Abstract - This paper compares different schemes that can be used to improve the performance of CDMA in wireless data systems. In particular, we consider a closed-loop power control scheme and an adaptive coding scheme. The comparison between these different techniques is performed in terms of mean transmission time and energy efficiency. Our aim is to show that an adaptive coding scheme can allow a good performance with respect to typical power control techniques.

I. Introduction

The air interface of third generation mobile communication systems will be based on Direct Sequence-Code Division Multiple Access (DS-CDMA). A particular advantage of DS-CDMA is its capability to support different data rates [1]. We consider a DS-CDMA wireless local area network that uses the 2.4 GHz Industrial Scientific and Medical (ISM) frequency band for data transmissions in a low mobility indoor system.

With CDMA all users transmit in the same frequency band; the transmissions in a cell suffer from interference from other transmissions in both this cell and adjacent cells. The interference limits the number of simultaneously active users per cell. Another problem is that the path losses from mobile users to the base station (i.e., uplink) are different depending on the distances of these users; moreover, signals may be attenuated by shadowing events. Hence, power control schemes must be used to compensate for different power levels received at the base station. We assume a slow power control for shadowing and path loss. As for short term fading, we consider both fast power control and no power control. In both cases, an adaptive coding scheme is envisaged [2]. The base station measures power and/or Signal-to-Interference Ratio (SIR) and sends these values to the mobile terminal; accordingly, the mobile terminal adapts its transmitted power level and/or the code protection level. Since the information bit rate depends on the code rate used, the adaptive scheme is well suited for delay tolerant data traffic sources. Our aim is to show that the use of an adaptive coding scheme can allow a good performance with respect to typical power control schemes.

Let \( R_b \) denote the maximum information bit rate of a user which is obtained with a minimum code protection. If a further code is added with rate \( R < 1 \), the channel bit rate does not change, but, the information bit rate becomes \( RR_b \). It has been considered \( R_b = 0.5 \) Mbit/s. User bits are multiplied by a Gold chip sequence to spread the signal on a 16 MHz bandwidth [3] (the spreading factor is 32).

II. System Model

Let us consider the uplink of a DS-CDMA wireless system. A power control loop is used to compensate for both path loss and shadowing attenuations. Moreover, we consider two cases for the short-term multipath fading:

(a) No fast power control,

(b) An ideal closed-loop fast power control.

In a real system we must account for errors in the power control that reduce its efficiency. However, the power control scheme (b) is considered ideal, since the scope of this paper is to show that the adapting coding scheme may be an attracting solution with respect to power control techniques. We will use the apex \( (\mathcal{A}, \alpha) \) for the case with adaptive coding and no power control, the apex \( (\mathcal{A}, \mathcal{B}) \) for the case with adaptive coding and power control, the apex \( (\mathcal{F}, \mathcal{B}) \) for the case with fixed coding and power control.

In a widely accepted tap channel model, the low-pass impulse response of a frequency-selective fading channel is

\[
\alpha(t) = \sum_{i} \alpha_i(t) \delta(t - \tau_i)
\]

where \( \delta(t) \) is the Dirac delta function, \( \alpha_i(t) \) and \( \tau_i, i = 1, ..., P \) are the tap coefficients and the relative delays, respectively. With an optimum single-user RAKE demodulator and perfect slow power control, the
power received at the base station from the \(i\)-th user is:

\[
P_{R,i} = U_i^2, \quad \text{for } i = 0, \ldots, n - 1
\]

where \(U_i^2 = \sum_{p=1}^{p=\Omega} \xi_{p,i}^2\) are random variables which have (without loss of generality) unit mean and where \(n\) is the random number of simultaneously active users in the same cell.

We assume a homogeneous cellular system, where the number of simultaneously active users has the same distribution in each cell. The standard gaussian approximation is adopted in order to derive the SIR experimented at the base station of a given cell for the zeroth (desired) user. By neglecting the thermal noise introduced at the receiver, the SIR\(_n\) at the base station for \(n\) simultaneously active users in the cell is [4]:

\[
SIR_n = \frac{U_0^2}{2G(n-1+ I_{mc}}
\]

where \(G\) is the processing gain and \(I_{mc}\) is the inter-cell interference.

At the denominator of (2) we have considered the mean of the power of the interference; the goodness of this approximation has been proved in [5]. In order to have an acceptable performance the received SIR can not undergo a given threshold, \(SIR\). The outage probability [6] conditioned on \(n\) simultaneously active users in the cell, \(P_{o|n}\), is:

\[
P_{o|n} = Pr \left[SIR_n < SIR \right]
\]

The conditioning on \(n\) is removed by using the distribution of \(n\) obtained in the next Section.

We have considered a Rayleigh channel derived from the indoor office channel model B in [7], since we expect that the channel characteristics at 2 GHz of the Universal Mobile Telecommunications Systems (UMTS) are quite close to those at 2.4 GHz. In particular, we have considered \(P = 6\) and a flat Doppler spectrum. The chip time value, \(T_c = 62\) ns, allows that all the paths of the channel model can be revealed by the RAKE receiver. The received power from the zeroth user, \(U_0^2\), is the sum of \(P\) independent exponentially distributed variables with mean values, \(\Omega_p\), \(p = 1, \ldots, P\). Each \(\Omega_p\) is the mean power of a given path (i.e., \(\Omega_p = E\left[\xi_p \xi_p^*\right]\)). The cumulative distribution of \(U_0^2\) is:

\[
F_{U_0}(x) = \sum_{p=1}^{P} \frac{\Omega_p}{\Omega_p - \Omega_1} \left(1 - e^{-\frac{x}{\Omega_p}}\right)
\]

From [7], we have: \(\Omega_1 = 0\) dB, \(\Omega_2 = -3.6\) dB, \(\Omega_3 = -7.2\) dB, \(\Omega_4 = -10.8\) dB, \(\Omega_5 = -18\) dB, \(\Omega_6 = -25.2\) dB. Without loss of generality, the \(\Omega_p\) values have been rescaled so that \(\sum_{p=1}^{P} \Omega_p = 1\) (i.e., the average received power is 1).

As for the characterization of the inter-cell interference, we refer to [6], where log-normal shadowing, distance path-loss, best cell site selection and slow power control based on signal strength are taken into account. Let \(\varepsilon\) denote the other-cell interference ratio, that is the mean inter-cell interference divided by the mean number of simultaneously active users per cell. This parameter is evaluated in [6] (Table I) under the assumption of a uniform user distribution, for different values of the variance of the log-normal shadowing distribution \(\sigma\). We have considered the worst case in [6]: \(\varepsilon = 0.634\) for \(\sigma = 8\) dB. With fast power control, this value of \(\varepsilon\) will be multiplied by a suitable factor, as detailed below.

In case (a), the SIR\(_n\), referred to as SIR\(_{wc}\), is given by (2), where \(I_{mc}\) must be replaced by \(I_{mc}(\varepsilon)\). We assume that the inter-cell interference is produced by a fixed number of simultaneously active users in each adjacent cell equal to \(E[n]\); the mean inter-cell interference is \(E[I_{mc}(\varepsilon)] = E[n]E[\beta^2]\). According to (2)-(4), \(P_{o|n}^{(a)}\) is:

\[
P_{o|n}^{(a)} = F_{U_0} \left(\frac{2n-1 + E[n]E[\beta^2]}{3G} SIR \right)
\]

Equation (5) gives the cumulative distribution of SIR\(_{wc}\) computed in SIR\(_n\) and conditioned on \(n\) simultaneously active users in the cell.

In case (b), it is assumed that each user multiplies the transmitted power level by \(\beta^2\). In an ideal power control scheme \(\beta^2 = 1/U_0^2\) (we do not consider any constraint on the maximum power that can be transmitted by a mobile terminal). Hence, the received power from the zeroth user becomes equal to 1 and \(E[I_{mc}(\varepsilon)] = E[n]E[\beta^2]\). The expected value of \(\beta^2\) can be numerically evaluated from the distribution of \(U_0^2\) in (4). Also in case (b) we consider that in each adjacent cell \(E[n]\) users are simultaneously active. Hence, \(P_{o|n}^{(b)}\) is:

\[
P_{o|n}^{(b)} = \begin{cases} 
1, & \text{if } SIR > \frac{3G}{2(n-1+E[n]E[\beta^2])} \\
0, & \text{otherwise}
\end{cases}
\]

Equation (6) is the cumulative distribution of SIR\(_{wc}\) computed in SIR\(_n\) and conditioned on \(n\) simultaneously active users in the cell.
III. System Analysis

Mobile terminals made asynchronous transmission attempts as soon as they need to send data messages. A very large population of users is envisaged, where each user transmits a very light traffic. Hence, the total data traffic generation is considered Poisson distributed with mean rate \( \lambda \) messages per second. Each message is composed of a random number of bits geometrically distributed with mean value \( L \). A cell can be modeled by a continuous-time Markov chain, where the state \( n \) is the number of simultaneously active users. We assume that the number of available codes is so high that a mobile user that starts a transmission can always find an available code. Hence, a cell is high that a mobile user that starts a transmission assumes that the number of available codes is so large that any message has a small probability of being dropped due to insufficient codes. We consider Poisson distributed with mean rate \( \lambda \) messages per second. Each message is composed of a random number of bits geometrically distributed with mean value \( L \). A cell can be modeled by a continuous-time Markov chain, where the state \( n \) is the number of simultaneously active users. We assume that the number of available codes is so high that a mobile user that starts a transmission can always find an available code. Hence, a cell is high that a mobile user that starts a transmission assumes that the number of available codes is so large that any message has a small probability of being dropped due to insufficient codes.

The code within \( \Phi \) is selected with the maximum rate \( R \) which permits to fulfill \( \text{SIR} \geq \text{SIR}/K \), and, hence, the same SIR. The code within \( \Phi \) is selected with the maximum rate \( R \) which permits to fulfill \( \text{SIR} \geq \text{SIR}/K \), and, hence, the same SIR. The code within \( \Phi \) is selected with the maximum rate \( R \) which permits to fulfill \( \text{SIR} \geq \text{SIR}/K \), and, hence, the same SIR. The code within \( \Phi \) is selected with the maximum rate \( R \) which permits to fulfill \( \text{SIR} \geq \text{SIR}/K \), and, hence, the same SIR.

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\[ \pi_n = \frac{\rho^n}{n! \prod_{i=1}^{n} E[R|l]} \sum_{l=1}^{\infty} \rho^{l} / \prod_{i=1}^{l} E[R|k] \]  

(11)

where \( \rho = \lambda L J R_0 \).

Equation (11) is used in both cases \((A, a)\) and \((A, b)\) provided to use respectively the distributions \(Y^{(A, a)}(n)\) or \(Y^{(A, b)}(n)\) to derive the rates \(U_n\).

In the state \( n \) we have an outage probability \( P_{o,n} \); when transmissions occur during an outage time they are carried out with an information bit rate \( R_0 R_c \). During a given time interval \( T \) the mean information loss is \( T R_n R_c P_{o,n} \) for any active user.

In the same time the mean information sent is \( T R_c E[R|n] \). Therefore, the loss probability, \( P_{loss,n} \), conditioned on state \( n \) is:

\[ P_{loss,n} = \frac{T R_n R_c P_{o,n}}{T R_c E[R|n]} = \frac{R_n}{E[R|n]} P_{o,n} \]  

(12)

The conditioning on \( n \) is removed in (12) by using the probability \( q_n \) that a given user is active when the system is in the state \( n \). This probability is biased with respect to the state probabilities:

\[ q_n = \frac{n \pi_n}{\sum_{i=1}^{\infty} \pi_i} \]  

(13)

Finally, the loss probability is:

\[ P_{loss} = \sum_{n=1}^{N_{max}} P_{loss,n} q_n = \sum_{n=1}^{N_{max}} \frac{R_n}{E[R|n]} P_{o,n} q_n \]  

(14)

In (14) we have neglected the contributions for \( n > N_{max} \) so that \( P_{o,n} q_n < 10^{-9} \); the same approximation has been also used in the following formulas.

For an acceptable performance, \( P_{loss} \) must be below a maximum acceptable value, \( P_{loss}^{max} \) that has been assumed equal to \( 10^{-4} \). Once \( G, SIR, \epsilon, \{\Omega_n\} \) and \( \Phi \) are selected, there is a maximum value of the load \( \rho \) beyond which \( P_{loss} < P_{loss}^{max} \) is not fulfilled.

The Energy Efficiency (EE) [6] is defined as the ratio between the mean energy required for the ideal transmission of a message (i.e., with \( R = 1 \)) and the actual mean energy required for the transmission of a message; this ratio must be multiplied by \((1 - P_{oas})\) to account for the waste of energy during outage. Without power control the transmitted power is constant and the above ratio is between mean times: the ideal mean transmission time \( T/R_0 \) and the actual mean transmission time, \( E[T_{msg}]^{(A,a)} \) in case (a) and \( E[T_{msg}]^{(A,b)} \) in case (b). However, in case (b) the ratio between times must be multiplied by \( 1/E[\beta] \) for the increase in the mean transmitted power due to power control.

From the Little’s law, the mean transmission time, \( E[T_{msg}]^{(A,a)} \) is:

\[ E[T_{msg}]^{(A,a)} = \sum_{n=1}^{N_{max}} n \pi_n^{(A,a)} \frac{\rho}{\lambda} = \frac{E[n]^{(A,a)}}{\lambda} \]  

(15)

\( E[T_{msg}]^{(A,b)} \) is formally analogous to \( E[T_{msg}]^{(A,a)} \). Finally, we attain the following energy efficiency expressions:

\[ EE^{(A,a)} = (1 - P_{oas}) \frac{\rho}{E[n]^{(A,a)}} \]  

\[ EE^{(A,b)} = (1 - P_{oas}) \frac{\rho}{E[\beta] E[n]^{(A,b)}} \]  

(16)

IV. Results and comparisons

A computer simulation has been used to validate the analysis presented in Sect. III. The time is divided in slots with duration \( H \); the channel is considered constant during time \( H \) (Sect. I). In each slot \( H \) the number of message arrivals is Poisson distributed with mean \( \lambda H \). A synchronization among users has been considered in the simulations, but, since \( H \) is quite low, the impact of synchronization is slight, as it will be verified by the agreement between simulation and analytical results.

In the theoretical study we have ideally assumed that code rate changes can occur at any instant, whereas in the simulations the rate adaptation is made every time \( H \), on the basis of the measures taken by the base station.

The block diagram of the simulated signal received from the \( i \)-th user is shown in Fig. 1(a). Since signal variations in \( H \) are negligible, the coefficients of the \( i \)-th user’s channel, \( \alpha_c(i) \), may be adequately generated by a white noise complex signal (unit variance) multiplied by \( \sqrt{\Omega} \) and processed by a Doppler digital Butterworth filter with normalized cut-frequency equal to \( f_c H \) so as to obtain a flat fading. For each active user \( i \) the channel in Fig. 1(a) is used to obtain its \( U_i^2 \). With power control, the power \( U_i^2 \) is adjusted slot by slot on the basis of the previously generated \( U_i^2 \).

The “Process 1” shown in Fig. 1(b) activates the users at the beginning of each slot \( H \), according to the Poisson process. Moreover, “Process 1” selects the code to be used on the basis of the actual SIR measured by the base station. At the end of each slot, “Process 1” evaluates the active users which terminate their messages and that must be deactivated. The signals from the active users and the inter-cell interference are then processed by the “Process 2” in Fig. 1(b). “Process 2” is responsible for establishing whether a packet has been correctly delivered on the basis of both the interference conditions and coding.
We have also shown the performance obtained with power control, but assuming a fixed code protection (i.e., without adaptive coding).

From Fig. 2 we have that only for low traffic the scheme with power control and fixed coding outperforms the scheme with adaptive coding and no power control. Otherwise, the fixed bit rate scheme with power control attains a low performance: its curves are interrupted, because for medium-high loads the requirement on \( P_{\text{req}} \) can not be fulfilled. A better performance is obtained with adaptive coding schemes. These techniques attain similar results from low-to-medium loads. Whereas, for high loads only the scheme \((A, b)\) permits to obtain an acceptable performance. In the case \((A, a)\) higher traffic loads could be managed only with powerful codes. However, we may expect that the traffic will not be so heavy on uplink.

From Fig. 3 we have that the solution with adaptive coding and no power control allows a significant performance improvement that can justify its use from low-to-medium loads. This confirm that the power control scheme entails an increase in the mean transmitted power, as shown in Sect. II

### IV. Conclusions

A wireless DS-CDMA system has been considered. Adaptive coding and power control have been compared by assuming a correlated channel. We have shown that from low-to-medium traffic loads adaptive coding permits a good efficiency without worsening the message delay performance. This is an interesting result in the light of future low-weight low-power mobile terminals.

![Simulation block diagram](image)

**Fig. 1:** Simulation block diagram.

Figs. 2 and 3 present the results obtained with adaptive coding, respectively in terms of the mean message delay and the energy efficiency. In Fig. 2 we have also shown the performance obtained with power control, but assuming a fixed code protection (i.e., without adaptive coding).

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![Mean message transmission time comparisons between power control scheme and adaptive coding scheme](image)

**Fig. 2:** Mean message transmission time comparisons between power control scheme and adaptive coding scheme.

![Energy efficiency comparison between power control scheme and adaptive coding scheme](image)

**Fig. 3:** Energy efficiency comparison between power control scheme and adaptive coding scheme.

### References


[7] Universal Mobile Telecommunications System (UMTS); Selection procedures for the choice of radio transmission technologies of the UMTS (UMTS 30.03 version 3.1.0).