Performance of Uplink SS-MC-MA Systems with Frequency Hopping and 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 where the different user signals propagate through different channels resulting in a high multiple access interference (MAI) at the base station, Spread Spectrum Multi-Carrier Multiple Access (SS-MC-MA) that use Frequency Division Multiple Access (FDMA) for user separation is considered as a good candidate for future cellular systems. It benefits from the diversity gain due to spread spectrum techniques (SS) and high spectral efficiency due to Orthogonal Frequency Division Multiplexing (OFDM). In this paper, SS-MC-MA with two-dimensional spreading and frequency hopping is studied. At first, we optimise the chip-mapping on the user-specific subset of highly correlated sub-channels in order to restore a quasi-orthogonality among code multiplexed signals. Beside, we propose a frequency hopping scheme to exploit at the receiving side the frequency diversity of the channel. In addition, we describe a very simple detection and channel estimation technique at the base station using spread pilot symbols. Simulation results in realistic scenarios show that SS-MC-MA is a good candidate for UL communication of future mobile cellular networks.

I. INTRODUCTION

For the future mobile cellular air interface, solutions that combine the advantages of diversity gain and interference mitigation offered by Spread Spectrum (SS) techniques and high spectral efficiency due to Orthogonal Frequency Division Multiplexing (OFDM) are considered today. For the downlink (DL), i.e. from the Base Station (BS) to the Mobile Terminals (MT), Multi-Carrier Code Division Multiple Access (MC-CDMA) has been widely studied [1]-[4]. This scheme combines the 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 by one or several spreading sequences (multi-code) of same or different lengths (variable spreading factor) depending on their data rate requirements. For the uplink (UL), i.e. from MT to the BS, the BS has to simultaneously estimate and strictly synchronise a plurality of channels and using MC-CDMA remains a challenge. Here, Spread Spectrum Multi-Carrier Multiple Access (SS-MC-MA) presents interesting features [4]. The users are Frequency Division Multiple Access (FDMA) separated so that channel estimation is simplified and synchronisation is relaxed. However, in contrast with MC-CDMA, SS-MC-MA looses some spreading properties, which makes it more sensitive to both channel selectivity and inter-cell interference. Hence, it needs to be associated with a frequency hopping scheme in order to get additional diversity and cope with cellular environments.

In this paper, we consider a SS-MC-MA scheme with a 2D chip mapping already proposed for MC-CDMA [2] [5], and frequency hopping as a potential candidate for the UL. For each MT assigned to a specific sub-band of the overall frequency band, the chips of a given symbol are mapped on adjacent sub-channels located at different time and frequency positions of the OFDM frame where the fading coefficients are almost constant. Thus, a quasi-orthogonality among code multiplexed signals can be obtained and Multiple Code Interference (MCI) is reduced. Here, we propose in addition to use this quasi-orthogonality to allow each MT to transmit a spread pilot-symbol together with code multiplexed data symbols for channel estimation at the BS. Furthermore, a MT specific frequency hopping scheme is added in order to exploit the frequency diversity of the total frequency band at the receiving side by the channel decoder associated with an efficient interleaver. In this scheme, the two-dimensional (2D) spreading i.e. 2D chip-mapping, and the frequency hopping scheme are optimised so as to fully benefit from the time and frequency characteristics of the channel in order to mitigate inter-cell interference and exploit diversity at the receiving side. This results in a robust UL system for mobile environments that can accommodate high system loads with very simple detection technique at the BS.

The paper is organised as follows. After a description of the proposed SS-MC-MA UL transmission system in section II, we present in section III the optimised 2D chip-mapping, the frequency hopping scheme and detail the spread pilot-based channel estimation. Numerical results are proposed in section IV for a realistic mobile cellular scenario. Concluding remarks are given in section V.

II. UPLINK SS-MC-MA SYSTEM DESCRIPTION

The figure 1 represents the SS-MC-MA UL system with channel estimation based on spread pilots for K active MTs transmitting signals to their dedicated BS, where each user k transmits exclusively on a subset of B sub-carriers of the available bandwidth composed of N_F sub-carriers. Hence, the maximum number of MTs that can transmit

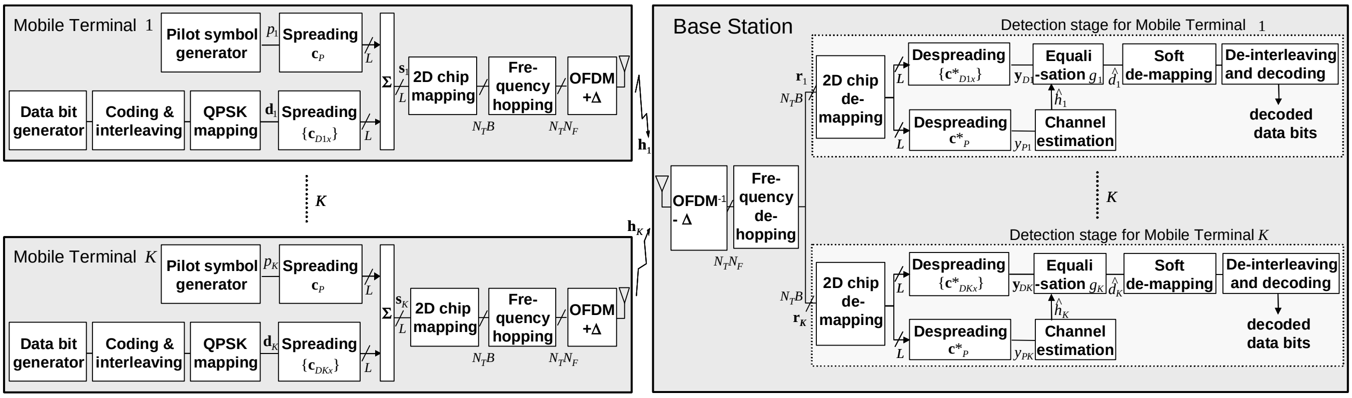

Figure 1: Block diagram of the proposed SS-MC-MA scheme with spread pilot-symbols.

simultaneously is equal to N_F/B.

At the MT side, for each user k, the information bits are first coded, interleaved, and mapped into data symbols. In addition, pilot symbols are generated to perform channel estimation at the BS side. X user data, d_{kx}, x=0,…,X-1 and a pilot symbol p_k, are then spread over L chips using different orthogonal, e.g. Walsh-Hadamard (W-H), assigned spreading vectors, respectively $\mathbf{c}_{Dkx}$ and $\mathbf{c}_P$. Thereby, we assume $X+1\leq L$. A summation of the user data and pilot chips generates the user chip stream $\mathbf{s}_k$ of length L. This user chip stream is then mapped in time over L_T time-slots and in frequency over L_F sub-carriers by the 2D chip mapping function on its dedicated subset of B sub-carriers along N_T time slots. Hence, N_T and B must be respectively a multiple of L_T and L_F. This chip mapping aims at minimising the MCI arising from the loss of orthogonality between the summed signals due to channel selectivity. A frequency-hopping scheme is then applied to exploit at the receiver side the diversity of the channel on the whole bandwidth of N_F sub-carriers. Indeed at reception, the channel decoder will benefit from this diversity 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 K synchronised MT signals on their dedicated subset of B sub-carriers.

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 its assigned subset of B among N_F sub-channels of the total available bandwidth, by a vector $\mathbf{h}_k$ of B flat fading coefficients $h_k(\ell),\ell=1\ldots B$. After frequency de-hopping and 2D chip de-mapping to yield received vector $\mathbf{r}_k$ of size L, the BS despreads the pilot and the X data signals in parallel. The channel frequency response is estimated based on its assigned received pilot symbols y_{Pk}. Then, the equaliser compensates the channel attenuations on the X despread data symbols using the channel estimates $\hat{h}_k$ ignoring channel variations along the chips. The X equalised data symbols $\hat{d}_{kx}$ are finally demapped into soft-bits, which are de-interleaved and decoded to retrieve the transmitted data information related to each user k.

III. TWO-DIMENSIONAL CHIP-MAPPING AND CHANNEL ESTIMATION BASED ON SPREAD PILOTS

A. Optimisation of Two-Dimensional Chip Mapping

In a transmission system based on SS-MC-MA, there are degrees of freedom for mapping the L chips of vector $\mathbf{s}_k=\{s_k(\ell),\ \ell=1\ldots L\}$ on the dedicated N_TB sub-channels of the k^{th} user-specific sub-band, where N_TB is a multiple of L. 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. For two-dimensional (2D) chip mapping, the L sub-channels are located in a rectangular area involving L_F consecutive sub-carriers and L_T consecutive time-slots, so that $L=L_TL_F$. 2D chip mapping schemes have been proposed for DL [2][6] and UL [5] MC-CDMA systems in order to reduce the effect of the channel selectivity by selecting the 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. Hereby, the correlation is maximised among the L sub-channels used by adjacent chips, thus maintaining as much as possible orthogonality between the users' multiplexed signals and minimising the Multiple Access Interference (MAI).

For SS-MC-MA, the users are FDMA separated and hence are not vulnerable to MAI but MCI. However, with 2D chip-mapping, each user chip stream $\mathbf{s}_k$ experiences a quasi-flat fading on the rectangular area, thus roughly maintaining at the receiving side, the orthogonality among code multiplexed signals of each user on the subset of L sub-channels thanks to the properties of W-H spreading sequences.

Here, we propose to use the so-called 2D *snake* chip-mapping schemes to fully benefit from the natural order of allocation of W-H sequences [7] [8], where the components of $\mathbf{s}_k$ are distributed over the subset of L sub-channels, starting from $s_k(1)$ to $s_k(L)$ in order to maximise the correlation between sub-channels used by consecutive chips of each modulated symbol. The *snake in frequency* scheme is performed for high mobility scenario and the *snake in time* scheme is considered for low and medium mobility scenario.

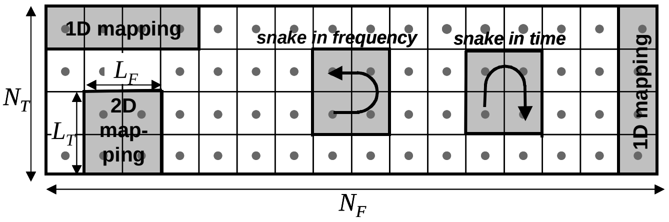

Figure 2: Examples of chip-mapping in the multi-carrier frame composed of N_F sub-carriers and N_T time slots.

B. Frequency Hopping scheme

For SS-MC-MA with no frequency hopping, the subsets of B sub-carriers assigned to each user are always located in the same areas of the OFDM frame, and the system is very sensitive to frequency selective fading. Frequency hopping, i.e. changing the frequency location of the user-specific subsets of sub-carriers in the OFDM frame at every hopping time, enables to exploit the frequency diversity of the whole channel and introduces robustness to multipath when it is associated to channel coding and an efficient bit interleaver.

The proposed frequency hopping scheme is illustrated in Figure 3, where the total available bandwidth of N_F sub-carriers is divided in N_F/B sub-bands of B sub-carriers, and is defined by the following parameters:

- $N_{hop}=N_T/T_{hop}$, the number of hops in a slot composed of N_T OFDM symbols, where T_{hop} is the number of OFDM symbols between two hops.
- Δf_{hop}, the spacing in frequency between two hops in number of sub-bands.

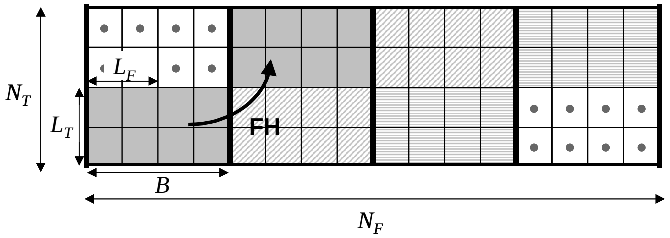

Figure 3: Example of the frequency hopping scheme in a slot FH($N_{hop}=N_T/L_T$, $\Delta f_{hop}=1$).

In order to benefit from the maximum frequency diversity of the channel the number of hops per slot must be as high as possible, i.e. T_{hop} must be as small as possible, and hence is chosen equal to L_T with 2D chip mapping, leading to N_T/L_T. It should be noted that maximising the number of hops does not reduce the spectral efficiency of the system since we use code multiplexed pilot symbols.

C. Channel Estimation Based on Spread Pilots

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

$$\mathbf{r}_k = \mathbf{h}_k \circ \left(\sum_{x=0}^{X-1} \mathbf{c}_{Dkx} d_{kx} + \mathbf{c}_P p_k \right) + \mathbf{n}_k \tag{1}$$

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

$$\begin{aligned} y_{Dkx} = \mathbf{c}_{Dkx}^H \mathbf{r}_k = & \underbrace{\frac{d_{kx}}{L} \sum_{\ell=1}^{L} h_k(\ell)}_{\text{desired data signal}} \\ & + \underbrace{\mathbf{c}_{Dkx}^H \sum_{x'=0, x' \neq x}^{X-1} \left(\mathbf{h}_k \circ \left(\mathbf{c}_{Dkx'} d_{kx'} + \mathbf{c}_P p_k \right) \right)}_{\text{Multiple Code Interference } (\mathrm{MCI}_{Dkx})} + \underbrace{\mathbf{c}_{Dkx}^H \mathbf{n}_k}_{\text{noise}} \end{aligned} \tag{2}$$

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

Equation (2) emphasises the desired data signal, an interference coming from the other data signals and from the desired pilot signal sent on the same subset of sub-channels referred to as multi-code interference and the AWGN.

Defining $n_{Dkx} = \mathbf{c}_{Dkx}^H \mathbf{n}_k$, we may re-write equation (2) as follows:

$$\begin{aligned} & y_{Dkx} = d_{kx} \bar{h}_k + \mathrm{MCI}_{Dkx} + n_{Dkx} \\ & \text{with } \bar{h}_k = \frac{1}{L} \sum_{\ell=1}^{L} h_k(\ell) \end{aligned} \tag{3}$$

where $\bar{h}_k$ is the exact average channel response of the L channel coefficients $h_k(\ell)$ affecting the considered data symbols d_{kx} of user k.

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

$$y_{Pk} = \mathbf{c}_P^H \mathbf{r}_k = p_k \bar{h}_k + \mathrm{MCI}_{Pk} + n_{Pk} \tag{4}$$

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:

$$\hat{h}_k = y_{Pk} / p_k = \bar{h}_k + \left(\mathrm{MCI}_{Pk} + n_{Pk} \right) / p_k \tag{5}$$

The right-hand side of equation (5) highlights a noisy term composed of the multi-code interference and the residual AWGN, which degrades channel estimate $\hat{h}_k$.

Finally, the equalisation coefficient g_k is equal to the inverse of the average channel estimate.

$$g_k = 1 / \hat{h}_k \tag{8}$$

And the equalised data symbol $\hat{d}_{kx}$ is calculated as:

$$\hat{d}_{kx} = g_k . y_{Dkx} \tag{9}$$

IV. NUMERICAL RESULTS

In this section, we evaluate the performance of the UL SS-MC-MA system with frequency hopping, 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 [10], which refers to a typical outdoor multi-path propagation at 5 GHz in small cells, and each active MT has a velocity of 60 and 200 km/h.

TABLE I. SIMULATION PARAMETERS

Carrier frequency	5 GHz
Sampling frequency	57.6 MHz
FFT size	1024
Number of modulated carriers (N_F)	736
Slot duration (in OFDM symbols) (N_T)	32
Cyclic prefix size (in samples)	216
Multi-path channel model	BRAN channel E
Mobile velocity	60 / 200 km/h
Spreading codes	Walsh-Hadamard
Spreading factor ($L=L_TL_F$)	32
Number of sub-carriers per user (B)	32
Modulation alphabet	QPSK
Block size of information bit	736
Convolutional coding scheme	$R_C=1/2$, $m=8$

In Figure 4, the performance in terms of Packet Error Rate (PER) versus E_b/N_0 where E_b is the energy per information bit (taking into account pilot overhead) and N_0 is the noise spectral density, for K=23 active users transmitting their data information with 23 spreading codes, where 2D chip mapping scheme are compared with 1D spreading in frequency (L_T=1). The performances of SS-MC-MA are evaluated for optimum SUD (Single User Detection), i.e. MMSE (Minimum Mean Square Error) with chip equalisation and assuming known channel coefficients for each sub-channels, with and without frequency hopping (FH), and channel estimation based on spread pilots (CHEST) with frequency hopping. Furthermore, the performance of MC-CDMA with same throughput, where the K=23 users use one spreading code with 2D chip mapping to transmit the data information on the whole bandwidth are given for optimum SUD, i.e. in UL, MRC (Maximum Ratio Combining) with chip equalisation. In the cases of perfect channel estimation no pilots are transmitted. When the channel is estimated based on spread pilots, the 2D *snake in time* chip mapping scheme with parameters L_T and L_F respectively equal to 8 and 4 gives the best performance on the BRAN E channel at 60 km/h.

For UL SS-MC-MA, at 60 km/h with perfect channel estimation, the 1D and 2D chip mapping gives the same performances with or without frequency hopping FH(4,1). Here, the higher MCI in 1D chip mapping is compensated by a larger diversity recovered by despreading. The frequency hopping scheme enables to benefit from the frequency diversity of the channel thanks to the Viterbi decoder associated with an efficient bit de-interleaver on a slot, thus improving the performances by 2.9 dB at a PER of 10^{-2}, the E_b/N_0 is equal to 9.8 dB. When comparing the performance of SS-MC-MA and MC-CDMA for same throughput when the channel is perfectly estimated with the corresponding optimum SUD and chip equalisation with 2D chip-mapping, MC-CDMA is 1.2 dB better than SS-MC-MA at PER equal to 10^{-2} as it benefits from a higher frequency diversity. However, by increasing the number of hops in the slot from 4 to maximum 32 with 1D chip mapping (i.e. from FH(4,1) to FH(32,1)), the performances of SS-MC-MA further improves and outperforms MC-CDMA by 0.85 dB at PER equal to 10^{-2}. Furthermore, when the channel is estimated based on spread pilots, SS-MC-MA with 1D chip mapping doesn't work anymore. Here the channel is too selective in frequency and the average channel estimation does not hold, which results in high MCI, only 2D chip mapping gives good performances (14.5 dB at PER equal to 10^{-2}). Note that the degradation due to channel estimation and pilot transmission with the frequency hopping scheme FH(4,1) is equal to 4.7 dB at a PER of 10^{-2}.

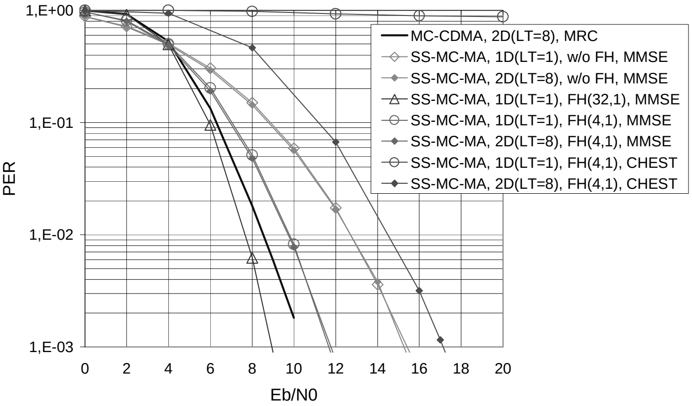

Figure 4: Performance of SS-MC-MA and MC-CDMA at 60 km/h (K=23), 1.07 Mb/s/user.

With the frequency hopping scheme FH(4,1), each user only hops on 1/6 of the total available bandwidth. This assigned user bandwidth may not provide as much frequency diversity as if every user would hop on the total available bandwidth. Furthermore, in Figure 4, the pilot symbol energy of the proposed channel estimation scheme is equal to the data symbol energy. By increasing the pilot energy it is likely to improve the channel estimation without increasing too much the interference on the desired data symbols, thus leading to global performance improvement.

Figures 5 and 6 show the performance in terms of PER versus E_b/N_0 of UL SS-MC-MA with 2D chip mapping and channel estimation based on spread pilots when the frequency hopping scheme and the relative pilot and data energy allocation are optimised for mobile cellular scenarios respectively at 60 km/h and 200 km/h. The performance of UL SS-MC-MA with non optimised frequency hopping and MC-CDMA with same throughput when the channel is perfectly estimated are also given.

At 60 km/h, the channel is more correlated in time than in frequency and the optimal 2D chip mapping with channel estimation, i.e. *snake in time* with L_T equal to 8, limits the number of hops in a slot of 32 OFDM symbols to 4. The optimum frequency hopping scheme FH(4,6) only leads to

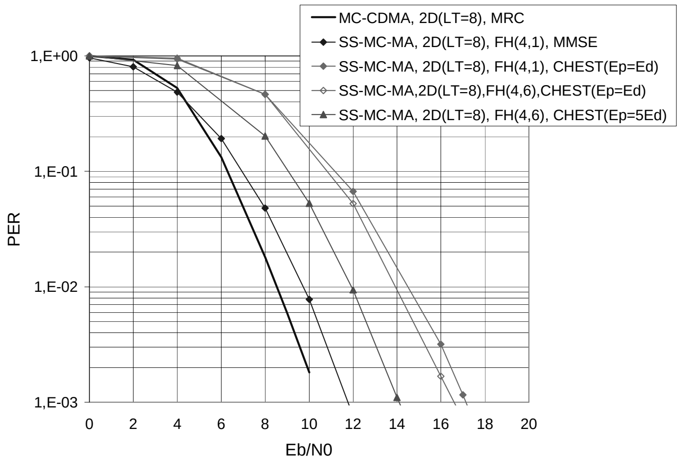

Figure 5: Performance of UL SS-MC-MA with optimised frequency hopping and pilot energy at 60 km/h (K=23).

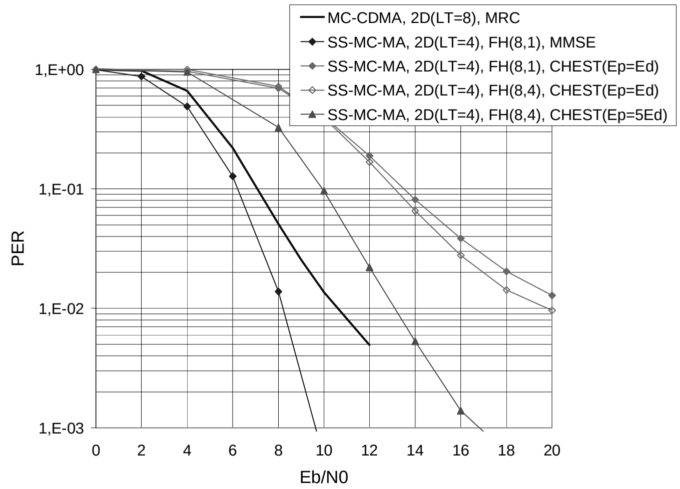

Figure 6: Performance of UL SS-MC-MA with optimised frequency hopping and pilot energy at 200 km/h (K=23).

a small performance improvement of 0.35 dB at PER 10^{-2} compared to the performance with the frequency hopping scheme FH(4,1). However increasing the pilot energy Ep from Ed to $5Ed$ enables to highly improve the performance by 2.2 dB, i.e. 2.2 dB from the performance with perfect channel estimation and FH(4,1).

At 200 km/h, the BRAN E channel is more correlated in frequency than in time and the 2D chip mapping scheme that allows efficient channel estimation is the *snake in frequency* scheme with parameters L_T and L_F respectively equal to 4 and 8, thus enabling a higher number of hops in a slot and a better exploitation of the frequency diversity of the channel. At that speed, the optimum frequency hopping scheme is the FH(8,4) and the optimum pilot energy allocation is Ep=5Ed. For this high mobility scenario, when pilots are transmitted with the same energy as the data symbols, the performance of SS-MC-MA even with the optimised frequency hopping scheme FH(8,4) (the E_b/N_0 is equal to 19.8 dB at a PER of 10^{-2}) are disappointing, the curves start to flatten due to a loss of efficiency of the average channel estimation. However, with Ep=5Ed channel estimation is reinforced, the performance greatly improves (i.e. 6.7 dB of improvement at PER equal to 10^{-2}) and the flattening disappears. A PER of 10^{-2} is reached at E_b/N_0 equal to 13.1 dB, that is 4.9 dB from the performance with perfect channel estimation.

Note that at 200 km/h, with perfect channel estimation, the SS-MC-MA even with the non-optimised frequency hopping performs 2.4 dB at a PER of 10^{-2} better than MC-CDMA with same throughput since this latter suffers from higher interference.

V. CONCLUSIONS

In this paper SS-MC-MA has been studied for the UL air interface of future cellular systems, with two-dimensional spreading and frequency hopping. The 2D optimised chip mapping, enables to restore the quasi-orthogonality among the code multiplexed signals and mitigates the multiple code interference. Furthermore, by using spread pilot symbols, the estimation of the channel at the base station is efficient, even at 200 km/h with a very low complexity detection scheme and reasonable pilot overhead. In addition, the frequency diversity on the total available bandwidth is exploited thanks to an efficient and simple frequency hopping scheme. This results show that a combination of CDMA and OFDM such as SS-MC-MA can be applied for future communication cellular systems also in the UL with much less requirements in terms of synchronisation and channel estimation with better performance than MC-CDMA.

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