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CHANNEL ESTIMATION FOR BLOCK-IFDMA

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Abstract In this paper, pilot multiplexing and channel estimation is investigated for two different signal models of DFT precoded OFDMA with block-interleaved subcarrier allocation (B-IFDMA). The influence of the B-IFDMA signal model on the bit error rate performance with and without perfect channel knowledge is presented. Moreover, the Peak-to-Average Power Ratio of the transmit signal, as well as the pilot symbol overhead required for channel estimation is given for the two signal models.

1. Introduction

For the uplink of B3G/4G mobile radio systems, Discrete Fourier Transform (DFT) precoded Orthogonal Frequency Division Multiple Access (OFDMA) is under consideration as candidate because it combines the advantageous properties of OFDMA, cf. e.g. [10], with a low Peak-to-Average Power Ratio (PAPR) [6]. For DFT precoded OFDMA, there exist different possibilities of how to allocate subcarriers to a user under consideration.

Blockwise subcarrier allocation leads to the Localized FDMA (LFDMA) scheme [9, 6], which, on the one hand, provides good robustness to carrier frequency offsets and due to the possibility of interpolation between different subcarriers, low pilot symbol overhead for channel estimation (CE) in frequency domain (FD). On the other hand, only low frequency diversity can be achieved [7].

Interleaved subcarrier allocation leads to the Interleaved FDMA (IFDMA) scheme [8, 4]. It provides high frequency diversity due to the spreading of the subcarriers over the total available bandwidth [2], and, compared to other DFT precoded OFDMA schemes, IFDMA exhibits the lowest PAPR. However, IFDMA is sensitive to carrier frequency offsets [3]. Moreover, in terms of CE, IFDMA requires a higher pilot

symbol overhead than LFDMA since, in general, for IFDMA interpolation between different subcarriers in FD is not possible [7].
A third possibility of subcarrier allocation, where the data of a specific user is transmitted on blocks of subcarriers that are equidistantly distributed over the available bandwidth, is currently under investigation and denoted as Block-IFDMA (B-IFDMA) [12]. In contrast to IFDMA, where a block is built by a single subcarrier, for B-IFDMA, each block consists of K_f adjacent subcarriers. Due to the blockwise allocation, B-IFDMA is assumed to exhibit higher robustness against carrier frequency offsets than IFDMA and, at the same time, maintain the advantage of high frequency diversity. Another advantageous aspect compared to IFDMA is less pilot symbol overhead required for CE because B-IFDMA supports interpolation in FD within each block of subcarriers.
In this paper, two different variants for B-IFDMA are introduced, that are denoted as Added Signal B-IFDMA and Joint DFT B-IFDMA in the following. The pilot insertion for CE as well as the CE algorithm are presented for each B-IFDMA variant for the case that interpolation is applied in FD and for the case that no interpolation is applied. The influence of the B-IFDMA variant on the performance results with perfect channel estimation (PCE) and with realistic channel estimation (RCE), and on the PAPR of the transmit signal is investigated. Moreover, the pilot symbol overhead required for CE is discussed for both B-IFDMA variants.
The paper is organized as follows. In Section 2, system models for Added Signal B-IFDMA and Joint DFT B-IFDMA are derived from the general system model of DFT precoded OFDMA. In Section 3, pilot insertion and CE are described for each B-IFDMA variant. In Section 4, the performance results with PCE and RCE, as well as the PAPR results and the pilot symbol overhead for Added Signal and Joint DFT B-IFDMA are presented. Section 5 concludes the work.

2. System Model

2.1 DFT Precoded OFDMA

In this Section, a general description of the DFT-precoded OFDMA system model is given. In the following, all signals are represented by their discrete time equivalents in the complex baseband. Further on, $(\cdot)^T$ denotes the transpose and $(\cdot)^H$ the Hermitian of a vector or a matrix. Assuming a system with K users, let $\mathbf{d}^{(k)} = (d_0^{(k)}, \cdots, d_{Q-1}^{(k)})^T$ denote a block of Q data symbols $d_q^{(k)}, q = 0, \cdots, Q-1$, at symbol rate $1/T_s$ transmitted by a user with index k, $k = 0, \cdots, K-1$. The data symbols

$d_q^{(k)}$ can be taken from the alphabet of a modulation scheme like Phase Shift Keying (PSK), that is applied to coded or uncoded bits. Let $\mathbf{F}_N$ and $\mathbf{F}_N^H$ denote the matrix representation of an N-point DFT and an N-point Inverse DFT (IDFT), respectively, where $N = K \cdot Q$ is the number of available subcarriers in the system. The assignment of Q subcarriers to a specific user can be described by a Q-point DFT precoding matrix $\mathbf{F}_Q$, an $N \times Q$ mapping matrix $\mathbf{M}^{(k)}$ and an N-point IDFT matrix $\mathbf{F}_N^H$ [2]. Thus, a DFT precoded OFDMA signal block at sample rate $1/T_c = K/T_S$ is given by

$$\mathbf{x}^{(k)} = \mathbf{F}_N^H \cdot \mathbf{M}^{(k)} \cdot \mathbf{F}_Q \cdot \mathbf{d}^{(k)}. \tag{1}$$

The insertion of a Cyclic Prefix, as well as the transmission over a channel and subsequent demodulation for an uplink scenario is given in [2] and will not be described in this work.

For B-IFDMA, two different variants can be derived as special cases of the general DFT precoded OFDMA system model. The first one, treated in Section 2.2, is based on an assignment of multiple IFDMA signals to one user and thus, named Added Signal B-IFDMA. The second one, treated in Section 2.3, is based on one joint DFT for all subcarriers assigned to a specific user and thus, named Joint DFT B-IFDMA. In the following, K_f denotes the number of subcarriers per block and T denotes the number of blocks assigned to a specific user k, with $Q = K_f \cdot T$. For $K_f = 1$, the B-IFDMA scheme merges into IFDMA.

2.2 Added Signal B-IFDMA

The Added Signal B-IFDMA signal can be obtained if K_f IFDMA signals that are mutually shifted by one subcarrier are superimposed and assigned to user k. The signal model for IFDMA is not described explicitly in this work as it has been introduced in detail in [2]. Let $\bar{\mathbf{d}}^{(m,k)}$ denote the m-th T elementary subblock of $\mathbf{d}^{(k)}$ with elements $d_t^{(m,k)} = d_{mT+t}^{(k)}$; $m = 0, ..., K_f - 1$ and $t = 0, ..., T-1$. The $N \times T$ mapping matrix $\mathbf{M}_{B_\Sigma}^{(m,k)}$ of the m-th IFDMA signal assigned to user k is given by its elements $M_{B_\Sigma}^{(m,k)}(n,t)$ in the n-th row, with $n = 0, ..., N-1$, and t-th column

$$M_{B_\Sigma}^{(m,k)}(n,t) = \begin{cases} 1 & \text{for } n = t \cdot \frac{N}{T} + m + k \cdot K_f \\ 0 & \text{else} \end{cases} . \tag{2}$$

Thus, for user k the Added Signal B-IFDMA signal is obtained by

$$\mathbf{x}_{B_\Sigma}^{(k)} = \sum_{m=0}^{K_f-1} \mathbf{F}_N^H \cdot \mathbf{M}_{B_\Sigma}^{(m,k)} \cdot \mathbf{F}_T \cdot \bar{\mathbf{d}}^{(m,k)}, \tag{3}$$

where $\mathbf{F}_T$ denotes a $T \times T$ DFT matrix.

2.3 Joint DFT B-IFDMA

For Joint DFT B-IFDMA, the mapping matrix has to characterize a block interleaved subcarrier allocation. The Joint DFT B-IFDMA mapping matrix $\mathbf{M}_{B_J}^{(k)}$ is given by its elements $M_{B_J}^{(k)}(n,q)$ in the n-th row and q-th column

$$M_{B_J}^{(k)}(n,q) = \begin{cases} 1 & n = t \cdot \frac{N}{T} + r + k \cdot K_f \\ 0 & \text{else} \end{cases}, \tag{4}$$

with $n = 0, \cdots, N-1$, and $q = r + t \cdot K_f$, where $r = 0, ..., K_f - 1$ and $t = 0, ..., T-1$. Therefore, the Joint DFT B-IFDMA transmit signal $\mathbf{x}_{B_J}^{(k)}$ of user k becomes

$$\mathbf{x}_{B_J}^{(k)} = \mathbf{F}_N^H \cdot \mathbf{M}_{B_J}^{(k)} \cdot \mathbf{F}_Q \cdot \mathbf{d}^{(k)}. \tag{5}$$

3. Pilot Insertion and Channel Estimation

In this Section, pilot assisted CE is introduced for both variants of B-IFDMA. As a first solution, a whole B-IFDMA symbol is used for pilot transmission, which is termed symbolwise pilot insertion (PI) in the following. In order to reduce pilot symbol overhead, it is beneficial to interpolate between subcarriers within each block of K_f adjacent subcarriers. Therefore, as a second solution, a certain subset of the Q subcarriers assigned to user k is used for pilot transmission. This solution is termed subcarrierwise PI in the following.

3.1 Signal Generation

In this Section, the two possibilities of PI are described for Added Signal and Joint DFT B-IFDMA.

Symbolwise Pilot Insertion. For symbolwise PI, the unmodulated pilot sequence (PS) $\tilde{\mathbf{p}}^{(k)} = (\tilde{p}_0^{(k)}, \cdots, \tilde{p}_{Q-1}^{(k)})^T$ with Q complex elements, e.g. taken from a Constant Amplitude Zero Autocorrelation (CAZAC) sequence [1], is modulated according to the particular signal model for B-IFDMA.

- *Added Signal B-IFDMA*
  For Added Signal B-IFDMA, the unmodulated PS $\tilde{\mathbf{p}}^{(k)}$ is divided into K_f T-elementary subblocks $\bar{\mathbf{p}}^{(m,k)}$ with $m = 0, ..., K_f - 1$. The modulated PS $\mathbf{p}_{B_\Sigma}^{(k)}$ is built in analogy to the B-IFDMA signal in (3) and, thus, is given by

$$\mathbf{p}_{B_\Sigma}^{(k)} = \sum_{m=0}^{K_f-1} \mathbf{F}_N^H \cdot \mathbf{M}_{B_\Sigma}^{(m,k)} \cdot \mathbf{F}_T \cdot \bar{\mathbf{p}}^{(m,k)}. \tag{6}$$

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- *Joint DFT B-IFDMA*
  For Joint DFT B-IFDMA, the modulated PS $\mathbf{p}_{B_J}^{(k)}$ of user k for symbolwise PI is given by

$$\mathbf{p}_{B_J}^{(k)} = \mathbf{F}_N^H \cdot \mathbf{M}_{B_J}^{(k)} \cdot \mathbf{F}_Q \cdot \tilde{\mathbf{p}}^{(k)}. \tag{7}$$

The modulated PS $\mathbf{p}_{B_{\Sigma/J}}^{(k)} = (p_0^{(k)}, \cdots, p_{N-1}^{(k)})^T$ is transmitted instead of one block $\mathbf{x}_{B_{\Sigma/J}}^{(k)}$ of the B-IFDMA signal in time domain (TD), i.e. $\mathbf{x}_{B_{\Sigma/J}}^{(k)} = \mathbf{p}_{B_{\Sigma/J}}^{(k)}$. The FD representation of the modulated PS $\mathbf{p}_{B_{\Sigma/J}}^{(k)}$ of user k is given by its N-point DFT

$$\mathbf{P}_{B_{\Sigma/J}}^{(k)} = \mathbf{F}_N \cdot \mathbf{p}_{B_{\Sigma/J}}^{(k)} = (P_0^{(k)}, \cdots, P_{N-1}^{(k)})^T. \tag{8}$$

The non-zero elements of $\mathbf{P}_{B_{\Sigma/J}}^{(k)}$ are combined in a vector $\mathbf{P}_{sy}^{(k)} = (P_{sy,0}^{(k)}, ..., P_{sy,Q-1}^{(k)})$ with elements $P_{sy,\hat{n}=(t\cdot K_f+r)}^{(k)} = P_{(t\cdot(K\cdot K_f)+r+k\cdot K_f)}^{(k)}$ for $r = 0, \cdots, K_f - 1$, $t = 0, ..., T-1$ and $\hat{n} = 0, ..., Q-1$.

Subcarrierwise Pilot Insertion. For subcarrierwise PI, N_p of the Q subcarriers allocated to a certain user are used for pilot transmission. Therefore, a PS $\tilde{\mathbf{p}}^{(k)} = (\tilde{p}_0^{(k)}, \cdots, \tilde{p}_{N_p-1}^{(k)})$ with N_p complex elements, e.g. taken from a CAZAC-sequence, is DFT precoded and mapped on the N_p subcarriers. N_p is dependent on the depth IP of interpolation in FD, e.g., for $IP = 2$ every 2nd subcarrier that is allocated to a specific user has to be used for pilot transmission. For simplicity, it is assumed that IP is always chosen such that the division $\frac{K_f}{IP}$ is integer. $N_p = T \cdot \frac{K_f}{IP}$ gives the number of subcarriers used for pilot transmission with T and K_f as defined in Section 2.

- *Added Signal B-IFDMA*
  For Added Signal B-IFDMA, the unmodulated PS $\tilde{\mathbf{p}}^{(k)}$ is divided into $\frac{K_f}{IP}$ subblocks $\bar{\mathbf{p}}^{(i,k)}$ with index $i = 0, ..., \frac{K_f}{IP}-1$, each consisting of T elements. The transmitted PS $\mathbf{p}_{B_\Sigma}^{(k)}$ is given by

$$\mathbf{p}_{B_\Sigma}^{(k)} = \sum_{i=0}^{\frac{K_f}{IP}-1} \mathbf{F}_N^H \cdot \mathbf{M}_{p\Sigma}^{(i,k)} \cdot \mathbf{F}_T \cdot \bar{\mathbf{p}}^{(i,k)}. \tag{9}$$

  The elements of the mapping matrix $\mathbf{M}_{p\Sigma}^{(i,k)}$ are given by

$$M_{p\Sigma}^{(i,k)}(n,t) = \begin{cases} 1 & \text{for } n = t \cdot \frac{N}{T} + k \cdot K_f + i \cdot IP \\ 0 & \text{else} \end{cases}, \tag{10}$$

with $n = 0, ..., N-1$, $t = 0, ..., T-1$. Within this block of pilot transmission, $Q - N_p$ subcarriers remain unused and thus, a DS $\tilde{\mathbf{d}}^{(k)} = (\tilde{d}_0^{(k)}, ..., \tilde{d}_{Q-N_p-1}^{(k)})$ can be mapped on the $Q - N_p$ subcarriers. The DS $\tilde{\mathbf{d}}^{(k)}$ is divided into $K_f - \frac{K_f}{IP}$ subblocks $\bar{\mathbf{d}}^{(m,k)}$ with index $m = 0, ..., K_f - \frac{K_f}{IP} - 1$, each consisting of T elements. The transmitted DS $\mathbf{d}_{B_\Sigma}^{(k)}$ is given by

$$\mathbf{d}_{B_\Sigma}^{(k)} = \sum_{m=0}^{K_f - \frac{K_f}{IP} - 1} \mathbf{F}_N^H \cdot \mathbf{M}_{d\Sigma}^{(m,k)} \cdot \mathbf{F}_T \cdot \bar{\mathbf{d}}^{(m,k)}, \tag{11}$$

with $m = b + r \cdot (IP - 1)$; $b = 0, ..., IP - 2$; $r = 0, ..., \frac{K_f}{IP} - 1$ and the elements of the mapping matrix $\mathbf{M}_{d\Sigma}^{(m,k)}$ given by

$$M_{d\Sigma}^{(m,k)}(n,t) = \begin{cases} 1 & \text{for } n = b + r \cdot IP + t \cdot \frac{N}{T} + k \cdot K_f + 1 \\ 0 & \text{else} \end{cases} \tag{12}$$

for $n = 0, ..., N-1$ and $t = 0, ..., T-1$.

- *Joint DFT B-IFDMA*
  For Joint DFT B-IFDMA, the PS $\mathbf{p}_{B_J}^{(k)}$ of user k for subcarrierwise PI is given by

$$\mathbf{p}_{B_J}^{(k)} = \mathbf{F}_N^H \cdot \mathbf{M}_{pJ}^{(k)} \cdot \mathbf{F}_{N_p} \cdot \tilde{\mathbf{p}}^{(k)}, \tag{13}$$

with the elements $M_{pJ}^{(k)}(n, q_p)$ of the mapping matrix $\mathbf{M}_{pJ}^{(k)}$ given by

$$M_{pJ}^{(k)}(n,q_p) = \begin{cases} 1 & \text{for } n = t \cdot \frac{N}{T} + r \cdot IP + k \cdot K_f \\ 0 & \text{else} \end{cases}, \tag{14}$$

for $q_p = r + t \cdot \frac{K_f}{IP}$ and $t = 0, ..., T-1$; $r = 0, ..., \frac{K_f}{IP} - 1$; $n = 0, ..., N-1$. Within the block of pilot transmission $Q - N_p$ subcarriers remain unused. The DS $\tilde{\mathbf{d}}^{(k)}$ is mapped on the $Q - N_p$ subcarriers and the transmitted DS $\mathbf{d}_{B_J}^{(k)}$ is given by

$$\mathbf{d}_{B_J}^{(k)} = \mathbf{F}_N^H \cdot \mathbf{M}_{d_J}^{(k)} \cdot \mathbf{F}_{Q-N_p} \cdot \tilde{\mathbf{d}}^{(k)}. \tag{15}$$

The elements $M_{dJ}^{(k)}(n, q_d)$ of the mapping matrix $\mathbf{M}_{d_J}^{(k)}$ are given by

$$M_{dJ}^{(k)}(n,q_d) = \begin{cases} 1 & \text{for } n = t \cdot \frac{N}{T} + r \cdot IP + b + k \cdot K_f + 1 \\ 0 & \text{else} \end{cases}, \tag{16}$$

with $q_d = b + r \cdot (IP-1) + t \cdot \frac{K_f}{IP}$ for $t = 0, ..., T-1$; $r = 0, ..., \frac{K_f}{IP} - 1$ and $b = 0, ..., IP-2$.

The non-zero elements of $\mathbf{p}^{(k)}_{B_{\Sigma/J}}$ in FD are combined in a vector $\mathbf{P}^{(k)}_{sc} = (P^{(k)}_{sc,0}, \ldots, P^{(k)}_{sc,N_p-1})$ with elements $P^{(k)}_{sc,\hat{n}=(t \cdot K_f/IP+r)} = P^{(k)}_{(t \cdot \frac{N}{T}+r \cdot IP+k \cdot K_f)}$ for $r = 0, \cdots, K_f - 1$, $t = 0, ..., T-1$ and $\hat{n} = 0, ..., N_p - 1$. For both variants of B-IFDMA, the sequence $\mathbf{x}^{(k)}_{B_{\Sigma/J}}$ transmitted in TD for CE with subcarrierwise PI is given by the sum of PS and DS and thus, $\mathbf{x}^{(k)}_{B_{\Sigma/J}} = \mathbf{d}^{(k)}_{B_{\Sigma/J}} + \mathbf{p}^{(k)}_{B_{\Sigma/J}}$.

3.2 CE Algorithm

In this Section, a CE algorithm is introduced for symbol- and subcarrierwise PI. In the following, only one user will be considered and the index k will be omitted for simplicity. Let $\mathbf{h} = (h_0, \cdots, h_{N-1})^T$ denote the vector representation of a channel with N coefficients h_i, $i = 0, \cdots, N-1$, at sample rate $1/T_c$. The values H_n denote the complex coefficients of the Channel Transfer Function (CTF) $\mathbf{H} = \mathbf{F}_N \cdot \mathbf{h} = (H_0, \cdots, H_{N-1})^T$ and $\breve{\mathbf{N}} = \mathbf{F}_N \cdot \breve{\mathbf{n}} = (\breve{N}_0, \cdots, \breve{N}_{N-1})^T$ denotes the Additive White Gaussian Noise (AWGN) on each subcarrier in FD. The channel is assumed to be time invariant for the transmission of the PS. The values V_n in FD with $n = 0, \cdots, N-1$, received on each subcarrier after transmission over the channel $\mathbf{h}$ can be described by one complex channel coefficient H_n due to flat fading on each subcarrier in FD and are given by

$$V_n = H_n \cdot P_n + \breve{N}_n. \tag{17}$$

At the non-zero samples $P_{sy/sc,\hat{n}}$ of the PS in FD, the channel transfer coefficients $H_{\hat{n}}$ can be estimated by

$$\hat{H}_{\hat{n}} = \frac{V_{\hat{n}}}{P_{\hat{n}}} = H_{\hat{n}} + \frac{\breve{N}_{\hat{n}}}{P_{\hat{n}}}. \tag{18}$$

The estimated coefficients $\hat{H}_{\hat{n}}$ are used for the equalization of $N_t = \frac{T_c}{5}$ consecutive blocks in TD, with T_c the coherence time of the channel.

Symbolwise Pilot Insertion. Thus, for symbolwise PI, the vector of estimated channel transfer coefficients is given by

$$\hat{\mathbf{H}} = (\hat{H}_0, ..., \hat{H}_{Q-1}). \tag{19}$$

Subcarrierwise Pilot Insertion. For subcarrierwise PI, the vector $\hat{\mathbf{H}}$ of estimated channel transfer coefficients is given by

$$\hat{\mathbf{H}} = (\hat{H}_0, ..., \hat{H}_{N_p-1}). \tag{20}$$

As interpolation is possible in FD, a linear interpolation filter is applied to the estimated channel transfer coefficients. The coefficients $\bar{H}_q^{(t)}$ with $q = 0, ..., K_f - 1$ of the vector $\bar{\mathbf{H}}^{(t)}$ for each block $t = 0, ..., T-1$ consisting of K_f elements are given by

$$\bar{H}_q^{(t)} = \begin{cases} \hat{H}_{t \cdot \frac{K_f}{IP} + r} & ; q = r \cdot IP \\ \delta_{\tilde{r}} \cdot (q - \tilde{r} \cdot IP) + \hat{H}_{t \cdot \frac{K_f}{Ip} + \tilde{r}} & ; q = \tilde{r} \cdot IP + b + 1 \\ \delta_{(\frac{K_f}{IP} - 2)} \cdot (q - K_f - 2IP) + \hat{H}_{\frac{K_f}{IP}(t+1) - 2} & ; q = K_f - IP + b + 1 \end{cases}, \tag{21}$$

with $r = 0, ..., K_f/IP - 1$; $\tilde{r} = 0, ..., K_f/IP - 2$; $b = 0, ..., IP - 2$; $\delta_x = \frac{\hat{H}_{t \cdot K_f/IP + x} - \hat{H}_{t \cdot K_f/IP + x + 1}}{IP}$. The vector $\tilde{\mathbf{H}}$ of interpolated channel transfer coefficients is given by

$$\tilde{\mathbf{H}} = (\bar{\mathbf{H}}^{(0)}, ..., \bar{\mathbf{H}}^{(T-1)}). \tag{22}$$

4. Performance Analysis

In this Section, the performance results with PCE and RCE, as well as the PAPR and the pilot symbol overhead are given for Added Signal B-IFDMA and Joint DFT B-IFDMA. The results are valid for the parameters given in Table 1. In Figure 1, the uncoded bit error rate (BER) performance is presented for Added Signal B-IFDMA and Joint DFT B-IFDMA with $K_f = 4$ and $T = 32$ resulting in a net bit rate of 10 MBit/s per user. The results are given for PCE and for RCE with symbol- and subcarrierwise PI. The results show that Added Signal B-IFDMA and Joint DFT B-IFDMA exhibit the same performances. For CE with symbolwise PI, both schemes show a performance degradation of about 3 dB at $BER = 10^{-2}$ compared to PCE. For CE with subcarrierwise PI, the degradation increases up to 3.6 dB at $BER = 10^{-2}$ due to interpolation errors, but, compared to symbolwise PI, an 0.2 MBit/s higher net bit rate is provided due to lower pilot symbol overhead. In Table 2, the pilot symbol overhead Λ in dB is presented for subcarrierwise PI in dependency of the number K_t of consecutive time division multiple access (TDMA) slots for Added Signal and Joint DFT B-IFDMA. It is assumed, that every 2. subcarrier in FD and one TDMA slot within K_t

Table 1. Simulation Parameters

Carrier Frequency	3.7 GHz	Coding	no Coding
Bandwidth	40 MHz	Equalizer	MMSE FDE
No. of Subcarriers	1024	Guard Interval	3.6 μs
Modulation	QPSK	Channel	WINNER SCM [11], 50 km/h

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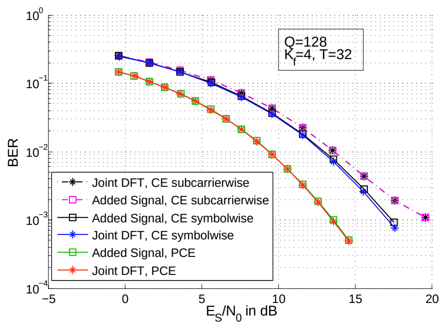

Figure 1. BER performance for added signal B-IFDMA and joint DFT B-IFDMA with PCE and RCE

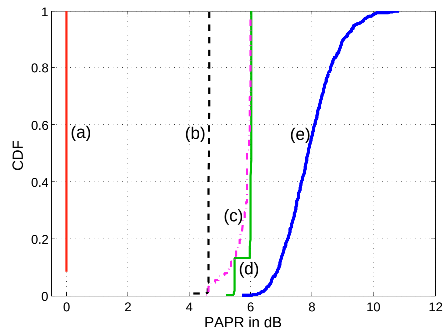

Figure 2. PAPR for (a)IFDMA, (b)Joint DFT B-IFDMA, (c)Joint DFT B-IFDMA with subcarrierwise PI, (d)Added Signal B-IFDMA with/without subcarrierwise PI, (e)OFDMA

Table 2. Pilot Symbol Overhead for $K_f = 4$

Number K_t of consecutive TDMA slots	1	3	12	24
Λ in dB for added signal B-IFDMA	3	0.8	0.18	0.09
Λ in dB for Joint DFT B-IFDMA	3	0.8	0.18	0.09

has to be used for pilot transmission. As the energy that has to be spent per data bit is increased relatively by pilot transmission, the overhead is equivalent to a Signal-to-Noise-Ratio (SNR)-degradation calculated according to the method introduced in [7]. The results in Table 2 show that Added Signal B-IFDMA and Joint DFT B-IFDMA require the same pilot symbol overhead for CE as the possibility of interpolation is identical for both. As it is always possible to interpolate within each block of K_f adjacent subcarriers, the pilot symbol overhead is independent from the data rate. The results show that the smaller the number K_t of consecutive TDMA slots, the higher the pilot symbol overhead, because the possibility of interpolation in TD decreases. Figure 2 presents the PAPR in dB for one block of Added Signal B-IFDMA with and without subcarrierwise PI, Joint DFT B-IFDMA with and without subcarrierwise PI and for IFDMA and OFDMA without PI as references. The results are given as cumulative density functions (CDF) and are valid for a net bit rate of 10 MBit/s and $K_f = 4$ for B-IFDMA. It can be seen that Joint DFT B-IFDMA exhibits a 1.4 dB lower PAPR than Added Signal B-IFDMA for 90% of all possible signals. If subcarrierwise PI is applied to the considered block, the PAPR degrades for Joint DFT B-IFDMA and both schemes show hardly a difference in PAPR for CDF values larger than 0.4.

5. Conclusion

In this work, Added Signal B-IFDMA and Joint DFT B-IFDMA have been introduced and investigated in terms of BER performance, pilot multiplexing for CE, PAPR and pilot symbol overhead. Both B-IFDMA variants provide the same BER performance for PCE as well as for the case with RCE. In terms of PAPR, Joint DFT B-IFDMA shows a clear better result than Added Signal B-IFDMA. This effect even intensifies for an increasing number K_f of subcarriers per B-IFDMA block. For subcarrierwise PI, there is hardly a difference for both schemes in terms of PAPR, but with increasing K_f, the PAPR of joint DFT B-IFDMA with subcarrierwise PI is expected to improve compared to Added Signal B-IFDMA with subcarrierwise PI. As both schemes exhibit the same subcarrier allocation, they require the same pilot symbol overhead for CE. If B-IFDMA is combined with TDMA, the pilot symbol overhead increases with decreasing number of consecutive TDMA slots.

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