Performance and Capacity Analysis of UWB Networks over 60GHz WPAN Channel

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***Abstract*— In this paper we evaluate the system performance and capacity of single carrier ultra-wideband (UWB) networks over 60GHz wireless personal area network (WPAN) channel. Symbol error rate is derived for both single user and multiple access scenario with a general system capacity and performance evaluation approach based on moment generation function. System outage probability and network throughput performance are also studied. Based on the current IEEE 802.15.3 WPAN standard work, different transmission scenarios have been explored and the performances with RAKE reception has been obtained. The channel model is also based on the recent work of IEEE 802.15 WPAN group. Numerical results are given to illustrate the system performance.**

***Index Terms*— Ultra-Wideband, WPAN, 60GHz channel, Fading channel, RAKE receiver**

I. INTRODUCTION

Ultra-Wideband (UWB) transmission is one of the most important technologies for the coming wireless networks. Wireless access systems transmit on 60GHz band could potentially provide up to 3Gbit/s data throughput. To satisfy the technical requirements of wireless personal area networks (WPAN) such as high throughput and low power consumption, it is necessary to design a low complexity modulation and detection algorithm for 60GHz WPAN, and evaluate its performance over practical channel models. Currently, international standard bodies such as IEEE 802.15.3c working group is working on the standard for 60GHz WPAN transmission system. To evaluate the possible performance and capacity of the future products based on these standards and technologies, it is important to explore the UWB system performance and capacity over the 60GHz WPAN channel with a general approach, which is the topic we will focus on in this paper.

WPAN networks focus on applications with a relatively short transmit distance (10-30 meters) and high data rate (480Mbit/s-3Gbits/s). Applications could be the new version of Bluetooth, high speed home or office wireless networking, and entertainment programs such as wireless access of high definition television (HDTV). Since the application scenarios cover a large scope, it is important to evaluate the system performance and capacity over some typical application scenarios, which can be represented by different kinds of channel modeling. However, the traditional mathematical channel models, such as Rayleigh fading or Nakagami fading, are not accurate enough to simulate the practical UWB or 60GHz radio channels. An evaluation of the designed UWB system over practical channel modeling is a must for the designing and evaluation of WLAN systems.

For wireless communication systems, multipath is always a troublesome radio channel effect. In addition to the direct path signal, many reflected signals will arrive at the receiver with different delays and attenuations, resulting in fading and inter-symbol interference (ISI). On another hand, since high radio frequency channels, such as UWB and 60GHz channels are multipath-rich channels, it is even more important for the WPAN receiver resolve and combine the multipaths so the energy carried by the multipath will not be treated solely as noise. Hence, for impulse radio or single carrier receiver, employing a RAKE receiver is an efficient means of overcoming these effects [1] [2].

Since WPANs are high speed networks which will not tolerate long system delay, and also the low power consumption rule requires the minimal possible data processing at both the transmitter and receiver sides, we use a very simple combining algorithm first introduced in [3], low complexity group decision general selection combining (GD-GSC) in this paper as our RAKE combining scheme. Based on the previous work in [3] [4], in this paper we employ a general approach to obtain the moment generation function (MGF) of the received signal, and study the average combined output signal to noise ratio (SNR) and symbol error probability (SEP). Outage probability and network throughput of the ultra-wideband transmission scheme over 60GHz WPAN channel are also studied. The results obtained in this paper can be easily generalized to other wireless systems, channel scenarios and RAKE combining schemes.

The remainder of this paper is organized as follows. Section II presents the system background, including the channel model, UWB modulation scheme, and RAKE combining scheme. In Section III, a general approach based on the MGF of the signals are used to evaluate the system performance for both single user and multiple access scenarios. In Section IV, outage probability and network throughput performance results are given. In

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Section V, numerical results are given based on different channel scenarios. Finally, Section V presents a summary of the paper.

II. System Model

A. Channel and Usage Model

The goal of this paper is to evaluate the performance and capacity from a practical perspective. The the 60GHz channel cannot be easily modeled by any existing mathematical models such as Rayleigh or Nakagami fading. In this paper we use the 60GHz WPAN fading channel models provided by the IEEE 802.15 group. The IEEE 802.15.3c channel model includes several application scenarios based on possible practical WPAN applications [5], in which we will use the indoor office and/or residential scenario, both the line of sight (LOS) and none line of sight (NLOS) cases. The MAC model used in this paper is a simplified IEEE 802.3b [5]. Specifically, in this paper the channel fading is assumed to be constant during each channel coherence time, but will become independent after one coherence time. This assumption stands for high data rate wireless communication system such as spread spectrum systems or UWB.

B. Ultra-Wideband Transmission

An UWB transmitter will have to transmit a huge number of modulated pulses over a very wide spectrum of frequency in each second for information transmitting. In that case, a simple modulation algorithm will be a must choice for less processing delay, high bandwidth efficiency and long batter life of the mobile device [6] [7] [8]. Currently in IEEE 802.3c there are two kinds of 60GHz transmission system propsoals, single carrier and orthogonal frequency-division multiplexing (OFDM) or multiple band (MB) UWB system. In this paper we employ single band impulse radio ultra-wideband (UWB) transmission, which is a simpler solution and is easy to implement. Even though the IEEE 60GHz WPAN standard group has not yet made the final decision on the modulation schemes for single carrier modulation scheme, a complex modulation scheme is not likely to be adopted for it will not be practical. Considering the current single carrier proposal in IEEE 803.15.3c [5], we employ a simple modulation scheme: single carrier quadrature phase-shift keying (QPSK) modulation in this paper to evaluate the performance of UWB systems, the direct sequence (DS) scheme introduced in [9] [10] is used for spreading.

C. RAKE Reception

A RAKE receiver shown in Fig. 1 is essentially a set of individual correlators (fingers of RAKE receiver) used to synchronize with different multi-path signals. Because of the WPAN receiver hardware complexity constraint, it is usually not practical and also not necessary to implement the same number of fingers as the number of resolvable paths, especially for ultra-wideband channels which might have hundreds of multiple paths. However, since the multi-path signal will carry a large part of the transmitted energy, a certain number of multi-path signals have to be resolved and demodulated. Since the multi-path signals will come in clusters, and also the WPAN devices might be used in mobile environments, it is important to select the strong paths to combine. The algorithm we use in this paper will select and combine the paths which will satisfy the SNR requirements while at the same time being simple and flexible.

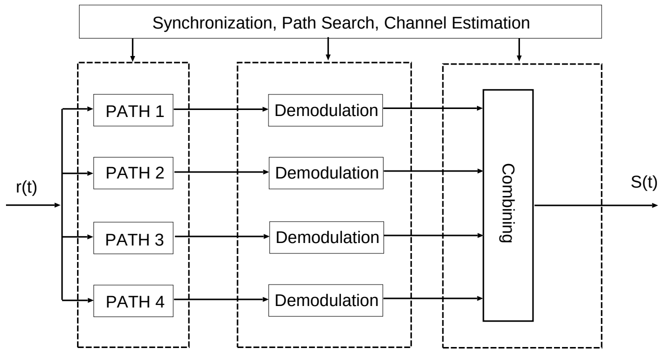

Figure 1. The structure of a RAKE receiver with $L_c = 4$ fingers.

In this paper we assume that there are L_c RAKE fingers available. We also assume that the receiver will only use L_c selected paths from all L resolvable paths. To select L_c diversity paths out of the L resolvable diversity paths, we divide the diversity paths into L_c groups with the multipaths from the same cluster assigned to different groups [3], and then select the best of each group by comparing their instantaneous signal to noise ratio (SNR) [3]. In this case, the receiver needs much less compare operations to get the selected diversity paths. If better performance is needed, or the number of the fingers is increased, we can either divide the resolvable paths into more groups, or we can select more than one path in each group by employing another selection algorithm such as generalized selection combining (GSC) within the group [3].

Considering the WPAN channel, in which we might have hundreds of multi-paths which are much more than we can resolve and combine, we will employ multilevel selection (by repeating the algorithm introduced in the previous paragraph) GD-GSC algorithms [3] to improve the performance and reduce computing complexity. Another possible approach is to combine the selected paths or stop after the SNR of the signal has reached a certain threshold before the complete comparing task has been fulfilled. By performing less compare operation and combining only those paths with better SNR, energy usage will be reduced and also the mobile terminal battery life will be increased. We can also avoid the increased noise and interferences caused by combining paths with very poor SNR.

III. Symbol Error Probability Performance

A. MGF of the Combined SNR

To analyze the system performance and outage probability of a wireless communication system with RAKE reception over fading channels, we need to obtain the statistical characterization of the SNR of the combined output signal. In this section, we give the general description of the MGF of the SNR of the output signal. Here we define G as the number of multi-paths in each GD-GSC group, assuming G is an integer, we have

$$G = \frac{L}{L_c}. \tag{1}$$

Based on the mode of operation of RAKE receiver, the combined output signal SNR, S, after maximal ration combining (MRC) (depend on the system design, other combine schemes such as Equal-Gain Combining (EGC) etc. could also be used) is [1]

$$S = \sum_{k=1}^{L_c} \gamma_k, \tag{2}$$

where γ_k is the instantaneous signal SNR of the kth selected multi-path (the path with largest SNR in the kth group) combined by the RAKE receiver. Note that $k = 1, \cdots, L_c$ are mutually exclusive events.

Here we define $M_S(t)$ as the MGF of S corresponding to the event that L_c paths out of a maximum of L paths are combined. We have

$$M_S(t) = \prod_{k=1}^{L_c} M_k(t), \tag{3}$$

where $M_k(t)$ is the MGF of the SNR of the kth acceptable path.

The PDF of the strongest signal selected from G signals is [11]

$$p_G(x) = G[P(x)]^{G-1} p(x) \tag{4}$$

where $p(x)$ and $P(x)$ are probability density function (PDF) and cumulative distribution function (CDF) of the fading signal, respectively.

Performing Laplace transform on the PDF of the combined signal, we can obtain the MGF of the combined signal as following

$$M_G(t) = G \int_0^{\infty} e^{-tx} p(x) P^{G-1}(x) dx. \tag{5}$$

if we assume that the signals are independent and identically distributed (i.i.d. case), the MGF of the combined signal will be:

$$M_S(t) = M_G^{L_c}(t). \tag{6}$$

B. Average Combined SNR

Based on the definition of signal MGF, the average combined SNR of a RAKE receiver can be calculated as the first moment from the MGF as

$$\bar{\gamma_c} = \frac{dM_S(t)}{dt}|_{t=0}. \tag{7}$$

As a numerical example, the average combined SNR for a RAKE receiver over Rayleigh fading channels when $G = 1$, $Lc = 1$ (no multi-path reception/diversity) and $G = 2$, $L_c = 2$ are

$$\bar{\gamma}_{1\times 1} = \bar{\gamma}, \tag{8}$$

and

$$\bar{\gamma}_{2\times 2} = 3\bar{\gamma}, \tag{9}$$

respectively.

C. Symbol Error Probability

With the expression for the MGF obtained in the previous part, we can evaluate the symbol error probability (SEP) of a radio receiver with RAKE reception over fading channel for different types of modulation [12].

For example, the average symbol error probability with M-ary PSK modulation can be obtained as

$$P_{MPSK}(E) = \frac{1}{\pi} \int_0^{\frac{(M-1)\pi}{M}} M_S(f(\phi)) d\phi, \tag{10}$$

where $f(\phi)$ is given by

$$f(\phi) = -\frac{\sin^2\left(\frac{\pi}{M}\right)}{\sin^2(\phi)}. \tag{11}$$

As a special numerical example, the average symbol error probability for a radio receiver with RAKE reception over Rayleigh fading channels with BPSK modulation when $G = 2$ and $L_c = 2$ is

$$P_S(E) = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \frac{4}{(1 - \frac{\bar{\gamma}}{\sin^2(\phi)})^2 (2 - \frac{\bar{\gamma}}{\sin^2(\phi)})^2} d\phi. \tag{12}$$

D. Multiple Access Performance

If we know the correlation between different users we can easily calculate the signal to interference plus noise Ratio (SINR). Assuming there are K active users in the system, and the correlation between user i and user j is $\sigma_{\{i,j\}}$, for a system with 3 active users, we have

$$\begin{aligned} SINR_1 &= \frac{S_1}{\sigma_{\{1,2\}} S_2 + \sigma_{\{1,3\}} S_3 + N_0} \\ &= \frac{\bar{\gamma_1}}{1 + \sigma_{\{1,2\}} \bar{\gamma_2} + \sigma_{\{1,3\}} \bar{\gamma_3}}, \end{aligned} \tag{13}$$

where S_i is the power of the signal of user i, N_0 is the AWGN power. With $SINR$ we can easily obtain the system error rate performance by calculation or computer simulation.

IV. Outage Bound and Throughput Performance

A. Outage Probability

Outage probability P_{out} is a very important and practical performance measure for wireless communication systems. For a system with RAKE reception, it is defined as the probability that the signal-to-noise ratio of the combined signal is below a threshold γ_{out}. To determine this outage probability, we first derive the PDF $p_S(x)$ for the SNR of the combined signal S by taking an inverse Laplace transform of its MGF $M_S(t)$

$$p_S(x) = L^{-1}\left[M_S(t)\right], \tag{14}$$

and then we integrate the PDF $p_S(x)$ to get the CDF of the SNR

$$P_S(x) = Pr[S \leq x] = \int_0^x p_S(u)du. \tag{15}$$

Let $x = \gamma_{out}$ in (15), we can get the outage probability for a certain threshold γ_{out}.

B. IEEE 802.15.3 MAC Model

In IEEE standard families, the IEEE 802.15.3b defined the MAC protocol for WPAN, which includes UWB and 60GHz systems. In the defined MAC, the channel scheduling is a combined scheme of CSMA/CA and TDMA. The TDMA component makes sure that only one transmission within a WPAN piconet is active at any given time. The 802.15.3b MAC data structure is built on superframes, which are usually composed of three parts: the beacon, the contention access period (CAP), and the channel time allocation period (CTAP). The CAP part, which is optional, uses CSMA/CA to implement multiple access, while the CTAP is the TDMA part where the transmission time is divided into time slots and allocated to different devices. In this paper, we use a simplified model of the 802.15 MAC with both CTAP and CAP to evaluate the MAC data throughput under different channel conditions. In the simulation we use Reed-Solomon (RS) as the error control coding scheme, and we do not implement equalization in our simulation.

C. 60GHz WPAN Throughput Performance

We use the IEEE 803.15.3c single carrier PHY and the IEEE 802.15.3b MAC to evaluate the network throughput for the 60GHz WPAN. The channelization is $2080MHz$ for each channel with four channels expand over $9GHz$ bandwidth, and we use Single Carrier (SC) OPSK modulation with Reed Solomon (RS) coding [5]. In the simulation we do not implement equalization and the length of cyclic prefix is 0. The payload length is 2048 byte. In this paper we assume the synchronization is perfect and we do not consider network delay. In the network simulation we assume there is no errors in the control signaling and the number of user is low so the access delay can be ignored.

V. Numerical Results

In this section, we evaluate the symbol error probability of an impulse radio UWB receiver with RAKE reception employing GD-GSC over multi-path WPAN fading channels. The details about the channel modeling could be found in [5]. We observe the channel models for office buildings with both LOS and NLOS channel scenarios, we also give the computing complexity compare of GD-GSC with other multi-path combining schemes.

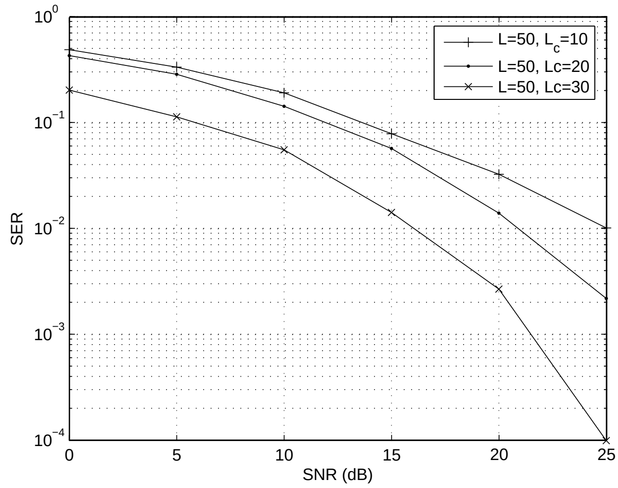

Figure 2. Symbol Error Rate with LOS Scenario.

Fig. 2 presents the symbol error rate of of the UWB transmission over multi-path fading with office building scenarios for LOS case. The parameters are $L = 50$ and $L_c = 10, 20, 30$. Fig. 3 presents the symbol error rate of of the UWB transmission over multi-path fading with office building scenarios for LOS case. The parameters are $L = 50$ and $L_c = 10, 20, 30$. Comparing the LOS again the NLOS performance, we can see that when the combined multi-path number is small $L_c = 10$, the LOS case performance has much better performance, however, when the combined multi-path number is large enough $L_c = 30$, there will not be any significant difference between the LOS and NLOS scenarios.

Fig. 4 presents the algorithm complexity estimation of several practical RAKE combining schemes for reader's reference. Fig. 5 shows the network simulation results on system throughput with the assumption of low number of active user (≤ 6). We can see the throughput increase with the increase of channel data rate and we can also see with a low number of users, the capacity for each user is not limited by ISI.

VI. Summary

In this paper we use a general approach for evaluating the system performance and capacity analysis of ultra-wideband (UWB) transmission over a practical 60GHz wireless personal area network (WPAN) channel.

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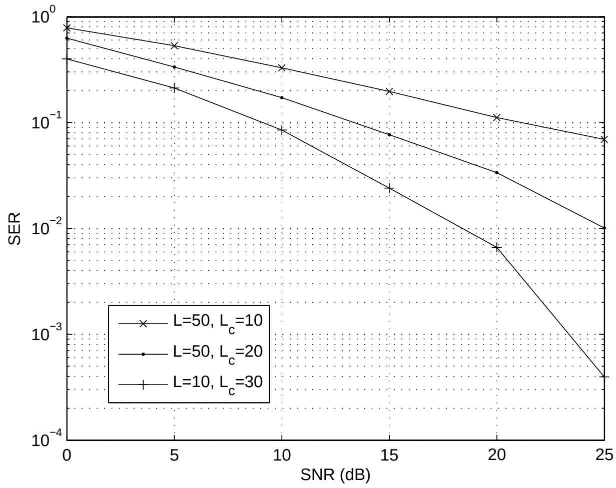

Figure 3. Symbol Error Rate with NLOS Scenario.

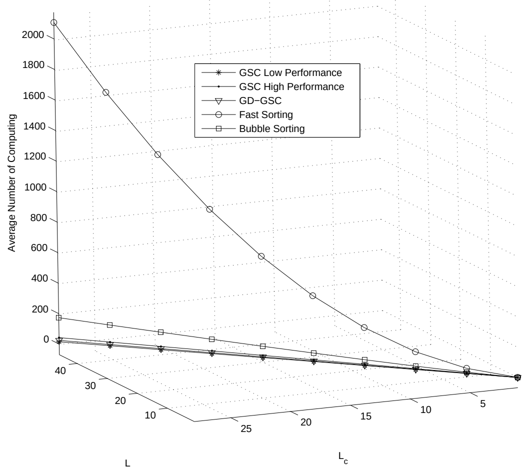

Figure 4. RAKE Combining Complexity.

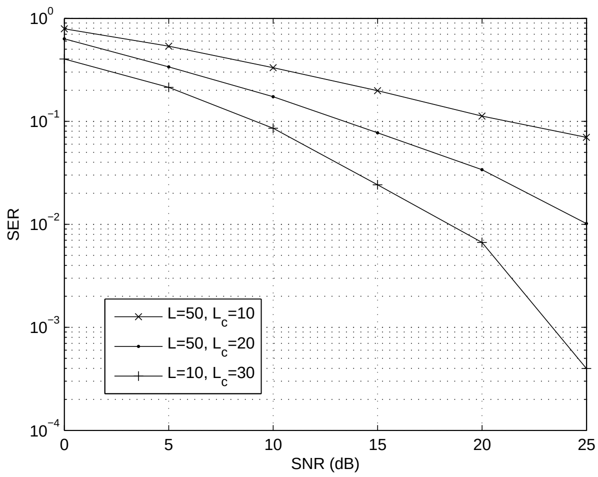

Figure 5. Symbol Error Rate with NLOS Scenario.

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