Analytical BER Calculation of TAS/MRC-Based Two Hop UWB Communication System Over IEEE 802.15.4a Channel

Anand Agrawal & Rakhesh Singh Kshetrimayum

To cite this article: Anand Agrawal & Rakhesh Singh Kshetrimayum (2018) Analytical BER Calculation of TAS/MRC-Based Two Hop UWB Communication System Over IEEE 802.15.4a Channel, IETE Technical Review, 35:5, 467-475, DOI: 10.1080/02564602.2017.1331759

To link to this article: https://doi.org/10.1080/02564602.2017.1331759

Published online: 06 Jun 2017.

Submit your article to this journal

Article views: 49

View Crossmark data
Analytical BER Calculation of TAS/MRC-Based Two Hop UWB Communication System Over IEEE 802.15.4a Channel

Anand Agrawal and Rakhesh Singh Kshetrimayum
Department of Electronics and Electrical Engineering, Indian Institute of Technology, Guwahati, India

ABSTRACT
In this paper, we calculate the bit error rate (BER) of the orthogonal binary signals in the two hop ultra-wideband (UWB) communication system with the transmit antenna selection scheme at the source and the relay terminals. In the two hop UWB system, relay is configured to perform the decode and forward cooperative strategy. In order to calculate the BER of the investigated UWB system, we consider the characteristic function-based approach to model the sum of path gains of the IEEE 802.15.4a channel. We assume that all the IEEE 802.15.4a channel links are independent and identically distributed and perfect channel state information is available at the transmitter. The results exhibit that the derived BER is a good match with the simulations and it has been significantly improved over the BER of the conventional UWB systems.

KEYWORDS
Cooperative communication and MIMO; TAS/MRC scheme; Ultra-wideband (UWB)

1. INTRODUCTION
The low-rate ultra-wideband (UWB) wireless communication is a promising wireless technology. It offers low power and large distance indoor communication because of its wide frequency spectrum. In 2002, Federal Communication Commission assigned the frequency band 2–10 GHz for the use of low-rate UWB communication and imposed the limit on the maximum allowable transmit power spectral density of the UWB signal to avoid the interferences with the other existing narrowband wireless technologies [1]. Due to this power constraint, the UWB communication system faces major design challenges and has been failed to achieve the wide coverage of the area. To address these issues, cooperative diversity has emerged as an effective scheme [2,3]. The basic idea of the cooperative scheme is to utilize the additional relay (R) terminal for transmitting the source (S) terminal information to the destination (D) terminal in order to improve the system performance. In general, the cooperative protocol strategy has been categorized into the amplify-and-forward (AF) and the decode-and-forward (DF) cooperative strategies. In [4–6], the bit error rate (BER) formulae of two hop UWB system over the AF and DF cooperative strategies were derived. In [7], authors have derived an expression of average BER of the DF cooperative strategy-based relay assisted high-data-rate UWB system over IEEE 802.15.3a channel model incorporated with the transmit antenna selection (TAS) at the source and the relay terminal. In [8,9], authors have incorporated the multiple input multiple output (MIMO) network with the conventional UWB system and with the two hop UWB system and results demonstrate that by incorporating the MIMO scheme, the performance of the investigated system has been improved. This improvement in the BER increases with the number of antennas in the MIMO network, but the increase in the number of antennas in the MIMO network introduces more hardware and design complexities. To overcome these challenges, TAS with maximum ratio combining (MRC) scheme play a viable solution suggested as in [10–12]. In [13–15], authors have evaluated the channel capacity and outage probability of UWB system over the simplified IEEE 802.15.4a channel model. In [16], the author analysed the BER of the conventional SISO communication over the generalized $\kappa - \mu$ and $\eta - \mu$ fading channels. $\kappa - \mu$ and $\eta - \mu$ are generalized models which accommodate most of the known fading models such as Rayleigh distribution when $\kappa \rightarrow 0$ and $\mu = 1$, Nakagami-$m$ distribution when $\kappa \rightarrow 0$ and $\mu = m$, and so on. In the above literature, most of the works have considered the narrow band flat or frequency flat Nakagami-$m$ fading channel statistics which is not appropriate for IEEE 802.15.4a channel model [1].

The two fundamental properties of the UWB system that make the IEEE 802.15.4a channel different from the narrow band flat or frequency flat Nakagami-$m$ channel. First, UWB system has large bandwidth, wider than the coherence bandwidth. Thus, the highly frequency selective fading exists. Second, extremely large bandwidth leads to the high-resolution of the arrival time, as a result...
UWB signals arrive in the form of clusters. The measurement results show that the IEEE 802.15.4a channel has some important characteristics. These additional characteristics introduced the new challenges for analysing the performance of the UWB system under IEEE 802.15.4a channel as discussed in the following:

- In the IEEE 802.15.4a channel, the multipath gain coefficient is modelled as Nakagami-$m$ distributed, where the parameter $m$ is a lognormal random variable.
- The number of clusters and rays within the clusters for the IEEE 802.15.4a channel are random numbers.
- Due to the insufficient number of arriving rays in the very narrow time bin, the central limit theorem is not applicable.

In this paper, we calculate the BER of the TAS/MRC-based two-hop UWB communication system over IEEE 802.15.4a channel. To the best of our knowledge, no work in the literature has calculated the BER of the investigated UWB system over IEEE 802.15.4a channel. This work uses Gauss–Hermite, Gauss–Laguerre, and Gauss–Legendre numerical formulae to calculate the intractable integrals involved in the analysis. This paper also compares the BER of the investigated UWB system with the reported results as in [16]. The accuracy of the derived BER expression has been verified via the simulation results.

The remaining part of this paper is organized as follows. The system and channel models are described in Section 2. The performance analysis of the investigated UWB communication system is done in Section 3. Section 4 presents the numerical results and discussion. Finally, the conclusion is drawn in Section 5.

2. SYSTEM AND CHANNEL MODELS

In this section, the investigated TAS/MRC-based two-hop relaying UWB system and IEEE 802.15.4a channel model for low-rate UWB wireless communication system are described in brief.

2.1 System Model

We consider the TAS/MRC-based two-hop relaying UWB system and it is depicted in Figure 1, where \{S, R\} terminals have \(N_T\) number of transmitting antennas and \{R, D\} terminals have \(N_R\) number of receiving antennas, respectively. The S and R terminals perform the \((N_T, 1; N_R)\) TAS/MRC scheme for the source to destination \((S - D)\) and relay to destination \((R - D)\) links. While in the source to relay \((S - R)\) link, S terminal does not perform the TAS scheme and uses the same transmitting antenna which has been selected in the \((S - D)\) link. The basic idea of \((N_T, 1; N_R)\) TAS/MRC scheme is that among the \(N_T\) transmitting antennas, one antenna is selected for the transmission such that the received signal to noise ratio (SNR) is maximum. The receiver utilizes the MRC diversity combining scheme to combine all the received signals that arrive at the \(N_R\) receiving antennas. In order to perform the TAS scheme, we assume that perfect channel state information (CSI) is available at the transmitter through a feed back channel link. Initially, all the transmitting antennas send the pilot signals to the receiver, and the receiver evaluates the instantaneous SNRs. Using the feed back link, the receiver transmits back the decision information \((I)\) of the instantaneous SNRs to the transmitter.

The mathematical expression of \(I\) is given as [17–19]

\[
I = \arg \max_{1 \leq m \leq N_T} \left\{ C_m = \sum_{n=1}^{N_R} |h_{m,n}|^2 \right\}
\]

(1)

where \(h_{m,n}\) denotes the channel impulse response (CIR) for the \(m^{th}\) \((m = 1, 2, ..., N_T)\) transmitting to the \(n^{th}\) \((n = 1, 2, ..., N_R)\) receiving antenna link, respectively. We present a detailed description of \(h_{m,n}\) in the next subsection. Under the assumption of the perfect CSI known at the transmitter, the \(C_m\)’s are arranged as \(C_{(1)} \leq C_{(2)} \leq ... \leq C_{(i)}\), where \(i \in \{m = 1, ..., N_T\}\). On the basis of this sequence, it is assumed that the received SNR is maximum for the \(i^{th}\) transmitting antenna and hence, it is selected for transmission. The probability density function (PDF) of \(i^{th}\) selected transmitting antenna, \(f_{C_{(i)}}(.)\) is given as [20,21]

\[
f_{C_{(i)}}(x) = N_T[F_{C_{(i)}}(x)]^{N_R-1}f_{C_{(i)}}(x)
\]

(2)

where \(f_{C_{(i)}}(.)\) and \(F_{C_{(i)}}(.)\) are the PDF and cumulative distribution function (CDF) of \(C_{(i)}\).

In the two hop DF-relaying wireless communication system, transmission is performed in two time slots. In the
first time slot, $S$ terminal broadcasts the information to the $D$ and $R$ terminals. In the second time slot, the $R$ terminal initiates the transmission to the $D$ terminal only if it can correctly decode the broadcasted information of the $S$ terminal in the first time slot. Let us define, $x$ to be the transmitted symbol and $p_1$, $p_2$ to be the transmitted powers at the $S$ and the $R$ terminals, respectively. The received signal vectors corresponding to the $(S-R)$, $(S-D)$ and $(R-D)$ links can be expressed, respectively as

$$y_{SR} = \sqrt{p_1}h^*_{SR}x + n_{SR}$$  

$$y_{SD} = \sqrt{p_1}h^*_{SD}x + n_{SD}$$  

$$y_{RD} = \sqrt{p_2}h^*_{RD}x + n_{RD}$$

where $y = (y_1, y_2, ..., y_{N_R})^T$ denotes the received signal vector and $h = (h_{11}, h_{12}, ..., h_{1N_R})^T$ is the CIR vector for the $N_R$ antennas. Similarly, the noise $n$ is the $(N_R \times 1)$ AWGN vector with $N_0$ power spectral density of each noise component. The superscripts and subscripts represent the corresponding links and the transmit antenna indexing, respectively.

### 2.2 IEEE 802.15.4a Channel Model

Task Group IEEE 802.15.4a (TG4a) has developed the IEEE 802.15.4a standard channel model for the large distance, low-rate UWB indoor communication system. Mathematically, the impulse response of IEEE 802.15.4a channel can be expressed as [1]

$$h(t) = \sum_{c=0}^{C} \sum_{r=0}^{R} \alpha_{r,c} e^{j\phi_{r,c}} \delta(t - T_c - \tau_{r,c})$$  

where $\alpha_{r,c}$ is the multipath gain coefficient (MPC) of the $r^{th}$ ray in the $c^{th}$ cluster, $T_c$ and $\tau_{r,c}$ are the cluster and ray arrival times, respectively. The $\phi_{r,c}$ is uniformly distributed in the range $[0, 2\pi]$ and $R$ is the number of rays. Number of clusters ($C$) is a random variable with the probability mass function given as

$$f_C(c) = \begin{cases} (1 + L) \exp(-L), & c = 1 \\ L^{c} \exp(-L)/c!, & c \geq 2 \\ 0, & \text{otherwise} \end{cases}$$  

where $L$ is the mean of the number of clusters. According to [1], the MPCs, ($\alpha$), is Nakagami-$m$ distributed. The $m$-parameter is modelled as a lognormally distributed random variable, whose logarithm has a mean ($\mu_m(\tau) = m_0 - k_m\tau$) and standard deviation ($\sigma_m(\tau) = m_0 - \hat{k}_m\tau$). The distributions of cluster and ray arrival times are modelled as Poisson and mixtures of two Poisson processes, respectively as follows:

$$f(T_c/T_{c-1}) = \Lambda e^{-\Lambda[T_1 - T_{c-1}]}$$  

$$f(\tau_{r,c}/\tau_{r-1,c}) = \beta \lambda_1 e^{-\lambda_1[\tau_1 - \tau_{r-1,c}]} + (\beta - 1)\lambda_2 e^{(-\lambda_2[\tau_2 - \tau_{r-1,c}])}$$  

where $\beta$ is the mixture probability, $\Lambda$ is the cluster arrival rate and $\{\lambda_1, \lambda_2\}$ are the ray arrival rates. $(m_0, k_m)$ and $(\hat{m}_0, \hat{k}_m)$ are the mean factor and the variance factor parameters of the Nakagami-$m$ parameter, respectively.

On the basis of practical measurement, the IEEE 802.15.4a channel model is categorized into five different environments: Residential, Indoor Office, Outdoor, Open Outdoor, and Industrial environments. Every channel environment is further classified according to the line-of-sight and non-line-of-sight paths. Detailed description of the channel parameters and their measured values corresponding to the every channel environment are given in the channel report of TG4a [1].

### 3. PERFORMANCE ANALYSIS

In this paper, we calculate the BER of the orthogonal binary signals in the TAS/MRC-based two hop UWB system over IEEE 802.15.4a channel model. In the investigated two hop system, relay terminal performs the decode and forward cooperative strategy. From [22], the end to end BER for the DF-two hop communication system can be expressed as

$$\bar{P}_e = P_e(SR)P_e(SD)P_e(SRD)$$  

$$+ P_e(SRD)(1 - P_e(SR))$$  

where $\{P_e(SR), P_e(SD), P_e(SRD)\}$ are the received SNR of the orthogonal binary signals with the coherent RAKE receiver corresponding to the $(S-R)$, $(S-D)$ and $(S-R-D)$ links, respectively. From [23], the average probability of error of the orthogonal binary signals with the coherent RAKE receiver is given as

$$P_e(\gamma) = \int_{0}^{\infty} Q(\sqrt{\gamma}) f_\gamma(\gamma)d\gamma$$  

where $\gamma$ is the received SNR.
3.1 Probability of error for the \((S - R)\) link:

In the \((S - R)\) link, the source terminal chooses the same transmitting antenna which has been selected in the \((S - D)\) link transmission whereas relay terminal performs the MRC scheme to combine all the \(N_{R}\) received signals. Now after performing the MRC, the received SNR at the R terminal can be computed as

\[
\gamma_{SR} = \frac{P_{1}}{N_{0}} \sum_{n=1}^{N_{R}} \left| h_{n}^{SR} \right|^2 = \frac{P_{1}}{N_{0}} C_{SR}^{i}
\]

(12)

where \(\gamma_{SR} = \sum_{n=1}^{N_{R}} \left| h_{n}^{SR} \right|^2\) is the total energy received at the R terminal corresponding to the \(i\)th transmitting antenna of the S terminal. Here, \(\gamma_{SR} = \left| h_{n}^{SR} \right|^2\) is the received energy at the \(n\)th antenna of the R terminal. Under the assumption of i.i.d. channel paths, the received energy at one antenna will be independent to the received energy at the another antenna. Therefore, the characteristic function (CF) of \(\gamma_{SR}^{i}\) can be calculated as

\[
\Psi_{\gamma_{SR}}(v) = \prod_{n=1}^{N_{R}} \Psi_{\gamma_{SR}^{n}}(v)
\]

(13)

where \(\Psi_{\gamma_{SR}}(v)\) is the CF of \(\gamma_{SR}^{n}\). The derivation of \(\Psi_{\gamma_{SR}}(v)\) is given in the Appendix. The PDF of the received energy in the \((S - R)\) link can be computed as

\[
\psi_{\gamma_{SR}}(x) = \frac{1}{2\pi} \sum_{k=1}^{N_{H}} w_{k}^{i} \Psi_{\gamma_{SR}}^{i}(v) \exp(-jvx)|_{v=x_{k}^{i}}
\]

(14)

where \(\{w_{k}^{i}\}\), \(\{x_{k}^{i}\}\), and \(N_{H}\) are the weights, abscissas, and number of nodes of the Gauss–Legendre quadrature, respectively. From Equations (11), (12), and (14), and using the Gauss–Laguerre quadrature after some simplifications, the probability of error in the \((S - R)\) link is given as

\[
P_{e(SR)}(\gamma_{SR}) = \frac{1}{2\pi} \sum_{q=1}^{M_{T}} \sum_{k=1}^{N_{H}} w_{k}^{q} w_{k}^{H} \Psi_{\gamma_{SR}}^{q}(x_{k}^{H})
\]

\[
\times F\left(p_{1}, N_{0}, x_{k}^{H}, x_{q}^{H}\right) \left(x_{q}^{H}\right)^{N_{T}-1}
\]

(15)

where \(\{w_{k}^{i}\}, \{x_{k}^{i}\}, M_{T}\) are the weights, \(i\)th root, and number of nodes of Gauss–Laguerre quadrature, respectively and the function \(F\left(r_{1}, r_{2}, r_{3}, r_{4}\right) = Q\left(\sqrt{\frac{r_{1}r_{3}}{r_{2}}}ight) e^{\left[\frac{\lambda}{2}\left(1-r_{3}\right)\right]}\).

3.2 Probability of error for the \((S - D)\) link

In the \((S - D)\) link, a single transmitting antenna at the source terminal which maximized the received SNR at the destination terminal is selected. Suppose the \(i\)th transmitting antenna maximized the received SNR and destination terminal applied the MRC scheme then the received SNR at the D terminal can be computed as

\[
\gamma_{SD} = \frac{P_{1}}{N_{0}} C_{SD}^{i}(i)
\]

(16)

where \(C_{SD}^{i}(i) = \max_{1 \leq i \leq N_{T}} \{C_{SD}^{i}\}\) and \(C_{SD}^{i} = \sum_{n=1}^{N_{R}} \left| h_{n}^{SD} \right|^2\).

In the i.i.d channel, the distribution of \(C_{SD}^{i}\) is equivalent to the distribution of \(\gamma_{SR}^{i}\). Therefore, its PDF can be calculated as in (14). However, the CDF of \(C_{SD}^{i}\) can be calculated as \(F_{C_{SD}^{i}}(x) = \int_{0}^{x} f_{C_{SD}^{i}}(t)dt\). Using the Gauss–Legendre quadrature, it can be expressed as

\[
F_{C_{SD}^{i}}(x) = \frac{x}{2} \sum_{s=1}^{N_{H}} w_{s}^{i} F_{\gamma_{SD}}^{i}\left(\frac{x}{2} (s_{j}^{i} + 1)\right)
\]

(17)

where \(\{x_{j}^{i}\}, w_{i}^{j}, N_{H}\) are the abscissas, weights, and number of nodes of Gauss–Legendre quadrature, respectively. From Equations (2), (11), (14), and (17), and some simplifications, the probability of error in the \((S - D)\) link is given as

\[
P_{e(SD)}(\gamma_{SD}) = \frac{N_{T}}{2(2\pi)^{N_{T}}} \sum_{q=1}^{M_{T}} \sum_{k=1}^{N_{H}} \left(w_{q}^{i} w_{k}^{H} \Psi_{C_{SD}^{i}}^{q}(x_{k}^{H})
\right.

\]

\[
\times F\left(p_{1}, N_{0}, x_{k}^{H}, x_{q}^{H}\right) \left(x_{q}^{H}\right)^{N_{T}-1}
\]

(18)

where

\[
X^{\text{link}}(a) = a \sum_{s=1}^{N_{H}} w_{s}^{i} w_{k}^{H} \Psi_{\gamma_{SD}}^{i}(x_{k}^{H}) e^{\left[(x_{j}^{i})^{2} - \frac{\lambda^{2}}{4}\right]}(s_{j}^{i}+1)\]

3.3 Probability of error for the \((S - R - D)\) link

In this link, destination terminal received the signal from the source terminal and from the relay terminal only when, relay is able to decode the received signals correctly. Suppose both \(S\) and \(R\) nodes select the \(i\)th transmitting antenna then the received SNR at the D terminal in the \((S - R - D)\) is equal to the sum of the received SNR in the \((S - D)\) link and the received SNR
in the \((R-D)\) link and it is given as

\[
Y_{SD} = Y_{R} + Y_{SD}
\]

\[
= \frac{P_1}{N_0} \left( \sum_{n=1}^{N} |a_{SD}\{i,j\},n|^2 \right) + \frac{P_2}{N_0} \left( \sum_{n=1}^{N} |a_{RD}\{i,j\},n|^2 \right)
\]

\[
(19)
\]

Suppose \(p_1 = p_2\) and for the i.i.d. channel links, the above expression can be written as

\[
Y_{SRD} = \frac{P_1}{N_0} \left( \sum_{n=1}^{N} |a_{SD}\{i,j\},n|^2 \right) = Y_{SD}|_{N_0 = 2N_0}
\]

\[
(20)
\]

The probability of error in the \((S-R-D)\) link can be calculated similarly as the probability of error in the \((S-D)\) link. Mathematically, it can be written as

\[
P_{e(SRD)}(Y_{SRD}) = P_{e(SD)}(Y_{SD})|_{N_0 = 2N_0, Y_{SRD} = Y_{SRD}}
\]

\[
(21)
\]

\[
P_e = \frac{N_T}{2(2\pi)^{1/2}} \left\{ \sum_{q=1}^{N_T} \sum_{k=1}^{N} w_q \Psi^T_{C_\\{z\}}(x_q^T) \times \Psi^T_{C_\\{R\}}(x_q^T) \times \left( \frac{x_q}{x_q^T} \right)^{N_T-1} \right\}
\]

\[
+ \left[ 2N_0 - \sum_{q=1}^{N_T} \sum_{k=1}^{N} w_q \Psi^T_{C_\\{R\}}(x_q^T) \right] \times \left( \frac{x_q}{x_q^T} \right)^{N_T-1} \right|_{N_0 = 2N_0}
\]

\[
(22)
\]

From Equations (10), (15), (17), and (21), the final BER expression for the investigated UWB system over IEEE 802.15.4a channel is given in Equation (22).

### 4. Numerical Results And Discussion

In this section, we present the simulated and the analytical BERs of the investigated UWB system over various environments of IEEE 802.15.4a channel. From Equation (22), it is noted that the accuracy of the derived BER is related to the precision of the numerical solutions. This precision is controlled by the number of nodes of the numerical formulae (Gauss–Hermit, Gauss–Legendre, and Gauss–Laguerre quadrature). We have calculated the degree of precision of these numerical methods for the various number of nodes by considering different tractable integrals [24]. The variations in the degree of precision with respect to the number of nodes are given in Table 1. It is observed that the degree of the precision goes up to 8 decimal places when the number of nodes are more than or equal to 40. The precision up to 8 decimal places of the numerical solutions is sufficient to make the analytical BER closer to the simulated one. Hence, we choose \(N_{\text{th}}^T = N_{\text{th}} = M^T = 40\). In the numerical analysis, we set \(T_p = 1\) ns and the number of bits = 10^5.

Figure 2 shows the effect of the number of RAKE receiver fingers on the BER of the \((3, 1; 3)\) TAS/MRC-based investigated UWB system over IEEE 802.15.4a CM1–6 channel models at SNR = 5 dB. Normally, the BER decreases as \(L\) increases. It is because more MPCs are received at the RAKE receiver. The result shows that for large values of \(L\) \((L \geq 15\) for CM1–2 and \(L \geq 25\) for CM3–6), the BER curves of investigated system go flat. This is because, at those values of \(L\), the RAKE receiver receives most of the signal energy. Therefore, for further simulations and the numerical calculations, we choose \(L = 25\) for all channel models so that performance can be fairly compared in all cases.

Figure 3 shows the effect of the number of antennas on the simulated and the analytical BERs of the investigated UWB system over IEEE 802.15.4a CM1. It also shows the comparison between the BER of the conventional (relay-based SISO) and the investigated UWB system. It is observed that there is a significant improvement in the BER of the investigated UWB system over conventional one. The performance of the investigated system is also improved with increase in the number of antennas in the TAS/MRC scheme. Similarly, the simulated and the analytical BERs of the \((3, 1; 3)\) TAS/MRC-based two hop UWB system over IEEE 802.15.4a CM1–6 channel

---

### Table 1: Degree of the precision for various number of nodes

<table>
<thead>
<tr>
<th>No. of nodes</th>
<th>Gauss–Hermit</th>
<th>Gauss–Legendre</th>
<th>Gauss–Laguerre</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>3–4</td>
<td>3–4</td>
<td>3–4</td>
</tr>
<tr>
<td>30</td>
<td>4–5</td>
<td>4–5</td>
<td>4–5</td>
</tr>
<tr>
<td>40</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>50</td>
<td>9–10</td>
<td>9–10</td>
<td>9–10</td>
</tr>
<tr>
<td>100</td>
<td>&gt;20</td>
<td>&gt;20</td>
<td>&gt;20</td>
</tr>
</tbody>
</table>
models are shown in Figure 4. The results show that analytical BER is a good match to the simulated one.

Figure 5 shows the BER of the SISO-UWB system (with relaying and without relaying) over IEEE 802.15.4a CM1 \((L=10)\) and the BER of the conventional SISO wireless communication system (with relaying and without relaying) over narrowband flat Nakagami-\(m\) fading channel \((m = 2.0324\) and \(m = 1\) for CM1) reported as in \[16, Equation (12)\]. As expected, it can be observed that the narrowband Nakagami-\(m\) fading (conventional SISO communication over Nakagami-\(m\) fading channel) has lesser BER than the SISO-UWB communication over IEEE 802.15.4a channel and it decreases when \(m\) increases.

Figure 6 shows the effect of the inter-cluster decay constant \((\Gamma(\text{ns}))\) on the BER of the conventional and the investigated UWB system over IEEE 802.15.4a channel CM1~2, at SNR = 10 dB. It is observed that the BER of both the UWB system decreases with increase in \(\Gamma\). But after the certain values of \(\Gamma\) (\(\Gamma = 22\) ns for CM1 and \(\Gamma = 26\) ns for CM2), the BER curves go flat. This is because initially the integrated energy of the \(m\)th cluster \((\Omega_m = \frac{1}{\gamma_m} \exp(-\frac{T}{\Gamma} - \frac{t}{\gamma_m}))\) increases with increase in \(\Gamma\). As a result, the energy captured by the RAKE receiver also goes on increasing and the BER decreases. Later on, at \(\Gamma = 22\) ns for CM1 and \(\Gamma = 26\) ns for CM2, most of the
m\textsuperscript{th} cluster energy gets integrated. Therefore, beyond these values of $\Gamma$, the BER curves goes flat.

5. CONCLUSION

In this paper, we have derived an expression of BER of the orthogonal binary signals for the TAS/MRC- based two hop UWB system over IEEE 802.15.4a channel model. Our results show that there is a significant improvement in the BER of the investigated UWB system compared to the reported conventional system. It also shows that the analytical BER of the investigated UWB system is closely matched to the simulation one, which verifies the accuracy of the derived BER expression and the approximations involved in the analysis.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

REFERENCES


APPENDIX

In the UWB communication, the total transmitted signal energy is dispersed over the MPCs and these MPCs can be resolved separately, which provide the higher order of diversity gain. To attain the diversity gain and collect all the multipath signals, we used L-fingers of the RAKE receiver.

A.1 Derivation of $\psi_v(v)$

For better understanding, we omit the antennas and link indexing. Let us assume that, $\hat{e}$ is close to the $\tilde{e}$, is the energy received by the L-RAKE receiver in the single IEEE 802.15.4a channel link. From [25,26], in the $[0,LT_p]$ time window, the $\hat{e}$ can be approximately calculated as

$$\hat{e} = \sum_{0 \leq T_r + \tau_s \leq LT_p} |\alpha_{r,s}|^2 = (\alpha_{0,0}^2 + \phi_{r,0} + \tilde{\phi}_{0})$$  \hspace{1cm} (A23)

where $T_p$ is the chip duration between two consecutive fingers. The parameter $\alpha_{0,0}^2$ is the squared path gain of first ray in the first cluster, $\phi_{r,0}$ is the sum of squared path gains of the first cluster excluding the $\alpha_{0,0}^2$ and $\tilde{\phi}_{0}$ is the sum of squared path gains of all the rays in the remaining clusters. Note that, these three parameters are statistically independent. Thus, the characteristic function $\psi_v(v)$ of $\hat{e}$ can be calculated as

$$\psi_v(v) = \mathcal{L}_{0,0}(v) \mathcal{A}(v) \mathcal{N}(v)$$ \hspace{1cm} (A24)

where $\mathcal{L}_{0,0}(v)$, $\mathcal{A}(v)$, and $\mathcal{N}(v)$ are the characteristic functions of $\alpha_{0,0}^2$, $\phi_{r,0}$, and $\tilde{\phi}_{0}$, respectively. As we know that, MPC ($\alpha$) is Nakagami-$m$ distributed then, the characteristic function $\mathcal{L}_{T,v}(v)$ of $\alpha^2$ can be computed as

$$\mathcal{L}_{T,v}(v) = \left(1 - \frac{jv\Omega}{m}\right)^{-m}$$ \hspace{1cm} (A25)

where $\Omega = \frac{1}{\gamma_m} \exp\left(-\frac{T - \frac{\lambda}{\gamma_m}}{\lambda}\right)$ is the integrated energy of the $m^{th}$ cluster, can be calculated from the cluster and rays power delay profiles of IEEE 802.15.4a channel and $m = \exp(m_0 + \frac{\lambda^2}{2})$ is the mean of the parameter-$m$ in the Nakagami-m distribution. Here, $\gamma_m = k_pT_m + \gamma_0$ and $\{k_p, \gamma_0\}$ are the intra cluster decay time constants. $\Gamma$ is the inter cluster decay constant.

From [27], $\mathcal{A}(v) = \exp(-\lambda \tilde{\psi}_v(0,L))$ and $\mathcal{N}(v) = \exp(-\lambda \tilde{J}(v,L))$, where $\lambda = \frac{\lambda_{0,0}^2}{(1-q_{|d_1}+q_{|d_2})}$ is the average rays arrival rate. The functions $\tilde{\psi}_v(0,L)$ and $\tilde{J}(v,L)$ can be evaluated numerically, e.g. using Gauss–Legendre quadrature, are given as

$$\tilde{\psi}_v(T,L) \approx \frac{LT_p - T}{2} \sum_{i=1}^{N_L} w_i^\delta \left(1 - \mathcal{L}_{T,v}(v)\right)|_{t=\delta_p}$$ \hspace{1cm} (A26)

and

$$\tilde{J}(v,L) \approx \frac{LT_p}{2} \sum_{i=1}^{N_L} w_i^\delta \left(1 - \mathcal{L}_{T,v}(v)\right) e^{-\lambda \tilde{\psi}_v(T,L)}|_{T=\delta_s}$$ \hspace{1cm} (A27)

where $\delta_p = \frac{LT_p - T}{2} x_{s_1}^L + \frac{LT_p + T}{2} x_{s_2}^L$ and $\delta_s = \frac{LT_p}{2} (x_{s_3}^L + 1)$. From Equations (24)–(27), the characteristic function of $\hat{e}$ is given as

$$\psi_v(v) = \left(1 - \frac{jv}{\gamma_0 \exp(m_0 + \frac{\lambda^2}{2})}\right) \times e^{-\frac{LT_p}{2} \sum_{i=1}^{N_L} w_i^\delta \left(1 - \mathcal{L}_{T,v}(v)\right)} \times e^{-\frac{LT_p}{2} \sum_{i=1}^{N_L} w_i^\delta \left(1 - \mathcal{L}_{T,v}(v)\right) e^{-\lambda \tilde{\psi}_v(T,L)}|_{T=\delta_s}}$$ \hspace{1cm} (A28)

where $\delta = \frac{LT_p}{2} (x_{s_3}^L + 1)$. 


Authors

Anand Agrawal received his MTech degree in digital communication engineering from National Institute of Technology (NIT), Bhopal, India, in 2010 and the BE degree in electronics and communication engineering (ECE) from Samrat Ashok Technological Institute (SATI), Vidisha, India, in 2008. He is currently a PhD candidate in the Department of Electronics and Electrical Engineering at Indian Institute of Technology, Guwahati, India. During September 2015 to January 2016, he was an exchange student with National Tsing Hua University, Taiwan, where he worked on performance analysis of millimeter wave communication systems. His research interests are in the areas of cooperative communication, UWB wireless communication systems, millimeter wave communication, and MIMO.

Email: anand.agrawal@iitg.ernet.in

Rakhesh Singh Kshetrimayum (S’02, M’05, SM’14) received the BTech degree in EE from IIT Bombay in 2000 and the PhD degree from the School of EEE, NTU Singapore in 2005. Since 2005, he has been working as a faculty member with the Department of EEE, IIT Guwahati and presently he is a professor. He worked as a postdoctoral scholar at the Department of EE, Pennsylvania State University (PSU), USA (2005), research associate at the Department of ECE, IISc Bangalore (2004–2005), and software engineer at Mphasis Pune, India (2000–2001). He has been involved in organizing several IEEE international conferences in various capacities including Technical Program Chair [communications track] of NCC, Guwahati, India, 2016, Session co-chair on MIMO Signal Processing of DSP, Singapore, 2015, Technical program co-chair of AEMC, Guwahati, India, 2015, WOCN, Paris, France, 2011, Session chair on Microwaves II of NCC, Bangalore, India, 2011, Publication co-chair of CMC, Shenzhen, China, 2010, and Program co-chair of NetCom, Chennai, India, 2009. He is the Editor-in-Chief of International Journal of Ultra Wideband Communications and Systems (Inderscience), 2009-., Editorial Board Member of International Journal of RF and Microwave Computer-Aided Engineering (Wiley), 2015, AEU International Journal of Electronics and Communications (Elsevier), 2016, Associate editor of IET Journal of Engineering, Editor of Transaction on Internet and Information Systems (Korean Society for Internet Information) and referee of several IEEE journals. Dr Kshetrimayum is the recipient of IETE M. Rathore Memorial Award (2015), Department of Science and Technology India (SERC) Fast Track Scheme for Young Scientists (2007–2010) and NTU Research Scholarship from 2001 to 2004. His current areas of research interests are in microwave/millimeter wave antennas/circuits, UWB communications and MIMO wireless communications. He has published over 100 research papers in the areas of his research interests. Since 2014, he is a fellow of the IETE, Optical Society of India, Antenna Test and Measurement Society of India, a Senior Member of IEEE, USA and life member of Applied Computational Electromagnetics Society, USA.

Email: krs@iitg.ernet.in