IFDMA - A Promising Multiple Access Scheme for Future Mobile Radio Systems

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***Abstract*— The Interleaved Frequency Division Multiple Access (IFDMA) scheme is based on compression, repetition and subsequent user dependent frequency shift of a modulated signal. Multiple access is enabled by the assignment of overlapping but mutually orthogonal subcarriers to each user. In this paper it is shown that IFDMA can be regarded as unitary precoded OFDMA with interleaved subcarriers. On the other hand, IFDMA is shown to be a CDMA variant with frequency domain orthogonal signature sequences and chip interleaving. Thus, it combines the advantages of single and multi carrier transmission such as low peak to average power ratio, orthogonality of the signals of different users even for transmission over a time dispersive channel and low complexity. Simulation results show the good performance of coded IFDMA transmission over a mobile radio channel for different data rates.**

I. Introduction

Presently, research for beyond 3rd generation mobile radio systems is in progress world wide. A future mobile radio system has to meet challenging requirements. On the one hand, it should enable different types of services from data rates of a few kbit/s up to several Mbit/s. Moreover, it should provide high flexibility and granularity as well as high performance. On the other hand, low cost and hence, low complexity implementation is requested, especially for mobile terminals.

High rate data transmission generally implies a small symbol duration. For transmission over time dispersive channels with a large maximum channel delay compared to the symbol duration many consecutive data symbols are affected by inter symbol interference. Thus, common time domain equalization methods become very complex. One method to overcome this problem is the use of multicarrier transmission. A well-established representative for multicarrier transmission is OFDMA. It provides low computational complexity and at the same time good performance. Orthogonality of the signals for different users is not affected by transmission over time dispersive channels. Furthermore, OFDMA is robust to time offsets by appropriate choice of the guard interval. However, OFDMA signals are sensitive to frequency offsets and suffer from high envelope fluctuations.

Another solution is block transmission of single carrier signals. If subsequent data blocks are assumed to be separated by a cyclic prefix, low complexity equalization is possible by the use of linear frequency domain equalizers [3]. A well known representative for single carrier transmission is DS-CDMA. It provides low envelope fluctuations and good robustness to frequency offsets. However, for transmisssion over time dispersive channels orthogonality of the signals of different users is lost and computationally complex algorithms for user separation are neccessary.

A further promising candidate for future mobile radio systems is Interleaved Frequency Division Multiple Access (IFDMA) [1] [2] [6]. It is based on compression, repetition and subsequent user dependent frequency shift of a modulated signal. In Section II, a system model for IFDMA is described and spectral characteristics of IFDMA are discussed. In Sections III and IV it is shown that IFDMA can be interpreted as a CDMA and also as an OFDMA variant. IFDMA combines important advantages of single and multicarrier schemes. The properties of IFDMA and its computational complexity are discussed in Section V and compared to OFDMA. Finally, performance results for coded IFDMA data transmssion over a mobile radio channel are presented for different data rates.

II. System Model

In this section, a system model for IFDMA is described. Based on a continuous time model, spectral characteristics of an IFDMA signal are described. Subsequently, IFDMA modulation, transmission over a time-dispersive channel and IFDMA demodulation are presented based on a discrete time model.

In the following, all signals are represented by their complex equivalents in the low-pass domain. We consider an IFDMA system with K users and user indices $k = 0, \ldots, K-1$. IFDMA performs blockwise transmission. A block containing Q data symbols is designated as IFDMA block. We consider a data vector $\mathbf{d}^{(k)}$ of user k consisting of Q linearly modulated data symbols at symbol rate $1/T_s$ denoted as

$$\mathbf{d}^{(k)} = (d_0^{(k)}, \ldots, d_{Q-1}^{(k)})^{\mathrm{T}}. \tag{1}$$

Let $x^{(k)}(t)$ designate a continuous time signal according to

$$x^{(k)}(t) = \sum_{q=0}^{Q-1} d_q^{(k)} \cdot \bar{f}_s(t - qT_s), \tag{2}$$

where $\bar{f}_s(t)$ designates a pulse shape filter given by

$$\bar{f}_s(t) = \begin{cases} 1 & 0 \le t < T_s \\ 0 & \text{else} \end{cases} . \tag{3}$$

According to [1], an IFDMA block is generated by compres-

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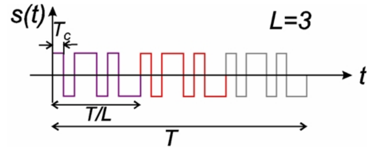

Fig. 1: IFDMA signal, example $Q = 8$ and $L = 3$

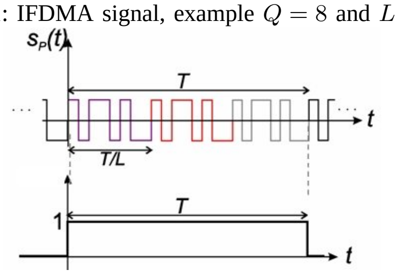

Fig. 2: Windowing, time domain, example $Q = 8$ and $L = 3$

sion in time of $x^{(k)}(t)$ by factor K and subsequent L-fold repetition of the compressed signal $x^{(k)}(Kt)$ with $L \geq K$. Thereafter, a user specific rotation by $e^{j\frac{2\pi}{KQ}\Delta f(k)t}$ corresponding to a shift by $\Delta f(k)$ in frequency domain is applied to the compressed and repeated signal. Thus, an IFDMA block for one user consists of LQ chips of length

$$T_c = \frac{T_s}{K}. \tag{4}$$

This is illustrated in Fig. 1 for $K = L = 3$ and $Q = 8$ with $T = Q \cdot T_s$ and $T/L = Q \cdot T_c$. The bandwidth of an IFDMA signal is given by

$$B = \frac{1}{T_c}. \tag{5}$$

The continuous time representation of an IFDMA block for the k-th user is given by

$$s^{(k)}(t) = \frac{1}{\sqrt{K}} \sum_{l=0}^{L-1} \sum_{q=0}^{Q-1} d_q^{(k)} \cdot \bar{f}_s(Kt - qT_s - lQT_s) \cdot e^{j2\pi\Delta f(k)t}, \tag{6}$$

where $\frac{1}{\sqrt{K}}$ is a normalization factor. Using a modified pulse shape filter according to

$$f_s(t) = \bar{f}_s(Kt), \tag{7}$$

Eq. (6) can be rewritten as

$$s^{(k)}(t) = \frac{1}{\sqrt{K}} \sum_{n=0}^{LQ-1} d_{\mathrm{nmod}Q}^{(k)} \cdot f_s(t - nT_c) \cdot e^{j2\pi\Delta f(k)t}. \tag{8}$$

In order to explain further the spectral characteristics of an IFDMA block we define a periodic signal

$$s_p^{(k)}(t) = \frac{1}{\sqrt{K}} \sum_{n=-\infty}^{\infty} d_{\mathrm{nmod}Q}^{(k)} \cdot f_s(t - nT_c) \cdot e^{j2\pi\Delta f(k)t} \tag{9}$$

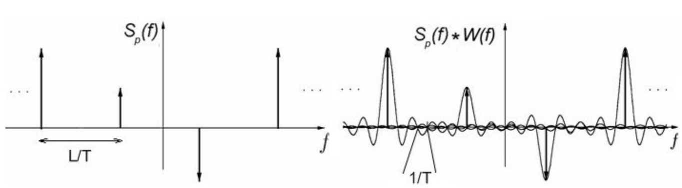

Fig. 3: Windowing, frequency domain, example $Q = 4$ and $L = 8$

$s_p^{(k)}(t)$ can be interpreted as an infinite number of repetitions of the compressed signal $x^{(k)}(Kt)$, cf. Fig. 2 for $Q = 8$ and $L = 3$. As $s_p^{(k)}(t)$ is periodic, it has a discrete spectrum as schematically depicted in Fig. 3 for $Q = 4$ and $L = 8$. The distance Δf_c between adjacent spectral lines is given by the inverse of the period of $s_p^{(k)}(t)$:

$$\Delta f_c = \frac{1}{QT_c}, \tag{10}$$

cf. Fig. 3 for $1/(QT_c) = L/T$. From Eq. (9), the IFDMA block $s^{(k)}(t)$ of Eq. 6 can be obtained by multiplication with a window function

$$w(t) = \begin{cases} 1 & 0 \leq t < Q \cdot T_s \\ 0 & \text{else} \end{cases}, \tag{11}$$

i.e.,

$$s^{(k)}(t) = s_p^{(k)}(t) \cdot w(t), \tag{12}$$

cf. Fig. 2. Let $S^{(k)}(f)$, $W(f)$ and $S_p^{(k)}(f)$ designate the Fourier Transforms of $s^{(k)}(t)$, $w(t)$ and $s_p^{(k)}(t)$, respectively. Thus, in frequency domain, Eq. (12) is given by

$$S^{(k)}(f) = S_p^{(k)}(f) * W(f), \tag{13}$$

where $*$ designates linear convolution. The convolution in Eq. (13) is schematically depicted in Fig. 3. The Fourier Transform of the window function $w(t)$ is given by

$$W(f) = \frac{\sin(\pi f Q T_s)}{\pi f} \cdot e^{j2\pi f \frac{T_s}{2}} \tag{14}$$

with zeros at $f = \eta/(QT_s)$ where η is an integer $\neq 0$. Hence, the spectrum of an IFDMA block consists of superimposed mutually orthogonal subcarriers. Each subcarrier is $\sin(x)/x$-shaped and has zeros in a distance of

$$\Delta f_z = 1/(QT_s). \tag{15}$$

The distance Δf_c of adjacent subcarriers of one user is K-times the distance of zeros of one subcarrier Δf_z. Thus, inbetween adjacent subcarriers of one user $K - 1$ zeros occur. Hence, the signals of $K - 1$ additional users can be accommodated in terms of multiple access by a user specific frequency shift of $\Delta f(k) = k \cdot \Delta f_z$. Comparison of Eq. (5) and Eq. (10) shows that within the bandwidth B, a number of Q subcarriers occur.

In the following, IFDMA modulation, transmission over a time-dispersive channel and IFDMA demodulation are described based on a discrete time model. This model is used for comparison of IFDMA with CDMA and OFDMA, respectively. In order to avoid inter block interference, subsequent IFDMA symbols are separated by a cyclic prefix (CP) that exceeds the maximum delay of the channel. A cyclic prefix can be easily obtained by appropriate choice of the repetition factor L. In the following, $L = K + K_\Delta$ is assumed, where $K_\Delta Q$ has to be an integer. We define a discrete time IFDMA block denoted as

$$\mathbf{s}^{(k)} = (s_{-K_\Delta Q}^{(k)}, \ldots, s_{KQ-1}^{(k)})^{\mathrm{T}}. \tag{16}$$

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$\mathbf{s}^{(k)}$ consists of $N{=}LQ{=}(K+K_\Delta)Q$ chips at chip rate T_c. The first $K_\Delta Q$ chips can be interpreted as cyclic prefix. According to Eq. (8), the chips of the IFDMA block are given by

$$s_n^{(k)} = \frac{1}{\sqrt{K}} \cdot d_{n \bmod Q}^{(k)} \cdot e^{j\frac{2\pi}{QK}nk};\ n = -K_\Delta Q, \ldots, KQ-1. \tag{17}$$

Let

$$\mathbf{y}^{(k)} = (y_{-K_\Delta Q}^{(k)}, \ldots, y_{KQ+M-1}^{(k)})^{\mathrm{T}} \tag{18}$$

designate the received signal after transmission over a time dispersive channel which is modeled by a finite impulse response filter of length M at chip rate $1/T_c$ denoted as

$$\mathbf{h}^{(k)} = (h_0^{(k)}, \ldots, h_{M-1}^{(k)})^{\mathrm{T}}. \tag{19}$$

Furthermore, let

$$\mathbf{n} = (n_{-K_\Delta Q}, \ldots, n_{KQ-1})^{\mathrm{T}} \tag{20}$$

designate an additive white Gaussian noise (AWGN) vector. The received signal is given by

$$\mathbf{r}^{(k)} = \mathbf{s}^{(k)} * \mathbf{h}^{(k)} + \mathbf{n}. \tag{21}$$

At the IFDMA demodulator, for each user the user specific rotation is reversed and the chips that belong to one data symbol $d_q^{(k)}$, $q = 0, \ldots, Q-1$, are added up. According to [1] the elements of the demodulated IFDMA signal vector denoted as

$$\boldsymbol{\rho}^{(k)} = (\rho_0, \ldots, \rho_{Q-1})^{\mathrm{T}} \tag{22}$$

are given by

$$\rho_q^{(k)} = \frac{1}{\sqrt{K}} \sum_{l=0}^{KQ-1} y_{lQ+q}^{(k)} \cdot e^{-j\frac{2\pi}{QK}lk},\ q = 0, \ldots, Q-1. \tag{23}$$

III. IFDMA as CDMA Variant

In this section, it is shown that IFDMA can be interpreted as a CDMA scheme with frequency domain orthogonal spreading sequences (FDOSS) [10] and interleaving applied to a rotated version of the data vector $\mathbf{d}^{(k)}$.

We consider a CDMA system with K users. Let

$$\mathbf{c}^{(k)} = (c_0^{(k)}, \ldots, c_{K-1}^{(k)})^{\mathrm{T}} \tag{24}$$

designate a CDMA spreading sequence of K elements at chip rate $1/T_c$ and let $\mathbf{C}^{(k)}$ designate a $(KQ{\times}Q)$ CDMA spreading matrix according to

$$\mathbf{C}^{(k)} = \begin{pmatrix} \mathbf{c}^{(k)} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{c}^{(k)} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{c}^{(k)} \end{pmatrix}, \tag{25}$$

where $\mathbf{0}$ is a vector of Q elements equal to zero. It is assumed that the K spreading sequences $\mathbf{c}^{(k)}$ for $k = 0, \ldots, K-1$ are chosen as frequency domain orthogonal spreading sequences with elements

$$c_\eta^{(k)} = \frac{1}{\sqrt{K}} e^{j\frac{2\pi}{K}k\eta};\ \ \eta = 0, \ldots, K-1, \tag{26}$$

where $1/\sqrt{K}$ is a normalization factor. Furthermore, we define a modified data vector denoted as

$$\tilde{\mathbf{d}}^{(k)} = (\tilde{d}_0^{(k)}, \ldots, \tilde{d}_{Q-1}^{(k)})^{\mathrm{T}} \tag{27}$$

with elements

$$\tilde{d}_q^{(k)} = d_q^{(k)} \cdot e^{j\frac{2\pi}{KQ}kq};\quad q = 0, \ldots, Q-1. \tag{28}$$

A CDMA signal at chip rate $1/T_c$ denoted as

$$\tilde{\mathbf{s}}^{(k)} = (\tilde{s}_0^{(k)}, \ldots, \tilde{s}_{KQ-1}^{(k)})^{\mathrm{T}} \tag{29}$$

using frequency domain orthogonal spreading sequences according to Eq. (25) and (26) applied to modified data symbols according to Eq. (28) results in

$$\tilde{\mathbf{s}}^{(k)} = \mathbf{C}^{(k)} \cdot \tilde{\mathbf{d}}^{(k)}. \tag{30}$$

With Eq. (28) and (26) the elements of $\tilde{\mathbf{s}}^{(k)}$ at chip rate $1/T_c$ are given by

$$\begin{aligned} \tilde{s}_n^{(k)} &= c_{n \bmod K}^{(k)} \cdot \tilde{d}_{n \operatorname{div} K}^{(k)} \\ &= \frac{1}{\sqrt{K}} d_{n \operatorname{div} K}^{(k)} \cdot e^{j\frac{2\pi}{KQ}k(Q[n \bmod K]) + [n \operatorname{div} K]}, \end{aligned} \tag{31}$$

where div designates integer division. We define a vector of interleaved chips denoted as

$$\mathbf{s}^{(k)} = (s_0^{(k)}, \ldots, s_{KQ-1}^{(k)})^{\mathrm{T}} \tag{32}$$

with elements

$$s_n^{(k)} = \tilde{s}_{n \operatorname{div} Q + K \cdot (n \bmod Q)}^{(k)}. \tag{33}$$

Thus, using Eq. (31) and (33), the elements of the interleaved chip vector are given by

$$s_n^{(k)} = \frac{1}{\sqrt{K}} d_{n \bmod Q}^{(k)} \cdot e^{j\frac{2\pi}{KQ}kn}. \tag{34}$$

Comparison of Eq. (34) and (17) shows that a CDMA signal with frequency domain orthogonal spreading sequences applied to the modified data symbols of Eq. (28) is equal to an IFDMA signal with $L = K$.

IV. IFDMA as OFDMA Variant

In this section, it is shown that IFDMA can be interpreted as an OFDMA scheme with interleaved subcarrier distribution and DFT precoding [4].

We consider a precoded OFDMA system with KQ subcarriers. Let $\mathbf{P}_{Q\times Q}$ designate an arbitrary precoding matrix and

$$\bar{\mathbf{d}}^{(k)} = (\bar{d}_0^{(k)}, \ldots, \bar{d}_{Q-1}^{(k)})^{\mathrm{T}} \tag{35}$$

designate the vector of precoded data symbols for the k-th user given by

$$\bar{\mathbf{d}}^{(k)} = \mathbf{P}_{Q\times Q} \cdot \mathbf{d}^{(k)}. \tag{36}$$

Let $\mathbf{M}_{KQ\times Q}^{(k)}$ designate an arbitrary mapping matrix with elements $M_{n,q}^{(k)}$ where $q = 0, \ldots, Q-1$ designates the index of the rows and $n = 0, \ldots, KQ-1$ designates the index of the columns. We assume that Q different subcarriers are assigned to each user. The mapping matrix allocates the Q precoded

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data symbols $\bar{d}_q^{(k)}$, $q = 0, \ldots, Q-1$, to the Q subcarriers assigned to the k-th user. Let $\mathbf{IDFT}_{KQ\times KQ}$ designate the $(KQ \times KQ)$ matrix representation of the Inverse Discrete Fourier Transform (IDFT). Thus, an OFDMA signal at chip rate $1/T_c$ denoted as

$$\bar{\mathbf{s}}^{(k)} = (\bar{s}_0^{(k)}, \ldots, \bar{s}_{KQ-1}^{(k)})^{\mathrm{T}} \tag{37}$$

with precoded data can be described by

$$\bar{\mathbf{s}}^{(k)} = \mathbf{IDFT}_{KQ\times KQ} \cdot \mathbf{M}_{KQ\times Q}^{(k)} \cdot \bar{\mathbf{d}}^{(k)} \tag{38}$$

In the following, interleaved subcarrier distribution is assumed. Thus, the elements of the mapping matrix are given by

$$M_{n,q}^{(k)} = \begin{cases} 1 & n = q \cdot K + k \\ 0 & \text{else} \end{cases} \tag{39}$$

Furthermore, the precoding matrix is chosen according to

$$\mathbf{P}_{Q\times Q} = \mathbf{DFT}_{Q\times Q}, \tag{40}$$

where $\mathbf{DFT}_{Q\times Q}$ designates a $(Q\times Q)$ Discrete Fourier Transform (DFT) matrix. Thus, the OFDMA signal of user k with interleaved subcarrier distribution and precoding according to Eq. (40) denoted as

$$\mathbf{s}^{(k)} = (s_0^{(k)}, \ldots, s_{KQ-1}^{(k)})^{\mathrm{T}} \tag{41}$$

is given by

$$\mathbf{s}^{(k)} = \mathbf{IDFT}_{KQ\times KQ} \cdot \mathbf{M}_{KQ\times Q}^{(k)} \cdot \mathbf{DFT}_{Q\times Q} \cdot \mathbf{d}^{(k)}. \tag{42}$$

Let

$$D_q^{(k)} = \frac{1}{\sqrt{Q}} \sum_{\eta=0}^{Q-1} d_\eta^{(k)} \cdot e^{-j\frac{2\pi}{Q}\eta q} \tag{43}$$

designate the Discrete Fourier Transform of the data symbols. Thus, the elements of $\mathbf{s}^{(k)}$ are given by [4]

$$\begin{aligned} s_n^{(k)} &= \frac{1}{\sqrt{KQ}} \sum_{q=0}^{Q-1} D_q^{(k)} \cdot e^{j\frac{2\pi}{KQ}(qK+k)n} \\ &= \frac{1}{\sqrt{K}} \frac{1}{Q} \sum_{\eta=0}^{Q-1} d_\eta^{(k)} \sum_{q=0}^{Q-1} e^{-j\frac{2\pi}{Q}q(\eta-n)} \cdot e^{j\frac{2\pi}{KQ}kn} \end{aligned} \tag{44}$$

As

$$\sum_{\eta=0}^{Q-1} e^{-j\frac{2\pi}{Q}q(\eta-n)} = \begin{cases} Q & \eta = n \bmod Q \\ 0 & \text{else} \end{cases}, \tag{45}$$

Eq. (44) reduces to

$$s_n^{(k)} = \frac{1}{\sqrt{K}} d_{n \bmod Q} \cdot e^{j\frac{2\pi}{KQ}kn}, \tag{46}$$

which is equal to the chips of an IFDMA signal for user k and $L = K$, cf. Eq. (17).

V. Properties of IFDMA

In the following, the properties of IFDMA will be discussed. IFDMA can be understood as both, CDMA variant and OFDMA variant and it combines the advantages of single and multicarrier schemes. As, according to Eq. (17), IFDMA signal generation is given by compression and repetition of a linearly modulated signal and subsequent rotation, the envelope fluctuations for an IFDMA signal for one user are very low which is typical for single carrier signals. Hence, in the uplink low-cost amplifiers can be used in the mobile terminals. Furthermore, IFDMA provides high frequency diversity as it is also typical for single carrier signals, because for IFDMA the subcarriers assigned to one user are spread over the whole bandwidth. At the same time, due to blockwise transmission with guard interval, IFDMA is robust to time synchronization errors if the length of the guard interval T_g is chosen according to

$$T_g > \tau_{max} + \Delta t, \tag{47}$$

where τ_{max} designates the maximum delay of the channel and Δt designates the maximum timing error between the users, which is a typical property of multi carrier signals. For IFDMA user separation is obtained by transmission over mutually orthogonal subcarriers. Thus, orthogonality of the signals of different users is not affected by transmission over time dispersive channels resulting in low computational complexity for user separation, which is also typical for multi carrier signals. However, IFDMA is sensitive to frequency offsets resulting, e.g., from doppler effects or from imperfect carrier synchronization [11]. The robustness of IFDMA to frequency offsets is similar to the robustness of OFDMA [7].

In the following, the computational complexity of an IFDMA system is discussed in terms of complex multiplications (mult.) and divisions (div.), respectively, and compared to OFDMA.

At the transmitter, IFDMA signal generation requires $M_{t,\mathrm{IFDMA}} = KQ$ complex mult. per user that result from the rotation of the KQ IFDMA chips by a user specific rotation factor, cf. Eq. (17). At the IFDMA demodulator the user specific rotation is reversed. Moreover, due to the use of cyclic prefix (CP), low complexity frequency domain equalization is possible. For IFDMA, frequency domain equalization is obtained by a Q-point Fast Fourier Transform (FFT) of the received IFDMA symbols $\rho_q^{(k)}$, $q = 0, \ldots, Q-1$, correction of the resulting Q DFT-domain samples by division of each by a complex number and subsequent Q-point Inverse Fast Fourier Transform (IFFT) [8]. In the following, we assume that for a N-point FFT the number of complex mult. is given by $N \cdot \mathrm{ld}(N)$. Thus, the computational complexity for IFDMA at the receiver results in $M_{r,\mathrm{IFDMA}} = KQ + 2 \cdot Q \cdot \mathrm{ld}(Q)$ complex mult. and $D_{r,\mathrm{IFDMA}} = Q$ complex div. per user.

For OFDMA with arbitrary subcarrier distribution the computational complexity at the transmitter is given by mapping the Q data symbols on Q user specific subcarriers and subsequent KQ-point IFFT. Omitting the computational effort for the mapping which depends on the mapping scheme,

TABLE I: Computational complexity of IFDMA, OFDMA and OFDMA with interleaved subcarriers (I-OFDMA)

	Transmitter	Receiver	
	multiplications	multiplications	divisions
IFDMA	KQ	$KQ + 2 \cdot Q \cdot \mathrm{ld}(Q)$	Q
OFDMA	$KQ \cdot \mathrm{ld}(KQ)$	$KQ \cdot \mathrm{ld}(KQ)$	Q
I-OFDMA	$KQ + Q \cdot \mathrm{ld}(Q)$	$KQ + Q \cdot \mathrm{ld}(Q)$	Q

TABLE II: Different data rates

Q	4	8	16	64	1024
$\frac{R_b}{\text{kbit/s}}$	78	156	313	1250	20000

the number of complex mult. per user for OFDMA at the transmitter is given by $M_{t,\mathrm{OFDMA}} = KQ \cdot \mathrm{ld}(KQ)$. At the receiver, a KQ-point FFT is applied to the received signal. The Q data symbols are corrected by division of each by a complex number. Thus, the computational complexity for OFDMA at the receiver is given by $M_{r,\mathrm{OFDMA}} = KQ \cdot \mathrm{ld}(KQ)$ complex mult. and $D_{r,\mathrm{OFDMA}} = Q$ complex div. per user.

A low complexity implementation for OFDMA with interleaved subcarrier distribution (I-OFDMA) has been presented in [9]. It is equal to IFDMA signal generation according to Eq. (17) with preliminary $(Q \times Q)$-IFFT. The computational complexity at the transmitter is given by $M_{t,\mathrm{I-OFDMA}} = KQ + Q \cdot \mathrm{ld}(Q)$ complex mult. Compared to IFDMA, at the receiver the $(Q \times Q)$-FFT of the frequency domain equalizer can be omitted. Thus, for OFDMA with interleaved subcarrier distribution the computational complexity at the receiver is given by $M_{r,\mathrm{I-OFDMA}} = KQ + Q \cdot \mathrm{ld}(Q)$ complex mult. and $D_{r,\mathrm{I-OFDMA}} = Q$ complex div. per user. The numbers of complex mult. and div. are summarized in Table I. It shows that at the transmitter, IFDMA provides the lowest computational complexity. The overall complexity of an IFDMA system combining transmitter and receiver is equal to the complexity of OFDMA with interleaved subcarrier distribution and lower compared to OFDMA with arbitrary subcarrier distribution for parameter choices relevant for practical system design.

VI. Coded Performance

In Fig. 4 simulation results for coded IFDMA transmission over a mobile radio channel are presented for different data rates. The simulation parameters are given in Table III. Different data rates can be accommodated by different numbers Q of data symbols transmitted per IFDMA block. The different data rates dependent on Q are given in Table II, where R_b designates the net bit rate. For high data rates a high number of subcarriers is assigned to each user and hence, high frequency diversity is provided. It can be observed that the lower the data rate, the higher the gain achievable by an increase of Q.

VII. Conclusion

In this paper, the spectral characteristics of IFDMA have been discussed based on a continuous time signal model. Based on a discrete time signal model, it has been shown that IFDMA can be regarded as OFDMA and also as CDMA variant. It combines the advantages of both, single and multicarrier schemes. Due to its various advantages, such as low envelope fluctuations, high frequency diversity, robustness to time offsets, low computational complexity for user separation and equalization and its good coded performance for transmission over a mobile radio channel IFDMA is a promising candidate for future mobile radio systems.

TABLE III: Simulation parameters

Carrier frequency	5 GHz	Decoder	MaxLogMAP
Bandwidth	20 MHz	Equalizer	MMSE FDE
No. of subcarriers	1024	Interleaving	Random
Modulation	QPSK	Interl. depth	0.5 ms
Code	Conv. Code	Guard interval	7 μs
Code rate	$1/2$	Channel	COST 207
Constraint length	6		TU, 70 km/h

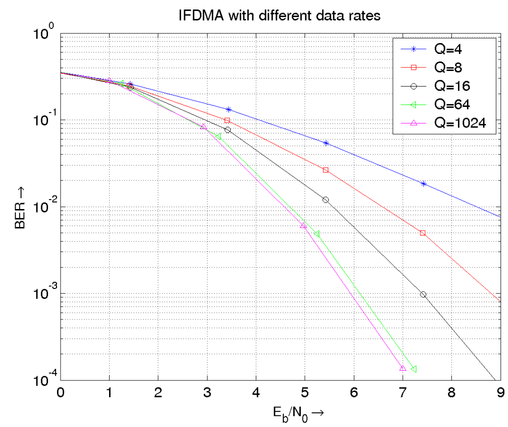

Fig. 4: Coded performance for IFDMA with different Data rates

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