RAKE RECEIVER ANALYTICAL STUDY FOR TD-CDMA DOWNLINK EVALUATION

Saloua Ammari [1], Armelle Wautier [2]

[1] Bouygues Telecom – R&D : 10, Rue Paul Dautier - 78944 Vélizy Cedex, France
[2] SUPELEC, Service Radio : 3, Rue Joliot-Curie - 91192 Gif sur Yvette, France
e-mail: sammari@bouyguestelecom.fr ; armelle.wautier@supelec.fr

ABSTRACT

CDMA systems generate intra-cell interference due to multipath propagation and or asynchronous transmission. Whereas interference cancellers or joint detectors are envisaged to reduce the interference in the uplink, CDMA mobile handsets are more limited in complexity. This paper is focused on the evaluation of the RAKE receivers when spreading sequences have short periods in a synchronous downlink transmission with multipath propagation. The bit-error-rate evaluation based on the randomness assumption of spreading codes can not be applied. We show that exact evaluation of the bit-error-rate, exploiting the sequences properties for any multipath channel profile (considering fractionally chip delayed paths) is feasible. This proposed evaluation is applied to the TD-CDMA mode of UMTS. This analytical study can be easily implemented and gives the performances for different scenarios avoiding simulations. It can also be useful to optimize the channel allocation code strategy or to evaluate the equivalent interference factor needed for capacity evaluation.

1. INTRODUCTION

In the third generation mobile system, the TDD (Time Division Duplex) mode is based on a combination of TDMA (Time Division Multiple access) and CDMA (Code Division Multiple Access) techniques. The TDD mode is intended for applications in micro and picocell environments and is well suited for asymmetric applications as well as for multirate applications with multi-slot and/or multicode allocation. The TDMA component combined with short spreading codes make the use of the joint detection feasible for the base station reception [1]. Mobile handsets may use a basic RAKE receiver or multi-user Joint detectors according to tradeoffs between performance and complexity. In any case, it must be pointed out that it is interesting to study the performances obtained with the basic RAKE receiver in order to determine the limits of such a receiver and to decide if or not the implementation of more complex receivers has to be done. In a single-user context the RAKE receiver is optimal on a white additive gaussian channel without multipath, since in that case, it corresponds to the matched filter receiver for direct spreading sequence modulations. The matched filter receiver is still optimal in a CDMA multi-user context when the spreading sequences are orthogonal. This is the case of a synchronous downlink transmission without multipath propagation. The RAKE receiver becomes a sub-optimal solution when multipath propagation occurs because it generates intersymbol as well as multiple access interference. The degradation depends on the channel time spreading and on the correlation properties between spreading sequences. The aim of this paper is to evaluate this degradation by evaluating analytically the RAKE receiver performance for the TD-CDMA downlink transmission. This evaluation is compared to the matched filter bound (MFB) in the case of a single code transmission. Indeed, the performances of a CDMA system in a multi-user context is lower bounded by this MFB due to multipath, which can be evaluated for any channel profile and for any signal waveform [2], [3], and in particular for specific signature CDMA spreading waveforms.

Although many papers have been devoted to the RAKE receiver in the literature, they are restricted to ideal code cases. Different studies have been focused on the performances of the RAKE receiver for random spreading sequences cases [4]. The performances obtained with this assumption are valid for CDMA systems with very long sequences, which can be modeled as random sequences. Papers have also been devoted to the case of pseudo-noise sequences [5]. In [6], a DS-CDMA system with random binary sequences is investigated assuming the interference to be gaussian in order to evaluate the bit-error-rate. In [7], Cheun has analyzed the RAKE receiver performances in the case of low spreading factors, assuming the inter-symbol and multi-access interference to be gaussian. He has shown that the gaussian approximate is not satisfactory for short spreading factors. Cheun has lead an exact evaluation by considering random sequences with a short spreading factor, by using appropriate binomial random variables instead of the gaussian approximate [7].

In the TD-CDMA system, spreading factor (equal to 16 in the downlink) is short and spreading sequences can neither be considered random nor long. The approximations used to carry out the receiver performances in the last mentioned works can not be applied in this case. The paper is structured as follows. Section 1 presents the system transmission model. In section 2, we derive the performance expressions of a RAKE receiver. In the third section, simulation results illustrate some applications showing the importance of this study. It can be useful for example to optimize the channel allocation code strategy or to evaluate the equivalent interference factor needed for evaluating downlink system capacity. It can also be exploited to show the limits of the gaussian approximate. In the last section, we draw some concluding remarks and insights.

2. SYSTEM TANSMISSION MODEL

For the development of the receiver performances, we need first to define the system model. We consider the downlink transmission, the spreading factor is the same for all the transmitted signals and all the multiplexed signals pass through the same propagation channel. The impulse response of the propagation channel experienced by mobile user n is expressed as:

$$h_c^{(n)}(t)=\sum_{k=1}^{M}c_k^{(n)}\delta(t-\tau_k^{(n)})$$

The baseband equivalent CDMA signal received by mobile user p can be written as:

$$r(t)=\sum_{k=1}^{K}\beta^{(k)}\sum_j u_j^{(k)}\sum_{l=1}^{M}c_l^{(n)}p_j^{(k)}(t-jT-\tau_l^{(n)})+\upsilon(t)$$

K denotes the number of allocated codes in the downlink, T stands for the symbol period, $u_j^{(k)}$ denotes the j^{th} transmitted modulated data symbol associated to code k ($u_j^{(k)}\in\{\pm1,\pm i\}$), $p_j^{(k)}(t)$ denotes the spreading waveform associated to code k on data symbol j, $\beta^{(k)}$ denotes the power amplifier gain, $c_k^{(n)}$ and $\tau_k^{(n)}$ denote respectively the coefficients and the delays of the baseband equivalent impulse response of the transmission channel for mobile user n and $\nu(t)$ is an additive white gaussian noise. The spreading waveforms are periodic of period the symbol period T. Therefore, the spreading waveform of the user n is identical for all the symbols and has the following form:

$$p_j^{(n)}(t)=p^{(n)}(t)=\sum_{p=0}^{15}\nu_p^{(n)}g(t-pT_c),$$

where $\nu_p^{(n)}=Sc_p^{(n)}.Ch_p^{(n)}$, Sc and Ch denote respectively the scrambling code which is cell specific and the channelization code issued from walsh sequences which is data flow mobile station specific. Scrambling codes belong to a set of 128 tabulated complex codes defined in the 3GPP Technical reports [8]. The emitted pulse shape $g(t)$ is a square-root raised cosine filter with a roll-off factor of 0.22. The mean energy per bit of the received modulated signal associated to user n is given by:

$$E_b^{(n)}=\beta^{(n)^2}\sum_{k=1}^{M}\sum_{l=1}^{M}c_k^{(n)*}c_l^{(n)}\pi^{(n,n)}\left(\tau_k^{(n)}-\tau_l^{(n)}\right)/2$$

where $\pi(t)$ denotes the convolution of $p(t)$ and $p(-t)^*$.

3. RAKE RECEIVER PERFORMANCES

3.1 Description of the RAKE receiver structure

3.1.1 Ideal finger locked RAKE receiver

Assuming an ideal channel impulse response estimation, the RAKE receiver locked to the most significant fingers is composed of a parallel rank of L matched filters

$$c_k^{(n)*}p_i^{(n)*}(t-iT-\tau_k^{(n)}).$$

The outputs of the matched filters are summed up and passed to a detector. For $L=M$, the decision variable for user n has the following expression:

$$U_i^{(n)}=\sum_{k=1}^{M}c_k^{(n)^*}\int_{-\infty}^{\infty}r(t)p_i^{(n)}(t-iT^{(n)}-\tau_k^{(n)})^*dt$$

After some development of this latter formula, the decision variable is the sum of only three different terms [9]: an inter-symbol interference term $X_i^{(n)}$, a multipath multi-user interference term $Y_i^{(n)}$ and a noise term $n_i^{(n)}$. These three terms can be expressed respectively as:

$$X_i^{(n)}=\beta^{(n)}\sum_n u_{i+n}^{(n)}\rho_{i+n,i}^{(n,n)},$$

$$Y_i^{(n)}=\sum_{p\neq1}\beta^{(p)}\sum_j u_j^{(p)}\rho_{j,i}^{(p,n)}$$

$$n_i^{(n)}=\sum_{l=1}^{M}c_l^{(n)*}\int\nu(t)p^{(n)}(t-iT^{(n)}-\tau_l^{(n)})^*dt$$

where:

$$\rho_{j,i}^{p,n}=\sum_{k,l}c_l^{(p)}c_k^{(n)*}\pi^{(p,n)}(iT^{(n)}-jT^{(p)}+\tau_k^{(n)}-\tau_l^{(p)})$$

The filtered noise at the output of the RAKE receiver is given by:

$$E[(\Re(n_i^{(n)}))^2]=N_0\rho_{i,i}^{(n,n)}$$

3.1.2 Finger locked RAKE receiver with imperfect channel estimation

When the different estimates of the channel attenuations and delays replace the real values of the channel parameters, the expression of the adapted filters is then written as:

$$\hat{c}_k^{(n)*}p_i^{(n)*}(t-iT-\hat{\tau}_k^{(n)}),$$

where $\hat{c}_k^{(n)}$ and $\hat{\tau}_k^{(n)}$ stand for the estimate channel parameters.

3.1.3 Discrete-time RAKE receiver

To circumvent the problem of delay estimation and finger selection in a practical conventional RAKE receiver, a discrete time RAKE receiver is an alternate solution [10]. It consists in sampling the filtered received signal $z(t)$ at twice the chip rate and by realizing the matched filter with a discrete filter:

$$U_i^{(n)}=A^hZ,$$

where A is the matrix obtained by the convolution of the channel impulse response and the spreading code.

3.2 Exact evaluation of the theoretical ideal RAKE receiver bit-error- rate

Without any loss of generality, we assume that our user of interest is the user number 1. The bit-error-rate is expressed as:

$$P^{(1)}=P(\hat{u}_i^{(1)}\neq u_i^{(1)})=\sum_{k,n}Q\left(\frac{\Re(X_i^{(1)+}(k)+Y_i^{(1)}(n))}{\sqrt{E\left[(\Re(n_i^{(1)}))^2\right]}}\right)P_i(k,n)$$

where $X_i^{(1)+}(k)$ refers to the possible values of $X_i^{(1)}$ assuming $u_i^{(1)}=+1$, and

$$X_i^{(1)+}(k)=\beta^{(1)}x_i^{(1)+}(k)$$
$$Y_i^{(1)}(n)=\sum_{p\neq 1}\beta^{(p)}y_i^{(1,p)}(n)$$
$$P\ (k,n)=P(X_i^{(1)}=X_i^{(1)+}(k),Y_i^{(1)}=y_i^{(1)}(n))$$

Then we can express the bit error verse the E_b/N_0 ratio of the user number 1 as follows:

$$P^{(1)}=\sum_{k,n}Q\left(\sqrt{\left(\frac{2x(\frac{E_b}{N_0})^{(1)}(\Re(x_i^{(1)+}(k)+\sum_{p\neq 1}\frac{\beta^{(p)}}{\beta^{(1)}}\Re(y_i^{(1,p)}(n)))^2}{\left[\sum_k\sum_l c_k^{(1)*}c_l^{(1)}\pi_{i,i}^{(1,1)}(\tau_k^{(1)}-\tau_l^{(1)})\right]^2}\right)}\right)P\ (k,n)$$

3.3 RAKE receiver performance's evaluation using the gaussian approximate

If we assume that the whole interference affecting the desired symbol of the user of interest has a gaussian distribution, then we can write the probability of error over the symbol i of the first user like:

$$P(\hat{u}_i^{(1)}\neq u_i^{(1)})\approx Q\left(\frac{E\left(\Re(U_i^{(1)+})\right)}{\sqrt{Var\left(\Re(U_i^{(1)+})\right)}}\right).$$

After development of the expression of the mean and the variance, we can write this probability of error as follows:

$$P(\hat{u}_i^{(1)}\neq u_i^{(1)})\approx Q\left(\sqrt{\frac{2(\frac{E_b}{N_0})^{(1)}}{1+2(\frac{E_b}{N_0})^{(1)}\xi^{(1,1)}+2(\frac{E_b}{N_0})^{(1)}\xi^{(1,p)}}}\right),$$

where the parameters $\xi^{(1,1)}$ and $\xi^{(1,p)}$ are given respectively by the following expressions:

$$\xi^{(1,1)}=\frac{\sum_{j\neq i}\left|\sum_{k,l}c_l^{(1)*}c_k^{(1)}\pi_{i,j}^{(1,1)}\left((i-j)T^{(1)}+\tau_l^{(1)}-\tau_k^{(1)}\right)\right|^2}{\left|\sum_{k,l}c_l^{(1)*}c_k^{(1)}\pi_{i,j}^{(1,1)}\left(\tau_l^{(1)}-\tau_k^{(1)}\right)\right|^2}$$

$$\xi^{(1,p)}=\frac{\sum_{j}\left|\sum_{k,l}c_l^{(1)*}c_k^{(p)}\pi_{i,j}^{(1,p)}\left(iT^{(1)}-jT^{(p)}+\tau_l^{(1)}-\tau_k^{(p)}\right)\right|^2}{\left|\sum_{k,l}c_l^{(1)*}c_k^{(1)}\pi_{i,j}^{(1,1)}\left(\tau_l^{(1)}-\tau_k^{(1)}\right)\right|^2}$$

4. SIMULATION RESULTS AND DISCUSSION

4.1 Exact evaluation performances in the downlink static channel

In the next example, we consider 8 data flows with the same scrambling Sc=1 and with walsh codes numbers given by: [1,2,3,4,5,6,7,8]. The propagation channel considered is a time-invariant channel. The attenuations in dB and the delays are given by: [0,-3dB,-6dB,-9dB] and [0,260 ns,521 ns,781 ns]. We draw the mono-user as well as the multi-user performances. We can notice that, in the mono user case, all the users have the same performances. However, in the multi-user case, we have three different curves depending on the chosen walsh codes.

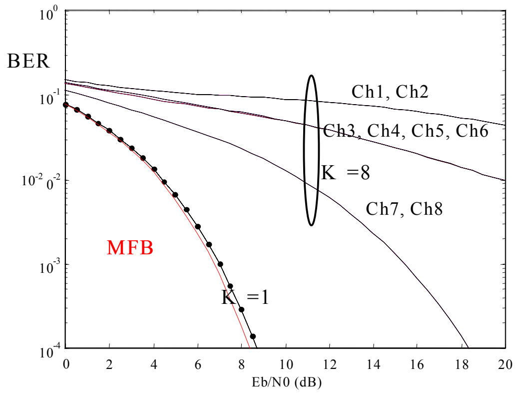

Figure 1 Performances of the RAKE receiver for K=8 for a time-invariant channel given by [0,-3dB,-6dB,-9dB] as attenuations and [0,260 ns,521 ns,781 ns] as delays

The propagation channel has a great effect on the performances. For instance, in **figure2**, we show the same simulation with a different time-invariant propagation channel with attenuations in dB and delays given by: [0dB,-10dB] and [0 ns,976 ns]. We notice that we have a different curve for each walsh code. We can notice that in this case the walsh code number 6 gives the best performances compared to the others. However, in the previous channel case, walsh codes 7 and 8 give the best performances.

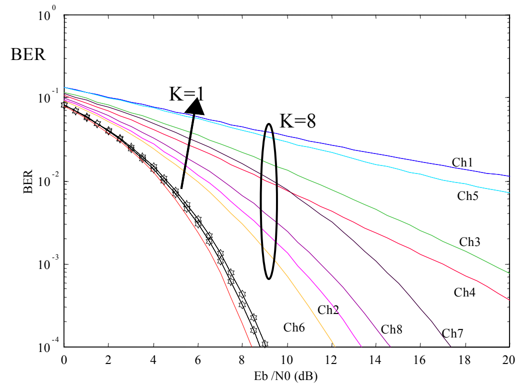

Figure 2 Performances of the RAKE receiver for K=8 in the case of a time-invariant channel with attenuations [0dB,-10dB] and delays [0,976 ns]

4.2 Simulation comparison between the exact evaluation and the gaussian approximate

4.2.1 Case of a static channel

In the next example we consider two users with scrambling code (Sc=1) and with channelization code numbers [1,2]. We show the BER of user 1 versus $(E_b/N_0)_1$ in two different cases. First when user 1 is alone and secondly when we consider the presence of user 2.

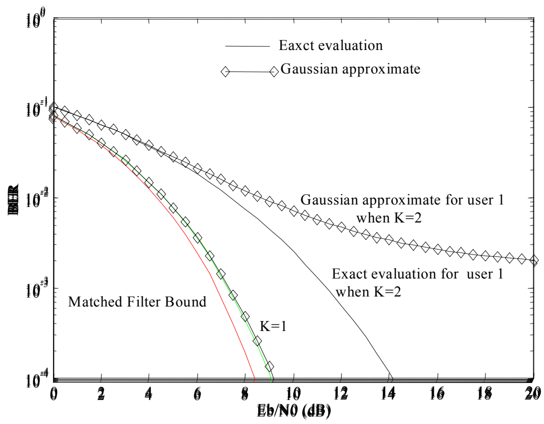

Figure 3 Comparison between the exact evaluation and the gaussian approximate for K=2 for a time-invariant channel with attenuations [0dB,-10dB] and delays [0 ns,976 ns]

It is worthwhile to note that the validity of the gaussian approximate is tightly related to the channel profile. Indeed, we carried out many simulations for different invariant-time channels having the same profile as the ITU channels and we found out that the gaussian assumption is less valuable for some channel profiles than others.

4.2.2 Case of a random channel

We consider as the previous example, 2 users with Sc=1 and channelization code numbers [1,2]. The next figure shows the BER of user number 1 versus $(E_b/N_0)_1$. The channel is a random 3GPP channel. We can notice that the gaussian approximate is less valuable in the case of a random channel than in the static channel case.

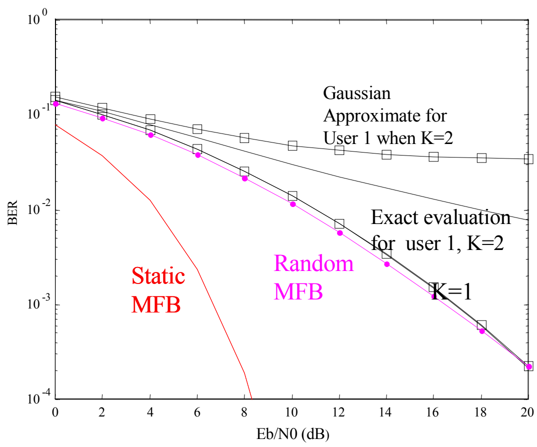

Figure 4 Performances of the RAKE receiver for K=2 for a random 3GPP channel with atenuations [0dB,-10dB] and delays [0 ns,976 ns]

5. CONCLUSION

The performance of the downlink of the TD-CDMA system with a RAKE receiver has been evaluated. Analytical closed-form expressions of the bit-error-rate are derived in a general multiple user case. This study shows that the gaussian approximate is not valid in this case. In fact, the spreading sequences used in such a system are short and not random. In this case, nor the gaussian approximation nor the random sequence property can be applied. Especially the distribution of the multiple access interference distribution in the forward link is not gaussian. Other applications of this study deserve also to be mentioned such as interference parameter determination for capacity evaluation, evaluation of the receiver sensitivity to the code choice. This study can be carried on and extended to multi-user detectors and to code allocation schemes.

REFERENCES

[1] M. Vollmer, M. Haardt, J. Götze, 'Comparative study of joint-detection techniques for TD-CDMA based mobile radio systems', IEEE JSAC, Vol.19, pp. 1461-1475, Aug. 2001.

[2] F. Ling, 'Matched Filter Bound for Time Discrete Multipath Rayleigh Fading Channels', IEEE Trans. on Communications, Vol.43 No.2/3/4, February/March/April 1995, pp.710-713.

[3] L. Husson, A. Wautier " Space and Path Diversity : Theoretical Matched Filter Bound and Comparison to Diversity Gain Obtained with Practical MLSE Receivers," *PIMRC'00,* Sept. 00.

[4] K. Chen, 'Performance of Direct-Sequence Spread-Spectrum RAKE Receivers with Random Spreading Sequences', IEEE Trans. on Communications, Vol.45, No.9, pp.1130-1143, September 1997.

[5] Don J. Torrieri, 'Performance of Direct sequence Systems with Long pseudonoise Sequences', IEEE JSAC, Vol.10, No.4, pp. 770-781, May 1992.

[6] G. L. Turin, 'The effects of multipath and fading on the performance of direct sequence CDMA systems', IEEE JSAC, Vol.SAC-2, pp.597-603, April 1984.

[7] K. Chul Hwang, K. B. Lee, 'Performance Analysis of Low Processing Gain DS-CDMA Systems with Random Spreading Sequences', IEEE Communications Letters, Vol.2, N°. 12, September 1998.

[8] 'Spreading and Modulation (TDD)', Technical Report 3G TS 25.223 V3.4.0 (2000-09).

[9] A. Wautier, S. Ammari, 'RAKE Receiver Sensitivity to Spreading Sequence', *VTC'01,* May 2001.

[10] H. Boujemaa, O. Fratou, M. Siala and P. Loubaton, 'On the performance of a discrete time rake', *PIMRC'00*, September 2000.