On the Performance of Coded OFDM with and without Spreading in an Interference Limited Environment

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***Abstract*— We address an OFDM-based air interface operating in an interference limited environment, which might be encountered in a cellular mobile communication system. For enhanced robustness, an OFDM system with spreading, known as multi-carrier (MC) CDMA, may operate not fully loaded. On the other hand, a lower code rate also improves the robustness. In this paper, the trade-off between code rate and system load constraint to the same spectral efficiency is analyzed in a cellular downlink scenario. It is demonstrated through simulations that a fully loaded MC-CDMA system always outperforms a non-fully loaded system, provided the code rate is chosen such that the throughput of both systems is equivalent. Moreover, the MC-CDMA system fails to outperform a coded OFDM system without spreading, even in a cellular environment.**

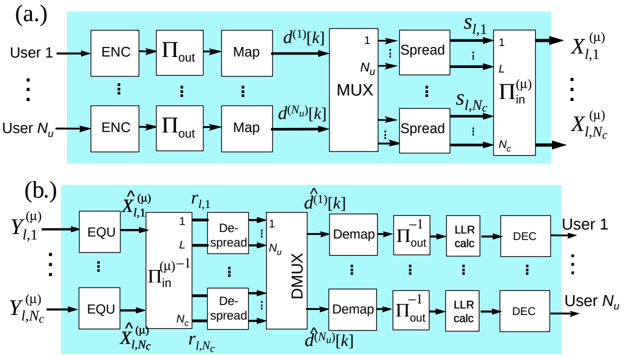

Fig. 1. MC-CDMA transmitter, (a.), and receiver, (b.).

I. Introduction

Multi-carrier modulation, in particular orthogonal frequency division multiplexing (OFDM), has emerged as an effective transmission technique for highly dispersive channels, and has been successfully applied to a wide variety of digital communications systems. For MC-CDMA, spreading in frequency and/or time direction is introduced in addition to the OFDM modulation [1–3]. MC-CDMA has been deemed a promising candidate for the downlink of future mobile communications systems [4, 5], and has recently been implemented by NTT DoCoMo in an experimental system [6].

We restrict the discussion to non-adaptive transmission, so no channel knowledge at the transmitter is assumed. A low signal to noise ratio (SNR) scenario is considered; which may occur if the transmission power is to be minimized, the coverage area is to be extended, or the interference level is high. The latter case is typically experienced near the cell edges of a mobile communications system having a frequency reuse of one. In order to mitigate the effects of cellular interference, it is often suggested to run a MC-CDMA system not fully loaded [5, 7]. While the multiple access interference (MAI) and the interference imposed on adjacent cells is reduced, the throughput is compromised. This means that robustness is traded with reduced system throughput.

On the other hand, rate compatible punctured convolutional (RCPC) codes also allow to flexibly adjust the data rate [8]. Provided sufficient interleaving, a coded multi-carrier system can efficiently exploit the diversity of a frequency selective channel.

The major difference between the considered OFDM systems with and without spreading is that the former utilizes Walsh-Hadamard spreading sequences. For MC-CDMA, a certain data rate can be achieved by different combinations of system loads and code rates. In an effort to optimize the performance, the trade-off between system load and code rate is analyzed. Simulation results suggest that a fully loaded MC-CDMA system always outperforms a not-fully loaded system. Moreover, OFDM without spreading achieves the best performance, as long as the code rate is equal or less than $1/2$. Since the considered low SNR scenario ultimately requires low code rates for acceptable performance, it appears reasonable to scrap the WH spreading operation. While the data rate can be adjusted more efficiently by RCPC codes; a cell-specific random subcarrier interleaver is effective to decorrelate the interference, as well as to exploit the diversity of the frequency selective channel. This means that the advantages of MC-CDMA in terms of flexibility and robustness are still in place, while multiple access interference as one severe drawback is mitigated

The remainder of this paper is structured as follows: in section II the system and channel model is introduced; scenarios and simulation results for the considered OFDM based downlink are presented in sections III and IV.

II. System & Channel Model

A. OFDM with spreading

Fig. 1.a shows the block diagram of a MC-CDMA transmitter serving N_u users. The bit stream for each user is encoded with a RCPC code with rate r and memory m. That is, a constituent code with rate r_c is punctured to match the desired code rate $r \geq r_c$ [8]. The encoded bit stream is subsequently bit interleaved by the outer

interleaver $\mathbf{\Pi}_{\text{out}}$, and fed to the symbol mapper with cardinality M. The energy per information bit and mapped symbol are given by E_b and $E_s = E_b\, r \log_2(M)$.

Subsequently, each data symbol is spread by a Walsh-Hadamard (WH) sequence with spreading factor $L \geq N_u$. The spreading operation establishes a multiple access scheme for N_u users. The spreading factor L can be significantly smaller than the number of available subcarriers N_c. In this case each user may transmit $N_d = N_c/L$ data streams in parallel. The system load of the MC-CDMA system is defined by $\rho = N_u/L$ and can be adjusted between 1 and $1/L$. This results in the average energy per spread chip:

$$E_c = E_s \cdot \tfrac{N_u}{L} = E_b \cdot \rho\, r \log_2(M) \qquad (1)$$

The spread chips of OFDM symbol ℓ are then frequency interleaved by the inner interleaver, $\mathbf{\Pi}_{\text{in}}^{(\mu)}$, over one OFDM symbol to maximize the diversity gain. The interleaver produces the sequence, $\mathbf{X}_\ell^{(\mu)} = [X_{\ell,1}^{(\mu)}, \cdots, X_{\ell,N_c}^{(\mu)}]^T$, of BS μ, subcarrier i and OFDM symbol ℓ.[1] One frame consists of N_{frame} OFDM symbols, each having N_c subcarriers. In order to distinguish signals from different BSs, the superscript μ was introduced. An inverse DFT (IDFT) with $N_{\text{DFT}} \geq N_c$ points is performed on each block to yield the time domain signal $x_{\ell,n}^{(\mu)} = \text{IDFT}\{X_{\ell,i}^{(\mu)}\}$. Subsequently a guard interval (GI) having N_{GI} samples is inserted in the form of a cyclic prefix.

After D/A conversion, the signal $x^{(\mu)}(t)$ is transmitted over a mobile radio channel. At the receiver the signal is sampled with rate nT_{spl}, and the guard interval is removed. Assuming perfect synchronization and neglecting cellular interference for the moment, a N_{DFT}–point DFT on the received signal, $y_{\ell,n}$, is performed, to obtain the output of the OFDM demodulation [9]

$$Y_{\ell,i} = \text{DFT}\{y_{\ell,n}\} = X_{\ell,i}^{(\mu)}\, H_{\ell,i}^{(\mu)} + N_{\ell,i} \qquad (2)$$

where $H_{\ell,i}^{(\mu)}$, and $N_{\ell,i}$ denote the the channel response from BS μ, and AWGN with zero mean and variance N_0.

Data Detection: A block diagram of a MC-CDMA receiver is depicted in Fig. 1.b. Due to frequency selectivity of the multipath fading channel and the random interleaving of the spread chips, the orthogonality of the spreading sequences is lost and multiple access interference (MAI) occurs, if $N_u > 1$. An efficient compromise between reducing MAI and utilizing the diversity of the frequency selective channel is the linear minimum mean squared error (MMSE) detector [10]. Applying the MMSE criterion to $Y_{\ell,i}$ with the constraint of a one tap equalizer, the output for subcarrier i becomes

$$\widehat{X}_{\ell,i}^{(\mu)} = \frac{H_{\ell,i}^{(\mu)\,*}}{|H_{\ell,i}^{(\mu)}|^2 + \frac{1}{\gamma_c}} \cdot Y_{\ell,i} \qquad (3)$$

where γ_c denotes the average SNR per subcarrier, which is $\gamma_c = \frac{N_u}{L}\frac{E_s}{N_0}$ for the single transmitter scenario.

The equalized signal sequence of OFDM symbol ℓ, $\widehat{\mathbf{X}}_\ell^{(\mu)}$, is subsequently deinterleaved by $\mathbf{\Pi}_{\text{in}}^{(\mu)\,-1}$ and despread. The symbol demapper maps the data symbols into bits, by also calculating the log-likelihood ratio (LLR) for each bit, which serves as reliability information for the decoder [11, 12]. The symbol demapper assumes the MAI to be white Gaussian noise with zero mean and appropriately scaled variance [13]. The code-bits are deinterleaved and finally decoded using a soft-in soft-out channel decoder. We use the Max-Log MAP algorithm for the channel decoder [14, 15], which is an approximation of the optimum maximum *a posteriori* (MAP) symbol-by-symbol detector [16].

[1] Variables which can be viewed as values in the frequency domain, such as $X_{\ell,i}^{(\mu)}$, where each entry modulates a certain subcarrier, are written in capital letters.

B. OFDM without spreading

OFDM without spreading may be viewed as a special case of MC-CDMA with spreading factor $L = 1$. To establish a multi-user system, OFDM is combined with FDMA, termed OFDMA. Then, the N_c subcarriers are equally assigned to N_u users, by allocating N_c/N_u subcarriers per OFDM symbol to each user. Unlike for MC-CDMA, one subcarrier is exclusively assigned to one user's symbol, so multiple access interference is avoided. Thus, the system load is fixed to $\rho = 1$, and the energy per subcarrier in (1) simplifies to $E_c = E_s = E_b\, r \log_2(M)$. In the block diagram of Fig. 1 the spreading block is omitted, all other system components are equivalent to the MC-CDMA system described previously.

The multi-user OFDMA system may also be viewed as a form spread spectrum system, in the way that the subcarrier interleaver $\mathbf{\Pi}_{\text{in}}^{(\mu)}$ distributes the data streams associated with different users, μ, over the whole frequency band; the induced frequency diversity is picked up by the channel decoder.

C. Channel Model

The channel transfer function (CTF), $H_{\ell,i}^{(\mu)}$, is obtained by sampling the analog CTF $H^{(\mu)}(t,f)$ at time and frequency instants $t = \ell T_{\text{sym}}$ and $f = i/T$, where $T_{\text{sym}} = (N_{\text{DFT}} + N_{\text{GI}})T_{\text{spl}}$ and $T = N_{\text{DFT}} T_{\text{spl}}$ represents the OFDM symbol duration with and without the guard interval, and T_{spl} is the sample duration. The CTF, $H^{(\mu)}(t,f)$, is the Fourier transform of the channel impulse response (CIR), $h^{(\mu)}(t,\tau)$. The frequency selective, Rayleigh fading channel, is modeled by a tapped delay line with Q_0 non-zero taps [17], described by $h^{(\mu)}(t,\tau) = \sum_{q=1}^{Q_0} h_q^{(\mu)}(t) \cdot \delta(\tau - \tau_q^{(\mu)})$. Accordingly, the CTF is given by

$$H_{\ell,i}^{(\mu)} = H^{(\mu)}(\ell T_{\text{sym}}, i/T) = \sum_{q=1}^{Q_0} h_{\ell,q}^{(\mu)}\, e^{-j2\pi\, \tau_q^{(\mu)}\, i/T} \qquad (4)$$

The channel of the q^{th} tap, $h_{\ell,q}^{(\mu)}$, impinging with time delay $\tau_q^{(\mu)}$, is a wide sense stationary (WSS), complex Gaussian random variable with zero mean.

D. Modeling Cellular Interference

Recently, there has been growing interest in applying an OFDM-based air interface to cellular systems. We focus on a system which should be robust against interference, rather than trying to avoid interference, as this ultimately would require inter-cell synchronization in time *and* frequency, which might be difficult to achieve in practice. This means that inter-cell interference can be

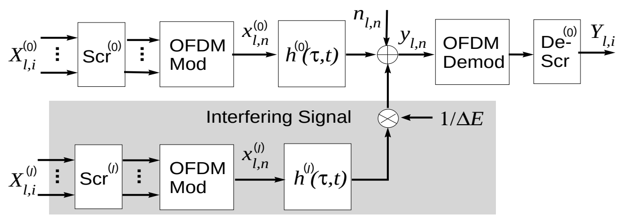

Fig. 2. Block diagram of the system simulator, comprising the transmitter chain for the desired as well as for one interfering signal.

significant, especially if the system is to operate with high frequency reuse factor. The application of the considered OFDM based system to a cellular downlink scenario was thoroughly described in [7] and [18], for a 2-cell and multi-cell environment, respectively.

In order to distinguish signals from different BSs and to further randomize the transmitted signal, $X_{\ell,i}^{(\mu)}$, is scrambled by a complex cell specific random sequence, $p_i^{(\mu)}$.

Moreover, for the subcarrier interleaver in Fig. 1, we choose a cell specific random interleaver for $\mathbf{\Pi}_{\text{in}}^{(\mu)}$, as proposed in [7, 19]. That is, the interleaver patterns for $\mathbf{\Pi}_{\text{in}}^{(\mu)}$ are mutually different for all BSs. The purpose of $\mathbf{\Pi}_{\text{in}}^{(\mu)}$ is twofold: first, by increasing the distance between adjacent symbols a diversity gain is achieved; second, the inter-cell interference between adjacent BSs is randomized. It was demonstrated in [19] that cell specific random interleaving effectively decorrelates signals from interfering BSs, even for low spreading factors L, and for channels which exhibit strong correlation between subcarriers.

At the receiver the cell specific scrambling sequence, $p_i^{(\mu)\,*}$, and subcarrier deinterleaver, $\mathbf{\Pi}_{\text{in}}^{(\mu)\,-1}$, are applied. A block diagram of how the cellular interference is modeled is shown in Fig. 2. The signal from the desired and interfering BS is received at the mobile with energy per symbol of E_s and $E_s/\Delta E$, where ΔE accounts for the difference in received signal power between the two interfering BSs.

The frequency domain received signal of the considered 2-cell scenario after OFDM demodulation is given by

$$Y_{\ell,i} = H_{\ell,i}^{(0)} X_{\ell,i}^{(0)} + \tfrac{1}{\sqrt{\Delta E}} H_{\ell,i}^{(I)} X_{\ell,i}^{(I)} + N_{\ell,i} \qquad (5)$$

The first and second term in (5) account for the desired and the interfering signal, respectively. The above expression describes the interference of a fully synchronized system. If adjacent BSs operate asynchronously, such a simple frequency domain model is no longer possible [19]. In any case, the system performance of a cellular OFDM based downlink depends only marginally on a synchronization offset between BSs [19].

For the MC-CDMA receiver, the carrier to interference ratio, γ_c, at the input of the MMSE equalizer from (3) needs to be adjusted according to

$$\gamma_c = \frac{1}{\frac{1}{\Delta E} + \frac{N_0}{E_b} \cdot \frac{1}{\rho\, r \log_2(M)}} \qquad (6)$$

As for the multiple access interference, the cellular interference of the MMSE equalizer is approximated by Gaussian noise. Hence, non-Gaussian interference will result in poorer performance. To this end, the considered 2-cell scenario is the worst case in terms of cellular interference, since more interfering signals mean the Gaussian approximation is matched more closely [18].

III. System Scenarios

For the following discussion it is assumed that all BSs are using exactly the same system parameters, i.e. the same system loads ρ, code rates r, etc.

In case the mobile is near the cell/sector boundary, ΔE in (5) will be close to one, so the carrier to interference ratio, γ_c, for a single antenna receiver approaches 0 dB. In order to maintain a reliable connection it is often suggested not to operate the system fully loaded, so $N_u < L$ [5, 7].

A reduction of N_u directly translates to reduced multiple access interference, since the energy per transmitted chip (subcarrier after spreading), E_c of (1), decreases with the system load $\rho = N_u/L$. Since all BSs run with the same load, ρ, the cellular interference also decreases by ρ, which obviously increases the robustness of the cellular system. This is traded with a ρ times lower spectral efficiency. The robustness towards cellular interference is sometimes claimed to be a major advantage for MC-CDMA over OFDMA [5].

On the other hand, channel coding is considered to be an essential part of any mobile communication system. Rate compatible punctured convolutional (RCPC) codes provide a powerful tool to flexibly adjust the data rate, giving an additional degree of freedom for the system design. RCPC codes are implemented by choosing a constituent code with the lowest rate $r_c \leq r$. Then, (almost) arbitrary code rates are generated through puncturing [8]. According to (1), the energy per subcarrier, E_c, carrying one coded symbol also decreases with lower r. This will in turn also reduce the cellular interference, similar to reducing ρ. Moreover, a lower r provides an increased coding gain.

Given a certain code rate, r, and system load, ρ, the spectral efficiency of the considered OFDM-based system is given by

$$\eta = \log_2(M) \cdot r \cdot \rho \qquad \text{in} \quad [\text{bit/s/Hz}] \qquad (7)$$

where M denotes the modulation cardinality, which is $M = 4$ for QPSK. In the above expression the loss due to the cyclic prefix and guard bands is neglected, since it is the same for all considered schemes. In the following the system performance is optimized subject to a given η, with respect to r and ρ.

IV. Simulation Results

The bit error rate (BER) performance of an OFDM-based system with and without spreading is evaluated by computer simulations. An MC-CDMA system with spreading factor $L = 8$ was implemented to examine the trade-off between code rate r and system load $\rho = N_u/8$, constraint to a constant spectral efficiency, η of (7). In order to allow a fair comparison between MC-CDMA and OFDMA, the number of users, N_u, for OFDMA are set equal to the spreading factor, L, for the compared

TABLE I

MC-CDMA AND OFDMA SYSTEM PARAMETERS

Bandwidth	B	101.5 MHz
# subcarriers	N_c	768
DFT length	N_{DFT}	1024
Guard interval (GI) length	N_{GI}	268
Sample duration	T_{spl}	7.4 ns
Frame length	N_{frame}	64
Spreading Factor	L	{1,8}
Modulation	QPSK	
Channel coding rate	r_c	1/4
Channel coding memory	m	6

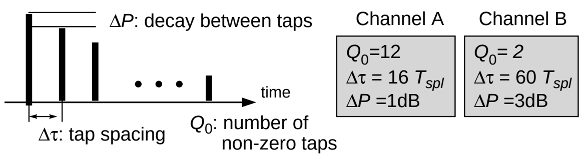

Fig. 3. The power delay profile of the used channel models.

MC-CDMA system. Since for OFDMA the system load is fixed to $\rho = 1$, the data rate can only be adjusted by the code rate r. For the RCPC codes a rate $r = 1/4$, memory $m = 6$ constituent code with puncturing patterns from [8] was taken. Since we are mainly interested in the low SNR region, the modulation cardinality will be fixed to $M = 4$ throughout. The system and channel model parameters are shown in Table I and Fig. 3.

The channel is modeled by a tap delay line model with Q_0 non-zero taps, a tap spacing of $\Delta\tau$, with an exponential decaying power delay profile, as illustrated in Fig. 3. The independent fading taps are generated using Jakes' model [20], each having a maximum Doppler frequency of $\nu_{max} = 10^{-4} \cdot T_{\text{sym}}$, with T_{sym} defined in (4), corresponding to a mobile velocity of about 3 km/h @5 GHz carrier frequency. Two different channel models are considered, as indicated in Fig. 3: Channel A with $Q_0 = 12$; and Channel B with two non-zero taps. Furthermore, an independent Rayleigh (IR) channel model has been implemented, such that all subcarriers and OFDM symbols are mutually uncorrelated.

For the results in Figures 4 and 5 Channel A was used.

Fig. 4 shows the BER against the E_b/N_0 for MC-CDMA ($L = 8$, $\rho = N_u/8$) in an isolated cell environment, where no inter-cell interference is encountered. Parts (a.), (b.) and (c.) of Fig. 4 show parameter sets with a spectral efficiency of $\eta = 1/2$, $2/3$, and 1 bit/s/Hz, respectively. In almost all cases,[2] it is seen that the higher the system load, ρ, the better the performance. If the code rate exceeds $r \geq 1/2$, the degradation of not-fully loaded MC-CDMA becomes severe. For comparison an equivalent OFDMA system without spreading ($L = 1$, $\rho = 1$, $N_u = 8$), is also shown in Fig. 4. It is seen that OFDMA always outperforms MC-CDMA on the link level. This is an expected result, due to the low code rates, $r \leq 1/2$, which has already been reported e.g. in [5, 21].

In order to assess the performance of a cellular system,

[2]Only the not fully loaded and uncoded system outperforms the fully loaded and coded system at very high interference levels, where the performance is unacceptable anyhow (see Fig. 4.a and 4.c). This is due to the well known effect that the performance of a coded system degrades for low SNR.

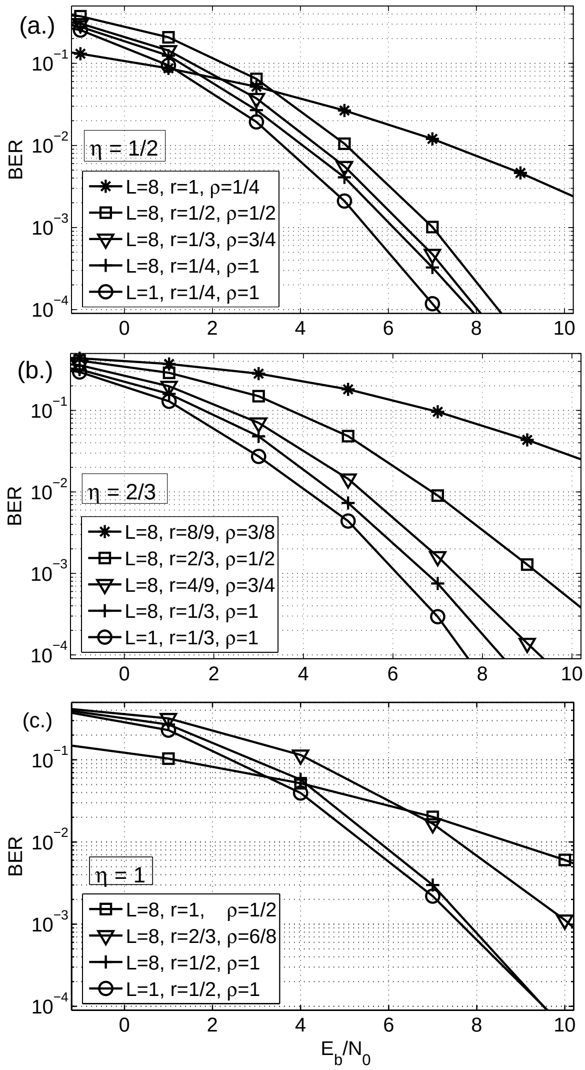

Fig. 4. BER vs E_b/N_0 for a MC-CDMA system ($L = 8$) with different number of system loads $\rho = N_u/8$ and code rates r for Channel A. Curves for OFDMA ($L = 1$, $\rho = 1$, $N_u = 8$) are plotted as a reference. Parameter sets with a spectral efficiency of $\eta = 1/2$, $2/3$ and 1 bit/s/Hz are shown in part (a.), (b.) and (c.), respectively.

the performance of a 2-cell scenario, as described in section II-D has been evaluated. Fig. 5 shows the BER against the difference in received signal power between the two interfering BSs, ΔE, for the same system parameters as in Fig. 4. So, for $\Delta E = 0$ dB the received signals of the desired and interfering BS have the same power. The AWGN was set to $E_b/N_0 = 10$ dB. Essentially the same conclusions as for the link level results in Fig. 4 can be drawn. That is, MC-CDMA with full load outperforms the half loaded system. Furthermore, even in a cellular environment OFDMA without spreading has superior performance than MC-CDMA.

Fig. 6 shows the system performance using a 2-tap channel (Channel B) and an independent Rayleigh (IR) channel, for the same 2-cell system as Fig. 5. Clearly, the performance strongly depends on the available diversity of the channel. The diversity order is 2 for Channel B and maximum for the IR channel. Note that the difference between fully loaded and half loaded system gets larger as the diversity order of the channel increases.

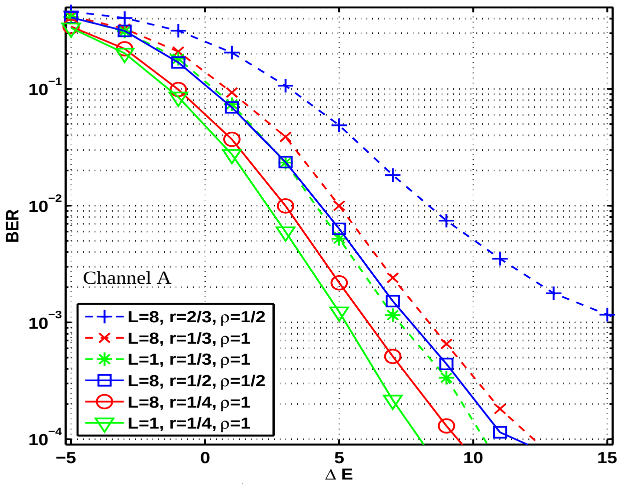

Fig. 5. BER vs ΔE @$E_b/N_0 = 10$ dB for a 2-cell MC-CDMA system with different number of users N_u and code rates r for Channel A. Parameter sets with a spectral efficiency of $\eta = 1/2$ and $2/3$ are marked by solid and dashed lines, respectively.

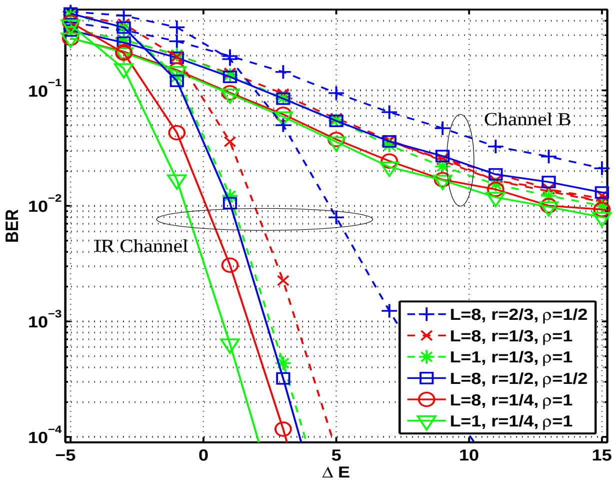

Fig. 6. BER vs ΔE @ $E_b/N_0 = 10$ dB for a 2-cell MC-CDMA system with different number of users N_u and code rates r, for Channel B and an independent Rayleigh (IR) channel. Parameter sets with a spectral efficiency of $\eta = 1/2$ and $2/3$ are marked by solid and dashed lines, respectively.

Generally, for all considered channel models coded OFDMA exhibits the best performance. Furthermore, coded OFDMA with spectral efficiency $\eta = 2/3$ is always equal or better than the half loaded MC-CDMA system with $\eta = 1/2$. A lower code rate providing a more powerful channel code appears superior in exploiting the available diversity, even in a cellular environment.

V. Conclusions

Operating a MC-CDMA system not fully loaded was shown to be inefficient, both for a link level and a cellular downlink scenario. The difference in system performance in favour of the fully loaded system is most significant, if the system load is reduced such that a code rate of $r \leq 1/2$ cannot be maintained. Furthermore, coded OFDMA without spreading outperforms MC-CDMA for the considered simulation parameters. RCPC codes allow to flexibly adjust the data rates, and a random interleaver on the subcarrier level was shown to be effective to randomize the interference, as well as to exploit the diversity of the frequency selective channel. On the other hand, it appears that little is to be gained by spreading with Walsh-Hadamard sequences.

References

[1] K. Fazel and L. Papke, "On the Performance of Convolutionally-Coded CDMA/OFDM for Mobile Communication Systems," in *Proc. IEEE Int. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC'93), Yokohama, Japan*, pp. 468–472, Sep. 1993.

[2] N. Yee, J. Linnartz, and G. Fettweis, "Multi-Carrier CDMA in Indoor Wireless Radio Networks," in *Proc. IEEE Int. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC'93), Yokohama, Japan*, pp. 109–113, Sep. 1993.

[3] A. Chouly, A. Brajal, and S. Jourdan, "Orthogonal Multicarrier Techniques Applied to Direct Sequence Spread Spectrum CDMA Systems," in *Proc. IEEE Global Telecommun. Conf. (Globecom '93). Houston, USA*, pp. 1723–28, Nov. 1993.

[4] S. Abeta, H. Atarashi, and M. Sawahashi, "Performance of Coherent Multi-Carrier/DS-CDMA and MC-CDMA for Broadband Packet Wireless Access," *IEICE Trans. Commun.*, vol. E84-B, pp. 406–414, Mar. 2001.

[5] H. Atarashi, S. Abeta, and M. Sawahashi, "Variable Spreading Factor-Orthogonal Frequency and Code Division Multiplexing (VSF-OFCDM) for Broadband Packet Wireless Access," *IEICE Trans. Commun.*, vol. E86-B, pp. 291–299, Jan. 2003.

[6] Y. Kishiyama, N. Maeda, K. Higuchi, H. Atarashi, and M. Sawahashi, "Experiments on Throughput Performance Above 100-Mbps in Forward Link for VSF-OFCDM Broadband Packet Wireless Access," in *Proc. IEEE Vehic. Technol. Conf. 2003-Fall (VTC'F03), Orlando, USA*, Oct. 2003.

[7] G. Auer, S. Sand, A. Dammann, and S. Kaiser, "Analysis of Cellular Interference for MC-CDMA and its Impact on Channel Estimation," *European Trans. Telecommun.*, vol. 15, pp. 173–184, May-June 2004.

[8] J. Hagenauer, "Rate-Compatible Punctured Convolutional Codes (RCPC Codes) and their Applications," *IEEE Trans. Commun.*, vol. 36, pp. 389–400, Apr. 1988.

[9] J. Bingham, "Multicarrier Modulation for Data Transmission: an Idea Whose Time Has Come," *IEEE Commun. Mag.*, pp. 5–14, May 1990.

[10] N. Yee and J. Linnartz, "Wiener Filtering of Multi-Carrier CDMA in Rayleigh Fading Channels," in *Proc. IEEE Int. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC'94), The Hague, The Netherlands*, pp. 1344–1347, Sep. 1994.

[11] A. Viterbi and J. Omura, *Principles of Digital Communication and Coding*. McGraw-Hill, New York, NY, USA, 1979.

[12] J. Hagenauer, "Source-Controlled Channel Decoding," *IEEE Trans. Commun.*, vol. 43, pp. 2449–57, Sep. 1995.

[13] S. Kaiser, "OFDM Code-Division Multiplexing in Fading Channels," *IEEE Trans. Commun.*, vol. 50, pp. 1266–1273, Aug. 2002.

[14] W. Koch and A. Baier, "Optimum and Sub-optimum Detection of Coded Data Disturbed by Time-varying Intersymbol Interference," in *Proc. IEEE Global Telecommun. Conf. (Globecom '90). San Diego, USA*, pp. 1679–84, Dez. 1990.

[15] P. Robertson, E. Villebrun, and P. Höher, "A Comparison of Optimal and Sub-Optimal MAP Decoding Algorithms Operating in the Log Domain," in *Proc. IEEE Int. Conf. Commun. (ICC'95), Seatle, USA*, vol. 2, pp. 1009–13, Jun. 1995.

[16] L. R. Bahl, J. Cocke, F. Jenilek, and J. Raviv, "Optimal Decoding of Linear Codes for Minimizing Symbol Error Rate," *IEEE Trans. Information Theory*, vol. IT-20, pp. 284–287, Mar. 1974.

[17] J. G. Proakis, *Digital Communications*. New York, NY, USA: McGraw-Hill, 3rd ed., 1995.

[18] S. Plass, S. Sand, and G. Auer, "Modeling and Analyis of a Cellular MC-CDMA Downlink System," in *IEEE Int. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC 2004), Barcelona, Spain*, Sep. 2004.

[19] G. Auer, A. Dammann, S. Sand, and S. Kaiser, "On Modelling Cellular Interference for Multi-Carrier based Communication Systems Including a Synchronization Offset," in *Proc. Int. Symp. Wireless Pers. Multimedia Commun. (WPMC'03), Yokosuka, Japan*, Oct. 2003.

[20] W. C. Jakes, *Microwave Mobile Communications*. Wiley, NY, 1974.

[21] S. Kaiser, "Trade-off between channel coding and spreading in multi-carrier CDMA systems," in *Proc. IEEE Int. Symp. Spread Spectrum Techniques and Applications (ISSSTA'96), Mainz, Germany*, pp. 1366–1370, Sep. 1996.