An OFCDM Uplink Transmission System with Channel Estimation Based on Spread Pilots

Nadine Chapalain, David Mottier, Damien Castelain

Mitsubishi Electric ITE-TCL
1, Allée de Beaulieu – CS 10806 – 35708 Rennes Cedex 7, FRANCE
email: {chapalain, mottier, castelain}@tcl.ite.mee.com

ABSTRACT

To overcome the limitations of uplink air-interfaces based on conventional Multi-Carrier Code Division Multiple Access (MC-CDMA) while still benefiting from the advantages of transmissions based on multi-carrier and CDMA, Orthogonal Frequency and Code Division Multiplexing (OFCDM) with two-dimensional spreading is considered. At first, we propose to optimise the chip-mapping on sub-channels that are highly correlated in order to restore a quasi-orthogonality among users' signals although they are propagated through different channels. On that basis, we describe a very simple detection and channel estimation technique at the base station using spread pilot symbols. Simulation results for realistic scenarios highlight the high system capacity of the proposed solution, which turns out to be a good candidate for future cellular networks.

I. INTRODUCTION

Multi-Carrier Code Division Multiple Access (MC-CDMA) has been studied and optimised for the down-link (DL) air interface of future cellular systems [1]-[3]. This scheme combines the Orthogonal Frequency Division Multiplex (OFDM) and CDMA schemes by spreading users' signals in the frequency domain. Thus, it offers robustness against both multipath propagation and inter-cell interference. Moreover, resource allocation is flexible since distinct users may be assigned one or several spreading sequences (multi-code) of same or different lengths (variable spreading factor) depending on their data rate requirements.

For the up-link (UL), i.e. from Mobile Terminals (MT) to the Base Station (BS), using MC-CDMA remains an open issue, not only because of the required complexity of the multi-user detection stage at the BS but also because of the difficulty to simultaneously estimate a plurality of channels. Therefore, several alternatives combining OFDM and CDMA have been studied. On one hand, the Spread-Spectrum Multi-Carrier Multiple-Access (SS-MC-MA) system [4] introduces an additional Frequency Division Multiple Access (FDMA) component between MTs so that the BS has to estimate only one channel for each sub-carrier. Moreover, the detection stage can be simplified and the synchronisation is relaxed. However, in contrast with MC-CDMA, the interference generated by SS-MC-MA looses some spreading properties, which may require more stringent frequency planning to cope with cellular environments. On the other hand, for Time Division Duplex systems, channel pre-equalisation at each MT [5] based on DL channel estimates suppresses the needs of channel estimation and complex detection in UL. Very high system capacity, suitability in multi-cell environment together with low-complexity base-band processing in each MTs can be achieved. However, the assumption of channel reciprocity between DL and UL may not hold for large MT velocities. Moreover, specific calibration devices are needed in the analogue unit of MTs to compensate for the distortion mismatches between receive and transmit components (filters, amplifiers, etc.).

In this paper, we consider the Orthogonal Frequency and Code Division Multiplexing (OFCDM) scheme, originally proposed for the DL in [2], as another alternative to conventional MC-CDMA for the UL. Based on MC-CDMA, OFCDM allows spreading in the two dimensions, i.e. chip mapping on sub-channels that are located at different time and frequency positions of the OFDM frame. For a given MT, depending on the channel selectivity in time and frequency, the chips of a given symbol can be mapped on adjacent sub-channels where the fading coefficients are almost constant. In this case, even if these fading coefficients differ from one MT to the other, a quasi-orthogonality among users' signals can still be obtained. Here, we propose to use this quasi-orthogonality to let each MT transmit a spread pilot-symbol in order to allow multi-channel estimation at the BS. Besides, we optimise the two-dimensional (2D) spreading, i.e. 2D chip-mapping, so as to fully benefit from the correlation in time and frequency while despreading. This results in a robust UL system for mobile environments that can accommodate high system loads with a very simple detection technique at the BS.

The remainder of the paper is as follows. After a description of the proposed OFCDM UL transmission system in section II, we present the optimised 2D chip-mapping in section III and detail the spread pilot-based channel estimation. Numerical results are proposed in section IV for a realistic cellular scenario derived from the results of the European IST MATRICE project [3]. Concluding remarks are given in section V.

II. UPLINK OFCDM SYSTEM DESCRIPTION

The figure 1 represents the OFCDM UL system with channel estimation based on spread pilots for K active MTs transmitting signals to their dedicated BS.

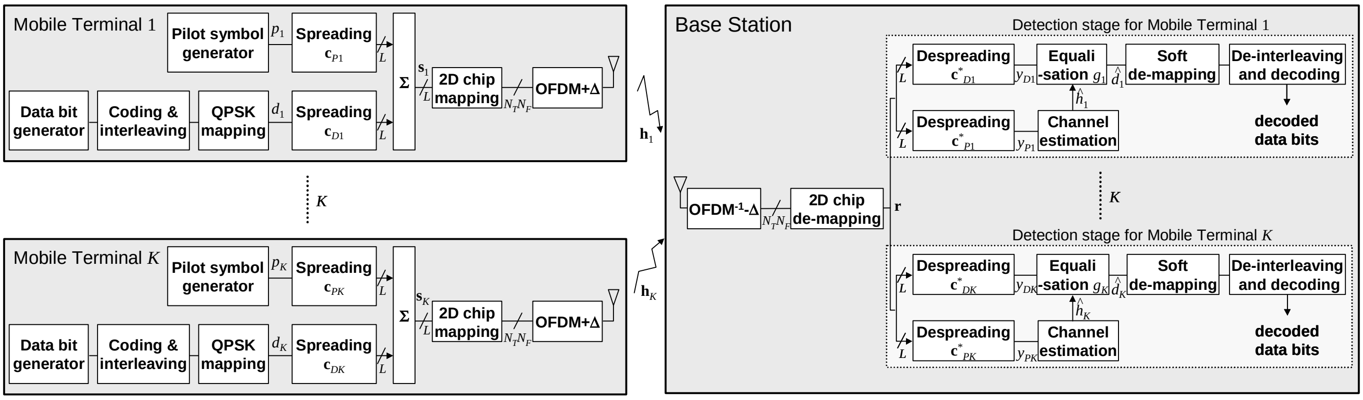


Figure 1: Block diagram of the proposed UL OFCDM scheme with spread pilot-symbols.

At the MT side, for each user k, the information bits are first coded, interleaved, and mapped into data symbols d_k. In addition, pilot symbols p_k are generated to perform channel estimation at the BS side. The data and pilot symbols, d_k and p_k, are then spread over L chips using two different orthogonal, e.g. Walsh-Hadamard (W-H), assigned spreading vectors, respectively $\mathbf{c}_{Dk}$ and $\mathbf{c}_{Pk}$. Thus, in this scheme a maximum of $L/2$ different MTs can transmit simultaneously in UL in a given spreading slot. A summation of the user data and pilot chips generates the user chip stream $\mathbf{s}_k$ of length L. This stream is then mapped in time and frequency by the 2D chip mapping function in the multi-carrier frame composed of N_F sub-carriers and N_T time slots. This chip mapping aims at minimising the Multi Access Interference (MAI) arising from the loss of orthogonality between users' signals due to channel selectivity, while the diversity of the channel is exploited by the channel decoder thanks to the bit interleaver. The OFDM modulation is carried out and a cyclic prefix Δ is added to avoid inter-symbol interference at the BS. The K signals are transmitted toward the BS and propagated through K distinct multipath channels corrupted by Additive White Gaussian Noise (AWGN). The BS is assumed to receive the sum of K synchronised MT signals.

At the BS, the cyclic prefix is removed and the observation signal is OFDM demodulated. We assume that the coherence time of each channel is much larger than the OFDM symbol duration, so as to represent the channel effect for user k on the group of L sub-channels by a vector $\mathbf{h}_k$ of L flat fading coefficients $h_k(\ell)$, $\ell=1\ldots L$. After 2D chip de-mapping to yield received vector $\mathbf{r}$ of size L and despreading, the BS estimates the channel frequency response of each user k based on its assigned received pilot observation y_{Pk}. Then, the equaliser compensates the channel impairments on the despread data symbols using the channel estimate $\hat{h}_k$ ignoring channel variations along the chips. The equalised data symbol $\hat{d}_k$ is finally demapped into soft-bits, which are de-interleaved and decoded to retrieve the transmitted data information of user k.

III. TWO-DIMENSIONAL CHIP-MAPPING FOR SPREAD PILOT-BASED CHANNEL ESTIMATION

A. Optimisation of Two-Dimensional Chip Mapping

In an OFCDM transmission network, there are degrees of freedom for mapping the L chips of vector $\mathbf{s}_k=\{s_k(\ell), \ell=1\ldots L\}$ on the N_TN_F sub-channels of the OFDM frame. As represented in figure 2, a mapping on L consecutive sub-carriers of the same time slot results in one-dimensional (1D) spreading in frequency. Similarly, a mapping of the L chips on the same sub-carrier at different consecutive time slots leads to a so-called 1D spreading in time. In [6], a two-dimensional (2D) chip mapping has been proposed for DL multi-carrier systems. This aims at reducing the effect of the channel selectivity by defining groups of L sub-channels that are highly correlated within the multi-carrier frame. These L sub-channels are located in a rectangular area involving L_F consecutive sub-carriers and L_T consecutive time-slots, so that $L=L_TL_F$. Given a spreading factor L, it is possible to select appropriate values for L_T and L_F according to the transmission scenario, i.e. the channel selectivity in frequency due to multipath propagation and in time due to mobile velocity. Thereby, the correlation is maximised among the L sub-channels used by adjacent chips, thus maintaining as much as possible orthogonality between the DL users' signals and minimising the MAI.

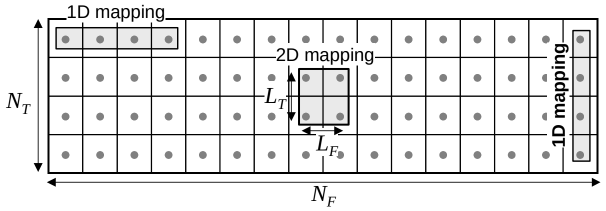
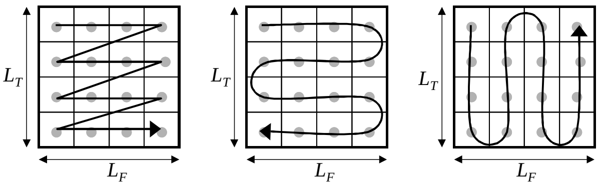


Figure 2: Examples of chip-mapping in the multi-carrier frame composed of N_F sub-carriers and N_T time slots.

In this paper, we propose to apply 2D chip-mapping for the UL. In this case, even if the channel differs from one user to another, each user's signal experiences a quasi-flat fading on the mapping area. Thus, quasi-orthogonality among users' signals can still be obtained at the received side thanks to the properties of W-H spreading sequences.



zigzag (*a*) snake in frequency (*b*) snake in time (*c*)

Figure 3: The different 2D chip mapping schemes evaluated.

Precisely, we propose to evaluate three different 2D chip-mapping schemes as depicted in figure 3. In each representation, the arrow indicates the way the components of $\mathbf{s}_k$ are distributed over the sub-channels, starting from $s_k(1)$ to $s_k(L)$. The conventional *zigzag* scheme (*a*) maps the chips starting from the first sub-carrier to the last one for the N_T successive OFDM symbols of the Multi-Carrier frame. For the *snake in frequency* scheme (*b*), the L chips are mapped so as to maximise the frequency correlation between sub-channels used by consecutive chips. Finally, the *snake in time* scheme (*c*) aims at maximising the time correlation between sub-channels used by consecutive chips. The so-called snake approaches are proposed to fully benefit from the natural order of allocation of W-H sequences for MAI mitigation [7] [8]. In that case, the correlation between sub-channels used by adjacent chip must be maximised.

B. Channel Estimation Based on Spread Pilots

To allow channel estimation at the BS, each of the K MTs transmits one pilot in parallel of X data symbols, i.e. by using X+1 spreading sequences of the W-H set of size L with a multi-code approach. Here, we must satisfy the following inequality:

$$K(X+1) \leq L \tag{1}$$

Without loss of generality, we restrict this description to the case where only two sequences for pilot and data are needed by each MT (X=1).

Thanks to the quasi-orthogonality among UL users' signals achieved by 2D chip mapping, the channel can then be evaluated in a simple way. This channel estimation scheme exploits the fact that, for each user k, the channel affects in the same manner the spread pilot p_k and the spread data symbol d_k and that the fading coefficients are almost constant on the mapping area containing the L chips of the data and pilot symbols.

After OFDM demodulation and 2D chip de-mapping, the received signal vector $\mathbf{r}$ on the set of L sub-channels is

$$\mathbf{r} = \sum_{k=1}^{K} \left(\mathbf{h}_k \circ \left(\mathbf{c}_{Dk} d_k + \mathbf{c}_{Pk} p_k \right) \right) + \mathbf{n} \tag{2}$$

where $\circ$ denotes the element-wise vector multiplication and vector $\mathbf{n}$ of size L gathers AWGN components. We assume normalised spreading vectors, i.e. $|\mathbf{c}_{Pk}|^2=|\mathbf{c}_{Dk}|^2=1/L$. Then, for each user k, the data observation y_{Dk} is obtained by despreading with code vector $\mathbf{c}_{Dk}$ as follows:

$$\begin{aligned} y_{Dk} = \mathbf{c}_{Dk}^H \mathbf{r} = & \underbrace{\frac{d_k}{L} \sum_{\ell=1}^{L} h_k(\ell)}_{\text{desired data signal}} + \underbrace{p_k \mathbf{c}_{Dk}^H \left(\mathbf{h}_k \circ \mathbf{c}_{Pk} \right)}_{\text{self interference}} \\ & + \underbrace{\mathbf{c}_{Dk}^H \sum_{k'=1, k' \neq k}^{K} \left(\mathbf{h}_{k'} \circ \left(\mathbf{c}_{Dk'} d_{k'} + \mathbf{c}_{Pk'} p_{k'} \right) \right)}_{\text{Multiple Access Interference } (\mathrm{MAI}_{Dk})} + \underbrace{\mathbf{c}_{Dk}^H \mathbf{n}}_{\text{noise}} \end{aligned} \tag{3}$$

where the superscript ^{H} denotes the hermitian operator.

Equation (3) emphasises 4 components: the desired data signal, an interference coming from the desired pilot signal referred to as self-interference, the multiple access interference MAI_{Dk} and the AWGN.

Defining $\alpha_k = \mathbf{c}_{Dk}^H \left(\mathbf{h}_k \circ \mathbf{c}_{Pk} \right)$ and $n_{Dk} = \mathbf{c}_{Dk}^H \mathbf{n}$, we may re-write equation (3) as follows:

$$\begin{aligned} & y_{Dk} = d_k \bar{h}_k + p_k \alpha_k + \mathrm{MAI}_{Dk} + n_{Dk} \\ & \text{with } \bar{h}_k = \frac{1}{L} \sum_{\ell=1}^{L} h_k(\ell) \end{aligned} \tag{4}$$

where $\bar{h}_k$ is the exact average channel response of user k defined as the average of the L channel coefficients $h_k(\ell)$ affecting the considered data symbol d_k.

Assuming spreading vectors with real components and defining $n_{Pk} = \mathbf{c}_{Pk}^H \mathbf{n}$, the pilot observation y_{Pk} is given in a similar way to (4) by:

$$y_{Pk} = \mathbf{c}_{Pk}^H \mathbf{r} = p_k \bar{h}_k + d_k \alpha_k + \mathrm{MAI}_{Pk} + n_{Pk} \tag{5}$$

Then, the BS, which has knowledge of the user-specific pilot symbol p_k, yields the average channel estimate $\hat{h}_k$ for each user k as:

$$\hat{h}_k = y_{Pk} / p_k = \bar{h}_k + \left(d_k \alpha_k + \mathrm{MAI}_{Pk} + n_{Pk} \right) / p_k \tag{6}$$

The right-hand side of equation (6) highlights a noisy term composed of the self-interference, the MAI and the residual AWGN, which degrades channel estimate $\hat{h}_k$.

The equalisation coefficient g_k is equal to the inverse of the average channel estimate and has the following expression depending on whether perfect average channel estimation or realistic average channel estimation based on spread-pilots is assumed.

$$\text{perfect average estimation:} \qquad g_k = 1 / \bar{h}_k \tag{7}$$

$$\text{realistic average estimation:} \qquad g_k = 1 / \hat{h}_k \tag{8}$$

Note that even in the case of perfect average estimation, applying symbol equalisation may degrade the performance as all L sub-channels do not experience exactly the same fading, i.e. $h_k(\ell) \neq \bar{h}_k$, $\forall \ell$=1…L. Finally, the equalised data symbol $\hat{d}_k$ is calculated as follows:

$$\hat{d}_k = g_k y_{Dk} \tag{9}$$

We may then evaluate the impact of the channel estimation technique through the expression of the Signal-to-Interference plus Noise-Ratio (SINR) of $\hat{d}_k$. Assuming normalised data symbols d_k, i.e. $\mathrm{E}[|d_k|^2]=1$, identical noise variance over pilot and data symbols, i.e. $E[|n_{Pk}|^2]=E[|n_{Dk}|^2]=\sigma^2$, we get after some mathematical manipulations the following SINR approximation:

$$\text{SINR} \approx \frac{\left|\bar{h}_k\right|^2 \left|P_{p_k}\right|^2}{\left|\alpha_k\right|^2 \left(1+\left|P_{p_k}\right|^4]\right) + \left(P_{\mathrm{MAI_k}} + \sigma^2\right)\left(1+\left|P_{p_k}\right|^2]\right)} \quad (10)$$

where $P_{\mathrm{MAI}k}$ is the energy of the MAI term, which is assumed equal for MAI_{Pk} and MAI_{Dk}. The range of validity of equation (10) holds for low energies of interference ($|\alpha_k|^2$ and $P_{\mathrm{MAI}k}$) and noise (σ^2).

In the case of pilot energy equal to data energy, i.e $|Pp_k|^2=1$, equation (10) simplifies to

$$\text{SINR} \approx \frac{\left|\bar{h}_k\right|^2}{2\left(\left|\alpha_k\right|^2 + P_{\mathrm{MAI_k}} + \sigma^2\right)} \quad (11)$$

From (11), we can see how spread pilots affect the SINR of the equalised data symbol $\hat{d}_k$. At first, the self-interference $|\alpha_k|^2$ due to its own pilot transmission is added to the multiple access interference $P_{\mathrm{MAI}k}$. In addition, compared to the case with perfect channel estimation and no pilot transmission, a division by 2, i.e. a 3 dB SINR loss, is experienced and added to the 3 dB pilot overhead loss when considering the Eb/N0, the ratio of the data bit energy Eb over the noise power spectral density N0. However, an optimisation of the relative energy between pilots and data with a multi-code approach as well as an improvement of the channel estimation algorithm is likely to reduce these losses.

IV. NUMERICAL RESULTS

In this section, we evaluate the performance of the OFCDM UL system with 2D chip mapping and channel estimation based on spread pilots. The simulation parameters are summarised in table 1 and match the requirements of a 4G mobile cellular system [3]. We use the BRAN E channel [9], which refers to a typical outdoor multi-path propagation at 5 GHz in small cells, where each active MT has a velocity of 72 km/h.

TABLE I. SIMULATION PARAMETERS

Carrier frequency	5 GHz
Sampling frequency	57.6 MHz
FFT size	1024
Number of modulated carriers	736
Slot duration (in OFDM symbols)	32
Cyclic prefix size (in samples)	216
Multi-path channel model	BRAN channel E
Channel coherence bandwidth	580 kHz
Mobile velocity	72 km/h
Channel coherence time	1.5 ms
Spreading codes	Walsh-Hadamard
Spreading factor ($L=L_TL_F$)	32
Modulation alphabet	QPSK
Block size of information bit	736
Convolutional coding scheme	$R_C=1/2$, $m=8$

In Figure 4, the performance, for K=16 active users, in terms of Bit Error Rate (BER) versus Eb/N0, of the three different 2D chip mapping schemes, i.e. *zigzag* (*a*), *snake in frequency* (*b*) and *snake in time* (*c*), are compared with 1D spreading in frequency (L_T=1) and in time (L_T=32) using symbol equalisation. For the three 2D chip mapping schemes the parameters L_T and L_F are respectively equal to 16 and 2 and match the best the frequency and time correlation of the BRAN E channel at 72 km/h. For comparison, the results of 2D chip mapping for OFCDM systems are compared with a conventional MC-CDMA system, for K=1 and K=16 users. To keep a similar complexity, this conventional MC-CDMA system applies chip interleaving in frequency where, for each time slot, the L chips of one data symbol are distributed on the N_F sub-channels to maximise the frequency diversity during the despreading process. In that case, optimum single user detection, i.e. MRC (Maximum Ratio Combining) with chip equalisation, is considered to keep a similar detection complexity. In all cases, perfect channel estimation is assumed with no pilot transmission.

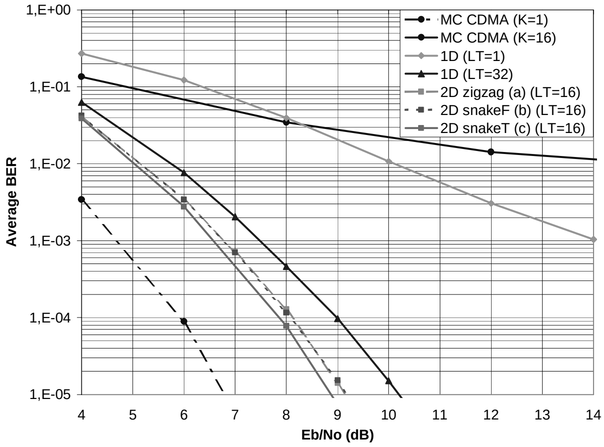


Figure 4: Influence of the chip-mapping strategy (K=16).

For OFCDM, when K=16 active users are transmitting, the 2D chip mapping performs much better than the conventional MC-CDMA system. Thus, chip mapping should be defined so as to benefit from the correlation between adjacent sub-channels, i.e. to restore a quasi-orthogonality among users' signals while the frequency diversity of the channel is best exploited at the bit level by the channel decoder. The three 2D chip mapping schemes outperform the 1D spreading in frequency (resp. in time) by more than 8 dB (resp. around 1 dB). This great performance difference shows that the adjacent sub-channels of the BRAN E channel at 72 km/h are more correlated in time. Among the three 2D chip mapping schemes, the *snake in time* scheme gives the best performance, Eb/N0=7.8 dB at a BER of 10^{-4}, i.e. 0.25 dB better than the *zigzag* and the *snake in frequency* schemes. These results confirm that an optimised chip mapping strategy can considerably improve the performance of OFCDM systems in UL.

Keeping the best 2D chip mapping scheme, the impact of the proposed channel estimation technique (proposed CE) is evaluated in terms of BER versus Eb/N0 in Figure 5. Two full system load scenarios are considered: 16 (resp. 8) active users, each of them having 2 (resp. 4) spreading sequences for pilot and data transmission, i.e. X=1 (resp. X=3) in (1). In order to quantify for K=16 the losses due to imperfect channel estimation, symbol equalisation (symbol EQ), self- and multiple-access interferences, the curves with perfect channel estimation (perfect CE) for both MRC-based chip equalisation (chip CE) and symbol equalisation (9), with or without spread pilots transmission are plotted. The pilot and data symbols have equal energy.

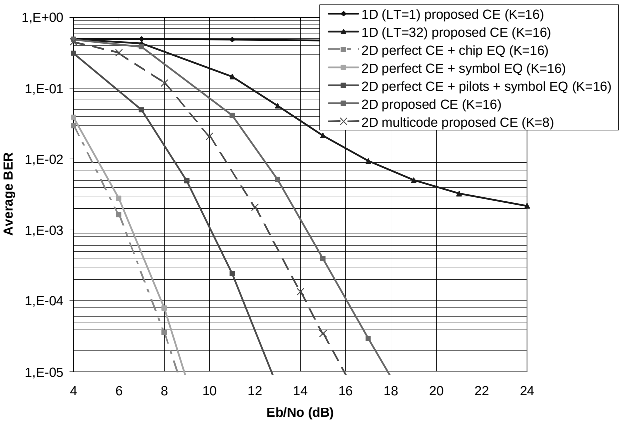


Figure 5: Performance of the channel estimation based on spread pilots (full load).

For K=16, the proposed UL OFCDM system with real channel estimation based on spread pilots requires Eb/N0=16 dB to achieve BER=10^{-4}. Note for comparison that the proposed channel estimation technique with 1D spreading in time is still better than with 1D spreading in frequency but is now far away from the performances with the optimised 2D chip mapping. Comparing to perfect channel estimation and chip equalisation based on MRC, the degradation is equal to 8.5 dB at a BER of 10^{-4}. This degradation can be decomposed into three different parts. The first loss, equal to 0.3 dB, results from the symbol equalisation based on the average channel coefficient $\overline{h}_k$ compared to a chip equalisation based on the exact knowledge of $h_k(\ell)$, ℓ=1…L. This loss is quite small with 2D chip mapping, because the channel coefficients are almost constant on the mapping area. The second loss is exclusively due to the transmission of pilots and is equal, for 16 active users, to 3.6 dB. This loss gathers the expected 3 dB loss due to pilot overhead plus a 0.6 dB loss due to self-interference $|\alpha_k|^2$ and increase of MAI coming from other users' pilot signal. The third loss of 4.6 dB is due to the channel estimation scheme which degrades the SINR. Thus, in this full load scenario with an efficient channel coding scheme, the assumption of a low level of interference and noise taken for (10) and (11) does not hold anymore so that this loss exceeds the estimated 3 dB loss.

With the proposed channel estimation scheme for K=16 users, transmitting one pilot for one data symbol introduces a large overhead and impacts quite a lot on the system performances (i.e. at least 6 dB). When adopting the multi-code approach, e.g. transmitting one pilot in parallel of X=3 data symbols per user stream as represented for K=8 users, the spectral efficiency of the system can be increased together with a reduction of the degradation due to channel estimation from 3.6 down to 2 dB.

V. CONCLUSIONS

Already recognised as a promising candidate for the DL air interface of future cellular systems, OFCDM with two-dimensional spreading shows a high performance for the UL. Thanks to an optimised chip mapping, a quasi-orthogonality among users' signals is restored, which mitigates the multiple access interference Thus, by using spread pilot symbols, the estimation of a plurality of channels at the base station becomes feasible and efficient with a low complexity detection scheme. This result contrasts with the poor performance and efficiency of the conventional MC-CDMA approach in UL.

In principle, the proposed solution limits the spectral efficiency by consuming as many spreading codes for pilots as the number of active users, which reduces the number of spreading codes available for data transmission. We showed that this limitation can be avoided by assigning in parallel several codes per user for data transmission. In that case, the introduction of a FDMA component on OFCDM may allow to cope with a higher number of simultaneous active users in the system.

ACKNOWLEDGMENTS

The work presented in this paper was supported by the European IST project MATRICE (MC-CDMA Transmission Techniques for Integrated Broadband Cellular Systems) [3].

REFERENCES

[1] S. Hara, R. Prasad, 'Overview of multicarrier CDMA,' *IEEE Communications Magazine*, vol. 35, pp. 126-133, Dec. 1997.

[2] H. Atarashi, N. Maeda, S. Abeta, M. Sawahashi, 'Broadband Wireless Access based on VSF-OFCDM and MC/DS-CDMA,' *Proc. of IEEE PIMRC 2002*, vol. 3, pp. 992-997, Sept. 2002.

[3] IST MATRICE project, web site http://www.ist-matrice.org.

[4] S. Kaiser, W.A. Krzymien, 'An asynchronous spread spectrum multi-carrier multiple access system,' *Proc. of IEEE GLOBECOM 1999*,vol. 1, pp. 314-319, Dec. 1999.

[5] D. Mottier, D. Castelain, 'Channel Pre- and Post-Equalization in Uplink OFCDM Systems with Mobility,' *Proc. of IEEE PIMRC 2003*, vol. 1, pp. 809-813, Sept. 2003.

[6] A. Persson, T. Ottosson, E. Ström, 'A. Per Time-frequency localized CDMA for downlink multi-carrier systems,' *Proc. of IEEE ISSSTA 2002*, vol. 1, pp. 118-122, Sept. 2002.

[7] D. Mottier, D. Castelain, 'A Spreading Sequence Allocation Procedure for MC-CDMA Transmission Systems,' *Proc. of IEEE VTC 2000 Fall*, vol. 3, pp. 1270-1275, Sept. 2000.

[8] D. Mottier, T. Sälzer, 'A Spreading Sequence Assignment in the Downlink of OFCDM Systems Using Multiple Transmit Antennas,' *Proc. of IEEE VTC 2004 Spring*, in press, May 2004.

[9] J. Medbo, 'Channel Models for Hiperlan/2 in different Indoor Scenarios,' *ETSI BRAN doc.* 3ERI085b, 1998.