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Suppression of Narrowband Interference in impulse radio based high data rate UWB WPAN communication system using NLOS Channel Model

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Abstract**—**Study on suppression of interference in time domain equalizers is attempted for high data rate impulse radio (IR) ultra wideband communication system. The narrow band systems may cause interference with UWB devices as it is having very low transmission power and the large bandwidth. SRAKE receiver improves system performance by equalizing signals from different paths. This enables the use of SRAKE receiver techniques in IR-UWB systems. But Rake receiver alone fails to suppress narrowband interference (NBI). A hybrid SRake-MMSE time domain equalizer is proposed to overcome this by taking into account both the effect of the number of rake fingers and equalizer taps. It also combats inter-symbol interference. A semi analytical approach and Monte-Carlo simulation are used to investigate the BER performance of SRAKE-MMSE receiver on IEEE 802.15.3a UWB channel models. Study on non-line of sight indoor channel models (both CM3 and CM4) illustrates that bit error rate performance of SRake-MMSE receiver with NBI performs better than that of Rake receiver without NBI. We show that for a MMSE equalizer operating at high SNR's the number of equalizer taps plays a more significant role in suppressing interference.

Keywords**—**IR-UWB, UWB, IEEE 802.15.3a, NBI, Data rate, Bit Error Rate

I. Introduction

The ultra-wideband (UWB) communications is a modern wireless system is to achieve higher data rates and better quality technique, due to its extremely large bandwidth. Ultra-wideband (UWB) has recently evoked great interest and its potential strength lies in its use of extremely wide transmission bandwidth. Furthermore, UWB is emerging as a solution for the IEEE 802.15a (TG3a) [4] standard which is to provide a low complexity, low cost, low power consumption and high data-rate among Wireless Personal Area Network (WPAN) devices. The very low transmission power and the large bandwidth used to enable an UWB system to co-exist with other narrowband and wideband communication system. Although UWB communication offers a promising solution to an increasingly overcrowded frequency spectrum, the overlay of UWB signals on coexisting narrowband system implies interference concerns for both UWB and narrow band system. An aspect of UWB transmission is to combat both interference and ISI. Rake receivers can be employed since they are able to provide multipath diversity [1-2]. Combination of spatial diversity combining and equalization is a well established scheme for frequency selective fading channels [1] and [3]. The working of UWB system in co-existence with other narrowband systems over their large bandwidth is challenging. Thus, UWB systems must cope with these narrowband interference (NBI) using their high processing gain [3] and [7]. As taking a large number of rake fingers are unfeasible, so rake receiver fail to suppress NBI. Further [5], a combined rake and equalizer structure was proposed for high data rate UWB systems. In this paper, the performance of a rake-MMSE equalizer receiver similar to [5] is investigated for different number of rake fingers and equalizer taps using a semi-analytical approach. We propose at first to study time equalization with combined Rake-MMSE equalizer structure. We show that, for a MMSE equalizer operating at low to medium SNR's, the number of Rake fingers is the dominant factor to improve system performance, while, at high SNR's the number of equalizer taps plays a more significant role in suppressing narrowband interference [6]. We show that for high frequency selective channels such as the CM4 one, a linear equalizer structure is not sufficient and must be replaced by a decision feedback equalizer (DFE) structure.

The rest of the paper is organized as follows. In Section II we study the signals and system model for IEEE UWB channel modeling. Section III is devoted for Rake receiver structure without and with NBI. In section IV performance analysis of RAKE-MMSE receiver with and without NBI are analyzed. Simulation results are discussed in Section V. Section VI concludes the paper.

II. Signals And System Model

For a single user system, the continuous transmitted data stream is written

$$s(t) = \sum_{k=-\infty}^{+\infty} d(k).\, p(t - k.T_s) \qquad (1)$$

Where $d(k)$ are stationary uncorrelated BPSK data and T_s is the symbol duration. We consider the application of a root raised cosine (RRC) transmit filter $p(t)$ with roll-off factor α = 0.3. The UWB pulse $p(t)$ has duration *Tuwb (Tuwb < Ts).* The channel models used in this paper are the model proposed by IEEE 802.15.3a Study Group [10]. For this paper two kinds of channel models, derived from the IEEE 802.15 channel modeling working group, are considered and named CM3 and CM4 channels. The first one CM3 corresponds to a non-line of sight communication with range 4-10 meters. The second CM4

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corresponds to a strong dispersion channel with delay spread of 26 nsec. The impulse response can be written as

$$h(t) = \sum_{p=0}^{M} h_p.\delta(t - \tau_p) \tag{2}$$

Parameter M is the total number of paths in the channel.

III. PRINCIPLE OF RECEIVER

A. SRake Receiver structure

The received signal first passes through the receiver filter matched to the transmitted pulse and is given by [9] and [11]

$$\begin{aligned} r(t) &= s(t) * h(t) * p(-t) + n(t) * p(-t) \\ &= \sum_{k=-\infty}^{+\infty} d(k) \sum_i h_i.m(t - k.T_s - \tau_i) + \hat{n}(t) \end{aligned} \tag{3}$$

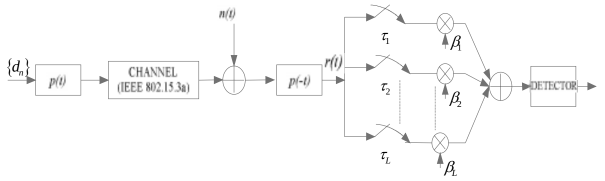

Fig. 1 UWB SRake receiver structure

where *p(-t)* represents the receiver matched filter, "*" stands for convolution operation and *n(t)* is the additive white Gaussian noise (AWGN) with zero mean and variance $N_0/2$. Also, $m(t) = p(t) * p(-t)$ and $n(t) = n(t) * p(-t)$.

Combining the channel impulse response (CIR) with the transmitter pulse shape and the matched filter, we have

$$\tilde{h}(t) = p(t) * h(t) * p(-t) = \sum_{i=0}^{M} h_i.m(t - \tau_i) \tag{4}$$

The output of the receiver filter is sampled at each Rake finger is given by [8]

$$v\left(n.T_s + \tau_l' + t_0\right) = \sum_{k=-\infty}^{+\infty} \tilde{h}\left((n-k).T_s + \tau_i' + t_0\right).d(k) \tag{5}$$

The minimum rake finger separation is $T_m = T_s / N_U$, where N_u is chosen as the largest integer value that would result in T_m spaced uncorrelated noise samples at the rake fingers and the SRake combiner output at time t = n.Ts is

$$y[n] = \sum_{l=1}^{L} \beta_l.v\left(n.T_s + \tau_l'\right) + \sum_{l=1}^{L} \beta_l.\hat{n}\left(n.T_s + \tau_l'\right) \tag{6}$$

where τ_l' is the delay time corresponding to the l^{th} rake finger and is an integer multiple of T_m. Parameter t_0 corresponds to a time offset and is used to obtain the best sampling time. Without loss of generality, t_0 will be set to zero in the following analysis.

B. SRake Receiver with NBI

The UWB system must cope with the narrow band interference (NBI) using their high processing gain. In our model, the interfering NBI signal is added to the desired signal in the channel and then passed through the UWB receiver as shown in Fig..2 and is presented by

$$i(t) = \sqrt{2I_B}\cos\left(\omega_i t + \theta_i\right) \tag{7}$$

Where, $i(t)$ is received interferer signal with transmitted power of I and I_B □ $\beta^2 i$. The received signal passes through the receiver filter matched is given by

$$r(t) = A(t) * h(t) * p(-t) + n(t) * p(-t) + i(t) * p(-t) \tag{8}$$

Interference coexisting with the same system generates extra signal which can't be easily detected at the output. Rather by coexisting with original pulse it will decrease the performance of receiver. However, due to the very low transmission power, it is expected that even this large processing gain is not sufficient to suppress NBI.

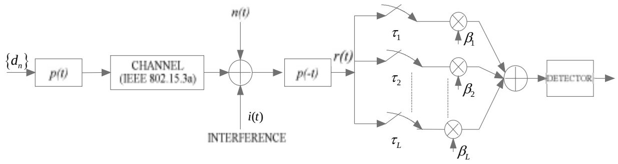

Fig. 2 UWB Rake receiver structure with NBI

IV. PERFORMANCE ANALYSIS

A. SRAKE-MMSE Receiver

To overcome these problems a hybrid SRAKE-MMSE time domain equalizer is proposed by taking into account both the effect of the number of rake fingers and equalizer taps. A major advantage of MMSE scheme relative to other interference suppression scheme is that explicit knowledge of interference parameter is not required. The receiver structure is illustrated in Fig. 3 and consists in a SRake receiver followed by a linear MMSE equalizer [11].

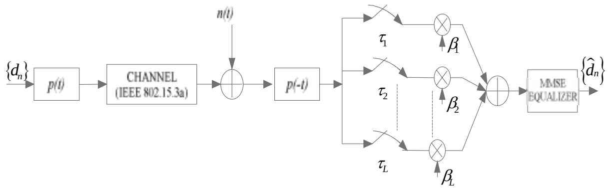

Fig. 3 UWB SRAKE-MMSE receiver structure

In this part, due to the lack of place we will only discuss the matrix block computation of linear equalizers. Furthermore, we suppose perfect channel state information (CSI). Assuming that the n data bit is being detected, the MMSE criterion consists in minimizing

$$E\left[\left|d(n) - \hat{d}(n)\right|^2\right]$$

where $\hat{d}(n)$ is the equalizer output. Rewriting the Rake output signal, one can distinguish the desired signal, the undesired ISI and the noise as [10]

$$\begin{aligned} y(n) = &\left[\sum_{l=1}^{L} \beta_l.\tilde{h}(\tau_l')\right].d(n) + \sum_{k \neq n} \sum_{l=1}^{L} \beta_l.\tilde{h}\left((n-k).T_s + \tau_l'\right).d(k) \\ &+ \sum_{l=1}^{L} \beta_l.\hat{n}\left(n.T_s + \tau_l'\right) \end{aligned} \tag{9}$$

where the first term is the desired output. The noise samples at different fingers, $n(n.Ts + \tau_l')$, $l = 1, ..., L$, are uncorrelated and therefore independent, since the samples are taken at approximately the multiples of the inverse of the matched filter bandwidth [9], [10] and [11]. It is assumed that the channel has a length of $(n_1 + n_2 + 1).T_s$. That is, there is pre-cursor ISI from the subsequent n_1 symbols and post-cursor ISI from the previous n_2 symbols, and n_1 and n_2 are chosen large enough to include the majority of the ISI effect. Using (8), the Rake output can be expressed now in a simple form as

$$y(n) = \alpha_0 . d(n) + \sum_{\substack{k=-n_1 \\ k \neq 0}}^{n_2} \alpha_k . d(n-k) + \tilde{n}(n) \quad (10)$$

$$= \phi^T d[n] + \tilde{n}(n)$$

where coefficient α_K's are obtained by matching (9) and (10). $\phi = [\alpha_{n_1} ... \alpha_0 ... \alpha_{n_2}]$ and $d[n] = [d(n+n_1) ... d(n) ... d(n-n_2)]^T$

The superscript denotes the transpose operation. The output of the linear equalizer is obtained as

$$\hat{d}(n) = \sum_{r=-k_1}^{k_2} c_r . y(n-r) = c^T \gamma(n) + c^T \eta(n) \quad (11)$$

where $c = [c_{-K_1} ... c_0 ... c_{K_2}]$ contains the equalizer taps. Also

$$\gamma[n] = [\phi^T d[n+K_1] ... \phi^T d[n] ... \phi^T d[n-K_2]]^T$$

$$\eta[n] = [\tilde{n}(n+K_1) ... \tilde{n}(n) ... \tilde{n}(n=K_2)]^T \quad (12)$$

The mean square error (MSE) of the equalizer,

$$E\left[\left| d(n) - c^T \gamma[n] - c^T \eta[n] \right|^2 \right] \quad (13)$$

which is a quadratic function of the vector c, has a unique minimum solution. Here, the expectation is taken with respect to the data symbols and the noise. Defining matrices R, p and N as

$$\mathbf{R} = E[\gamma[n] . \gamma^T[n]] \quad (14)$$

$$\mathbf{p} = E[d(n) . \gamma[n]] \quad (15)$$

$$\mathbf{N} = E[\eta[n] . \eta^T[n]] \quad (16)$$

The equalizer taps are given by

$$c = (R + N)^{-1} . p \quad (17)$$

and the MMSE is

$$J_{\min} = \sigma_d^2 - p^T (R+N)^{-1} . p \quad (18)$$

$$\sigma_d^2 = E[|d(n)|^2]$$

Evaluating the expectation over R and p with respect to the data and the noise, we have

$$p = [\alpha_K ... \alpha_0 ... \alpha_{-K_2}]^T \quad R = [r_{i,j}]_{K_1+K_2+1, K_1+K_2+1} \quad (19)$$

$$N = E[\eta[n] . \eta^T[n]] = \frac{N_0}{2} . \left(\sum_{l=1}^{L} \beta_l^2 \right) . I_{K_1+K_2+1} \quad (20)$$

where I is the identity matrix. This Rake-equalizer receiver will eliminate ISI as far as the number of equalizer's taps gives the degree of freedom required. In general, the equalizer output can be expressed as

$$\hat{d}(n) = q_0 . d(n) + \sum_{i=0} q_1 . d(n-i) + w(n) \quad (21)$$

The variance of $w(n)$ is

$$\sigma_{w(n)}^2 = \left(\sum_{i=-K_1}^{K_2} c_i^2 \right) \left(\sum_{l=1}^{L} \beta_1^2 \right) . E_p . N_0 / 2 \quad (22)$$

Where E_p is the pulse energy. In the case of DFE, assuming error free feedback, the input data vector can be written in the form of

$$\gamma_{DFE}[n] = [\Phi^T d[n+K_1] ... \Phi^T d[n] \, d[n-1] ... d_{n-K_2}] \quad (23)$$

Using the same approach as for the linear equalizer, the MMSE feed forward taps for tap equalizer are obtained as

$$C_{DFE} = (R_{DFE} + N_{DFE})^{-1} p_{DFE} \quad (24)$$

Conditioned on a particular channel realization, $h = [h_1 .... h_l]$, an upper bound for the probability of error using the chernoff bound technique given by [11]

$$P(\hat{d}_n \neq d_n | h) \leq \exp\left(- \frac{1 - J_{\min} / \sigma_d^2}{2 J_{\min}} \right) \quad (25)$$

An exact BER expression with independent noise and ISI terms can be expressed as a series expansion is given by

$$P(\hat{d}_n \neq d_n | h) = \frac{1}{2} - \frac{2}{\pi} \sum_{\substack{z=1 \\ zodd}}^{z} \frac{\exp(-z^2 w^2 / 2) \sin(zwq_0)}{z} \times \prod_{\substack{n=N_1 \\ n \neq 0}}^{N_2} \cos(zwq_n) \quad (26)$$

In the case of DFE, we can simply set the q_i 's that are within the span of the feedback taps to be 0, which corresponds to zero post-cursor ISI for the span of feedback taps.

B. SRAKE-MMSE Receiver with NBI

The received signal sampled at the l^{th} Rake finger in the n^{th} data symbol interval is given by equation. The Rake combiner output at time $t = n.T_s$ is

$$y[n] = \sum_{l=1}^{L} \beta_l . v(n.T_s + \tau_l') + \sum_{l=1}^{L} \beta_l . i(n.T_s + \tau_l') + \sum_{l=1}^{L} \beta_l . \hat{n}(n.T_s + \tau_l') \quad (27)$$

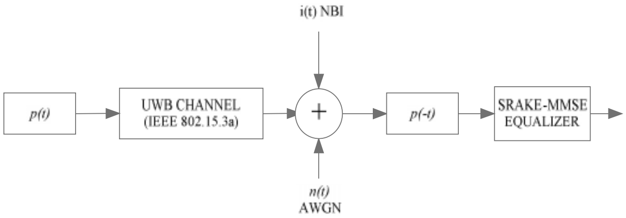

Fig. 4 UWB SRAKE-MMSE receiver structure with NBI

The Rake output can be expressed now in a simple form as

$$y(n) = \alpha_0 . d(n) + \sum_{\substack{k=-n_1 \\ k \neq 0}}^{n_2} \alpha_k . d(n-k) + \tilde{i}(n) + \tilde{n}(n) \quad (28)$$

The received signal is sampled at pulse repetition frequency after passing through the correlation receiver. The samples are linearly combined using the MMSE criterion, so that weights are effective to suppress the NBI. The equalizer taps are given by

$$c = (R + I_N + N)^{-1} . p \quad (29)$$

where R, I_N, N are the autocorrelation of the signal, the NBI and the noise respectively. So the MMSE is

$$J_{\min} = \sigma_d^2 - p^T (R + I_N + N)^{-1} . p \quad (30)$$

$$\sigma_d^2 = E[|d(n)|^2]$$

Then similarly applying all the previous steps we will found that both noise and interference are suppressed by the same receiver structure. In the NBI suppression analysis, the correlation between the samples of the received signal plays the main role. Assuming $n(t)$ is not correlated to $i(t)$ and has an impulsive auto-correlation, Hence the NBI is modeled as single tone.

V. SIMULATION STUDY AND ANALYSIS

A. Channel Model Parameter

Simulations are studied by using UWB channels CM3 and CM4. A oversampling factor of eight is used for the root raised cosine (RRC) pulse [10] and [11]. This choice enables to gather 99% of the channel energy. The data rate is chosen to be 200 Mbps, one of the optional data rates proposed for IEEE standard. The size of the transmitted packets is equal to 2560 BPSK symbols including a training sequence of length 512. CIR remains constant over the time duration of a packet. The root raised cosine (RRC) pulse with roll off factor α = 0.5 is employed as the pulse-shaping filter. Channel models CM3 and CM4 is given in Fig..5 and Fig.6:

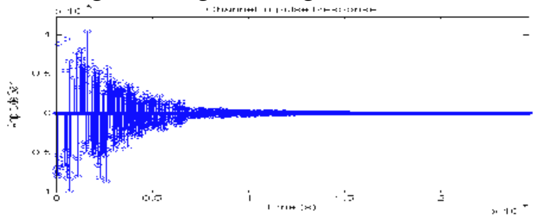

Fig. 5 Channel Impulse Response of CM3 (NLOS)

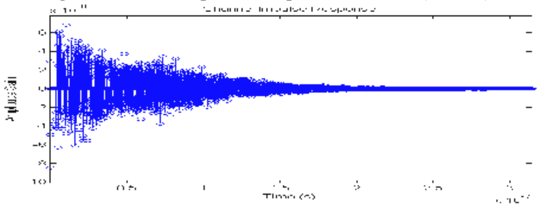

Fig. 6 Channel Impulse Response of CM4 (NLOS)

The power delay profile for CM3 and CM4 channel model is given in Fig..7 and 8:

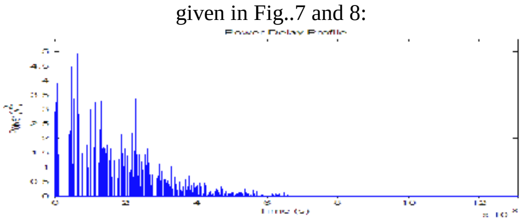

Fig. 7 Delay Profile of CM3 channel model

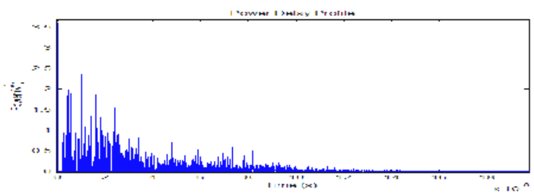

Fig. 8 Delay Profile of CM4 channel model

B. SRAKE-MMSE Receiver

Table.1 provides all the simulation parameter used for SRAKE-MMSE receiver. Performance of UWB SRAKE-MMSE receiver varying length of equalizer taps and rake fingers for CM3 and CM4 as shown in Fig. 9 and 10.

TABLE.I
SIMULATION PARAMETER FOR SRAKE-MMSE RECEIVER

Parameter	Values
Data rate	200 Mbps
Pulse width	0.35 ns
Symbol duration	5ns
Pulse energy	1
T_m	0.1786 ns
N_u	28
Channel spread	CM3=70, CM4=100
Pilot carrier	500

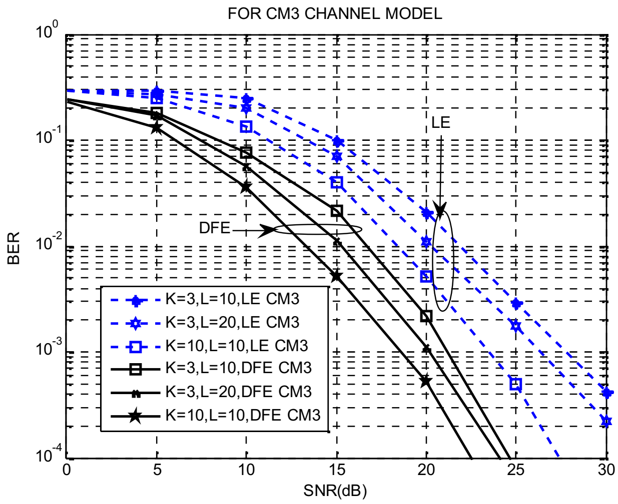

Fig.9 shows that keeping the number of rake fingers constant (K=3), almost 1dB SNR gain at a BER level of 10^{-3} is observed with increase in length of equalizer taps from L=10 to 20.

Fig. 9 Performance of UWB SRAKE-MMSE-receiver for different length of equalizer taps and rake fingers for CM3 channel model

Whereas keeping the number of equalizer taps same (L=10), around 4dB SNR improvement is obtained increasing the rake fingers from K=3 to 10. Further decision feedback equalizer (DFE) provides more than 5dB SNR improvement than that of linear equalizer (LE) for K = 10, L = 10 in case of CM3 channel model. The performance improvement is noticeable when the number of rake fingers and the equalizer taps are simultaneously increased to K = 20 and L = 10 as shown in Fig. 10. It is observed that on comparing the BER performances at different UWB NLOS channel models, LE fails to perform satisfactorily at high SNR's. These can be overcome by using DFE of same filter length. A DFE outperforms a linear equalizer of the same filter length, and the performance further improves with more equalizer tap length. At high and low SNR's, ISI and the system noise degrades the system performance respectively. At high SNR, the receiver with more number of rake fingers outperforms the one that has more equalizer taps.

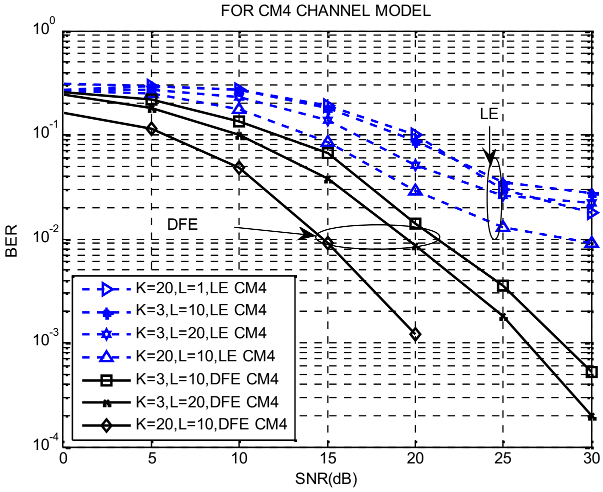

Fig. 10 Performance of UWB SRAKE-MMSE-receiver for different length of equalizer taps and rake fingers for CM4 channel model

C. Ber Analysis For Srake-Mmse Receiver With Nbi

In the case of time domain equalization, we have at first to optimize the number of Rake fingers and the number of equalizer taps as 5 and 20 respectively. The Rake fingers are regularly positioned according to time channel spread and the number of fingers.

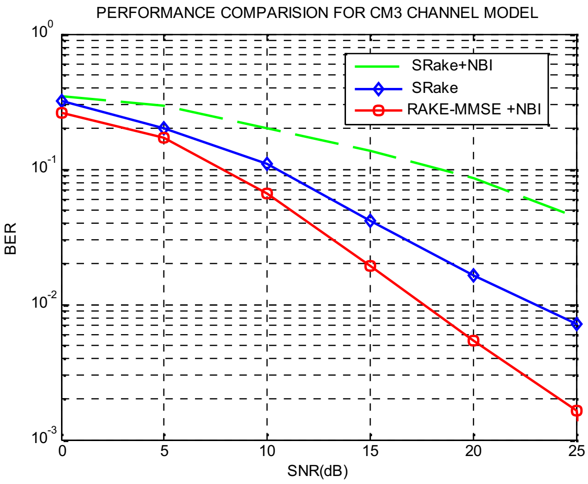

Fig. 11 Performance of UWB SRAKE-MMSE receiver with NBI in CM3 channel

Fig. 11 and 12 shows when interference is added to the SRake receiver, it fails to suppress the interference and the performance degrades. For SRAKE-MMSE structure, at high SNR's, a 20 tap equalizer with 5 Rake fingers outperforms a 5 Rake finger SRake receiver without NBI for both CM3 and CM4 channel model. At low to medium SNR's, however, the receivers with more number of Rake fingers are able to suppress the interference. This result can be explained by considering the fact that at high SNR's it is mainly the ISI that affects the system performance

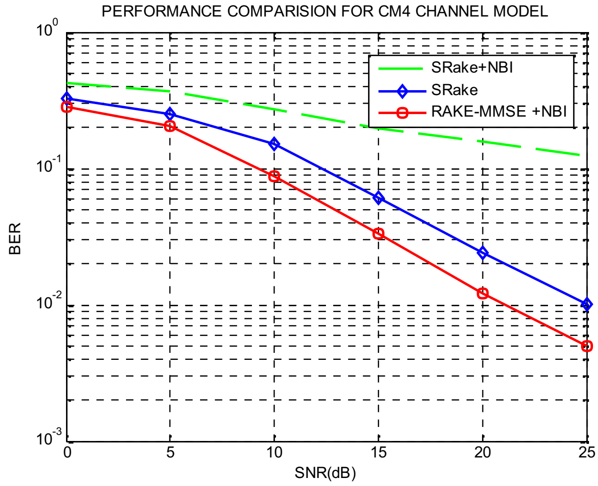

Fig. 12 Performance of UWB SRAKE-MMSE receiver with NBI in CM4 channel

The performance noticeably improves when the number of Rake fingers and the equalizer taps are increased simultaneously. As expected the receiver has better performance over CM3 with smaller delay spread than CM4.

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