

# Performance Evaluation of a Novel CDMA Detection Technique: The Two-State Approach

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The use of code division multiple access (CDMA) makes third-generation wireless systems interference limited rather than noise limited. The research for new methods to reduce interference and increase efficiency led us to formulate a signaling method where fast impulsive silence states are mapped on zero-energy symbols. The theoretical formulation of the optimum receiver is reported and the asymptotic multiuser efficiency (AME) as well as an upper bound of the probability of error have been derived and applied to the conventional receiver and the decorrelating detector. Moreover, computer simulations have been performed to show the advantages of the proposed two-state scheme over the traditional single-state receiver in a multiuser CDMA system operating in a multipath fading channel.

**Keywords and phrases:** code division multiple access, communication signal theory, wireless communications, impulsive information sources.

## 1. INTRODUCTION

Bandwidth represents the last challenge in wireless personal communications. Due to the average increase of the radio-link bandwidth requirements and the hostile urban radio channel for the interference-limited CDMA, the system capacity will meet its physical limitations even in a moderated deployment scenario.

Moreover, the grown of the short-range wireless communication world (IEEE 802.11x, ultra-wideband, etc.) has been due to the rising request for higher and higher data transfers and capacity. Future wireless techniques have to answer two fundamental issues: how to guarantee fast data transfer and how to share the limited resource with a larger and larger number of users. Hence, every technology capable of increasing the spectral efficiency of the radio link deserves a particular attention in the future wireless systems. Typical short-range wireless transmissions involve high-capacity broadband link for few times per connection. Burst communications are normally identified by regular periods of data transfer (talk state) followed by a silence period.

The proposed two-state technique takes advantage of low probability of talk communications.

Power consumption at the handheld terminal is another key issue. Mobile terminals are requested to operate complex computational tasks at the expense of a reduced duration of the batteries. The techniques able to save energy by optimizing the transmission scheme play a fundamental role in the design phase of the next-generation wireless communications.

Those considerations lead to the development of the transmission scheme presented in this paper. The basic idea is the extension of the traditional informative symbol set with a *zero-energy* symbol. The silence symbol is integrated with the informative ones and delivered to the radio link layer for transmission. The end-to-end signaling between the applications can be avoided and the radio layer does not need to receive any explicit *transmit on/off* commands from higher layers. The two-state receiver is able to realize when a talk symbol or the silence symbol has been sent. The classical thresholds of the symbol constellation (e.g., BPSK, QPSK, etc.) have been modified in order to take into account the silence state.

The performance has been evaluated by using two instruments: first, the asymptotic multiuser efficiency has been derived for the two-state detector, then, an upper bound for the probability of error has been found. Comparisons with the classical single-state receiver are reported in the paper for different bursty source, that is, for different values of probability of talk/silence.

Convolutional and turbo coding theories can be modified to work with the presented constellation (this topic will be addressed separately and published shortly).

The proposed reception scheme is also fully compatible with traditional single-state transmissions. In this case, the silence symbols thresholds collapse to 0 and the receiver degenerates in a traditional single-state receiver.

The following list highlights some the advantages of the proposed solution:

- (i) the reduction of the average transmit power from a CDMA terminal, obtained by employing silence symbols, reduces the interference on other users;
- (ii) the radio layer need not be integrated with the silence-state management function of the application layer;
- (iii) silence symbols allow very short traffic bursts and a great variety of fractional bit rates without increasing the multiple-access interference (MAI) level.

It is important to point out that the paper mainly deals with the theoretical formulation of the proposed two-state reception in a generic CDMA system, but an application of the two-state transmission-reception scheme to the UMTS environment is also reported for the sake of completeness.

The paper has been organized as follow. In Section 2, the proposed two-state CDMA communication strategy is described and the optimum detector is derived. In Section 3, the asymptotic multiuser detection for the conventional, the decorrelating, and the MMSE receivers are calculated. Section 4 shows the near-far resistance of the above-mentioned receivers and Section 5 reports the upper bound of the probability of error. The application of the proposed two-state scheme to the W-CDMA simulated environment is described in Section 7. Numerical results and implementation issues are shown in Sections 6 and 8, respectively. Section 9 concludes the paper.

## 2. CDMA TWO-STATE RECEPTION

With the proposed scheme, the general baseband transmission signal of the  $k$ th user is

$$s_k(t) = \sum_{n=-\infty}^{n=\infty} s_k(t)^{(n)}, \quad (1)$$

$$s_k(t)^{(n)} = A_k m_k^{(n)} b_k^{(n)} g_k^{(n)}(t - nT_s),$$

where

$$g_k^{(n)}(t) = \sum_{i=1}^G c_k^{(n)}(i) p(t - iT_c) \quad (2)$$

and

- (a)  $T_s$  is the symbol time,
- (b)  $T_c$  is the chip time,
- (c)  $G = T_s/T_c$  is the processing gain,
- (d)  $A_k = \sqrt{E_k}$  the transmitted amplitude for user  $k$ ,
- (e)  $p(t)$  is the complex-valued chip waveform due to the shaping pulse filter,
- (f)  $c_k^{(n)}$  is the  $k$ th normalized<sup>1</sup> spreading code of user  $k$  referred to the  $n$ th symbol interval,
- (g)  $m_k^{(n)}$  is the mask symbol which assumes one of the two possible values  $\{0, 1\}$ . It determines the state of the transmitter in the  $n$ th time interval: *talk* or *silent*,
- (h)  $b_k^{(n)}$  is the informative symbol transmitted during the  $n$ th interval, chosen among the alphabet symbol of the chosen modulation (e.g., for a BPSK signaling,  $b_k^{(n)} \in \{-1, 1\}$ ). It has no significance when the transmitter is in the *silence* state.

The received signal  $r(t)$  expresses the observable part of the transmission chain. The received signal can be written as

$$r(t) = \sum_{k=1}^K s_k(t) + n(t), \quad (3)$$

where  $n(t)$  is the white Gaussian noise with variance  $\sigma^2$ . The discretized filter output (decision variable) of user  $k$  can be written as

$$y_k = A_k [\mathbf{LR}]_{kk} b_k + \sum_{j=1, j \neq k}^K A_j [\mathbf{LR}]_{kj} b_j + w_k, \quad (4)$$

where  $\mathbf{L}$  is the linear transformation that yields the desired receiver, for example,  $\mathbf{L} = \mathbf{I}$  is simply the conventional receiver (matched filter),  $\mathbf{R}$  is the normalized cross-correlation matrix between the desired user code  $k$  and the other interfering codes whose generic element is  $\mathbf{R}_{kj} = \int_0^{T_s} g_k(t) g_j^*(t) dt$ , and  $w_k$  is the output filter noise with zero mean and variance  $[\mathbf{LRL}^T]_{kk} \sigma^2$  [1, 2].

The unknown mask and symbol transmitted by the user over the transmission channel can be grouped in the two-state information symbol  $q^{(n)}$  defined as

$$q^{(n)} = m^{(n)} b^{(n)}. \quad (5)$$

The *optimum detector* [3], for a given set of transmitted two-state symbols, will choose the symbol  $\hat{q}^{(n)}$  corresponding to the largest *posterior probability* based on the observation of  $r(t)$  (MAP criterion). Formally,

$$\hat{q}^{(n)} = \arg \max_q P(q|r(t)^{(n)}), \quad (6)$$

where we have dropped here the  $k$  index for simplicity. We can assume that the two states are alternating independently

<sup>1</sup>Without loss of generality, the code energy is assumed to be unitary, that is,  $\sum_{i=1}^G c_k(i)^2 = 1$ .

TABLE 1: BPSK + signaling.

Symbol	Transmitter state	Informative symbol	Transmitted symbol
$q_0$	Talk	0	1
$q_1$	Talk	1	-1
$q_2$	Silence	Not admitted	0

of the informative stream, constituted by  $M$  equally probable symbols. This leads to

$$P(q_{\text{talk}} \text{ is transmitted}) = \frac{P_{\text{talk}}}{M}, \quad (7)$$

$$P(q_{\text{silence}} \text{ is transmitted}) = 1 - P_{\text{talk}},$$

where  $P_{\text{talk}}$  is the absolute probability of a talk symbol. The two-state symbol  $q$  is thus possibly one of the equally probable  $M$  informative symbols or the single “silence” one. The transmission model described above needs a more complex performance characterization with respect to the traditional one. The receiver is characterized by a general *probability of error* which is specialized in

- (i) probability of false detection of a silence state,  $P_{e,\text{silence}}$ ,
- (ii) probability of symbol error conditioned to a talk state,  $P_{e,\text{symb}}$ .

We now consider, as a first example, a reference case. The receiver performance index is the probability of error  $P_{eu}$  defined as

$$P_{eu} = P_{e,\text{silence}} + P_{e,\text{symb}}. \quad (8)$$

The  $P_{e,\text{silence}}$  and the  $P_{e,\text{symb}}$  occurrences are disjoint. The receiver performs two operations: the first one is a talk/silence status detection of the desired source, followed by the talk symbol detection if the source is found in the talk state. The single-user two-state receiver consists in the traditional set of linear filters matched to the talk symbols only since the silence symbol is represented in the signal space spanned by the talk symbols with a null vector.

The receiver is deduced by assuming the following:

- (1) an AWGN channel is considered,  $\sigma^2$  being the variance of the noise process,
- (2) BPSK + signaling ( $M = 2$  plus the silence symbol), where  $E_k$  is the talk-symbol energy,
- (3) the a priori probability of a talk symbol is  $P_{\text{talk}}$ .

For clarity, the symbols are labelled as in Table 1.

If the transmitted symbol is a talk symbol,  $q_0$  or  $q_1$ , the receiver can commit a *transmitter-state detection error* (described by  $P_{e,\text{silence}}$  in (8)) or a *symbol detection error* (described by  $P_{e,\text{symb}}$  in (8)). Following the classical MAP criterion [4], defining  $y$  as the matched filter output (i.e. the decision metrics) a state detection error for the transmitted symbol  $q_0$  occurs when

$$p(y|q_0)P(q_0) < p(y|q_2)P(q_2). \quad (9)$$

A symbol detection error for the transmitted symbol  $q_0$  is

$$p(y|q_0)P(q_0) < p(y|q_1)P(q_1). \quad (10)$$

Analogous expressions are found if the transmitted symbol is  $q_1$  by switching the subscript “1” with “2” in (10) and (9).

If the transmitted symbol is the *silence* symbol  $q_2$ , the only error the receiver can commit is a state detection error that occurs when

$$p(y|q_2)P(q_2) < p(y|q_0)P(q_0) \quad (11)$$

or

$$p(y|q_2)P(q_2) < p(y|q_1)P(q_1). \quad (12)$$

By applying the MAP criterion, a correct decision when the transmitted symbol is  $q_0$  is performed if

$$p(y|q_0)P(q_0) > p(y|q_i)P(q_i), \quad i = 1, 2. \quad (13)$$

The equations of (13) lead to

$$\frac{p(y|q_0)}{p(y|q_1)} > \frac{P(q_1)}{P(q_0)}, \quad (14)$$

$$\frac{p(y|q_0)}{p(y|q_2)} > \frac{P(q_2)}{P(q_0)}.$$

Under the AWGN hypothesis<sup>2</sup> and taking the natural logarithm of the expressions, we obtain

$$\sqrt{E_k}y > \frac{\sigma^2}{2} \ln \frac{P(q_1)}{P(q_0)}, \quad (15)$$

$$\sqrt{E_k}y > \sigma^2 \ln \frac{P(q_2)}{P(q_0)} + \frac{E_k}{2}.$$

The system of two equations in (15) is fully satisfied when the second one is. Equations in (15) define the optimum receiver by assigning two decision thresholds  $\theta_{0,2}$  and  $\theta_{1,2}$  defined as follows:

$$\theta_{0,2} \doteq \frac{\sigma^2}{\sqrt{E_k}} \ln \frac{P(q_2)}{P(q_0)} + \frac{\sqrt{E_k}}{2}, \quad (16)$$

$$\theta_{1,2} \doteq \frac{\sigma^2}{\sqrt{E_k}} \ln \frac{P(q_1)}{P(q_0)} - \frac{\sqrt{E_k}}{2},$$

where the symbols are labeled as in Table 1, and  $E_k$  is the symbol energy.

The decision regions for the described receiver, with  $y$  being the observable metric, are described by

$$y < \theta_{1,2}, \quad \text{the symbol } q_1 \text{ is selected,}$$

$$\theta_{1,2} \leq y < \theta_{0,2}, \quad \text{the symbol } q_2 \text{ is selected,} \quad (17)$$

$$\theta_{0,2} \leq y, \quad \text{the symbol } q_0 \text{ is selected.}$$

The decision regions are represented in Figure 1.

<sup>2</sup>If the  $q_0$  symbol is transmitted, the pdf of the matched filter output corrupted by AWGN noise is  $p(y|q_0) = (1/\sqrt{2\pi\sigma^2}) \exp(-(y - \sqrt{E_k})^2/2\sigma^2)$ .

### 3. TWO-STATE ASYMPTOTIC MULTIUSER EFFICIENCY

The asymptotic multiuser efficiency [5] is a measure of the influence that interfering users have on the bit error rate (BER) of the user of interest. Defining the effective  $k$ th user energy  $e_k(\sigma)$  as the energy that would be required in an additive white Gaussian noise (AWGN) channel when only one user is present to achieve the same BER that is observed in the presence of other users, the asymptotic multiuser efficiency is given by the ratio between the energy required in the multiple-user system and the energy required in the single-user system to have the same performance in the high signal-to-noise ratio (SNR),

$$\eta_k = \lim_{\sigma \rightarrow 0} \frac{e_k(\sigma)}{E_k}, \quad (18)$$

and, de facto, represents the performance loss when the dominating impairment is the existence of interfering users rather than the additive channel noise. The parameter  $\eta_k$  lies between 0 and 1, where a value of 1 indicates that the user of interest is not affected by the other users' presence. The  $k$ th user asymptotic efficiency can also be written as

$$\eta_k = \sup \left\{ 0 \leq r \leq 1 : \lim_{\sigma \rightarrow 0} \frac{P_k(\sigma)}{Q(\sqrt{rE_k}/\sigma)} < +\infty \right\}, \quad (19)$$

where  $P_k(\sigma)$  is the probability of error associated to the selected detector. It is straightforward to find that the  $k$ th user's asymptotic efficiency achieved by a generic linear transformation  $L$  [6] is

$$\begin{aligned} \eta_k^{(1s)}(L) &= \max^2 \left\{ 0, \frac{1}{\sqrt{E_k}} \cdot \frac{A_k(\mathbf{L}\mathbf{R})_{kk} - \sum_{j \neq k} A_j |(\mathbf{L}\mathbf{R})_{kj}|}{\sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^T)_{kk}}} \right\}, \end{aligned} \quad (20)$$

where  $\mathbf{R}$  is the codes' correlation matrix.

The asymptotic efficiency for a two-state' system can be derived by analysing independently the talk and the silence conditions of the desired source.

Let  $\eta_k^{(2st)}$  be the asymptotic efficiency of the  $k$ th user when it is in the talk state, while let  $\eta_k^{(2sls)}$  be the asymptotic efficiency of the  $k$ th user when it is in the silence state.

By applying the asymptotic efficiency definition, we obtain

$$\eta_k^{(2st)} = \sup \left\{ 0 \leq r \leq 1 : \lim_{\sigma \rightarrow 0} \frac{P_k^{(2st)}(\sigma)}{Q((\sqrt{rE_k} - \theta')/\sigma)} < +\infty \right\}, \quad (21)$$

where

$$\theta' = \theta'(r) = \frac{\sigma^2}{\sqrt{r}\sqrt{E_k}} \ln \left( \frac{P(q_2)}{P(q_0)} \right) + \frac{\sqrt{r}\sqrt{E_k}}{2} \quad (22)$$

is the two-state decision threshold (Figure 1). Hence,  $Q((\sqrt{rE_k} - \theta')/\sigma)$  is the probability of symbol detection error of a two-state single-user receiver according to the asymptotic efficiency definition.<sup>3</sup>

During a silence state of the desired ( $k$ th) user, we obtain

$$\eta_k^{(2sls)} = \sup \left\{ 0 \leq r \leq 1 : \lim_{\sigma \rightarrow 0} \frac{P_k^{(2sls)}(\sigma)}{Q(\theta'/\sigma)} < +\infty \right\}, \quad (23)$$

where  $Q(\theta'/\sigma)$  is the probability of silence-state detection error of a single-user receiver.

We can derive the *multiuser asymptotic efficiency* for a two-state system as follows:

$$\eta_k^{(2s)} = \eta_k^{(2st)} P_{\text{talk}} + \eta_k^{(2sls)} (1 - P_{\text{talk}}). \quad (24)$$

We assume, without loss of generality, that  $N_z = z < K$  users are in the silence state. In such a case, the two-state probability of error for the  $k$ th user can be written as

$$\begin{aligned} P_k^{(2s)} &= \frac{1}{2} \underbrace{[\text{Prob}\{y_k > \theta_{1,2} \mid b_k = -1, P_{\text{talk}}, N_z\} + \text{Prob}\{y_k < \theta_{0,2} \mid b_k = +1, P_{\text{talk}}, N_z\}]}_{P_{e,\text{symbol}}} \cdot P_{\text{talk}} \\ &+ \frac{1}{2} \underbrace{[\text{Prob}\{y_k < \theta_{1,2} \mid b_k = 0, P_{\text{talk}}, N_z\} + \text{Prob}\{y_k > \theta_{0,2} \mid b_k = 0, P_{\text{talk}}, N_z\}]}_{P_{e,\text{silence}}} \cdot (1 - P_{\text{talk}}), \end{aligned} \quad (25)$$

where the first term is the probability of symbol error, that is to say, the probability of detecting the symbol 0 or 1 if  $-1$  is transmitted and the probability of detecting the symbol 0 or  $-1$  if 1 is transmitted. The second term is the probability of false detection, that is to say, the probability of detecting the symbol  $\pm 1$  if 0 is transmitted. See

Figure 2 for the summarization of the previous considerations.

<sup>3</sup>The  $Q(\cdot)$  function is the cumulative normal distribution function and it is defined as  $Q(x) = (1/\sqrt{2\pi}) \int_0^x e^{-t^2/2} dt$ .

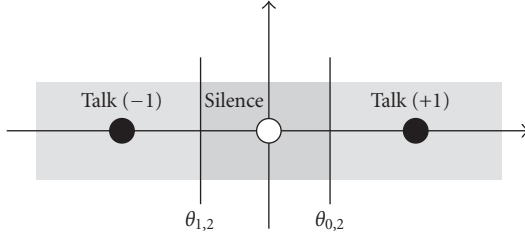


FIGURE 1: BPSK + decision regions.

Equation (25) represents the total probability of error for a generic linear two-state CDMA receiver.

### 3.1. Talk state

If the user of interest is in the talk state, the probability of error for a two-state linear CDMA receiver can be written as

$$P_k^{(2s|t)} = [\text{Prob} \{y_k > \theta_{1,2} \mid b_k = -1, P_{\text{talk}}, N_z\} + \text{Prob} \{y_k < \theta_{0,2} \mid b_k = +1, P_{\text{talk}}, N_z\}] \cdot P_{\text{talk}}. \quad (26)$$

Due to the symmetry of the problem, the final probability of symbol error can be written as

$$P_k^{(2s|t)} = \sum_{\mathbf{b} \in (-1,0,1)^K, b_k = -1} (P_{\text{talk}})^{K-1-z} (1 - P_{\text{talk}})^z \cdot Q\left(\frac{A_k(\mathbf{L}\mathbf{R})_{kk} - \sum_{j=1, j \neq k}^{K-z} A_j(\mathbf{L}\mathbf{R})_{kj} b_j + \theta_{1,2}}{\sigma \sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^T)_{kk}}}\right). \quad (27)$$

The  $Q(\cdot)$  function is dominated by the one that has the smallest argument, for example, (27) results in

$$Q\left(\frac{A_k(\mathbf{L}\mathbf{R})_{kk} - \sum_{j=1, j \neq k}^{K-z} A_j(\mathbf{L}\mathbf{R})_{kj} b_j + \theta_{1,2}}{\sigma \sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^T)_{kk}}}\right) \leq Q\left(\frac{A_k(\mathbf{L}\mathbf{R})_{kk} - \sum_{j=1, j \neq k}^{K-z} A_j(\mathbf{L}\mathbf{R})_{kj} |b_j| + \theta_{1,2}}{\sigma \sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^T)_{kk}}}\right). \quad (28)$$

Without loss of generality, we have supposed here that the  $N_z = z$  interfering users in the silence state are the last  $z$  among the total  $K$  users.

Taking into account (21) and noting that  $\theta_{1,2} \rightarrow -\sqrt{E_k}/2$  and  $\theta' \rightarrow \sqrt{E_k}/2$  as  $\sigma \rightarrow 0$ , the asymptotic multiuser efficiency of a two-state CDMA linear receiver conditioned to have  $N_z = z$  "silent" users when the desired user is in the talk

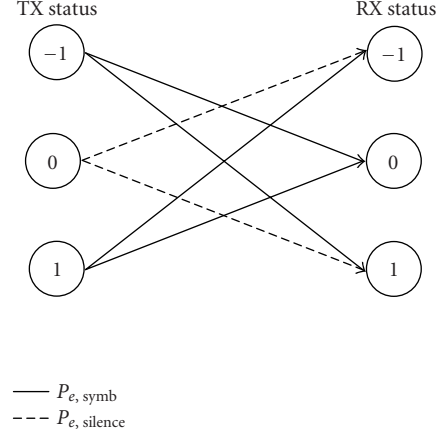


FIGURE 2: Probability of symbol error and probability of false detection for the two-state receiver.

state can be written as

$$\eta_k^{(2s|t)}(P_{\text{talk}}, N_z) = \max^2 \left\{ 0, \frac{1}{\sqrt{E_k}} \cdot \frac{2A_k(\mathbf{L}\mathbf{R})_{kk} - 2 \sum_{j=1, j \neq k}^{K-z} A_j(\mathbf{L}\mathbf{R})_{kj} |b_j| - \sqrt{E_k}}{\sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^T)_{kk}}} \right\}. \quad (29)$$

Thus, the mean value of the asymptotic multiuser efficiency for a two-state linear receiver when the desired user is in the talk state can be written as

$$\bar{\eta}_k^{(2s|t)} = \sum_{N_z} \eta_k^{(2s|t)}(P_{\text{talk}}, N_z) \cdot \text{Prob} \{N_z = z\} = \sum_z \binom{K-1}{z} \eta_k^{(2s|t)}(P_{\text{talk}}, z) \cdot P_{\text{talk}}^{K-1-z} (1 - P_{\text{talk}})^z. \quad (30)$$

### 3.2. Silence state

If the user of interest is in the silence state, that is, it is included into the  $z$  users that are not transmitting, the probability of error for a two-state linear CDMA receiver can be written as

$$P_k^{(2s|s)} = [\text{Prob} \{y_k < \theta_{1,2} \mid b_k = 0, P_{\text{talk}}, N_z\} + \text{Prob} \{y_k > \theta_{0,2} \mid b_k = 0, P_{\text{talk}}, N_z\}] \cdot (1 - P_{\text{talk}}). \quad (31)$$

Due to the symmetry of the problem, the final probability of state error can be written as

$$P_k^{(2s|s)} = \sum_{\mathbf{b} \in (-1,0,1)^K, b_k = 0} (P_{\text{talk}})^{K-1-z} (1 - P_{\text{talk}})^z \cdot Q\left(\frac{\theta_{0,2} - \sum_{j=1, j \neq k}^{K-z} A_j(\mathbf{L}\mathbf{R})_{kj} b_j}{\sigma \sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^T)_{kk}}}\right). \quad (32)$$

As above, the  $Q(\cdot)$  function is dominated by the one that has the smallest argument, for example, (32) results in

$$\begin{aligned} & Q\left(\frac{\theta_{0,2} - \sum_{j=1, j \neq k}^{K-z} A_j (\mathbf{L}\mathbf{R})_{kj} b_j}{\sigma \sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^\top)_{kk}}}\right) \\ & \leq Q\left(\frac{\theta_{0,2} - \sum_{j=1, j \neq k}^{K-z} A_j |(\mathbf{L}\mathbf{R})_{kj}|}{\sigma \sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^\top)_{kk}}}\right). \end{aligned} \quad (33)$$

Taking into account (23) and noting that  $\theta_{0,2} \rightarrow \sqrt{E_k}/2$  and  $\theta' \rightarrow \sqrt{r}\sqrt{E_k}/2$  as  $\sigma \rightarrow 0$ , the asymptotic multiuser efficiency of a two-state CDMA linear receiver conditioned to have  $N_z = z$  "silent" users including the desired user can be written as

$$\begin{aligned} & \eta_k^{(2s|s)}(P_{\text{talk}}, N_z) \\ & = \max^2 \left\{ 0, \frac{1}{\sqrt{E_k}} \cdot \frac{\sqrt{E_k} - 2 \sum_{j=1, j \neq k}^{K-z} A_j |(\mathbf{L}\mathbf{R})_{kj}|}{\sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^\top)_{kk}}} \right\}. \end{aligned} \quad (34)$$

Thus, the mean value of the asymptotic multiuser efficiency for a two-state linear receiver when the desired user is in the silence state can be written as

$$\begin{aligned} \bar{\eta}_k^{(2s|s)} & = \sum_{N_z} \eta_k^{(2s|s)}(P_{\text{talk}}, N_z) \cdot \text{Prob}\{N_z = z\} \\ & = \sum_z \binom{K-1}{z} \eta_k^{(2s|s)}(P_{\text{talk}}, z) \cdot P_{\text{talk}}^{K-1-z} (1 - P_{\text{talk}})^z. \end{aligned} \quad (35)$$

Substituting (35) and (30) into (24), the global asymptotic multiuser efficiency for a generic linear CDMA receiver can be obtained. In particular, setting  $\mathbf{L} = \mathbf{I}^4$ , the AME of the conventional CDMA receiver can be computed, while the substitution  $\mathbf{L} = \mathbf{R}^{-1}$  results in the decorrelating detector. For specific calculation details, see [7, 8].

The results of the AME comparison between the proposed two-state and the classical CDMA systems are reported in Section 6.

#### 4. TWO-STATE NEAR-FAR RESISTANCE

Another commonly used performance measure for a multiuser detector is the near-far resistance (NFR). It is heavily related to the previous defined asymptotic multiuser efficiency,

$$\gamma_k = \inf_{E_j | l| \geq 0, (l,j) \neq (0,k)} \eta_k. \quad (36)$$

In fact, it is defined as the minimum asymptotic multiuser efficiency over the received energies of all the interfering users.

It is worth to note that the interfering-user energies are time dependent. Near-far resistance is thus a measure of the intrinsic receiver immunity toward the interfering-user amplitudes fluctuations.

In the following, the NFR for the conventional detector as well as the decorrelating detector in a two-state CDMA system is derived and compared with the NFR of the traditional CDMA system.

##### 4.1. Conventional receiver

We suppose, first, that the desired user is in the talk state. Substituting  $\mathbf{L} = \mathbf{I}$  in (29), the AME for the conventional two-state CDMA detector can be obtained:

$$\begin{aligned} & \eta_k^{(2s|t)}(\text{conv} | P_{\text{talk}}, N_z) \\ & = \max^2 \left\{ 0, \frac{1}{\sqrt{E_k}} \cdot \frac{2A_k(\mathbf{R}_{kk}) - 2 \sum_{j=1, j \neq k}^{K-z} A_j |\mathbf{R}_{kj}| - \sqrt{E_k}}{\sqrt{(\mathbf{R}_{kk})}} \right\} \\ & = \max^2 \left\{ 0, 1 - 2 \sum_{j=1, j \neq k}^{K-z} |\mathbf{R}_{kj}| \cdot \frac{\sqrt{E_j}}{\sqrt{E_k}} \right\}, \end{aligned} \quad (37)$$

while the traditional single-state CDMA receiver has the well-known AME:

$$\begin{aligned} \eta_k^{(1s)}(\text{conv}) & = \max^2 \left\{ 0, \frac{1}{\sqrt{E_k}} \cdot \frac{A_k(\mathbf{R}_{kk}) - \sum_{j=1, j \neq k}^K A_j |\mathbf{R}_{kj}|}{\sqrt{\mathbf{R}_{kk}}} \right\} \\ & = \max^2 \left\{ 0, 1 - \sum_{j=1, j \neq k}^K |\mathbf{R}_{kj}| \cdot \frac{\sqrt{E_j}}{\sqrt{E_k}} \right\}. \end{aligned} \quad (38)$$

It is easy to show that both the two-state and single-state conventional CDMA detectors are not near-far resistant because, for an enough high value of the interfering energies  $E_j$  the minimum value of the asymptotic multiuser efficiency is zero unless  $|\mathbf{R}_{kj}| = 0$  for all  $j \neq k$ ; that is,

$$\gamma_k^{(1s)}(\text{conv}) = \gamma_k^{(2s|t)}(\text{conv}) = 0. \quad (39)$$

Anyway, comparing the term inside (37),

$$1 - 2 \sum_{j=1, j \neq k}^{K-z} |\mathbf{R}_{kj}| \cdot \frac{\sqrt{E_j}}{\sqrt{E_k}} \quad (40)$$

with the one inside (38),

$$1 - \sum_{j=1, j \neq k}^K |\mathbf{R}_{kj}| \cdot \frac{\sqrt{E_j}}{\sqrt{E_k}}, \quad (41)$$

it is easy to note that the two-state scheme gets less elements in the sum than the one-state conventional receiver (38). This is because the two-state receiver is not affected by the interfering users in the silence state.

<sup>4</sup>where  $\mathbf{I}$  represents the identity matrix.

Moreover, in the two-state scheme, if the interfering energy  $E_j$  is greater than the threshold defined by

$$\sqrt{E_j} > \frac{\sqrt{E_k}}{2(K-1-z)\rho}, \quad (42)$$

where  $\rho = \max_j |\mathbf{R}_{kj}|$  is the maximum cross-correlation value, the near-far resistance falls down to zero. Analogously, in the one-state case, the energy threshold is

$$\sqrt{E_j} > \frac{\sqrt{E_k}}{(K-1)\rho}. \quad (43)$$

Comparing the two equations (43) and (42), we can deduce that when

$$z > \frac{(K-1)}{2}, \quad (44)$$

the two-state receiver's near-far resistance is "higher" than the single-state one, that is, it can tolerate higher interfering energy  $E_j$  before the inferior value collapses to zero in (37). On the other hand, when

$$z < \frac{(K-1)}{2}, \quad (45)$$

the one-state receiver performs better.

If the user of interest is in the silence state, the two-state AME (34) becomes

$$\begin{aligned} \eta_k^{(2s|s)}(\text{conv} | P_{\text{talk}}, N_z) &= \max^2 \left\{ 0, \frac{1}{\sqrt{E_k}} \cdot \frac{\sqrt{E_k} - 2 \sum_{j=1, j \neq k}^{K-z} A_j |\mathbf{R}_{kj}|}{\sqrt{(\mathbf{R}_{kk})}} \right\} \\ &= \max^2 \left\{ 0, \frac{1}{\sqrt{\mathbf{R}_{kk}}} \left[ 1 - 2 \sum_{j=1, j \neq k}^{K-z} |\mathbf{R}_{kj}| \cdot \frac{\sqrt{E_j}}{\sqrt{E_k}} \right] \right\} \end{aligned} \quad (46)$$

and the same conclusions of above can be deduced, that is,

$$\gamma_k^{(1s)}(\text{conv}) = \gamma_k^{(2s|t)}(\text{conv}) = \gamma_k^{(2s|s)}(\text{conv}) = 0. \quad (47)$$

#### 4.2. Decorrelating receiver

In the decorrelating detector, the AME does not depend on the interfering users' energies, so that it is near-far resistant.

The AME of the two-state decorrelating detector is obtained by substituting the inverse of the correlation matrix  $\mathbf{R}^{-1}$  in (30).

If the desired user is in the talk state, (29) becomes<sup>5</sup>

$$\begin{aligned} \eta_k^{(2s|t)}(\text{dec} | P_{\text{talk}}, N_z) &= \max^2 \left\{ 0, \frac{1}{\sqrt{E_k}} \frac{2\sqrt{E_k} - 0 - \sqrt{E_k}}{\sqrt{((\mathbf{R}^{-1})^\top)_{kk}}} \right\} \\ &= \frac{1}{((\mathbf{R}^{-1})^\top)_{kk}} \end{aligned} \quad (48)$$

which is equal to the well-known near-far resistance of the one-state decorrelator [5].

If, on the contrary, the user of interest is in the silence state, (34) becomes

$$\begin{aligned} \eta_k^{(2s|s)}(\text{dec} | P_{\text{talk}}, N_z) &= \max^2 \left\{ 0, \frac{1}{\sqrt{E_k}} \frac{\sqrt{E_k} - 0}{\sqrt{((\mathbf{R}^{-1})^\top)_{kk}}} \right\} \\ &= \frac{1}{((\mathbf{R}^{-1})^\top)_{kk}} \end{aligned} \quad (49)$$

and it is obvious that

$$\gamma_k^{(1s)}(\text{dec}) = \gamma_k^{(2s|t)}(\text{dec}) = \gamma_k^{(2s|s)}(\text{dec}). \quad (50)$$

The near-far resistance of the two-state decorrelating detector is exactly the same as that of the classical one-state decorrelator. Hence, there is no performance loss in using the two-state CDMA communication system, but only benefits due to lower average transmit power request and no transmission delay due to impulsive information sources.

The linear minimum mean square error (LMMSE) receiver has the same asymptotic multiuser efficiency as the decorrelating receiver [6]. Thus, the results derived in this section are valid for the LMMSE detector as well.

## 5. TWO-STATE PROBABILITY OF ERROR

In this section, an estimate of the probability of symbol error for the conventional detector and the decorrelating detector is computed. The global probability of error for a two-state linear receiver is computed in accordance with (8).

The MAI term in (27) can be upper bounded by

$$\sum_{j=1, j \neq k}^{K-z} A_j |(\mathbf{L}\mathbf{R})_{kj}| \leq (K-1-z)\rho(\mathbf{L}), \quad (51)$$

where

$$\rho(\mathbf{L}) = \max_{k'} \{A_{k'} (\mathbf{L}\mathbf{R})_{kk'}\}. \quad (52)$$

By substituting (51) in (27), the probability of symbol error conditioned to the *talk* state of the  $k$ th source can be upper

<sup>5</sup>The following results have been used:  $(\mathbf{R}^{-1}\mathbf{R})_{kk} = 1$ ,  $(\mathbf{R}^{-1}\mathbf{R})_{kj} = 0$ ,  $A_i = \sqrt{E_i}$ .

bounded as in the following:

$$P_k^{(2s|t)} \leq \sum_{z=0}^{K-1} \binom{K-1}{z} P_{\text{talk}}^{K-1-z} (1 - P_{\text{talk}})^z \cdot Q\left(\frac{A_k(\mathbf{L}\mathbf{R})_{kk} - (K-1-z)\rho(\mathbf{L}) + \theta_{1,2}}{\sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^\top)_{kk}}\sigma}\right). \quad (53)$$

Analogously, during the *silence* state of the reference  $k$ th user, the probability of state mismatch results in

$$P_k^{(2s|s)} \leq \sum_{z=0}^{K-1} \binom{K-1}{z} P_{\text{talk}}^{K-1-z} (1 - P_{\text{talk}})^z \cdot Q\left(\frac{\theta_{0,2} - (K-1-z)\rho(\mathbf{L})}{\sqrt{(\mathbf{L}\mathbf{R}\mathbf{L}^\top)_{kk}}\sigma}\right). \quad (54)$$

Finally, the generalized probability of error for the two-state receiver is obtained by weighting the probabilities in (53) and (54) with  $P_{\text{talk}}$ :

$$P_{eu} = P_{e,\text{silence}} + P_{e,\text{symp}} = P_k^{(2s|s)} (1 - P_{\text{talk}}) + P_k^{(2s|t)} P_{\text{talk}}. \quad (55)$$

### 5.1. Probability of error for the two-states conventional detector

In order to get the probability of error for a two-state CDMA conventional receiver, it is enough to substitute  $\mathbf{L} = \mathbf{I}$  in (53) and (54):

$$P_{k,\text{conv}}^{(2s|t)} \leq \sum_{z=0}^{K-1} \binom{K-1}{z} P_{\text{talk}}^{K-1-z} (1 - P_{\text{talk}})^z \cdot Q\left(\frac{\sqrt{E_k} - (K-1-z)\rho + \theta_{1,2}}{\sigma}\right), \quad (56)$$

$$P_{k,\text{conv}}^{(2s|s)} \leq \sum_{z=0}^{K-1} \binom{K-1}{z} P_{\text{talk}}^{K-1-z} (1 - P_{\text{talk}})^z \cdot Q\left(\frac{\theta_{0,2} - (K-1-z)\rho}{\sigma}\right),$$

where  $\rho = \max_j \{A_j | \mathbf{R}_{kj} | \}$  is the maximum element in the cross-correlation matrix. The generalized probability of error is obtained by substituting (56) in (55).

Analogously, the probability of error of a traditional one-state conventional detector can be written as

$$P_{k,\text{conv}}^{(1s)} \leq Q\left(\frac{\sqrt{E_k} - (K-1)\rho}{\sigma}\right). \quad (57)$$

A numerical analysis of (55) and (57) for the conventional receiver is reported in Section 6.

### 5.2. Probability of error for the two-state decorrelating detector

The probability of error for the two-state CDMA decorrelating detector is obtained by substituting in (53) and (54) the

linear transformation

$$\mathbf{L} = \mathbf{R}^{-1}. \quad (58)$$

The transformation (58) completely removes the interference coming from the other users' data bits on the desired user's bit interval.

The two terms of the generalized probability of error of the two-states decorrelating receiver are

$$P_{k,\text{dec}}^{(2s|t)} \leq Q\left(\frac{\sqrt{E_k} + \theta_{1,2}}{\sqrt{\mathbf{R}_{kk}^{-1}}\sigma}\right), \quad (59)$$

$$P_{k,\text{dec}}^{(2s|s)} \leq Q\left(\frac{\theta_{0,2}}{\sqrt{\mathbf{R}_{kk}^{-1}}\sigma}\right). \quad (60)$$

The generalized probability of error is obtained by substituting (60) and (59) in (55).

This global two-state probability of error has to be compared with the CDMA single-state decorrelating detector probability of error given by [5]

$$P_{k,\text{dec}}^{(1s)} \leq Q\left(\frac{\sqrt{E_k}}{\sqrt{\mathbf{R}_{kk}^{-1}}\sigma}\right). \quad (61)$$

## 6. ANALYTICAL PERFORMANCE EVALUATION

In this section, the performance bounds of (30), (35), and (56) are reported for both the two-state and the single-state receivers. The dependence of the asymptotic multiuser efficiency on the operating point of the proposed CDMA communication scheme has been analyzed.

It should be noted that the asymptotic multiuser efficiency permits a significant comparison between the single- and the two-state receivers since it takes into account the performance degradation introduced by MAI. The comparisons reported in this document, however, do not take into account the additional information available at the proposed receiver concerning the status of the transmitter. This additional information in a conventional receiver requires a signaling which has an impact on the overall performance. In this sense, the results shown below are not completely fair to the proposed receiver concerning the offered service.

In Figure 3, the curves of the averaged asymptotic multiuser efficiency for both the single- and two-state receivers are shown. These curves are plotted versus the  $P_{\text{talk}}$  probability, defined by the absolute probability of a nonsilence symbol for each user. The  $\rho$  parameter expresses the maximum cross-correlation value among the spreading signatures of the active users.

As shown, the low activity region ( $P_{\text{talk}} < 0.5$ ) is characterized by a substantial improvement of the proposed transmission scheme over the traditional "always on" transmission. As the probability of the nonsilence symbol grows, the increase of the interfering power and the smaller decision regions for the nonsilence information symbols introduce a degradation over the traditional reception scheme.



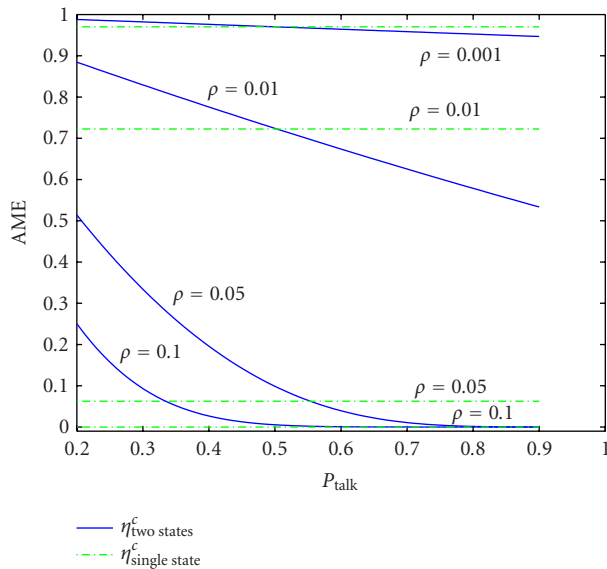


FIGURE 3: Asymptotic multiuser efficiency as a function of the probability of talk ( $P_{\text{talk}}$ ) for different values of the maximum cross-correlation coefficient ( $\rho$ ). The proposed two-state receiver is compared to the conventional single-state receiver in a 16 CDMA asynchronous users system.

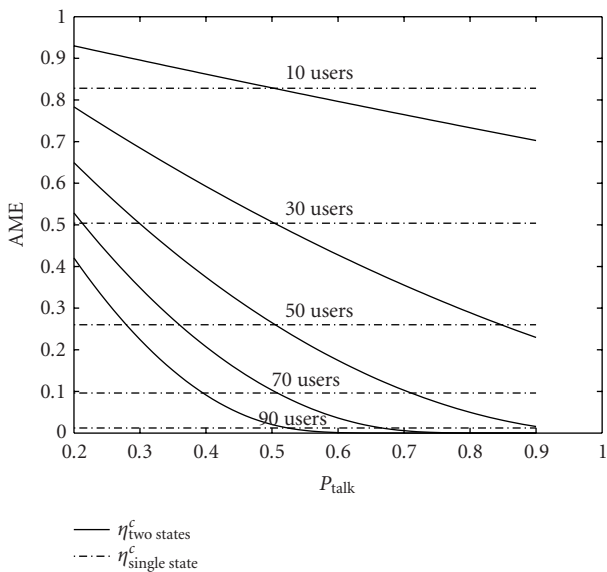


FIGURE 4: Asymptotic multiuser efficiency as a function of the probability of talk ( $P_{\text{talk}}$ ) for different number of asynchronous CDMA active users (from 10 to 90) in the system. The value of the maximum cross-correlation coefficient ( $\rho$ ) is set to 0.01. The proposed two-state receiver is compared to the conventional single-state receiver.

The dependence of the asymptotic efficiency on the increasing number of users is reported in Figure 4.

Again, the increase of the MAI interference is mitigated by the average reduced activity of the sources as shown by

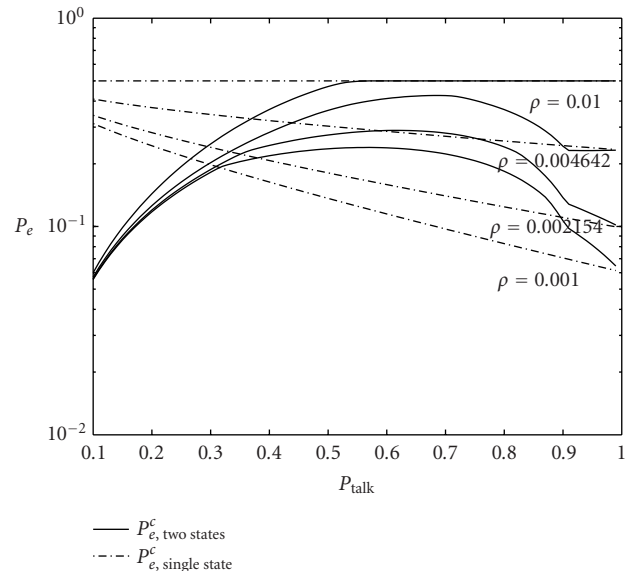


FIGURE 5: Probability of error ( $P_e$ ) as a function of the probability of talk ( $P_{\text{talk}}$ ) for different values of the maximum cross-correlation coefficient ( $\rho$ ). 128 asynchronous CDMA users are contemporary transmitting in the system. The value of the (SNR) ratio is set to 8 dB. The proposed two-state receiver is compared to the conventional single-state receiver.

the curves for low values of  $P_{\text{talk}}$ . This leads us to conclude that the proposed CDMA communication scheme is able to get practical advantages over the traditional CDMA communication systems.

In Figure 5, the generalized probability of error for the two-state detector is compared to the probability of error of the conventional single-state receiver. The figure refers to a CDMA system with 128 active users at  $E_b/N_0 = 8$  dB. The curves are reported for different values of the normalized cross-correlation index ( $\rho$ ) and different values of  $P_{\text{talk}}$ . The comparison has been computed with the same average received power, thus the conventional single-state receiver performance depends on  $P_{\text{talk}}$  as well. As expected, in the low  $P_{\text{talk}}$  region, that is, the region of interest for the proposed receiver, the proposed scheme significantly outperforms the traditional single-state receiver. When the probability of talk is approaching the unity ( $P_{\text{talk}} \rightarrow 1$ ), both receivers show the same performance.

## 7. W-CDMA SIMULATED ENVIRONMENT

In this section, some evaluations of the proposed reception scheme applied to the W-CDMA context are reported. Through computer simulations, the proposed two-state receiver has been compared to the traditional single-state one, operating at the same throughput and the same peak transmitted power.<sup>6</sup>

<sup>6</sup>The average transmitted power of the two-state CDMA system depends linearly on  $P_{\text{talk}}$ .

A W-CDMA communication environment has been built up following the 3GPP standard specifications [9]. The complex envelope of the received DPDCH at symbol time  $n$  can be written as

$$r^{(n)}(t) = \sum_{k=1}^K A_k b_k^{(n)} \sum_{l=1}^L h_{k,l}^{(n)} g_k(t - nT_s - \tau_k - \tau_{k,l}) + n(t), \quad (62)$$

where  $n(t)$  is the complex additive white Gaussian noise (AWGN) with zero mean and variance  $\sigma^2$ , while the entire received signal is

$$r(t) = \sum_{n=0}^{N_b-1} r^{(n)}(t), \quad (63)$$

where  $N_b$  is the number of observed symbols. An *asynchronous* W-CDMA system implies that users delays  $\tau_k$  are uniformly distributed random variables into the interval  $[0, T_s)$  for all  $k$ . This property is extended to the user paths in a multipath fading channel, so that  $\tau_{k,l}$  are uniformly distributed in the interval  $[0, T_s)$  for all  $k, l$ . This fact comes from the assumption that the transmitted signals pass through separated and independent channels in an asynchronous system. It is assumed here that the channel acts like a linear filter with impulse response  $h_k^{(n)}(t)$  and consists of  $L$  discrete multipath components.

A multipath fading channel with  $L = 4$  independent paths has been simulated as specified in the suburban channel model shown in the 3GPP specifications [9]. Channel coefficients are supposed to have a Rayleigh distributed amplitude and uniform distributed phase. Classical (Jake's) Doppler spectrum is assumed with 100 Hz Doppler spread. Both DPDCH (data) and DPCCH (control) have been simulated although only the data channel is considered in the BER calculation.

It is important to highlight that the two-state optimal threshold has been derived for a single-user AWGN channel, and it does not take into account the presence of the MAI as well as the fading process. Thus, the performance of the two-state CDMA receiver reported in the paper has to be considered as a worse estimate. Results of the optimal two-state threshold for a multipath-multiuser channel will be soon available.

The comparison between the proposed two-state RAKE receiver and the standard one-state RAKE receiver has been carried out in the following summarized cases:

- (1) 4 users at 960 kbps (100% of the system load) with a  $P_{\text{talk}}$  ranging from 0.5 to 0.0625;
- (2) 8 users at 240 kbps (50% of the system load) with a  $P_{\text{talk}}$  ranging from 0.5 to 0.0625;
- (3) 8 users at 480 kbps (100% of the system load) with a  $P_{\text{talk}}$  ranging from 0.5 to 0.0625.

A multipath relatively fast-fading channel with 4 independent paths shared by the asynchronous users is supposed.

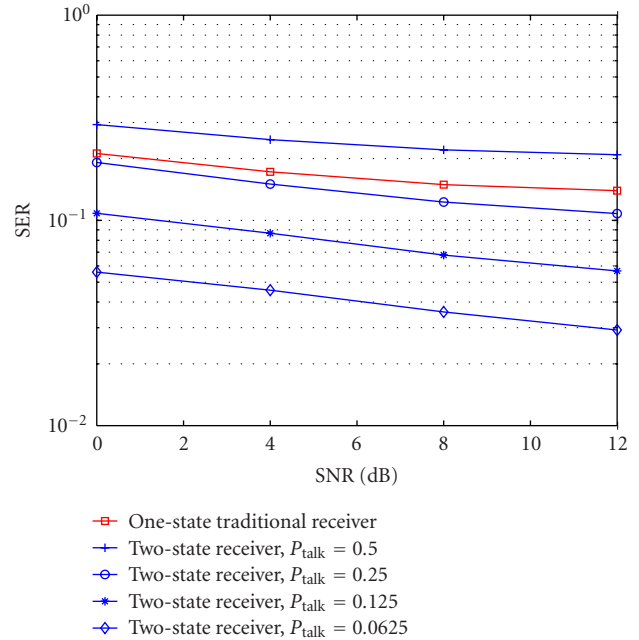


FIGURE 6: Symbol error rate as a function of the average SNR with 4 asynchronous users at 960 kbps (100% system load) for various  $P_{\text{talk}}$ .

It is important to highlight that for the two-state receiver, all the possible errors have been here computed, that is, both the symbol errors and the false detection errors take part of the final BER.

In Figures 6, 7, and 8, the total bit error rate of the two-state CDMA receiver is compared to the bit error rate for the single-state receiver. The curves are reported for different values of the SNR and different values of  $P_{\text{talk}}$  (for the two-state receiver only). All simulations assume that the two compared communication systems had the same throughput. In the high  $P_{\text{talk}}$  region the performance of the proposed scheme is not significantly different from the traditional single-state receiver. For quasicontinuous sources, the presence of a third decision region results in a higher probability of error when the transmitter is in the talk state. As the probability of a talk symbol decreases, the two-state transmission method performs significantly better than the standard one. This is due to the fact that when  $P_{\text{talk}}$  is low, the silence state occurs frequently but with a short time duration and, hence, the average MAI can be limited without any signaling overhead.

All the derived results, coupled with the lower power consumption of the proposed scheme, lead us to conclude that the proposed two-state CDMA communication scheme is able to get practical advantages over the traditional CDMA communication systems even in multipath fading channels.

## 8. IMPLEMENTATION ISSUES

The proposed reception scheme can be integrated into the current W-CDMA architectures with little effort. The major advantages, however, can be found in those systems where

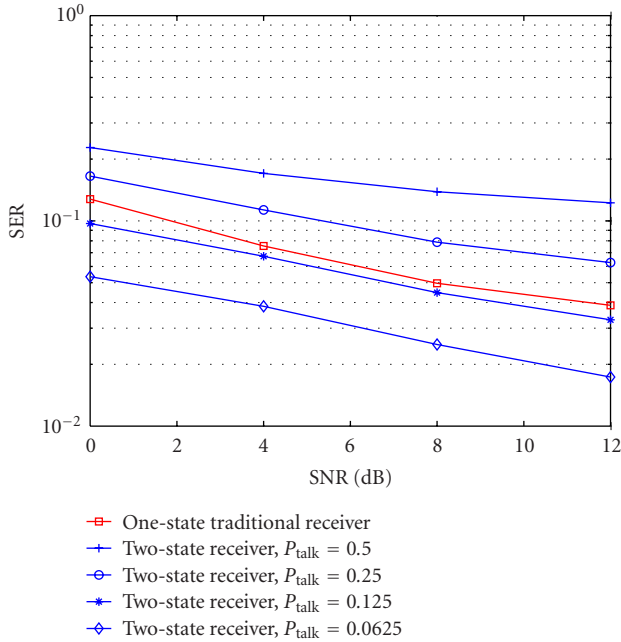


FIGURE 7: Symbol error rate as a function of the average SNR with 8 asynchronous users at 240 kbps (50% system load) for various  $P_{\text{talk}}$ .

the two-state concept is applied to both the transmitter and the receiver. If a conventional receiver is adopted and a silence state is inserted only in the transmitter, the main benefit is found in the power consumption and global MAI reductions. It is obtained at the expense of an increased processing at the receiver side for depuncturing noninformative silence symbols. If both the transmitter and receiver implement the two-state scheme, the depuncturing process can be avoided and the resulting bitstream provided to upper layers contains only true informative symbols. It is worth noting that the evolution of a traditional single-state CDMA receiver towards the novel two-state detector simply implies the modification of the signal processing block in the transmitter and receiver chain; no changing involves the other blocks (RF section, etc.). In the future, the software defined radio technology can provide the reconfigurability to adaptively switch to the two-state algorithm when needed. Moreover, a two-state version of convolutional coding and decoding can even improve the performance of the detection/depuncturing process. Results on this topic will be presented soon.

## 9. CONCLUSIONS

In this paper, an improved CDMA transmission scheme based on a nonconstant energy symbols constellation called “two-state” transmission is presented. The theoretic analysis shows the convenient use of the proposed signaling method in CDMA systems where the multiple-access interference and the power consumption are the dominant limiting factors. The asymptotic multiuser efficiency and an upper bound of the probability of error of the conventional and the decor-

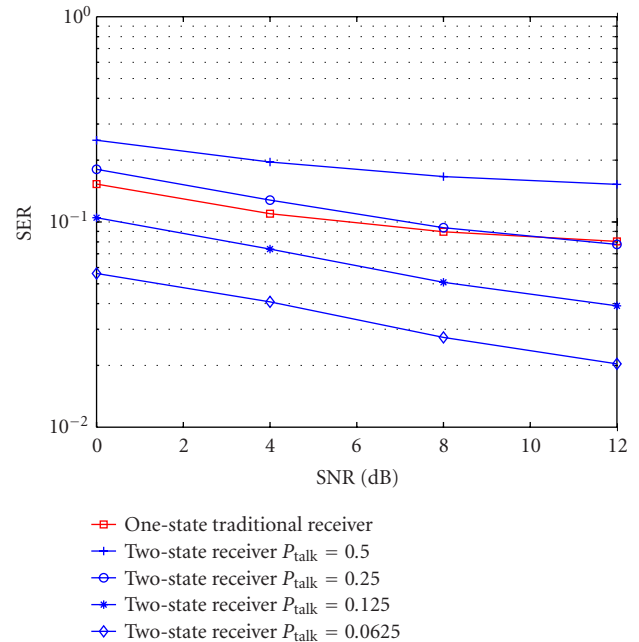


FIGURE 8: Symbol error rate as a function of the average SNR with 8 asynchronous users at 480 kbps (100% system load) for various  $P_{\text{talk}}$ .

relating receivers have been derived. Moreover, the advantages of the proposed receiver over the traditional single-state scheme have been evaluated in a multipath fading wireless channel by computer simulations. For such a purpose, a W-CDMA system has been simulated following the 3GPP specifications. As a final comment, it should be noted that the two-state reception uses signals which are completely compatible with the traditional ones, making it possible to implement hybrid schemes where the two states represents an option to increase spectral efficiency in specific traffic conditions.

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