Multipath Compensation Technique for Pulse-based Ultra-Wideband System using Multi-band Pulse with RAKE Reception

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Abstract This paper discusses a multipath compensation technique for body area network systems using a pulse-based ultra-wideband method. In the paper, a combined RAKE reception and multi-band template pulse is proposed. RAKE reception is an effective time domain multipath compensation technique. The multi-band template pulses can be used to control the powers of the sub-band pulses and adaptively approximate the received signals. The normalized root mean square error between the ideal received signal and the template pulse is then evaluated. The performance improves when using an iterative weight determination scheme for selective RAKE reception and the multi-band pulses, because the template pulse correlation in each RAKE branch can be reduced and the frequency-selective fading can be compensated. The bit error rate (BER) performance is also evaluated. The results show that the BER is improved and that the number of RAKE branches can be reduced when using the proposed scheme.

Keywords: body area network, multi-band pulse, multipath compensation, RAKE reception, ultra-wideband.

1. Introduction

Ultra-wideband (UWB) radio techniques enable the realization of low power consumption communication systems, high-accuracy ranging and communications applications. UWB radio is expected to form the physical layer for body area network (BAN) systems. BAN systems are expected to be used in medical and healthcare systems and in entertainment systems. The sensing information is collected from sensor nodes that are worn around the human body and is then sent to a coordinating device, such as a smart phone. The collected information is then used for user healthcare or for virtual games using communications via the BAN system.

In BAN systems, reliable and low-latency communications are necessary because important data are being transmitted and received and real-time communication without re-forwarding is necessary for use in the intended applications. However, when these radio systems are used in narrower indoor environments, such as an individual room, many multipath signals are generated. In addition, the direct radio path is often interrupted by human bodies. UWB-IR (UWB-impulse radio) systems and DS (direct sequence) -UWB systems both have high multipath resolution capabilities, because they transmit pulses with very short widths. RAKE reception is one effective technique that can be used for pulse-based UWB systems for multipath wave detection in rich multipath environments.

The partial RAKE (P-RAKE) and selective RAKE (S-RAKE) systems were evaluated for UWB systems in . The S-RAKE system can provide better reception performance than the P-RAKE system, because more powerful paths can be detected. In RAKE reception, equal gain combining (EGC) and maximum ratio combining (MRC) techniques are commonly used to determine the combining weight . The minimum mean square error (MMSE) combining scheme was also widely studied. However, in the MMSE scheme, estimation of the noise amplitude is necessary. To reduce inter-symbol interference, the least mean square RAKE method was proposed for longer channel delay spread conditions. The integrative multipath interference canceller was also proposed to mitigate inter-path interference for high data rate UWB systems . In this scheme, the decision feedback equalizer is used with the...
MRC S-RAKE technique.

The received signal strength varies in fading environments because many multipath waves are present. It is important to compensate for the effects of frequency-selective fading in UWB systems because these systems use extremely wide bandwidths. In orthogonal frequency division multiplexing (OFDM) systems, frequency equalization is commonly used to compensate for frequency-selective fading \(^{11}\). However, in pulse-based UWB, the demodulation process is performed in the time domain without use of a fast Fourier transform (FFT). Therefore, frequency-selective fading compensation for time domain demodulation is essential. Frequency domain equalization in RAKE reception for UWB-IR and DS-UWB systems has also been proposed \(^{12} \) \(^{13} \). However, FFT/discrete Fourier transform (DFT) processing is necessary before the equalization process.

To compensate for multipath effects, a template pulse waveform approximation scheme for UWB systems that is based on orthogonal functions has been reported \(^{14} \). The multi-band pulse has been proposed as a technique for interference mitigation between UWB systems and other radio systems \(^{15} \) \(^{16} \). A multi-band pulse consists of several narrower bandwidth sub-band pulses and is approximated using various UWB pulse waveforms. Conventional S-RAKE and threshold RAKE (T-RAKE) reception by MRC using multi-band pulses has also been considered \(^{17} \).

In this paper, we propose a RAKE reception scheme that uses multi-band template pulses to compensate for multipath effects. First, an iterative weight determination (IWD) scheme for S-RAKE reception is proposed to avoid inter-pulse interference among the RAKE branches. Next, a combined technique that is composed of S-RAKE with a multi-band template pulse in each RAKE branch is proposed. The basic idea for this scheme and some simulation examples were previously presented briefly \(^{18} \). The performances of the proposed RAKE reception schemes are evaluated using the normalized root mean square error (NRMSE) between the received signal waveform and the template waveform and the resulting bit error rate (BER) performance, which takes the number of RAKE branches into consideration, demonstrates the effectiveness of the two proposed schemes.

This paper is organized as follows. In Section 2 and Section 3, we explain the proposed RAKE reception scheme and the scheme that uses RAKE reception combined with the multi-band template pulse, respectively. The performances of these schemes are then evaluated and the effectiveness of both schemes is shown in Section 4. In Section 5, we draw our conclusions.

2. RAKE Reception

The received signals in wireless communications consist of many multipath signals. At the receiver, multiple delayed signals are received. The RAKE receiver is one of the most effective techniques for catching these multipath signals and thus improving the overall reception performance of pulse-based UWB systems. In a RAKE receiver, the delayed signals are caught by the RAKE branches and their correlation values are then combined. Therefore, the diversity gain can be obtained and the reception performance can then be improved.

In this section, the system model of a UWB transmitter and receiver using RAKE reception and conventional RAKE reception using the MRC technique are introduced. Additionally, the proposed technique to improve the RAKE reception scheme by using iterative processing is explained.

2.1 System model

The system model for pulse-based UWB is explained first. Figure 1 shows the pulse-based UWB transmitter-receiver model with RAKE reception. The transmitted signal is expressed as follows:

\[ s(t) = \sum_{i=-\infty}^{+\infty} b_i p(t - iT_i), \]

where \( p(t) \) denotes the UWB pulse waveform, \( T_i \) denotes the pulse repetition interval and \( i \) denotes the \( i \)-th UWB pulse. \( b_i \) denotes the data symbol. When the pulse is modulated using binary phase shift keying (BPSK) modulation, \( b_i \) becomes either +1 or −1. The channel is then expressed as follows:

\[ h(t) = \sum_{k=0}^{K-1} a_k \delta(t - \tau_{dk}), \]

where \( K \) is the number of paths, \( a_k \) is the amplitude of the path and \( \tau_{dk} \) is the delay time of the \( k \)-th path.

![Fig. 1 Transmitter-receiver structure for pulse-based UWB system.](image-url)
The received signal can be expressed as follows:

\[ r(t) = h(t)^\ast s(t) + n(t) = \sum_{k=1}^{K} \sum_{l=0}^{L} a_{kl} p(t - \tau_{kl}) + n(t), \]

where \( \ast \) denotes a convolution operation and \( n(t) \) denotes additive white Gaussian noise (AWGN). The received signal consists of numerous multipath signals. Therefore, the use of multipath compensation techniques is significant in the receiver.

The RAKE receiver structure for use in pulse-based UWB systems is shown in Figure 2. In this paper, the RAKE reception schemes are considered to compensate for the multipath channel effects and produce a better BER performance. The received signal is correlated with the template pulse, \( v(t) \). The \( m \)-th output of the correlator at a RAKE branch is then expressed as follows:

\[ y_{i,m} = \int_{-\frac{T}{2}}^{\frac{T}{2}} r(t) v_m(t - \tau_m) dt, \]

where \( \tau_m \) is the time period of the template waveform and \( v_m(t) \) is the template waveform in \( m \)-th RAKE branch. In a conventional pulse-based UWB system, the template waveform that is used has the same waveform as the transmitted pulse waveform (i.e., \( v_0(t) = \ldots = v_m(t) = p(t) \)). In this paper, the template pulse waveform is also considered. The sampling interval of a RAKE branch is expressed as follows when all RAKE branches are aligned in time order:

\[ \delta t = \tau_m - \tau_{m-1}. \]

The sampling intervals and the number of RAKE branches are both important values, because the reception performance is highly dependent on these two parameters.

The correlation values of the branches are multiplied by the weights and are then combined as follows:

\[ Z_i = \sum_{m=0}^{M-1} y_{i,m} w_{i,m}, \]

where \( M \) is the number of RAKE branches and \( w_{i,m} \) is the weight used to combine each of the RAKE branches. In RAKE reception, the performance is strongly dependent on the weight and thus the weight determination method is also significant.

The output is then compared with the threshold to make the required decision.

\[ \hat{b}_i = \begin{cases} 1 & (Z_i \geq D_{th}) \\ 0 & (Z_i < D_{th}) \end{cases}. \]

When the UWB signal is modulated using BPSK, \( D_{th} \) then becomes zero.

### 2.2 Selective RAKE Reception by MRC

As a conventional scheme, the S-RAKE and MRC scheme is explained here. Figure 3 shows an illustration of the S-RAKE detector model using an example in which the number of RAKE fingers is three. The paths are correlated in an order that is based on the most powerful paths. Higher power signals can thus be captured by S-RAKE reception.

The detected paths are then multiplied by the weights and are subsequently combined. The weights are decided by the MRC technique. The weight of the \( m \)-th branch is given as follows:

\[ w_m = \frac{h_m}{\sum_{m=0}^{M-1} |h_m|^2}. \]

where \( h_m \) is the channel of the \( m \)-th RAKE path.

In the S-RAKE scheme, the branches are selected as follows:
The threshold value \( w_{th} \) becomes the \( M \)-th most powerful path.

### 2.3 Selective RAKE Reception by IWD

RAKE reception is very effective in UWB systems because the UWB pulses have very narrow pulse widths. However, the correlation among the branches increases because these UWB pulses actually have finite pulse widths. In this paper, the IWD scheme for S-RAKE reception is proposed. The receiver structure required is as shown in Figure 4.

In correlation-based detection, the BER performance is best when the received pulse and the template waveform are identical, as follows:

\[
r_i(t) = h(t) * p(t - iT_f),
\]

where \( r_{i,0}(t) \) is the ideal received signal without noise. It is assumed that the ideal received signal can be detected to enable reception of plural preamble pulses and that these pulses are then averaged to avoid the effects of noise when the channel coherence time is much longer than that of the pulse repetition cycle.

To obtain improved BER performance, the template waveform is approximated using the function \( r_{i,0}(t) \). If the template waveform can be approximated perfectly, then the error between the received signal and the template waveform becomes zero, as follows:

\[
e_m = \int_0^{T_f} \left[ r_{i,0}(t) - v(t) \right]^2 dt.
\]

The error function subsequently takes the following form:

\[
e_0 = \int_0^{T_f} \left[ r_{i,0}(t) - w_{i,0}v_0(t - \tau_0) \right]^2 dt.
\]

To minimize the error function, it is partially differentiated by \( w_0 \) and is then zeroed.

\[
\frac{\partial e_0}{\partial w_0} = 0. \tag{17}
\]

The weight then becomes:

\[
w_0 = \frac{\int_0^{T_f} r_{i,0}(t)v_0(t - \tau_0) dt}{\int_0^{T_f} v_0^2(t - \tau_0) dt}. \tag{18}
\]

The detected path is then subtracted from \( r_{i,0}(t) \) as follows:

\[
r_{i,1}(t) = r_{i,0}(t) - w_0v_0(t - \tau_0). \tag{19}
\]

Next, the second most powerful path is found from \( r_{i,1}(t) \), as follows:

\[
c_1 = \int_0^{T_f} r_{i,1}(t)v_1(t - \tau_1) dt. \tag{20}
\]

The corresponding weight can then also be derived:

\[
w_1 = \frac{\int_0^{T_f} r_{i,1}(t)v_1(t - \tau_1) dt}{\int_0^{T_f} v_1^2(t - \tau_1) dt}. \tag{21}
\]

The subtracted signal is then expressed as follows:

\[
r_{i,2}(t) = r_{i,1}(t) - w_1v_1(t - \tau_1). \tag{22}
\]
The process is performed in an iterative manner until \( m \) reaches the number of RAKE branches (\( M \)). The weights of the IWD can then be expressed as follows:

\[
 w_m = \frac{\int_{-\tau_m}^{\tau_m} v_m(t) g(t) dt}{\int_{-\tau_m}^{\tau_m} v_m^2(t) dt}.
\]  

(23)

3. RAKE Reception Using Multi-band Pulse

In the conventional receiver for pulse-based UWB systems, the template waveform is the same as the transmitted pulse waveform (i.e., \( v_g(t) = \ldots = v_m(t) = p(t) \)). The multi-band pulse is effective for interference avoidance\(^\text{15}\). This type of pulse is thus used as a template waveform and sub-band pulses are then removed, depending on the frequency band of the interfering signal. In addition, multi-band pulses are effective for use in frequency-selective fading compensation techniques because a multi-band pulse can control the pulse spectrum in the frequency domain\(^\text{16, 17}\). In this section, we propose the use of the multi-band pulse with the RAKE reception method that was explained in the previous section.

The multi-band pulse is approximated by a UWB pulse using a Gabor transform. The Gabor transform is a short-time Fourier transform that uses a Gaussian window function and is given as follows:

\[
 G(f) = \int_{-\infty}^{\infty} x(t) g(t-b) \exp(-j2\pi ft) dt,
\]

\[
 g(t) = \exp(-\frac{at^2}{2}),
\]  

(24)  

(25)

where \( x(t) \) is the analyzed pulse waveform and \( g(t) \) is the Gaussian window function, which also becomes the envelope for the sub-band pulses. \( a = \log_2 10 \) is the amplitude of the -10 dB point that is used to define the pulse width \( t_m \) (is one half of the pulse width and thus \( 2\tau = t_m \)). The pulse can be reconstructed using the inverse Gabor transform as follows:

\[
 x(t) \equiv \hat{x}(t) = \frac{1}{2\pi} \text{Re} \left[ \int_{-\infty}^{\infty} G(f) g(t) \exp(j2\pi ft) df \right]
\]

\[
 = \frac{1}{2\pi} \text{Re} \left[ \int_{-\infty}^{\infty} G(f) g(t) \cos(2\pi ft) df \right] - \text{Im} \left[ G(f) g(t) \sin(2\pi ft) df \right].
\]  

(26)

The frequency is then sampled using \( f = nf_s \) to yield:

\[
 \hat{z}(t) = \frac{1}{N_s} \sum_{n=-\infty}^{\infty} \left[ \text{Re} \left[ G(nf_s) g(t) \cos(2\pi nf_s t) \right] - \text{Im} \left[ G(nf_s) g(t) \sin(2\pi nf_s t) \right] \right],
\]  

(27)

where \( f_s \) is the sub-band pulse interval, \( Lf_s \) is the lowest center frequency of the sub-band pulse and \( N_s \) is the number of sub-band pulses. The \( n \)-th sub-band pulse is expressed as follows:

\[
 s_n(t) = \text{Re} \left[ G(nf_s) g(t) \cos(2\pi nf_s t) \right] - \text{Im} \left[ G(nf_s) g(t) \sin(2\pi nf_s t) \right].
\]  

(28)

The multi-band pulse that is used as a template waveform in each RAKE branch is given as follows:

\[
 v_m(t) = \hat{x}(t) = \sum_{n=1}^{N_s} s_n(t).
\]  

(29)

The template waveform is then used for either Equation (4) or Equation (13).

In the proposed scheme, channel estimation is performed to determine the weights of the sub-band pulses. These weights are derived at each RAKE branch. Therefore, the waveforms of the multi-band template signals must be different in each RAKE branch to enable matching of the waveform to the received signal.

4. Performance Evaluation

In this paper, the root-raised cosine UWB pulse is used as follows:

\[
 \rho(t) = \sin \left[ \frac{\pi t}{T_0} \left(1 - \alpha \right) \right] + \cos \left[ \frac{4\alpha t}{T_0} \left(1 + \alpha \right) \right] \cos(2\pi f_c t),
\]  

(30)

where \( \alpha \) denotes the roll-off factor, \( f_c \) denotes the center frequency of the pulse and \( T_0 \) is the inverse of the pulse bandwidth \( B \). The parameters used are shown in Table 1 and are taken from IEEE802.15.6, which is the standard for wireless body area network systems\(^\text{11}\).

The performances of the methods are evaluated under the channel conditions used by the IEEE802.15.6

| Pulse Shape | Root Raised Cosine Pulse |
|-------------|-------------------------|
| Roll-off Factor: \( \alpha \) | 0.5 |
| Bandwidth: \( B \) | 499.2 MHz |
| Center Frequency: \( f_c \) | 3993.5 MHz |
working group. In this paper, channel models CM3 and CM4 are used. CM3 and CM4 are models of the channel from body surface to body surface and from the body surface to the exterior of the body, respectively. In CM4, the models are divided with respect to the body direction at 90° intervals. In this paper, the performances are evaluated using CM3 and CM4 with the body directions $\theta_d = 0°$ and $\theta_d = 270°$. The differences in the delay spread are as shown in Table 2. The delay spread of the IEEE802.15.6 channel model is greater than that of other channel models, such as the IEEE 802.15.3a or IEEE802.15.4a channel models. The delay spread of CM4 is larger than that of CM3. CM4 when $\theta_d = 270°$ represents the worst case for this channel model.

The degree of approximation between the received pulse waveform and the template waveform is evaluated using the NRMSE. The NRMSE is expressed as follows:

$$\text{NRMSE} = \sqrt{\frac{1}{T_2} \int_{-T_2}^{T_2} (r_d(t) - v(t))^2 dt}.$$

(31)

Both pulses are then normalized as follows:

$$\int_{-T/2}^{T/2} r_d(t)^2 dt = \int_{-T/2}^{T/2} v(t)^2 dt = 1.$$

(32)

When the pulse is approximated well, then the NRMSE decreases.

The BER performance can be derived from the NRMSE using the following equation when the UWB system is modulated by BPSK:

$$\text{BER} = \frac{1}{2} \text{erfc}\left(\sqrt{\frac{N_0}{\text{NRMSE}^2}} \cdot \frac{\text{NRMSE}^2}{4}\right).$$

(33)

The equation shows that a smaller NRMSE will lead to improved BER performance. When the NRMSE is equal to zero, the BER has the same value as it would for the BPSK theoretical performance. In this case, it is assumed that the inter-symbol interference caused by the delayed paths does not occur.

### 4.1 Multi-band pulse parameters

To determine the parameters of the multi-band template pulses, the NRMSEs are evaluated based on the assumption of an AWGN channel. In this paper, two types of multi-bands with sub-band pulse width ($t_{w}$) values of 10 ns and 20 ns are considered. When the wider sub-band pulse duration is used, it is then possible to control the power in the frequency domain more precisely. However, the number of sub-band pulses is also increased and thus the receiver structure becomes more complex.

In Figure 5, the NRMSE values are shown when the ideal received signal $r_{d}(t)$ has the same waveform as $p(t)$. The center frequency at the middle of the sub-band pulse is set to be the same as the center frequency of the UWB pulse. By increasing the number of sub-band pulses $N_s$, the pulse waveform can then be approximated and the NRMSE become lower. The optimum sub-band pulse interval $f_s$ can be observed because the multi-band pulse spectrum becomes warped when $f_s$ is wider, while the bandwidth of the multi-band pulse narrows when $f_s$ is narrower.
Table 3 Multi-band pulse parameters.

| Parameter                  | Value 1 | Value 2 |
|----------------------------|---------|---------|
| Sub-band pulse width (2, f) | 10ns    | 20ns    |
| Sub-band pulse interval (f) | 134.7MHz| 66.9MHz |
| Number of sub-band pulses (N) | 5       | 11      |
| MSE between v(t) and p(t)   | 2.0x10^-3 | 3.1x10^-4 |

Table 3 shows the multi-band pulse parameters that are used in this paper. After consideration of the receiver structure, a smaller $N_s$ value is chosen. In Figure 6, the spectrum and waveform of the multi-band pulse are illustrated in the time domain when $t_w$ is 10 ns. The multi-band pulse can be approximated well using the Gabor transform.

4.2 Approximation between received signal and template signal

The differences in terms of NRMSE between the received signal under the IEEE802.15.6 channel model and the template waveform are evaluated because the NRMSE is dependent on the BER. In Figure 7, the NRMSE simulation results are shown for various values of the sampling interval $\delta \tau$. The number of branches $M$ is set to be 10. It is assumed that the channel estimation is perfect for the purposes of this simulation.

In the S-RAKE reception scheme with MRC, the NRMSEs increase for smaller values of $\delta \tau$, because the correlations between each of the RAKE branches increase. In contrast, when $\delta \tau$ is higher, the NRMSE also deteriorates because the more powerful paths cannot be captured. Therefore, an optimum $\delta \tau$ must exist. In the S-RAKE reception with IWD scheme, $\delta \tau$ must be smaller to obtain a smaller NRMSE. The NRMSEs of the IWD scheme become smaller than the NRMSEs of the MRC technique. However, the number of calculations is higher when using the IWD scheme when compared with the number required for the MRC scheme. The NRMSE for CM4 with $\theta_d = 270^\circ$ becomes higher than that for CM3 because the delay spread of the channel response also increases.

When using the proposed multi-band template waveform with RAKE reception, the NRMSE characteristics are improved when compared with those that were obtained using the ordinary template pulse.
waveform that is identical to the transmitted pulse waveform in both the MRC and IWD schemes. The NRMSEs of the IWD scheme are lower than the NRMSEs of the MRC scheme. The difference between these RAKE reception schemes decreases when the multi-band pulse is used as the template pulse rather than the ordinary template pulse. When the sub-band pulse width is wider, at $t_w = 20$ ns, the NRMSE decreases because the bandwidth of the sub-band pulse is then narrower and the number of sub-band pulses is thus greater. Also, the optimum $\delta \tau$ is higher in the MRC scheme.

Using the proposed RAKE reception and multi-band template pulse scheme, a smaller NRMSE can be obtained when using the BAN channel model.

4.3 BER performance evaluation with RAKE reception

The BER performance when using RAKE reception and the multi-band pulse is evaluated as shown in Figure 8. In this evaluation, it is assumed that the channel estimation is perfect. The $\delta \tau$ value for each scheme is set to be the minimum NRMSE obtained, as shown in Figure 7 for each reception scheme. In the conventional system without RAKE reception, the maximum path is searched at intervals of 1 ns and the received signal is then correlated with the template pulse, which has the same waveform as the transmitted pulse waveform. The BER of CM4 with $\theta_d = 0^\circ$ is better in the conventional system than either CM3 or CM4 with $\theta_d = 270^\circ$, because a more powerful direct path exists in CM4 when $\theta_d = 0^\circ$. The performances of CM3 and CM4 with $\theta_d = 270^\circ$ are worse because their direct paths are weaker and because they have potential for their direct paths to be interrupted by human bodies.

The use of RAKE reception allows the delayed signals to be captured and the BER performances are then improved when using CM3, CM4 with $\theta_d = 0^\circ$ and CM4 with $\theta_d = 270^\circ$. In the proposed scheme based on use of RAKE reception and multi-band pulses, the BER performances are all improved because the template pulse waveform can be approximated using the ideal template pulse waveform, which is the same as the received pulse waveform without noise. Comparison of the performance levels obtained using the ordinary template waveform and using the proposed multi-band template waveform shows that the BERs improve from 0.5 dB to 2 dB to obtain a BER of $10^{-5}$. In CM3 in particular, the BERs of the proposed scheme are almost same as those of the BPSK theoretical curve. The sub-band pulse widths should be wider to obtain improved BER performance because the template pulses can then be approximated with fewer errors. The BER performance is worst in CM4 with $\theta_d = 270^\circ$ because the delay spread is wider. However, the influence of the proposed RAKE reception scheme then becomes more effective.

Figure 9 shows the BER performances when the number of RAKE branches is varied, where CM3 and CM4 with $\theta_d = 270^\circ$ produce the smallest and largest delay spreads, respectively. $E_b/N_0$ is set at 10 dB. $\delta \tau$ for
each of these schemes is the same as that shown in Figure 7. The S-RAKE reception with IWD scheme can produce a better BER performance when the conventional template pulse that is identical to the transmitted pulse is used. The number of RAKE branches can also be reduced to obtain the same BER. When using the proposed reception scheme, the number of RAKE branches required decreases and the converged BER performance improves. In CM3, the BER is converged when using 10 branches and 15 branches in the cases where \( \theta_d = 20\) and \( \theta_d = 10\), respectively. Because the delay spread of CM4 with \( \theta_d = 270\)° is higher than that of CM3, more branches are needed to allow the performances to converge and thus reduce the BER; however, the BER is greatly improved when using the proposed technique. From the results shown here, the BER performances improve and the number of RAKE branches can be reduced when using the multi-band pulse template waveform that consists of narrower bandwidth sub-band pulses.

### 4.4 Channel estimation

RAKE reception and the multi-band template waveform require channel estimation processes to determine the weights in the receiver. In general, the channel is estimated using the preamble signal. The received preamble signal is expressed as follows:

\[
\text{BER} = \frac{1}{N_{\text{pre}}} \sum_{i=0}^{N_{\text{pre}}-1} h(t) * c_i p(t - iT_{\text{pre}}) + n(t),
\]

where \(N_{\text{pre}}\) is the number of preamble pulses, \(T_{\text{pre}}\) is the pulse repetition interval in the preamble signal and \(c_i\) is previously known pseudo-random sequence. The preamble signal is affected by noise. Under static channel conditions, the influence of noise can be reduced when many pulses are transmitted as preamble signals over a longer period and the received preamble pulses are subsequently averaged.

The signal-to-noise ratio of the preamble signal is decided by the correlation values after averaging of the preamble signal for channel estimation as follows:
The signal-to-noise ratio ratio is calculated using the template waveform $v(t)$, which is assumed to be an ideal waveform that is the same as the received pulse waveform including the influence of the channel $(v(t) = h(t) \ast p(t))$.

In Figure 10, the BER performances are shown when using the template waveform that was determined from the channel estimation process that used the preamble signals, including noise. The relative performances are evaluated and CM3 and CM4 with $\theta_2 = 270^\circ$ produce the smallest and largest delay spreads, respectively. The abscissa of Fig. 10 shows the signal-to-noise ratio in the preamble signal used for channel estimation. $E_b/N_0$ represents the signal energy per bit-to-background noise power spectrum density ratio when the data pulses are demodulated.

When $SNR_{pre}$ is less than 20 dB, the BERs of all RAKE reception schemes are almost identical. The proposed RAKE reception schemes that use the multi-band template pulse have better BER performances when compared with the S-RAKE reception with MRC scheme using the conventional template pulse waveform when $SNR_{pre}$ is higher. A longer preamble signal is then necessary under noisy environment conditions. As the results show, the proposed RAKE reception scheme can obtain a better BER performance than the ordinary RAKE reception scheme, even when the channel estimation is not perfect.

5. Conclusions

In this paper, a RAKE reception scheme for UWB BAN systems is discussed. An S-RAKE reception with IWD scheme is proposed by which the weights required for RAKE reception are derived by minimizing the error between the received signal waveform and the combined template waveform from the RAKE branches. We also propose the use of a multi-band template pulse for RAKE reception when using MRC and IWD methods. The multi-band pulse consists of several narrower pulses and is approximated with the received pulse waveform by using a Gabor transform in each RAKE branch.

The performances are evaluated under IEEE802.15.6 BAN channel model conditions. When using RAKE reception and the multi-band template pulse, the performance can be improved because the proposed scheme can compensate in both the time domain and the frequency domain. The number of RAKE branches can be reduced by using multi-band pulses to obtain the same BER performance. The proposed scheme is therefore effective in channel environments where the power of the direct path is weaker and the delay spread is larger.

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