MC-CDMA VERSUS OFDMA IN CELLULAR ENVIRONMENTS

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ABSTRACT

In this paper, two candidates for a next generation (4G) downlink system in a multi-cell environment are studied in respect to their error performance. We investigate on the one hand, an orthogonal frequency division multiplexing (OFDM) based multiple access scheme (OFDMA), and on the other hand, a multi-carrier code division multiple access (MC-CDMA) scheme. The studies of both transmission schemes are done in a cellular structure. The cellular environment model takes into account path loss and shadowing depending on the position of the mobile terminal. To enhance the performance of OFDMA, we introduce a radio resource management (RRM). Error performances are given to compare the two multiple access proposals. The results show that OFDMA outperforms MC-CDMA at the edge of the cell for low resource loads by using the RRM. In the inner part of the cell, OFDMA can gain up to 0.5 dB at a target bit error rate of 10^{-3} in a fully-loaded system. For a not fully-loaded system, MC-CDMA surpasses the OFDMA performance by utilizing its whole diversity of used sub-carriers. In this scenario, MC-CDMA can even gain 2 dB compared to OFDMA.

1. INTRODUCTION

Currently, there are several ongoing research projects regarding the design and development of a high flexible and scalable next generation (4G) mobile radio access concept with respect to high data rates and spectral efficiency. For this 4G system several attractive candidates of transmission schemes exists [1–3]. They are based on orthogonal frequency division multiplexing (OFDM) [4].

A major benefit of OFDM is the robustness against multipath propagation channels, and therefore, high data rate transmissions are possible. Furthermore, OFDM is a low-complex technique to modulate multiple sub-carriers in a bandwidth-efficient way. The assignment of one or several sub-carriers to each user in an OFDM system leads to the multiple access scheme OFDMA. Contrary to OFDMA, the multi-carrier code division multiple access (MC-CDMA) scheme transmits in parallel chips of a spread data symbol on different sub-carriers [1]. In OFDMA, user-data symbols are allocated directly to channel resources and therefore offers no diversity without channel coding but adaptive transmission is possible. In contrast, an MC-CDMA transmission scheme spreads the user-data symbol energy over all channel resources and therefore offers diversity.

It is necessary to extend investigations to more realistic scenarios, *i.e.*, cellular structures. Therefore, this paper includes a distance-dependent propagation model for each impinging signal over all cells. Since each user allocates its own sub-carriers in an OFDMA system, each OFDMA system per cells can be managed by a radio resource management (RRM) for better performances.

This paper investigates and discusses the two technologies in anticipation of 4G requirements. It is the goal to make first statements of a comparison between MC-CDMA and OFDMA in a cellular structure regarding the error performances and the E_b/N_0 performance at a target bit error rate (BER) of $P_\mathrm{b} = 10^{-3}$.

The outline of this paper is as follows. The next section introduces the used multi-carrier systems, including the transmitter, receiver, and assumed channel model. Section 3 describes in more detail the model for the different propagation impairments affecting the cellular system and the used RRM for OFDMA. The cellular interference modeling is also in the focus of that section. Finally in Section 4, we provide error and E_b/N_0 performances for the used transmission schemes in a multi-cell environment.

2. MULTI-CARRIER SYSTEMS

The transmitter and receiver of an OFDMA and MC-CDMA transmission scheme differ only in the sub-carrier allocation and the additional spreading and detection component for MC-CDMA. In this paper, the terminology, notation, and description is identical for both systems, and the differences are pointed out in this section.

The block diagram of a transmitter using OFDMA/MC-CDMA is shown in Figure 1. The information bit stream of the N_u active users are convolutionally encoded and interleaved by the outer interleaver $_\mathrm{out}$. With respect to the modulation alphabet, the bits are mapped to complex-valued data symbols. In the sub-carrier allocation block N_d symbols per user are arranged for each transmission scheme. In the case of MC-CDMA, the kth data symbol is multiplied by a user-specific Walsh-Hadamard spreading sequence which provides so-called chips. The spreading length L corresponds to the maximum number of active user $L = N_{\mathrm{u,max}}$.

An inner sub-carrier interleaver $_\mathrm{in}$ 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 interleaving in frequency and time direction is possible.

Finally, an OFDM modulation is performed which includes an inverse fast Fourier transformation (FFT) and insertion of a guard interval to avoid inter-symbol and inter-carrier interference.

On the receiver side, see Figure 2, the transmitter signal processing is inverted.

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 linear minimum mean square error (MMSE) one-tap equalizer. The resulting MMSE equalizer coefficients are

$$G_{l,i} = \frac{H_{l,i}^{(j)*}}{|H_{l,i}^{(j)}|^2 + \frac{L}{N_\mathrm{u}}\sigma^2}\,, \qquad i = 1,\ldots,N_\mathrm{c}\,, \tag{1}$$

where σ^2 is the actual variance of the additive white Gaussian noise (AWGN) process and $H_{l,i}^{(j)}$ is the channel transfer function from base station (BS) j to the mobile terminal (MT). Furthermore, N_c is the number of sub-carriers and the indices j and i represent the OFDM symbol and sub-carrier, respectively. In contrast, for OFDMA the data symbols can be directly demodulated with the knowledge of $H_{l,i}^{(j)}$.

Then the symbol demapper maps the data symbols to bits. In addition, it calculates the log-likelihood ratio for each bit based on the selected alphabet. The code bits are deinterleaved and finally decoded using soft-decision Viterbi decoding [1].

For the multi-carrier schemes a resource load (RL) can be defined. For the OFDMA system, the RL is the ratio of the number of assigned sub-carriers to the total number of available sub-carriers N_c. This corresponds directly to the RL of the MC-CDMA system, which is defined by the ratio of the number of active users to the number of maximum users. Note that in terms of total transmitted signal energy, the following relation holds

$$\mathrm{RL} = \mathrm{RL}_\mathrm{OFDMA} = \frac{N_\mathrm{d}N_\mathrm{u}}{N_\mathrm{c}} = \mathrm{RL}_\mathrm{MC-CDMA} = \frac{N_\mathrm{u}}{L}\,. \tag{2}$$

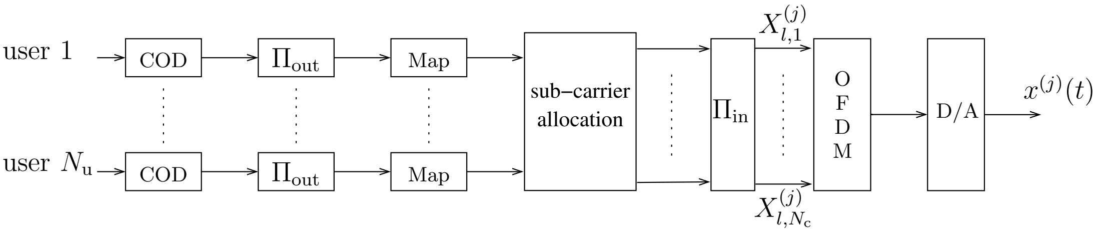


Figure 1: *OFDMA/MC-CDMA transmitter of the jth base station*

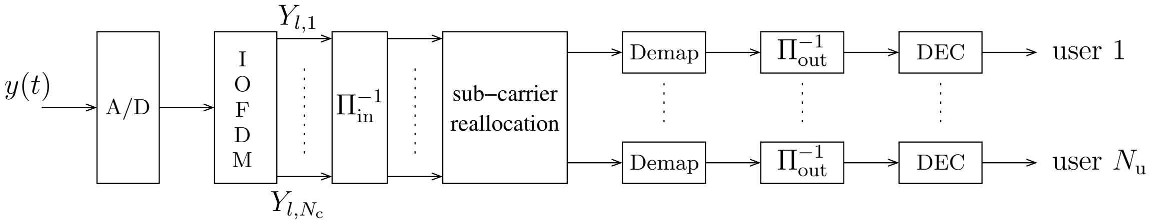


Figure 2: *OFDMA/MC-CDMA receiver*

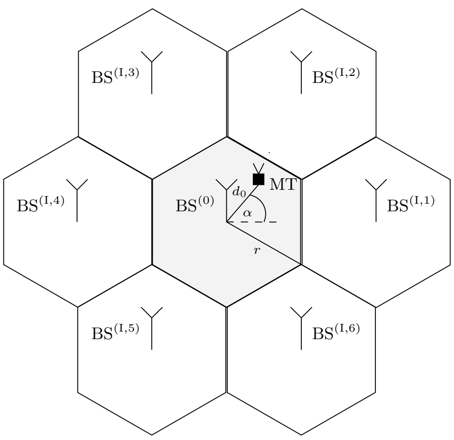


Figure 3: *One-tier multi-cell environment*

2.1 Channel Model

The mobile radio channel is assumed to be a time-variant, frequency-selective fading channel. It is modeled by a tapped delay-line with Q_0 non-zero taps [5]. We consider that the Q_0 channel taps are mutually uncorrelated and all tap delays $\tau_q^{(j)}$ are in the range $[0, \tau_{max}]$. The channel fading is assumed to be a wide-sense stationary uncorrelated scattering (WSSUS) random process, *i.e.*, the channel has a fading statistic that remains constant over a period of time [6].

3. MULTI-CELL ENVIRONMENT

A typical hexagonal structure is assumed for the cellular network where all cell sizes are equal as depicted in Figure 3. A whole tier of interfering cells around the desired cell is assumed. The BS and the MT are perfectly synchronized in time and frequency. The distance between the desired BS and MT is denoted as d_0, and the cell radius r is normalized to 1. For example, the mobile can be situated along a line from the desired BS to the intersection of the desired cell and two interfering cells. In this case, the angle $\alpha = 30°$. A propagation model represents the locally averaged received energy from the jth BS at the MT. The slowly varying signal energy attenuation due to path loss is generally modeled as the product of the γth power of distance d_j and a log-normal component representing shadowing losses [7]. Therefore the resulting received signal energy is

$$E_j = E_{t,j} \cdot d_j^{-\gamma} \cdot 10^{\eta_j/10\mathrm{dB}}, \tag{3}$$

where $E_{t,j}$ is the transmitted signal energy from the jth BS. The path decay factor γ is assumed to be 4 and the standard deviation of the Gaussian-distributed shadowing factor η_j is set to 8 dB. The cellular simulation environment is taken from [8].

3.1 Radio Resource Management for OFDMA

Introduction of a radio resource management for assigning sub-carriers should maximize the performance in the case of OFDMA. In a fully-synchronized system, it is possible to assign the sub-carriers per BS in such a way that no double allocation of sub-carriers between the BSs occurs. This can be guaranteed up to a resource load of RL $= 1/m_{RRM}$, where m_{RRM} is the total number of managed cells. The managed m_{RRM} BSs need the same inner interleaver $_{in}$ after the sub-carrier allocation. In spite of RRM, the frequency diversity of the OFDMA system is preserved. The unmanaged cells use their own independent inner interleaver. By exceeding the RL, the succeeding assignment of sub-carriers is done in such a way that the assigned sub-carriers per additional active user are randomly distributed over the remaining sub-carriers. Therefore, the probability that any user is entirely disturbed is reduced.

3.2 Cellular Interference Modeling

The cellular interference can be modeled as depicted in Figure 4. The channels have the same Doppler power spectrum and delay profile, but are uncorrelated. The ratio of the received signal energy from the desired BS and from an interfering BS j is denoted by $E_j = E_0/E_j$. Therefore, the interfering signals from BS$^{(I,j)}$ are weighted with the energy factor $1/\sqrt{E_j}$.

By including the interfering BSs, the received lth OFDM symbol at sub-carrier i becomes

$$Y_{l,i} = X_{l,i}^{(0)} H_{l,i}^{(0)} + \sum_{j=1}^{m-1} \frac{1}{\sqrt{E_j}} X_{l,i}^{(j)} H_{l,i}^{(j)} + N_{l,i}, \tag{4}$$

where $X_{l,i}^{(j)}$ denotes the value of the ith sub-carrier in the lth OFDM symbol at BS j and $N_{l,i}$ is AWGN with zero mean and variance N_0. This scenario represents a power-controlled desired user at distance d_0 as well as power-controlled interfering cells.

In the case of MC-CDMA, the signals are passed to an MMSE equalizer after the deinterleaving process in the receiver. The coefficients in (1) have to be modified in such a way that the interfering signals are assumed to be an additional noise variance term in the denominator [8].

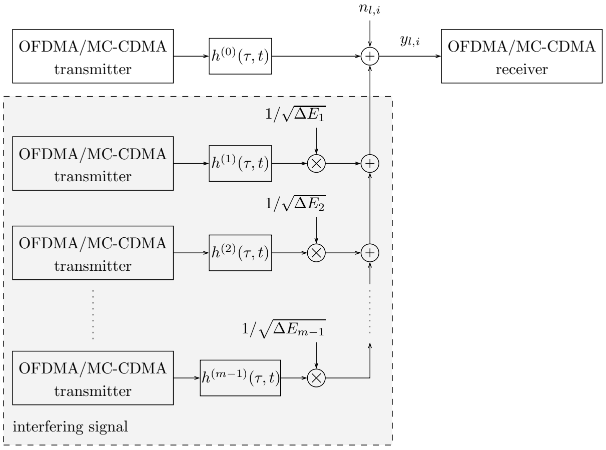


Figure 4: *Model of the cellular system*

Table 1: *Parameters of the transmission systems*

Bandwidth	B	101.25 MHz
# sub-carriers	N_c	768
FFT length	N_{FFT}	1024
Guard interval length	N_{GI}	226
Sample duration	T_{samp}	7.4 ns
Frame length	N_{frame}	64
# active users	N_u	$\{1\ldots8\}$
Spreading length (MC-CDMA)	L	8
Modulation		QPSK
Channel coding		CC $(171,133)_{\text{oct}}$
Channel coding rate	R	1/2
Channel coding memory	M_{CC}	6

4. SIMULATION RESULTS

Table 1 illustrates the system parameters of the used transmission systems. The used channel model is depicted in Figure 5, see also Section 2.1, with an exponentially decaying power delay profile. Corresponding to a mobile velocity of about 3 km/h at 5 GHz carrier frequency, each tap has a normalized maximum Doppler frequency $f_{\text{Dnorm,max}} = f_{\text{D,max}} \cdot T_s = 14\ \text{Hz} \cdot 7.5\ \mu\text{s} = 10^{-4}$, where T_s represents the OFDM symbol duration. These parameters are taken from [9]. We assume perfect channel knowledge. In the case of MC-CDMA, the spreading length is set to $L = 8$. Finally, for all users in the simulations, E_b/N_0 is defined by the average energy per bit divided by the average noise power of AWGN.

For the following simulations, the interfering BSs have the identical parameters as the desired BS which also includes the number of active users. The MT moves from the BS in an angle of $\alpha = 30°$. The statistics of the used distance dependent propagation model remain constant over the period of one OFDM frame. The two closest interfering BSs to the MT have the largest influence of disturbance in a multi-cell environment [10]. Therefore, in the case of RRM for OFDMA, the resources of the desired BS and the two closest interfering BSs are managed, see also Section 3.1.

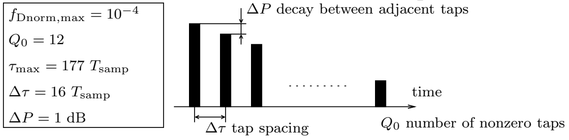
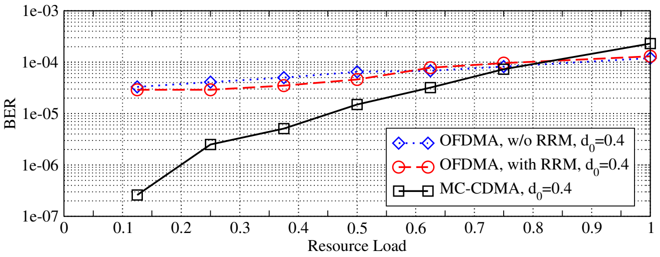
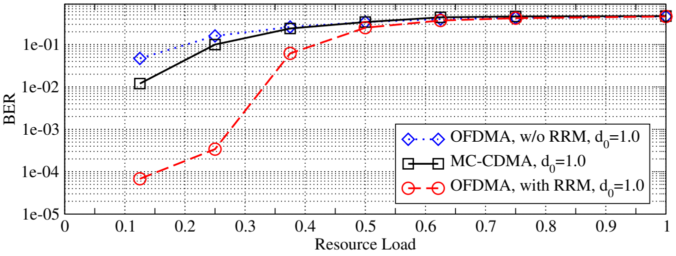


Figure 5: *Parameters of the used power delay profile of the channel model*



(a) *Distance* $d_0 = 0.4$



(b) *Distance* $d_0 = 1.0$

Figure 6: *BER versus resource load @* $E_b/N_0 = 10$ dB *for an OFDMA and MC-CDMA system in a multi-cell environment and perfect channel estimation for two different* d_0

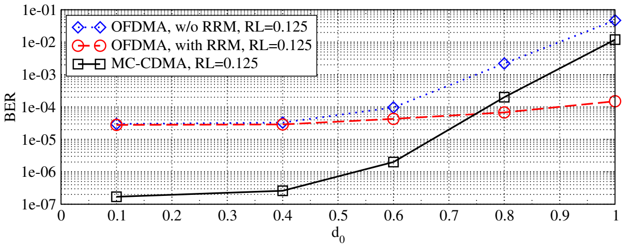
We show simulation results of a direct comparison between the two 4G proposals OFDMA and MC-CDMA in a cellular environment. Since the number of active users, the maximum number of users, the data symbols per user, and the frame size are equal, the comparison of the systems is fair in that case. Two scenarios are always illustrated and discussed. Figure 6 presents the BER versus the RL at $E_b/N_0 = 10$ dB in each cell.

First scenario, $d_0 = 0.4$: Since interference is negligible for $d_0 \leq 0.4$ [10], the RRM does not enhance the OFDMA performance. The OFDMA performance keeps almost constant by increasing the RL in contrast to the performance of MC-CDMA. For small RLs, MC-CDMA outperforms OFDMA by far because MC-CDMA can utilize the whole diversity of all assigned sub-carriers. Since the multiple access interference (MAI) increases for higher RLs, the benefit of MC-CDMA reduces with increasing RL.

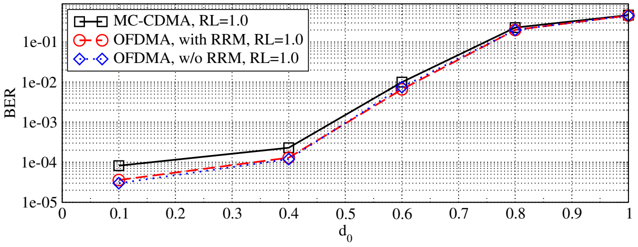
Second scenario, $d_0 = 1.0$: The MT is at the cell boundary, where two interfering BS are at the same distance as the desired BS. Thus, the cellular interference is maximal. Only in a small region of lower RLs MC-CDMA gains in comparison to OFDMA without RRM. At a RL of 3/8, the performances merge and keep constant. OFDMA with RRM has a huge performance gain up to a RL = 3/8. The RRM can avoid any collision with the major interfering signals from the neighboring cells up to a RL = 1/3.

In [8] and [10], it was shown that in the peripheral area of the desired cell, a strong disturbance by the adjacent interfering cells exists. In contrast, the core of the desired cell ($d_0 \leq 0.4$) obtains a minimum of interference. Therefore, we see in Figure 6 a huge performance degradation between the two scenarios $d_0 = 0.4$ and $d_0 = 1.0$. In the same way, the performances of Figure 7 are influenced. The BER is plotted as a function of the distance d_0 for different transmission schemes in the same multi-cell environment at $E_b/N_0 = 10$ dB in each cell. The performances show a distinctively steeper slope for $d_0 > 0.4$.

The performance for OFDMA with RRM and an RL = 1/8 in Figure 7 keeps roughly constant because no sub-carriers are doubly allocated due to the RRM. A small performance loss exists, resulting from the higher inter-cell interference. Again, MC-CDMA outperforms OFDMA for RL = 1/8 in the inner cell area up to $d_0 = 0.75$. In contrast, OFDMA slightly exceeds the MC-CDMA performance in the fully-loaded scenario because the MAI is the major degradation factor of MC-CDMA. Since all sub-carriers are allocated in the fully-loaded case, there is no difference between OFDMA with RRM and without RRM.



(a) *Resource load* $= 0.125$



(b) *Resource load* $= 1.0$

Figure 7: *BER versus* d_0 *@* $E_\mathrm{b}/N_0 = 10$ dB *for an OFDMA and MC-CDMA system in a multi-cell environment and perfect channel estimation for two different resource loads*

Figure 8 shows performances of the two systems in terms of required E_b/N_0 in all cells for achieving a target BER of $P_\mathrm{b} = 10^{-3}$ for different resource loads. The performances are illustrated for E_b/N_0 versus the position of the MT. The fully-loaded scenario shows in Figure 8(b) that only in the core of the cell the target BER can be reached by an E_b/N_0 between 7.5 dB and 8 dB for OFDMA. MC-CDMA looses 0.5 dB versus OFDMA because of the high MAI.

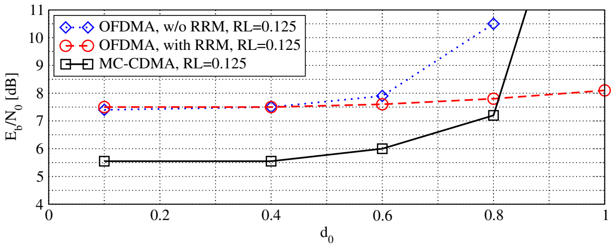
In the case of RL $= 1/8$, Figure 8(a) shows quite the same behavior as the scenario of Figure 7. We see that the target BER can be achieved in the whole cell for OFDMA with RRM. At the edge of the cell, MC-CDMA and pure OFDMA cannot provide the BER. OFDMA with RRM needs a higher E_b/N_0 up to $d_0 = 0.8$ than MC-CDMA. Furthermore, OFDMA has the same E_b/N_0 level as in the fully-loaded case. In contrast, MC-CDMA can gain up to 2 dB compared to OFDMA.

It is to mention that the OFDMA system can be seen as perfectly designed by using RRM. In contrast, the used MC-CDMA system does not exploit its full design potential. There is the possibility of using iterative decoding and soft-interference cancellation for the additional enhancing of the error performance [11]. A RRM can also be implemented by using the *M&Q*-modification [1]. The performance of MC-CDMA would consequently improve.

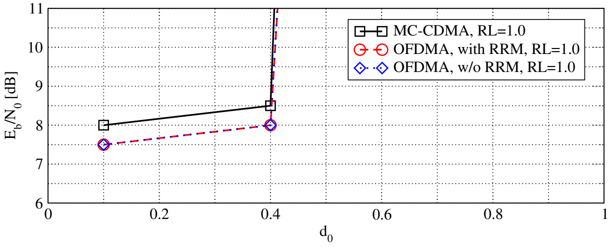
5. CONCLUSION

This paper handles two proposed transmission schemes for 4G systems, namely OFDMA and MC-CDMA. Simulations compare the error and E_b/N_0 performance of these two in a cellular environment. The multi-cell scenario is described by a propagation model for the path loss and shadowing is taken into account. In case of the OFDMA system an idealized radio resource management is introduced.

The simulations show that MC-CDMA can outperform ordinary OFDMA in the case of varying resource loads. In the core of the cell, MC-CDMA exploits the whole sub-carrier diversity and outperforms OFDMA for resource loads smaller than $3/4$. The use of the radio resource management for OFDMA can highly enhance the OFDMA performance in the peripheral cell area and OFDMA surpasses the MC-CDMA performance. Regarding the E_b/N_0 behavior at a target BER of $P_\mathrm{b} = 10^{-3}$, the simulation results present 0.5 dB gain for OFDMA compared to MC-CDMA in a fully-loaded system. In contrast, MC-CDMA can gain up to 2 dB in a lower-loaded system.



(a) *Resource Load* $= 0.125$



(b) *Resource Load* $= 1.0$

Figure 8: E_b/N_0 *versus* d_0 *@ target BER of* $P_\mathrm{b} = 10^{-3}$ *for an OFDMA and MC-CDMA system in a multi-cell environment and perfect channel estimation for two different resource loads*

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