DFT-OQAMA: An Alternative Multiple Access for Future Mobile Networks

Mohamed Gharba [1], Hao Lin[1], Pierre Siohan[1] and Fabrice Labeau[2]
[1]Orange Labs, 4 rue du Clos Courtel, 35512 Cesson-Sévigné Cedex, France
Email: [mohamed.gharba,hao.lin,pierre.siohan]@orange.com
[2]McGill University, Electrical and Computer Engineering, 3480 rue University Montreal, H3A 0E9 Quebec, Canada
Email: [fabrice.labeau]@mcgill.ca

***Abstract*—In order to reduce the Peak-to-Average Power Ratio (PAPR) of multicarrier signals, a DFT-precoding technique can be particularly useful. In this paper we propose to combine such a DFT precoding with the OFDM/OQAM modulation to provide a new frequency access scheme, that we call in short DFT-OQAMA. This DFT-OQAMA technique is compared to the Single-Carrier Frequency Division Multiplex Access (SC-FDMA) recently proposed for the UpLink (UL) of the 3GPP LTE system.**

***Index Terms*—DFT-OQAMA, SC-FDMA, 3GPP/LTE, uplink, channel estimation, channel equalization.**

I. Introduction

Mobile radio transmission is affected by the time and frequency dispersion of the channel. The well-known Orthogonal Frequency Division Multiplexing (OFDM) modulation [1] constitutes an efficient and simple mean to avoid the first, i.e. time dispersion, impairment. Furthermore, if properly dimensioned, i.e. selecting an appropriate number of subcarriers and Cyclic Prefix (CP) length, up to a certain point, CP-OFDM can also support mobility, i.e. time selectivity. It is why CP-OFDM has been adopted in various standardized air interfaces, as for instance in DAB, DVB-T, IEEE 802.11, 802.16 [2]. OFDM is also a simple way to share the radio resource in frequency and it is why OFDMA has also been retained for downlink 3GPP/LTE transmission [3]. Nevertheless, OFDM systems have a few drawbacks; a first one is the loss of spectral efficiency due to the use of the CP, while a second one is its bad sinc-shaped frequency response. Both drawbacks can be avoided replacing the standard constellation, e.g. Quadrature Amplitude Modulation (QAM), used to modulate each sub-carrier by a time-offset modulation, e.g. Offset QAM (OQAM). We, then, get the OFDM/OQAM modulation scheme, see e.g. [4], that can be also used as a frequency access technique, named OQAMA in [5].

On the other hand, CP-OFDM and OFDM/OQAM have a common drawback which is related to their relatively high Peak to Average Power Ratio (PAPR). Stated otherwise the use of MCM may complicate the analog amplification stage design and increase its cost. This problem may be partly solved by a Discrete Fourier Transform (DFT) precoding technique as recently illustrated with the SC-FDM approach adopted for the 3GPP LTE uplink (UL). Similarly, we can also envision to combine DFT precoding with OFDM/OQAM to get reduced PAPRs as already illustrated in [6], and to analyze it as a frequency access technique that we call DFT-OQAMA.

Indeed, in this paper, we discuss the suitability of using DFT-OQAMA instead of SC-FDMA for the UL 3GPP/LTE scenario, considering perfect time and frequency synchronization. The paper is organized as follows. Section II presents the basic principles of SC-FDMA and DFT-OQAMA radio interfaces. Section III presents the receiver techniques used for DFT-OQAMA system; we mainly present a technique for preamble-based channel estimation (CE) and the equalization method. Section IV presents the adaptation of the DFT-OQAMA system in a 3GPP-like environment. Section V evaluates the efficiency of the proposed system. Finally Section VI summarizes the main conclusions of this work and outlines the work perspectives.

II. Principles of DFT-OQAMA

In this section we briefly present the two different modulation and access schemes, SC-FDMA and DFT-OQAMA, considered in this paper and reported in Fig. 1. In this schematic description the non-colored blocks correspond to the common functionalities while the blue blocks are for SC-FDMA, and the green blocks are for DFT-OQAMA. Our descriptions are in discrete-time and the AFE (Analog Front End) functionalities (DAC, ADC, RF) are common to all considered systems.

A. Principle of OFDM/OQAM

Contrary to CP-OFDM, the OFDM/OQAM modulation does not require the use of any guard interval, which directly leads to a gain in spectral efficiency. Furthermore, the OFDM/OQAM prototype function is not restricted, as for CP-OFDM, to the rectangular window. To obtain a sufficient robustness to the channel variations, this prototype function must be well localized in both time and frequency domains. Having a good localization in time leads to the reduction of Inter Symbol Interference while improving the localization in frequency permits a limitation of the Inter Carrier Interference due for instance to Doppler effect. In OFDM/OQAM, for the $m-th$ subcarrier at time symbol n, a real-valued symbol $a_{m,n}$ is emitted which corresponds to either the real or the imaginary

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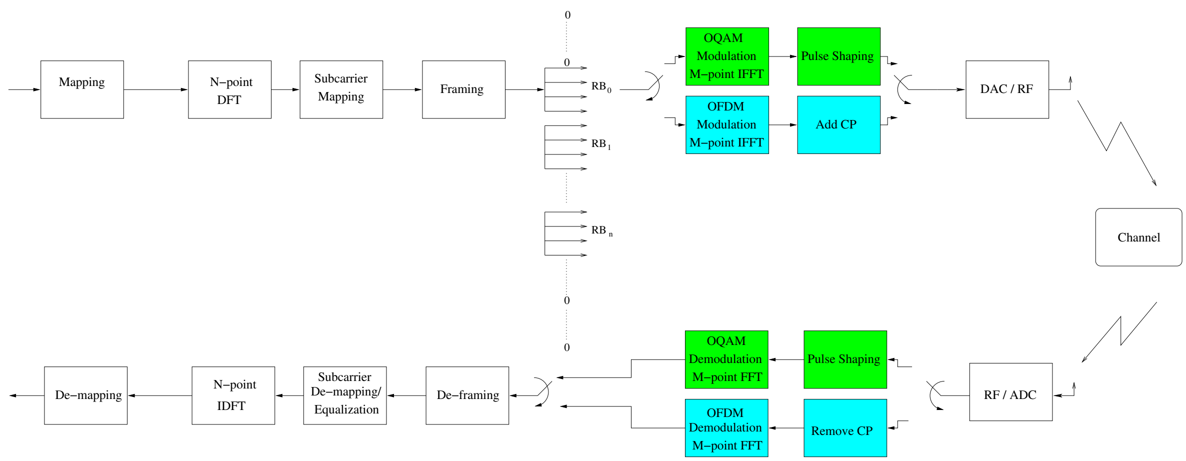

Fig. 1. UL SC-FDMA and DFT-OQAMA system configurations (the key difference between SC-FDMA and DFT-OQAMA is highlighted in different colors.

part of a complex OFDM data symbol $c_{m,n}$ obtained from QAM constellations.

In the following we denote by T_0 the duration of the $c_{m,n}$'s, then $\tau_0 = \frac{T_0}{2}$ is the duration of the real OQAM data symbols $a_{m,n}$. This leads to two main implications: the orthogonality only holds in the real field and the M-point (I)FFT(s) have to run twice faster than for OFDM. Note however that the IFFT cost can be reduced by a factor greater than 2 [7], which at the end, even including the implementation cost of the prototype filter, leads to an OFDM/OQAM modulator with a complexity that may be quite similar to the CP-OFDM one. Denoting by F_0 the intercarrier spacing we have $\tau_0 F_0 = \frac{1}{2}$. This means that the density of the subcarriers in the time-frequency plane for OFDM/OQAM is twice that of OFDM. Therefore, the spectral efficiency of OFDM/OQAM is the same as for OFDM without CP.

Setting $T_0 = MT_s$ with T_s the sampling period, as shown in [4], the discrete-time baseband OFDM/OQAM signal is expressed as follows:

$$s[k] = \sum_n \sum_{m=0}^{M-1} a_{m,n} \underbrace{g[k - n\frac{M}{2}] e^{j\frac{2\pi}{M} m (k - \frac{L-1}{2})} e^{j\phi_{m,n}}}_{g_{m,n}[k]}, \quad (1)$$

where $j = \sqrt{-1}$, L is the length of the prototype filter g, M is the even number of subcarriers, $\phi_{m,n}$ is the phase term chosen here such that $\phi_{m,n} = \frac{\pi}{2}(m+n)$.

B. Adaptation from OFDM/OQAM to DFT-OQAMA

Here, we propose a multiple access scheme based on the combination of DFT spreading and OFDM/OQAM modulation. We can see the schematic description of DFT-OQAMA in Fig. 1, where a mapping block converts the binary input into a multilevel sequence of baseband symbols leading to several possible constellation formats, including BPSK, QPSK, 16-QAM and 64-QAM. Then, after a DFT precoding process, the transmitter groups the symbols and maps them to dedicated resource blocks (RBs), after which MCM is performed.

The main principle of DFT-OQAMA is the same as for OFDM/OQAM, while the key difference comes from the fact that we apply a DFT matrix before OFDM/OQAM modulation in order to reduce the PAPR of the modulated signal. According to Fig. 1, the transmission processing of DFT-OQAMA can be illustrated as follows. The mapped constellations $c_{k,n}^u$, which belong to user u and later to be mapped to time index n of the frame frequency-time grid, are firstly transformed by an N-point DFT process where the value of N depends on the number of RBs being allocated to user u, i.e.,

$$\widetilde{c}_{m,n}^u = \frac{1}{N} \sum_{k=0}^{N-1} c_{k,n}^u e^{-j\frac{2\pi k m}{N}}. \quad (2)$$

Then, after the RBs mapping and framing processes, the precoded symbols $\widetilde{c}_{m,n}^u$ are separated in their real and imaginary parts before conducting the OFDM/OQAM modulation, i.e.,

$$s_u[k] = \sum_n \sum_{m=0}^{M-1} \widetilde{a}_{m,n}^u g_{m,n}[k], \quad (3)$$

where $\widetilde{a}_{m,n}^u$ is either the real or imaginary part of the complex signal $\widetilde{c}_{m,n}^u$. Thanks to the DFT precoding, it would be less frequently that the power of the modulated signal $s_u[k]$ is aggregated to a few samples. Thus, we can have a reduced PAPR value [6]. Finally, in time domain, the DFT-OQAMA signal can be expressed as

$$s_{\text{DFT-OQAMA}}[k] = \sum_{u=0}^{U-1} s_u[k], \quad (4)$$

with U the total number of allocated users.

III. Receiver Techniques

To take into account its specificities, namely the absence of CP and an orthogonality feature that only holds in the real field, new channel estimation and equalization methods have been built for the OFDM/OQAM modulation. They can also be used for its DFT precoded version. In this section we recall the basic principle of the efficient channel estimation and equalization methods that will be used afterwards.

A. Channel Estimation (CE)

Assuming the channel is linearly time invariant and the prototype filter is well localized in time and frequency, noise taken apart, the received signal at phase-space (m, n) is given by [8]

$$y_{m,n} \approx H_{m,n}(a_{m,n} + ja_{m,n}^{(i)}), \quad (5)$$

where $a_{m,n}^{(i)}$ is called intrinsic interference and $H_{m,n}$ is the channel coefficient. As long as we have the knowledge of $a_{m,n} + ja_{m,n}^{(i)}$, the channel estimates can be obtained by

$$\hat{H}_{m,n} = \frac{y_{m,n}}{a_{m,n} + ja_{m,n}^{(i)}}. \quad (6)$$

In [8], the authors proposed to use a preamble of duration $3\tau_0$, i.e. 3 consecutive values of the time index n, for which naturally the pilot values $a_{m,n}$ are known. The knowledge of this preamble also permits to get an accurate approximation of the resulting interference component $a_{m,n}^{(i)}$. Thus, this CE method was called Interference Approximation Method (IAM). Selecting a particular structure for this preamble, alternating pure real and pure imaginary pilot values, we get the variant named IAM-I (I stands for imaginary). In [8], it is shown that IAM-I can provide a significant advantage to OFDM/OQAM in comparison to CP-OFDM. To justify it shortly, let us just say that only transmitting a sequence $\{a_{m,n}\}$ of pilot symbols, the receiver takes advantage of all the power of the sequence $\left\{a_{m,n} + ja_{m,n}^{(i)}\right\}$ which constitutes a virtual pilot and provides a virtual boosting.

Thus, in our proposed DFT-OQAMA system, we will reuse IAM-I preamble structure.

B. Equalization

As the OFDM/OQAM signal does not contain any CP, the interference cannot be avoided. Then, either the channel is not too harmful and/or small constellation orders are used, so that a low Signal to Noise Ratio (SNR) at the reception is sufficient, making the interference component negligible. Otherwise, we need to operate at higher SNR and then the interference cannot be neglected anymore. In the first case a one-tap equalization can be appropriate while in the second one more powerful equalizers are required.

In this paper, we reuse the adaptation to OFDM/OQAM [9] of the Complex FIR Subcarrier Equalizer (CFIR-SCE) method [10]. This carrier-wise 3-tap CFIR-SCE equalizer can be written as, at the carrier index m, $E_m^{CFIR-SCE}(z) = e_{0m}z + e_{1m} + e_{2m}z^{-1}$, where the equalizer coefficients e_{im} are listed in below [9, (7.3)]

$$e_{0m} = -\frac{1}{2}\left(\frac{\eta_{-1m} - \eta_{1m}}{2} - j(\eta_{0m} - \frac{\eta_{-1m} + \eta_{1m}}{2})\right)$$
$$e_{1m} = \frac{\eta_{-1m} + \eta_{1m}}{2}$$
$$e_{2m} = -\frac{1}{2}\left(\frac{\eta_{-1m} - \eta_{1m}}{2} + j(\eta_{0m} - \frac{\eta_{-1m} + \eta_{1m}}{2})\right)$$

where η_{im} is the target channel response at a chosen frequency. If a Minimum Mean Square Error (MMSE) criterion is considered, this coefficient reads

$$\eta_{im} = \frac{H^*(e^{(2m+i)\frac{\pi}{M}})}{|H(e^{(2m+i)\frac{\pi}{M}})|^2 + \sigma_n^2}$$

with σ_n^2 the noise variance and where $(.)^*$ denotes complex conjugation.

IV. Environment and system parameters

In the 3GPP/LTE, the decision was in favor of the OFDMA and SC-FDMA techniques. However, at an earlier stage of the 3GPP debates, OFDM/OQAM was among the candidates [11] but at that time the experience around it was relatively limited when compared to OFDM. In the last few years OFDM/OQAM has become a more and more mature transmission technique and, as illustrated for example in Section III, simple and efficient channel estimation/equalization techniques are now available. In [5], we have already shown that furthermore OFDM/OQAM can be made compatible with a 3 GPP LTE UL framing. In this section we first review the basic principle of this adaptation to the LTE.

For this purpose, since OFDM/OQAM does not require CP, we need to change some parameters to match the LTE system frame structure. To introduce the OFDM/OQAM within the 3GPP/LTE framework, we start from the 3GPP/LTE system parameters in short CP configuration considered for the 20 MHz FDD mode [3]. In this transmission mode, in a slot duration equal to 0.5 ms, 7 complex CP-OFDM symbols are transmitted as shown in Fig. 2. A subframe is constituted of two such successive slots and it also corresponds to the minimum transmission duration. Thus, over a 1 ms period of time, a subframe transmits 14 OFDM symbols. Thus, aggregating 14 OFDM symbols plus their 14 CP durations we obtain $14T_0 + T_0 = 1$ ms, which allows us to put 30 OFDM/OQAM symbols within one slot as shown in Fig. 2. This can be formulated as: $K \times (\frac{M}{2F_s}) = 0.5$ ms, where K is the number of OQAM data symbols. For $F_s = 30.72$ MHz and $M = 2048$, we have $K = 15$. In other words, in one slot, we can transmit the full payload over $15\tau_0 = 7.5T_0$ duration which is longer than CP-OFDM case (only $7T_0$ for payload, and $0.5T_0$ for CP). This extra time-slot can be used for CE.

In 3GPP/LTE, in each subframe, the 4^{th} and 11^{th} SC-FDMA symbols are used for the UL reference signals transmission, especially for CE. The reference signals, based on Zadoff Chu sequences [3], are transmitted as preamble on the RBs used for the user payload. While the IAM-I CE method (presented in subsection III-A) is used for DFT-OQAMA.

As depicted in Fig. 2, we insert the IAM-I preamble in the OFDM/OQAM slots. Their time occupancy is equal to $3\tau_0$. The OFDM/OQAM slots being composed of 15 real-valued symbols ($= 15\tau_0$), these pilots are inserted in positions #7, #8 and #9, the rest are the data symbols from #1 to #6 and from #10 to #15. As to the prototype filter, in order to effectively squeeze the modulated signals into the subframe, it is preferable to use a prototype filter length as short as

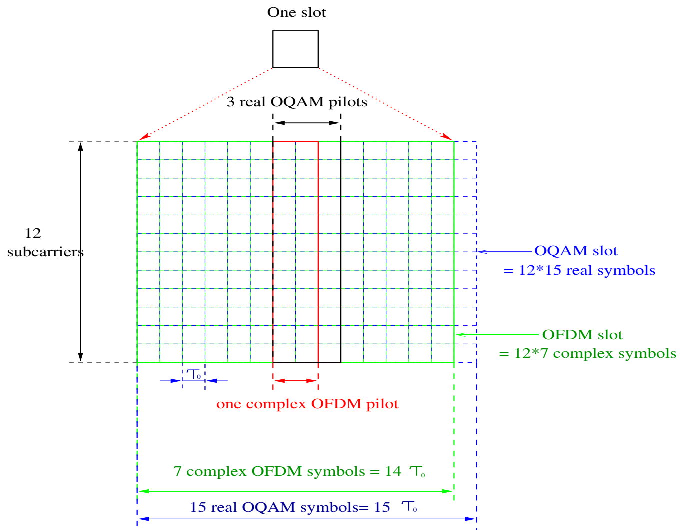

Fig. 2. The structure of CP-OFDM and OQAM slots in 3GPP/LTE UL.

possible. Indeed, with OFDM/OQAM the overlap between each OQAM multicarrier symbols increases with L. When this overlap occurs at the edge of two subframes allocated to two different users, this creates a multi-user interference. To avoid this a guard interval between two subframes needs to be inserted. Or, as shown recently in the particular case of a short prototype filter ($L = M$) [12], using appropriate simple transmission and reception techniques for the frontier symbols, one can avoid the transmission of the overlapping samples and the insertion of any guard interval, while still being able to recover all the subframe symbols. On the other hand, for a time-frequency dispersive channels, time-frequency localization (TFL) is an appropriate design criterion for the prototype filters. Then, as shown in [4] for this criterion, it is possible to get by a discrete-time optimization a short prototype filter ($L = M$) performing nearly as well as a four times longer IOTA (Isotropic Orthogonal Transform Algorithm) prototype filter. Furthermore, in addition to its shorter length, as shown in [8], TFL1 has another advantage over IOTA which is to provide with IAM-I a better CE. Therefore, for all these reasons, in our proposed DFT-OQAMA system, as in [8], we choose the TFL1 prototype filter.

V. Simulations

Our simulations have been carried out with a TU6 (Typical Urban with 6 taps) channel model [13] and modulation parameters that are borrowed from the 3GPP/LTE standard. The channel profile and the main parameters of the system used are: sampling frequency $F_s = 30.72$ MHz, number of paths=6, power profile (in dB)= -3, 0, -2, -6, -8 and -10, delay profile (μs)= 0, 0.2, 0.5, 1.6, 2.3 and 5, binary turbo coding scheme of one half rate [14], QPSK modulation and $M = 2048$, the transmission scheme used in our simulations is illustrated in Fig. 1. The TFL1 prototype filter is used. For DFT-OQAMA it matches the frame size, causes no extra latency, and has a reduced complexity.

Two extreme cases are evaluated in our simulation comparison, i.e., A) all the 20 RBs are allocated to one user and B) only 1 RB is assigned to one user. Furthermore, we also proceed our simulations under two different velocity scenarios and they are 3 km/h and 120 km/h, respectively. The Zadoff Chu sequence is used as the preamble for SC-FDMA channel estimation while the IAM-I method is adopted for DFT-OQAMA system [8]. Regarding the channel equalization methods, we choose 1-tap ZF for SC-FDMA and the previously presented 3-tap CFIR-SCE for DFT-OQAMA.

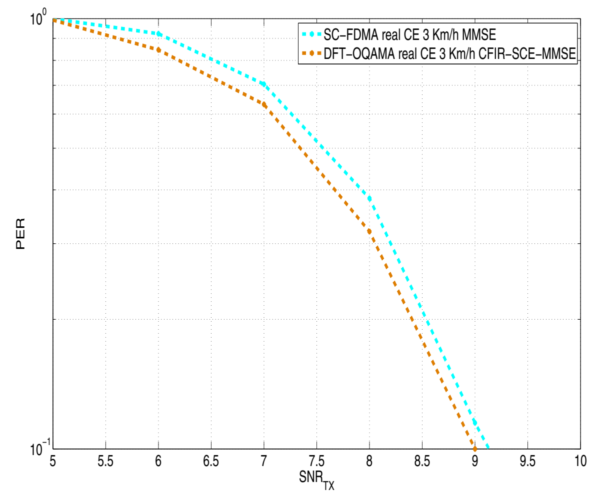

Fig. 3. PER versus transmitted SNR for case-A at 3 km/h.

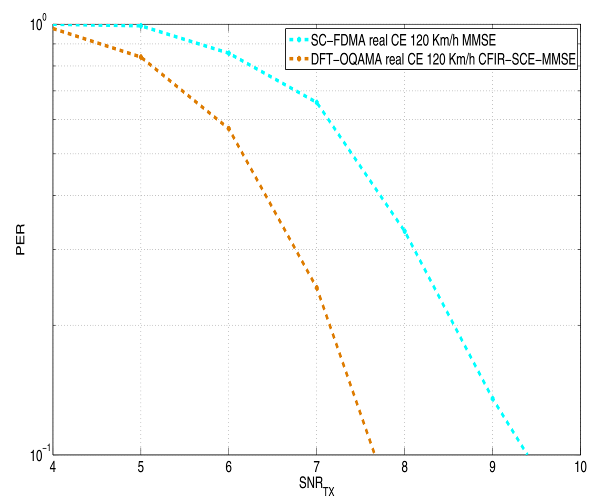

Fig. 4. PER versus transmitted SNR for case-A at 120 km/h.

Figs. 3 and 4 show the performance comparisons in the case A in the form of PER (Packet Error Rate) versus SNR at the transmitter side (SNR_{TX}). We observe that at a pedestrian speed the DFT-OQAMA outperforms SC-FDMA by 0.2 dB for a 10^{-1} PER value. This gain can be considered as the benefit of using IAM-I CE method. Moreover, this performance gain

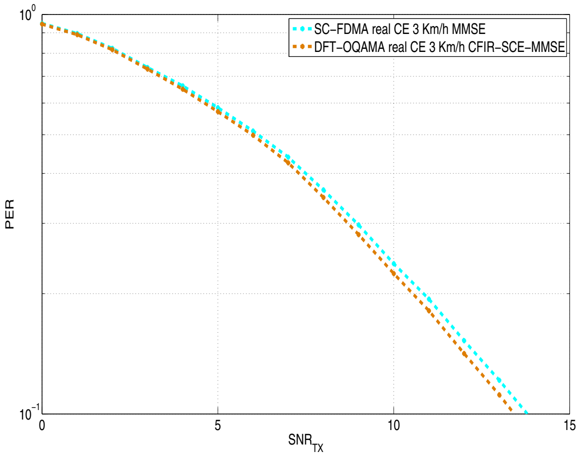

Fig. 5. PER versus transmitted SNR for case-B at 3 km/h.

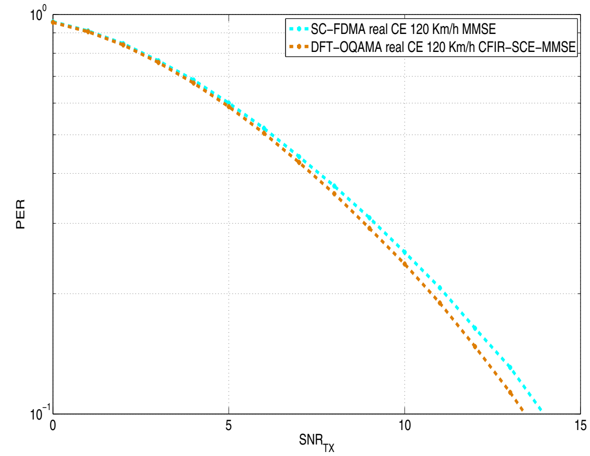

Fig. 6. PER versus transmitted SNR for case-B at 120 km/h.

increases to 1.7 dB while the mobile user's speed increases to 120 km/h as shown in Fig. 4. This could be understood by the fact that, in addition to the CE gain, DFT-OQAMA can exploit more gains from its Doppler resistance.

On the other hand, based on the results displayed in Figs. 5 and 6, we observe that in the case B the performances of both systems are worse than the ones in the case A. This is actually expected since transmitting over whole band obviously could exploit more diversity. Thus, for the user allocation the frequency hopping is usually suggested to benefit the frequency diversity of the whole band. Otherwise, the relative comparison between DFT-OQAMA and SC-FDMA in the case B retains the same conclusion as the one obtained in the case A.

As a result we also see in these last figures that for the same targeted 10^{-1} PER, DFT-OQAMA has a SNR gain over SC-FDMA that is either around 0.2 or 0.4 dB at low and high mobility, respectively. It is again due to the robustness of the pilot symbols produced by the IAM-I method, which yields to a boosted pseudo virtual pilot power that is superior to the CP-OFDM instantaneous pilots power. So the use of preamble pilot symbols in the 3GPP/LTE framework is in favor of DFT-OQAMA compared to SC-FDMA showing that DFT-OQAMA is robust for the UL 3GPP/LTE transmission.

VI. Conclusion

We have proposed an alternative multiple access scheme based on OFDM/OQAM to the well-known SC-FDMA technique for the UL transmission in 3GPP/LTE context. Similarly to SC-FDMA, it operates in frequency and also takes advantage of a DFT precoding, so it was named DFT-OQAMA. The DFT-OQAMA frame structure has been adapted to map the 3GPP/LTE framework. The two resulting systems have been compared in a frame transmission mode considering similar theoretical spectral efficiency, i.e. no CP for DFT-OQAMA but a longer preamble. It has been shown that the use of the IAM-I method for CE, initially proposed for OFDM/OQAM [8], also improves the DFT-OQAMA performance compared to SC-FDMA. The price for this improvement is a slightly higher complexity, that mainly concerns the receiver. All this shows that DFT-OQAMA may be a strong candidate for future radio networks. Indeed it has the advantage of a better spectrum efficiency, which is an essential feature we need to face the scarceness of frequency band.

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