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On the Performance of Rake Receivers for the UWB System in a Realistic Exponential-Lognormal Model

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Abstract

We analyze the performance of Rake receiver for Ultra Wideband system using Exponential-Lognormal multi-path statistical propagation channel model, which is based on extensive measurements in diversified Residential & Commercial environments. We evaluate the link performance of an UWB system using sub-optimum Rake receivers, which are based on either partial combining (PRake) or selective combining (SRake). The receiver SNR distribution statistics generated using standard cluster model and realistic exponential-lognormal model are compared for their relative performance. We investigate average bit error performance of commonly used Binary data modulation. Through semi-analytical evaluations of the Average Bit Error Probability (ABEP) and distribution of output SNR, we show that the simple PRake receiver is almost as good as the SRake for optimum number of fingers.

Keywords: Ultra Wide-Band channel, Exponential-Lognormal model, Rake Receiver, Diversity Combining, Average bit error probability.

Introduction

ULTRA wideband (UWB) wireless transmission is ideally suited for short range, high speed wireless Personal Area Networks (WPANs). The potential strength of the UWB radio technique lies in its use of extremely wide transmission bandwidth and limited power spectral density ,which results in desirable capabilities including high Multipath resolvability, accurate position location and ranging, immunity to fading, high multiple access capability, covert communications, and possible easier material penetration.[1-2]. This higher resolvability and lower per path energy also results in the requirement to rake in a large number of paths to boost the received SNR [3-5]. UWB-SS techniques for multiple access wireless communications were first proposed in the 1990s to meet the demands of future wireless networks [6-7]. In 2002, commercial interest in UWB techniques increased significantly after the US Federal Communications Commission (FCC) allowed unlicensed UWB communications. At the same time, the Task Group (TG 3a) was established within the IEEE 802.15 to define a standard for high data rate communication systems based on UWB technology. The physical layer modulation techniques that have been proposed for IEEE 802.15.3a are based on Impulse Radio [7-8], Direct-sequence (DS) SS techniques [9-10] and Multiband OFDM combined with time-frequency interleaving [11]. Multiband OFDM does not involve the Rake receiver architecture that is the centre point of this paper, and will not be discussed here.

In order to build systems that realize UWB potential, it is first required to understand UWB propagation and the channel properties arising from its propagation. The choice of Rake receiver structure and the relative performance of different modulations also depend on the propagation channel. There has been a great deal of activity to characterize the UWB propagation channel [12-14]. To evaluate the UWB system performance in realistic UWB indoor channel environment Exponential-Lognormal model [14] based on extensive measurements has been selected in this paper. Earlier work on performance of UWB systems using Rake receiver has been done with Stochastic Tap Delay Line model and Cluster model in [15] and [16], respectively. The Exponential-Lognormal model gives best fit to measured data statistics than the Cluster model as reported in [23], because its numeric parameters are derived from the extensive measurement database. As such the Exponential-Lognormal model will provide realistic results for the system performance analysis. In this paper, we compare the performance of Partial Rake (PRake), Selective Rake (SRake) and Optimum Rake (ARake) receivers that employ maximal-ratio combining. The cumulative distribution functions (CDF) of the output SNR have been computed for both SRake and PRake structures. The comparative investigation has been done on the results obtained from both cluster model and exponential-lognormal model generated profiles. Average bit error performance an analysis has also been done for commonly used binary data modulations.

The rest of the paper is organized as follows: in Section II, the generated profiles of realistic Exponential-Lognormal model are compared with Cluster model for both line of sight (LOS) and non line of sight (NLOS) Channel scenarios. We then analyze the output SNR CDF of sub-optimal SRake and PRake receiver structures. The discrete approximation of CDF generated using both the models are compared. The optimum numbers of Rake fingers are identified in different channel scenarios. We then describe the semi-analytical procedure and obtain the ABEP of Binary Modulated signals using the SRake, PRake and ARake. We also investigate the performance variation as the Channel scenario, number of Rake taps and data modulation changes. The ABEP results are discussed in section IV, followed by Section V, wherein we conclude the paper.

Channel Model

It is imperative to design the receiver using realistic channel model since performance analysis of the receiver is based on statistics of the channel. We briefly describe here the model used to statistically characterize the Power Delay Profile (PDP) of the UWB channel. The PDP in general form is given by

$$p(\tau) = \sum_i p_i \delta(\tau - \tau_i); \sum_i p_i = 1 \tag{1}$$

Thus, PDP is described by the power-delay set $\{p_i, \tau_i\}$. In a given bandwidth, W, sampling theory explains that the PDP is characterized via a set of samples spaced by $1/W$ (i.e., $\tau_i = i/W$, $i = 0, 1, 2.$), and the result is suitable for any bandwidth of W or smaller. There are two versions of the multipath delay profile generally used i.e. one corresponds to PDP at a fixed point receiver and other is locally (spatially) averaged PDP. The latter type also called as small scale averaged PDP (SSA-PDP) in [5, 12] has been used in this work. In the Exponential- Lognormal model given in [14] the SSA-PDP for NLOS paths varies with delay as a decaying exponential times a noise-like variation that behaves as a correlated lognormal random process.

$$p_i = k.e^{\left(-\frac{\tilde{\alpha}.\tau_i}{\overline{\tau}_{rms}}\right)}.s(\tau_i) \quad i \geq 0 \tag{2}$$

For LOS T-R paths, there is a separate term at the minimum delay followed by an exponential-lognormal term i.e.

$$p_i = \begin{cases} 10^{A/10} & i = 0 \\ k.e^{\left(-\frac{\tilde{\alpha}.\tau_i}{\overline{\tau}_{rms}}\right)}.s(\tau_i) & i > 0 \end{cases} \tag{3}$$

where $\tilde{\alpha}$ is a decay constant and A is the direct (LOS) ray amplitude both varies with Tx-Rx distance d; $s(\tau_i)$ is a noise-like variation with delay behaves like a correlated lognormal process; $\overline{\tau}_{rms}$ is a global average of the RMS delay spread; and k is a normalizing factor such that the sum of all $p_i = 1$.

The dB value of parameters $\tilde{\alpha}$ can be characterized as

$$\alpha = \alpha_0 - \gamma.log_{10}(d) + \varepsilon \tag{4}$$

where α_0 is a numeric constant; ε is a zero-mean Gaussian random variable with standard deviation σ_α and $\gamma = \overline{\gamma} - 2$, $\overline{\gamma}$ is a gamma distributed random variable given in [14] using fitting parameters *u* and *v*. The LOS amplitude in dB is

$$A = A_0 - 10.\gamma_A.log_{10}(d) + \varepsilon_A \tag{5}$$

where A_0 and γ_A are constants, ε_A is a zero-mean Gaussian random variable with standard deviation σ_A .

The dB value of lognormal variation parameter $s(\tau_i)$ is

$$S_i = \sigma_s \left[\sigma_0 . e^{\left(\frac{-\beta_i}{W.\bar{\tau}_{rms}}\right)} \right] . x_i \tag{6}$$

where σ_s , σ_0 and β_i are constants, x_i is a zero-mean Gaussian sequence with correlation function

$$\rho_x(x) = a.e^{\left(\frac{-|n|.b}{W.\bar{\tau}_{rms}}\right)} \quad |n| > 0 \tag{7}$$

where *a* and *b* are constants and distance *d* is in meters. From the above description, we see that the exponential-lognormal model can be specified by 10 numeric parameters for NLOS and using 13 numeric parameters for LOS. These parameters are quantified in [14] for LOS and NLOS channel scenarios. The parameters corresponding to Residential LOS and NLOS SSA-PDP (*W*=6 GHz) has been used for generating the Ensemble SSA-PDP. The channel realizations of SSA-PDP for LOS CM1 and NLOS CM2 using cluster model [5] and exponential-lognormal model described above are shown in Fig. 1 to 4. The SSA-PDP ensemble using the two models is generated for relative performance analysis. The cluster model generates large number of visible clusters, but the measured channel response display insignificant clustering in contrast as reported in [23]. The exponential-lognormal model shows exponential decay with no clustering. Fig. 5 depicts the mean across the generated ensemble SSA-PDP as a function of delay. The correlated lognormal process is responsible for small variations across different values of delay in both channel categories, using exponential-lognormal model. Abrupt changes in SSA-PDP as a function of delay is due to random occurrence of clusters across different realizations using cluster model. Also, comparative analysis shows that the cluster model for LOS CM1 does not take account of the strong LOS component that frequently appears at zero delay.

Another drawback of the Cluster model is that we cannot easily obtain accurate estimates of parameters and there is no established method available for extracting model parameters from the channel measurements[23].Therefore it is desirable that the channel model lends itself to easy estimation of relevant parameters. Although, large number of numeric parameters are required in Exponential-Lognormal model compared to the cluster model, but they are easy to derive from measured data. An important virtue of this model is that it accounts for both the frequent presence of a strong LOS component and the fluctuations of the SSA-PDP as a function of delay. Also, the generated statistical attributes using this model provides good fit with measured data statistics [23]. Keeping in view, the aforesaid considerations Exponential-Lognormal model has been used for realistic UWB link performance analysis.

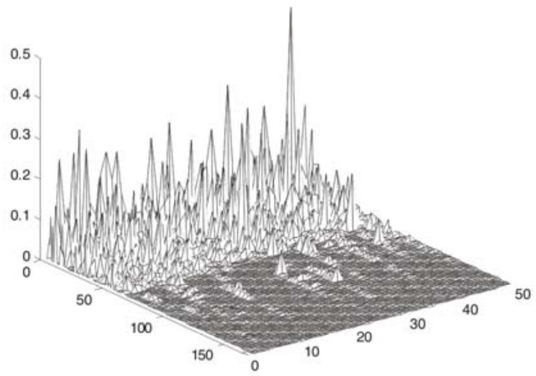

Figure 1: Ensemble SSA-PDP generated using Cluster model in LOS CM1.

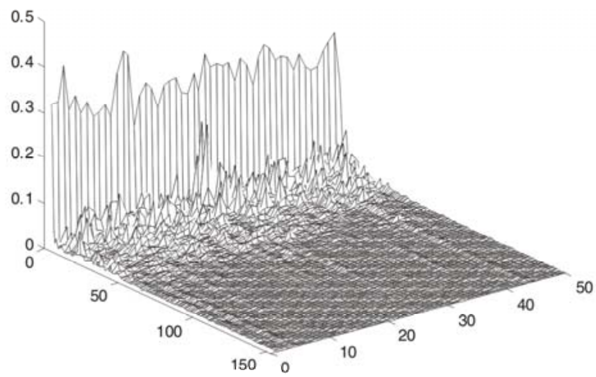

Figure 2: Ensemble SSA-PDP generated using Exponential-Lognormal model in LOS CM1 ($\gamma < 5.0$).

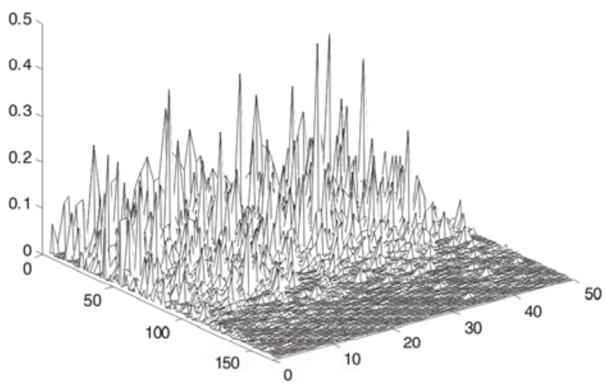

Figure 3: Ensemble SSA-PDP generated using Cluster model in CM2.

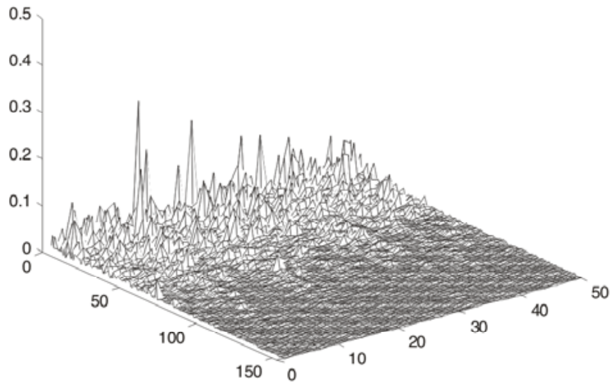

Figure 4: Ensemble PDP generated using Exponential-Lognormal model in NLOS CM2 (γ < 5.6).

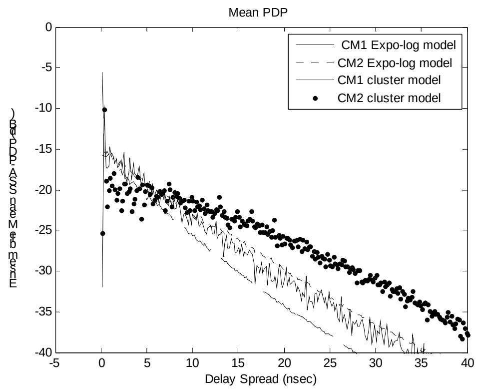

Figure 5: Mean SSA-PDP over ensemble of channel realizations in LOS & NLOS conditions.

Mrc-Rake Receivers

The SRAKE and PRAKE receiver performance are evaluated using a channel model based on indoor channel measurements in the 2-8 GHz centered at 5GHz, as described in Section II. The cluster model [5] has also been used for providing the comparative performance results in both LOS and NLOS channel conditions. The basic version of the Rake receiver consists of multiple correlators where each of the correlators can detect/extract the signal from one of the multipath components provided by the channel. The outputs of the correlators are appropriately weighted and combined to take the benefits of multipath diversity [18]. For analysis simplicity, we assume that all multipath components are resolvable and multipath gain coefficients are estimated perfectly with ideal autocorrelation properties of the spreading sequence. In the following, we will assume that these conditions are fulfilled. The term ARake has been largely used in the literature to indicate the receiver with unlimited resources (taps or correlators) and instant adaptability, so that it can combine all of the resolved multipath components (MPCs). However, the number of MPCs that can be utilized in a typical Rake combiner is limited by power consumption, design complexity and channel estimation [19]. Thus, we consider the ARake receiver only as a reference that provides an upper limit of achievable performance. We consider two realistic sub-optimum reduced-complexity Rake receivers, SRake and PRake structures. The SRake selects the L_b best paths (a subset of the L_r available resolved multipath components) and PRake selects the first L_p paths (which are not necessarily the best) then combines the selected subset using Maximal Ratio Combining (MRC). The combiner produces a decision variable at its output which is then processed by a data detector. In order to find the variation of the output SNR, which could possibly degrade the receiver performance, the distribution of output SNR is investigated. The discrete realizations for the CDF of output SNR are shown in Fig. 6 to 9, using both cluster and exponential-lognormal models. The SSA-PDPs has been generated for normalized channel with unit energy. The average SNR is set to 60 dB and path loss model of [22] is used. The transmitter-receiver distance is set to 1m. In the following sub-sections we discuss the results of instantaneous output SNR CDF for sub-optimum Rake receivers in different channel categories. The comparative performance has also been presented in terms of CDF obtained using both cluster and exponential-lognormal models.

Line of Sight channel conditions

Fig. 6 & 7 shows the CDF of the output SNR for SRake and PRake receivers in the LOS CM1 channel Condition. In the case of cluster model, two fingers SRake compared to PRake gives 3.31 dB more average SNR. This SNR difference increases to about 5 dB at 10% outage probability. The 2 finger SRake structure performs marginally (about 1 dB) better than PRake as shown in Fig.7, using exponential-lognormal model. This is difference in performance is due to the absence of strong LOS component at zero delay in the SSA-PDP generated by the cluster model. The strong LOS component frequently appears in the first bin of the measured database ensemble as reported in [14, 23], is also generated by Exponential-lognormal model at zero delay as shown in Fig. 2. The slope of the CDF in case of SRake and PRake is quite different in cluster model, which is attributed to relative difference between amplitudes in the initial delay bins of the generated SSA-PDP as shown in Fig 1. Both models show similar difference in diversity gain performance of about 1 dB with 16 finger structures. Thus, the simple PRake structure performance is very close to SRake in the realistic LOS CM1 channel condition even for lesser number of Rake taps, unlike the one shown by the cluster model.

Non Line of Sight channel conditions

Fig. 8 & 9 shows the CDF of the output SNR for SRake and PRake receivers in the NLOS CM2 channel Conditions. The average received SNR has been observed to be diminishing in NLOS channel conditions. The rake structures capture relatively smaller energy as shown by the CDF curves generated using exponential-lognormal model than cluster model. The average performance loss of PRake is about 4 dB in cluster model profile and 6 dB in exponential-lognormal model profile for 2 finger structure. This is because of the presence of relatively stronger multipath components in the initial delay bins of the cluster model generated profile shown in Fig.3. The performance gap in 16 finger rake structures is found to be less than 1 dB using cluster model and 1.5 dB using exponential-lognormal model profiles. The smaller performance gap in cluster model is due to random appearance of high energy clusters, as indicated by rapid fluctuation of mean SSA-PDP as a function of delay in Fig. 5.

For 2 finger structures the diversity gain performance gap between SRake and PRake widens in NLOS channel conditions, as the first & second multipath components may not be the strong components. This degrades the PRake performance more than SRake. At 10% outage probability the value of performance gap in terms of SNR difference in CM2 increases to 8dB, using exponential-lognormal model generated profile. But with in the delay spread of (16 x 0.167) 2.67 nsec the gap in terms of average SNR reduces to as low as 2.5dB.

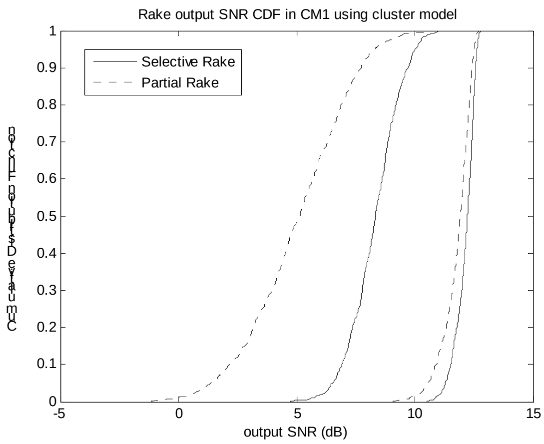

Figure 6: CDF of RAKE receivers SNR distribution in CM1

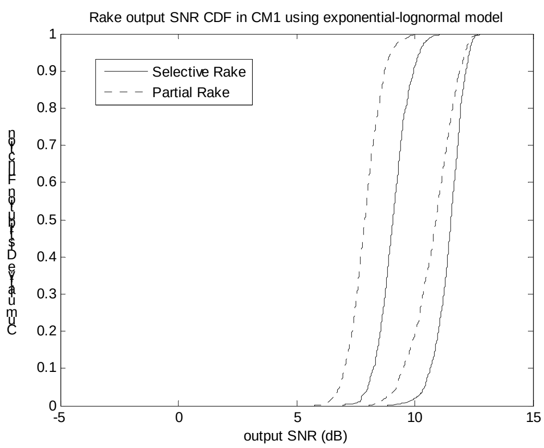

Figure 7: CDF of RAKE receivers SNR distribution in CM1

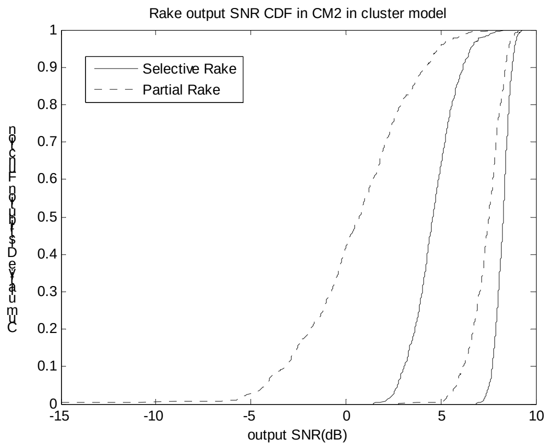

Figure 8: CDF of RAKE receivers SNR distribution in CM2.

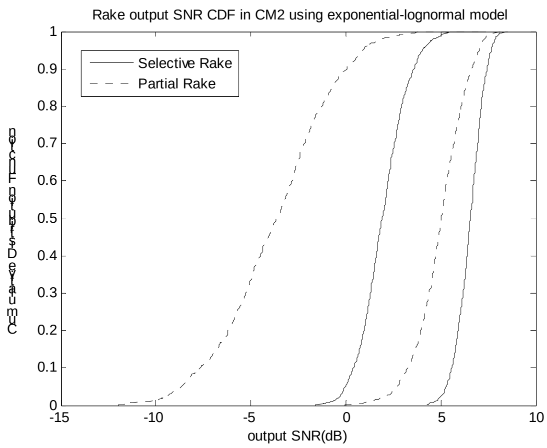

Figure 9: CDF of RAKE receivers SNR distribution in CM2.

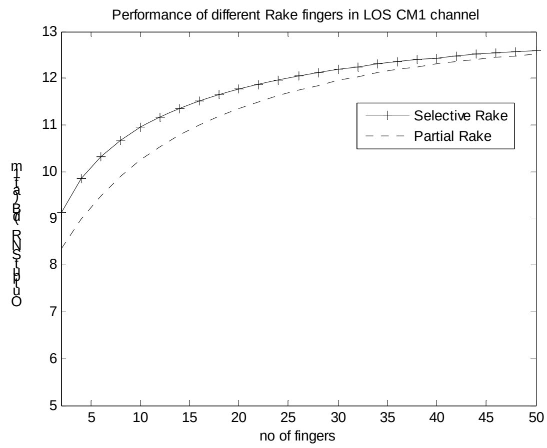

Figure 10: Cumulative SNR Capturing with Rake taps in CM1.

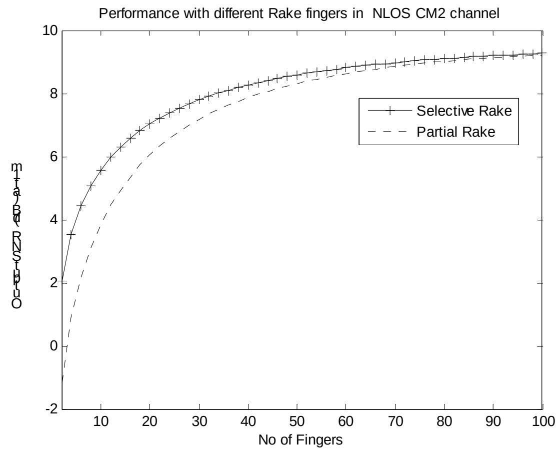

Figure 11: Cumulative SNR Capturing with Rake taps in CM2.

Selection of optimum Rake fingers

The Cumulative output SNR for the PRake and the SRake is shown in Fig. 9 & 10 as a function of number of paths captured by the Rake. The average transmitter SNR is set to be 60dB in all the channel categories. The Transmitter-Receiver distance is 1m for CM1 and CM2 channel conditions. The standard mean path-loss model of [22] has been used. The increase in Cumulative output SNR with increase in number of taps is observed, as is the reduced marginal gain in SNR as the number of taps increases. This leads to a good choice for the number of taps in the neighborhood of the “knee” of the curve. The SRake is noted to perform better than the PRake; however as the number of taps increases this difference is insignificant. The UWB channel model in Section II results in a lower probability for high amplitude paths at large delays, leading to these lower gains for the SRake as compared to the PRake. CM2 correspond to higher delay spread, as such it captures smaller energy for the same number of Rake fingers than CM1 channel category. Because of the availability of strong LOS energy components in the initial bins of CM1, there is smaller performance appreciation in CM1 than CM2 with increasing taps.

Performance Analysis

The most common performance criterion, in the context of a wireless communication system subjected to multipath fading impairment is the Average Bit error Probability (ABEP) [20]. We evaluate the ABEP of all three Rake structures in the realistic UWB channels using Exponential-Lognormal model. We assume that the fading is sufficiently slow that a large number of bits are transmitted within the channel coherence time. The (P_b) Average Bit Error Probability is obtained by averaging the conditional BEP $P_b(\gamma_b)$ (conditioned on the received instantaneous SNR per bit) over the probability density function $p_{\gamma_b}(\gamma_b)$ of the instantaneous SNR at the output of the Rake receiver [20].

$$P_b = \int_0^{\infty} P_b(\gamma_b) p_{\gamma_b}(\gamma_b)\, d\gamma_b \tag{8}$$

where $P_b(\gamma_b)$ is Bit Error Probability in AWGN and $p_{\gamma_b}(\gamma_b)$ is the distribution of the SNR in the fading conditions. The instantaneous SNR at the Rake output depends on the channel conditions and the type of the Rake receiver structure. For the ARake receiver and PRake receiver with MRC, the instantaneous output SNR is the sum of L_r and L_p independent but non-identically distributed random variables, respectively. But, in the case of the SRake receiver, the best L_b components are selected amongst the available multipath components, which mean complete estimation of the channel. The instantaneous SNR at the combiner output is the sum of L_b ordered random variables. Each of the underlying random variable in each tap follows a different stochastic distribution.

We have used a semi-analytical approach to compute the ABEP. A normalized channel has been considered with unit total energy. This allows a better insight into different Rake structures since their relative ABEP is independent of the total received energy. Standardized Path-Loss model in [22] has been used. The SSA-PDPs have been generated according to the procedure enumerated in previous section, and selected the total L_r available taps or L_p first taps (for the ARake and the PRake), or the strongest L_b paths (for the SRake), respectively. The SNRs for the selected taps are added in each of the Rake structures, which give us the total SNR at the Rake combiner output. In this section, we compute the ABEP vs Average SNR per bit for commonly used Binary Data Modulations for UWB such as 2BOK, orthogonal PPM (BPPM), optimum PPM. The ABEP vs average SNR per bit of binary data modulations for different Rake fingers and channel categories have been plotted in Fig 12 to 17. For comparison ABEP of ARake, PRake and SRake are plotted. The SNR gain to achieve target BEP (e.g. 10^{-4}) and slope of ABEP curves are compared. As anticipated, ARake has the best performance and taken as reference for SNR loss computation in PRake and SRake. The ABEP results obtained in [5] are also compared.

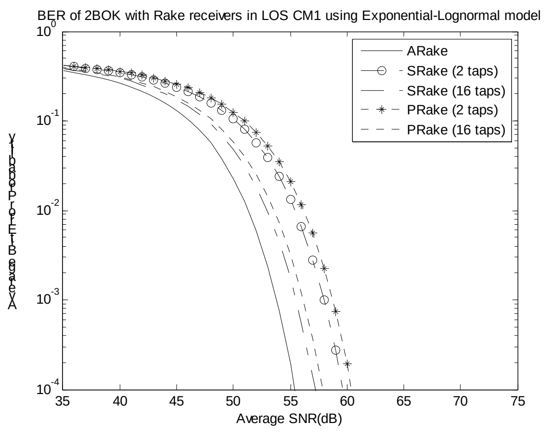

Figure 12: Average BEP of 2BOK for Rake receivers in CM1 (Tx-Rx 1m).

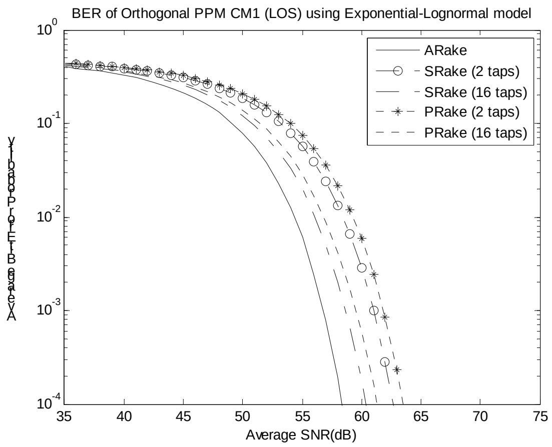

Figure 13: Average BEP of BPPM for Rake receivers in CM1 (Tx-Rx 1m).

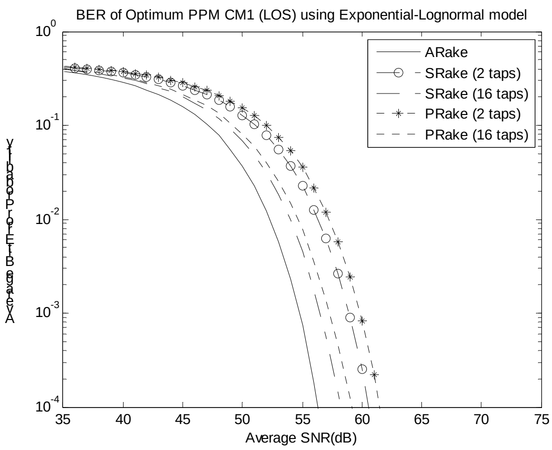

Figure 14: Average BEP of Op-PPM for Rake receivers in CM1 (Tx-Rx 1m).

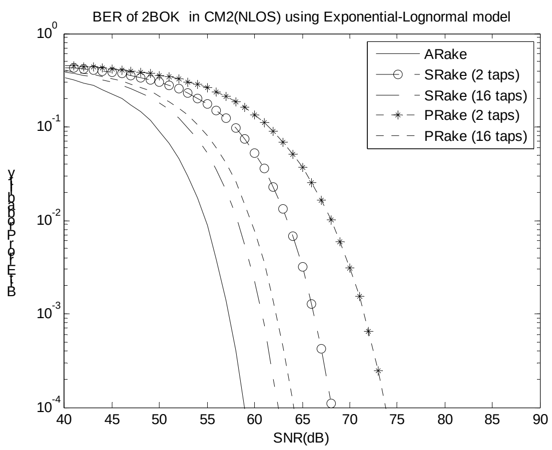

Figure 15: Average BEP of 2BOK for Rake receivers in CM2 (Tx-Rx 1m).

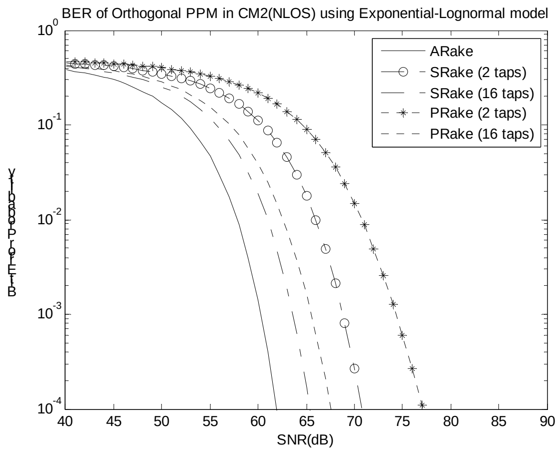

Figure 16: Average BEP of BPPM for Rake receivers in CM2 (Tx-Rx 1m).

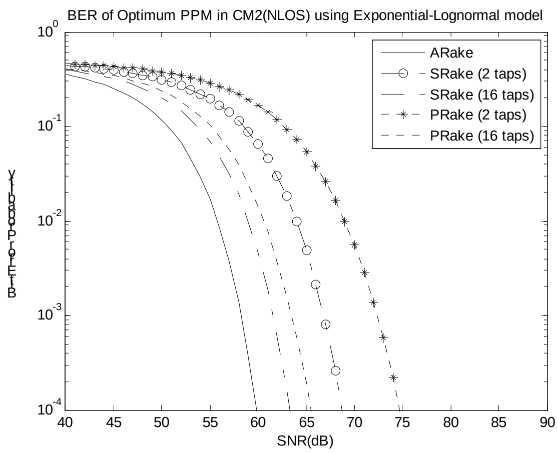

Figure 17: Average BEP of Op-PPM for Rake receivers in CM2 (Tx-Rx 1m).

Table I shows the ABEP SNR loss of different Rake structures in diversified UWB channels. We discuss here the two and sixteen finger SRake and PRake structures in different channel categories. For the target ABEP of 10^{-4}, the SRake performance gain over PRake in CM1 is about 6dB for BPPM as shown in [Fig.5, 5]. On the other hand, the performance gain of SRake is found to be only 1 dB in CM1 using exponential-lognormal model, due to frequent presence of strong LOS component in the first delay bin. The performance gap between SRake and PRake remains nearly same even for 16 finger structure. The performance loss of PRake compared to SRake increases to about 6dB in CM2 (NLOS) channel. This is due to relatively pronounced degradation of PRake performance in CM2.The difference in PRake and SRake curves increases in CM2 as fewer strong components are available in the beginning of temporal axis and the energy spread is over larger number of resolvable paths. For 16 finger structure, the performance loss of PRake is about 9dB using cluster model as shown in [Fig.5, 5]. This performance gap is due to the presence of strong cluster components at larger delay and PRake structure is unable to capture these MPCs. On the contrary, the 16-finger PRake performance loss reduces to about 2dB in CM2 using realistic exponential-lognormal model. Thus, ABEP performance using the realistic channel model favors simple PRake structure for both LOS & NLOS channel categories with optimum number of taps.

Table 1: ABEP Performance

LOS (CM1) Tx-Rx separation 1m.							
Modulation formats	SRake loss (dB)		PRake loss (dB)		Arake (dB)	PRake vs SRake	
	2tap	16tap	2tap	16tap		2tap	16tap
2BOK	4	1.8	4.8	2.2	55.3	0.8	0.4
Or-PPM	4	2	5	3	58.3	1	1
Op-PPM	4	2	5	2.7	56.3	0.9	0.7
NLOS (CM2) Tx-Rx separation 1m.							
2BOK	9.1	3.2	15	5.5	59	5.9	1.9
Or-PPM	9.1	3.6	15.5	5.9	62	6.4	2.3
Op-PPM	8.6	3.6	15	5.5	60	6.4	2.3

The optimum value of Autocorrelation function using [21] is evaluated to be -0.6 which makes optimum PPM 2dB more power efficient than orthogonal PPM with ARake. The 2BOK gives 3 dB SNR gain over the Orthogonal PPM with ARake and has a simpler receiver structure. But PRake & SRake with 2 tap using all three data modulations shows comparable performance in a given channel condition. The performance loss in PRake compared to SRake widens in Non LOS channel conditions using 2 finger structures. But this relative loss decreases to about 2dB when the numbers of fingers are increased to 16 in CM2. The ABEP curve slope at higher SNR values decides the diversity order, which differ appreciably in lower order tap structures of SRake and PRake in NLOS. But the ABEP slope of SRake and PRake matches in higher order tap structures.

Conclusions

A semi-analytical evaluation of the realistic UWB link performance was made based on Exponential-Lognormal indoor channel model. The output SNR distributions of Selective Rake and Partial Rake detectors generated using standard cluster model and exponential-lognormal model are compared for LOS and NLOS channel scenarios. The performance of simple PRake in realistic LOS channel is found to be very close to that of SRake. The performance loss of PRake in NLOS also reduces appreciably by incorporating marginally higher taps of the order of 16. Thus, the simpler PRake structure may be used in rich diversity UWB channel. The Average BEP analysis for 2BOK, Orthogonal PPM and Optimum PPM data modulation formats showed similar degradation in all channel conditions with 2 fingers SRake and PRake reception, but 2BOK gives the better modulation efficiency in higher order Rake structures.

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