Interference Mitigation for IR-UWB Ad-hoc WPAN Based on Chip Decision RAKE Receiver

Saleh M. Al-Qaraawy * and Natiq A. Ali **

Received on : 2 / 12 /2007
Accepted on :30 / 6 /2008

Abstract

Impulse radio ultra wideband (IR-UWB) communication is becoming an important technology for future Wireless Personal Area Networks (WPANs). A critical challenge in IR-UWB system design is the multi-user interference (MUI). A RAKE receiver is proposed to mitigate the MUI that occurs in some ad-hoc networks like WPAN for IR-UWB system where concurrent transmissions are allowed without power control. The proposed RAKE receiver is shown to contribute to a mitigation of the multiple access interference (MAI) especially at medium input bit energy-to-noise ratio (E_b/N_o) values and small number of RAKE taps (fingers). This receiver is based on chip decision after the maximum ratio combining and then the final decision based on the number of pulses per symbols. In such scenarios, the conventional RAKE receiver is completely fails to get the expected BER, and does not always perform well. On the other hand, the proposed RAKE receiver has similar complexity as the conventional RAKE. The binary phase shift keying (BPSK) modulation scheme is used in this paper. The performance of the proposed RAKE is evaluated with the Non Line of Sight (NLOS) indoor channel model proposed by the IEEE 802.15.3a (COM3) for WPAN with distances (4-10) m.

***Key words:** IR-UWB, WPANs, ad hoc, MUI, and RAKE.*

الخلاصة

يعتبرارسال النبضات الضيقة جدا Impulse Radio (IR) – وبحزمة اتساع عريضة جدا Ultra-Wideband (UWB) نظام تكنولوجي مهم للطبقةِ الفيزياوية لتطبيقاتِ شبكات الــ WPAN . أهم تحدي في نظام الــ IR هو التداخلُ بين المستخدمين MUI. تم اقتراح مستلم نوع RAKE لتَسكين الــ MUI الذي يَحدثُ في بَعْض الشبكاتِ الخاصّةِ مثل الــ WPAN لنظام IR حيث الإرسال المتلاقي المَسْمُوح به بدون سيطرة للقدرةَ. إنّ مستلمَ الــ RAKE المُقتَرَح يعمل على المُسَاهَمَة في تخفيف الــ MUI خصوصا لقيم (E_b/N_o) متوسّطةِ وعدد صغير مِنْ أصابع الــ RAKE . هذا المستلم يستند على قرار الرقاقةِ بَعْدَ النسبة القصوى للجَمْعُ وبعد ذلك القرار النهائي يستند على عددِ النبضاتِ لكلّ الرموز. في مثل هذه السيناريوهات، المستلم RAKE التقليديِ يُخفقُ بالكامل للحُصُول على قيمة BER المتوقعة، ولا يُؤدّي اداءا جيّد دائما. من الناحية الأخرى، مستلم RAKE المُقتَرَح له تعقيدُ مماثلُ للــ RAKE التقليدي. تَم استخدام التضمين BPSK في هذا البحث. إنّ أداءَ الــ RAKE المُقتَرَح تم اختباره بوجود الــ NLOS وباستخدام القناة الداخلية الكثيفة متعددة الطرق نوع IEEE 802.15.3a (COM3) ولشبكات الــ WPAN ولمسافة (٤–١٠) متر.

* University of Technology, ** Technical College - Najaf

1. Introduction

In the past few years, IR-UWB communication has received considerable attention in both academia and industry. Compared to traditional narrow band systems, UWB can provide high data rate (> 100 Mb/s) with very low-power emission (less than −41 dBm/MHz) in a short range. These features make UWB particularly suitable for WPAN applications. Currently, IEEE 802.15.3a working group is studying the use of IR-UWB as an alternative physical layer technique [1].

The ultimate benefits that UWB could bring to ad hoc networking from increase network data rate mitigate MUI, and increased capacity [2].

The concept of ad hoc networking gathered in the last few years an increasing interest, as it opens the way to new network scenarios and applications that were precluded to traditional, infrastructure-based, wireless networks [3].

In general, there are many benefits to operating over a very wide bandwidth, one of which is the ability to resolve individual multipath components at the receiver. This property of the signal also significantly reduces fading which typically results from the destructive overlap of multipath reflections arriving at the receiver, since the short impulse nature of the UWB waveform prevents a significant overlap of the signals. However, combining many too paths using a RAKE receiver significantly increases the complexity of the implementation, and thus makes the quantitative performance vs. complexity tradeoff studies necessary for choosing an appropriate receiver architecture. This work focuses on the performance of possible receiver architectures for detecting UWB impulses that includes the effects of multipath propagation, additive white Gaussian noise (AWGN) and with no inter-symbol interference (ISI) – an assumption in this study - .A conventional receiver suitable for UWB modulation over a mutipath and AWGN channels is considered, which uses a bank of correlators followed by a RAKE combiner (maximum ratio combiner (MCR)), as shown in the next section. In order to capture the energy in the multipath components, multiple RAKE arms are needed which independently track different reflections of the channel [4,5].

Many literatures studied and focused on the MUI cancellation or mitigation using conventional RAKE receiver with all its types. In [6], the authors provide an analytical framework for determining the performance of RAKE receivers with MRC for UWB systems employing binary block-coded modulation with PPM or OOK. The analysis can be easily modified to accommodate antipodal signaling, as well as a tapped-delay-line channel model. In [7], the authors proposed a successive interference cancellation schemes, the proposed receiver does not require active decoding of each interferer. Thus there is no need to synchronize the receiver with all the interfering users, which would be impractical in an IR-UWB system that is likely to be run in ad hoc mode. To model MUI they considered a hidden Markov model (HMM) and a Gaussian mixture model (GMM). We find that the HMM models interference better than the GMM. The proposed model being more of theoretical nature, there are several aspects that have been omitted on purpose. First of all they did not do a complexity analysis for the choice of the interference model.

In the best of our knowledge, this is the first attempt to mitigate the MUI in within a certain level by using a chip decision based technique after the MCR without using channel coding. This can be done by modifying the structure of the conventional RAKE receiver.

2. The Rake Receiver

The basic version of the conventional Rake receiver - see figure (1) - consists of multiple correlators (fingers) where each of the fingers can detect/extract the signal from one of the multipath components provided by the channel. The outputs of the fingers are appropriately weighted and combined to reap the benefits of multipath diversity [8]. All-rake (ARake), selective-rake (SRake), or partial-rake (PRake) receivers are all feasible approaches to collect all, strongest, or first arriving resolvable multipath components, respectively. Optimal combining of the multipath components in white noise is achieved by maximal ratio combining (MRC), where the finger weights are designed based on the channel tap weights to maximize the output SNR [9].

In realistic UWB multipath fading channels, the number of powerful multipath components is much more than 4 and less than 50. This implies a moderate to high implementation complexity for a perfect RAKE or an all-RAKE (ARAKE) receiver. Therefore, in practice non-perfect RAKE receivers are considered. Non-perfect RAKE receivers do not receive all multipath components and the number of fingers is less than the number of arrived components. Two main non-perfect RAKE receiver structures proposed for UWB systems are the selective-RAKE (SRAKE) receiver and partial-RAKE (PRAKE) receiver. The PRAKE receiver does not need to detect the multipath components with the largest gain resulting in a lower implementation complexity. It has been shown that the performance of the PRAKE receiver approximates the performance of the SRAKE receiver with the same number of fingers for $N_B > 4$ [10].

On other side, in a *dense* channel model, it is sufficient to always choose the first arriving multipath components, as those are usually the strongest using PRAKE receiver. In a *sparse* model, the SRAKE receiver must be chosen which searches for the strongest multipath components and then places the Rake fingers at those delays. A low-cost partial Rake would thus be the method of choice in a dense channel, but not in a sparse one [11].

Therefore, PRAKE receiver is assumed to be used in this work. Also, PRAKE receiver employs N_B IR-UWB correlators that are located in successive bins each with duration 1 ns.

3. Interference in UWB: The MUI

In addition to the radio channel, the interference in UWB systems affects the receiver performance and the receiver choice significantly. Interference can be due to various sources including MUI, narrow band interference (NBI), inter-symbol interference (ISI), and inter-frame interference (IFI). Note that, compared with the AWGN, these interferences are colored and the receivers can take advantage of the correlation for improving the receiver design. Coherent detection allows cancellation of several sources of interference. However, many interference cancellation routines require additional a priori information about interference statistics, like operation frequency, power, time/frequency/space correlation, and code of the interfering signal [9]. In this paper, we focus on MUI and ignore other types.

The coexistence of a large number of UWB transmitters in a dense environment is very important. The transmitted signals of each user share the same spectrum, and simultaneous transmissions by multiple users are popularly achieved by TH or DS spreading codes. Ideally, it is desired to have orthogonal codes for each user. However, in practice the received signal from different users is not orthogonal because of multipath, asynchronous transmission. Also, designing perfect codes with zero auto- and cross-correlation properties for all shifts is not possible. As a result, MAI in UWB communication systems is a major problem. The effectiveness of interference cancellation receivers relies on the ability to separate the desired signal from the interferer(s) [9].

Multi-user interference introduces a major limitation in IR-UWB ad-hoc WPANs especially when the concurrent transmissions are employed in this study without power control. This effect was included in the analysis in the next section. The MUI model that is used in this study is shown in figure (2). As it is notice, many nodes (users) are transmitting concurrently and only single receiver was employed for the user of concern.

4. Signal Model

We consider a synchronous, binary phase shift keyed IR-UWB system with K users, in which the transmitted signal from user k is represented by [12]:

$$S_{tx}^{(k)}(t) = \sqrt{E_f^k} \sum_{j=-\infty}^{\infty} b_j^{(k)} \sum_{i=1}^{N_s} p_{tx}(t - jT_f - c_i^{(k)}T_c) \quad \ldots (1)$$

where $p_{tx}(t)$ is the transmitted UWB pulse having a shaping factor value that determine its width, E_f^k is the bit energy of user k, T_f is the "frame" time, N_s is the number of pulses representing one information symbol, and $b_j^{(k)} = \{+1,-1\}$ is the binary information symbol transmitted by user k. In order to allow the channel to be shared by many users and avoid catastrophic collisions, a TH sequence $\{c_j^{(k)}\}$, where $c_j^{(k)} \in \{1,2,\ldots,N_c\}$, is assigned to each user. This TH sequence provides an additional time shift of $c_j^{(k)} T_c$ seconds to the j^{th} pulse of the k^{th} user where T_c is the chip interval and is chosen to satisfy $T_c \le T_f / N_c$ in order to prevent the pulses from overlapping. We assume that $T_f = N_c T_c$ without loss of generality.

Consider the discrete presentation of the channel, $\alpha^{(k)} = [\alpha_1^{(k)} \cdots \alpha_L^{(k)}]$ for user k, where L is assumed to be the number of multipath components for each user, and T_c is the multipath resolution. Then, the received signal can be expressed as:

$$S_{rx}^{(k)}(t) = \sum_{k=1}^{K} \sqrt{E_f^k} \sum_{j=-\infty}^{\infty} b_j^{(k)} \sum_{i=1}^{N_s} \sum_{l=1}^{L} \alpha_l^{(k)} p_{rx}\left(t - jT_f - c_i^{(k)}T_c - (l-1)T_c\right) + \sigma_n n(t) \quad \ldots\ldots (2)$$

where $p_{rx}(t)$ is the received unit-energy UWB pulse, which is usually modeled as the derivative of $p_{tx}(t)$ due to the effects of the receive antenna, and $n(t)$ is zero mean white Gaussian noise with unit spectral density.

The template signal for the l^{th} path of the incoming signal can be expressed as:

$$S_{temp,l}^{(1)}(t) = \sum_{j=iN_s}^{(i+1)N_s-1} p_{rx}\left(t - jT_f - c_i^{(1)}T_c - (l-1)T_c\right) \quad \ldots\ldots (3)$$

For the i^{th} information symbol, we consider user 1 as the desired user, without loss of generality. In other words, by using a correlator for each multipath component that we want to combine, we can have symbol-rate sampling at each branch, as shown in Figure 2.

Let $L = \{l_1, \ldots, l_M\}$ denote the set of multipath components that the receiver collects (Figure 2). At each branch, the signal is correlated with the template signal in (3) corresponding to the multipath component at that branch and sampled once for each symbol. Then, the discrete signal for the l^{th} path can be expressed, for the i^{th} information symbol, as:

$$r_l = s_l^T A + n_l$$

for $l = l_1, \ldots, l_M$, where $A = diag\left\{\sqrt{E_1}, \ldots, \sqrt{E_K}\right\}$, and $n_l \approx N(0, \sigma_n^2)$. s_l is a $K \times 1$ vector, which can be can be expressed as a sum of the desired signal part (SP) and MAI terms:

$$s_l = s_l^{(SP)} + s_l^{(MAI)}$$

where the k^{th} elements can be expressed as :

$$\left[s_l^{(SP)}\right]_k = \begin{cases} \alpha_l^{(1)} & for \quad k=1 \\ 0 & for \quad k=2,\ldots\ldots,K \end{cases}$$

$$\left[s_l^{(MAI)}\right]_k = \begin{cases} 0 & for \quad k=1 \\ \sum_{m=1}^{L} \alpha_m^{(k)} I_{l,m}^{(k)} & for \quad k=2,\ldots\ldots,K \end{cases}$$

With $I_{l,m}^{(k)}$ being the indicator function that is equal to 1 if the m^{th} path of user k collides with the l^{th} path of user 1, and 0 otherwise.

5. The Proposed Receiver

In conventional Rake detection methods, each correlator correlates the received signal with a template, then summing the outputs in MRC scheme. The summed signal is collected and summed again for Ns pulses, after that a single decision device decides the estimated bit illustrated in the simplified diagram shown in figure (3).

This method has a severe drawback when MUI is present. If one of the pulses at the output of MRC is corrupted with a pulse of a near or far - by interferer, this interfering pulse can affect the correlation result significantly. In other word, one or more strong interfere may be highly dominants a single pulse negatively (negative interferer pulse (NIP)), results in a wrong decision despite the remaining pulse's results. This occurs especially in the case of antipodal modulation such as BPSK.

On the other hand, the interfering pulse may enhance the correlation result positively (positive interferer pulse (PIP)) , especially when highly AWGN corrupted the desired pulse, then the interfering pulse(s) enhancing the energy of the intended pulse of interest results in true decision.

In order to solve this problem, first threshold detection devices are placed before the MRC. This would decide whether a chip pulse (Z_{chip}) is detected true or wrong. The decisions in these cases take the values {-1 , +1}. N_s summing unit, sums these decisions. The result again enforces a final decision unit which decides the estimated symbol Z_{bit} . The proposed RAKE receiver is shown in figure (4).

6. System Assumptions

The following assumptions were made in the system analysis and simulation:

- The nodes are randomly distributed within a rectangular area of (10 x 10) m.
- All nodes are homogeneous.
- Concurrent transmissions, all nodes transmit with P_{max}, and no power control.
- No ISI, IFI and IPI.
- There is only one transmitter - receiver pair.
- Only one very wide channel is available for all communication.
- Simple model for path loss.

7. Simulation Results

To simulate the system, we implemented it in various types of network topologies. The data that are used in the simulation is given table (1):

1. Topology/1: The interferers and the sender form a circle around the intended receiver which is in the center. The distance between senders and the receiver is (4 – 10). We studied two different scenarios that correspond to two different numbers of interferers; 3 and 8. For each scenario, we ran 500 channel realizations with 500 different THS to get the optimal performance. See figure (5).

As shown in figure (6), the BD-RAKE is completely fail in detecting symbols, whereas CD-RAKE is outperformed BD-RAKE even in the case of $N_u = 8$.

2. Topology/2: The interferers form a circle around the intended receiver which is in the center but the sender is near the receiver. Also, We studied six different scenarios that correspond to six different numbers of interferers; 2, 3, 4, ……. 10. For each scenario, we ran 500 channel realizations with 500 different THS to get the optimal performance. See figure (5).

The distance of the user of interest is set to 5 m. The distances of interferers are set 10 m. As shown in figure (8), the CD-RAKE is outperformed BD-RAKE for all values of N_u except for $N_u = 1$. The reason for that is the absence of any interfering users, so, the BD-RAKE is perform better than CD-RAKE in collecting pulses energy.

3. Topology/3: The interferers form a circle around the intended receiver which is in the center but the sender is far the receiver. Also, We studied six different scenarios that correspond to six different numbers of interferers; 2, 3, 4, ……. 10. For each scenario, we ran 500 channel realizations with 500 different THS to get the optimal performance. See figure (9).

The distance of the user of interest is set to 10 m. The distances of interferers are set 5 m. As shown in figure (10), the CD-RAKE is also outperformed BD-RAKE for all values of N_u except for $N_u = 1$. The reason for that is the absence of any interfering users, so, the BD-RAKE is perform better than CD-RAKE in collecting pulses energy. The difference between this result and the previous result is that a worse BER values appear due to the larger distance of the user of interest.

4. Topology/4: Random scenario in which the sender and the interferers are randomly distributed around the intended receiver and the sender is near from the intended receiver but at least one of the interferers is very near to the intended receiver. See figure (11).

In this random topology, the distance of the user of interest is set to 5 m. The distances of interferers are randomly distributed between (4 – 10) m. As shown in figure (12), the CD-RAKE is outperformed BD-RAKE for all values of N_u except for $N_u = 1$. The reason for that is the absence of any interfering users, so, the BD-RAKE is perform better than CD-RAKE in collecting pulses energy.

5. Topology/5: Random scenario in which the sender and the interferers are randomly distributed around the intended receiver and the sender is far from the intended receiver but at least one of the interferers is very near to the intended receiver. See figure (13).

In the last random topology, the distance of the user of interest is set to 10 m. The distances of interferers are randomly distributed between (4 – 10) m. As shown in figure (14), the CD-RAKE is also outperformed BD-RAKE for all values of N_u except for $N_u = 1$. The reason for that is the absence of any interfering users, so, the BD-RAKE is perform better than CD-RAKE in collecting pulses energy. The difference between this result and the result of topology/4 is that a worse BER values appear due to the larger distance of the user of interest.

8. Conclusion

In this paper, an MUI mitigation scheme is proposed based on a modified version of RAKE receiver. This proposed receiver is based on chip decision level after the MRC not on bit decision scheme as the one in the conventional RAKE receiver. The performance of the proposed receiver is tested on various types of WPAN topologies. The obtained results indicate that the proposed receiver is outperforming the conventional RAKE. A BER improvement is obtained which states that an MUI is mitigated in a certain level.

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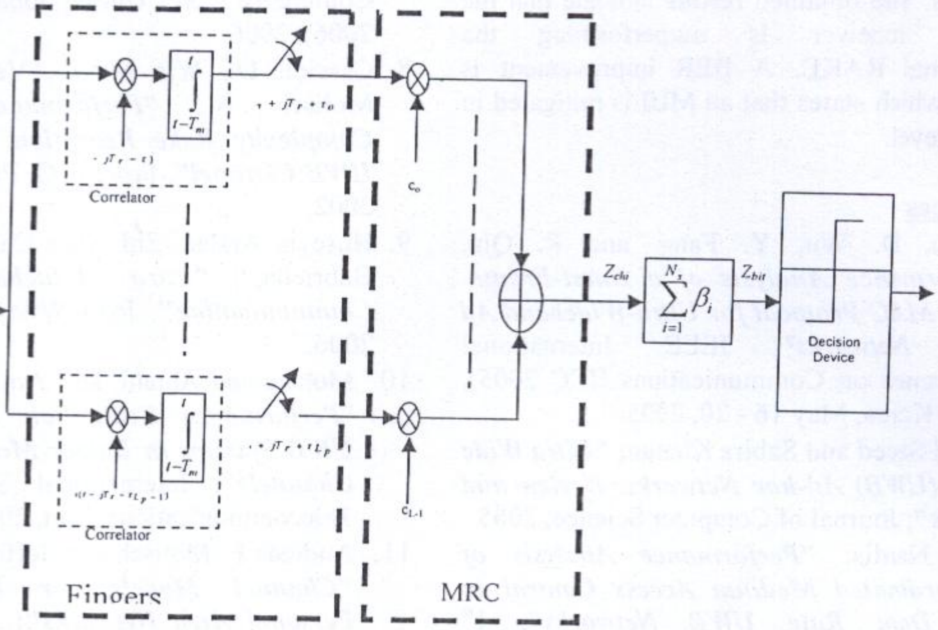

Figure (1): The Conventional Rake receiver

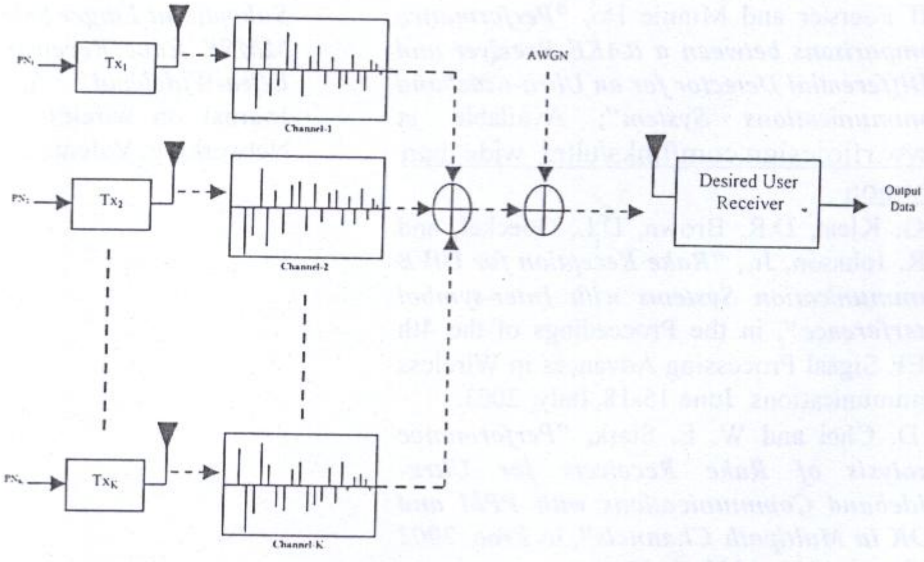

Figure (2): The MUI model

Table (1): Simulation Parameters

Parameter	*Value*
Sampling frequency	50 GHz
Pulse duration	1ns
Shaping factor for the pulse	0.25 ns
Number of bits generated by the source	1000
Time resolution	1 ns
Number of pulses per bit	5
Number of PRAKE finger	5
Signal-to-noise ratio E_f/N_o	30 dB
Interferers powers	-20 dB
Transmitted power (P_{tx})	variable
User 1 distance	variable
Interferers distances	variable
WPAN dimension	4 – 10 m
WPAN topologies	5 Various topologies

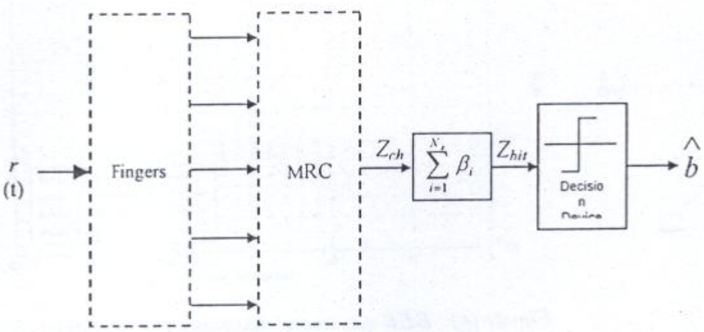

Figure (3): The simplified diagram of Rake Receiver

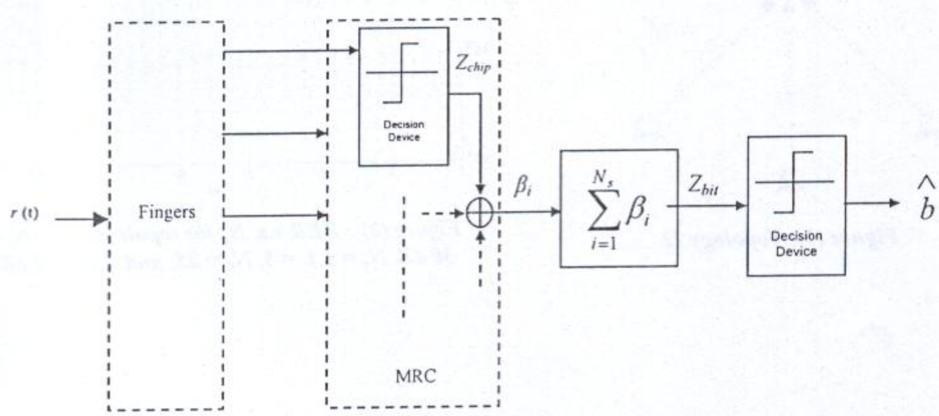

Figure (4): The proposed Rake receiver

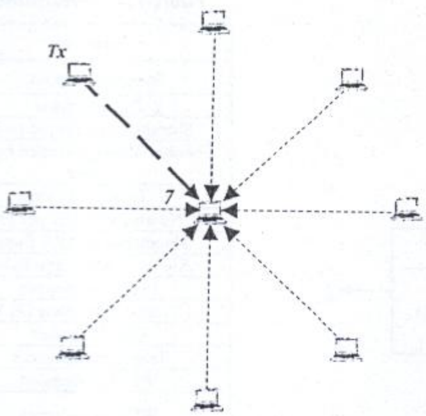

Figure (5): Topology /1

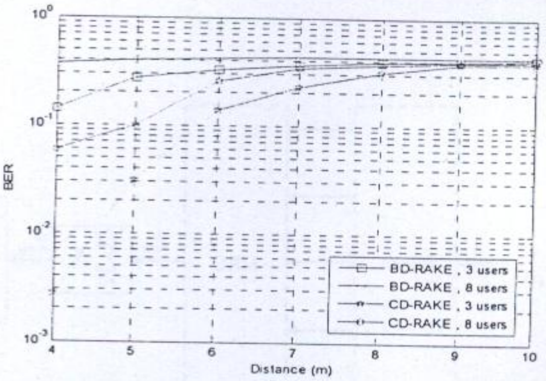

Figure (6) : BER v.s. users' distances for topology/1, E_b/N_o = 30 dB, $N_c = 5$, $L = 5$, $N_h = 25$, and $P_{tv} = -25$ dB.

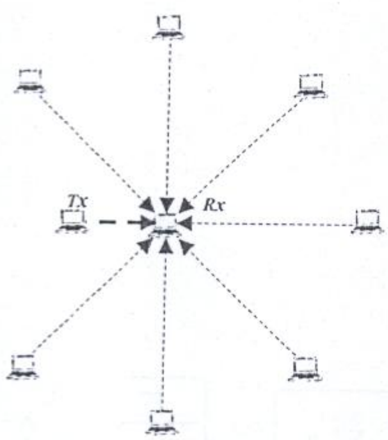

Figure (7): Topology /2

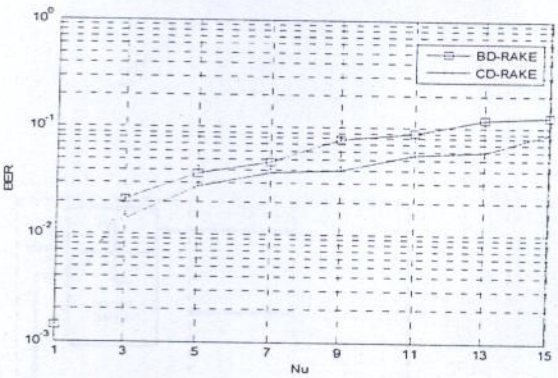

Figure (8) : BER v.s. N_u for topology/2, E_b/N_o = 30 dB, $N_s = 5$, $L = 5$, $N_h = 25$, and $P_{tx} = -20$ dB.

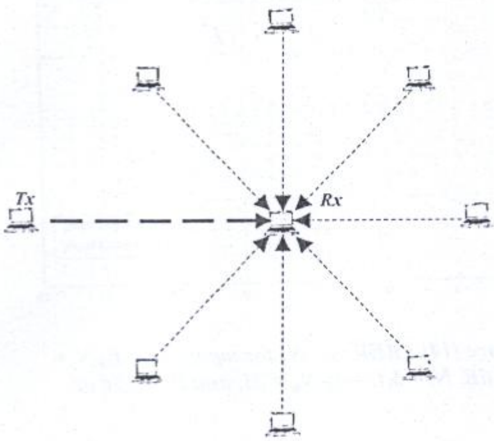

Figure (9): Topology /3

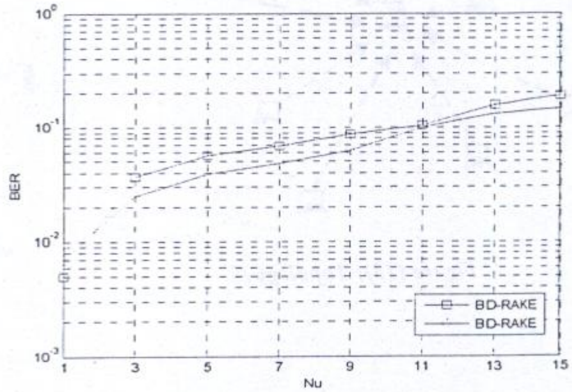

Figure (10) : BER v.s. N_u for topology/3, E_b/N_o = 30 dB, N_s = 5, L = 5, N_h = 25, and P_{tx} = -20 dB.

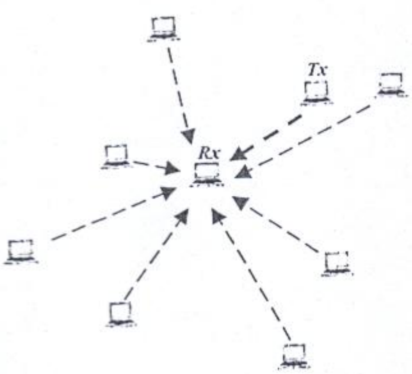

Figure (11): Topology /4

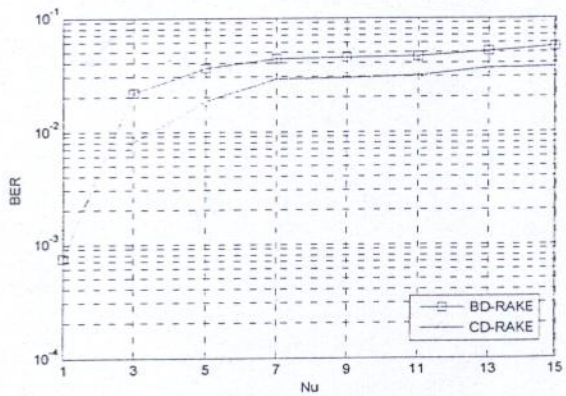

Figure (12) : BER v.s. N_u for topology/4, E_b/N_o = 30 dB, N_s = 5, L = 5, N_h = 25, and P_{tx} = -20 dB.

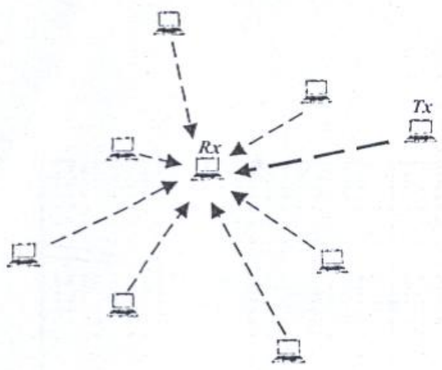

Figure (13): Topology /5

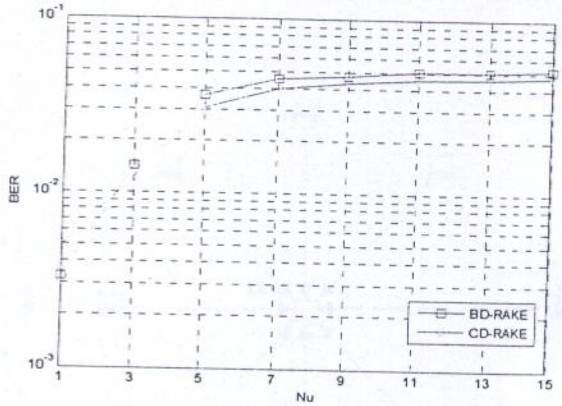

Figure (14) : BER v.s. N_u for topology/5, E_b/N_o = 30 dB, N_s = 5, L = 5, N_h = 25, and P_{tx} = -20 dB.