B-IFDMA - A Power Efficient Multiple Access Scheme for Non-frequency-adaptive Transmission

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Abstract— **Within the EU FP6 Integrated Projects WINNER and WINNER II, multiple access schemes for frequency-adaptive and non-frequency-adaptive transmission for a future broadband mobile wireless system are investigated. This paper presents a novel power efficient multiple access scheme for non-frequency-adaptive uplink transmission denoted Block Interleaved Frequency Division Multiple Access (B-IFDMA), which provides large frequency-diversity, potential power savings by user terminal sleep mode, modest high power amplifier backoff and robustness to frequency-offsets, and phase noise.**

I. Introduction

In the WINNER system concept, resources are allocated based on a chunk concept [1]. A chunk is a time-frequency unit, that is chosen in such a way that it experiences essentially flat fading in its time-frequency extent also in largely frequency selective channels and for users at vehicular speeds. Spatial reuse of these resources are denoted chunk layers. Frequency-adaptive transmission that adapts to the individual small-scale fading of these resources enables a large increase in the system capacity due to the gains in multi-user scheduling and chunk-wise link adaptation, which could be very important for high cell load situations [1], [2].

With non-frequency-adaptive allocation, bits from each flow are allocated onto sets of chunks and/or chunk layers that are dispersed in frequency and/or space. Forward Error Correction (FEC) coding and interleaving collect the diversity and are used to combat the small-scale frequency selective fading. Link adaptation may be performed with respect to shadow fading, but not with respect to frequency-selective fading, but the resource scheduling is fast both for frequency-adaptive and non-frequency-adaptive flows, with around 1 ms minimum delay over the radio interface [1].

Thus, a non-frequency-adaptive transmission mode offers a robust option for scheduled flows, and is required as a fallback solution for frequency-adaptive transmission, since frequency-adaptive transmission becomes less reliable below a certain SINR threshold and above a certain user terminal velocity [2]. Non-frequency-adaptive transmission is also required for control signalling and is assumed for point-to-multipoint transmission in multicasting and broadcasting support [3].

In WINNER II, various DFT precoded time-frequency multiple access schemes for the non-frequency-adaptive uplink have been evaluated [3] as power efficient candidates due to their low signal envelope fluctuation property. The insights gained by these investigations lead to the multiple access scheme proposal presented in this paper denoted Block-Interleaved Frequency Division Multiple Access (B-IFDMA) for the non-frequency-adaptive uplink, and it is a generalization of DFT precoded OFDMA with interleaved subcarrier allocation, also denoted Interleaved Frequency Division Multiple Access (IFDMA) [4].

B-IFDMA allocates equidistant blocks containing adjacent subcarriers with a TDMA component within a chunk. Thus, B-IFDMA provides as large frequency diversity as IFDMA, and the scheme introduces the possibility to enter micro-sleep mode also in scheduled slots at the cost of a slightly larger requirement on backoff for the high power amplifier (HPA) in the user terminal (UT). B-IFDMA maintains a subcarrier allocation pattern that enables the same resource addressing overhead as for IFDMA, which is lower than in an unstructured OFDMA allocation approach. Moreover, the sensitivity to frequency offsets should be better than for IFDMA. Depending on the time-frequency variability within the subcarrier blocks, the channel estimation performance could be slightly better or slightly worse compared to IFDMA with the same pilot overhead.

The paper is organized as follows: We start in Section II by discussing and comparing important properties of B-IFDMA like pilot symbol overhead, power consumption, HPA power backoff requirements, robustness to carrier frequency offsets and frequency diversity gains to other DFT precoded OFDMA schemes. Then, in Section III we give a detailed generic signal definition for DFT precoded schemes including B-IFDMA, IFDMA and DFT precoded OFDMA with blockwise subcarrier allocation, also denoted Localized Frequency Division Multiple Access (LFDMA).

II. Properties of B-IFDMA

In this section we discuss the properties of B-IFDMA by comparing the scheme with other candidate DFT-precoded multiple access schemes for an OFDM based non-frequency adaptive uplink; Interleaved Frequency Division Multiple Access (IFDMA) and DFT precoded OFDMA with blockwise subcarrier allocation, also denoted Localized Frequency Division Multiple Access (LFDMA), and LFDMA with frequency hopping (FH-LFDMA). The allocation patterns of these schemes are shown in Fig. 1, and a detailed generic signal definition for these schemes is presented in Section III.

A. Pilot Symbol overhead for Channel Estimation

Due to the blockwise transmission with cyclic prefix (CP), the extension of DFT precoded OFDMA by a TDMA component

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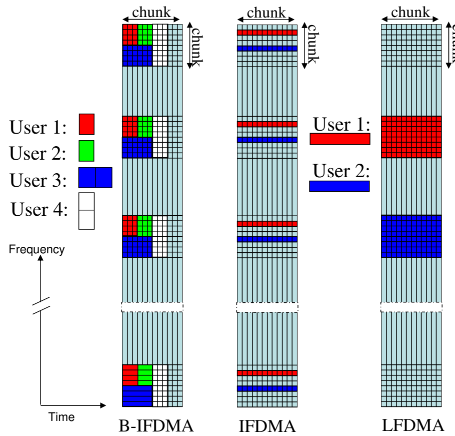

Fig. 1. Example of B-IFDMA parameterization using block size 4 subcarriers x 3 OFDM symbols (basic rate) with the tentative WINNER FDD chunk size. High rate users could be allocated more blocks per chunk in either the time direction (user 3 with less sleep mode possibility) or in the frequency direction (user 4 with larger power amplifier backoff requirement). LFDMA is shown for comparison along with IFDMA assuming the same data rate as B-IFDMA (basic rate) and IFDMA using 8 blocks/subcarriers per chunk duration.

is straightforward. The overhead for pilot symbols required for channel estimation in the time direction is determined by the length of the TDMA component. For a high number of consecutive OFDM symbols within a chunk assigned to a user, the overhead can be reduced by time-interpolation of the channel estimates [5]. With Frequency Hopping (FH) a new set of pilot symbols is required for each hop, and even for a high number of consecutive OFDM symbols assigned to a user the pilot symbol overhead becomes high, with an associated additional decoding delay if spanning multiple chunk durations.

In the frequency-direction, the pilot overhead depends on the subcarrier allocation. If adjacent subcarriers are assigned to a user as in B-IFDMA and LFDMA, interpolation in the frequency direction is possible, see Fig. 1. However, for IFDMA the distance between the subcarriers assigned to a user is typically large compared to the coherence bandwidth of the channel and interpolation in the frequency direction cannot be used [5]. Thus, for IFDMA the number of consecutive OFDM symbols assigned to a user in a TDMA slot has to be larger compared to B-IFDMA and LFDMA, assuming the same pilot overhead.

B. Power Saving Sleep Mode in User Terminals

A significant part of the power consumption in a user terminal is due to the transceiver chain. Typically, the transceiver can be in (at least) five different modes [6]; Off mode, Sleep mode, Idle mode, Receive mode and Transmit mode. Each of these states consumes different power levels from the energy source in the UT, sorted in increasing order in the list. The transmit mode consumes most energy, but according to the numbers given in e.g. [6] for a WaveLan modem, the difference in Transmit, Receive and Idle mode is rather small, see Table 1 in [6]. On the other hand, the energy savings while entering Sleep mode could be substantial.

Thus, if the multiple access scheme can support a TDMA component with long enough time intervals for the UT to be able to enter sleep mode, substantial energy savings could be possible in the UT. In [6], savings of 16.0 dB for Transmit mode to Sleep mode, 15.85 dB for Receive mode to Sleep mode and 15.8 dB for Idle mode to Sleep mode are reported based on measurements. Note that, these figures show that sleep mode is important also for the downlink as seen from the user terminal[1].

By allocating equidistant blocks of subcarriers as in B-IFDMA, we can preserve the same frequency diversity and channel estimation and addressing overhead as in IFDMA and still introduce a TDMA component with a low number of consecutive OFDM symbols assigned to a user within the chunks, see Fig. 1. Thus, if transition times of the HW in the UT allows, B-IFDMA enables *intra-chunk* sleep mode[2], in which the UT can be in power saving sleep mode during parts of a chunk scheduled for the UT.

The feasibility of intra-chunk sleep mode have been investigated in WINNER [3] using the WINNER FDD chunk definition. It is indicated by a UT manufacturer within WINNER II that ”hibernation”, i.e. switching off/on the HPA, the low noise amplifier (LNA), and other selected RF parts and possibly baseband processing is possible within a few microseconds. Thus, the transition time for hibernation mode is in the WINNER FDD mode within one OFDM symbol (28.8 μs). This could be useful, since the HPA and the LNA are expected to be major sources of power consumption in the transceiver during Idle mode. Switching off/on also the synthesizer is estimated to take a few hundred microseconds and cannot be done within a WINNER FDD chunk duration.

The potential power savings by intra-chunk sleep mode are related to the periods of no power supply to selected components, which should save overall power consumption of the transceiver. However, assuming the same data rate and required RF energy per data symbol for B-IFDMA and IFDMA (having no TDMA component) implies that B-IFDMA would need a larger instantaneous transmit power, which could reduce this gain. If the transceiver design can provide power savings associated to hibernation in the order of the figures in [6], there is a potential power saving on the order of one to a few decibels by allocating B-IFDMA blocks with a duration less than half a chunk time.

C. Power Backoff Requirements

Backoff from the maximum available HPA power is necessary in the UT to avoid nonlinear distortion of the HPA output signal. Even modest amounts of nonlinear distortion can cause the transmitted spectrum to exceed the allowed bounds imposed by a spectral mask. Larger amounts of nonlinearity will also cause distortion and BER performance degradation of the received signal. On the other hand, a large required backoff lowers amplifier efficiency and increases the maximum output power required from the HPA, thus increasing its cost and battery drain. The minimum required HPA power backoff depends on several factors like distribution of the transmitted signals' amplitude, nonlinear input-output characteristic of the HPA and the power spectrum mask to which the HPA output power spectrum must be confined.

[1] We have proposed a similar scheme to B-IFDMA denoted Block Equidistant Frequency Division Multiple Access (B-EFDMA) for the non-frequency-adaptive downlink in WINNER. The only difference to B-IFDMA is that the DFT-precoding step is not included [3].

[2] In WINNER, we also consider *inter-chunk* sleep mode in which a UT can be in sleep mode for the full duration of a chunk when not scheduled.

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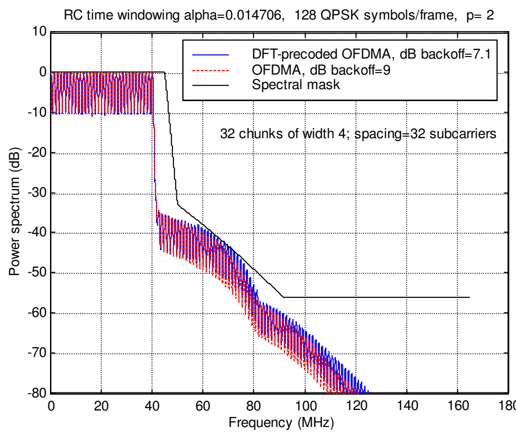

Fig. 2. Spectrum mask and HPA power backoff requirements for B-IFDMA using QPSK modulation with non-DFT-precoded OFDMA as a comparison. The spectral mask is derived for WINNER narrowband mobile terminal outputs in [7] by considering allowed power leakage into adjacent users' channels, and is scaled to the studied wideband signal bandwidths.

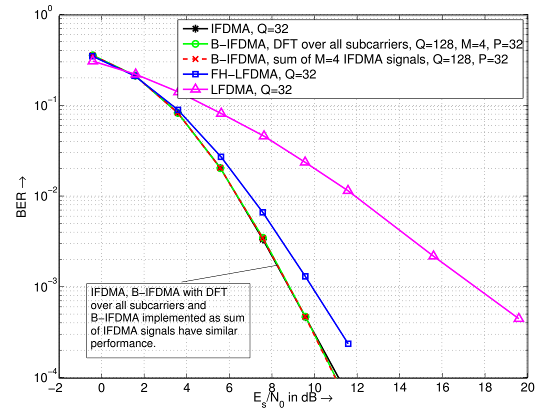

Fig. 3. Simulation of BER versus E_s/N_0 for the considered multiple access schemes. M=number of subcarriers per B-IFDMA block, P=number of blocks per chunk time with block size 4 subcarriers x 3 OFDM symbols, and Q=number of subcarriers used in IFDMA, LFDMA and FH-LFDMA.

TABLE I

SUMMARY OF HPA BACKOFF REQUIREMENTS

Scheme	Backoff (dB)
IFDMA with 32 subcarriers ($\alpha = 0.05$, 40 MHz signal bandwidth)	6.9 (9.0)
B-IFDMA with 32 subchunks of width 4 ($\alpha = 0.015$, 40 MHz signal bandwidth)	7.1 (9.0)
IFDMA with 8 subcarriers ($\alpha = 0.125$, 10 MHz signal bandwidth)	6.9 (9.0)
B-IFDMA with 8 subchunks of width 4 ($\alpha = 0.05$, 10 MHz signal bandwidth)	7.7 (9.2)
B-IFDMA as sum of 4 frequency interleaved adjacent IFDMA signals with 8 subcarriers each ($\alpha = 0.05$, 10 MHz signal bandwidth)	8.5 (9.2)

TABLE II

SIMULATION PARAMETERS

Carrier	3.7 GHz	Equalizer	MMSE FDE
Bandwidth	40 MHz	Interleaving	Random
Subcarriers	1024	Interl. depth (B-IFDMA)	0.35 ms (0.09 ms)
Modulation	QPSK		
Code	Convolutional	Freq. hopping	per OFDM symbol
Code rate	1/2	Guard interval	2.7 μs
Constr. length	6	Channel [11]	WINNER SCM, Urban, 70 km/h
Decoder	MaxLogMAP		

In Table I, we show the required HPA power backoff for the considered schemes, cf. Section III-C for signal definitions. The HPA non-linearity is modelled by a Rapp model with non-linearity parameter p=2 [8]. The results were obtained by manually adjusting the power backoff, with appropriate raised cosine time-windowing parameter α, so that the power spectrum barely grazed the spectral mask. As a reference, non-DFT-precoded OFDMA is shown in parenthesis. The difference between that average power and the saturated output power from the nonlinearity is the signal's required power backoff. The resulting HPA output power spectra alongside with the spectral mask can be obtained from [3], and is here illustrated in Fig. 2 for B-IFDMA using 40 MHz signal bandwidth.

In general, different nonlinearity characteristics and spectral masks will change the absolute values of backoffs for different types of signals, but would not be expected to change the relative values. Thus, from these investigations we conclude that, similar to IFDMA, B-IFDMA can provide a low power backoff requirement compared to non-DFT-precoded OFDMA.

D. Robustness to Carrier Frequency Offsets and Phase Noise

In the uplink, a performance degradation resulting from user specific carrier frequency offset (CFO) due to, e.g., Doppler shifts or oscillator imperfections and Phase noise (PN) is expected. Schemes with interleaved subcarrier allocation like IFDMA are well known to be more sensitive to CFOs and PN compared to schemes with block allocation like LFDMA [9], [10]. Due to its block interleaved subcarrier allocation, B-IFDMA is expected to be more robust to CFOs an PN compared to IFDMA and less robust compared to LFDMA.

E. Frequency Diversity Gains

To illustrate the performance of the different DFT-precoded OFDMA schemes, the BER versus E_s/N_0 has been simulated using the WINNER assumptions given in Table II, see Section III for a detailed system model used in the simulations. The results in Fig. 3 show that the performance of B-IFDMA is the same as IFDMA under the assumption of perfect channel estimation and perfect synchronization. Referring to Section III-C, there is also no difference in the BER vs E_s/N_0 results by using one common DFT or summing four IFDMA signals when generating the B-IFDMA signal (but there is a power backoff difference as shown in Table I). As seen, there is a large diversity gain for a distributed allocation in a wide bandwidth scenario compared to a localized allocation with LFDMA. With frequency-hopping the difference becomes smaller, but the pilot overhead for FH-LFDMA would be higher, cf. Section II-A.

III. SYSTEM MODEL

In this section, system models for IFDMA, LFDMA and B-IFDMA are derived as special cases of a system model for DFT-precoded OFDMA. In the following, all signals are represented

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by their discrete time equivalents in the complex baseband. Further on, $(\cdot)^{\mathrm{T}}$ denotes the transpose, $(\cdot)^{-1}$ the inverse and $(\cdot)^{\mathrm{H}}$ the Hermitian of a vector or a matrix, respectively.

For a system with K users with user index k, $k = 0, \ldots, K-1$, let

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

denote a block of Q data symbols $d_q^{(k)}$, $q = 0, \ldots, Q-1$, of user k at symbol rate $1/T_s$. For sake of simplicity, throughout this section it is assumed that the same number Q of subcarriers is assigned to each user. However, note that for IFDMA, LFDMA and B-IFDMA also different numbers of subcarriers may be assigned to each user, e.g., using methods as described in [12]. The data symbols $d_q^{(k)}$ may be taken from the alphabet of a bit mapping scheme like Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM), applied after Forward Error Correction (FEC) coding and interleaving. Further on, let $\mathbf{F}_N^H$ denote the matrix representation of an N-point Inverse DFT (IDFT), where $N = K \cdot Q$ denotes the number of subcarriers available in the system. The assignment of the data symbols $d_q^{(k)}$ to a user specific set of Q subcarriers is assumed to be described by an $N \times Q$ subcarrier allocation matrix $\mathbf{M}^{(k)}$. Thus, in general, a DFT-precoded OFDMA signal $\mathbf{x}^{(k)} = (x_0^{(k)}, \ldots, x_{N-1}^{(k)})^{\mathrm{T}}$ of user k can be described by N elements $x_n^{(k)}$, $n = 0, \ldots, N-1$, at sample rate $1/T_c = K/T_s$ and is given by

$$\mathbf{x}^{(k)} = \mathbf{F}_N^H \cdot \mathbf{M}^{(k)} \cdot \mathbf{F}_Q \cdot \mathbf{d}^{(k)}, \tag{2}$$

where $\mathbf{F}_Q$ denotes a Q-point DFT matrix for precoding.

In the following, we consider an uplink scenario. Let $\mathbf{h}^{(k)} = (h_0^{(k)}, \ldots, h_{L-1}^{(k)}, 0, \ldots, 0)^{\mathrm{T}}$ denote an $N \times 1$ vector representation of the time dispersive channel of user k with L non-zero coefficients $h_l^{(k)}$, $l = 0, \ldots, L-1$, at sample rate $1/T_c$ and $L \leq N$. Before transmission over the channel $\mathbf{h}^{(k)}$ a Cyclic Prefix (CP) is applied to $\mathbf{x}^{(k)}$ which is removed at the receiver before demodulation. For the time interval T required for transmission of the DFT-precoded OFDMA signal $\mathbf{d}^{(k)}$ and the CP, the channel is assumed to be time invariant. It is well known that insertion of the CP, transmission over the channel $\mathbf{h}^{(k)}$ and removal of the CP at the receiver can be described by an equivalent $N \times N$ circulant channel matrix

$$\mathbf{H}^{(k)} = \begin{pmatrix} h_0^{(k)} & \ldots & \ldots & h_{L-1}^{(k)} & 0 & \ldots & \ldots & 0 \\ 0 & h_0^{(k)} & \ldots & \ldots & h_{L-1}^{(k)} & 0 & \ldots & 0 \\ \vdots & \ddots & \ddots & \ldots & \ddots & \ddots & \ddots & \vdots \\ h_1^{(k)} & \ldots & h_{L-1}^{(k)} & 0 & \ldots & \ldots & 0 & h_0^{(k)} \end{pmatrix}^{\mathrm{T}} \tag{3}$$

[13]. Let $\mathbf{n} = (n_0, \ldots, n_{N-1})^{\mathrm{T}}$ denote an Additional White Gaussian Noise (AWGN) vector with samples n_n, $n = 0, \ldots, N-1$ at sample rate $1/T_c$. Further on, perfect synchronization is assumed. In the uplink, the received signal after removal of the cyclic prefix is given by the superposition of the signals of the K users transmitted over the user specific equivalent circulant channels $\mathbf{H}^{(k)}$ and distorted by AWGN according to

$$\mathbf{r} = \sum_{k=0}^{K-1} \mathbf{H}^{(k)} \cdot \mathbf{x}^{(k)} + \mathbf{n}. \tag{4}$$

In the following, we regard the user specific part for user k of a receiver for DFT-precoded OFDMA in the uplink. In order to perform OFDMA demodulation, in a first step an N-point DFT is applied to the received signal $\mathbf{r}$. In a second step, the demodulated signal is user specifically demapped. The demapping matrix is given by the $Q \times N$ matrix $\mathbf{M}^{(k)\dagger}$, where $(\cdot)^{\dagger}$ denotes the pseudo-inverse of a matrix. Furthermore, it is assumed that after demapping the impact of the channel for user k is compensated by application of a Frequency Domain Equalizer (FDE) as described in [14]. Note that for DFT-precoded OFDMA an FDE based on the Minimum Mean Square Error (MMSE) criterion provides better performance compared to an FDE based on the zero forcing (ZF) criterion [15], [16]. It is assumed that $\mathbf{E}^{(k)}$ denotes the $Q \times Q$ matrix representation of the FDE. Finally, the DFT precoding has to be compensated by a Q-point IDFT $\mathbf{F}_Q^H$. Thus, at the receiver, an estimate $\hat{\mathbf{d}}^{(k)}$ of the transmitted data block $\mathbf{d}^{(k)}$ for user k is given by

$$\hat{\mathbf{d}}^{(k)} = \mathbf{F}_Q^H \cdot \mathbf{E}^{(k)} \cdot \mathbf{M}^{(k)\dagger} \cdot \mathbf{F}_N \cdot \mathbf{r}. \tag{5}$$

A. IFDMA

A system model for IFDMA can be obtained from the generalized system model for DFT-precoded OFDMA by setting $\mathbf{M}^{(k)} = \mathbf{M}_I^{(k)}$, where $\mathbf{M}_I^{(k)}$ denotes an interleaved subcarrier allocation matrix. The elements $M_I^{(k)}(n,q)$ in the n-th row, $n = 0, \ldots, N-1$, and q-th column, $q = 0, \ldots, Q-1$, of the interleaved subcarrier allocation matrix $\mathbf{M}_I^{(k)}$ are given by

$$M_I^{(k)}(n,q) = \begin{cases} 1 & n = q \cdot K + k \\ 0 & \text{else} \end{cases}. \tag{6}$$

Let $\mathbf{I}_Q$ denote a $Q \times Q$ identity matrix and let $\mathbf{R}$ denote an $N \times Q$ repetition matrix $\mathbf{R}$ obtained by stacking K identity matrices according to $\mathbf{R} = (\mathbf{I}_Q, \ldots, \mathbf{I}_Q)^{\mathrm{T}}$. Further on, let $\mathbf{\Phi}^{(k)} = \mathrm{diag}(\phi_0^{(k)}, \ldots, \phi_{N-1}^{(k)})$, define a user dependent $N \times N$ diagonal matrix with diagonal elements $\phi_n^{(k)} = 1/\sqrt{K} \cdot e^{j\frac{2\pi}{N} \cdot k \cdot n}$; $n = 0, \ldots, N-1$. It is shown in [17] that the signal obtained through insertion of the interleaved subcarrier allocation matrix (III-A) into Eq. (2) can be reformulated as

$$\mathbf{x}_I^{(k)} = \mathbf{\Phi}^{(k)} \cdot \mathbf{R} \cdot \mathbf{d}^{(k)}. \tag{7}$$

From Eq. (7) follows that the IFDMA signal can be efficiently generated using a low complexity implementation performing K-fold compression and repetition in time of the data block $\mathbf{d}^{(k)}$ of user k and subsequent user specific phase rotation according to matrix $\mathbf{\Phi}^{(k)}$, cf. [17], [4]. In the uplink, at the receiver estimates $\hat{\mathbf{d}}^{(k)}$ of the data symbols $\mathbf{d}^{(k)}$ can be obtained by setting $\mathbf{M}^{(k)\dagger} = \mathbf{M}_I^{(k)\dagger}$ in Eq. (5).

B. LFDMA

A system model for LFDMA can be obtained from the generalized system model for DFT-precoded OFDMA by setting $\mathbf{M}^{(k)} = \mathbf{M}_L^{(k)}$, where $\mathbf{M}_L^{(k)}$ denotes a subcarrier allocation matrix for block allocation. The elements $M_L^{(k)}(n,q)$ in the n-th row, $n = 0, \ldots, N-1$, and q-th column, $q = 0, \ldots, Q-1$, of matrix $\mathbf{M}_L^{(k)}$ are given by

$$M_L^{(k)}(n,q) = \begin{cases} 1 & n = k \cdot Q + q \\ 0 & \text{else} \end{cases}. \tag{8}$$

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At the receiver estimates $\hat{\mathbf{d}^{(k)}}$ of the data symbols $\mathbf{d}^{(k)}$ can be obtained by setting $\mathbf{M}^{(k)\dagger} = \mathbf{M}_L^{(k)\dagger}$ in Eq. (5).

C. B-IFDMA

In the following, two different system models for B-IFDMA are derived as special cases of the system model for DFT-precoded OFDMA. The first one is based on the application of one DFT over all subcarriers assigned to a specific user k, the second one is based on the assignment of multiple IFDMA signals to one user. In the sequel, let M denote the number of subcarriers per block and let P denote the number of blocks assigned to a specific user k, with $Q = M \cdot P$.

For the first signal model for B-IFDMA, the elements $M_B^{(k)}(n,q)$ in the n-th row, $n = 0, \ldots, N-1$, and q-th column, $q = p \cdot M + m$; $p = 0, \ldots, P-1$; $m = 0, \ldots, M-1$, of a block interleaved subcarrier allocation matrix $\mathbf{M}_B^{(k)}$ are defined as

$$M_B^{(k)}(n,q) = \begin{cases} 1 & n = p \cdot \frac{N}{P} + m + kP \\ 0 & \text{else} \end{cases} . \qquad (9)$$

Thus, a possible transmit signal for B-IFDMA is given by setting $\mathbf{M}^{(k)}$ in Eq. (2) to $\mathbf{M}^{(k)} = \mathbf{M}_B^{(k)}$. At the receiver, estimates $\hat{\mathbf{d}}^{(k)}$ of the data block $\mathbf{d}^{(k)}$ can be obtained by setting $\mathbf{M}^{(k)\dagger}$ in Eq. (5) to $\mathbf{M}^{(k)\dagger} = \mathbf{M}_B^{(k)\dagger}$.

Another B-IFDMA signal can be obtained if M IFDMA signals, each with P subcarriers, are superimposed. Thus, in order to get the second signal model for B-IFDMA, it is assumed that M IFDMA signals that are mutually shifted by one subcarrier bandwidth are assigned to user k. The resulting signal can be described as follows: Let $\bar{\mathbf{d}}^{(m,k)}$ denote the m-th P elementary subblock of $\mathbf{d}^{(k)}$ with elements

$$\bar{d}_p^{(m,k)} = d_{mP+p}^{(k)}; \;\; p = 0, \ldots, P-1. \qquad (10)$$

The $N \times P$ subcarrier allocation matrix $\mathbf{M}_I^{(m,k)}$ of the m-th IFDMA signal assigned to user k is defined by its elements

$$M_I^{(m,k)}(n,p) = \begin{cases} 1 & n = p \cdot \frac{N}{P} + m + kM \\ 0 & \text{else} \end{cases} . \qquad (11)$$

Thus, for user k the B-IFDMA signal based on a sum of M mutually shifted IFDMA signals can be obtained by

$$\mathbf{x}^{(k)} = \sum_{m=0}^{M-1} \mathbf{F}_N^H \cdot \mathbf{M}_I^{(m,k)} \cdot \mathbf{F}_P \cdot \bar{\mathbf{d}}^{(m,k)}, \qquad (12)$$

where $\mathbf{F}_P$ denotes a $P \times P$ DFT matrix. Since, according to Eq. (7), IFDMA can be implemented efficiently by compression, repetition and user specific phase shift, the efficient implementation for IFDMA can be utilized in order to generate a B-IFDMA signal according to Eq. (12). At the receiver, estimates $\hat{\bar{\mathbf{d}}}^{(m,k)}$ of the M subblocks $\bar{\mathbf{d}}^{(m,k)}$ of $\mathbf{d}^{(k)}$ can be obtained by using $\mathbf{M}_I^{(m,k)\dagger}$ instead of $\mathbf{M}^{(k)\dagger}$ in Eq. (5).

IV. Conclusion

In this paper we have introduced a novel multiple access scheme for non-frequency-adaptive uplinks denoted Block Interleaved Frequency Division Multple Access (B-IFDMA) that provides large frequency-diversity, low power backoff requirements for the user terminals and possibility for power saving micro-sleep mode. B-IFDMA provides higher robustness to CFOs and PN compared to IFDMA and a possibility for low addressing overhead and flexibility in resource assignments by trading requirements on sleep mode and HPA backoff requirements in the user terminals. With a short B-IFDMA block duration, robustness for fast moving users is also improved. Further work on channel estimation, integration of spatial diversity techniques, refinement of block size and repetition distance and co-existence with resources for frequency-adaptive transmission are needed in the overall MAC work in WINNER II.

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References

[1] IST-2003-507581 WINNER, "D2.10 Final report on identified RI key technologies, system concept, and their assessment," Dec. 2005.

[2] M. Sternad, S. Falahati, T. Svensson, and D. Aronsson, "Adaptive TDMA/OFDMA for wide-area coverage and vehicular velocities," in *Proc. IST Mobile and Vehicular Summit*, Dresden, Germany, June 2005.

[3] IST-4-027756 WINNER II, "D4.6.1 The WINNER II air interface: Refined multiple access concepts," Nov. 2006.

[4] U. Sorger, I. De Broeck, and M. Schnell, "IFDMA - A New Spread-Spectrum Multiple-Access Scheme," in *Multi-Carrier Spread-Spectrum*. Netherlands: Kluwer Academic Publishers, 1997, pp. 111–118.

[5] A. Sohl, T. Frank, and A. Klein, "Channel Estimation for DFT precoded OFDMA with blockwise and interleaved subcarrier allocation," in *Proc. International OFDM Workshop 2006*, Hamburg, Germany, August 2006.

[6] P. Havinga and G. Smit, "Energy-efficient tdma medium access control protocol scheduling," in *Proc. Asian International Mobile Computing Conference (AMOC 2000)*, Penang, Malaysia, Nov. 2000.

[7] IST-2003-507581 WINNER, "D2.5 Duplex arrangements for future broadband air interfaces," Oct. 2004.

[8] C. Rapp, "Effects of HPA-nonlinearity on a 4-DPSK/OFDM-signal for a digital sound broadcasting signal," in *ESA, Second European Conference on Satellite Communications (ECSC-2)*, Oct. 1991, pp. 179–184.

[9] A. Tonello, N. Laurenti, and S. Pupolin, "Analysis of uplink for an asynchronous multi-user dmt ofdma system impaired by time offsets, frequency offsets, and multi-path fading," in *Proc. of VTC'00(Fall)*, Sep. 2000, pp. 1094–1099.

[10] R. Dinis, C. T. Lam, and D. Falconer, "Carrier Synchronization Requirements for CDMA Systems with Frequency-Domain Orthogonal Signature Sequences," in *Proc. of ISSSTA2004*, Sydney, Australia, Aug./Sep. 2004, pp. 821–825.

[11] IST-2003-507581 WINNER, "D5.4 v. 1.4 Final report on link level and system level channel models," Nov. 2005.

[12] T. Frank, A. Klein, E. Costa, and E. Schulz, "Interleaved Orthogonal Frequency Division Multiple Access with Variable Data Rates," in *Proc. International OFDM Workshop 2005*, Hamburg, Germany, Aug./Sep. 2005, pp. 179–183.

[13] Z. Wang and G. Giannakis, "Wireless Multicarrier Communications," *IEEE Signal Processing Magazine*, pp. 29–48, May 2000.

[14] H. Sari, G. Karam, and I. Jeanclaude, "Frequency domain equalization of mobile radio terrestrial broadcast channels," in *Proc. GLOBECOM*, San Francisco, USA, Nov./Dec. 1994, pp. 1–5.

[15] A. Arkhipov and M. Schnell, "Interleaved Frequency Division Multiple Access System with Frequency Domain Equalization," in *Proc. International OFDM Workshop 2004*, Dresden, Germany, September 2004.

[16] D. Falconer, S. Ariyavisitakul, A. Benyamin-Seeyar, and B. Eidson, "Frequency domain equalization for single-carrier broadband wireless systems," *IEEE Communications Magazine*, vol. 40, April 2002.

[17] T. Frank, A. Klein, E. Costa, and E. Schulz, "IFDMA - A Promising Multiple Access Scheme for Future Mobile Radio Systems," in *Proc. PIMRC 2005*, Berlin, Germany, Sep. 2005.

T. Svensson, T. Frank, D. Falconer, M. Sternad, E. Costa and A. Klein, "B-IFDMA - A power efficient multiple access scheme for non-frequency-adaptive transmission," in Proc. IST MObile and Wireless Communications Summit, Budapest, Hungary, July 2007