IFDMA - A scheme combining the advantages of OFDMA and CDMA

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***Abstract*— Future mobile radio systems have to fulfill challenging requirements. Some of them are met by single carrier based multiple access (MA) schemes like CDMA and others by multi carrier based MA schemes like OFDMA. Thus, MA schemes integrating the characteristics of both are receiving more and more interest. In this article, candidate MA schemes based on the idea of integration are summarized and classified using a new framework. Moreover, Interleaved Frequency Division Multiple Access (IFDMA) is shown to be a scheme that combines the advantages of both, CDMA and OFDMA, and is a promising candidate MA scheme especially for non-adaptive transmission in the uplink of future mobile radio systems.**

I. INTRODUCTION

Currently, research on beyond 3rd and 4th generation (B3G/4G) mobile radio systems is in progress worldwide. A future mobile radio system will provide packet oriented data services carrying multi-media contents. Thus, on the one hand, properties like high spectral efficiency as well as high flexibility and granularity in terms of different data rates from a few kbit/s up to several Mbit/s are essential. On the other hand, low cost implementation and high power efficiency are important, especially for mobile terminals. Moreover, high user mobility has to be taken into account [1]. The choice of the multiple access (MA) scheme has a great impact on the achievable features of a future cellular mobile radio system [2]. The candidate MA schemes can be classified in single carrier based and multi carrier based MA schemes.

Prominent representatives of single carrier based MA schemes are Time Division Multiple Access (TDMA), which is used in 2nd generation (2G) mobile radio systems like the Global System for Mobile Communications (GSM), and Direct Sequence Code Division Multiple Access (DS-CDMA), which is used in 2G mobile radio system like IS-95 as well as in 3rd generation (3G) mobile radio systems like IMT-2000/UMTS. Typically, single carrier based MA schemes provide low complexity for signal generation and, for the uplink, low envelope fluctuations of the transmit signal. DS-CDMA and TDMA provide high frequency diversity since a large bandwidth is used for transmission. However, especially for high data rates, single carrier based MA schemes suffer from high computational complexity at the receiver for channel equalization [3] or, in case of DS-CDMA, user separation [4].

Recently, also multi carrier based MA schemes have been receiving wide interest. The most prominent multi carrier scheme, Orthogonal Frequency Division Multiplexing (OFDM), and its MA derivate Orthogonal Frequency Division Multiple Access (OFDMA) [5], are currently used, e.g., in WLAN standards HIPERLAN/2 and IEEE802.11a, and they are also key technologies of IEEE802.16e (WIMAX) and 3GPP LTE [6]. Moreover, they are considered as promising schemes, e.g., in the European Union research project WINNER [1]. For multi carrier based MA schemes like OFDMA, Inter-Symbol Interference (ISI) can be avoided by application of a guard interval and orthogonality of different users' signals is maintained even for transmission over time dispersive channels. Thus, low computational effort at the receiver for compensation of the channel and for user separation is achieved which enables high data rate transmission with acceptable computational effort. Moreover, OFDMA provides low computational complexity due to efficient implementation using the Fast Fourier Transform (FFT) algorithm and high spectral efficiency due to the concept of overlapping but mutually orthogonal narrowband subcarriers. However, multi carrier based MA schemes suffer from high envelope fluctuations of the transmit signals [7]. Thus, expensive linear power amplifiers are required which, especially for the uplink, results in undesirable additional costs for the mobile terminals. Moreover, due to the high envelope fluctuations, a power back-off is necessary which reduces the power efficiency of the amplifier and results in a waste of battery power [8]. A reduction of the envelope fluctuations can be obtained by techniques like clipping, windowing or coding at the expense of additional implementation effort, out of band radiation or additional overhead [7].

Further interesting MA schemes can be obtained from the combination of techniques from single and multi carrier transmission. One concept is the combination of multi carrier modulation and spread spectrum techniques [9] that results in Multi-Carrier CDMA (MC-CDMA). Another concept is the application of block transmission with cyclic prefix (CP), which is common for OFDM(A), also to single carrier based MA schemes [3]. It enables the combination of properties of multi carrier based MA schemes like low complexity for user separation and channel equalization and properties of single carrier based MA schemes like low envelope fluctuations.

In the remainder of this article, in a first step, different multiple access schemes based on a combination of techniques from single and multi carrier transmission are briefly summarized and classified using a new framework. In a second step, a promising MA scheme which entirely combines the

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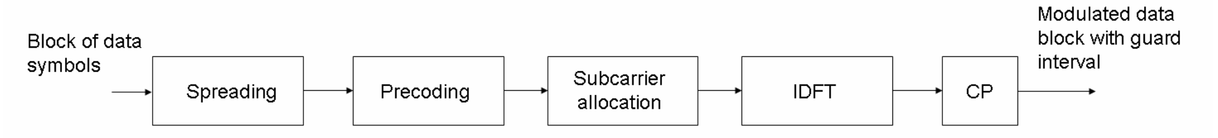
TABLE I: Overview over block transmission based multiple access schemes

	Spreading	Precoding	Subcarrier Allocation	Multiple Access
OFDMA	-	-	arbitrary	FDMA
B-OFDMA	-	-	blockwise	FDMA
I-OFDMA	-	-	interleaved	FDMA
MC-(DS-)CDMA	Walsh-Hadamard	-	full bandwidth	CDMA
Block transmission DS-CDMA	Walsh-Hadamard	DFT	full bandwidth	CDMA
IFDMA	-	DFT	interleaved	FDMA
	FDOSS	DFT	full bandwidth	CDMA
VSCRF-CDMA	Walsh-Hadamard	DFT	interleaved	CDMA+FDMA
LFDMA	-	DFT	blockwise	FDMA



advantages of CDMA and OFDMA is discussed in detail. The scheme has been introduced in [10] as Interleaved Frequency Division Multiple Access (IFDMA). Throughout this article, IFDMA is derived from a CDMA perspective as well as from an OFDMA perspective and the properties of the scheme and its applicability for B3G mobile radio systems are discussed.

II. INTEGRATION OF SINGLE CARRIER AND MULTI CARRIER CHARACTERISTICS

Since both, single and multi carrier based MA schemes, provide interesting advantages, the integration of characteristics of both is receiving more and more interest for investigation towards B3G/4G mobile radio systems. The schemes discussed throughout this section which are all based on block transmission with CP, are classified using a new framework. It is assumed that, in general, the schemes can be described by an arbitrary spreading operation, a precoding operation, a specific subcarrier allocation and subsequent OFDM modulation performed by an inverse Discrete Fourier Transform (IDFT) followed by insertion of a CP as guard interval. The resulting scheme depends on the type of spreading, precoding and subcarrier allocation that is used. The different schemes are summarized in Table I. E.g. conventional OFDMA uses no spreading and no precoding. The subcarrier allocation may be arbitrary, or blockwise leading to B-OFDMA, or interleaved leading to I-OFDMA.

The combination of multi carrier modulation and spreading, e.g., using Walsh-Hadamard codes, results in MC-CDMA. In general, MC-CDMA provides high spectral efficiency and high flexibility. For synchronized downlink transmission, low computational complexity is provided since, similar to OFDMA, ISI and Inter-Carrier-Interference (ICI) can be avoided [9]. MC-CDMA with spreading in time direction (MC-DS-CDMA) provides lower envelope fluctuations compared to OFDMA [9]. However, since users are separated by codes, in the uplink MC-DS-CDMA and MC-CDMA suffer from high computational effort for user separation. For further details of the scheme we refer to [9] and references therein.

Application of block transmission with cyclic prefix (CP) to single carrier based MA schemes enables low complexity equalization using a one-tap frequency domain equalizer (FDE) [11] also for single carrier based MA schemes. However, as long as the users are separated by codes like, e.g., Walsh-Hadamard, in the uplink the orthogonality of different users' signals is lost due to multipath propagation and, thus, high computational effort for user separation at the receiver is required.

In the sequel, a promising block transmission scheme with CP that is robust to multipath propagation and, therefore, provides low computational complexity at the receiver, even for uplink transmission, is discussed. The scheme has been described under several names: It has been denoted Interleaved Frequency Division Multiple Access (IFDMA) in [10], OFDM-FDMA in [12] and CDMA using FDOSS in [13]. A combination of IFDMA and CDMA with Walsh-Hadamard spreading is denoted Variable Spreading and Chip Repetition Factor (VSRF-) CDMA [14]. IFDMA can be derived from a DS-CDMA perspective by replacing the conventional spreading sequences like Walsh-Hadamard or Gold sequences by Frequency Domain Orthogonal Signature Sequences (FDOSS). At the same time, it can be derived from an OFDMA perspective by introduction of an interleaved subcarrier allocation and unitary precoding with a Discrete Fourier Transform (DFT). As a scheme that can be regarded as both, single carrier based and multi carrier based MA scheme, IFDMA benefits from the advantages of both. Besides low envelope fluctuations of the transmit signal and low computational complexity for equalization and user separation, IFDMA provides an efficient implementation at the transmitter which has an even lower complexity than a transmitter for OFDM(A). Moreover, due to spreading of the data over the total available bandwidth, IFDMA provides high frequency diversity and, thus, good spectral efficiency even without channel state information at the transmitter.

Another scheme resulting from application of DFT precoding to B-OFDMA is denoted localized FDMA (LFDMA) [6], [15]. Similar to IFDMA, LFDMA also provides low envelope fluctuations of the transmit signal and low complexity for user separation and equalization, even for uplink transmission.

However, since LFDMA provides low frequency diversity, high spectral efficiency has to be obtained by exploitation of multi-user diversity by adaptive multi-user scheduling. Thus, in order to provide good performance, LFDMA requires channel state information at the transmitter.

Currently, IFDMA as well as LFDMA are investigated in 3GPP LTE and WINNER as promising candidates for the uplink and for robust signalling [1], [6].

III. IFDMA AND ITS RELATION TO CDMA AND OFDMA

In this section, IFDMA is derived from conventional DS-CDMA and the properties and the implementation are initially discussed. Further on, IFDMA is derived from an OFDMA perspective.

In a first step, a block transmission system with consecutive modulated data blocks separated by CP is assumed. It is well known that application of block transmission with CP over a time dispersive channel can be modelled as transmission over a channel with circulant channel matrix [3], [16]. In frequency domain, the circulant channel matrix can be expressed as a diagonal matrix which can be easily compensated at the receiver by a linear one-tap FDE [11].

Within each data block, we assume a DS-CDMA signal resulting from spreading of a block of modulated data symbols, each multiplied with the elements of an arbitrary spreading sequence. Application of conventional spreading codes like Walsh Hadamard or Gold codes results in a block transmission CDMA signal with properties similar to those of continuous transmission DS-CDMA as used, e.g., in UMTS. Since the orthogonality of Walsh Hadamard or Gold codes is affected by multipath propagation, especially in the uplink, high computational effort has to be spent for Multiple Access Interference (MAI) cancellation and user separation.

In [13] a set of Frequency Domain Orthogonal Signature Sequences (FDOSS) has been proposed which maintains the orthogonality of different users' signals even for transmission over multipath channels. The FDOSS consist of complex exponentials similar to the complex rotation factors of the DFT. For further details of FDOSS we refer to [13]. A scheme using block transmission and CDMA with FDOSS thus provides low computational complexity for equalization due to the applicability of a one-tap FDE and low complexity for user separation since the orthogonality of different user's signals is maintained. At the same time, the envelope fluctuations of the signal are in the same order of magnitude as for CDMA since the elements of the FDOSS have an amplitude equal to one.

An efficient implementation of the scheme can be obtained by modification of the block transmission CDMA signal with FDOSS according to Fig. 1, without affecting the signal properties. The additional phase rotation and the chip interleaving results in a signal which can be obtained from compression of the input data symbols from symbol duration T_s to chip duration $T_c = T_s/K$ for a spreading factor K. Subsequently, the compressed data symbol block is K-times repeated and, finally, the compressed and repeated data symbol block is multiplied elementwise by the complex exponentials. Thus, signal generation can be summarized by compression, repetition and subsequent phase rotation of each data symbol block, cf. [17]. The efficient implementation of block transmission CDMA with FDOSS is well known as IFDMA [10].

The same scheme can be also derived from an OFDMA perspective. For that purpose a conventional OFDMA scheme, which provides the same block structure with CP as assumed above, is considered. Equidistantly interleaved subcarrier mapping is applied in order to spread the signal over the total available bandwidth which results in high frequency diversity.

In order to obtain single carrier like properties for an OFDM(A) signal, before modulation a DFT operation can be applied to the data symbols [12]. Thus, compared to a conventional OFDM(A) system, each carrier of a user specific set of equidistantly interleaved subcarriers carries the elements of the DFT of a set of data symbols instead of the data symbols themselves.

An efficient implementation of DFT precoded interleaved OFDMA can be performed in time domain. It can be shown that the combination of DFT precoding, interleaved subcarrier mapping and OFDMA modulation yields the same compression, repetition and phase rotation operation as described for the efficient implementation of block transmission CDMA with FDOSS [18]. From an OFDMA perspective, the user specific phase rotation can be interpreted as a shift of a set of interleaved subcarriers to a user specific position in frequency domain. Thus, IFDMA is a scheme which is equivalent, on the one hand, to DFT precoded interleaved OFDMA and, on the other hand, to block transmission CDMA with FDOSS and chip interleaving.

IV. PROPERTIES OF IFDMA

In this section, the properties of IFDMA are discussed and the scheme is compared to other single and multi carrier based MA schemes.

A. Computational Complexity

As already discussed, IFDMA signal generation is given by compression in time by a factor K and subsequent K-fold repetition of a given block of data symbols followed by a phase rotation. Thus, the computational complexity at the transmitter is very low. Assuming that each of the compressed and repeated data symbols within one block has to be multiplied by one complex exponential and assuming that each data block consists of Q data symbols which are repeated K times, the computational effort for IFDMA at the transmitter is given by $N = Q \cdot K$ complex multiplications.

For CDMA, the effort for signal generation is also very low since typically the spreading sequences consist of elements +1 and -1. However, the difference between the signal processing effort at the transmitter for IFDMA and conventional CDMA is small.

From an OFDMA perspective, N can be also interpreted as the number of subcarriers available in the system. Conventional OFDMA modulation can be implemented by a user specific subcarrier allocation followed by a Inverse N-point DFT. Thus, for conventional OFDMA, omitting the effort for subcarrier allocation, the complexity for signal generation at

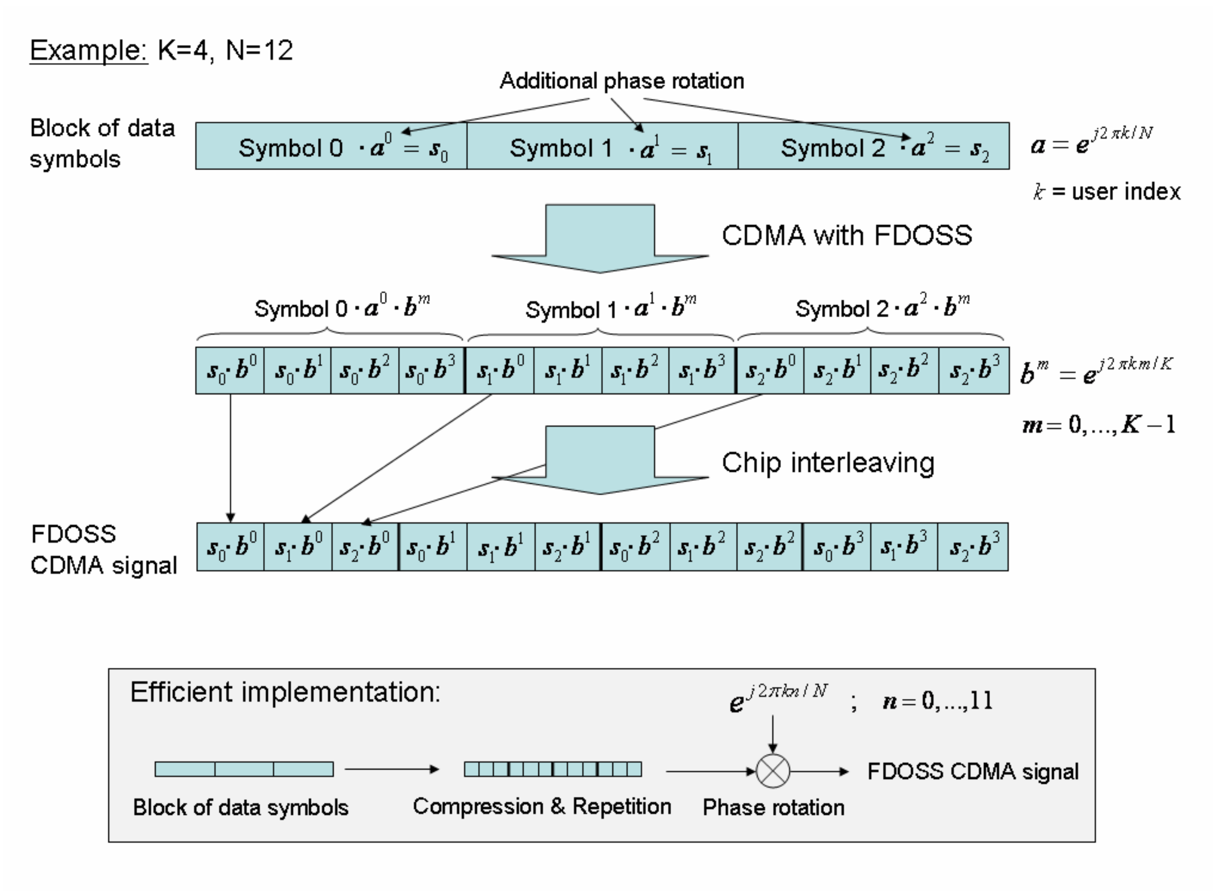


Fig. 1: IFDMA signal generation based on FDOSS CDMA

the transmitter is given by the computational effort required for an N-point IDFT. If N is chosen as a power of 2 and the Inverse Fast Fourier Transform (IFFT) algorithm is used, the required effort for an N-point IDFT is $1/2 \cdot N \cdot \mathrm{ld}(N)$ complex multiplications.

Thus, compared to OFDMA, the signal processing effort at the transmitter for IFDMA is slightly lower. However, OFDMA can be already regarded as low complex.

The receiver structure for IFDMA in the uplink is typically based on the fact that IFDMA can be regarded as DFT precoded OFDMA. Thus, the receiver consists of OFDMA demodulation, subcarrier demapping, FDE and subsequent inversion of the DFT precoding by an IDFT operation. Thus, compared to conventional OFDMA, IFDMA requires one additional Q-point IDFT per user which is unproblematic in the uplink.

Compared to CDMA, the computational effort for IFDMA and OFDMA is significantly lower since due to the robustness to multipath propagation for IFDMA and OFDMA user separation is obtained by the demapping operation whereas for CDMA in the uplink a high computational effort for user separation and interference cancellation is required. Especially for high cell loads, this is a major drawback of CDMA.

B. PAPR

Since IFDMA can be regarded as a CDMA variant and since the elements of the FDOSS have amplitude 1, the PAPR of IFDMA is similar to the PAPR of CDMA. It is solely determined by the modulus of the mapping scheme which maps data bits to data symbols and by the pulse shaping. E.g., for rectangular pulse shaping and using Phase Shift Keying (PSK) a constant envelope is obtained.

Regarding the 99.9-percentile and taking realistic pulse shaping into account, for QPSK IFDMA provides a PAPR which is more than 6 dB lower than the PAPR for OFDMA [15]. Even for 64QAM IFDMA provides a PAPR which is more than 3 dB lower than the PAPR for OFDMA, cf. [15].

For LFDMA, which is a DFT precoded OFDMA scheme with blockwise subcarrier allocation, also a lower PAPR compared to OFDMA is expected. However, a comparison of the PAPR of LFDMA and IFDMA with realistic pulse shaping shows that the PAPR of IFDMA is more than 3 dB lower than the PAPR for LFDMA for QPSK and still more than 1 dB lower for 64QAM. [15].

Thus, even for realistic pulse shaping, IFDMA provides a significantly lower PAPR than OFDMA and LFDMA. The effect is reduced but still significant also for higher modulation order such as 64QAM [15].

Due to the low PAPR for IFDMA a cheaper power amplifier can be used and, thus, the cost for the mobile terminals can be reduced. Moreover, the required power back-off is lower and, thus, the power consumption at the transmitter is reduced which is an important property especially for mobile terminals.

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C. Flexibility

It has been shown that IFDMA requires a specific regularly interleaved subcarrier allocation. Moreover, for a given Modulation Coding Scheme (MCS) the data rate depends on the number of subcarriers assigned to each user. Thus, accommodation of different data rates within one cell means co-existence of users with different numbers of subcarriers per user which all have to be regularly interleaved. In this context the question arises how to support transmission with different data rates within one cell while keeping the interleaved subcarrier allocation for all users without destroying orthogonality of different users' signals, on the one hand, and without waste of resources due to not occupied subcarriers on the other hand.

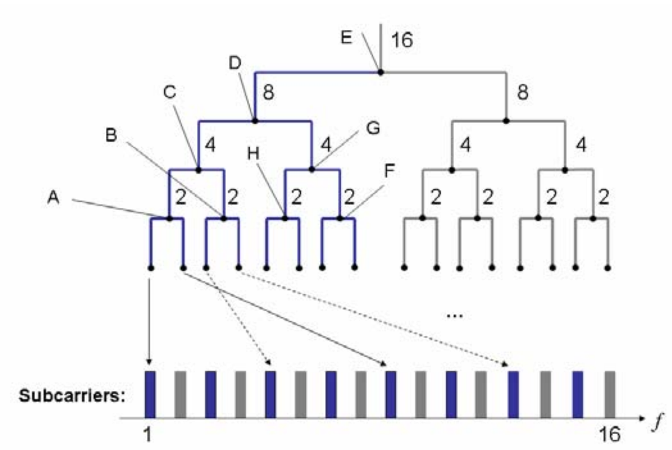

Fig. 2: Tree structure for accommodation of different data rates for IFDMA

This problem is addressed in [19]. It is shown that, similar to Orthogonal Variable Spreading Factor (OVSF) Codes which are well known for CDMA, also for IFDMA a tree structure can be used for assignment of the subcarriers avoiding MAI. The tree structure is depicted in Fig. 2 for an example of $N = 16$ subcarriers. Each tail of a branch is one-to-one assigned to a specific subcarrier. The assignment is done such that all tails originating from the same node are assigned to an equidistantly interleaved set of subcarriers. E.g., the two tails originating from node A as well as the two nodes originating from node B are mapped to a set of three equidistant subcarriers. At the same time, the 4 tails originating from node C are mapped to a set of 4 equidistant subcarriers.

Using this tree structure, the subcarrier allocation can be obtained by assigning one node of the tree to a specific user. The rules for assignment of nodes within one cell are simple:

- Different nodes have to be assigned to different users.
- When a node is assigned to a specific user, all nodes of the branch originating from this node are occupied.
- Additionally, all nodes where the assigned node is originating from are occupied.
- Only the nodes that are not occupied can be assigned to other users.

E.g., when node C is assigned to a specific user, node A and node B as well as node D and E are occupied. Node F, e.g., could be assigned to a second user. When in addition to node C, also node F is assigned, node G and again node D are occupied. Hence, node H and all nodes in the branch in the right originating from node E are not occupied and, thus, could be assigned to other users.

Since each node corresponds to a certain number of subcarriers, assignment of a node according to the above given rules guarantees interleaved subcarrier allocation for all users as well as orthogonality of different users' signals even for different data rate requests of different users. Moreover, resources can be assigned as long as the requested data rate fits to the number of unused resources. Thus, no resources are wasted.

Since, in general, the number of subcarriers within one system is high, sufficient flexibility and granularity in terms of different data rates is provided. The maximum granularity is given for a total number of subcarriers chosen as a power of 2. In this case, the tree structure is equivalent to the tree for OVSF codes. However, it is also possible to choose another total number of subcarriers as long as this number is not prime [19]. Note that, if higher granularity in terms of data rates than provided by the accommodation of numbers of subcarriers which are a power of 2 is required, puncturing or different combinations of modulation and coding schemes can be used. For further details of the presented scheme we refer to [19].

Thus, although the advantages of IFDMA such as low computational complexity and low PAPR are obtained at the expense of a reduced flexibility compared to conventional OFDMA with arbitrary subcarrier allocation, the flexibility and granularity in terms of different data rates is sufficient for mobile radio applications since for higher granularity also the effort of required signalling overhead increases.

D. Performance

The coded performance of IFDMA with FDE is similar to the performance of coded OFDMA with interleaved subcarrier allocation [3]. Since for IFDMA the subcarriers are equidistantly interleaved over the total available bandwidth, IFDMA provides a high amount of frequency diversity and, thus, a significant performance gain compared to LFDMA and OFDMA with block allocation (B-OFDMA). The lower the number of subcarriers assigned to a specific user the higher the performance gain since transmission in LFDMA and B-OFDMA is localized on a restricted portion of bandwidth whereas for IFDMA the signal is spread over the whole available bandwidth. However, in the case, where only one subcarrier is assigned both schemes are identical. For a given Modulation and Coding Scheme (MCS), a lower number of subcarrier assigned is equivalent to a lower data rate. Thus, except for the assignment of one subcarrier per user, the diversity gains of IFDMA compared to LFDMA increase with decreasing data rates.

For LFDMA and B-OFDMA the frequency diversity can be increased by means of frequency hopping (FH) of the blocks of subcarriers assigned to each user per OFDM symbol and applying coding and bit interleaving over several consecutive OFDM symbols.

In Figs. 3 and 4 the performance of IFDMA is compared to the performance of LFDMA, LFDMA with FH and OFDMA with interleaved subcarrier allocation for different data rates

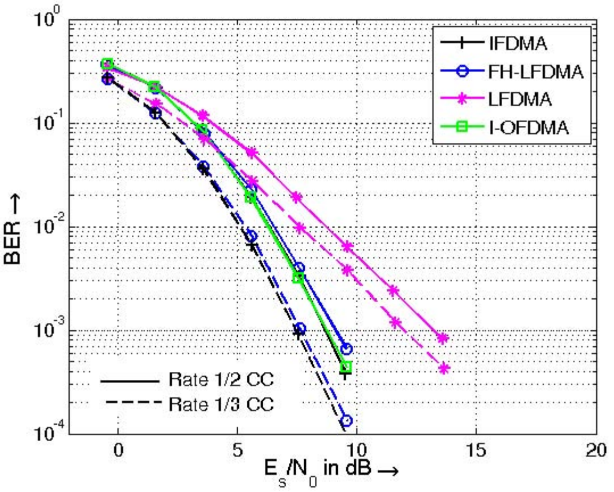

Fig. 3: Bit error performance at 5 Mbit/s

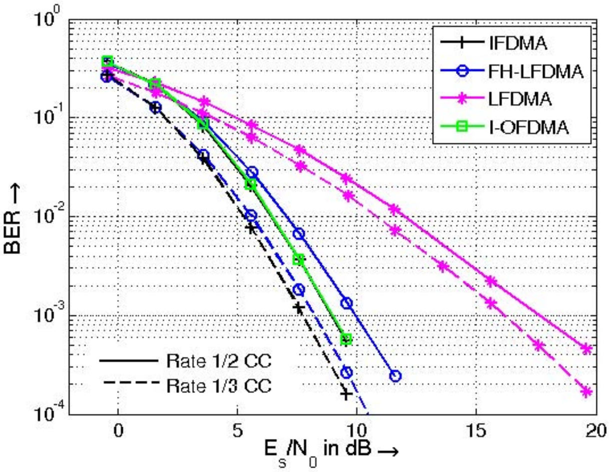

Fig. 4: Bit error performance at 1.25 Mbit/s

in a typical wide area mobile radio scenario with parameters according to Table II.

From Figs. 3 and 4 it follows that for a net bit rate of 1.25 Mbit/s (5 Mbit/s) IFDMA provides a performance gain of 0.9 dB (0.5 dB) compared to LFDMA with FH and a performance gain of 8.6 dB (4.7 dB) compared to LFDMA without FH at a Bit Error Rate (BER) of 10^{-3}. In presence of spatial diversity due to application of multiple antennas and Space-Time Coding (STC) the performance gain of IFDMA with respect to LFDMA is reduced but is still considerable [21].

In the following, the losses due to pilot symbol overhead for channel estimation are briefly discussed. Assuming pilot assisted channel estimation, due to its interleaved subcarrier allocation, for IFDMA the possibility to interpolate between pilot symbols in frequency direction is restricted. As soon as the distance between two subcarriers exceeds the coherence bandwidth, i.e., especially for moderate to low data rates, IFDMA requires one pilot symbol per subcarrier. For LFDMA, instead, interpolation in frequency direction between the pilot symbols is possible. Thus, for LFDMA only a few pilot symbols per coherence bandwidth are required. However, as long as the duration of one modulated block with CP is small compared to the coherence time, interpolation in time is possible for both LFDMA and IFDMA. The pilot symbol overhead can be expressed as amount of energy that has to be additionally spent for transmission of each information bit. In other words, due to the pilot symbol overhead a higher amount of energy per bit is required in order to achieve the same Bit Error Rate as without overhead. This additionally required amount of energy per bit can be directly compared to the performance gains of IFDMA due to higher frequency diversity [22] and, taking both aspects into account, an overall gain can be deduced.

TABLE II: Simulation parameters

Carrier frequency	5 GHz	Decoder	MaxLogMAP
Bandwidth	20 MHz	Equalizer	MMSE FDE
No. of subcarriers	512	Interleaving	Random
Modulation	QPSK	Interl. depth	0.3 ms
Code	Conv. Code	Guard interval	5 μs
Code rate	$1/2$, $1/3$	Channel	WINNER [20] Urban, 70 km/h
Constraint length	6		

Due to the interpolation in time, for the parameters given in Table II the additionally required amount of energy per bitdue to pilot symbol overhead for channel estimation is smaller than the frequency diversity gains. The overall performance gain of IFDMA compared to LFDMA for 1.25 Mbit/s (5 Mbit/s) results in 8.3 dB (4.4 dB) at a BER of 10^{-3}. Note that, considering realistic channel estimation, for LFDMA an additional performance degradation due to the interpolation error in frequency direction compared to IFDMA has to be expected. For LFDMA with frequency hopping for moderate to low data rates interpolation in time is not possible any longer due to the frequency hopping period of one OFDM symbol. Thus, for moderate to low data rates the pilot symbol overhead is higher than for IFDMA. The overall performance gain of IFDMA compared to LFDMA with FH at a BER of 10^{-3} for 1.25 Mbit/s (5 Mbit/s) is increased to 3.5 dB (3.1 dB).

FH could be also applied to IFDMA in order to provide inter-cell interference averaging. In this case, in a multi-cell scenario the performance is expected to be improved at the expense of an improved pilot symbol overhead.

IFDMA has been shown to provide a significant overall performance gain compared to LFDMA although it requires a higher pilot symbol overhead for channel estimation.

E. Sensitivity to Frequency Offsets

So far, IFDMA has been shown to provide many advantages. However, due to the interleaved subcarrier allocation, similar to OFDMA with interleaved subcarriers, IFDMA is sensitive to frequency offsets in that the inter-carrier interference turns into Multiple Access Interference since adjacent subcarriers belong to different users [17]. Compared to LFDMA or B-OFDMA the sensitivity to frequency offsets is expected to be higher since in case of IFDMA, for each subcarrier the number of interfering neighboring subcarriers is higher. Typically, frequency offsets result mainly from Doppler shifts or oscillator imperfections. For the parameters given in Table II, but for a velocity of 250 km/h, the maximum Doppler

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shift, which only occurs when the user moves with an angle of 0° towards the base station, is smaller than 3% of the subcarrier bandwidth. Thus, the effect of Doppler shifts in the given scenario can be considered as small for the majority of the users. For a carrier frequency of 5 GHz, oscillator imperfections of 1ppm result in a frequency offset of 13% of the subcarrier bandwidth. However, frequency offsets due to oscillator imperfections are expected to change very slowly. Thus, using appropriate synchronization algorithms [23] the offsets can be estimated at the base station and reported to the mobile station at the expense of low signalling overhead. As soon as the frequency offset is known at the mobile station it can be easily corrected by insertion of a correction term in the phase rotation of the IFDMA transmitter.

F. Spatial Diversity

The application of multiple antennas and space time coding has been shown to provide large performance and capacity gains for wireless mobile radio applications. In the context of this article the question arises if it is possible to utilize multiple antennas and space time coding also for IFDMA in a way that the low PAPR for the signals at each transmit antenna is maintained and at the same time spatial diversity can be exploited. In [24] a method for application of Space Time Block Codes (STBCs) from orthogonal or quasi orthogonal design to single carrier block transmission schemes has been introduced. The applicability of the scheme to IFDMA as well as to LFDMA is discussed in [21]. The scheme is based on the application of a double DFT operation before IFDMA modulation and Space Time Block Coding. Since the double DFT can be implemented by a simple permutation of the elements of the data symbols within each block [24], application of STBCs from orthogonal or quasi orthogonal design requires negligible additional signal processing effort at the transmitter. At the same time, the low PAPR of the signals at each transmit antenna is maintained. In [21] the scheme for application of STBCs to IFDMA from [24] is shown to provide additional spatial diversity gains. Comparison of IFDMA and LFDMA shows that LFDMA can benefit more from the additional spatial diversity than IFDMA. However, even when Alamouti Space Time Coding IFDMA still considerably outperforms LFDMA due to the higher frequency diversity gains of IFDMA.

In [25], a simple Space Time Trellis Code denoted as Cyclic Delay Diversity (CDD) is introduced for multi carrier systems with cyclic prefix. In [26] the applicability to IFDMA and LFDMA is discussed. For application of CDD to IFDMA also the low PAPR property for the signals at each transmit antenna is maintained and the scheme can be implemented with marginal additional signal processing effort at transmitter and receiver In [26]. However, the spatial diversity gains for CDD are smaller than for orthogonal STBCs.

Thus, applying CDD and applying STBC, respectively, to IFDMA, spatial diversity can be exploited with only low additional signal processing effort. At the same time the low PAPR property for the signals at each transmit antenna is maintained.

V. IFDMA AND ITS APPLICATION TO B3G MOBILE RADIO SYSTEMS

In the previous sections, it has been shown that IFDMA combines many advantages of single and multi carrier based MA schmemes. Due to its properties, basically due to the low complexity especially at the transmitter side, the low PAPR of the transmit signal, the good power efficiency, IFDMA is a well suited candidate especially for the uplink of a B3G mobile radio system. Moreover, the high frequency diversity gains and the resulting good performance enable an extension of the coverage. Thus, IFDMA is an appropriate scheme also for wide area scenarios. For transmission based on high adaptivity using adaptive modulation and adaptive multi-user scheduling in order to exploit multi user diversity, an OFDMA scheme with blockwise subcarrier allocation would be preferred [1]. However, adaptive modulation and multi user scheduling requires reliable channel knowledge at the transmitter which in many cases is not available, e.g., due to high user velocities or bad Signal-to-Interference-and-Noise Ratio (SINR). Since IFDMA is based on the exploitation of diversity by mitigation of the channel variations by means of averaging, it provides good performance without channel knowledge at the transmitter and thus, is well qualified for a non-adaptive transmission mode [1]. Due to its block transmission characteristic with CP also co-existence of IFDMA and adaptive OFDMA in one system is possible [1].

VI. CONCLUSION

In this article, based on a new framework, different promising candidate MA schemes for future wireless communication systems have been classified and summarized, that combine characteristics of single and multi carrier based MA schemes. It has been shown that IFDMA, which can be regarded a CDMA variant as well as an OFDMA variant, combines the advantages of CDMA, namely low complexity for signal generation, low PAPR and high frequency diversity, and the advantages of OFDMA, namely low complexity for user separation and channel equalization. At the same time, it provides sufficient robustness and flexibility in terms of different data rates. Moreover, multiple antenna techniques exploiting spatial diversity can be easily applied to IFDMA. Since IFDMA does not require any channel state information at the transmitter, it is a promising candidate MA scheme, especially for non-adaptive transmission in the uplink of B3G/4G mobile radio systems.

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