(\alpha_{l,n}^{(u)} \alpha_{l_f,n}^{(1)} \right)^2 \\ &\times \int_0^{T_s} \left(\int_0^{2T_p} w\left(t - \tau_{l,n}^{(u)}\right) v(t)\, dt \right)^2 d\tau_{l,n}^{(u)} \end{aligned} \tag{13}$$

Assuming that all delays are identically distributed, the total MUI energy σ_m^2 in (13) can be written as

$$\begin{aligned} \sigma_m^2 &= \frac{N_s}{T_s} \int_0^{T_s} \left(\int_0^{2T_p} w(t - \tau) v(t)\, dt \right)^2 d\tau \\ &\quad \times \sum_{n=0}^{N-1} \sum_{l_f=0}^{L_f^{(1)}-1} \sum_{u=2}^{N_u} \sum_{l=0}^{L_T^{(u)}-1} E_{rp,n}^{(u)} \left(\alpha_{l,n}^{(u)} \alpha_{l_f,n}^{(1)} \right)^2 \\ &= \frac{N_s}{T_s} \int_{-T_p}^{2T_p} \left(R(\tau) - R(\tau - \varepsilon) \right)^2 d\tau \\ &\quad \times \sum_{n=0}^{N-1} \sum_{l_f=0}^{L_f^{(1)}-1} \sum_{u=2}^{N_u} \sum_{l=0}^{L_T^{(u)}-1} E_{rp,n}^{(u)} \left(\alpha_{l,n}^{(u)} \alpha_{l_f,n}^{(1)} \right)^2 \end{aligned} \tag{14}$$

In the case of orthogonal pulses, or $\varepsilon \geq T_p$, the equation in (14) can be rewritten as

$$\sigma_m^2 = \frac{N_s}{T_s} 2 \int_{-T_p}^{T_p} R^2(\tau) d\tau \sum_{n=0}^{N-1} \sum_{l_f=0}^{L_f^{(1)}-1} \sum_{u=2}^{N_u} \sum_{l=0}^{L_T^{(u)}-1} E_{rp,n}^{(u)} \left(\alpha_{l,n}^{(u)} \alpha_{l_f,n}^{(1)} \right)^2 \tag{15}$$

The variance of the SI component can be obtained by the analytic approach similar to the above MUI case as

$$\sigma_s^2 = \frac{N_s}{T_s} 2 \int_{-T_p}^{T_p} R^2(\tau) d\tau \sum_{n=0}^{N-1} \sum_{l_f=0}^{L_f^{(1)}-1} \sum_{l=0, l \neq l_f}^{L_T^{(1)}-1} E_{rp,n}^{(1)} \left(\alpha_{l,n}^{(1)} \alpha_{l_f,n}^{(1)} \right)^2 \tag{16}$$

It is assumed that the number of users and the number of multipaths are sufficiently large. By the central limit theorem, Z_{mui} and Z_{si} can be modeled as a zero-mean Gaussian random variables characterized by variance σ_m^2 and σ_s^2, respectively. Under this Gaussian approximation hypothesis, the probability of bit error $\Pr_b$ for 2PPM-TH-UWB SIMO systems can be written as

$$\Pr_b = \frac{1}{2} erfc \left(\sqrt{ \frac{1}{2} \frac{E_{rxb}}{\sigma_s^2 + \sigma_m^2 + \sigma_\eta^2} } \right) \tag{17}$$

V. SIMULATION RESULTS

The system parameters for all the simulations are taken as the following: sampling frequency $f_c = 2.5$ GHz, frame time $T_s = 60$ ns, chip time $T_c = 1$ ns, pulse duration $T_p = 0.5$ ns, pulse shape factor $\alpha = 0.2$ ns, PPM shift $\varepsilon = 0.5$ ns, total received energy $E_{rp,n} = 1$, bit rate $R_b = 16.67 \times 10^6$ bits/s, total number of multipaths $L_T = 20$, and total number of multiple users $N_u = 6$. Two different propagation scenarios for the IEEE channel model are considered. First one assumes that in the case of LOS the position of the receiver is two meters away from the transmitter between transmitter and receiver. For such a scenario, the channel model uses the following parameters: cluster arrival rate 0.0233 (1/ns), ray arrival rate 2.5 (1/ns), cluster decay factor 7.1, ray decay factor 4.3, standard deviation of the cluster fading and ray fading $\sigma_{cluster} = \sigma_{ray} = 3.3941$ dB and

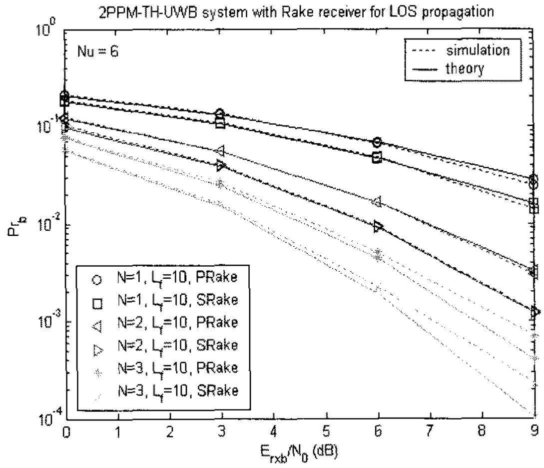

Fig. 1. BER vs. E_{rxb} / N_0 for different numbers of antenna elements

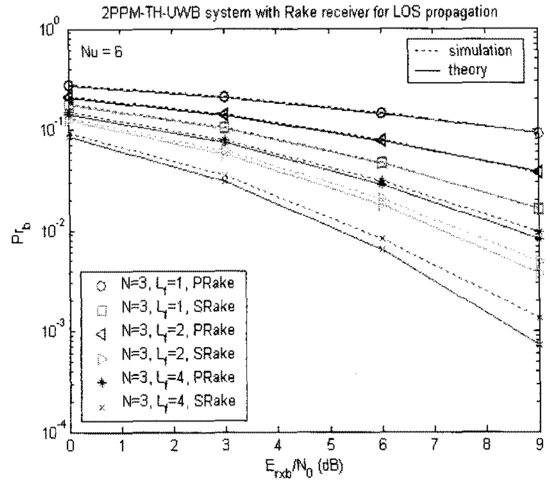

Fig. 2. BER vs. E_{rxb} / N_0 for different numbers of rake fingers

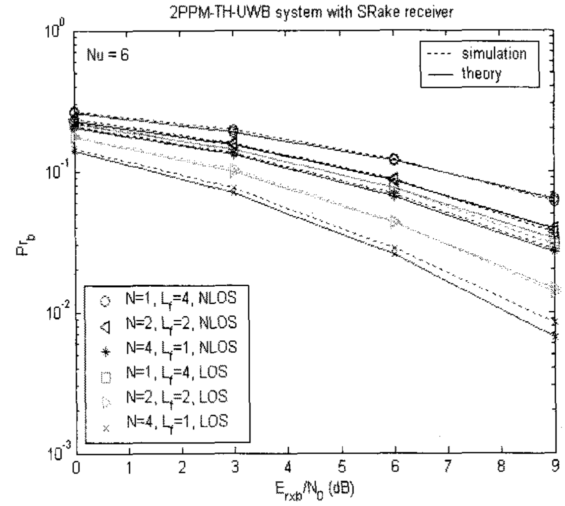

Fig. 3. Tradeoff between *N* and the number of rake fingers

standard deviation of the channel amplitude gain with 3 dB. Another scenario where the receiver is 8 meters away from the transmitter for NLOS is analyzed. The parameters are considered as follows: cluster arrival rate $0.0667\,(1/\text{ns})$, ray arrival rate $2.1\,(1/\text{ns})$, cluster decay factor 14, ray decay factor 7.9, standard deviation of the cluster fading, ray fading, and channel amplitude gain is the same as the LOS.

Fig. 1 shows the theoretical and simulation results for 2PPM-TH-UWB SIMO systems with different numbers of antenna elements when $L_f = 10$ is used. It is shown that the BER performance of the SRake and PRake receivers in LOS is improved by adding the number of receive antenna elements. This improvement is due to the effect of the spatial diversity through multiple receive antennas. It is also found that the SRake provides enhanced performance over the PRake. These results are due to the fact that in the SRake case, the transmitted signals are generated by using the information on the L_f strongest paths, while in the PRake case, the transmitted signals are generated by using the information on the L_f first arriving paths that are not necessarily the strongest ones.

Fig. 2 represents the effect of the number of selected paths on the BER when a NLOS scenario is considered. In this case, we can see that the BER performance is enhanced as the number of selected paths increases. This is because when more paths are selected, the total energy captured by the receiver increases. The tradeoff between the antenna array size and the number of the Rake fingers is compared in Fig. 3. This result demonstrates that the performance improvement from the spatial diversity is superior to that from the path diversity.

VI. CONCLUSIONS

The BER performance of the 2PPM-TH-UWB SIMO systems was evaluated in multipath channel scenarios. The multiple receive antennas were used to exploit the spatial diversity. Moreover, the temporal diversity provided by the Rake receiver was employed to capture more energy from multipaths. The results exhibited that as the number of the antenna elements and/or the Rake fingers increases, the BER performance of the IR-UWB systems is boosted. Furthermore, we showed that the SRake is more effective to achieve a good BER performance than the PRake.

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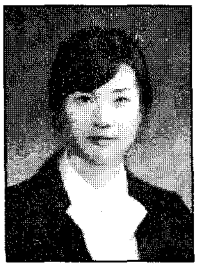

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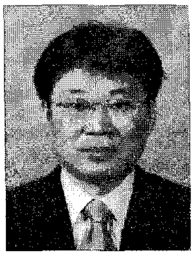

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