Research Article

Transmit Diversity at the Cell Border Using Smart Base Stations

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We address the problems at the most critical area in a cellular multicarrier code division multiple access (MC-CDMA) network, namely, the cell border. At a mobile terminal the diversity can be increased by using transmit diversity techniques such as cyclic delay diversity (CDD) and space-time coding like Alamouti. We transfer these transmit diversity techniques to a cellular environment. Therefore, the performance is enhanced at the cell border, intercellular interference is avoided, and soft handover procedures are simplified all together. By this, macrodiversity concepts are exchanged by transmit diversity concepts. These concepts also shift parts of the complexity from the mobile terminal to smart base stations.

1. INTRODUCTION

The development of future mobile communications systems follows the strategies to support a single ubiquitous radio access system adaptable to a comprehensive range of mobile communication scenarios. Within the framework of a global research effort on the design of a next generation mobile system, the European IST project WINNER—Wireless World Initiative New Radio—[1] is also focusing on the identification, assessment, and comparison of strategies for reducing and handling intercellular interference at the cell border. For achieving high spectral efficiency the goal of future wireless communications systems is a total frequency reuse in each cell. This leads to a very critical area around the cell borders.

Since the cell border area is influenced by at least two neighboring base stations (BSs), the desired mobile terminal (MT) in this area has to scope with several signals in parallel. On the one hand, the MT can cancel the interfering signals with a high signal processing effort to recover the desired signal [2]. On the other hand, the network can manage the neighboring BSs to avoid or reduce the negative influence of the transmitted signals at the cell border. Due to the restricted power and processing conditions at the MT, a network-based strategy is preferred.

In the region of overlapping cells, handover procedures exist. Soft handover concepts [3] have shown that the usage of two base stations at the same time increases the robustness of the received data and avoids interruption and calling

resources for reinitiating a call. With additional information about the rough position of the MT, the network can avoid fast consecutive handovers that consume many resources, for example, the MT moves in a zigzag manner along the cell border.

Already in the recent third generation mobile communications system, for example, UMTS, macrodiversity techniques with two or more base stations are used to provide reliable handover procedures [4]. Future system designs will take into account the advanced transmit diversity techniques that have been developed in the recent years. As the cell sizes decrease further, for example, due to higher carrier frequencies, the cellular context gets more dominant as users switch cells more frequently. The ubiquitous approach of having a reliable link everywhere emphasizes the need for a reliable connection at cell border areas.

A simple transmit diversity technique is to combat flat fading conditions by retransmitting the same signal from spatially separated antennas with a frequency or time offset. The frequency or time offset converts the spatial diversity into frequency or time diversity. The effective increase of the number of multipaths is exploited by the forward error correction (FEC) in a multicarrier system. The elementary method, namely, delay diversity (DD), transmits delayed replicas of a signal from several transmit (TX) antennas [5]. The drawback are increased delays of the impinging signals. By using the DD principle in a cyclic prefix-based system, intersymbol interference (ISI) can occur due to too large delays.

This can be circumvented by using cyclic delays which results in the cyclic delay diversity (CDD) technique [6].

Space-time block codes (STBCs) from orthogonal designs [7] improve the performance in a flat and frequency selective fading channel by coherently adding the signals at the receiver without the need for multiple receive antennas. The number of transmit antennas increases the performance at the expense of a rate loss. The rate loss could be reduced by applying nearly orthogonal STBCs which on the other hand would require a more complex space-time decoder. Generally, STBCs of orthogonal or nearly orthogonal designs need additional channel estimation, which increases the complexity.

The main approach of this paper is the use and investigation of transmit diversity techniques in a cellular environment to achieve macrodiversity in the critical cell border area. Therefore, we introduce cellular CDD (C-CDD) which applies the CDD scheme to neighboring BSs. Also the Alamouti scheme is addressed to two BSs [8] and in the following this scheme is called cellular Alamouti technique (CAT). The obtained macrodiversity can be utilized for handover demands, for example.

Proposals for a next generation mobile communications system design favor a multicarrier transmission, namely, OFDM [9]. It offers simple digital realization due to the fast Fourier transformation (FFT) operation and low complexity receivers. The WINNER project aims at a generalized multicarrier (GMC) [10] concept which is based on a high flexible packet-oriented data transmission. The resource allocation within a frame is given by time-frequency units, so called chunks. The chunks are preassigned to different classes of data flows and transmission schemes. They are then used in a flexible way to optimize the transmission performance [11].

One proposed transmission scheme within GMC is the multicarrier code division multiple access (MC-CDMA). MC-CDMA combines the benefits of multicarrier transmission and spread spectrum and was simultaneously proposed in 1993 by Fazel and Papke [12] and Yee et al. [13]. In addition to OFDM, spread spectrum, namely, code division multiple access (CDMA), gives high flexibility due to simultaneous access of users, robustness, and frequency diversity gains [14].

In this paper, the proposed techniques C-CDD and CAT are applied to a cellular environment based on an MC-CDMA transmission scheme. The structure of the paper is as follows. Section 2 describes the used cellular multicarrier system based on MC-CDMA. Section 3 introduces the cellular transmit diversity technique based on CDD and the application of the Alamouti scheme to a cellular environment. At the end of this section both techniques are compared and the differences are highlighted. A more detailed analytical investigation regarding the influence of the MT position for the C-CDD is given in Section 4. Finally, the proposed schemes are evaluated in Section 5.

2. CELLULAR MULTICARRIER SYSTEM

In this section, we first give an outline of the used MC-CDMA downlink system. We then describe the settings of the cellular environment and the used channel model.

2.1. MC-CDMA system

The block diagram of a transmitter using MC-CDMA is shown in Figure 1. The information bit streams of the N_u active users are convolutionally encoded and interleaved by the outer interleaver Π_{out}. With respect to the modulation alphabet, the bits are mapped to complex-valued data symbols. In the subcarrier allocation block, N_d symbols per user are arranged for each OFDM symbol. The kth data symbol is multiplied by a user-specific orthogonal Walsh-Hadamard spreading code which provides chips. The spreading length L corresponds to the maximum number of active users $L = N_{u,max}$. The ratio of the number of active users to $N_{u,max}$ represents the resource load (RL) of an MC-CDMA system.

An inner random subcarrier interleaver Π_{in} allows a better exploitation of diversity. The input block of the interleaver is denoted as one OFDM symbol and N_s OFDM symbols describe one OFDM frame. By taking into account a whole OFDM frame, a two-dimensional (2D) interleaving in frequency and time direction is possible. Also an interleaving over one dimension (1D), the frequency direction, is practicable by using one by one OFDM symbols. These complex valued symbols are transformed into time domain by the OFDM entity using an inverse fast Fourier transform (IFFT). This results in N_{FFT} time domain OFDM symbols, represented by the samples

$$x_l^{(n)} = \frac{1}{\sqrt{N_{FFT}}} \sum_{i=0}^{N_{FFT}-1} X_i^{(n)} \cdot e^{j(2\pi/N_{FFT})il}, \qquad (1)$$

where l, i denote the discrete time and frequency and n the transmitting BS out of N_{BS} BSs. A cyclic prefix as a guard interval (GI) is inserted in order to combat intersymbol interference (ISI). We assume quasistatic channel fading processes, that is, the fading is constant for the duration of one OFDM symbol. With this quasistatic channel assumption the well-known description of OFDM in the frequency domain is given by the multiplication of the transmitted data symbol $X_{l,i}^{(n)}$ and a complex channel transfer function (CTF) value $H_{l,i}^{(n)}$. Therefore, on the receiver side the lth received MC-CDMA symbol at subcarrier i becomes

$$Y_{l,i} = \sum_{n=0}^{N_{BS}-1} X_{l,i}^{(n)} H_{l,i}^{(n)} + N_{l,i} \qquad (2)$$

with $N_{l,i}$ as an additive white Gaussian noise (AWGN) process with zero mean and variance σ^2, the transmitter signal processing is inverted at the receiver which is illustrated in Figure 2. In MC-CDMA the distortion due to the flat fading on each subchannel is compensated by equalization. The received chips are equalized by using a low complex linear minimum mean square error (MMSE) one-tap equalizer. The resulting MMSE equalizer coefficients are

$$G_{l,i} = \frac{H_{l,i}^{(n)*}}{\left| H_{l,i}^{(n)} \right|^2 + (L/N_u)\sigma^2}, \quad i = 1, \dots, N_c. \qquad (3)$$

Furthermore, N_c is the total number of subcarriers. The operator $(\cdot)^*$ denotes the complex conjugate. Further, the symbol demapper calculates the log-likelihood ratio for each bit
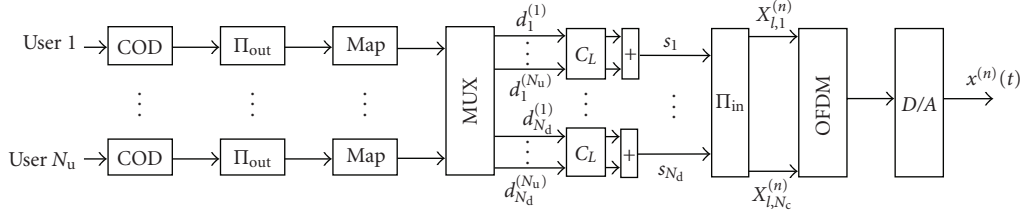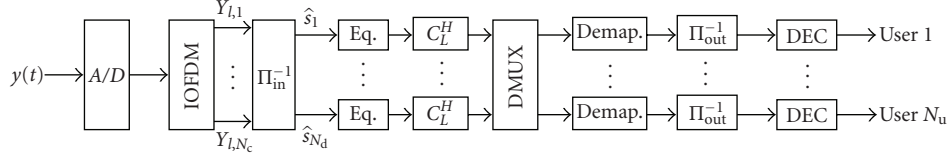
FIGURE 1: MC-CDMA transmitter of the nth base station.
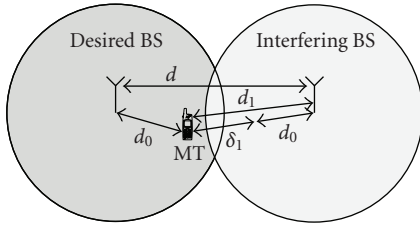

FIGURE 2: MC-CDMA receiver.

FIGURE 3: Cellular environment.

based on the selected alphabet. The code bits are deinterleaved and finally decoded using soft-decision Viterbi decoding [15].

2.2. Cellular environment

We consider a synchronized cellular system in time and frequency with two cells throughout the paper, see Figure 3. The nth BS has a distance d_n to the desired MT. A propagation loss model is assumed to calculate the received signal energy. The signal energy attenuation due to path loss is generally modeled as the product of the γth power of distance and a log-normal component representing shadowing losses. The propagation loss normalized to the cell radius r is defined by

$$\alpha(d_n) = \left(\frac{d_n}{r}\right)^{-\gamma} \cdot 10^{\eta/10\,\mathrm{dB}}, \tag{4}$$

where the standard deviation of the Gaussian-distributed shadowing factor η is set to 8 dB. The superimposed signal at the MT is given by

$$\begin{aligned} Y_{l,i} &= X_{l,i}^{(0)}\alpha(d_0)H_{l,i}^{(0)} + X_{l,i}^{(1)}\alpha(d_1)H_{l,i}^{(1)} + N_{l,i} \\ &= S_{l,i}^{(0)} + S_{l,i}^{(1)} + N_{l,i}. \end{aligned} \tag{5}$$

Depending on the position of the MT the carrier-to-interference ratio (C/I) varies and is defined by

$$\frac{\mathrm{C}}{\mathrm{I}} = \frac{E\{|S_{l,i}^{(0)}|^2\}}{E\{|S_{l,i}^{(1)}|^2\}}. \tag{6}$$

3. TRANSMIT DIVERSITY TECHNIQUES FOR CELLULAR ENVIRONMENT

In a cellular network the MT switches the corresponding BS when it is requested by the BS. The switch is defined as the handover procedure from one BS to another. The handover is seamless and soft when the MT is connected to both BSs at the same time. The subcarrier resources in an MC-CDMA system within a spreading block are allocated to different users. Some users might not need a handover as they are (a) in a stable position or (b) away from the cell border. In both cases these users are effected by intercell interference as their resource is also allocated in the neighboring cell. To separate the different demands of the users, users with similar demands are combined within time-frequency units, for example, chunks, in an OFDM frame. The requested parameters of the users combined in these chunks are similar, like a common pilot grid. The spectrum for the users could then be shared between two cells within a chunk by defining a broadcast region. By this the affected users of the two cells would reduce their effective spectrum in half. This would be a price to pay avoiding intercellular interference. Intercellular interference could be tackled by intercellular interference cancellation techniques at complexity costs for all mobile users. Smart BSs could in addition try to balance the needed transmit power by risking an increase of intercellular interference also in neighboring cells. The approach presented in the following avoids intercellular interference by defining the effected area as a broadcast region and applying transmit diversity schemes for a cellular system, like cyclic delay diversity and STBCs. Part of the ineluctable loss of spectrum efficiency are compensated by exploiting additional diversity gains on the physical layer, avoiding the need of high complex intercellular cancellation techniques and decreasing the overall intercellular interference in the cellular network for the common good.

In the following, two transmit diversity techniques are in the focus. The first is based on the cyclic delay diversity (CDD) technique which increases the frequency diversity of the received signal and requires no change at the receiver to
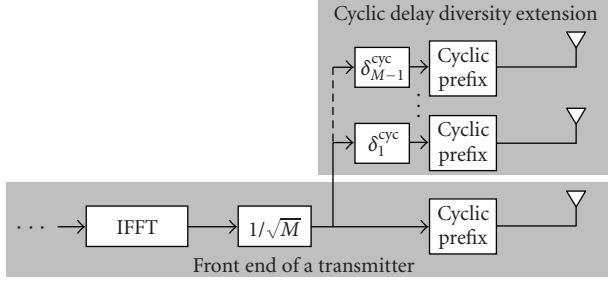
FIGURE 4: Principle of cyclic delay diversity.

exploit the diversity. The other technique applies the Alamouti scheme which flattens the frequency selectivity of the received signal and requires an additional decoding process at the mobile.

3.1. Cellular cyclic delay diversity (C-CDD)

The concept of cyclic delay diversity to a multicarrier-based system, that is, MC-CDMA, is briefly introduced in this section. Later on, the CDD concept will lead to an application to a cellular environment, namely, cellular CDD (C-CDD). A detailed description of CDD can be found in [16]. The idea of CDD is to increase the frequency selectivity, that is, to decrease the coherence bandwidth of the system. The additional diversity is exploited by the FEC and for MC-CDMA also by the spreading code. This will lead to a better error performance in a cyclic prefix-based system. The CDD principle is shown in Figure 4. An OFDM modulated signal is transmitted over M antennas, whereas the particular signals only differ in an antenna specific cyclic shift δ_m^{cyc}. MC-CDMA modulated signals are obtained from a precedent coding, modulation, spreading, and framing part; see also Section 2.1. Before inserting a cyclic prefix as guard interval, the time domain OFDM symbol (cf. (1)) is shifted cyclically, which results in the signal

$$x_{l-\delta_m^{\text{cyc}} \bmod N_{\text{FFT}}} = \frac{1}{\sqrt{N_{\text{FFT}}}} \sum_{i=0}^{N_{\text{FFT}}-1} e^{-j(2\pi/N_{\text{FFT}})i\delta_m^{\text{cyc}}} \cdot X_i \cdot e^{j(2\pi/N_{\text{FFT}})il}. \tag{7}$$

The antenna specific TX-signal is given by

$$x_l^{(m)} = \frac{1}{\sqrt{M}} \cdot x_{l-\delta_m^{\text{cyc}} \bmod N_{\text{FFT}}}, \tag{8}$$

where the signal is normalized by $1/\sqrt{M}$ to keep the average transmission power independent of the number of transmit antennas. The time domain signal including the guard interval is obtained for $l = -N_{\text{GI}}, \ldots, N_{\text{FFT}} - 1$. To avoid ISI, the guard interval length N_{GI} has to be larger than the maximum channel delay $\tau_{\max}$. Since CDD is done before the guard interval insertion in the OFDM symbol, CDD does not increase the $\tau_{\max}$ in the sense of ISI occurrence. Therefore, the length of the guard interval for CDD does not depend on the cyclic delays δ_m^{cyc}, where δ_m^{cyc} is given in samples.

On the receiver side and represented in the frequency domain (cf. (2)), the cyclic shift can be assigned formally to the channel transfer function, and therefore, the overall CTF

$$H_{l,i} = \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} e^{-j(2\pi/N_{\text{FFT}})\delta_m^{\text{cyc}} \cdot i} \cdot H_{l,i}^{(m)} \tag{9}$$

is observed. As long as the effective maximum delay $\tau'_{\max}$ of the resulting channel

$$\tau'_{\max} = \tau_{\max} + \max_m \delta_m^{\text{cyc}} \tag{10}$$

does not intensively exceed N_{GI}, there is no configuration and additional knowledge at the receiver needed. If $\tau'_{\max} \gg N_{\text{GI}}$, the pilot grid and also the channel estimation process has to be modified [17]. For example, this can be circumvented by using differential modulation [18].

The CDD principle can be applied in a cellular environment by using adjacent BSs. This leads to the cellular cyclic delay diversity (C-CDD) scheme. C-CDD takes advantage of the aforementioned resulting available resources from the neighboring BSs. The main goal is to increase performance by avoiding interference and increasing diversity at the most critical areas.

For C-CDD the interfering BS also transmits a copy of the users' signal as the desired BS to the designated MT located in the broadcast area. Additionally, a cyclic shift δ_n^{cyc} is inserted to this signal, see Figure 5. Therefore, the overall delay in respect to the signal of the desired BS in the cellular system can be expressed by

$$\delta_n = \delta(d_n) + \delta_n^{\text{cyc}}, \tag{11}$$

where $\delta(d_n)$ represents the natural delay of the signal depending on distance d_n. At the MT the received signal can be described by

$$Y_{l,i} = X_{l,i}^{(0)} \left(\alpha(d_0) H_{l,i}^{(0)} e^{-j(2\pi/N_{\text{FFT}})\delta_0 \cdot i} + \alpha(d_1) H_{l,i}^{(1)} e^{-j(2\pi/N_{\text{FFT}})\delta_1 \cdot i} \right). \tag{12}$$

The transmission from the BSs must ensure that the reception of both signals are within the guard interval. Furthermore, at the MT the superimposed statistical independent Rayleigh distributed channel coefficients from the different BSs sum up again in a Rayleigh distributed channel coefficient. The usage of cyclic shifts prevents the occurrence of additional ISI. For C-CDD no additional configurations at the MT for exploiting the increased transmit diversity are necessary.

Finally, the C-CDD technique inherently provides another transmit diversity technique. If no cyclic shift δ_n^{cyc} is introduced, the signals from the different BSs may arrive at the desired MT with different delays $\delta(d_n)$. These delays can be also seen as delay diversity (DD) [5] for the transmitted MC-CDMA signal or as macrodiversity [19] at the MT. Therefore, an inherent transmit diversity, namely, cellular delay diversity (C-DD), is introduced if the adjacent BSs just transmit the same desired signal at the same time to the designated MT. The C-CDD techniques can be also easily extended to more than 2 BSs.
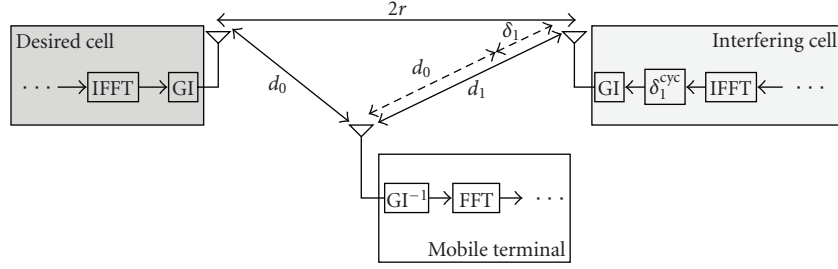
FIGURE 5: Cellular MC-CDMA system with cellular cyclic delay diversity (C-CDD).

3.2. Cellular Alamouti technique (CAT)

In this section, we introduce the concept of transmit diversity by using the space-time block codes (STBCs) from orthogonal designs [7], namely, the Alamouti technique. We apply this scheme to the aforementioned cellular scenario. These STBCs are based on the theory of (generalized) orthogonal designs for both real- and complex-valued signal constellations. The complex-valued STBCs can be described by a matrix

$$\mathbf{B} = \begin{pmatrix} b_{0,0} & \cdots & b_{0,N_{BS}-1} \\ \vdots & \ddots & \vdots \\ b_{l-1,0} & \cdots & b_{l-1,N_{BS}-1} \end{pmatrix} \begin{matrix} \uparrow \\ \text{time} \\ \downarrow \end{matrix}, \qquad (13)$$

where l and N_{BS} are the STBC length and the number of BS (we assume a single TX-antenna for each BS), respectively. The simplest case is the Alamouti code [20],

$$\mathbf{B} = \begin{pmatrix} x_0 & x_1 \\ -x_1^* & x_0^* \end{pmatrix}. \qquad (14)$$

The respective assignment for the Alamouti-STBC to the kth block of chips containing data from one or more users is obtained:

$$\vec{y}^{(k)} = \begin{pmatrix} y_0^{(k)} \\ y_1^{(k)*} \end{pmatrix}$$
$$= \begin{pmatrix} h^{(0,k)} & h^{(1,k)} \\ h^{(1,k)*} & -h^{(0,k)*} \end{pmatrix} \cdot \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} + \begin{pmatrix} n_0^{(k)} \\ n_1^{(k)*} \end{pmatrix}. \qquad (15)$$

$\vec{y}^{(k)}$ is obtained from the received complex values $y_i^{(k)}$ or their conjugate complex $y_i^{(k)*}$ at the receiver. At the receiver, the vector $\vec{y}^{(k)}$ is multiplied from left by the Hermitian of matrix $\mathbf{H}^{(k)}$. The fading between the different fading coefficients is assumed to be quasistatic. We obtain the (weighted) STBC information symbols

$$\vec{\hat{x}} = \mathbf{H}^{(k)H} \cdot \vec{y}^{(k)} = \mathbf{H}^{(k)H} \cdot \mathbf{H}^{(k)} \vec{x} + \mathbf{H}^{(k)H} \cdot \vec{n}^{(k)}$$
$$= \mathbf{H}^{(k)H} \cdot \vec{n}^{(k)} + \vec{x} \cdot \sum_{i=0}^{1} |h^{(i,k)}|^2, \qquad (16)$$

corrupted by noise. For STBCs from orthogonal designs, MIMO channel estimation at the receiver is mandatory, that is, $h^{(n,k)}$, $n = 0, \dots, N_{BS} - 1$, $k = 0, \dots, K - 1$, must be
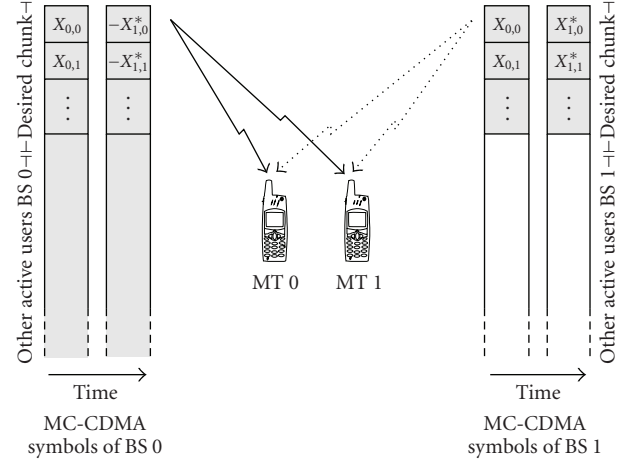

FIGURE 6: MC-CDMA symbol design for CAT for 2 MTs.

estimated. Disjoint pilot symbol sets for the TX-antenna branches can guarantee a separate channel estimation for each BS [8]. Since the correlation of the subcarrier fading coefficients in time direction is decreasing with increasing Doppler spread—that is, the quasistationarity assumption of the fading is incrementally violated—the performance of this STBC class will suffer from higher Doppler frequencies. Later we will see that this is not necessarily true as the stationarity of the fading could also be detrimental in case of burst errors in fading channels.

Figure 6 shows two mobile users sojourning at the cell borders. Both users data is spread within one spreading block and transmitted by the cellular Alamouti technique using two base stations. The base stations exploit information from a feedback link that the two MTs are in a similar location in the cellular network. By this both MTs are served simultaneously avoiding any interference between each other and exploiting the additional diversity gain.

3.3. Résumé for C-CDD and CAT

Radio resource management works perfectly if all information about the mobile users, like the channel state information, is available at the transmitter [21]. This is especially true if the RRM could be intelligently managed by a single genie manager. As this will be very unlikely the described schemes C-CDD and CAT offer an improved performance especially

at the critical cell border without the need of any information about the channel state information on the transmitter side. The main goal is to increase performance by avoiding interference and increasing diversity at the most critical environment. In this case, the term C/I is misleading (cf. (6)), as there is no I (interference). On the other hand, it describes the ratio of the power from the desired base station and the other base station. This ratio also indicates where the mobile user is in respect to the base stations. For C/I = 0 dB the MT is directly between the two BSs, for C/I > 0 dB the MT is closer to the desired BS, and for C/I < 0 dB the MT is closer to the adjacent BS. Since the signals of the neighboring BSs for the desired users are not seen as interference, the MMSE equalizer coefficients of (3) need no modification as in the intercellular interfering case [22]. Therefore, the transmit diversity techniques require no knowledge about the intercellular interference at the MT. By using C-CDD or CAT the critical cell border area can be also seen as a broadcast scenario with a multiple access channel.

For the cellular transmit diversity concepts C-CDD and CAT, each involved BS has to transmit additionally the signal of the adjacent cell; and therefore, a higher amount of resources are allocated at each BS. Furthermore, due to the higher RL in each cell the multiple-access interference (MAI) for an MC-CDMA system is increased. There will be always a tradeoff between the increasing MAI and the increasing diversity due to C-CDD or CAT.

Since the desired signal is broadcasted by more than one BS, both schemes can reduce the transmit signal power, and therefore, the overall intercellular interference. Using MC-CDMA for the cellular diversity techniques the same spreading code set has to be applied at the involved BSs for the desired signal which allows simple receivers at the MT without multiuser detection processes/algorithms. Furthermore, a separation between the inner part of the cells and the broadcast area can be achieved by an overlaying scrambling code on the signal which can be also used for synchronization issues as in UMTS [4].

Additionally, if a single MT or more MTs are aware that they are at the cell border, they could already ask for the C-CDD or CAT procedure on the first hand. This would ease the handover procedure and would guarantee a reliable soft handover.

We should point out two main differences between C-CDD and CAT. For C-CDD no changes at the receiver are needed, there exists no rate loss for higher number of transmit antennas, and there are no requirements regarding constant channel properties over several subcarriers or symbols and transmit antenna numbers. This is an advantage over already established diversity techniques [7] and CAT. The Alamouti scheme-based technique CAT should provide a better performance due to the coherent combination of the two transmitted signals [23].

4. RESULTING CHANNEL CHARACTERISTICS FOR C-CDD

The geographical influence of the MT for CAT has a symmetric behavior. In contrast, C-CDD is influenced by the posi-

tion of the served MT. Due to $\delta_0^{\mathrm{cyc}} \neq \delta_1^{\mathrm{cyc}}$ and the relation in (11), the resulting performance regarding the MT position of C-CDD should have an asymmetric characteristic. Since the influence of C-CDD on the system can be observed at the receiver as a change of the channel conditions, we will investigate in the following this modified channel in terms of its channel transfer functions and fading correlation in time and frequency direction. These correlation characteristics also describe the corresponding single transmit antenna channel seen at the MT for C-CDD.

The frequency domain fading processes for different propagation paths are uncorrelated in the assumed quasistatic channel. Since the number of subcarriers is larger than the number of propagation paths, there exists correlation between the subcarriers in the frequency domain. The received signal at the receiver in C-CDD can be represented by

$$Y_{l,i} = X_{l,i} \cdot \underbrace{\sum_{n=0}^{N_{\mathrm{BS}}-1} e^{-j(2\pi/N_{\mathrm{FFT}})i\delta_n}\alpha(d_n)H_{l,i}^{(n)}}_{H'_{l,i}} + N_{l,i}. \tag{17}$$

Since the interest is based on the fading and signal characteristics observed at the receiver, the AWGN term $N_{l,i}$ is skipped for notational convenience. The expectation

$$\mathbf{R}(l_1, l_2, i_1, i_2) = E\{H'_{l_1,i_1} \cdot H'^{*}_{l_2,i_2}\} \tag{18}$$

yields the correlation properties of the frequency domain channel fading. Due to the path propagations $\alpha(d_n)$ and the resulting power variations, we have to normalize the channel transfer functions $H_{l,i}^{(n)}$ by the multiplication factor $1/\sqrt{\sum_{n=0}^{N_{\mathrm{BS}}-1}\alpha^2(d_n)}$ which is included for $\mathbf{R}_{\mathrm{n}}(l,i)$.

The fading correlation properties can be divided in three cases. The first represents the power, the second investigates the correlation properties between the OFDM symbols (time direction), and the third examines the correlation properties between the subcarriers (frequency direction).

Case 1. Since we assume uncorrelated subcarriers the autocorrelation of the CTF ($l_1 = l_2 = l, i_1 = i_2 = i$) is

$$\mathbf{R}(l,i) = \sum_{n=0}^{N_{\mathrm{BS}}-1} \underbrace{e^{-j(2\pi/N_{\mathrm{FFT}})i\delta_n} \cdot e^{+j(2\pi/N_{\mathrm{FFT}})i\delta_n}}_{=1}\alpha^2(d_n)$$

$$\cdot \underbrace{E\{H_{l,i}^{(n)} \cdot H_{l,i}^{(n)*}\}}_{E\{|H_{l,i}^{(n)}|^2\}=1} = \sum_{n=0}^{N_{\mathrm{BS}}-1}\alpha^2(d_n), \tag{19}$$

and the normalized power is

$$\mathbf{R}_{\mathrm{n}}(l,i) = \sum_{n=0}^{N_{\mathrm{BS}}-1}\alpha^2(d_n)E\left\{\left|\frac{H_{l,i}^{(n)}}{\sqrt{\sum_{n=0}^{N_{\mathrm{BS}}-1}\alpha^2(d_n)}}\right|^2\right\} = 1. \tag{20}$$
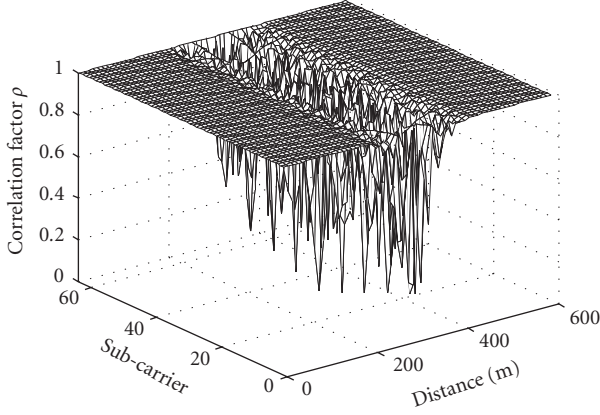
FIGURE 7: Characteristic of correlation factor ρ over the subcarriers depending on the distance d_0.

Case 2. The correlation in time direction is given by $l_1 \neq l_2$, $i_1 = i_2 = i$. Since the channels from the BSs are i.i.d. stochastic processes, $E\{H_{l_1,i}^{(n)} \cdot H_{l_2,i}^{(n)*}\} = E\{H_{l_1,i} \cdot H_{l_2,i}^*\}$ and

$$\mathbf{R}(l_1 \neq l_2, i) = E\{H_{l_1,i} H_{l_2,i}^*\} \sum_{n=0}^{N_{BS}-1} \alpha^2(d_n),$$

$$\mathbf{R}_n(l_1 \neq l_2, i) = E\left\{ \frac{H_{l_1,i} H_{l_2,i}^*}{\sum_{n=0}^{N_{BS}-1} \alpha^2(d_n)} \right\} \sum_{n=0}^{N_{BS}-1} \alpha^2(d_n) \quad (21)$$

$$= E\{H_{l_1,i} H_{l_2,i}^*\}.$$

We see that in time direction, the correlation properties of the resulting channel are independent of the MT position.

*Case 3.* In frequency direction ($l_1 = l_2 = l$, $i_1 \neq i_2$) the correlation properties are given by

$$\mathbf{R}(l, i_1 \neq i_2) = E\{H_{l,i_1} H_{l,i_2}^*\} \cdot \sum_{n=0}^{N_{BS}-1} \alpha^2(d_n) \underbrace{e^{-j(2\pi/N_{FFT})(i_1-i_2)\delta_n}}_{\text{C-CDD component}}.$$

$$(22)$$

For large d_n ($\alpha(d_n)$ gets small) the influence of the C-CDD component vanishes. And there is no beneficial increase of the frequency diversity close to a BS anymore. The normalized correlation properties yield

$$\mathbf{R}_n(l, i_1 \neq i_2) = E\{H_{l,i_1} H_{l,i_2}^*\}$$

$$\cdot \underbrace{\frac{1}{\sum_{n=0}^{N_{BS}-1} \alpha^2(d_n)} \cdot \sum_{n=0}^{N_{BS}-1} \alpha^2(d_n) e^{-j(2\pi/N_{FFT})(i_1-i_2)\delta_n}}_{\text{correlation factor } \rho}.$$

$$(23)$$

The correlation factor ρ is directly influenced by the C-CDD component and determines the overall channel correlation properties in frequency direction. **Figure 7** shows the characteristics of ρ for an exemplary system with $N_{FFT} = 64$, $\gamma = 3.5$, $N_{BS} = 2$, $r = 300$ m, $\delta_0^{cyc} = 0$, and $\delta_1^{cyc} = 7$. One
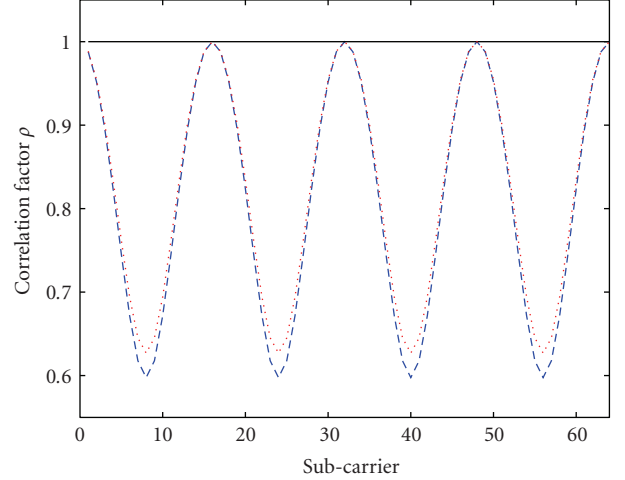
- - - $d_0 = 334$ m
——— $d_0 = 335$ m
········ $d_0 = 336$ m

FIGURE 8: Correlation characteristics over the subcarriers for $d_0 = [334\,\text{m}, 335\,\text{m}, 336\,\text{m}]$.

- -□- SNR gain at BER = $1e - 03$
- -○- C-CDD, C/I = 0 dB
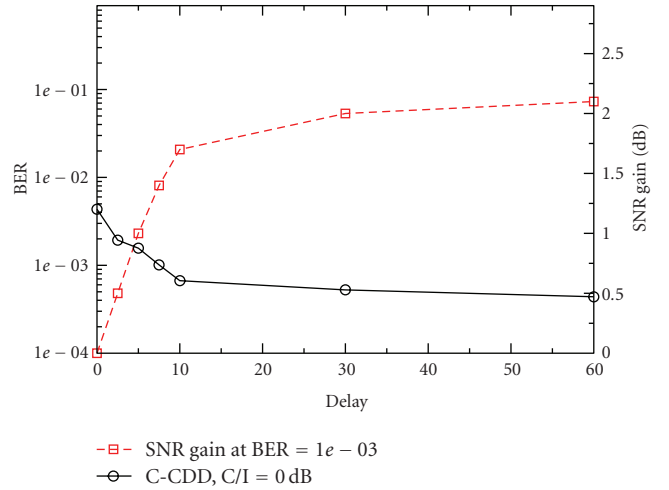
FIGURE 9: BER and SNR gains versus the cyclic delay at the cell border (C/I = 0 dB).

sample of the delay represents 320 microseconds or approximately 10 m, respectively. In the cell border area (200 m < d_0 < 400 m), C-CDD increases the frequency diversity by decorrelating the subcarriers. As mentioned before, there is less decorrelation the closer the MT is to a BS.

A closer look on the area is given in **Figure 8** where the inherent delay and the added cyclic delay are compensated, that is, for $d_0 = 335$ m the overall delay is $\delta_1 = \delta(265\,\text{m}) + \delta_1^{cyc} = -70\,\text{m} + 70\,\text{m} = 0$ (cf. (11)). The plot represents exemplarily three positions of the MT ($d_0 = [334\,\text{m}, 335\,\text{m}, 336\,\text{m}]$) and shows explicitly the degradation of the correlation properties over all subcarriers due to the nonexisting delay in the system. These analyses verify the asymmetric and δ^{cyc} dependent characteristics of C-CDD.

TABLE 1: Parameters of the cellular transmission systems.

Bandwidth	B	100.0 MHz
No. of subcarriers	N_c	1664
FFT length	N_{FFT}	2048
Guard interval length	N_{GI}	128
Sample duration	T_{samp}	10.0 ns
Frame length	N_{frame}	16
No. of active users	N_u	$\{1,\ldots,8\}$
Spreading lengh	L	8
Modulation	—	4-QAM, 16-QAM
Interleaving C-CDD	—	2D
Interleaving CAT	—	1D, 2D
Channel coding	—	CC $(561, 753)_{oct}$
Channel coding rate	R	1/2
Channel model	—	IEEE 802.11n Model C
Velocity	—	0 mph, 40 mph
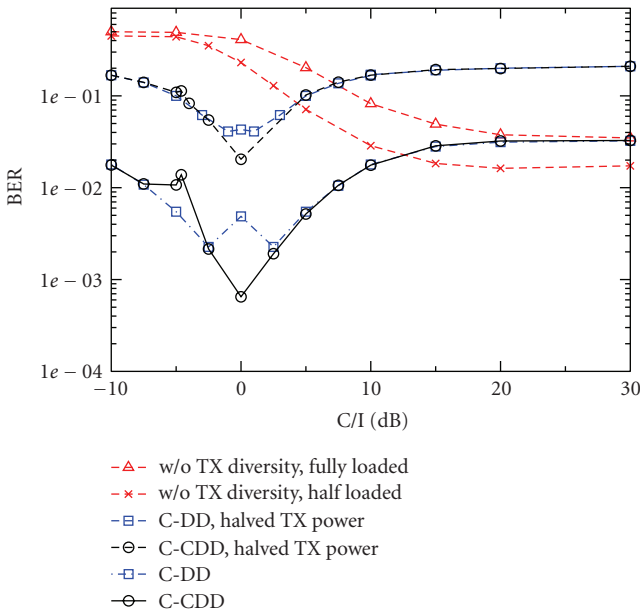
FIGURE 10: BER versus C/I for an SNR of 5 dB using no transmit diversity technique, C-DD, and C-CDD for different scenarios.

5. SIMULATION RESULTS

The simulation environment is based on the parameter assumptions of the IST-project WINNER for next generation mobile communications system [24]. The used channel model is the 14 taps IEEE 802.11n channel model C with $\gamma = 3.5$ and $\tau_{max} = 200$ nanoseconds. This model represents a large open space (indoor and outdoor) with non-light-of-sight conditions with a cell radius of $r = 300$ m. The transmission system is based on a carrier frequency of 5 GHz, a bandwidth of 100 MHz, and an FFT length of $N_c = 2048$. One OFDM symbol length (excluding the GI) is 20.48 microseconds and the GI is set to 0.8 microseconds (corresponding to 80 samples). The spreading length L is set to

8. The number of active users can be up to 8 depending on the used RL. 4-QAM is used throughout all simulations and for throughput performances 16-QAM is additionally investigated. For the simulations, the signal-to-noise ratio (SNR) is set to 5 dB and perfect channel knowledge at the receiver is assumed. Furthermore, a $(561, 753)_8$ convolutional code with rate $R = 1/2$ was selected as channel code. Each MT moves with an average velocity of 40 mph (only for comparison to see the effect of natural time diversity) or is static. As described in Section 3, users with similar demands at the cell border are combined within time-frequency units. We assume i.i.d. channels with equal stochastic properties from each BS to the MT. If not stated otherwise, a fully loaded system is simulated for the transmit diversity techniques, and therefore, their performances can be seen as upper bounds. All simulation parameters are summarized in Table 1. In the following, we separate the simulation results in three blocks. First, we discuss the performances of CDD; then, the simulation results of CAT are debated; and finally, the influence of the MAI to both systems and the throughput of both systems is investigated.

5.1. C-CDD performance

Figure 9 shows the influence of the cyclic delay δ_1^{cyc} to the bit-error rate (BER) and the SNR gain at the cell border (C/I = 0 dB) for C-CDD. At the cell border there is no influence due to C-DD, that is, $(\delta_1 = 0)$. Two characteristics of the performance can be highlighted. First, there is no performance gain for $\delta_1^{cyc} = 0$ due to the missing C-CDD. Secondly, the best performance can be achieved for an existing higher cyclic shift which reflects the results in [25]. The SNR gain performance for a target BER of 10^{-3} depicts also the influence of the increased cyclic delay. For higher delays the performance saturates at a gain of about 2 dB.

The performances of the applied C-DD and C-CDD methods are compared in Figure 10 with the reference system using no transmit (TX) diversity technique. For the reference system both BSs are transmitting independently
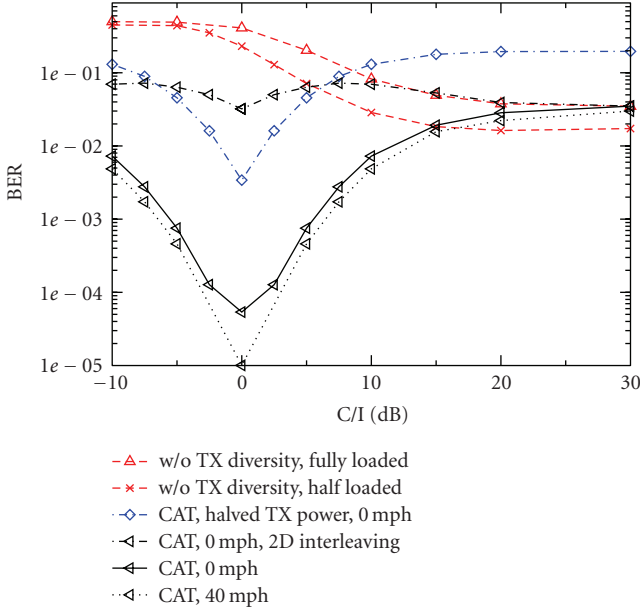
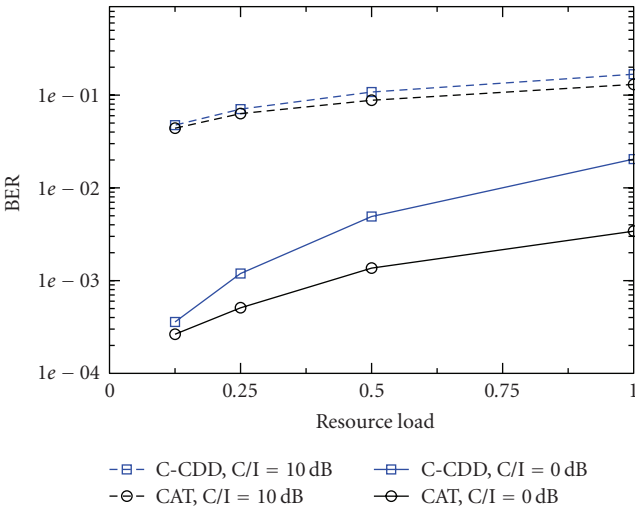FIGURE 11: BER versus C/I for an SNR of 5 dB using no transmit diversity and CAT for different scenarios.

FIGURE 12: Influence of the MAI to the BER performance for varying resource loads at the cell border and the inner part of the cell.
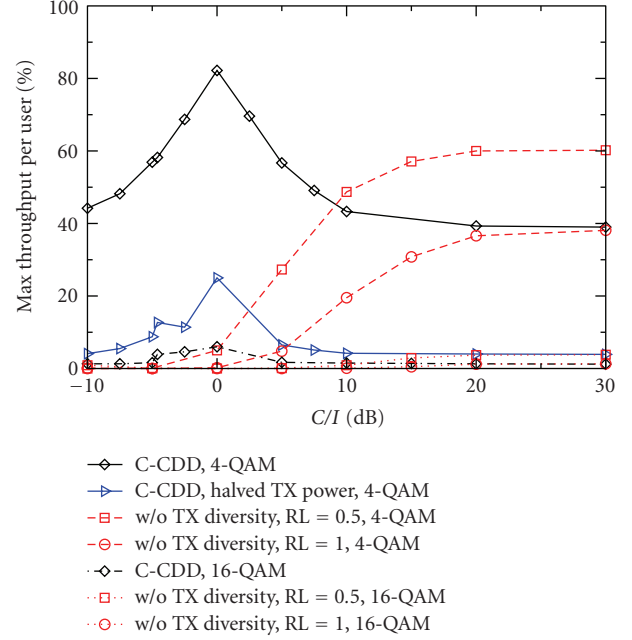

FIGURE 13: Throughput per user for 4-QAM versus C/I using no transmit diversity or C-CDD with full and halved transmit power.

as the single BS in the reference system, the received signal power at the MT is doubled. Therefore, the BER performance of C-DD and C-CDD at $\delta = 0$ is still better than the reference system performance. For higher C/I ratios, that is, in the inner cell, the C-DD and C-CDD transmit techniques lack the diversity from the other BS and additionally degrade due to the double load in each cell. Thus, the MT has to cope with the double MAI. The loss due to the MAI can be directly seen by comparing the transmit diversity performance with the half-loaded reference system. The fully loaded reference system has the same MAI as the C-CDD system, and therefore, the performances merge for high C/I ratios. To establish a more detailed understanding we analyze the C-CDD with halved transmit power. For this scenario, the total designated received power at the MT is equal to the conventional MC-CDMA system. There is still a performance gain due to the exploited transmit diversity for C/I < 5 dB. The performance characteristics are the same for halved and full transmit power. The benefit of the halved transmit power is a reduction of the intercellular interference for the neighboring cells. In the case of varying channel models in the adjacent cells, the performance characteristics will be the same but not symmetric anymore. This is also valid for the following CAT performances.

5.2. CAT performance

Figure 11 shows the performances of the applied CAT in the cellular system for different scenarios. If not stated otherwise, the systems are using a 1D interleaving. In contrast to the conventional system, the BER can be dramatically improved at the cell border. By using the CAT, the MT exploits the additional transmit diversity where the maximum is given at the

their separate MC-CDMA signal. From Figure 9, we choose $\delta_1^{\text{cyc}} = 30$ samples and this cyclic delay is chosen throughout all following simulations. The reference system is half (RL = 0.5) and fully loaded (RL = 1.0). We observe a large performance gain in the close-by area of the cell border (C/I = -10 dB, ..., 10 dB) for the new proposed diversity techniques C-DD and C-CDD. Furthermore, C-CDD enables an additional substantial performances gain at the cell border. The C-DD performance degrades for C/I = 0 dB because $\delta = 0$ and no transmit diversity is available. The same effect can be seen for C-CDD at C/I = -4.6 dB ($\delta_1 = -30$, $\delta_1^{\text{cyc}} = 30 \Rightarrow \delta = 0$); see also Section 4. Since both BSs in C-DD and C-CDD transmit the signal with the same power
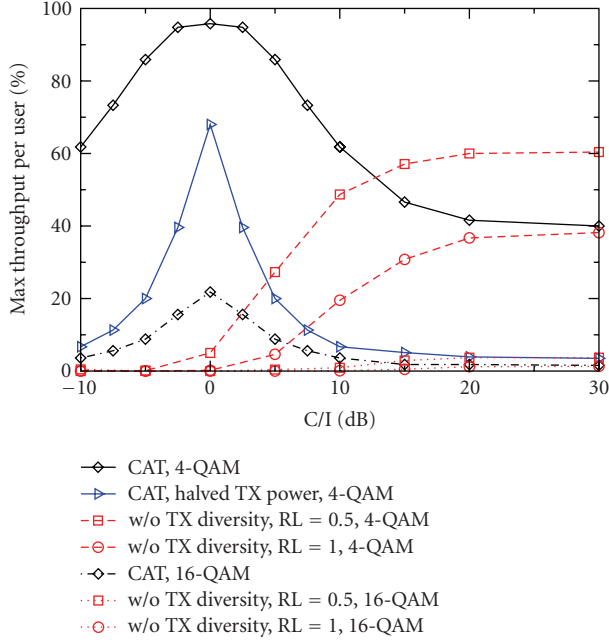
FIGURE 14: Throughput per user for 4-QAM and 16-QAM versus C/I using no transmit diversity or CAT with full and halved transmit power.

cell border. If the MT moves with higher velocity (40 mph), the correlation of the subcarrier fading coefficients in time direction decreases. This incremental violation of the quasistationarity assumption of the fading is profitable compensated by the channel code. The total violation of the aforementioned constraint of CAT (cf. Section 3.2) is achieved by a fully interleaved (2D) MC-CDMA frame. There is a large performance degradation compared to the CAT performance with a noninterleaved frame. Nevertheless, a residual transmit diversity exists, the MT benefits at the cell border, and the performance is improved. The applied CAT is not only robust for varying MT velocities but also for non-quasistatic channel characteristics. Similar to C-CDD, there is still a performance gain due to the exploited transmit diversity for C/I < 5 dB in the case of halved transmit powers at both BSs.

5.3. MAI and throughput performance of C-CDD and CAT

The influence of the MAI is shown in Figure 12. The BER performance versus the resource load of the systems is presented. Two different positions of the MT are chosen: directly at the cell border (C/I = 0 dB) and closer to one BS (C/I = 10 dB). Both transmit diversity schemes suffer from the increased MAI for higher resource loads which is in the nature of the used MC-CDMA system. CAT is not influenced by the MAI as much as C-CDD for both scenarios. Both performances merge for C/I = 10 dB because the influence of the transmit diversity techniques is highly reduced in the inner part of the cell.

Since we assume the total number of subcarriers is equally distributed to the maximum number of users per cell,

each user has a maximum throughput of $\eta_{\max}$. The throughput η of the system, by using the probability $P(n)$ of the first correct MC-CDMA frame transmission after $n - 1$ failed retransmissions, is given by

$$\eta = \sum_{n=0}^{\infty} \frac{\eta_{\max}}{n+1} P(n) \geq \eta_{\max}(1 - \text{FER}). \qquad (24)$$

A lower bound of the system is given by the right-hand side of (24) by only considering $n = 0$ and the frame-error rate (FER). Figures 13 and 14 illustrate this lower bound for different modulations in the case of C-CDD and CAT.

C-CDD in Figure 13 outperforms the conventional system at the cell border for all scenarios. Due to the almost vanishing performance for 16-QAM with halved transmit power for an SNR of 5 dB, we do not display this performance curve. For 4-QAM and C-CDD, a reliable throughput along the cell border is achieved. Since C-CDD with halved transmit power still outperforms the conventional system, it is possible to decrease the intercellular interference.

The same performance characteristics as in C-CDD regarding the throughput can be seen in Figure 14 for applying the transmit diversity technique CAT. Due to the combination of two signals in the Alamouti scheme, CAT can provide a higher throughput than C-CDD in the cell border area. The CAT can almost achieve the maximum possible throughput in the cell border area. For both transmit diversity techniques, power and/or modulation adaptation from the BSs opens the possibility for the MT to request a higher throughput in the critical cell border area. All these characteristics can be utilized by soft handover concepts.

6. CONCLUSIONS

This paper handles the application of transmit diversity techniques to a cellular MC-CDMA-based environment. Addressing transmit diversity by using different base stations for the desired signal to a mobile terminal enhances the macrodiversity in a cellular system. Analyses and simulation results show that the introduced cellular cyclic delay diversity (C-CDD) and cellular Alamouti technique (CAT) are capable of improving the performance at the severe cell borders. Furthermore, the techniques reduce the overall intercellular interference. Therefore, it is desirable to use C-CDD and CAT in the outer part of the cells, depending on available resources in adjacent cells. The introduced transmit diversity techniques can be utilized for more reliable soft handover concepts.

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