Non-Gaussian Noisy Channel Effect on Multi-user IDMA-UWB Communication System

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***Abstract*- In this paper, multi-user communication scenario for Ultra Wide Band (UWB) system has been considered. For effective use of spectrum in multi-user communication, a new variant of CDMA scheme known as Interleave-Division Multiple-Access (IDMA) scheme has been proposed. IDMA inherits many advantages from CDMA such as diversity against fading, mitigation of the interference among users efficiently. This paper investigates the effectiveness of IDMA scheme for multi-user detection in UWB indoor environment subjected to non-Gaussian noise. Two different non-Gaussian noise models, Laplacian and Gaussian Mixture Model (GMM), have been studied which are more realistic models for UWB systems. Simulations are performed using UWB channel model proposed by IEEE 802.15.3a working group. The performance of the proposed IDMA-UWB scheme under non-Gaussian noise models have been evaluated and compared with its performance under AWGN model. The results show that the IDMA-UWB scheme outperforms well under the studied noise models in the proposed IDMA-UWB system, also achieves near single user performance in situations with large numbers of users while maintaining low cost and low complexity Chip By Chip Iterative Receiver (CBC-IR).**

Keywords*-IDMA-UWB; Chip By Chip Iterative Receiver (CBC-IR); Laplacian noise; Gaussian Mixture Model (GMM); etc.

I. INTRODUCTION

Due to inherent advantages of high speed transmission, immunity towards multipath, low power and low cost, Ultra Wide Band (UWB) has become the key technology for the next generation of wireless communication systems [1]. Recently, Impulse Radio (IR) based Time Hopping (TH) Ultra Wide Band (UWB) technologies for short-range high-rate multiuser wireless communications have attracted significant interests [2].

For a multiuser UWB system, the capability of providing high data rate with relatively low complexity and low power consumption is a challenging task. Many authors are aware of the power of CDMA (Code Division Multiple Access Scheme) to detect multiple users in UWB system [3, 4]. In a conventional CDMA scheme, interleavers are placed before the spreaders and they are effective only when used in conjunction with channel coding. Recent papers have discussed the roles of interleavers in multiple access systems [5-8]. A very interesting technique using chip-level interleavers known as interleave-division multiple-access (IDMA) which considered a new variant of CDMA scheme for multi user detection in UWB indoor environment has been introduced in [9]. In this scheme, each user's chip sequence is interleaved by a user-specific distinct random interleaver which provides a mean to reduce the multiple access interference (MAI) from other users, and the receiver applies a low-complexity iterative multiuser detection (MUD) principle at the chip level. The IDMA scheme employs the interleavers as the only means of user separation in order to ensure privacy related to signals or data of users.

Although the multiple access techniques for UWB channel have been extensively investigated, the nature of the noise phenomenon and its impact on UWB systems has thus far been ignored. The traditional approach of considering just the thermal noise, modeled as a stationary and memory less Gaussian random process, does not agree with relevant field measurements. As in [10], indoor environments are subject to impulsive (non-Gaussian) noise because of electronic equipment widely deployed in every office as well as home environment. A set of measurements have been performed to determine the sources of impulsive noise. It has been found that photocopiers, printers, elevators and microwave ovens are sources of significant noise with amplitudes of 50dB above thermal noise. So the Gaussian noise model is not appropriate due to infrequent and high level noise spikes. Hence, the noise distribution for UWB systems should be discussed as non-Gaussian. Commonly used impulsive (non-Gaussian) noise models are Laplacian, and GMM [11].

The remainder of this paper is organized as follows. Section II describes the IDMA-UWB system, its transmitter and receiver structure, and chip by chip iterative detection. Section III presents the UWB channel models. Section IV presents two different non-Gaussian noise models (Laplacian, GMM). Section V proposes the simulation results. Section VI concludes the paper.

II. IDMA-UWB SYSTEM

In communication systems, interleaving is referred to be technique commonly used to overcome correlated channel noise such as burst error or fading [12]. In interleaving mechanism, the input data rearranges itself such that consecutive data bits are split among different blocks and is swapped in a known pattern amongst them. At the receiver end, the interleaved data is arranged back into the original sequence with the help of de-interleaver. As a result of interleaving, correlated noise introduced in the transmission channel appears to be statistically independent at the receiver and thus allows better error correction.

The user-specific interleavers play vital role in the efficiency of IDMA system. It not only provides decorrelation between adjacent bit sequences, but also facilitates a means for decorrelating various users [13]. The correlation between interleavers should measure how strongly signals from other users affect the decoding process of a specific user. The decorrelation among the user- specific interleavers provides a mean to reduce the multiple access interference (MAI) from other users thus helping in the convergence of detection process.

A. IDMA-UWB Transmitter and Receiver Structures

Consider a spread spectrum communication system with $\mathbf{K}$ users. The transmitter and receiver structures are shown in Fig. 1. At the transmitter side, the $\mathbf{n^{th}}$ bit $\mathbf{d_n^{(k)}} \in \{+1,-1\}, \mathbf{n} = 1,2,\ldots,\mathbf{N},$ in the input data stream $\mathbf{d^{(k)}}$ from user- $\mathbf{k}$ is spread using a length- $\mathbf{S}$ spreading sequence $\mathbf{s^{(K)}}$ in the form $\mathbf{d_n^{(k)}} \rightarrow \mathbf{d_n^{(k)}} \mathbf{s^{(k)}}$. We write the chip sequence obtained after spreading as $\left\{ \mathbf{c_j^{(k)}}, \mathbf{j} = 1,2,\ldots,\mathbf{J} \right\}$, where $\mathbf{J} = \mathbf{N} \times \mathbf{S}$ is the frame length. A chip-level interleaver $\pi^{(\mathbf{k})}$ is then applied to produce the transmitted signals $\left\{ \mathbf{x_j^{(k)}}, \mathbf{j} = 1,2,\ldots,\mathbf{J} \right\}$. Removing the interleaver $\pi^{(\mathbf{k})}$ in Fig. 1 leads to a conventional CDMA scheme, in which the different signature sequences $\{\mathbf{s^{(k)}}, \mathbf{k} = 1,2,\ldots,\mathbf{K}\}$ are employed for user separation. Alternatively, we can use a common spreading sequence for all users, i.e., setting $\mathbf{s}(1) = \mathbf{s}(2) = \ldots = \mathbf{s}(\mathbf{k}) = \ldots = \mathbf{s}(\mathbf{K}) = \mathbf{s}$, and employ user-specific interleavers $\{\pi^{(\mathbf{k})}, \mathbf{k} = 1,2,\ldots,\mathbf{K}\}$ for user separation. This results in the so-called IDMA scheme, which inherits many advantages from CDMA such as diversity against fading and mitigation of other-cell user interference [14].

B. Chip By Chip Iterative Receiver

For simplicity, we only consider synchronous BPSK systems over a time-invariant single-path channel. The received signal at time instant j can be written as

$$r_j = \sum_{k=1}^{K} h^{(k)} x_j^{(k)} + N_j, \qquad j = 1,2,\ldots\ldots,J \tag{1}$$

Where $x_j^{(k)} \in \{+1,-1\}$ denotes the transmitted chip from user-k at time instant j, $h^{(k)}$ the channel coefficient for user-k, and $N_j = n_j + In_j$. n_j is zero-mean additive white Gaussian noise (AWGN) with variance $\sigma^2 = \frac{N0}{2}$, and In_j is zero-mean Impulsive noise with different variances . We will assume perfect knowledge of the channel coefficients at the receiver. To simplify discussion, we also assume that the channel coefficients $\{h^{(k)}\}$ are real, but the principle can be extended to situations with complex channel coefficients [15].

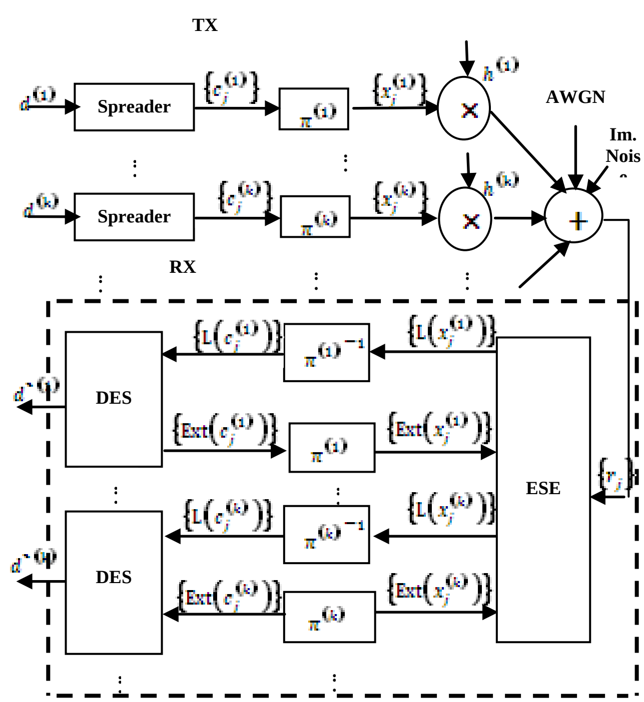

Figure 1. IDMA UWB Transmitter and Receiver Structures

The iterative chip-by-chip receiver in Fig. 1 consists of an elementary signal estimator (ESE) and a bank of K single-user a posteriori probability decoders for the dispreading operation (DES) working in a turbo-type manner, as shown in Fig. 1. The ESE performs coarse chip-by chip estimation. We concentrate on $x_j^{(k)}$ and re-write (1) as

$$r_j = \boldsymbol{h}^{(k)} x_j^{(k)} + \xi_j^{(k)} \tag{2}$$

Where $\xi_j^{(k)} = r_j - \boldsymbol{h}^{(k)} x_j^{(k)}$ represents a distortion (including interference plus noise) with respect to user- K . We treat each $x_j^{(k)}$ as a random variable with mean $E\left(x_j^{(k)}\right)$ and variance $Var\left(x_j^{(k)}\right)$ (initialized to 0 and 1 respectively). Then from (1), we have

$$E(r_j) = \sum_{k=1}^{K} \boldsymbol{h}^{(k)} E\left(x_j^{(k)}\right) \tag{3a}$$

$$Var(r_j) = \sum_{k=1}^{K} |\boldsymbol{h}^{(k)}|^2 \, Var\left(x_j^{(k)}\right) + \sigma^2 \tag{3b}$$

Using the central limit theorem, $\xi_j^{(k)}$ in (2) can be approximated by a Gaussian random variable with

$$E(\xi_j^{(k)}) = E(r_j) - E(\boldsymbol{h}^{(k)} x_j^{(k)}) \tag{4a}$$

$$Var(\xi_j^{(k)}) = Var(r_j) - |\boldsymbol{h}^{(k)}|^2 Var(x_j^{(k)}) \tag{4b}$$

The ESE outputs are the logarithm likelihood ratios (LLRs) about $\left\{x_j^{(k)}\right\}$ computed based on (3) (using (4)) as

$$L\left(x_j^{(k)}\right) \equiv \log\left(\frac{Pr\left(x_j^{(k)} = +1 \middle| r_j\right)}{Pr\left(x_j^{(k)} = -1 \middle| r_j\right)}\right)$$

$$= \log\left(\frac{\exp\left(-\frac{\left(r_j - E\left(\xi_j^{(k)}\right) - \boldsymbol{h}^{(k)}\right)^2}{2Var\left(\xi_j^{(k)}\right)}\right)}{\exp\left(-\frac{\left(r_j - E\left(\xi_j^{(k)}\right) + \boldsymbol{h}^{(k)}\right)^2}{2Var\left(\xi_j^{(k)}\right)}\right)}\right)$$

$$= \left(\frac{2\boldsymbol{h}^{(k)}\left(r_j - E\left(\xi_j^{(k)}\right)\right)}{Var\left(\xi_j^{(k)}\right)}\right) \quad \forall k, j \tag{5}$$

For user- k , the corresponding ESE outputs $\left\{L\left(x_j^{(k)}\right), j = 1,2,\ldots,J\right\}$ are de-interleaved to form $\left\{L\left(c_j^{(k)}\right), j = 1,2,\ldots,J\right\}$ and delivered to the DES for user- k . The DES performs a soft-in/soft-out chip-by-chip de-spreading operation as detailed below [15].

For simplicity, we focus on the chips related to d_1^k , the first bit of user-k . The treatment for other chips is similar. Recall that d_1^k is spread into the chip sequence $d_1^k s^k = \left\{c_j^k, j = 1,2,\ldots,S\right\}$, where $s^{(k)} = \left\{s_j^{(k)}\right\}$ is the binary signature sequence (over {+1, −1}) for user-k . We assume that $\left\{L\left(c_j^{(k)}\right)\right\}$ are uncorrelated (which is approximately true due to interleaving [21]). Let the interleaving for user- k be expressed as $\pi^{(k)}(j) = j'$, i.e., $c_j^{(k)} = x_j'^{((k))}$ (see Fig. 1). Then based on (5), the a posteriori LLR for d_1^k can be computed using $\left\{L\left(c_j^{(k)}\right)\right\}$ as

$$L(d_1^{(k)}) \equiv \log\left(\frac{Pr(d_1^{(k)} = +1|r)}{Pr(d_1^{(k)} = -1|r)}\right)$$

$$= \log\left(\frac{\prod_{j=1}^{s} Pr\left(c_j^{(k)} = s_j^{(k)} \middle| r_j'\right)}{\prod_{j=1}^{s} Pr\left(c_j^{(k)} = -s_j^{(k)} \middle| r_j'\right)}\right)$$

$$= \sum_{j=1}^{s} \log\left(\frac{Pr\left(c_j^{(k)} = s_j^{(k)} \middle| r_j'\right)}{Pr\left(c_j^{(k)} = -s_j^{(k)} \middle| r_j'\right)}\right)$$

$$= \sum_{j=1}^{s} s_i^{(k)} \, L\left(c_j^{(k)}\right) \tag{6}$$

The extrinsic LLR for a chip $c_j^{(k)}$ within $d_1^{(k)} s^{(k)}$ is defined by:

$$Ext\left(c_j^{(k)}\right) = \log\left(\frac{Pr\left(c_j^{(k)} = +1 \middle| r\right)}{Pr\left(c_j^{(k)} = -1 \middle| r\right)}\right) - L\left(c_j^{(k)}\right)$$

We notice that $c_j^{(k)} = +1$ if $s_j^{(k)} = d_1^{(k)}$ and $c_j^{(k)} = -1$ otherwise. Therefore we have [18]

$$Ext\left(c_j^{(k)}\right) = s_j^{(k)} \, L(d_1^{(k)}) - L\left(c_j^{(k)}\right) \tag{7}$$

The extrinsic LLRs $\left\{Ext\left(c_j^{(k)}\right)\right\}$ form the outputs of the DES and are fed back to the ESE after interleaving (see Fig. 1). In the next iteration, $\left\{Ext\left(x_j^{(k)}\right)\right\}$ are used to update $\left\{E\left(x_j^{(k)}\right)\right\}$ and $\left\{Var\left(x_j^{(m)}\right)\right\}$ as [14]

$$E\left(x_j^{(k)}\right) = \frac{exp\left(Ext\left(x_j^{(k)}\right) - 1\right)}{exp\left(Ext\left(x_j^{(k)}\right) + 1\right)} = tan\boldsymbol{h}\left(\frac{Ext\left(x_j^{(k)}\right)}{2}\right) \quad (8a)$$

$$Var\left(x_j^{(k)}\right) = 1 - E\left(x_j^{(k)}\right)^2 \quad (8b)$$

This iterative process is repeated a preset number of times. In the final iteration the DES produces hard decisions $\hat{d}^{(k)}$ on information bits $d^{(k)}$ based on (6).
The principle can be generalized to situations with multipath fading [16].

For complexity, notice that (3) involves summations over all of the users, but the results (and so the cost) are shared by all of the users. The related cost is only two additions and two multiplications per chip per user per iteration. Several more simple operations per chip per user per iteration are required in (4)-(8).

Overall, the normalized complexity per information bit per user per iteration increases linearly with the spreading length but is independent of the number of users K .

III. UWB CHANNEL MODEL

The accurate design of channel model is a very important issue for ultra wideband WPAN (Wireless Personal Area Network) communication system. Such a model creates the facility for calculation of large and small-scale characteristics. The standardized channel model for indoor UWB environments proposed by the channel modeling subcommittee of the IEEE 802.15.3a Task Group is a modified version of the Saleh–Valenzuela (S–V) model [17], where the Rayleigh distribution of the channel coefficient amplitude in the S–V channel model is replaced by the log-normal distribution.

The measurements of S–V channel shows that the multipath components arrive from transmitter to receiver in the form of clusters. Indoor channel environments are classified as CM1, CM2, CM3, and CM4 [17]. CM1 describes a line-of-sight (LOS) scenario with T-R separation less than 4m. CM2 describes the same range for T-R separation but it is in NLOS (non line of sight). CM3 describes a NLOS medium for separation between transmitter and receiver of range 4-10m. CM4 describes an environment of more than 10m with strong delay dispersion.

According to [17], the channel impulse response is defined as

$$\boldsymbol{h}(t) = X \sum_{l=0}^{L-1} \sum_{k=0}^{K-1} [\alpha_k \ \delta(t - T_l] \ |-\tau_{k,l}\ ) \quad (13)$$

Where, {$\alpha_{k,l}$ } a are the multipath gain coefficient of k th ray related to l th cluster, {T_l } is the delay or arrival time of first path of the l th cluster, { $\tau_{k,l}$ } is the delay of the k th multipath component within the l th cluster relative to arrival time { T_l },{ X } denotes the lognormal shadowing term. Equation 14 shows the cluster arrival time and the ray arrival distribution time

$$p(T_l|T_{l-1}) = \Lambda \exp[-\Lambda(T_l - T_{l-1})] \quad , l > 0$$

$$p\left(\tau_{k,l}\middle|\tau_{(k-1),l}\right) = \lambda \exp\left[-\lambda\left(\tau_{k,l} - \tau_{(k-1),l}\right)\right] \ , k > 0, l > 0 \quad (14)$$

Where, $\tau_{0,l} = 0$. If the channel coefficients are considered as real, then $p_{k,l}$ takes real random value +1 or −1. The channel coefficients are defined as:

$$\alpha_{k,l} = p_{k,l}\xi_l\beta_{k,l} \quad (15)$$

If complex base band channel is considered, the channel co-efficient phase is uniformly distributed over the interval [0, 2π], is the amplitude of the UWB signal. It is based on lognormal distribution and is given as

$$20log_{10}\ \xi_l\beta_{k,l} \propto Normal\left(\mu_{k,l}, \sigma_1^2 + \sigma_2^2\right) \quad (16)$$

$$\left|\xi_l\beta_{k,l}\right| = 10^{\frac{\mu_1+\mu_2}{20}}$$

where σ_1 is the standard deviation of cluster lognormal fading term, σ_2 is the standard deviation of ray lognormal fading term n_1 and n_2 are independent and correspond to the fading on each cluster and ray. The behavior of the averaged power delay profile is

$$E\left[\left|\xi_l\beta_{k,l}\right|^2\right] = \boldsymbol{\Omega_0}\ e^{-T_l/\square}\ e^{\tau_{k,l}/\gamma} \quad (17)$$

Where, $\boldsymbol{\Omega_0}$ is the mean energy of the first path of the first cluster. The $\mu_{k,l}$ is given by

$$\mu_{k,l} = \frac{10\ln(\Omega_0)\ 10^{T_l/\Gamma}\ \ 10^{\tau_{k,l}/\gamma}}{\ln(10)} \quad (18)$$

Where, $\xi_{k,l}$ correspondence the fading associated with the l^{th} cluster, and $\beta_{k,l}$ corresponds to the fading associated with the k^{th} ray of the l^{th} cluster. This reflects the exponential decay of each ray as well as decay of the total cluster power with respect to delay. X is the shadowing term and it is characterized by following

$$20log_{10}(X) \propto Normal\ (0, \sigma^2) \quad (19)$$

is the standard deviation of lognormal shadowing term.

IV. UWB Non-Gaussian noise models

Recently, there has been considerable interest in the detection of signals in non-Gaussian noise. One form of frequently encountered non-Gaussian noise is that known as impulsive noise. Impulsive noise is typically characterized as noise whose distribution has an associated "heavy tail" behavior. That is, the probability density function (pdf) approaches zero more slowly than a Gaussian pdf. Commonly used non-Gaussian (Impulsive) noise models are Laplacian , and GMM which will be introduced below .

A. Laplacian Noise Model

Laplacian noise model has been used in ultra-wideband receiver design and in modeling impulsive noise. Notice that Laplace noise has the heavy tail behavior associated with impulsive noise. The pdf of Laplacian noise is given by

$$f_n(x) = \frac{1}{\sqrt{2\sigma^2}}\ exp\left(-\sqrt{\frac{2}{\sigma^2}}|x|\right) \ ,-\infty < x < \infty \quad (20)$$

Where, σ^2 is the noise variance [18].

B. Gaussian Mixture Model

The Gaussian mixture model has been found to provide a good fit to empirical noise data. The mixture Gaussian model is the more realistic model for UWB systems whose main application will be in indoor environments. As shown in [10], the indoor noise is typically impulsive in nature due to the interference emanating from other man-made devices.
The pdf of Gaussian Mixture Model is

$$f_{n_{j,l}}(x) = (1-\epsilon)g(x) + \epsilon h(x) \quad (21)$$

Where, $g(.)$ is the nominal Gaussian pdf with variance N_0 and $h(.)$ is the heavier tailed Gaussian with variance kN_0, where $\mathbf{k}$ is the impulsive part's relative variance with respect to nominal Gaussian noise variance $(\mathbf{k} \geq 1)$. The parameter $\epsilon \in [0,1]$ controls the contribution of impulsive component to the whole pdf.

The main assumption about the channel noise is that the samples are independent and identically distributed so that an impulsive noise source can be studied by modeling its first-order probability density function [11]. The pdf model is constructed as the mixture of two Gaussian random processes with zero mean and different variances, where one is a multiple of the other for the representation of the heavy tail of the distribution producing large amplitudes.

Therefore, the noise samples $n_{j,l}$, have the variance $(1-\epsilon)N_0 + \epsilon kN_0$. When, $k = 1,$ the usual AWGN case is obtained. The ϵ -mixture model is an approximation to Middleton's class-A noise model pdf, which consists of an infinite expansion of Gaussian density functions with different variances and identical means. In [19], it is shown that the first two terms of the expansion sufficiently describe the class-A noise pdf. In addition, the ϵ -mixture model is much more tractable than the class-A noise pdf.

V. IDMA-UWB Simulation Results

In this section, BER performance of IDMA scheme is shown. These simulation results are shown using the parameters: user data 128 bits, spreading length 32 bit length, number of iteration 3. These simulations are performed using channel sounding of 2-8 GHz band collected in residential setting, for bit rates of 100Mbps and spreading length 32, for all users present in the system. The discrete time channel model proposed by the IEEE 802.15.3a working group [17] is utilized, which is based on the modified S–V model. We focus on the line-of-sight (LOS) channel model 1 (CM1) which corresponds to a short-range (0–4 m) indoor wireless environment.

The simulation results are averaged over a large number of channel realizations. Not only AWGN is considered here but also non-Gaussian noise models like Laplacian noise, and Gaussian mixture noise. Figures (2-8) show the BER performance of IDMA-UWB scheme for varying users in LOS scenario under different conditions.

The system performance have been studied using 3 different noise models, AWGN, Laplacian noise, GMM respectively, and then the results have been compared together as shown in figures from (2-5).

Figure (2) illustrates that the proposed IDMA-UWB scheme is considered near single user performance under AWGN model until 16 users and degrades by 1.5 dB at 32 users.
Figures (3,4) show that the system performance under laplacian, and GMM is degraded by 2dB ,and 2.5 dB respectively until 16-users compared with AWGN case and the degradation increases largely at 32 users.

Figure (5) shows the performance comparison between the previous noise models mentioned above and demonstrates that the system outperforms well with multi-users under AWGN model and the performance have a little degradation compared with AWGN model in case of laplacian, GMM models respectively for the same system parameters.

Figure (6) shows the performance of the proposed scheme under different numbers of iterations. It is observed that the performance is improved by increasing the iteration numbers to 3 while, it gives a fixed response after 3 iterations.

Finally, figures (7,8) show the effect of control parameter ϵ and impulsive parameter K on the system performance. It is clear that the BER performance is degraded by increasing the value of those parameters.

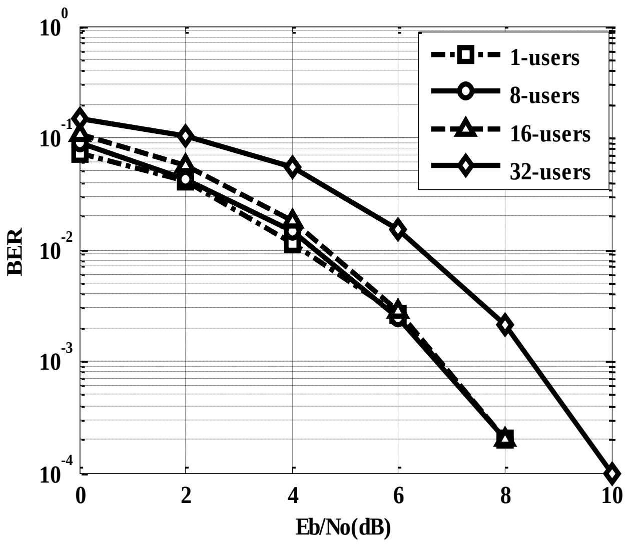

Figure 2. BER of IDMA-UWB under AWGN in CM1 for different users (N=128, Sp=32, It=3)

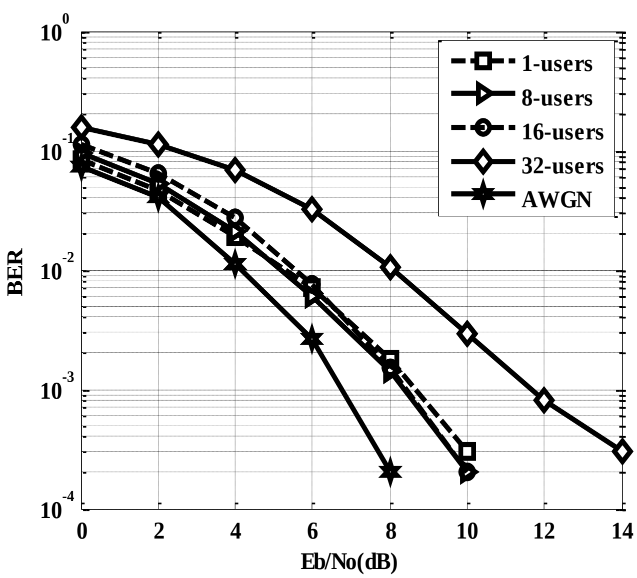

Figure 3. BER of IDMA-UWB for various users under Laplacian noise in CM1(N=128, Sp=32, It=3)

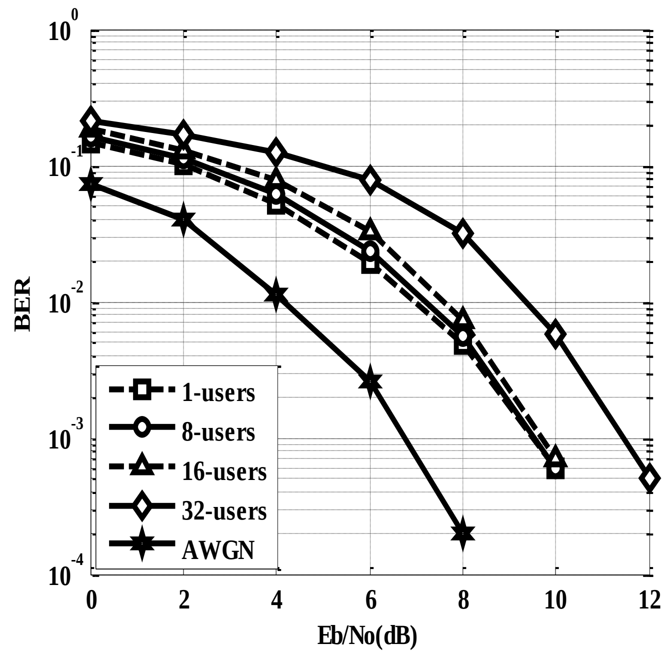

Figure 4. BER of IDMA-UWB under GMM for various users in CM1 (N=128, Sp=32, It=3, $\epsilon = 0.1, K = 10$)

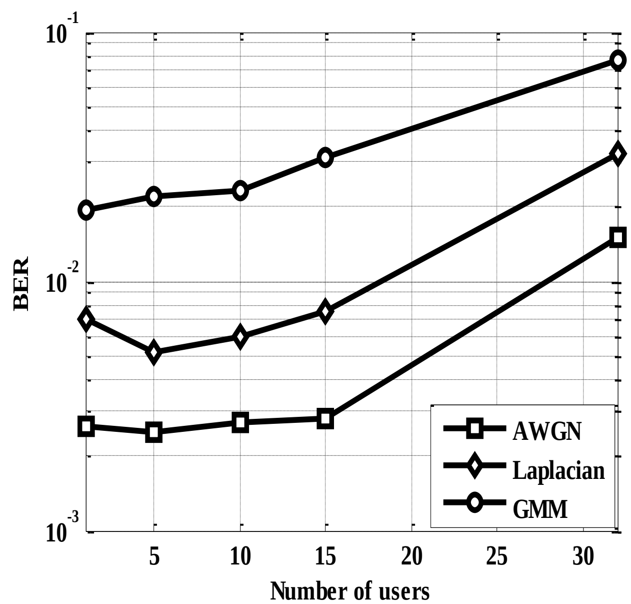

Figure 5. BER of IDMA-UWB for 3 models of noise in CM1 ($Eb/_{No} =$ 6dB, N=128, Sp=32, It=3, $\epsilon = 0.1,$ $K = 10$)

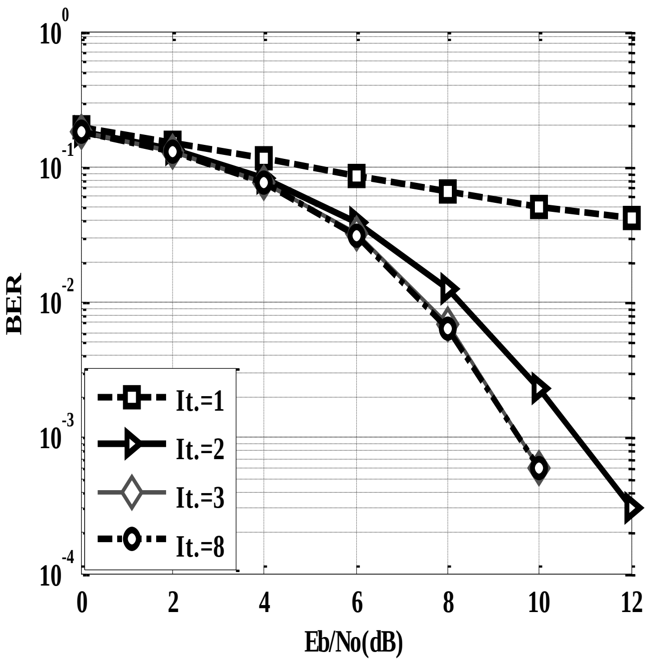

Figure 6. BER of IDMA-UWB in GMM with different iterations (16-users, N=128, Sp=32, $\epsilon = 0.1$, $K = 10$)

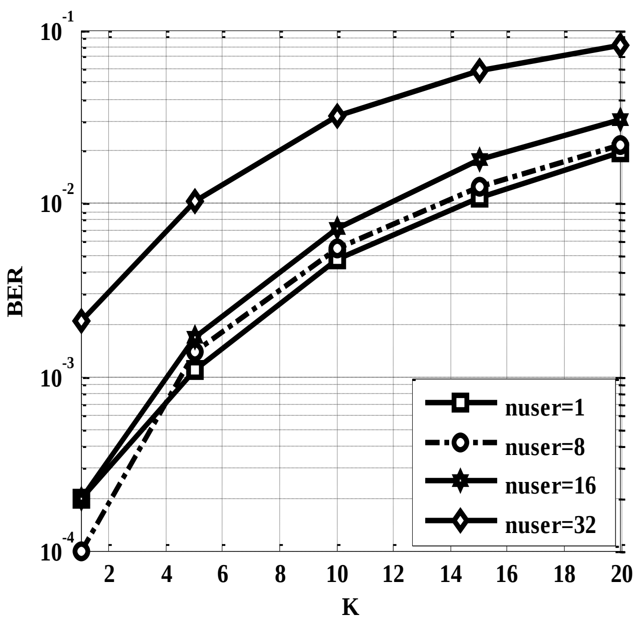

Figure 7. Effect of impulsive parameter K on the BER of IDMA-UWB ($Eb/_{No} =$ 8dB and $\epsilon = 0.1$)

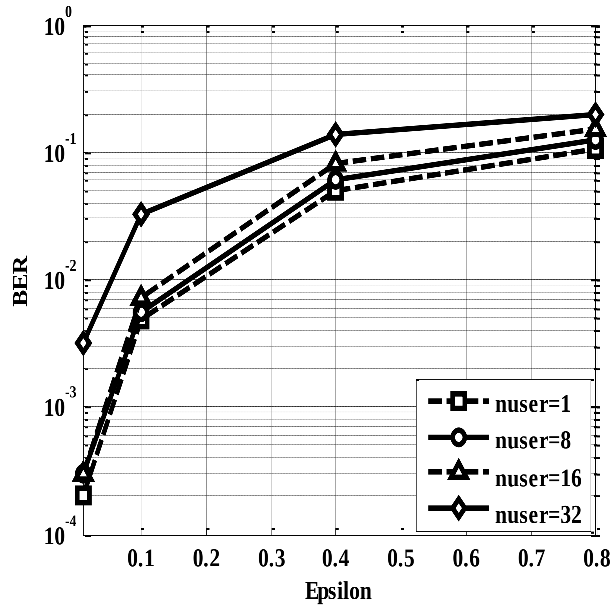

Figure 8. Effect of control parameter ϵ on BER of IDMA-UWB ($Eb/_{No} =$ 8dB, $K = 10$)

VI. Conclusion

This paper addresses the performance of Interleave Design Multiple Access scheme (IDMA), for UWB signals over non-Gaussian noisy channels. The effectiveness of new multiple access scheme IDMA is issued to detect multiple users in UWB indoor environment.

Because of the Gaussian noise model is not appropriate for UWB indoor environments due to infrequent and high level noise spikes, non-Gaussian noise models include Laplacian noise, and mixture noise have been proposed which is more realistic models for UWB systems.

Simulations are performed using UWB channel model considered proposed by IEEE 802.15.3a working group. A performance comparison shows that, from 1 to 16 users, the BER performance under laplacian, and GMM degrades by about 2dB ,and 2.5 dB respectively compared with AWGN case and this degradation increases largely at 32-users.

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