Performance Trade-off Investigation of B-IFDMA

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***Abstract*— A performance trade-off investigation is carried out between different possible uplink multiple access schemes, that are based on Orthogonal Frequency Division Multiplexing (OFDM), for International Mobile Telecommunication (IMT) Advanced systems. Between the Discrete Fourier Transform (DFT) precoded systems with different subcarrier allocation mappings and systems lacking DFT-precoders, Block Interleaved Frequency Division Multiple Access (B-IFDMA) is shown to provide a good trade-off between the frequency diversity collected, envelope properties achieved, and channel estimation performance compared to the other mapping schemes. The schemes are analyzed in the presence of the different possible modules which include equalizers, modulators, interleavers, and channel codes. In particular, robust codes such as Turbo codes are able to collect the diversity provided by such schemes, and B-IFDMA systems is shown to be able to beat the other systems in bit error rate (BER) performance terms.**

I. Introduction

The wireless communication industry has always been under tremendous improvements in the past few decades, but will the needs for improvement reach an end? Not at all! Future wireless systems need to operate in widely different deployment scenarios and carry traffic with widely varying characteristics. As part of the International Telecommunication Union Radiocommunication Sector (ITU-R), IMT-Advanced capable Wireless World Initiative New Radio (WINNER) system concept, a diversity based multiple access scheme for robust uplink transmission denoted as Block Interleaved Frequency Division Multiple Access (B-IFDMA) was proposed to be used in scenarios where transmit channel state information is not readily available due to the imposed overhead, e.g. as with high speed or low data rate and for short control packets. The scheme obtains its robustness by means of a dispersed allocation of multiple blocks with equidistant spacing in frequency, where each block consists of a few consecutive subcarriers in a few consecutive Orthogonal Frequency Division Multiple Access (OFDMA) symbols over time [1]. This resource allocation structure enables a tunable degree of frequency diversity and low allocation signaling overhead. Moreover, it provides support for high power amplifier (HPA) efficiency in the uplink by the use of a DFT-precoding step. In addition, the possibility of a sub-slot allocation enables robust and efficient transmission for small packets and, at the same time, improves the battery life in user terminals.

The B-IFDMA multiple access scheme is a generalization of the DFT-precoded OFDMA with interleaved subcarrier allocation, denoted as Interleaved Frequency Division Multiple Access (IFDMA) in the original paper [2] or Single-Carrier Frequency Division Multiple Access (SC-FDMA) with distributed mapping in 3GPP Long Term Evolution (LTE) [3]. B-IFDMA is also a generalization of Localized Frequency Division Multiple Access (LFDMA) [4], denoted SC-FDMA with localized mapping in LTE [3]. Moreover, B-IFDMA follows the same mapping as the non DFT-precoded OFDMA with equidistant block subcarrier allocation denoted as Block Equidistant FDMA (B-EFDMA) [1].

In this paper, Section II provides the system model of the uplink multiple access schemes followed by a generic signal definition for all the different schemes, together with the parameters used in the simulations. Then, in Section III, an end-to-end analysis of B-IFDMA and the other candidate multiple access DFT-precoded schemes IFDMA, LFDMA, together with the non DFT-precoded B-EFDMA is carried out under different usage scenarios. Finally, the conclusion highlights the extracted best parameters since the results are highly dependent on all the modules involved ranging from the equalization schemes, modulation techniques, channel coding methods, to the channel estimation performance at the receiver.

II. System Model

In this section, the system model for DFT-precoded OFDMA (IFDMA, LFDMA, B-IFDMA), and non DFT-precoded OFDMA (B-EFDMA) schemes is shown for a single user. Discrete time representation of the signals is used in accordance with the following notations: $(.)^T$ as the transpose, $(.)^{-1}$ as the inverse, $(.)^\dagger$ as the pseudo inverse, and $(.)^H$ as the Hermitian.

Throughout the derivations, a system with Q users will be used with user index q, where $q = 0, 1, \ldots, Q-1$ and raw data for each user denoted as $\mathbf{d}^{(q)}$. The block diagram with the corresponding matrix representation is shown in Fig. 1. The raw data is firstly processed by the channel encoder block using Convolutional or Turbo coding. The coded bits in one chunk duration are then randomly interleaved, where a chunk is a time-frequency unit in which the subcarriers included experiences flat fading, and the interleaver depth is affected by the number of allocated subcarriers in the chunk duration. This is followed by baseband modulation (QPSK or 16-QAM) where the energy of the modulated symbols are normalized. So the modulated symbols in one OFDMA/SC-FDMA symbol is denoted as $\mathbf{s}_K^{(q)} = (s_0^{(q)}, \ldots, s_k^{(q)}, \ldots, s_{K-1}^{(q)})^T$, where K is the number of subcarriers allocated to a user, $k = 0, 1, \ldots, K-1$

Authors contributed equally to this work.

is the subcarrier index of a user. The data rate achieved for a particular user is directly proportional to K.

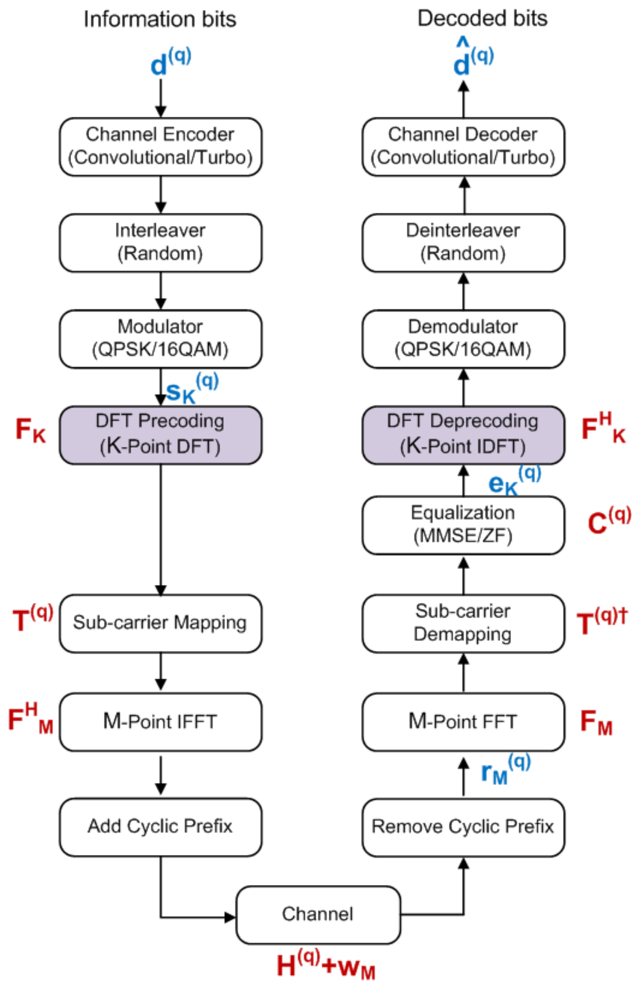

Fig. 1. Uplink System Model.

In the case of non DFT-precoded OFDMA, the modulated symbols are considered as frequency symbols and mapped on the available subcarriers allocated to a user. These are then transmitted over the channel by applying Inverse Fast Fourier Transform (IFFT). So the received symbol in a non DFT-precoded OFDMA system can be expressed as a vector of length M samples (i.e. total number of subcarriers in the system where $M = Q \cdot K$) defined as:

$$\mathbf{r}^{(q)}_{M,nonDFT} = \mathbf{H}^{(q)} \cdot \mathbf{F}^{H}_{M} \cdot \mathbf{T}^{(q)} \cdot \mathbf{s}^{(q)}_{K} + \mathbf{w}_{M}, \quad (1)$$

where $\mathbf{T}^{(q)}$ is the subcarrier mapping matrix which is user dependent, $\mathbf{F}^{H}_{M}$ is the matrix representation of the M-point Inverse Fast Fourier Transform (IFFT), $\mathbf{H}^{(q)}$ is the normalized multipath propagation channel coefficient matrix of a metropolitan typical urban macro-cell scenario modelled by the WINNER channel (C2 NLOS) for the q^{th} user [5] , and $\mathbf{w}_M$ is the Additive White Gaussian Noise (AWGN). The cyclic prefix is not included in the equation since it is an addition and removal of some redundant bits to eliminate the ISI but has no effect on the mathematical modeling of the overall system as long as its length is at least equal to the maximum delay spread of the channel.

The only difference between DFT-precoded and non DFT-precoded OFDMA schemes is the presence of the DFT-precoding block which is shaded in the block diagram. In other words, the modulated symbols are DFT-precoded resulting in the frequency domain symbols, and the same procedure is followed as in the non DFT-precoded case. The mathematical representation of the received symbol becomes:

$$\mathbf{r}^{(q)}_{M,DFT} = \mathbf{H}^{(q)} \cdot \mathbf{F}^{H}_{M} \cdot \mathbf{T}^{(q)} \cdot \mathbf{F}_{K} \cdot \mathbf{s}^{(q)}_{K} + \mathbf{w}_{M}. \quad (2)$$

To compensate for the impact of the channel in both cases (DFT-precoded and non DFT-precoded), equalization is applied and the equalized received samples can be expressed as a vector of length K defined by

$$\mathbf{e}^{(q)}_{K} = \mathbf{C}^{(q)} \cdot \mathbf{T}^{(q)\dagger} \cdot \mathbf{F}_{M} \cdot \mathbf{r}^{(q)}_{M}, \quad (3)$$

where $\mathbf{F}_M$ represents the M-point Fast Fourier Transform (FFT), $\mathbf{T}^{(q)\dagger}$ is the subcarrier demapping matrix, $\mathbf{C}^{(q)}$ is the equalization matrix. Note that for any user, Zero Forcing (ZF) equalization and Minimum Mean Square Error (MMSE) equalization are the two Frequency Domain Equalizers (FDE) that are used in this system and are defined as:

$$\mathbf{C}_{ZF} = \frac{1}{\mathbf{H}}, \quad (4)$$

$$\mathbf{C}_{MMSE} = \frac{\mathbf{H}^{H}}{|\mathbf{H}|^2 + \frac{\sigma_w^2}{\sigma_s^2}}, \quad (5)$$

where σ_w^2 is the variance of the AWGN, and σ_s^2 is the variance of the modulated symbols, and H is the channel frequency response.

In the case of non DFT-precoded OFDMA/SC-FDMA, the equalized samples are then demodulated, deinterleaved and decoded to get the estimated transmitted data block $\hat{\mathbf{d}}^{(q)}$. Whereas in the case of DFT-precoded OFDMA/SC-FDMA, the above mentioned steps are preceded by a DFT-predecoder.

The difference between the subcarrier mapping schemes is nothing but how the K modulated symbols corresponding to one user are mapped onto the K allocated subcarriers in one OFDMA/SC-FDMA symbol which has a length equal to the total number of subcarriers in the system.

Assuming equal number K of subcarriers allocated to each active user, the subcarrier mapping allocation matrix $\mathbf{T}^{(q)}$ of size $M \times K$ for user q in the different schemes can be represented by the following:

- *IFDMA*

$$\mathbf{T}^{(q)}_{IFDMA}(m,k) = \begin{cases} 1, & m = k \cdot Q + q \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

- *LFDMA*

$$\mathbf{T}^{(q)}_{LFDMA}(m,k) = \begin{cases} 1, & m = q \cdot K + k \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

- *B-IFDMA* and *B-EFDMA*

$$\mathbf{T}^{(q)}_{B-IFDMA}(m,k) = \begin{cases} 1, \; m = p \cdot \frac{M}{P} + l + q \cdot L \\ 0, \; \text{otherwise} \end{cases} \tag{8}$$

$$\mathbf{T}^{(q)}_{B-EFDMA}(m,k) = \mathbf{T}^{(q)}_{B-IFDMA}(m,k), \tag{9}$$

where L is the number of subcarriers in each block, $l = 0, 1, \ldots, L-1$ is the subcarrier index per block, $P = K/L$ denotes the number of blocks assigned to a specific user, $p = 0, 1, \ldots, P-1$ is the index of the blocks, and $m = 0, 1, \ldots, M-1$ is the system's subcarrier index.

TABLE I

SIMULATION PARAMETERS.

Bandwidth	80 MHz
Carrier Frequency (Fc)	3.7 GHz
Sampling Time (Ts)	12.5 ns
Sampling Rate (Fs)	1/(12.5 ns)
Guard Interval	1.47 μs
Total Number of Subcarriers (M)	1024
Number of Subcarriers per User (K)	64, 128
Subcarriers per Block (L)	4, 16
Chunk Width (Nt)	12 OFDM Symbols
Modulation	QPSK, 16-QAM
Channel Coding	Convolutional Code [6], Code Rate = 1/2, G1 = $1 + D^2 + D^4 + D^5$, G2 = $1 + D + D^2 + D^3 + D^5$, Constraint Length = 6, Soft Input Viterbi Decoder
	Turbo Code [7], Code Rate = 1/2, G1 = $1 + D + D^2 + D^3 + D^4$, G2 = $1 + D^4$, Constraint Length = 5, LogMAP Decoder
Interleaver	Random
Equalizer	MMSE FDE, ZF FDE
Channel	WINNER C2 NLOS, User Velocity = 50 Km/h, Coherence Bandwidth = 680.27 KHz, Coherence Time = 5.8 ms
Channel Estimation	Perfect CSIR, Estimated CSIR with Wiener Filter

Table I shows the different parameters involved to define the different possible usage scenarios that are investigated.

III. RESULTS

In this section, the peak-to-average power ratio (PAPR) and Bit error rate (BER) performance of B-IFDMA is scrutinized against the other uplink multiple access schemes, taking into consideration the different possible configuration scenarios, in the presence and absence of perfect channel state information at the receiver (CSIR).

A. PAPR Analysis

By definition, the PAPR of a transmitted signal $x(t)$ is $\frac{max|x(t)|^2}{E[|x(t)|^2]}$, and this acts as a measure of the envelope properties of this signal, which in turn affects the HPA efficiency levels that can be achieved.

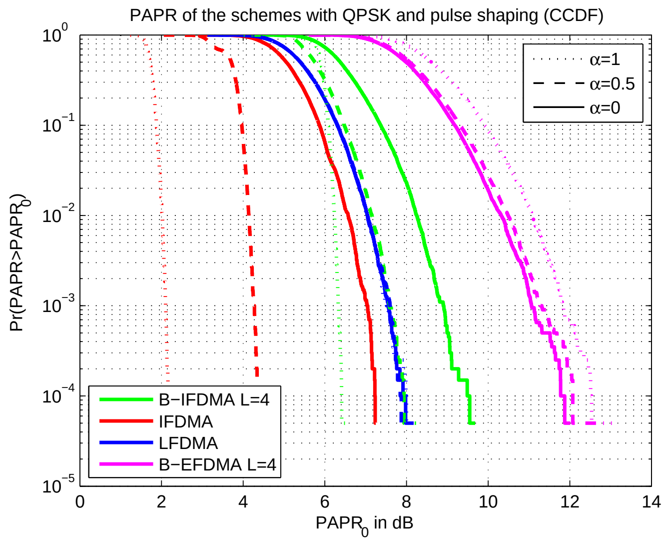

Fig. 2. Complementary Cumulative Distribution Funtion (CCDF) of the PAPR for the schemes with QPSK and Raised Cosine pulse shaping filter with roll-off factor α.

In the absence of pulse shaping with QPSK modulation, DFT-precoded schemes have a lower back-off requirements on the HPA compared to the non DFT-precoded B-EFDMA and that is because the time domain signal of the latter is the superposition of all the subcarriers with different carrier frequencies thus high amplitude peaks are inevitable. In the DFT-precoded schemes, IFDMA has the lowest PAPR, LFDMA has the worst PAPR, and B-IFDMA with a block size L of 4 is in between. The reason why IFDMA has the lowest PAPR is due to its time domain representation and the fact that the transmitted signal is nothing but Q repetitions of the original signal scaled by a factor of $\frac{1}{Q}$, where Q is the number of users in the system [4]. In the presence of pulse shaping equipped with QPSK modulation as shown in Fig. 2, DFT-precoded systems still perform better than the non DFT-precoded ones, but the former gains from increasing the roll-off factor unlike the latter. The analytical reason for this behavior of B-EFDMA which is a variant of OFDMA is elaborated in [8]. Moreover, the PAPR difference between the different schemes is lessened in the presence of pulse shaping than with no pulse shaping. The same trend is valid for systems with 16-QAM modulation but the overall performance is deteriorated due to the multi-level amplitude squared constellation.

B. BER Analysis

In Fig. 3 to Fig. 6, we show the BER performance of the considered schemes in various scenarios. In all cases, the same number K of subcarriers per user are allocated.

Fig. 3 shows the ability of MMSE equalizer to take into consideration the effect of noise while equalizing thus beating the same system equipped with ZF equalizer. For the ZF

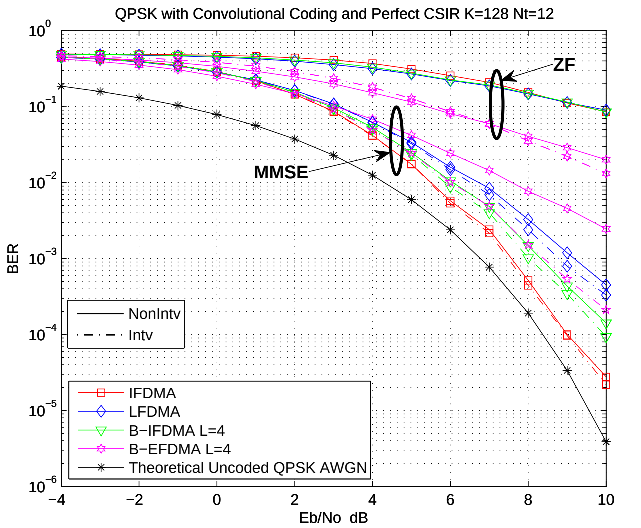

Fig. 3. BER for QPSK with and without Interleaver (Intv/NonIntv respectively), in the presence of Convolutional coding, Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) Equalizers ,with perfect CSIR.

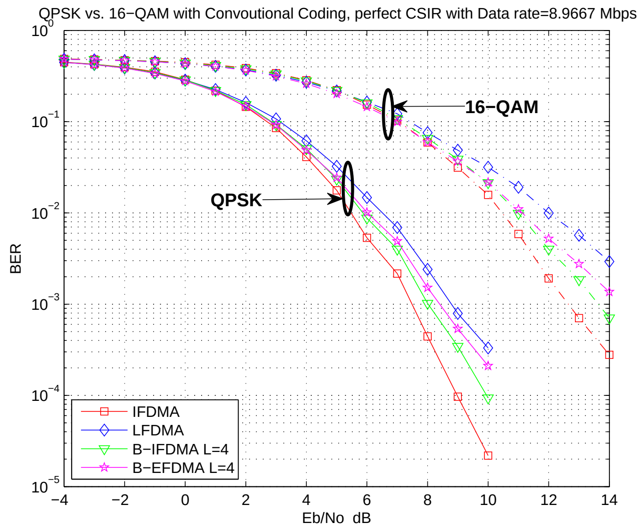

Fig. 4. BER for QPSK (K=128) and 16-QAM (K=64) with data rate of 8.9667 Mbps, in the presence of Convolutional coding, MMSE equalizer, interleaver over whole chunk duration Nt=12, with perfect CSIR.

case, non DFT-precoded systems perform better than the DFT-precoded ones. The reason for that is DFT-precoding which introduces intersymbol interference (ISI) due to the shortened modulated symbols' duration, and where the ZF equalizer is not able to mitigate this ISI effect. As for the diversity measure, decreasing the block size L for B-EFDMA leads to a better performance after a signal-to-noise ratio (SNR) threshold of 7 dB. Moreover, for the DFT-precoded case, LFDMA performs the best followed by B-IFDMA and then IFDMA up till 10 dB and viceversa after an SNR of 10 dB. This simply means that decreasing the block size improves the performance after an SNR of 10 dB. For the MMSE case, the DFT-precoded system has a better performance than the non DFT-precoded case after an SNR of 2 dB, and decreasing the block size after this SNR improves the performance for both cases.

In the presence of ZF equalizer, interleaver improves the performance of the non DFT-precoded B-EFDMA case after an SNR of 6 dB, and the reason for that is because less error events are generated allowing the interleaver to provide diversity gain. Whereas, for the DFT-precoded case, up till the simulated SNRs, the interleaver worsens the performance as presented in [9], but it should provide with much better diversity gain at higher SNRs. However, with the use of MMSE equalizer, the interleaver provides a better performance after an SNR of 3 dB for both DFT and non DFT-precoded cases with more gain in the non DFT-precoded case (B-EFDMA).

Fig. 4 shows the performance with interleaving and MMSE equalization for both modulation schemes at the same data rate of 8.9667 Mbps. It is obvious that QPSK outperforms 16-QAM on the behalf of having double the number of subcarriers per user which leads to better frequency diversity collection, at

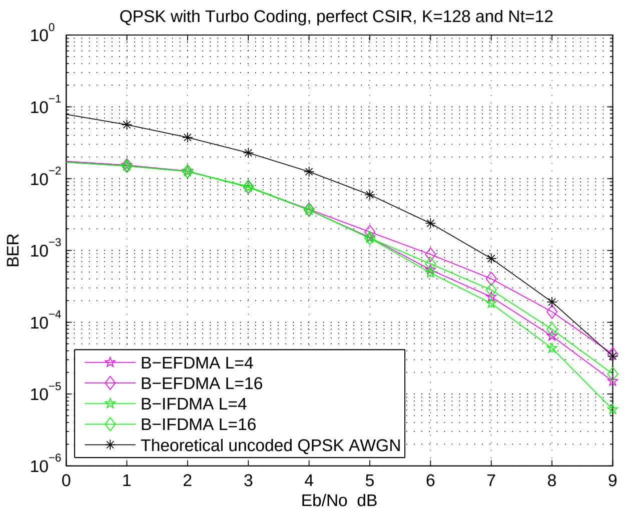

Fig. 5. BER for QPSK with interleaver, in the presence of Turbo coding, MMSE equalizer, with perfect CSIR.

the cost of lower spectral efficiency. Another reason supporting 16-QAM's poor performance, is its tighter decision boundaries which leads to more error events. It can be noted that there is around 6 dB degradation with 16-QAM modulation compared to the QPSK case at high SNRs.

Investigations are done to see the effect of deploying more robust codes compared to the convolutional codes to highlight their strengths in how much frequency diversity they can collect from the different subcarrier mapping schemes. Fig. 5 shows the BER performance of B-IFDMA and B-EFDMA and the ability of Turbo codes to collect this diversity provided by these schemes. It is obvious that B-IFDMA beats B-EFDMA

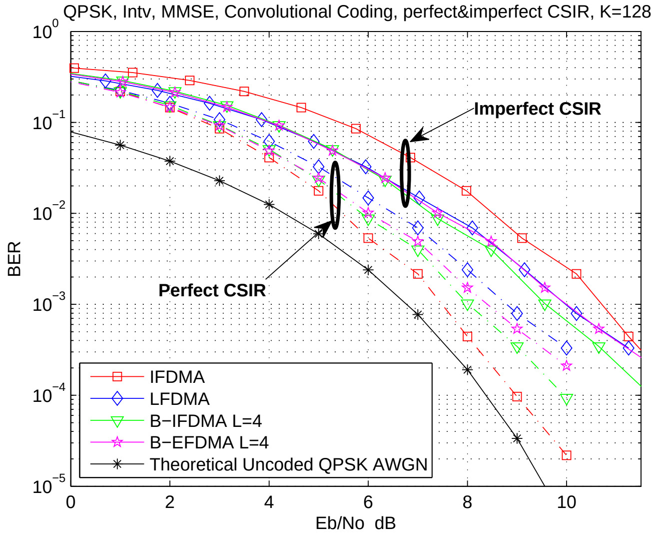

Fig. 6. BER for QPSK with interleaver, in the presence of Convolutional coding, MMSE equalizer, with perfect and imperfect CSIR with Nt=12.

after an SNR of 5 dB having the same block size allocation, while the two are almost performing the same before that SNR. This shows the importance of DFT-spreading and its immunity against channel fades. Moreover, it is clear that reducing the block sizes allocated to users for both schemes enhances the BER performance due to the more frequency diversity collected by the smaller blocks.

Till now and in the presence of perfect CSIR, better performance is accompanied with decreased block sizes due the better frequency diversity collection. But this story changes when there is a lack of perfect CSIR as shown in Fig. 6 for the interleaved case with MMSE equalization. In [10], it has been shown that the effect of channel estimation errors on various detection algorithms in OFDM receivers can be well modeled as an additional white noise contribution with a variance given by the channel estimation error variance. Using the performance degradation values due to imperfect channel estimation at the receiver presented in [11] for chunk-based Wiener filtering, LFDMA performance which was the worst in the presence of perfect CSIR, approaches B-IFDMA and B-EFDMA up till an SNR of 6 dB. The reason for that is because LFDMA allows interpolation in the frequency domain, which leads to a better channel estimation performance. For the IFDMA scheme which is performing the best in the case of perfect CSIR, it has now the worst BER performance since interpolation in the frequency domain is impossible leading to a poor channel estimation performance. Asymptotically, IFDMA will perform better due to its larger frequency diversity collection ability. After an SNR of 6 dB, it can be noticed that regardless of the good channel estimation performance that LFDMA offers, collecting more frequency diversity is of a greater importance. In case of persistent scheduling, Kalman filter based channel estimation would lower this SNR threshold even further [11]. As a result, B-IFDMA which combines the advantages of collecting frequency diversity and having a decent channel estimation performance, is shown to beat all the other schemes.

IV. Conclusion

The essence of this work highlights the trade-off between frequency diversity, PAPR, and channel estimation (Perfect, Imperfect) at the receiver, in the presence of different equalizers (ZF, MMSE), channel codes (Convolutional, Turbo), for different modulation (QPSK, 16-QAM) schemes for the uplink multiple access (DFT-precoded, Non DFT-precoded) intended for IMT-Advanced.

The investigations show the novelty of B-IFDMA and its high capability in collecting frequency diversity, while offering a low back-off requirements on the HPA, besides providing a good BER performance under imperfect CSIR. On the other hand, B-EFDMA together with a strong channel code has also the ability to collect frequency diversity, and good channel estimation performance, but it severely suffers from high PAPR which is a critical constraint for mobile terminals. Besides these main parameters, deploying different modulation techniques and changing the type of channel codes only have a shifting effect on the BER curves. Furthermore, the performance of the different schemes in the presence of an interleaver is highly dependent on the type of equalizer used.

Finally, B-IFDMA is indeed a promising candidate for the IMT-Advanced uplink, offering a high performance while maintaining a good trade-off between the other involved critical parameters.

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