

## Increasing the Efficiency of Rake Receivers for Ultra-Wideband Applications

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Published online: 21 July 2010  
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**Abstract** In diversity rich environments, such as in Ultra-Wideband (UWB) applications, the *a priori* determination of the number of strong diversity branches is difficult, because of the considerably large number of diversity paths, which are characterized by a variety of power delay profiles (PDPs). Several Rake implementations have been proposed in the past, in order to reduce the number of the estimated and combined paths. To this aim, we introduce two adaptive Rake receivers, which combine a subset of the resolvable paths considering simultaneously the quality of both the total combining output signal-to-noise ratio (SNR) and the individual SNR of each path, reducing the number of combined paths, while keeping the desirable performance. These schemes achieve better adaptation to channel conditions compared to other known receivers, without further increasing the complexity. Their performance is evaluated in different practical UWB channels, whose models are based on extensive propagation measurements. The proposed receivers compromise between the power consumption, complexity and performance gain for the additional paths, resulting in important savings in power and computational resources.

**Keywords** RAKE receivers · UWB propagation channels

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## 1 Introduction

Ultra-Wideband (UWB) systems have attracted great research interest since early 90's. One of the key advantages of UWB signals is the immunity to fading, since the bandwidth of several gigahertz improves the capability of resolving multipath components (MPCs) [1]. Each of the resolved MPCs can be viewed as independently fading, thereby providing a high degree of diversity (delay diversity, frequency diversity) for the transmission. By incorporating Rake receivers, which have the ability to extract and individually process several signal multipath components, the performance and reliability of wireless communication systems can be significantly improved.

The optimal diversity combining scheme, in terms of performance, is the all-Rake (ARake) receiver which combines all the resolvable paths [2–5]. However the performance gain comes at the cost of power consumption and increased complexity of the utilized hardware, which are significant factors in environments with more than 100 MPCs, such in UWB applications [6]. A Rake receiver that overcomes these obstacles at the cost of performance is the selective Rake (SRake) receiver [2–5]. SRake combines the  $L_b$  strongest resolvable paths, but still requires full channel estimation for every path. Recently, partial Rake (PRake) receiver was proposed in [7]. PRake combines only the first arriving  $L_p$  paths out of the available resolvable MPCs, and therefore requires only synchronization, but not full channel estimation. Both SRake and PRake receivers have a fixed processing complexity, since the number of the combined paths is predetermined (i.e.,  $L_p$  paths are combined), leading to some disadvantages regarding the compromise between complexity and performance. More specifically, in channels with strong MPCs, SRake may combine unnecessarily too many paths, while the desirable performance could be achieved by combining considerably less paths. On the other hand, in channels with weak MPCs, SRake unnecessarily combines the weak paths without increasing the signal's quality. Similarly, PRake may also combine unnecessarily too many paths, but it could also combine insufficient number of paths, since it resolves only the first arriving  $L_p$  paths, without guaranteeing the desired quality. These issues are important for communication systems operating in wireless channels with intense power delay profiles (PDPs), such as the UWB channel, where the number of resolvable paths is extremely large.

Alternative Rake implementations that aim to reduce the number of the estimated and combined paths, include the generalized selection combining (GSC) receivers that are divided into two categories: in the first one the combined paths are determined by the signal-to-noise ratio (SNR) of each individual path (absolute threshold GSC (AT-GSC), normalized threshold GSC (NT-GSC) [8]), while in the latter one the same decision is based on the combiner's output SNR (minimum selection GSC (MS-GSC), output threshold GSC (OT-GSC), minimum estimation and combining GSC (MEC-GSC), [9–13]). However, in Rake receivers of the former category the selected branches may be unnecessarily too many, while a sufficient quality of communication could be possibly attained with less, especially in environments with strong multipaths. Similarly, the Rake receivers of the latter category could keep adding weak paths (e.g. in diversity rich environments with strong PDPs) in an attempt to reach the predetermined threshold, while a slightly worse or the same performance could be achieved by combining only the strong branches.

Motivated by the advantages and disadvantages that each of the above mentioned receivers offer, we propose an Adaptive Selective Rake (ASRake), combining the paths that satisfy simultaneously two predetermined criteria: *the SNR of each individual path and the quality of the expected combined output SNR*. More specifically, ASRake keeps adding the strongest paths in order to reach the predetermined quality of service (QoS), unless it estimates that the addition of another path will not compensate the expected performance improvement. In this

way, the receiver compromises between complexity and performance, since it achieves the best possible performance with the least necessary combined paths. Furthermore, we propose an Adaptive Partial Rake (APRake) receiver with similar operation as that of ASRake, but now the resolvable paths are not ranked with respect to their signal powers. By evaluating the error performance of the ASRake and APRake receivers in realistic UWB channels [7], it is shown that the improved adaptation leads to important savings in power and computational resources. Thus, the contribution of this work is twofold. First, we propose two novel adaptive Rake receivers, which offer important savings in power and computational resources, when operating in realistic UWB channels, compared to previously proposed receivers. Second, we evaluate the performance of several Rake receivers in practical UWB channels, which have been proved to have considerable differences from the narrowband wireless channels [14].

The remainder of the paper is organized as follows. The channel models employed in the analysis are briefly described in Sect. 2. In Sect. 3, we present the mode of operation of the proposed receiver, while its performance is evaluated in Sect. 4. Finally, some concluding remarks are presented in Sect. 5.

## 2 Channel Models

The differences between the UWB and the narrowband wireless channel are important, especially when the fading statistics and the time of arrival of the MPCs are considered. These differences raise from the fact that the UWB systems cover a bandwidth of almost 10 GHz, generating new effects, which make the central limit theorem not applicable and therefore the amplitude of fading statistics is not Rayleigh [14].

The most suitable channel models for practical UWB applications are the low-frequency (LF) and the high-frequency (HF) models [7]. The former was accepted by the IEEE 802.15.4a standardization group and is appropriate for applications below 1 GHz. The latter was accepted by the IEEE 802.15.3a standardization group and is used in high-data-rate UWB communications systems. Next, we evaluate the performance of the proposed receivers over the LF and HF channels. Details concerning these UWB channel models can be found in [7]. In the following, the main characteristics of these models are given for the reader's convenience.

### 2.1 LF Channel Model

The LF UWB channel model is based on experimental data collected in a typical office building using baseband pulses with duration 1 nsec with a resulting bandwidth of 500 MHz [15–18]. The channel's PDP is characterized as a stochastic tapped-delay line model, where the  $k$ th tap is determined by the time delay,  $\tau_k = 2(k - 1)$ , and the path gain  $G_k$ , which is the superposition of large and small scale fading. In the small-scale region, the  $G_k$  are random variables, with a probability density function (pdf) that can be approximated by a Gamma distribution, with mean  $\overline{G}_k$  and shape parameter  $m_k$ . The values of  $\overline{G}_k$  are specified in [7, (Eq. 1)], while  $m_k$  are Gaussian-distributed random variables.

### 2.2 HF Channel Model

The HF UWB channel model is based on the Saleh-Valenzuela channel model [19] and is intended to represent the channel characteristics in the frequency range from 3.1 to 10.6 GHz

[20]. According to this model, the received signal rays arrive in  $L$  clusters each containing  $K$  rays. The channel impulse response of the  $i$ -th realization is defined as

$$h_i(t) = X_i \sum_{l=0}^L \sum_{k=0}^K a_{k,l}^i \delta(t - T_l^i - \tau_{k,l}^i) \tag{1}$$

where  $a_{k,l}^i$  is the tap weight associated with the  $k$ -th ray of the  $l$ -th cluster,  $X_i$  is the log-normal shadowing and  $T_l^i, \tau_{k,l}^i$  are the cluster and ray arrival times, respectively. Compared to the LF channel mode, the HF model has two important differences; the arrival statistics of the MPCs and the distribution of their amplitudes. More specifically, the LF channel is more dense, i.e. the rays are almost continuous with an exponential decay, while in the HF channel the PDP is more sparse, in the sense that many paths may not carry any energy, which means that the first arriving path is not necessarily the strongest one. Regarding the distribution of the MPCs' amplitude, in the HF model MPCs follow a lognormal distribution with variance that is independent of the path delays. On the other hand, in the LF model, the MPCs distribution is the Nakagami whereas the  $m$ -parameters decrease with delay.

### 3 System Model and Mode of Operation

Regardless of the statistical channel model assumed, the UWB channel response has the following general mathematical form

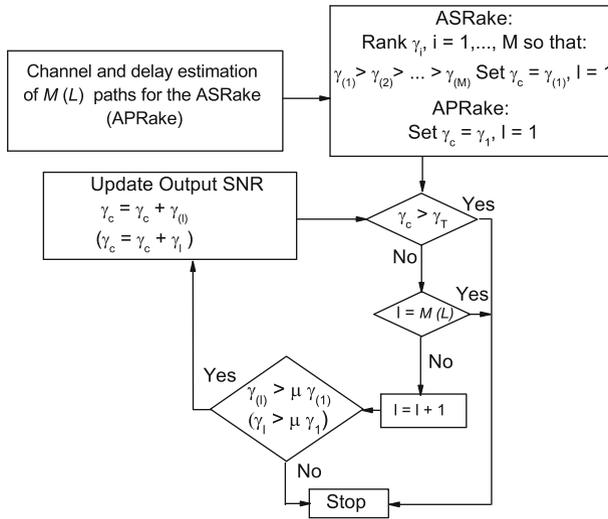
$$h(t) = \sum_{m=0}^{M-1} h_m \delta(t - \tau_m) \tag{2}$$

where  $h_m$  denotes the channel gain of the  $m$ -th resolvable path out of  $M$  available ones and  $\tau_m$  is the arrival delay with respect to the first arriving path. The statistics of both  $h_m$  and  $\tau_m$  are determined by the channel model that is utilized (e.g. the HF channel model). We consider a Rake receiver, which is assumed to be capable of ideally (i.e. no channel or delay estimation errors occur at the receiver) capturing the energy of the  $M$  paths, and combines them using maximal-ratio combining (MRC). We note, that these assumptions have been followed in the majority of previously published works and leads to the study of the optimum lower bound of the error rate performance. The receiver actually sums the SNR of the resolvable paths, so that the total combined signal has a SNR

$$\gamma_{\text{total}} = \sum_{p \in R_M} \gamma_p = \sum_{p \in R_M} E_s \frac{h_p}{N_0} \tag{3}$$

where  $R_M$  is the subset of the paths that are combined and depends on the Rake receiver that is applied (e.g. for ARake  $R_M$  involves all the  $M$  paths),  $\gamma_p$  is the SNR of the  $p$ -th path of subset  $R_M$ ,  $E_s$  denotes the transmitted symbol's energy,  $h_p$  stands for the gain of the  $p$ -th path and  $N_0$  is the power spectral density of the additive white Gaussian noise (AWGN).

The characteristic that diversifies the Rake receivers is the number of the estimated and combined branches. For example, ARake estimates and combines  $M$  branches, SRake estimates  $M$  channels and combines  $L$  paths, while PRake estimates  $L$  channels and combines  $L$  paths. In the following, the proposed receivers are presented in details.



**Fig. 1** ASRake and APRake: mode of operation

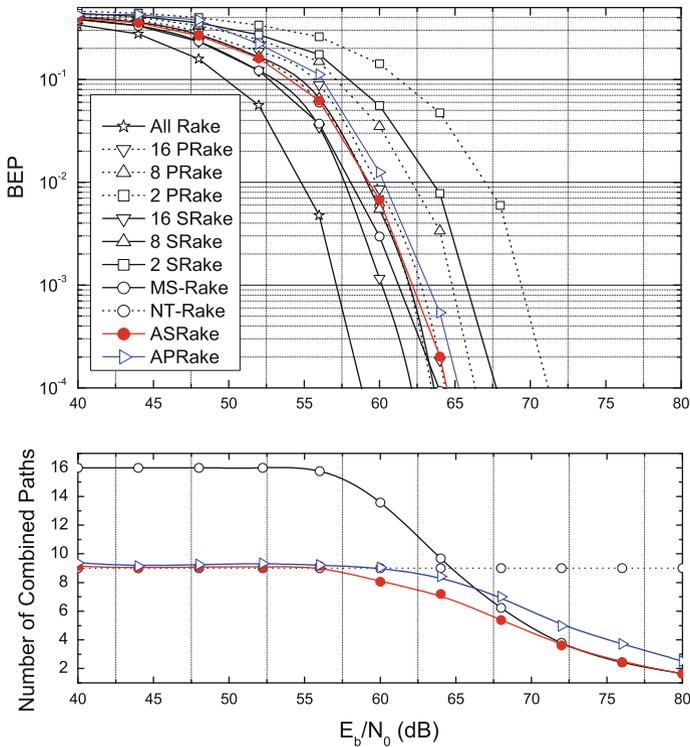
### 3.1 Adaptive SRake

Figure 1 describes the operation mode of the ASRake receiver. More specifically, ASRake receiver introduces two parameters, which control the number of the “significant” paths that will be taken into account through the combining process. The first parameter is the threshold,  $\gamma_T$ , which determines the overall required quality of communication, usually adjusted dynamically according to the service in use. The second parameter,  $\mu$ , controls the expected performance improvement that each path should provide in case of selection and equals to the ratio of the SNR of each branch to the SNR of the first one. The first branch is set as the reference one for the evaluation of the performance improvement that each path offers, as it is the strongest one after the ranking. The value of this parameter is specified by the system’s designer and is usually determined after taking into account the transmission environment and theoretical or simulation results (e.g. NT-GSC Receivers). The ASRake receiver keeps adding paths only if the sum of their SNR has not reached the predefined threshold  $\gamma_T$  and the ratio of each branch (see Fig. 1) to the first one is below  $\mu$ . ASRake receiver, similar to the SRake one, estimates the instantaneous powers of all the  $M$  resolvable paths so that it can sort the  $L$  ones according to their powers. Additionally, compared to SRake, the proposed receiver performs at most  $2M$  more algebraic comparisons, which is however a negligible complexity increment, compensated by the reduction of the combined paths.

The main advantage of the ASRake receiver is the power consumption reduction, compared to ARake, because it avoids to combine those paths that practically do not offer much in the system performance (i.e. the low SNR paths), or it stops combining paths as soon as the desirable quality has been reached. This is important, especially in diversity rich environments, where the resolvable paths are more than a hundred and combining a fixed number of them results in insufficient exploitation of system resources.

### 3.2 Adaptive PRake

The mode of operation for the APRake receiver is also described in Fig. 1 and is similar to that of the ASRake receiver; that is, the receiver keeps adding paths until either the desired



**Fig. 2** The ABEP and the number of combined branches versus the first path SNR for the CM1 channel model

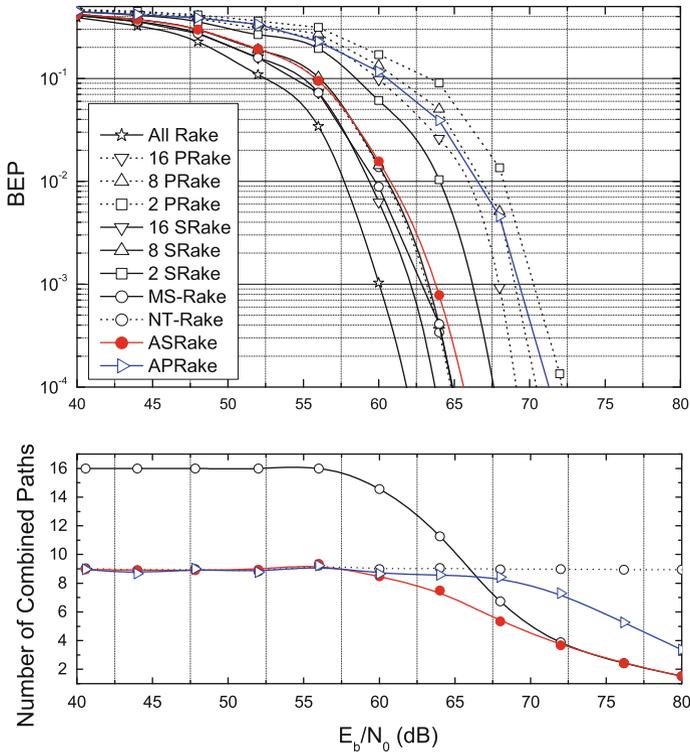
output combined SNR is achieved or the addition of the next path does not compensate the expected performance improvement. However, the APRake receiver estimates considerably less paths, since it combines the first arriving paths and not the strongest ones as the SRake does.

Consequently, APRake receiver offers lower complexity and power consumption, compared to SRake receivers. In comparison to PRake receiver, APRake offers the advantage of adaptation to channel conditions, since it stops estimating and combining branches, as soon as the two predetermined conditions are not fulfilled.

### 4 Performance Analysis

#### 4.1 Bit Error Probability (ABEP) vs. SNR

In this Section, we evaluate the performance of Rake receivers, well-known in the literature, i.e. SRake, PRake, NT-GSC, MS-GSC and compare them with the proposed ASRake and APRake. The comparison is made in terms of the average BEP and the number of combined branches. As mentioned above, we consider realistic UWB channels, and we follow the semi-analytical evaluation of the BEP that was presented in [7]. Moreover, for comparison reasons, the simulation parameters are the same as those in the latter work, as well as the path-loss channel model [21]. The maximum number of combined paths for the NT-GSC, MS-GSC

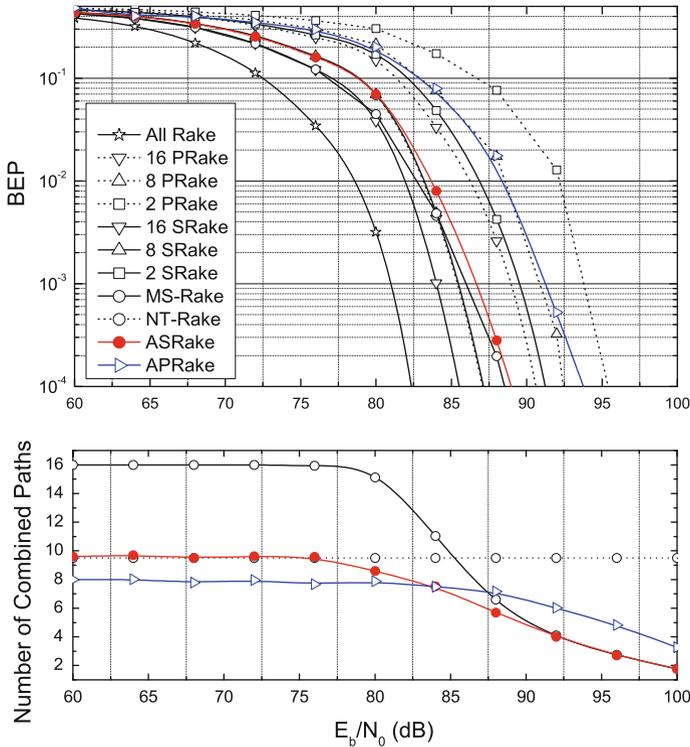


**Fig. 3** The ABEP and the number of combined branches versus the first path SNR for the CM2 channel model

and the proposed receivers is set to 16. In Fig. 2, the ABEP and the number of the combined branches are plotted against SNR for the CM1 channel model. The threshold,  $\gamma_T$ , has been set to 25 dB and  $\mu = 0.6$  and  $\mu = 0.3$  for the ASRake and APRake, respectively. We note that the performance of the ARake receiver is a lower bound to the ABEP and serves only as a benchmark, since it cannot be implemented in practice. By inspection of this figure, two major conclusions can be drawn:

- the receiver’s adaptability to channel conditions results in reduction of the number of the required combined paths without significant performance degradation.
- the simultaneous adaptability to more than one criterion (e.g. the output combined SNR, each path’s SNR) further reduces the number of the combined paths.

More specifically, we can observe that the receivers that take into account quality criteria, i.e. the NT-GSC, MS-GSC and the proposed ASRake and APRake receivers, combine less paths under certain conditions than the SRake and PRake receivers. For example, NT-GSC combines in average 9 paths and has an ABEP degradation of less than 2 dB, compared to the 16-SRake. Similarly, the proposed ASRake receiver achieves a performance close to that of 16-SRake by combining in average less than the half paths compared to the latter. However, the receivers that adjust the number of their combined branches using one criterion (i.e. the MS-GSC and the NT-GSC), have some disadvantages. For example, when using the NT-GSC, the selected paths (i.e., those that satisfy the test per branch rule) can be unnecessarily too



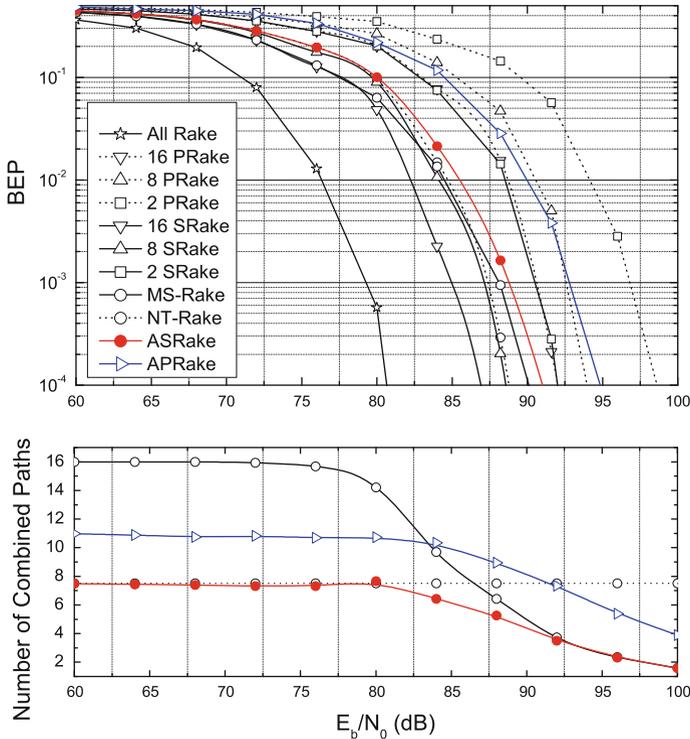
**Fig. 4** The ABEP and the number of combined branches versus the first path SNR for the CM3 channel model

many, while a sufficient quality of communication could be possibly attained by combining less paths (e.g. for SNR greater than 55 dB).

On the other hand, MS-GSC keeps adding weak paths in its attempt to reach the predetermined threshold, while a slightly worse or the same performance can be achieved by combining only the strong paths (e.g. for SNR less than 67 dB). These disadvantages can be efficiently opposed by taking into account the quality of both the output SNR and the SNR of each individual path as in the case of the proposed receivers. We can see that for the whole SNR range ASRake uses always less or equal number of paths compared to MS and NT-GSC, with performance degradation less than 1 dB. In other words, the proposed receivers achieve better adaptation to channel conditions for a predetermined required quality of communication.

The results are also important for the case of the APRake receiver. The reduction in the number of the combined paths in combination with the fact that PRake estimates the power of the first arriving paths (in contrast to SRake), results in a Rake receiver with lower complexity. Regarding the impact of the ratio of the two indexes, the number of the combined branches, and as a result the offered quality, is increased with the threshold and decreased with the augmentation of  $\mu$ .

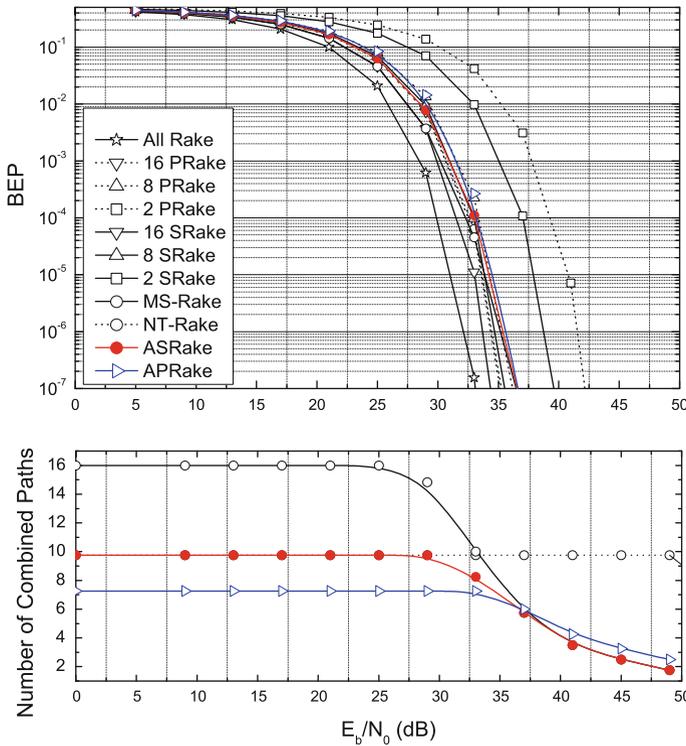
The results in Fig. 3 are based on the CM2 channel model, which is a non line-of sight (NLOS) model. The threshold  $\gamma_T$  has been set to 25 dB and  $\mu = 0.45$  and  $\mu = 0.01$  for the ASRake and APRake respectively. Regarding the SRake receivers, the conclusions do not differ from those related to the CM1 model. However, we can observe that in this case



**Fig. 5** The ABEP and the number of combined branches versus the first path SNR for the CM4 channel model

the PRake receivers achieve considerably worse performance, since in NLOS environments the scattering is severe and the probability that the first arriving paths are the strongest ones is very low. Fig. 4 shows the same results for the CM3 model, where the threshold  $\gamma_T$  has been set to 25 dB and  $\mu = 0.6$  and  $\mu = 0.2$  for the ASRake and APRake, respectively. The values of the system parameters  $\gamma_T$  and  $\mu$  depend on the quality requirements and the wireless channel. Note, that for the case of the PRake and the CM2 model,  $\mu$  has been set to a lower value than that for the CM3 case. This is highly related with the arrival rate of path within each cluster, which is lower for the CM2 model. As a result the difference in power between two sequential paths is small. Similar results are obtained for the CM4 model depicted in Fig. 5.

Finally, Fig. 6 shows the BEP for the case of the LF channel model ( $\gamma_T = 25$  dB and  $\mu = 0.55$ ). The results are interesting, since as it can be seen, the proposed receivers combine considerably less paths than the other receivers, with performance loss smaller than 2 dB compared to the 16-SRake. Furthermore, APRake achieves a performance similar to that of 16-SRake, by combining always less than 7 paths. This concludes that in LF channels there is a high probability of combining unnecessarily too many paths, resulting in wasting power and computational resources. Additionally, APRake does not require power estimation of all the resolvable paths, since it only combines the  $L$  first arriving ones. Therefore, in LF UWB channels, APRake would be a low complexity and efficient receiver, which achieves the desired quality with minimal resources

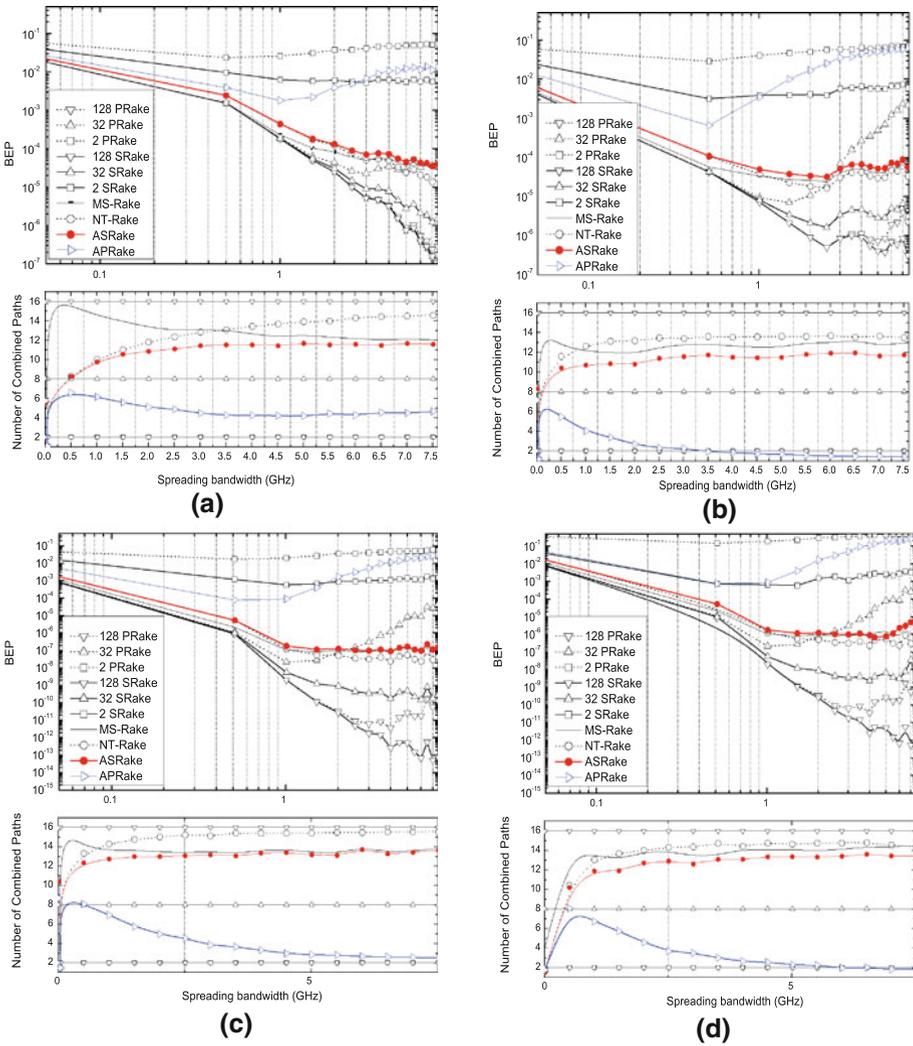


**Fig. 6** The ABEP and the number of combined branches versus the first path SNR for the LF channel model

#### 4.2 BEP vs. Spreading Bandwidth

In this subsection we analyze the influence of the spreading bandwidth on the performance of the Rake receivers, assuming that the power spectral density (PSD) is fixed. In Fig. 7, the BEP and the number of the combined paths that each Rake receiver uses, are plotted versus the spreading bandwidth (SB), considering the HF channel models CM1-4 and SNR equal to 60 dB. It can be observed that there is a minimum value of the SB, at which the BEP is minimized. This happens due to the fact that the increment of the SB implies both an increment of the diversity gain (the number of resolvable diversity paths increases) and a reduction of the average SNR per multipath, since the energy is spreaded among more multipaths. As seen, PRake receivers are more sensitive to the increment of the SB. This is explained by the fact that these receivers collect the energy from the first arriving multipaths and therefore, as the energy is spreaded among more multipaths, the probability that the first paths have almost no energy increases. In other words, when reaching the trade off, PRakes deteriorate as they can not identify and overcome the deep fade effects and the spreading of the energy to more paths.

On the other hand, SRake receivers are less sensitive to the SB increment, since they select the best multipaths and the deep fade effects are reduced (for fixed average SNR per path). Consequently, most of the diversity gain is obtained and the system performance is improved. However, their performance also deteriorates at some point, since the total energy is not infinite and the average SNR per path decreases with the increase of the spreading



**Fig. 7** The ABEP vs. the spreading bandwidth (BW) in a Log-Log scale for the HF channel (CM1–CM4). A constant PSD is assumed

bandwidth. Therefore there is a point, at which the diversity gain due to the multipaths implies less performance gain than the performance loss due to the energy spreading among these multipaths.

Considering the performance of the proposed Rake receivers, it can be seen that for the case of the line of sight (CM1), ASRake can achieve a BEP comparable to other receivers, but with less combined paths. The results do not differ from that obtained in the previous subsection, leading to an additional conclusion; that is the adaptability of the proposed receivers is not affected by the SB. The optimum point of operation of the system, is more distinct on the CM2, CM3 and CM4 channel model. This is because CM1 channel model refers to LOS (0–4 m), which means that the effect of deep fade is not considerable.

## 5 Conclusions

Two adaptive Rake receivers for UWB applications, called ASRake and APRake, were presented and analyzed. The proposed schemes achieve better adaptation to channel conditions compared to other previously known receivers, reducing the number of estimated or combined paths without considerably increasing the complexity. Their performances were evaluated in various practical UWB channels, whose models are based on extensive propagation measurements. The suggested receivers compromise between the hardware complexity, power consumption and performance gain, resulting in significant savings in power and computational resources.

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