# MULTI-CELLULAR CDMA SYSTEMS WITH INTERFERENCE CANCELLATION: EFFECTS OF PATH LOSS, SHADOWING AND HANDOVER STRATEGIES

*Alexander Lampe, Ralf R. Müller and Johannes B. Huber*

Laboratorium für Nachrichtentechnik, Universität Erlangen-Nürnberg
Cauerstr. 7, D-91058 Erlangen, Germany
e-mail: alampe@nt.e-technik.uni-erlangen.de

## ABSTRACT

Multi–cell CDMA Systems with interference cancellation and powerful single–user channel coding close to channel capacity are investigated for randomly chosen signature sequences and single cell site processing. Due to path loss and shadowing they show superior power and bandwidth efficiency on the AWGN channel compared with orthogonal multiple access. Moreover, attenuation controlled handover turns out to be significantly preferable in comparison with distance controlled handover if shadowing to different cell-sites is correlated.

## 1. INTRODUCTION

Cellular communication systems are topic of intensive research since mobile communications have been become popular consumer products. In the beginning of mobile communications development multi–path Rayleigh fading was the main problem to be solved. Nowadays, there are many different suggestions and solutions to overcome the effects of fast fading, e.g. powerful error–correction coding and/or spread–spectrum techniques. Recent results in information theory [1, 2, 3, 4] show that different signal attenuations which are track–able by transmitter and receiver also play an important role in finding an optimum system implementation.

This paper puts more emphasis on the track–able fading than on the untrack–able one. In order to pay attention to the untrack–able multi–path fading we consider a coded direct sequence code division multiple access (CDMA) system with random signature sequences which approximately transforms the multi–path channel into an additive white Gaussian noise (AWGN) channel by averaging out fading effects. For this channel we can apply the well–known results of multiuser information theory [5] and the transmit power considerations given in [1, 2, 4].

The basic principle of multiuser information theory on the AWGN channel is interference cancellation (IC) [5]. Considering fading channels with imperfect channel state estimation the problem of imperfect cancellation occurs even if transmission is error–free [6]. This problem is *not* neglected, but modelled by the cancellation factor $\beta$ denoting the ratio of interference power after cancellation to that one before the cancellation procedure. Although intercellular interference cancellation, also called multiple cell site processing, is required to avoid interference limitation of cellular systems [7] we do not consider such a model as it involves huge implementational complexity. We restrict the considerations to a multicellular model with single cell site processing. Such a model has been analyzed in detail for untrack–able fading, but without respect to path loss and shadowing in [8].

Our communication model introduced in Section 2 emphasizes path loss and correlated shadowing. The derivation of the users' required transmit energies based on this model is discussed in Section 3. Moreover, a comparison between distance and power controlled handover is given in Section 4 as well as considerations on the influence of channel coding failing to operate arbitrarily close to the capacity limit. Finally, Section 5 points out the conclusions.

## 2. COMMUNICATIONS MODEL

We consider symbol synchronous transmission in an idealized cellular communication system given in Fig. 1.

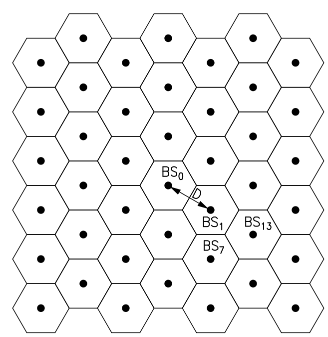


Figure 1: Idealized cellular system.

The normalized distance between two neighboring base stations is chosen as $D = 2$ and the number of base stations is $M \gg 1$. We assume a uniform user distribution within the whole system's area with $K$ users assigned to each base station in the average. Next, we suppose that each user's complex Gaussian distributed signal is demodulated using only the signal received at the base station this user is allocated to. For simplification of notation all is considered from $\mathrm{BS}_0$'s point of view being no restriction because of the whole system's symmetry. Further, we denote the average energy per symbol received at base station $\mathrm{BS}_0$ from a user $k$ assigned to $\mathrm{BS}_0$ as $E_k$. In contrast to this, the energy of the signal received at $\mathrm{BS}_0$ but having been transmitted by another user $k$ whose service is supported by $\mathrm{BS}_{j\neq 0}$ is denoted as $\widehat{E}_k^j$.

In the following we will use the superscripts also for all other variables to distinguish users being assigned to different base stations and omit the superscript 0 if the users belong to $\mathrm{BS}_0$. Furthermore, we assume that the received signal at each cell site is corrupted by AWGN with power spectral density $N_0$. Thus, we get for the average signal-to-interference ratio of user $k$ being assigned to $\mathrm{BS}_0$ the general expression

$$\mathrm{SIR}_k = \frac{E_k}{N_0 + I_k + \sum_{j\neq 0} I_k^j}, \tag{1}$$

where $I_k$ and $I_k^j$ denote the multiuser interference due to users assigned to $\mathrm{BS}_0$ and $\mathrm{BS}_{j\neq 0}$, respectively.

Now, we consider a conventional CDMA receiver with interference cancellation where the users are indexed in the order of being demodulated and cancelled. Then, under the condition that all users employ randomly chosen spreading sequences consisting of $N$ chips we have, see [9]

$$\mathrm{SIR}_k = \frac{E_k}{N_0 + \beta \sum_{i=1}^{k-1} \frac{E_i}{N} + \sum_{i=k+1}^{K} \frac{E_i}{N} + \sum_{j\neq 0} \sum_{i=1}^{K} \frac{\widehat{E}_i^j}{N}}. \tag{2}$$

The factor $\beta \in [0,1]$ models the imperfect cancellation of the previous users $1,\ldots,k-1$ resulting from inaccurate channel estimation.

Further, we assume that all users intend to transmit at the same rate $R$ and apply single user coding allowing reliable transmission close to the capacity of the AWGN channel, i.e. $R = \mathrm{ld}\,(1+\mathrm{SIR})$. Hence, the average signal-to-interference ratio $\mathrm{SIR}_k$ has to be equal for all users and must satisfy $\mathrm{SIR}_k = \mathrm{SIR}, \quad \forall k$. This condition has to be fulfilled by appropriate control of the receive energies $E_k$, $\forall k$. Replacing $\mathrm{SIR}_k$ in Eq. (2) by SIR we get for $N \gg \mathrm{SIR}$ the recursive formula (see [10])

$$E_{k,\not\perp} = E_{K,\not\perp}\, a^{K-k}, \tag{3}$$

where $a \triangleq \exp\left(\frac{1}{N}\mathrm{SIR}(1-\beta)\right)$ and

$$E_{K,\not\perp} = \mathrm{SIR}\left(N_0 + \beta \sum_{i=1}^{K-1} \frac{E_{i,\not\perp}}{N} + \sum_{j\neq 0}\sum_{i=1}^{K} \frac{\widehat{E}_{i,\not\perp}^j}{N}\right). \tag{4}$$

In the rest of this paper we use the subscript $\not\perp$ for CDMA with randomly chosen spreading sequences because it is a nonorthogonal multiple access technique. Considering TDMA with time slots of equal length as an example of orthogonal multiple access which is labeled with the subscript $\perp$ we obtain

$$E_{k,\perp} = \mathrm{SIR}\left(N_0 + \sum_{j\neq 0} \widehat{E}_{k,\perp}^j\right). \tag{5}$$

Based on the required receive energies, the users' transmit energies $\tilde{E}_k$, $\forall k$, have to be adapted according to $\tilde{E}_k = \exp(\Lambda_k)\, E_k$, where $\Lambda_k$ denotes the $k$th user's logarithmic attenuation. We assume that the signal amplitudes fade slowly enough and each user's attenuation is known to his/her base station such that perfect power control is possible. Eq. (5) yields that the required receive energies $E_{k,\perp}$, $\forall k$, are the same under the condition of equal average multiuser interference for all $K$ users. In contrast to this, the necessary receive energies applying CDMA with IC rise exponentially, cf. Eq. (3). This increase in the required transmit energies can be combatted by an appropriate mapping of the users indices to their attenuations resulting in a flat transmit energy distribution (see [11]). More explicitly, the user with the highest attenuation needs the smallest receive energy whereas the highest receive energy is required by the user having the smallest attenuation. Of course, in a TDMA system it would be possible (and necessary) to scale the users' time slots according to their attenuations to improve the bandwidth efficiency [12]. However, we assume equal time slot lengths throughout the paper because of their practical relevance. In addition, it can be shown that the basic results are still valid.

In this paper we derive the average required transmit energy per bit taking into account the effects of path loss as well as long term fading. Thus, the logarithmic attenuation $\Lambda_k$ is given as [13]

$$\Lambda_k = \log A + \alpha \log d_k + \gamma_k. \tag{6}$$

The summands $\log A$, $d_k$, $\alpha$ and $\gamma_k$ model basic attenuation, normalized distance $d_k$ between user $k$ and $\mathrm{BS}_0$, attenuation exponent and stochastic log-normal fading, respectively. $\gamma_k$ is a zero mean Gaussian distributed random variable with standard deviation $\sigma$. In the same way the attenuation $\Lambda_k^j$, $\forall k$, $j \neq 0$, to $\mathrm{BS}_j$ of another $k$th user being supported by $\mathrm{BS}_j$ can be described. As to ease our considerations we assume $A = 1$ in the following. Further, the energy $\widehat{E}_k^j$ interfering the received signal at $\mathrm{BS}_0$ caused by any user $k$ allocated to $\mathrm{BS}_{j\neq 0}$ is given as

$$\widehat{E}_k^j = \exp\left(-\widehat{\Lambda}_k^j\right) \tilde{E}_k^j = \exp\left(\Lambda_k^j - \widehat{\Lambda}_k^j\right) E_k^j, \tag{7}$$

where $\widehat{\Lambda}_k^j$ denotes the logarithmic attenuation the interfering user's transmit energy $\tilde{E}_k^j = \exp\left(\Lambda_k^j\right) E_k^j$ is decreased by at $\mathrm{BS}_0$. With Eq. (6) we get

$$\exp\left(\Lambda_k^j - \widehat{\Lambda}_k^j\right) = \left(\frac{d_k^j}{\widehat{d}_k^j}\right)^{\alpha} \exp\left(\gamma_k^j - \widehat{\gamma}_k^j\right). \tag{8}$$

As in general the shadowing processes influencing the users' transmission paths to the several base stations are correlated we introduce a joint normal distribution $f_{\gamma_j,\widehat{\gamma}_j}(\cdot,\cdot)$ with zero mean, standard deviation $\sigma$ and correlation $\rho$ as to model this effect.

## 3. TOTAL MULTIUSER CAPACITY

In this section we outline the derivation of the necessary average transmit energy per bit to noise ratio

$\tilde{E}_b/N_0$ in dependence of the required total multiuser capacity $\Gamma$.

First, we consider the transmission using CDMA with IC. Assuming $K \gg 1$ the symmetry of the idealized cellular system implies that the interference due to users of other cells is the same at each cell site. Hence, the optimum receive energy per symbol of the latest demodulated users has to be equal at all base stations and we get with Eq. (3), (4), (7)

$$E_{K,\not\perp} = \frac{\mathrm{SIR} N_0}{1 - \frac{\mathrm{SIR}}{N}\left(\beta \sum_{i=1}^{K-1} a^{K-i} + \sum_{j\neq 0}\sum_{i=1}^{K} a^{K-i} \mathrm{e}^{\Lambda_i^j - \widehat{\Lambda}_i^j}\right)}.$$

Due to our assumptions, the average multiuser interference caused by users allocated to base stations $\mathrm{BS}_{j\neq 0}$ located at the same distance $d_{\mathrm{BS}_0,\mathrm{BS}_j}$ is equal. Hence, it is sufficient to calculate the interference for each possible distance $d_{\mathrm{BS}_0,\mathrm{BS}_{j\neq 0}}$ only once and to multiply this value by the number of base stations at this radius. Moreover, because significant interference results only from base stations located within the three nearest cell rings around $\mathrm{BS}_0$ [9] and supposing $K \gg 1$ and $N \gg \mathrm{SIR}$ we can introduce the interference factor $\zeta_{I,\not\perp}$

$$\zeta_{I,\not\perp} \triangleq \frac{1}{K}\sum_{i=1}^{K} a^{K-i} \exp\left(\Lambda_i^I - \widehat{\Lambda}_i^I\right)$$
$$\approx \underset{\Lambda^I,\widehat{\Lambda}^I}{\mathcal{E}} \left\{ \mathrm{e}^{\left(\frac{K}{N}\left(1-\frac{k}{K}\right)\mathrm{SIR}(1-\beta) + \Lambda^I - \widehat{\Lambda}^I\right)} \right\}.$$

$I$ is defined as $I \in \{1, 7, 13\}$ (see Fig. 1) corresponding to the distances $d_I \triangleq d_{\mathrm{BS}_0,\mathrm{BS}_I} \in \{2, 2\sqrt{3}, 4\}$ and $\mathcal{E}_x\{\cdot\}$ denotes the expectation operation with respect to $x$. Under the above conditions we find

$$\left(\frac{\tilde{E}_b}{N_0}\right)_{\not\perp} = \frac{1}{KRN_0}\sum_{k=1}^{K} E_{K,\not\perp} a^{K-i} \exp\left(\Lambda_k\right)$$
$$\approx \frac{\frac{\mathrm{SIR}(1-\beta)}{R} \underset{\Lambda}{\mathcal{E}}\left\{\mathrm{e}^{\left(\frac{K}{N}\left(1-\frac{k}{K}\right)\mathrm{SIR}(1-\beta)+\Lambda\right)}\right\}}{1 - \beta \mathrm{e}^{\left(\frac{K}{N}\mathrm{SIR}(1-\beta)\right)} + \frac{6K\mathrm{SIR}(1-\beta)}{N}\sum_I \zeta_{I,\not\perp}}.$$

Next, treating the ratio $k/K$ as a continuous variable for $K \gg 1$ with the range $0 \leq k/K \leq 1$, the appropriate sorting of the users' required receive energies for CDMA according to their attenuations (see section 2) results in $F_\Lambda(\Lambda_k) = k/K$, where $F_\Lambda(\Lambda_k)$ denotes the cumulative distribution function of the attenuation $\Lambda$. So, we obtain

$$\left(\frac{\tilde{E}_b}{N_0}\right)_{\not\perp} = \frac{\frac{\mathrm{SIR}(1-\beta)}{R}\mathrm{g}_n(\mathrm{SIR})}{\mathrm{g}_d(\mathrm{SIR})}, \qquad (9)$$

where

$$\mathrm{g}_n(\delta) \triangleq \underset{\Lambda}{\mathcal{E}}\left\{\mathrm{e}^{\left(\frac{K}{N}(1-F_\Lambda(\Lambda))\delta(1-\beta)+\Lambda\right)}\right\}$$

$$\mathrm{g}_d(\delta) \triangleq 1 - \beta \mathrm{e}^{\left(\frac{K}{N}\delta(1-\beta)\right)} - \frac{6K(1-\beta)\delta}{N}\sum_I \zeta_{I,\not\perp}(\delta)$$

$$\zeta_{I,\not\perp}(\delta) \triangleq \underset{\Lambda^I,\widehat{\Lambda}^I}{\mathcal{E}}\left\{\mathrm{e}^{\left(\frac{K}{N}\left(1-F_\Lambda\left(\Lambda^I\right)\right)\delta(1-\beta)+\Lambda^I-\widehat{\Lambda}^I\right)}\right\}.$$

Further, we solve for TDMA

$$\left(\frac{\tilde{E}_b}{N_0}\right)_{\perp} = \frac{\mathrm{SIR}\,\underset{\Lambda}{\mathcal{E}}\{\exp(\Lambda)\}}{R\left(1 - 6\,\mathrm{SIR}\sum_I \zeta_{I,\perp}\right)}, \qquad (10)$$

where $\zeta_{I,\perp} = \mathcal{E}_{\Lambda^I,\widehat{\Lambda}^I}\left\{\exp\left(\Lambda^I - \widehat{\Lambda}^I\right)\right\}, \forall I$. As already mentioned we assume that all users apply single user coding allowing reliable transmission at rate $R$ arbitrarily close to the capacity of the complex AWGN-channel [5]. Further, the total multiuser capacity $\Gamma_{\not\perp}$ of a $\not\perp$ multiuser system is defined as $\Gamma_{\not\perp} \triangleq RK/N$ [9]. Thus, the signal-to-interference ratio for CDMA is $\mathrm{SIR} = 2^{\Gamma_{\not\perp}\frac{N}{K}} - 1$ while we have for TDMA $\mathrm{SIR} = 2^{\Gamma_\perp} - 1$. Using this definition we get

$$\left(\frac{\tilde{E}_b}{N_0}\right)_{\not\perp} = \frac{\left(2^{\Gamma_{\not\perp}\frac{N}{K}} - 1\right)(1-\beta)\,\mathrm{g}_n\left(2^{\Gamma_{\not\perp}\frac{N}{K}} - 1\right)}{\Gamma_{\not\perp}\frac{N}{K}\,\mathrm{g}_d\left(2^{\Gamma_{\not\perp}\frac{N}{K}} - 1\right)} \qquad (11)$$

and

$$\left(\frac{\tilde{E}_b}{N_0}\right)_{\perp} = \frac{\left(2^{\Gamma_\perp} - 1\right)\underset{\Lambda}{\mathcal{E}}\{\exp(\Lambda)\}}{\Gamma_\perp\left(1 - \left(2^{\Gamma_\perp} - 1\right)6\sum_I \zeta_{I,\perp}\right)}. \qquad (12)$$

We find the ratio $K/N$ to be a free parameter in $\left(\tilde{E}_b/N_0\right)_{\not\perp}$ and its optimization yields

$$\min_{\frac{K}{N}}\left(\frac{\tilde{E}_b}{N_0}\right)_{\not\perp} = \lim_{\frac{K}{N}\to\infty}\left(\frac{\tilde{E}_b}{N_0}\right)_{\not\perp} \qquad (13)$$
$$= \frac{\ln(2)(1-\beta)\,\mathrm{g}_n(\frac{N}{K}\ln(2)\Gamma_{\not\perp})}{\mathrm{g}_d(\frac{N}{K}\ln(2)\Gamma_{\not\perp})}.$$

## 4. NUMERICAL RESULTS

In this section we calculate $\left(\tilde{E}_b/N_0\right)_{\not\perp}$ and $\left(\tilde{E}_b/N_0\right)_{\perp}$ depending on the required total multiuser capacity assuming $\alpha = 4$ and $\sigma \mathrel{\hat{=}} 8$ dB. These parameters are often used to compare the performance of different multiple access techniques for cellular mobile communications systems [13]. Further, as to ease our study the transmit energies depicted in the figures are normalized by $A$.

### 4.1. DISTANCE CONTROLLED HANDOVER

First, we study the case that all users are allocated to the closest base station. For the sake of analytical tractability we approximate the hexagonal cells by circular cells of the same cell size. This yields the pdf $f_d(d) = \frac{2d}{R^2}, 0 \le d \le R$, for the distance between a user and its supporting base station ($R \approx 1.05$). Using this and Eq. (6) we obtain for the pdf $f_A(A)$

$$f_A(A) = \mathrm{Q}\left(\frac{A - \log A + \frac{2\sigma^2}{\alpha} - \alpha\log(R)}{\sigma}\right)$$
$$\frac{2}{\alpha}\exp\left(\frac{2A}{\alpha} - \frac{2\log A}{\alpha} + \frac{2\sigma^2}{\alpha^2} - 2\log(R)\right),$$

where $\mathrm{Q}(x) \triangleq \int_x^\infty \frac{1}{2\pi}\exp\left(-t^2/2\right)\,\mathrm{d}t$. Then, the distribution function $F_A(A) = \int_{-\infty}^{A} f_A(\theta)\,d\theta$ is solved as

$$F_A(A) = 1 - \mathrm{Q}\left(\frac{A - \log A - \alpha\log(R)}{\sigma}\right) + \frac{\alpha}{2}f_A(A).$$

We can derive an analytical expression for the expectation value $\mathcal{E}_A\{\exp(A)\} = \frac{2}{2+\alpha}R^\alpha A \exp\left(\frac{\sigma^2}{2}\right)$. In contrast to this $\zeta_{\perp,I}$ depends on the specific value of $n$. Furthermore, $\mathrm{g}_n(\mathrm{SIR})$ and $\mathrm{g}_d(\mathrm{SIR})$ have to be obtained by means of numerical integration. The achievable total multiuser capacities versus $\tilde{E}_b/(AN_0)$ are depicted in Fig. 2 and 3.

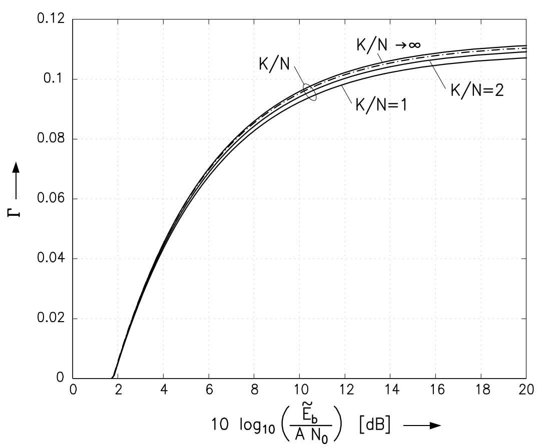


Figure 2: CDMA (–) and TDMA (–·) for $\alpha = 4, \sigma \,\hat{=}\, 8$ dB$, \rho = 0$ with parameter $K/N = 1, 2, \infty$ and distance controlled handover. We omitted the curve for $K/N = 4$ as it merges with that one for TDMA.

First, we can see from the graphs the significant dependence of $\tilde{E}_b/(AN_0)$ on the correlation $\rho$. This is due to the distance controlled handover which ignores the possibility that a user's signal is received stronger at the base station of a neighbouring cell than at the base station of its own cell. Especially the users at the boundary of each cell cause severe multiuser interference due to this allocation algorithm which leads to performance degradations with decreasing values of $\rho$, i.e. for uncorrelated shadowing, and rising values of the standard deviation $\sigma$. As a consequence, there is no significant difference between TDMA and the considered CDMA scheme if the shadowing is highly correlated. In contrast, we find a CDMA system employing randomly chosen spreading sequences and IC can outperform any orthogonal transmission scheme

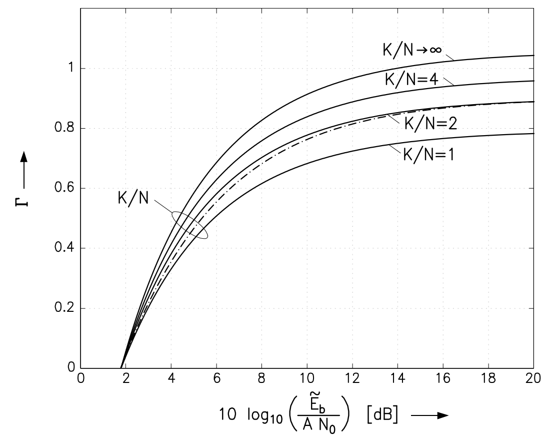


Figure 3: CDMA (–) and TDMA (–·) for $\alpha = 4, \sigma \,\hat{=}\, 8$ dB$, \rho = 7$ with parameter $K/N = 1, 2, 4, \infty$ and distance controlled handover.

for sufficiently large $K/N$ and low correlation $\rho$. This is a result of the proper mapping of the users' indices to their attenuations applied and is the significant advantage of this IC scheme compared to orthogonal transmission. The "breakthrough" ratio $(K/N)_{\mathrm{bt}}$ depends on the system parameters and is in our examples about 2 to 4. Of course, $(K/N)_{\mathrm{bt}}$ has to be larger than 1 as orthogonal transmission is optimum for $K \le N$. This is confirmed by the above results. Further, we find that the superiority of CDMA with IC for given $K/N > 1$ depends for small ratios $K/N$ on the specific total capacity $\Gamma_{\not\perp}$ chosen.

## 4.2. ATTENUATION CONTROLLED HANDOVER

A possibility to reduce the average required transmit energy as well as the multiuser interference is to apply so called "attenuation controlled" handover. That is, each user is assigned to that base station which receives the least attenuated signal from him/her regardless of the user's actual position.

Since the analytical derivation of the pdfs $f_A(A)$ and $f_{A^I,\widehat{A}^I}(A,\widehat{A})$, $\forall I$, is not feasible for "attenuation controlled" handover we obtained these pdf's by simulation. Then, we used Eq. (12) and (11) as to derive $\left(\tilde{E}_b/N_0\right)_\perp$ and $\left(\tilde{E}_b/N_0\right)_{\not\perp}$, respectively. The resulting spectral efficiencies are plotted vs. $\tilde{E}_b/(AN_0)$ in Fig. 4 and 5 for the same parameters as the one chosen for distance controlled handover.

We realize that power-controlled handover leads to a considerable increase in total multiuser capacity compared to distance controlled handover. However, as it is well-known any handover technique cannot eliminate the limitation of the maximum multiuser capacity caused by intercellular multiuser interference. Next, the plots indicate that the enormous differences in total multiuser capacities found for $\rho = 0$ and $\rho = 0.7$ in the previous section are significantly reduced by application of attenuation controlled handover. In other words, attenuation controlled handover copes considerably better with the

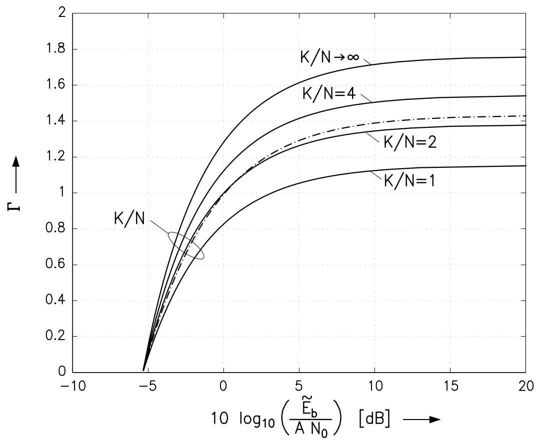


Figure 4: CDMA (−) and TDMA (−·) for $\alpha = 4, \sigma \,\widehat{=}\, 8$ dB, $\rho = 0$ with parameter $K/N = 1, 2, 4, \infty$ and attenuation controlled handover.

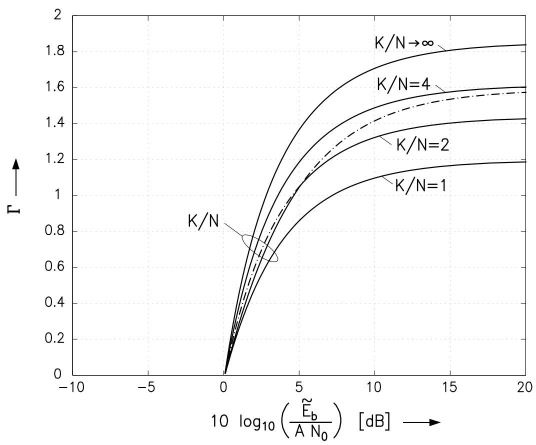


Figure 5: CDMA (−) and TDMA (−·) for $\alpha = 4, \sigma \,\widehat{=}\, 8$ dB, $\rho = 0.7$ with parameter $K/N = 1, 2, 4, \infty$ and attenuation controlled handover.

correlation between the shadowing processes than distance controlled handover. Moreover, the superiority of CDMA with IC compared to orthogonal multiple access is now also remarkable for low correlations $\rho$. Further, the minimum $\tilde{E}_b/(AN_0)$ required for $\Gamma \to 0$ is no longer independent of $\rho$ but is reduced at a large degree for small correlations. The explanation can be found considering Fig. 6.

First, it can be seen that the average logarithmic attenuation $\Lambda$ rises for increasing correlations $\rho$. Second, for $\Gamma \to 0$ the main contribution to the interference is provided by the additive white Gaussian noise. Hence, the ratio $\tilde{E}_b/(AN_0)$ depends mainly on $f_\Lambda(\Lambda)$. This explains the differences for small values of $\Gamma$. In contrast to this, multiuser interference dominates if $\Gamma > 1$ and the disadvantage of the users' widespread distribution close to other base stations for $\rho = 0$ (see Fig. 7) outweights the advantages resulting from $f_\Lambda(\Lambda)$.

## 4.3. IMPLEMENTABLE CODES AND IMPERFECT CANCELLATION

In the derivation of the previous results we assumed ideal single user coding as well as perfect successive

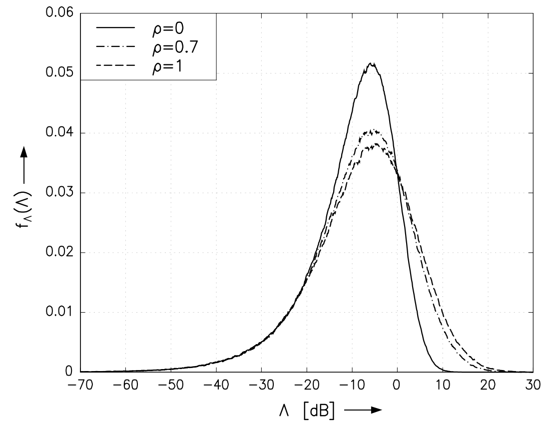


Figure 6: $f_\Lambda(\Lambda)$ with $\rho = 0, 0.7, 1$.

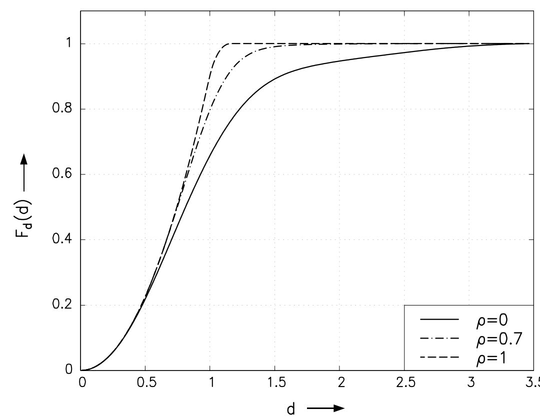


Figure 7: $F_d(d) = \int_{-\infty}^{d} f_d(t)\,\mathrm{d}t$ with $\rho = 0, 0.7, 1$.

cancellation, i.e. $\beta = 0$. The effects of imperfect channel coding can be modeled by

$$\mathrm{SIR}_{\mathrm{nonid}} = \mathrm{SIR}_{\mathrm{id}} V, \qquad (14)$$

where $\mathrm{SIR}_{\mathrm{id}}$ denotes the required signal-to-interference ratio as to transmit reliable at rate $R$ using ideal coding and $\mathrm{SIR}_{\mathrm{nonid}}$ if nonideal coding is applied. The variable $V > 1$ determines the increase in the required SIR caused by nonideal codes. Practical values are $V \approx 1$ dB which can be achieved by Turbo Codes [14] and $V \approx 6$ dB corresponding to the application of simple convolutional codes. Replacing $\mathrm{SIR}_{\mathrm{id}}$ by $\mathrm{SIR}_{\mathrm{nonid}}$ in Eq. (9), (10) yields

$$\left(\frac{\tilde{E}_b}{N_0}\right)_{\not\perp} = \frac{\left(2^{\Gamma_{\not\perp}\frac{N}{K}}-1\right) V(1-\beta)\,\mathrm{g}_n\left(\left(2^{\Gamma_{\not\perp}\frac{N}{K}}-1\right)V\right)}{\Gamma_{\not\perp}\frac{N}{K}\,\mathrm{g}_d\left(\left(2^{\Gamma_{\not\perp}\frac{N}{K}}-1\right)V\right)}$$

$$\left(\frac{\tilde{E}_b}{N_0}\right)_{\perp} = \frac{\left(2^{\Gamma_\perp}-1\right) V\,\underset{\Lambda}{\mathcal{E}}\{\exp(\Lambda)\}}{\Gamma_\perp\left(1-\left(2^{\Gamma_\perp}-1\right)6V\sum_I \zeta_{I,\perp}\right)}$$

Of course, the terms $\zeta_{I,\not\perp}$ and $\zeta_{I,\perp}$ have to be modified in the same manner. As already pointed out in [11] non-orthogonal systems employing successive cancellation suffer from imperfect coding at a greater degree than orthogonal systems since $V$ appears not only as a linear factor in the numerator and denominator but it is contained in the exponent, too. In Fig. 8 the to-

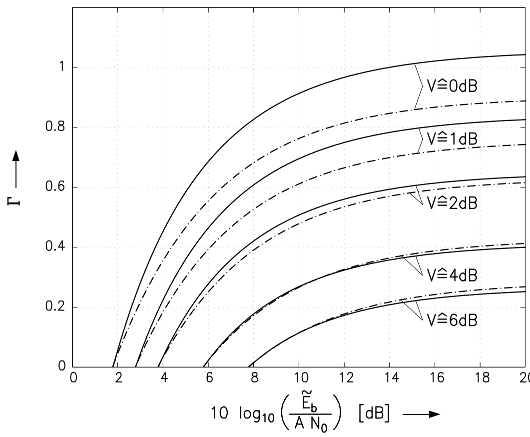


Figure 8: CDMA (–) and TDMA (–·) for $\alpha = 4, \sigma \mathrel{\widehat{=}} 8\,\text{dB}, \rho = 0.7, \beta = 0, K/N \to \infty$ with parameter $V \mathrel{\widehat{=}} 0, 1, 2, 4, 6\,\text{dB}$ and distance controlled handover.

tal multiuser capacity is plotted versus $\tilde{E}_b/(AN_0)$ for distance controlled handover. The graphs show that the gain provided by CDMA with IC depends significantly on the gap $V$. For $V \mathrel{\widehat{=}} 1, \ldots, 4$ dB orthogonal transmission is worse than CDMA in the whole depicted range of $\Gamma$. But, if simple convolutional codes are employed causing a gap of approximately 6 dB the advantages due to CDMA vanish.

Finally, the results in Fig. 9 illustrate the additional performance degradation of CDMA combined with IC if nonideal cancellation ($\beta = 0.1$) is assumed. It implies that accurate successive cancellation is essential to exploit the performance advantages offered by CDMA with IC even if powerful codes are applied. An indispensable prerequisite for this is the virtually exact knowledge of the channel parameters what underlines the importance of this problem.

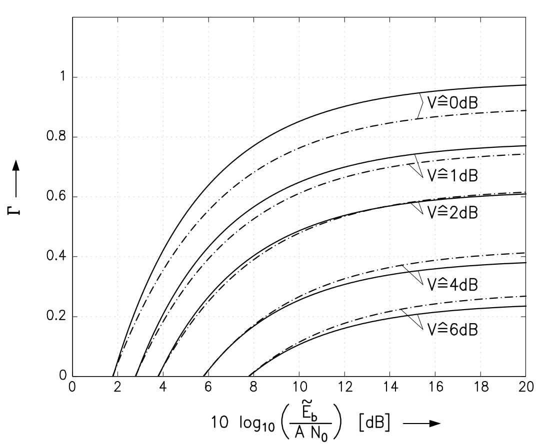


Figure 9: CDMA (–) and TDMA (–·) for $\alpha = 4, \sigma \mathrel{\widehat{=}} 8\,\text{dB}, \rho = 0.7, \beta = 0.1, K/N \to \infty$ with parameter $V \mathrel{\widehat{=}} 0, 1, 2, 4, 6\,\text{dB}$ and distance controlled handover.

## 5. CONCLUSIONS

The superiority of wideband transmission strategies on Gaussian multiple–access channels with track–able fading found by Hanly and Whiting [1] has been shown to keep valid in practical scenarios under certain restrictions. On the one hand, very powerful channel coding and sufficiently accurate channel state information is requested. On the other hand, attenuation controlled handover is a much better choice than distance controlled handover if shadowing is uncorrelated. With increasing correlation, the influence of the handover strategy reduces. Nonetheless, it can be shown by some examples that neither one of the discussed handover strategies nor the proposed user sorting are optimum. They are heuristic assumptions offering enough impact, but encourage also future research.

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