Channel Pre- and Post-Equalization in Uplink OFCDM Systems with Mobility

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Abstract—**In this paper, we propose an up-link Orthogonal Frequency and Code Division Multiplexing (OFCDM) mobile cellular system that uses channel pre-equalization at the Mobile Terminal (MT) and adaptive detection at the Base Station (BS). Assuming a time division duplex that may offer channel reciprocity between down- and up-links, a low-complexity channel pre-equalization avoids explicit channel estimation at the BS with a very good performance for low MT velocities. A data-aided adaptive detection at the BS starting directly in a tracking mode thanks to pre-equalization can compensate for the increasing mismatch between channel pre-equalization and actual channel response caused by large velocities all along the uplink frame. Simulation results using a 4G realistic scenario show that the proposed uplink OFCDM system offers a good performance with a high spectral efficiency, as it is able to transmit large data rates with mobility and no need of pilot symbols.**

Keywords: OFCDM, MC-CDMA, Uplink, TDD, Pre-equalization, Doppler, Adaptive detection.

I. INTRODUCTION

The Orthogonal Frequency and Code Division Multiplexing (OFCDM) technique has already been recognized as a good candidate for the air interface of future mobile cellular systems and wireless local area networks [1] [2]. OFCDM, which is also referred to as Multi-Carrier Code Division Multiple Access (MC-CDMA), applies CDMA spreading before Orthogonal Frequency Division Multiplex (OFDM) modulation so that the signals of different users are orthogonal in the frequency domain [3]. Thus, OFCDM inherits the OFDM and CDMA benefits: High spectral efficiency, robustness against multi-path propagation, multiple access flexibility, good robustness against inter-cell interference.

In contrast with the Down-Link (DL) that has been widely investigated, an optimized use of OFCDM in Up-Link (UL), i.e. from Mobile Terminals (MT) to the Base Station (BS), is an open issue since a few difficulties must still be solved. In particular, dealing with signal envelope with a large peak-to-average power ratio at the MT and estimating a plurality of channels for equalization at the BS remain challenging tasks. This paper focuses on the second aspect.

In a Time Division Duplex (TDD) communication system, an alternative solution to multi-channel estimation and equalization at the BS is UL channel pre-equalization processed at MTs. This implicitly assumes that the channel is reciprocal between consecutive DL and UL transmission periods, i.e. slots. The channel estimates, which can be easily computed by each MT during a DL slot, e.g. using a DL pilot-based channel estimation technique [4], are re-used during the next UL slot for channel pre-compensation. This principle has been proposed for OFCDM UL systems in [5] using a zero-forcing algorithm. However, such a rough approach may induce a very large increase of the transmit power, which cannot be tolerated by MTs. In contrast, we recently proposed two pre-equalization algorithms that aim at maximizing the Signal over Interference plus Noise Ratio (SINR) at the BS with a constrained transmit power at MTs [6]. Assuming perfect channel knowledge and channel reciprocity, an optimized solution was shown to outperform a conventional UL OFCDM system with multi-user detection at the BS. Alternatively, a sub-optimum solution yields a good trade-off between performance and complexity. However, when mobility is considered, the assumption of channel reciprocity may not hold anymore. Then, the performance of systems based on channel pre-equalization degrades rapidly and channel post-equalization at the BS becomes mandatory.

In this paper, we extend the UL OFCDM communication scheme proposed in [6] to deal with mobility. The low-complexity channel pre-equalization of [6] is improved to compensate for part of the unpredictable variations of the channel response in the UL slot caused by the Doppler effect. In addition, adaptive equalization is used at the BS to track the channel variations within the UL slot transmission. Thus, adaptive equalization does not need any acquisition phase since it starts in a correctly initialized mode thanks to pre-equalization at MTs. As a consequence, channel reciprocity between DL and UL slots is only required between the last symbol of the DL slot and the first symbol of the next UL slot. Thus, pilot-aided channel estimation is avoided at the BS with a good performance even with moving MTs. The remainder of this paper is organized as follows: We describe the proposed system in section II. In section III, we present an improvement of the pre-equalization scheme proposed in [6] to limit the degradation due to mobility. We also describe how adaptive detection is processed at the BS and estimate the limitations with respect to the Doppler effect. Section IV provides simulation results and section V concludes the paper.

II. TDD-BASED OFCDM SYSTEM

The proposed TDD-based OFCDM system is represented in Fig. 1 with one BS and K active MTs. We focus on the DL and UL communications of MT i.

In DL, for each user k, data symbol $d_k(m)$ at time m is spread over L_D chips with spreading vector $\mathbf{c}_{Dk}$. A summation of all users' chips generates a multi-user data chip stream. Pilot chips are inserted at both ends of the DL slot to allow channel estimation at the MT side. Then, OFDM modulation is carried out using N_C sub-carriers and a cyclic prefix is inserted to avoid inter-symbol interference. Moreover, a guard time τ_0 is added at the end of each slot to prevent interference between UL and DL. The corresponding signal is sent through the multi-path channels of the different MTs. At MT i, cyclic prefix removal and OFDM demodulation is carried out on the received signal corrupted by an Additive White Gaussian Noise (AWGN). We assume that the OFDM symbol duration is chosen to be much smaller than the channel coherence time and the cyclic prefix is dimensioned to absorb the delay spread of the channel. Therefore, the impact of the i-th multipath channel on each sub-carrier can be modeled by complex fading coefficients $h_i^\ell(m)$. Based on pilot chips, estimates of these coefficients are computed for the detection stage.

In UL, we use the last channel estimates $h_i^\ell(m=0)$ computed by MT i at the end of the preceding DL slot in order to pre-equalize the channel at time n>0. The data symbol $d_i(n)$ is first spread using an orthogonal, e.g. Walsh-Hadamard, spreading vector $\mathbf{c}_{Ui}$ of size L_U with elements c_{Ui}^ℓ taking value in $\{-1/\sqrt{L_U}, 1/\sqrt{L_U}\}$. We assume that the number of sub-carriers N_C is a multiple of L_U so that we get N_C/L_U independent sub-systems in parallel. Focusing on a given sub-system, on each sub-carrier ℓ, the chip $c_{Ui}^\ell d_i(n)$ is multiplied by a pre-equalization coefficient $w_i^\ell(n)$, which is a function of channel estimate $h_i^\ell(0)$. The L_U pre-equalized chips are then distributed over the sub-carriers of the OFDM multiplex. After OFDM modulation and insertion of the cyclic prefix, the signal of MT i is transmitted towards the BS through the i-th multi-path channel. The BS is assumed to receive the sum of K synchronized MT signals, which have propagated through K distinct channels, corrupted by AWGN. Removing the cyclic prefix, a single OFDM demodulation yields the observation vector $\mathbf{r}(n)$ of size L_U defined as:

$$\mathbf{r}(n) = \sum_{k=1}^{K} \left(\mathbf{h}_k(n) \circ \mathbf{w}_k^*(n) \circ \mathbf{c}_{Uk}\right) d_k(n) + \mathbf{b}(n) \qquad (1)$$

where $\mathbf{h}_k(n)$, $\mathbf{w}_k(n)$ and $\mathbf{b}(n)$ are vectors of size L_U containing for each sub-carrier the channel coefficients $h_k^\ell(n)$, the pre-equalization coefficients computed at MT k and the AWGN components respectively. The symbol $\circ$ defines the vector multiplication processed element by element and the superscript * is the complex conjugate operator.

Due to each MT velocity, Doppler variations impact the K distinct UL channels independently all along the communication period. Then, the pre-equalization, which has been processed at MT i on the basis of initial channel estimates $\mathbf{h}_i(0)$, may not match the channel response at time n>0. Thus, a post-detection stage including equalization and despreading becomes mandatory at the BS to avoid performance degradations. This required user-specific detection involves vector $\mathbf{g}_i(n)$, so that a soft estimate $\tilde{d}_i(n)$ of the desired symbol of MT i is:

$$\begin{aligned}\tilde{d}_i(n) &= \mathbf{g}_i^H(n)\mathbf{r}(n) \\ &= \mathbf{g}_i^H(n)\sum_{k=1}^{K}\left(\mathbf{h}_k(n) \circ \mathbf{w}_k^*(n) \circ \mathbf{c}_{Uk}\right) d_k(n) + \mathbf{g}_i^H(n)\mathbf{b}(n)\end{aligned} \qquad (2)$$

where the superscript ^{H} denotes the conjugate-transpose complex operator.

In order to emphasize the separate contribution of the desired signal, the Multiple Access Interference (MAI) and the noise, we can rewrite (2) as:

$$\begin{aligned}\tilde{d}_i(n) &= \underbrace{\mathbf{g}_i^H(n)\left(\mathbf{h}_i(n) \circ \mathbf{w}_i^*(n) \circ \mathbf{c}_{Ui}\right) d_i(n)}_{\text{desired signal}} \\ &+ \underbrace{\mathbf{g}_i^H(n)\sum_{k=1,k\neq i}^{K}\left(\mathbf{h}_k(n) \circ \mathbf{w}_k^*(n) \circ \mathbf{c}_{Uk}\right) d_k(n)}_{\text{MAI}} + \underbrace{\mathbf{g}_i^H(n)\mathbf{b}(n)}_{\text{noise}}\end{aligned} \qquad (3)$$

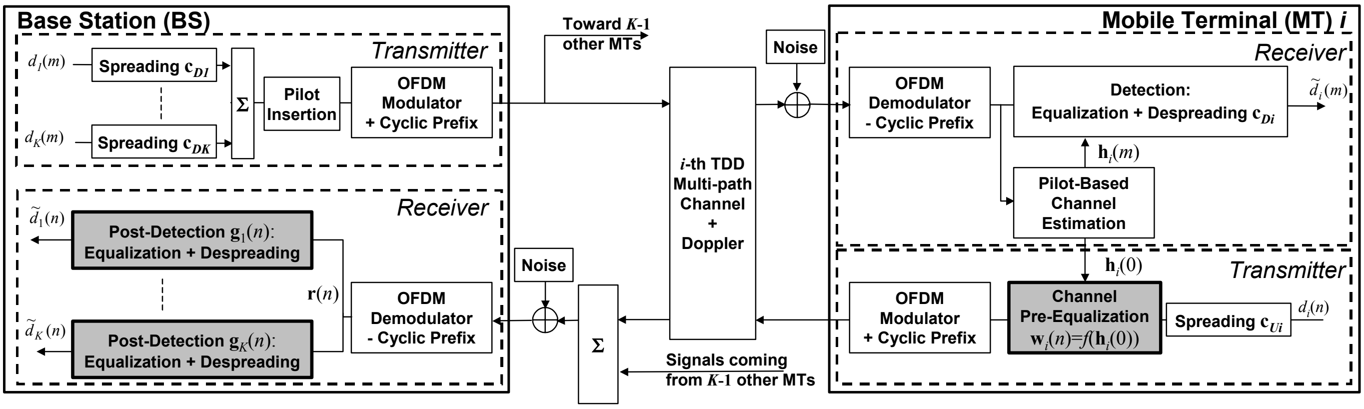

Figure. 1: OFCDM-TDD communication system with K users.

III. CHANNEL PRE-EQUALIZATION AND ADAPTIVE POST-DETECTION

Applying UL channel pre-equalization aims at pre-compensating for distortions that are predictable from the MTs' point of view. In a complementary way, adaptive post-detection at BS is in charge of correcting the unpredictable degradations due to MT velocity.

A. Channel Pre-Equalization in case of Doppler

In [6], we proposed a pre-equalization filter assuming stationary channels. Using a fixed transmit power constraint given by $|\mathbf{w}_i(n)|^2=L_U$, we aimed at maximizing a so-called modified SINR defined at the BS for MT i as:

$$m\text{-SINR}_i = \frac{P_{Di}}{\sum\limits_{k\neq i} P_{\mathrm{MAI}}(i/k)+\sigma^2} \tag{4}$$

where P_{Di} is the power of the desired signal, $P_{MAI}(i/k)$ defines the MAI power contribution of MT i on MT k and σ^2 is the variance of the noise term in (3).

This modified SINR does not require knowledge of the channel coefficients of the interfering MTs at MT i, which offers practical advantages for the network. On that basis, we derived two algorithms: an Optimum Modified SINR-based Pre-equalization (OMSP) and a Sub-Optimum Modified SINR-based Pre-equalization (S-OMSP). As the former solution involves solving a $L_U\times L_U$ linear system, which may require a large computational effort and since we need low-complexity MTs, we focus on the latter solution. Thus, the S-OMSP coefficients are computed on a per-carrier basis as [6]:

$$w_i^\ell(n) = \frac{\lambda\cdot h_i^\ell(n)}{(K-1)\cdot\left|h_i^\ell(n)\right|^2+L_U\sigma^2} \tag{5}$$

where $w_i^\ell(n)$ is the ℓ-th component of vector $\mathbf{w}_i(n)$ and λ is a scalar chosen with respect to the fixed transmit power constraint.

However, in practice, the channel coefficients are only computed by the MTs at time m=0, i.e. at the end of the DL slot. This would lead to the approximated pre-equalization coefficients $\tilde{w}_i^\ell(n)$ defined as:

$$\tilde{w}_i^\ell(n) = \frac{\lambda'\cdot h_i^\ell(0)}{(K-1)\cdot\left|h_i^\ell(0)\right|^2+L_U\sigma^2} \quad \forall n>0 \tag{6}$$

where λ' is a scalar chosen to respect the fixed transmit power constraint. Depending on the mobile velocity, using (6) may not correctly pre-compensate for the channel distortions during the entire UL slot transmission. Therefore, we propose to optimize the pre-equalization vector by anticipating as much as possible at MTs the UL channel variations in presence of Doppler. Precisely, we propose to consider statistical knowledge of the channel coefficients using the narrow-band assumption [7] to describe the $h_i^\ell(n)$ process on each sub-carrier ℓ of the OFDM multiplex as:

$$h_i^\ell(n) = \frac{1}{\sqrt{P_i}}\sum_{p=1}^{P_i}\rho_p\exp\left(j\phi_p\right)\exp\left(j2\pi f_d\left(nT+\tau_0\right)\cos\theta_p\right) \tag{7}$$

where P_i is the number of paths of the i-th channel, ρ_p and ϕ_p are the amplitude and phase uniformly distributed over $[0,2\pi[$ of path p at time 0, θ_p is the angle of arrival uniformly distributed over $[0,2\pi[$ of path p, f_d is the maximum Doppler frequency, T is the OFDM total symbol duration (including the cyclic prefix) and τ_0 is the UL/DL guard interval.

Thus, instead of the optimum formulation in (5) that cannot be computed due to a lack of knowledge at MTs, we propose pre-equalization vector $\overline{\mathbf{w}}_i(n)$, whose components are defined as:

$$\overline{w}_i^\ell(n) = \frac{\lambda\cdot \mathrm{E}\left[h_i^\ell(n)\right]}{(K-1)\cdot\mathrm{E}\left[\left|h_i^\ell(n)\right|^2\right]+L_U\sigma^2} \tag{8}$$

where E[x] is the statistical expectation of x.

(8) involves first and second order statistics of the channel coefficient $h_i^\ell(n)$ instead of actual values. By doing so, we aim at improving the performance of pre-equalization by taking into account some channel variations due to mobility.

Defining $\varepsilon=2\pi f_dT$ and $\varepsilon_0=2\pi f_d\tau_0$, having knowledge of $h_i^\ell(0)$ which is assumed to be normalized, we get the following results after some mathematical manipulations [7]:

$$\begin{aligned}\mathrm{E}\left[\left|h_i^\ell(n)\right|^2\right] &= \left|h_i^\ell(0)\right|^2 J_0{}^2(n\varepsilon+\varepsilon_0)+1-J_0{}^2(n\varepsilon+\varepsilon_0)\\ \mathrm{E}\left[h_i^\ell(n)\right] &= h_i^\ell(0)\cdot J_0(n\varepsilon+\varepsilon_0)\end{aligned} \tag{9}$$

where $J_0(x)$ is the Bessel function of the first kind of order 0.

Considering the approximation $J_0(x)$=1-x^2/4 for small values of x and using (9) in (8), we get the following approximation of the ℓ-th component of $\overline{\mathbf{w}}_i(n)$:

$$\overline{w}_k^\ell(n) \approx \frac{\lambda''\cdot h_i^\ell(0)}{(K-1)\left(\left|h_i^\ell(0)\right|^2+\dfrac{(n\varepsilon+\varepsilon_0)^2}{2}\right)+L_U\sigma^2} \quad \forall n>0 \tag{10}$$

where λ'' is chosen to match the transmit power constraint.

Compared to (6), (10) requires at each MT knowledge of f_d, i.e. the mobile velocity, which may be already available in the network, e.g. for location based services or cell assignment optimization. From (10), we can interpret the impact of Doppler on each chip as an additional noise of variance $0.5(K\text{-}1)(n\varepsilon+\varepsilon_0)^2$, which is proportional to the number of interfering users and increases with delay n between last available channel estimate at time 0 and actual transmission time n.

B. Adaptive MMSE Post-Detection

The previous improvement of the channel pre-equalization induces a mitigation of the MAI with respect to the noise and the Doppler effect. However, it does not ensure a correct coherent demodulation at the BS side. Thus, post-detection involving adaptive equalization is required at the BS side to compensate for the mismatch between pre-equalization based on $\mathbf{h}_i(0)$ and channel response $\mathbf{h}_i(n)$ that increases with n.

Therefore, we consider a decision-directed adaptive detection at the BS, which seems particularly suitable in this context: the acquisition of initial filter coefficients $\mathbf{g}_i(0)$ can be avoided thanks to pre-equalization, so that self-decisions can be used to track the channel non-stationarities with no need of pilot symbols.

The proposed detection stage relies on the Adaptive Linear Combiner (ALC) structure [8], whose convergence is controlled by the Normalized Least Mean Square (N-LMS) algorithm [9]. By using the N-LMS algorithm, we aim at minimizing the Minimum Mean Square Error (MMSE) after detection with a good trade-off between performance and complexity. The user-specific update rule of coefficient vector $\mathbf{g}_i(n)$ is the following:

$$\begin{aligned} &\mathbf{g}_i(1) = \mathbf{c}_{Ui} \\ &\mathbf{g}_i(n+1) = \mathbf{g}_i(n) + \mu(n)\, e_i(n)\mathbf{r}^*(n) \quad \forall n > 1 \end{aligned} \tag{11}$$

where $\mu(n)$ is the N-LMS step-size [9] and $e_i(n)$ is the error signal directing the convergence of the algorithm.

When applying (11) for n=1, the detection stage only consists in a simple despreading using sequence $\mathbf{c}_{Ui}$. Hereby, we assume low channel variations during $T+\tau_0$. Thus, thanks to pre-equalization, the decision variable after threshold $\hat{d}_i(1)$ may be reliable enough to be used as a reference for the computation of the error at time n=2. Therefore, we propose a decision-directed error signal:

$$e_i(n) = \hat{d}_i(n) - \tilde{d}_i(n) \tag{12}$$

where $\tilde{d}_i(n)$ is a soft estimate of $d_i(n)$ as expressed in (2), and $\hat{d}_i(n)$ is a hard decision on $\tilde{d}_i(n)$. Thus, we perform an adaptive MMSE detection with no need of pilot-symbols.

Due to the adaptive process, some limitations can be expected. Indeed, for a fixed SINR after despreading, the SINR per chip decreases with the spreading factor while the size of vector $\mathbf{g}_i(n)$ increases. Moreover, an ALC with a larger number of taps requires a lower step-size to achieve a given MSE performance [9]. This induces a reduction of the ALC tracking capabilities that may degrade the performance in case of channel non-stationarities. Thus, in case of large Doppler variations, we expect that the ALC will be all the more effective as the spreading factor decreases.

IV. Simulation Results

In this section, we evaluate the performance of the proposed OFCDM scheme with Doppler-based S-OMSP pre-equalization at MTs and adaptive post-detection at the BS in case of mobility. The simulation parameters, which are summarized in Table 1, match the requirements of a 4G mobile cellular system [2].

TABLE I. SIMULATION PARAMETERS

Carrier frequency	5 GHz
Sampling frequency	57.6 MHz
FFT size	1024
Number of modulated carriers	736
Slot duration	0.667 ms
Cyclic prefix duration	3.75 µs
Multi-path channel model	BRAN channel E
UL/DL guard time (τ_0)	20.83 µs
MT velocity (v)	20km/h / 60 km/h
Spreading codes	Walsh-Hadamard
Spreading factor (L_U)	8 / 16 / 32
Modulation alphabet	QPSK

We use the BRAN channel E [10], which refers to a typical outdoor multipath propagation at 5 GHz in small cells. Channel responses $\mathbf{h}_i(0)$ obtained at the end of the DL slot are assumed perfectly estimated. When adaptive detection is used, the N-LMS step size $\mu(n)$ is 0.3. No channel coding is considered.

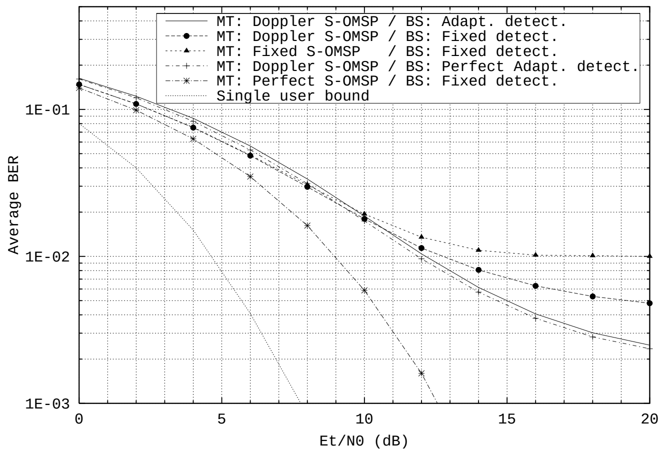

Figure 2: Performance of pre-equalization and post-detection (L_U=32, full load, 20km/h)

Fig. 2 represents the Bit Error Rate (BER) performance of different UL OFCDM schemes as a function of Et/N0, i.e. the ratio of transmitted bit energy Et over the noise power spectral density N0. We assume a normalized channel response on average. A full system load ($K=L_U$=32) is considered where each MT, having a 20 km/h velocity, is offered a 2.07 Mbit/s modulation bit rate. We compare the performance of the proposed scheme to the performance of UL OFCDM systems with perfect (5), fixed (6) and Doppler-based (10) S-OMSP pre-equalization at MTs and only despreading without post-equalization at the BS. The proposed scheme is also evaluated with perfect adaptive detection, i.e perfect estimates $\hat{d}_i(n)$ in (12).

First, we confirm the results given in [6] and show that perfect S-OMSP pre-equalization in full load yields very good performance compared to the single user bound. The loss is only 4.5 dB to achieve BER=10^{-2}, which may be considered as a realistic operating point before any channel decoding process. Using Doppler-based S-OMSP pre-equalization and adaptive detection, only 3 additional dB are required. This emphasizes the good robustness of the proposed solution even in a high interference scenario with mobility. Using self-decisions $\hat{d}_i(n)$ in the adaptive process is reliable enough for tracking the channel variations since replacing them by perfect decisions does not significantly improve the performance. Besides, a system using fixed pre-equalization and no adaptive detection can hardly achieve BER=10^{-2} with an additional increase of 4 dB in Et/N0. Compared to the proposed scheme, a 0.5 dB loss is also faced by the system with Doppler-based pre-equalization and fixed detection. This emphasizes the necessity to consider the proposed transmitter and receiver improvements in case of mobility.

In Fig. 3, we plotted the ratio Et/N0 required by the proposed solution to achieve BER=10^{-2} as a function of the system load. Curves are given for different velocities v and spreading factors L_U. For a 20 km/h velocity, using L_U=8, 16 or 32 does not significantly impact the performance. Going into further details, using L_U=32 seems advantageous for low loads, e.g. 12.5%, as the diversity obtained by the transmission increases with L_U, whereas the noise component induced by interfering users and depending on the Doppler value remains negligible. In contrast, for high loads, e.g. 100%, this noise component is increased and it becomes beneficial to use low spreading factors (L_U=8).

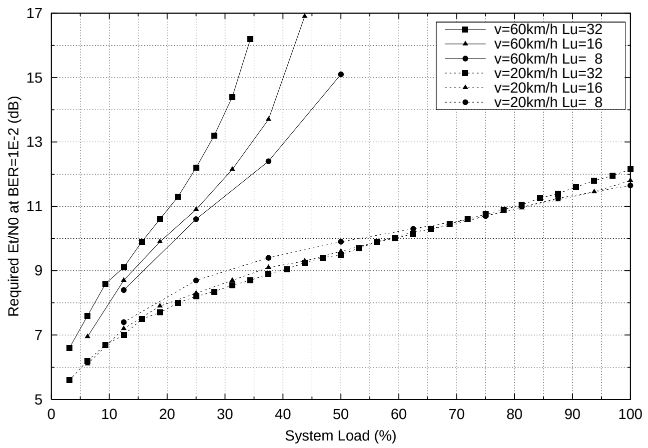

Figure 3: Influence of mobility and system load (BER=10^{-2}).

In case of high mobility, these performance differences are more obvious. At 60 km/h, with a limited transmit power (< 17 dB), the proposed system can tolerate up to 50% of system load if L_U=8, i.e. the total modulation bit rate is 33.12 Mbit/s. For comparison, larger spreading factors reduce the tolerable system load down to 44% (L_U=16) and 34% (L_U=32). In this case, as discussed in section III.B, the efficiency of the ALC is limited by the vector size and lower chip SINR value when the spreading factor is increased. Thus, we may conclude that large spreading factors are favorable for low mobility scenarios whereas low spreading factors must be considered for high mobility scenarios.

V. CONCLUSION

Initially considered for stationary conditions, channel pre-equalization can also be effective in mobile environments. In this paper, we considered it for the reverse link of a TDD-based OFCDM system in order to face the requirements of a 4G cellular system with mobility. We focused on a low-complexity pre-equalization technique at MTs with an improvement to limit the degradations caused by Doppler. This pre-equalization is used to properly initiate the UL transmission with no need of pilot symbols. Thus, it avoids the difficult task of UL channel estimation at the BS, where an adaptive detection using self-decisions is able to track the channel variations during the UL slot transmission. Using a realistic TDD-based simulation scenario, we showed the good performance of the proposed solution for moderate MT speeds up to 60 km/h. We emphasized the benefit of using low spreading factors in case of large Doppler in order to maximize the system load. This must not be considered as a limit of the system to deal with a high number of active MTs. Indeed, MTs with low velocity may still be allowed to use large spreading factors. Moreover, the large number of available sub-carriers offered by 4G OFDM-based systems allows us to introduce a Frequency Division Multiple Access (FDMA) component.

OFCDM is commonly recognized as an efficient scheme for the DL of future mobile cellular systems, whereas alternative schemes are often considered for the UL due to the difficulty to perform estimation of different channels at the BS [1]. By solving this problem thanks to pre-equalization, we proposed an efficient and symmetrical TDD-based OFCDM air-interface, which is able to cope with the typical mobility encountered in dense areas (hot spots).

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