

An Efficient Finger Allocation Method for the Maximum Likelihood RAKE Receiver

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Abstract. In wideband wireless communication systems the RAKE receiver is commonly used to collect the resolvable multipath energy and counter the effects of fading through diversity. However, in channels with large delay and energy spread, its high complexity still remains a major issue. This motivates the study and application of computationally efficient finger placement algorithms that significantly reduce the receiver complexity with a reasonable performance loss. In this paper, a low-complexity maximum likelihood RAKE receiver, the Suboptimum – Maximum Power Minimum Correlation (S-MPMC) RAKE is proposed. The allocation of its first two fingers is based on the received signal correlation properties. Their positions determine also the placement of the rest of the fingers. Simulation results are provided to show the operation of the receiver and demonstrate its performance. Comparisons with relevant methods are performed to corroborate the merits of the proposal. The balance on the performance and the complexity of the technique makes it suitable for use in commercial wideband communication systems.

Keywords

Code division multiple access, correlation, maximum likelihood detection, multipath channels, rake diversity, wireless communications.

1. Introduction

Originally, wireless communication systems were motivated by and intended for mobile voice services. However, nowadays subscribers are looking further for broadband services and Internet access and demand a vast range and diversity of converged devices, applications, and networks, [1], [2]. An effective wireless access technology for supporting high-speed mobile data services and great system capacity adopted in third generation (3G) air interface is Wideband Code Division Multiple Access (WCDMA), [3], [4]. With the current growth in demand for wireless systems, new methods are proposed to improve system performance and quality of services.

The design of highly efficient receivers with a good balance in both performance and complexity is a major

challenge for engineers. In WCDMA communications, the RAKE receiver is frequently used [5]. This structure has multiple correlators which collect the resolvable multipaths. After despreading by a local copy of the delayed version of the transmitter's spreading code, the signals are suitably combined to exploit multipath diversity gain. Common diversity combining methods include maximal ratio combining (MRC), a maximum likelihood (ML) criterion, equal gain combining (EGC), and generalized selection combining (GSC), (see, for example, [5-10]).

An important issue in the design of RAKE receivers is fingers allocation. Usually finger spacing equals the chip period, which is the optimal choice for the MRC RAKE under the assumption of uncorrelated finger signals [11]. However, when a correlation between the desired, interference, and noise signals at the output of each finger is considered, MRC is no longer optimum. In [6], a combining rule based on the ML criterion, improved system performance by setting the finger spacing below the chip duration. Maximum likelihood principles were also used in [12-14] for the estimation of optimum fingers positions or combining weights. However, the great complexity of these techniques is a major drawback, especially in wideband channels. As a result, computationally efficient methods, e.g. [15-17], that significantly reduce the complexity of the optimal solution with a reasonable performance loss are of great interest.

In this paper, a suboptimum reduced complexity RAKE receiver is proposed. The Maximum Power Minimum Correlation (MPMC) criterion, [14], is used for the allocation of the first two fingers of the receiver. This means that their positions are determined by the simultaneous maximization of the sum of squares of average received signal power in each one and minimization of the correlation between them. The rest of the fingers are uniformly distributed at distances equal to the distance between the first two ones. Notice that the MPMC criterion, as applied in [14], is based on the minimization of the sum of squares of the correlation between the fingers signals. However, in the proposed receiver, the suboptimum MPMC (S-MPMC) RAKE, the criterion is simplified because optimization involves only two fingers. ML principles are finally used for the combining of the fingers' outputs and the determination of the decision variable, [5], [6], [9], [10], [12-14].

The main contribution of the proposal is its simplicity compared to the MPMC RAKE. In that receiver, the fingers were optimally spaced within the channel spread and its outputs were suitably combined using the ML criterion. However, its major drawback was its high complexity, especially in wideband environments. On the contrary, the S-MPMC RAKE is far simpler and effective in environments with large energy and delay spread where a larger number of fingers is required. In order to show the merits of the proposal, comparisons between the proposed receiver and relevant structures are performed.

The paper is organized as follows. In Section 2, the transmitter and channel model is introduced. The proposed finger allocation method and the S-MPMC RAKE receiver are described in Section 3. In Section 4, numerical results and discussions are provided. Finally, conclusions are drawn in Section 5.

2. Transmitter and Channel Model

Consider a direct sequence (DS) CDMA communication system with K active users. Let T_b and T_c are the bit and chip period respectively, G the processing gain, and E_b the signal energy per bit. For simplicity and without loss of generality, E_b is assumed equal for all users. Considering BPSK modulation, the equivalent low-pass data modulated transmitted signal of the k th user is

$$s_k(t) = \sqrt{\frac{2E_b}{G}} \sum_{\lambda=-\infty}^{\infty} b_{\lfloor \lambda/G \rfloor}^k a_{\lambda}^k p(t - \lambda T_c) \quad (1)$$

where $b_{\lfloor \lambda/G \rfloor}^k$ and a_{λ}^k are the binary data and spreading sequences of the k th user respectively. Notation $\lfloor x \rfloor$ denotes the largest integer not greater than x and $p(t)$ is the normalized chip waveform. For simplicity, the transmitted pulses are assumed time-limited rectangular, a common assumption in CDMA systems (see, for example [6], [14], [18], [19]); since the tails of the chip waveform can be designed to decay rapidly, [10], the previous assumption is not far from reality, [18].

The wireless channel is modeled as a wide-sense stationary uncorrelated scattering (WSSUS) frequency-selective Rayleigh fading one. Therefore, the total received signal at the receiver front-end is

$$r(t) = \sum_{k=0}^{K-1} r_k(t - \tau_k) + n(t) \quad (2)$$

where $n(t)$ is a low-pass equivalent process of Additive White Gaussian Noise (AWGN) with double-sided power spectral density $N_0/2$, τ_k is the time of arrival of the k th user's signal, and $r_k(t)$ is the received signal due to the k th user given by, [20]:

$$r_k(t) = \int_{-\infty}^{\infty} h_k(\tau; t) s_k(t - \tau) d\tau \quad (3)$$

where $h_k(\tau, t)$ is the channel impulse response of the k th user's link at delay τ and time instant t , modeled as a complex zero-mean Gaussian random process. Its autocorrelation function is the power delay profile (PDP) of the channel expressed as

$$g(\tau) = E \left\{ |h_k(\tau; t)|^2 \right\}. \quad (4)$$

In the case of a uniform PDP channel, (4) becomes

$$g(\tau) = \begin{cases} 1/\tau_{\max}, & \tau \in [0, \tau_{\max}] \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

where τ_{\max} is the maximum delay spread of the channel. When the propagation channel is described by an exponential PDP with decay constant τ_d , (4) gives that

$$g(\tau) = \frac{1}{\tau_d} e^{-\tau/\tau_d} \cdot U(\tau) \quad (6)$$

where $U(\tau)$ is the unit step function.

3. Proposed Receiver

The proposed L -finger receiver model is illustrated in Fig. 1. The receiver is matched to the desired user's pseudo-noise (PN) signature sequence. The received signal $r(t)$ is passed through a tapped delay line with fingers positioned at T_i , $i=1,2,\dots,L$ time instants. At each finger, the received signal is despread by passing through a correlator matched to the desired user's signature sequence.

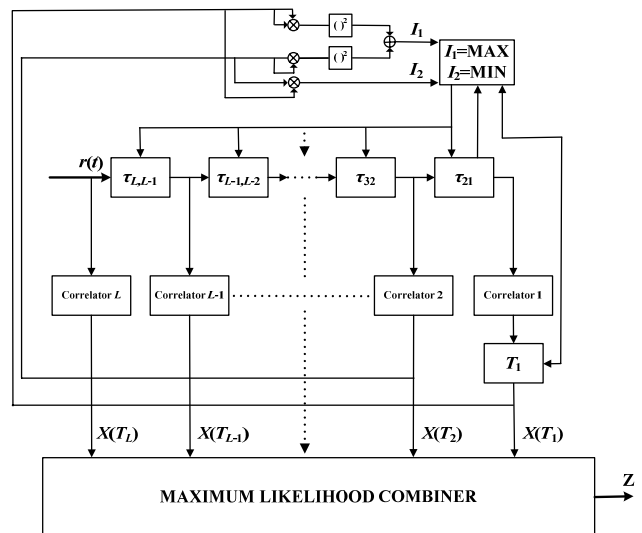


Fig. 1. Proposed receiver model.

A further improvement in the receiver performance is obtained by the introduction of an additional timing offset at the output of the first correlator. In Fig. 1, it is $\tau_{j,j-1} = T_j - T_{j-1}$, $j=2,3,\dots,L$, and

$$I_1 = E \left\{ |X(T_1)|^2 \right\}^2 + E \left\{ |X(T_2)|^2 \right\}^2, \quad (7)$$

$$I_2 = E\{X(T_1) \cdot X^*(T_2)\} \quad (8)$$

the sum of squares of the average received power in each one of the first two fingers and the crosscorrelation of their outputs respectively. The outputs of the fingers are

$$X(t) = X_d(t) + \sum_{k=1}^{K-1} X_k(t) + X_s(t) + X_n(t) \quad (9)$$

where $X_d(t)$, $X_k(t)$, $X_s(t)$, and $X_n(t)$ are the desired user ($k=0$) signal, the multiple user interference (MUI) due to the k th user, the intersymbol interference (ISI), and the AWGN components, respectively. These are, [6]:

$$X_d(t) = \sqrt{2E_b} b_1^0 h_0(t) \otimes R_{hh}(t), \quad (10)$$

$$X_k(t) = \sqrt{2E_b} \sum_{n=-\infty}^{\infty} h_k(t) \otimes d_n^k R_{hh}(t - nT_c - \tau_k), \quad (11)$$

$$X_s(t) = \sqrt{2E_b} \sum_{\substack{n=-\infty \\ n \neq 0}}^{\infty} h_0(t) \otimes d_n^0 R_{hh}(t - nT_c), \quad (12)$$

$$X_n(t) = \frac{1}{\sqrt{G}} \sum_{\lambda=0}^{G-1} n(t) \otimes a_{\lambda}^{0*} p^*(-t - \lambda T_c) \quad (13)$$

where \otimes denotes the convolution operator, b_1^0 is the first bit of the desired user data sequence, d_n^k is the discrete crosscorrelation function between the desired and the k th user calculated from

$$d_n^k = \frac{1}{G} \sum_{\lambda=0}^{G-1} b_{[(\lambda+n)/G]}^k a_{\lambda+n}^k a_{\lambda}^{0*}, \quad (14)$$

and $R_{hh}(t)$ is the autocorrelation function of $p(t)$ given by

$$R_{hh}(t) = \int_{-\infty}^{\infty} p(\xi+t) p^*(\xi) d\xi. \quad (15)$$

The receiver has exact knowledge of the chip waveform shaping filters in transmitter and receiver and the desired user channel response. The last is achieved using a known bit sequence that is either time multiplexed with the information (pilot symbols) or transmitted as a separate channel (pilot channel).

As already mentioned, in the proposed receiver fingers allocation is based on the correlation properties of the signal outputs of the first two fingers. The autocorrelation of a finger output gives its average received signal power. In the S-MPMC RAKE, the squares of the autocorrelation of the first two fingers are added giving I_1 . Their crosscorrelation I_2 is also calculated. The optimum finger placement of the first two fingers is derived from the simultaneous maximization of I_1 and minimization of I_2 . The rest of the fingers are spaced at distances equal to the distance of the first two fingers, i.e. it is $\tau_{j,j-1} = T_j - T_{j-1}$, $\forall j \in \{2, 3, \dots, L\}$. This multi-objective optimization criterion is a subcase of the MPMC criterion, [14], and is expressed as:

$$\text{find } \mathbf{T}: \begin{cases} \text{maximize} & E\{|X(T_1)|^2\} + E\{|X(T_2)|^2\} \\ \text{minimize} & E\{X(T_1) \cdot X^*(T_2)\} \end{cases} \quad (16)$$

or equivalently:

$$\text{find } \mathbf{T}: \max_{\mathbf{T}} \mathbf{F}(\mathbf{T}) \quad (17)$$

where $\mathbf{T} = \{T_1, T_2\}$ the vector that contains the positions of the first two fingers and $\mathbf{F}(\mathbf{T}) = \{f_1(\mathbf{T}), f_2(\mathbf{T})\}$ with $f_1(\mathbf{T}) = I_1$ and $f_2(\mathbf{T}) = 1/I_2$. Considering that $X_d(t)$, $X_k(t)$, $X_s(t)$, and $X_n(t)$ are generated from independent sources from (9)-(13) comes, [6], that:

$$E\{X(t_1) \cdot X^*(t_2)\} = E\{X_d(t_1) \cdot X_d^*(t_2)\} + \sum_{k=1}^{K-1} E\{X_k(t_1) \cdot X_k^*(t_2)\} + E\{X_s(t_1) \cdot X_s^*(t_2)\} + E\{X_n(t_1) \cdot X_n^*(t_2)\} \quad (18)$$

$$E\{X_d(t_1) \cdot X_d^*(t_2)\} = 2E_b \times \int_{-\infty}^{\infty} g(\xi) R_{hh}(t_1 - \xi) R_{hh}^*(t_2 - \xi) d\xi \quad (19)$$

$$E\{X_k(t_1) \cdot X_k^*(t_2)\} = \frac{2E_b}{GT_c} \times \int_{-\infty}^{\infty} R_{hh}(\xi) R_{hh}^*(\xi - (t_1 - t_2)) d\xi \quad (20)$$

$$E\{X_s(t_1) \cdot X_s^*(t_2)\} = \frac{2E_b}{G} \times \left[\sum_{\substack{n=-\infty \\ n \neq 0}}^{\infty} \int_{-\infty}^{\infty} \left(g(\xi) R_{hh}(t_1 - \xi - nT_c) \times \right. \right. \\ \left. \left. \times R_{hh}^*(t_2 - \xi - nT_c) \right) d\xi + \sum_{\substack{n=-G \\ n \neq 0}}^G \left(1 - \frac{|n|}{G} \right) \int_{-\infty}^{\infty} \left(g(\xi) R_{hh}(t_1 - \xi + nT_c) \times \right. \right. \\ \left. \left. \times R_{hh}^*(t_2 - \xi - nT_c) \right) d\xi \right] \quad (21)$$

$$E\{X_n(t_1) \cdot X_n^*(t_2)\} = 2N_0 R_{hh}(t_1 - t_2). \quad (22)$$

In this paper, the lexicographic method, [21], has been applied to solve the optimization problem. Maximization of I_1 was the *premier importance* optimization problem. The second optimization problem (minimization of I_2) is equivalent to the maximization of $1/I_2$. Notice that this method is not the most appropriate for this kind of problems (see, for example, [22]). However, its simplicity and low computational cost allows its use in real-time applications. Comparisons with a *Pareto* based methods have given similar results in a shorter amount of time. The small number of variables to be optimized allows the use of exhaustive search algorithms also, [23].

Finally, the outputs of the fingers are suitably combined using the ML criterion, [6], to determine the decision variable Z .

4. Numerical Results and Discussions

In this Section, results of the evaluation of the proposed finger allocation method and the performance of the

S-MPMC RAKE receiver are presented. Comparisons with the conventional MRC RAKE¹, [5], [9], [10], the ML RAKE with constant finger spacing², [6], the MPMC RAKE, [14], and the generalized G-RAKE, [12], are conducted. In the simulations, rectangular chip pulses and propagation channels with uniform and exponential PDP have been used. Without loss of generality, the processing gain is assumed $G=256$. In the ML RAKE adjacent fingers are spaced at distance 0.7 chip periods as in [6].

In Fig. 2, the error probability P_e is illustrated versus E_b/N_0 for various receivers. A uniform PDP channel with maximum delay spread two chip periods is considered. Totally ten users are present. The S-MPMC RAKE performs better than the MRC and the ML RAKE, especially at high E_b/N_0 . For example, at $E_b/N_0=15$ dB the error probability of the S-MPMC 3RAKE³ is around 30% smaller compared to the ML 3RAKE; at $E_b/N_0=30$ dB it is around 35%. In the 4-finger receivers, it is 15% and 55% smaller respectively. At low E_b/N_0 improvement is smaller (around 15% and 5% at $E_b/N_0=5$ dB for the 3-finger and 4-finger receivers respectively). Compared to the MRC RAKE the proposed receiver performs even better. Performance of the MPMC and the S-MPMC RAKE is almost identical (differences are less than 5%) as a result of the small number of fingers. However, the computational and hardware complexity of the S-MPMC RAKE are obviously smaller. The fingers' positions (in chip periods) of the MPMC and the S-MPMC RAKE are given in Tab. 1. It easily comes that the proposed finger allocation method gives results close to the ones that are derived from the application of the MPMC criterion to all the fingers.

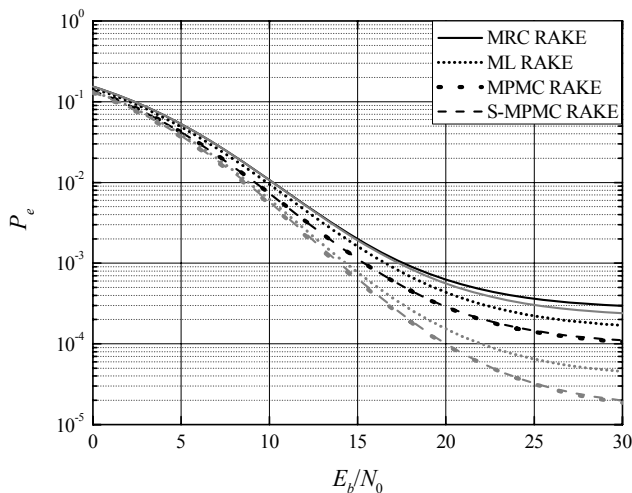


Fig. 2. Bit error rate performance for different finger allocation in the uniform PDP channel (black (gray) lines represent the performance of the 3-finger (4-finger) receivers).

¹ In the text, it will be mentioned as MRC RAKE for brevity.

² In the text, it will be mentioned as ML RAKE for brevity.

³ In the text, the notations 3RAKE and 4RAKE are considered equivalent to the 3-finger and 4-finger RAKE respectively.

Fingers settings:	T_1	T_2	T_3	T_4
S-MPMC 3RAKE	0.33	1.00	1.67	–
MPMC 3RAKE	0.28	0.98	1.69	–
S-MPMC 4RAKE	0.25	0.75	1.25	1.75
MPMC 4RAKE	0.28	0.65	1.30	1.70

Tab. 1. Fingers allocation in the uniform PDP propagation channel.

In the simulation examples presented in Fig. 3, the PDP of the channel is exponential with a decay constant equal to two chip periods. The 4-finger RAKE receivers are considered. The rest of the system parameters are the same as before. From Figs. 2 and 3, it comes that performance improvement due to the non-uniform finger spacing is smaller in the exponential PDP channel. The fingers' positions (in chip periods) are given in Tab. 2. In contrary to the previous example, significant differences are observed in the fingers allocation between the S-MPMC and the MPMC RAKE receivers. However, the impact on system performance is negligible.

Fingers settings:	T_1	T_2	T_3	T_4
S-MPMC 4RAKE	0.22	0.91	1.60	2.29
MPMC 4RAKE	0.31	1.00	1.74	2.64

Tab. 2. Fingers allocation in the exponential PDP propagation channel.

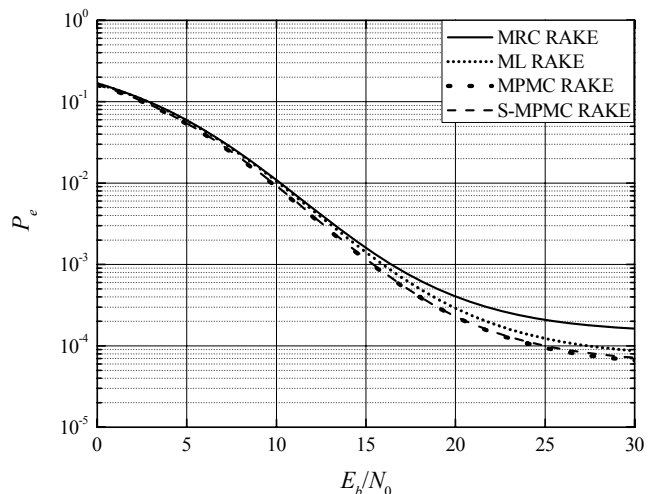


Fig. 3. Bit error rate performance for different finger allocation in the exponential PDP channel.

In Fig. 4, the maximum number of users allowed in the system versus E_b/N_0 is presented. An error probability smaller than 10^{-3} (a value adequate for speech services, [24]) is expected. The 3-finger and 4-finger RAKE receivers are considered. The radio channel is a uniform PDP one with maximum delay spread two chip periods. An increase in the number of users of up to 50% is noticed for the S-MPMC and the MPMC RAKE compared to the MRC receiver. Compared to the ML RAKE the increase is around 30%. Performance of the MPMC and the S-MPMC RAKE is similar especially at high E_b/N_0 .

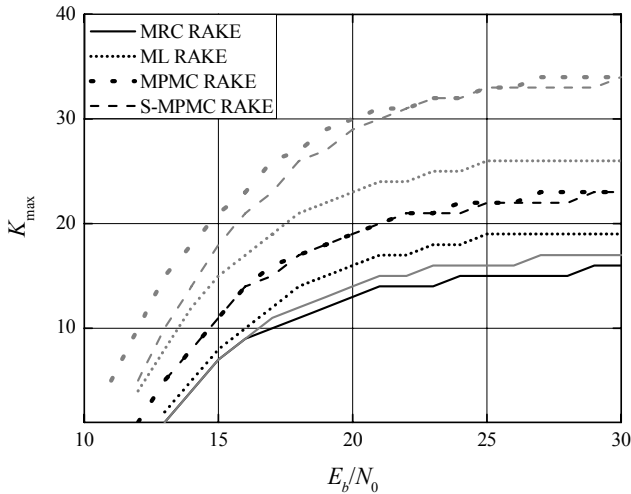


Fig. 4. Maximum number of users versus E_b/N_0 for different finger allocation in the uniform PDP channel (black (gray) lines represent the performance of the 3-finger (4-finger) receivers).

In general, increasing the number of fingers up to a point degrades MRC RAKE performance because the energy gathered from the additional fingers is only due to noise components. However, a larger number of fingers with narrower spacing over the full range of delay spread allow ML, MPMC, and S-MPMC RAKE receivers to overcome this problem by collecting more energy. The optimized finger allocation of the MPMC and the suboptimum MPMC RAKE offers an enhanced performance of these receivers over ML RAKE by reducing the received noise and interference.

A critical issue in the receiver design is the balance on the performance and complexity in a wideband channel. One of the most promising commercial proposals, [25], is the G-RAKE, [12]. The instantaneous optimum G-RAKE, (IOG-RAKE) and the average optimum G-RAKE, (AOG-RAKE), are considered. In implementations with few fingers, performance gain⁴ compared to the conventional RAKE receivers is 1.2-1.7 dB in signal to noise ratio, depending on the number of the fingers. Similar or even improved, at high E_b/N_0 , performance gain is achieved by using the S-MPMC RAKE, see Fig. 2.

In Fig. 5, performance degradation due to increase in the number of users of several 8-finger RAKE receivers is studied ($E_b/N_0=10$ dB). The 8-ray Rayleigh fading vehicular channel with equal rays spacing is considered, [12]. The fingers settings (in chip periods) of the MPMC and the S-MPMC RAKE are given in Tab. 3. As expected, the G-RAKE receivers show an improved performance compared to the proposed one (in the G-RAKE both fingers positions and weights are optimized). However, in this case, finger allocation is based on exhaustive search algorithms adding further computational complexity. Also, at low P_e values differences are small. Similar conclusions are derived from the comparison between the MPMC and

the S-MPMC RAKE. On the contrary, the S-MPMC RAKE performs significantly better than the MRC and the ML RAKE.

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
I	0.38	1.13	1.88	2.63	3.38	4.13	4.88	5.63
II	0.40	1.31	2.21	3.00	3.64	4.50	5.36	6.00

Tab. 3. Fingers allocation in the 8-ray Rayleigh fading vehicular channel. Row I responds to the S-MPMC and row II to the MPMC RAKE receiver.

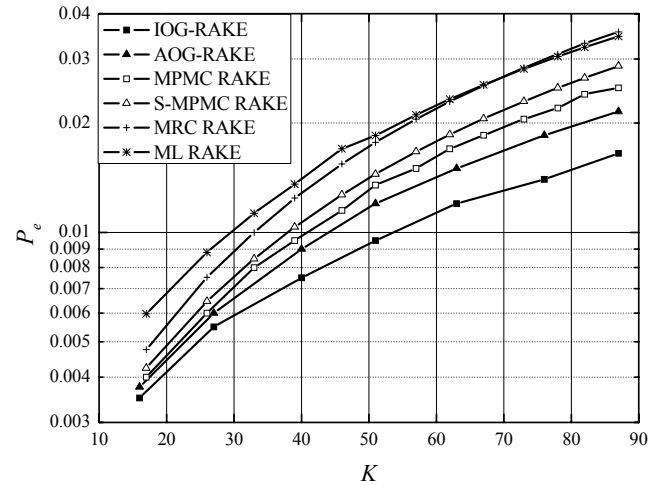


Fig. 5. Comparative performance of different RAKE receivers in a wideband environment.

As a final comment to the efficiency of the proposal, the complexity of the proposed receiver and the MPMC RAKE should be discussed. The computational complexity of the proposed finger allocation method is significantly smaller as long only two, instead of L , variables are optimized. The reduction in hardware complexity is also significant. The L -finger MPMC RAKE has $L^2/2+3L/2$ correlators, L at the outputs of the fingers and $L(L+1)/2$ in the correlation coefficients estimation unit, [14]. On the other hand, the L -finger S-MPMC RAKE uses only $L+3$ correlators. This denotes a reduction in the correlators when using the S-MPMC instead of the MPMC RAKE receiver, which is inversely proportional to the number of fingers. The significant reduction in computational and hardware complexity also results in lower size, cost, and power consumption of the terminals.

5. Conclusion

In this paper, an efficient finger allocation method has been proposed for the maximum likelihood RAKE receiver. Placement of the first two fingers is determined from the maximization of the sum of the squares of the total received power from each one and the simultaneous minimization of the crosscorrelation between them. The rest of the fingers are spaced at distances equal to the distance of the first two fingers. Simulation examples have shown that the proposed receiver performs better than the

⁴ 14th line, 2nd col., pp. 1543, in [12].

conventional MRC and the ML RAKE with constant finger spacing. In wideband channels the reduced complexity of the S-MPMC RAKE compensates for its worst performance compared to the MPMC and the G-RAKE receivers. The major advantage of the proposal is its lower computational cost. Concluding, the decreased hardware complexity, power consumption, size, and cost of the proposed receiver make it an interesting solution for mobile systems.

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