A SEMI-BLIND CHANNEL EQUALISATION STRATEGY FOR THE UMTS-TDD DOWNLINK

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ABSTRACT

In this paper, we propose a semi-blind channel equalisation scheme for the downlink time-division duplex (TDD) component of the universal mobile telecommunication system (UMTS). The main two concepts introduced consist of: first exploiting the constant modulus carried by the decoded symbols of all active users ; and second making use of the inactive users to load a suitable number of pilot signals. In response to this scenario, a semi-blind equalisation is performed in the data fields, whereby the equaliser weights are updated by minimising a hybrid CM/MSE cost function based on the constant modulus (CM) criterion for all active users and a mean square error (MSE) criterion for both absent users and pilot signals. Computer simulations are used to assess and analyse the channel equalisation strategy in terms of MSE and BER performance over a quasi-static dispersive channel

1. INTRODUCTION

The time division duplex (TDD) component of the universal mobile telecommunication system (UMTS) provides a high transmission rate, an efficient use of the spectrum and a flexible capacity allocation. It has previously become the basis for the third generation (3G) standard, and most likely will be selected as the main duplex mode operation for the fourth generation (4G) systems [1].

In the UMTS TDD mode the transmitted users are multiplexed by orthogonal codes, which provide intrinsic protection against multi-access interference (MAI). Nevertheless, transmission over a dispersive channel destroys the mutual orthogonality of these codes, and as a result, the received and code-demultiplexed user signals are subject not only to inter-symbol interference (ISI) due to channel dispersion but also to MAI caused by the loss of code orthogonality. Consequently the conventional code-matched filter receiver suffers from sever performance degradation; hence better detection strategies are required. Thus, significant efforts have been directed towards developing multiuser detection /equalisation techniques to suppress MAI and ISI [2]. Optimum detection in the maximum likelihood (ML) sense [3] is perhaps the most popular technique in spite of the computational complexity which increases exponentially with the number users and the delay spread of the channel [4]. Due to the unrealistic complexity of the optimum detector, several-sub optimum schemes have been proposed, yet all of them require explicit knowledge of the channel impulse response [2, 4]. Alternatively, several blind detection strategies, where no explicit knowledge of the channel or neither pilot signals or training sequences are necessary, offer better spectrum efficiency with reasonable trade-off between performance and complexity [5, 6, 7].

A popular approach to suppress MAI and ISI on a user is the minimum output power (MOE) algorithm which blindly cancels MAI and ISI terms but passes the desired user by code-constraints [8], which is essentially Frost's linearly constrained minimum variance beamformer [9]. For the DS-CDMA downlink, the recovery of several synchronous users at the same time exploits more knowledge of the system. Non-blind multiuser schemes, such us using the mean squared error (MSE) criterion, in turn are based either on the knowledge of a pilot [10, 11] or training bursts [12]. Blind schemes have been performed using a constant modulus (CM)criterion [13, 14], neglecting either the dispersiveness of the channel [14] or spreading [13, 6], whereby the later algorithms additionally require mutual decorrelation of the recovered user sequences. In [7], a blind scheme similar to [13, 6] has been developed, whereby the despreading in the DS-CDMA receiver ensures the orthogonality of the recovered sequences, and a CM criterion on all users suffices. The algorithm in [7] is however only suitable for a fully loaded system, in which all possible users are active. A hybrid CM/MSE algorithm, appropriate for partial loading scenario, has been derived in [15].

In this paper we propose a semi-blind channel equalisation strategy for the downlink of the UMTS TDD component. In addition to the basic MSE chip rate equalisation performed over the training field, a semi-blind adaptation, similar in structure to [15] is adopted over data fields. In a partially loading scenario, a number of inactive users are exploited as pilots, in order to eliminate the phase ambiguity and to enhance the system performance. In Sec. 2 a description of the UMTS TDD physical channel is given. Based on the definition of a signal model in Sec. 3, the hybrid CM/MSE cost function is derived in Sec. 4. Sec. 5 presents a stochastic gradient algorithm used for the semi-blind adaptation. The performance of the proposed scheme in terms of MSE and BER in both fully and partially loaded systems are presented in Sec. 6 through various simulations, and finally conclusions are drawn in Sec. 7.

2. UMTS TDD PHYSICAL CHANNEL

The UMTS TDD mode provides up- and downlink services within the same frequency band, and separated in time through the use of different time slots, each of which can support parallel spreading codes with a maximum spreading factor of 16 [16]. 15 of these time slots are gathered in one frame, whereby each frame has a duration of 10 ms [16] as shown in Fig. 1(a). Within every time slot users can transmit their signals simultaneously by means of different spreading codes. The time slot contribution from a single user is referred to as a burst.

The UMTS TDD physical channel is a combination of two data fields, a midamble, and a guard period. There are two burst types proposed in [16], namely burst type 1 and type 2. As illustrated in Fig. 1(b), both types have the same length of 2560 chips and are terminated by a guard period of 96 chips in order to avoid overlapping with consecutive time slots. Burst type 1 has a longer midamble suitable for cases where long training periods are required for adaptation and tracking.

3. SIGNAL MODEL

We consider the UMTS-TDD downlink model in Fig. 2 with a maximum of N symbol-synchronous active users. We assume that $N = 16$ in the following, and for simplicity that users have the same rate. In the case of a partially loaded system with $K \leq N$, we assume the first K users with signals $u_l[n]$, $l = 0(1)K-1$, to be active, and the following $N_p \leq N-K$ to be pilots with signals $p_l[n]$, $l = 0(1)N_p-1$ while the remaining $N-K-N_p$ user signals are assumed to be zeros. The signals $u_l[n]$ are code multiplexed using Walsh sequences of length N extracted from a Hadamard matrix $\mathbf{H}$. The resulting chip rate signal, running at N times the symbol rate, is further scrambled by $c[m]$ prior to transmission over a channel with dispersive impulse response $g[m]$ and corruption by additive white Gaussian noise $v[m]$,

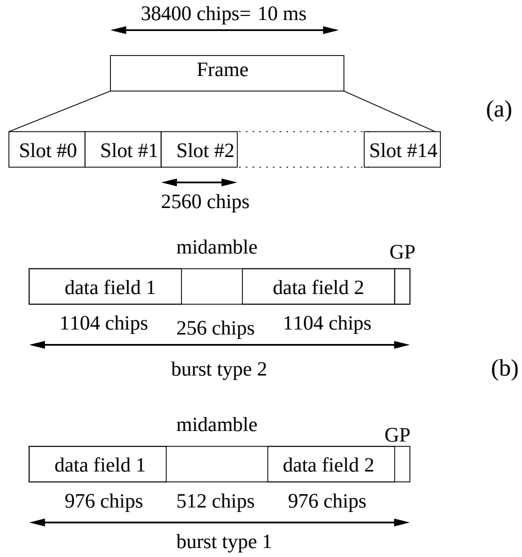

Fig. 1. Time structure in UMTS TDD: (a) basic frame structure, and (b) burst structure.

which is assumed to be independent of the transmitted signal $s[m]$.

The dispersive channel $g[m]$ destroys the orthogonality of the Walsh codes, such that direct decoding of the received signal $r[m]$ with descrambling by $c^*[m]$ and code-matched filtering by $\mathbf{H}^{\mathrm{T}}$ will lead to MAI and ISI corruption of the decoded user signals $\hat{u}_l[n]$, $l = 0(1)K-1$. In order to re-establish orthogonality of the codes, a chip level equaliser $w[m]$ can be utilised [11]. The equalisation is performed in both midamble period and data fields — in the former by means of the training sequence at the chip rate in the MSE sense, in the latter by using a semi-blind scheme. In the following, we propose a semi-blind updating scheme for the equaliser coefficients $w[m]$.

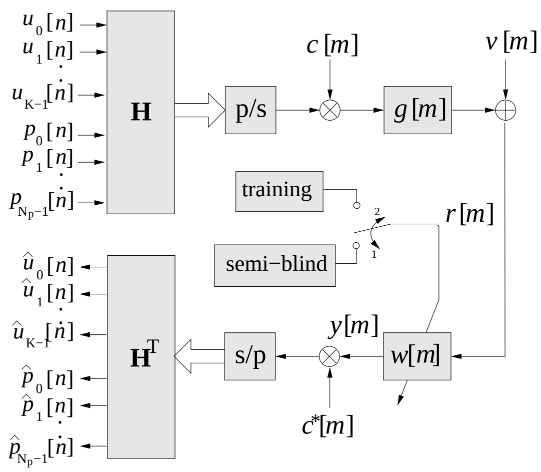

Fig. 2. Signal model.

4. SEMI-BLIND EQUALISATION CRITERIA

We first derive the detected user signals $\hat{u}_l[n]$ and the pilot signals $\hat{p}_l[n]$ as a function of the equaliser $w[m]$. Based on this, we state a suitable cost function based on which the equaliser can be adapted.

4.1. Demultiplexed User and pilot Signals

For the decoding, Walsh sequences are used as matched filters. The sequence for decoding the lth user, contained in a vector $\mathbf{h}_l$, can be taken from an $N \times N$ Hadamard matrix,

$$\mathbf{H}^{\mathrm{T}} = [\mathbf{h}_0 \;\; \mathbf{h}_1 \;\; \cdots \;\; \mathbf{h}_{N-1}]^{\mathrm{T}} . \qquad (1)$$

The lth user is thus decoded as

$$\begin{aligned}\hat{u}_l[n] &= \mathbf{h}_l^{\mathrm{T}} \cdot \begin{bmatrix} c^*[nN] & & & \mathbf{0} \\ & c^*[nN-1] & & \\ & & \ddots & \\ \mathbf{0} & & & c^*[nN-N+1] \end{bmatrix} \cdot \begin{bmatrix} y[nN] \\ y[nN-1] \\ \vdots \\ y[nN-N+1] \end{bmatrix} \\ &= \tilde{\mathbf{h}}_l^{\mathrm{T}}[nN] \cdot \begin{bmatrix} \mathbf{w}^{\mathrm{H}} & & & \mathbf{0} \\ & \mathbf{w}^{\mathrm{H}} & & \\ & & \ddots & \\ \mathbf{0} & & & \mathbf{w}^{\mathrm{H}} \end{bmatrix} \cdot \begin{bmatrix} r[nN] \\ r[nN-1] \\ \vdots \\ r[nN-L-N+2] \end{bmatrix}\end{aligned}$$

whereby the descrambling code $c^*[m]$ has been absorbed into a modified and now time-varying code vector $\tilde{\mathbf{h}}_l[nN]$, and $\mathbf{w} \in \mathbb{C}^L$ contains the equaliser's L chip-spaced complex conjugate weights. Rearranging $\mathbf{w}$ and $\tilde{\mathbf{h}}_l[nN]$ yields

$$\begin{aligned}\hat{u}_l[n] &= \mathbf{w}^{\mathrm{H}} \cdot \begin{bmatrix} \tilde{\mathbf{h}}_l^{\mathrm{T}}[nN] & & & \mathbf{0} \\ & \tilde{\mathbf{h}}_l^{\mathrm{T}}[nN] & & \\ & & \ddots & \\ \mathbf{0} & & & \tilde{\mathbf{h}}_l^{\mathrm{T}}[nN] \end{bmatrix} \cdot \begin{bmatrix} r[nN] \\ r[nN-1] \\ \vdots \\ r[nN-L-N+2] \end{bmatrix} \\ &= \mathbf{w}^{\mathrm{H}} \, \mathbf{H}_l[nN] \, \mathbf{r}_{nN} , \end{aligned} \qquad (2)$$

with $\mathbf{H}_l[nN] \in \mathbb{C}^{L \times (N+L-1)}$ being a convolutional matrix comprising of the lth either user's modified code vector $\tilde{\mathbf{h}}^{\mathrm{T}}[n]$ and $\mathbf{r}_{nN} \in \mathbb{C}^{N+L-1}$. Similarly, (2) holds for the lth decoded pilot signal $\hat{p}_l[n]$, whereby $\mathbf{H}_l[nN]$ contains the pilot's modified code vector.

4.2. Cost Function

Since the modulation scheme used for UMTS-TDD is mainly the quadrature phase shift keying (QPSK), or in some cases 8-PSK [16], the K active user signals $u_l[n]$ consist of symbols with a constant modulus γ. Therefore, by forcing all received user symbols $\hat{u}_l[n]$ onto the constant modulus γ and the received pilot symbols $\hat{p}_l[n]$ onto the known transmitted ones $p_l[n]$, a semi-blind cost function ξ is proposed to

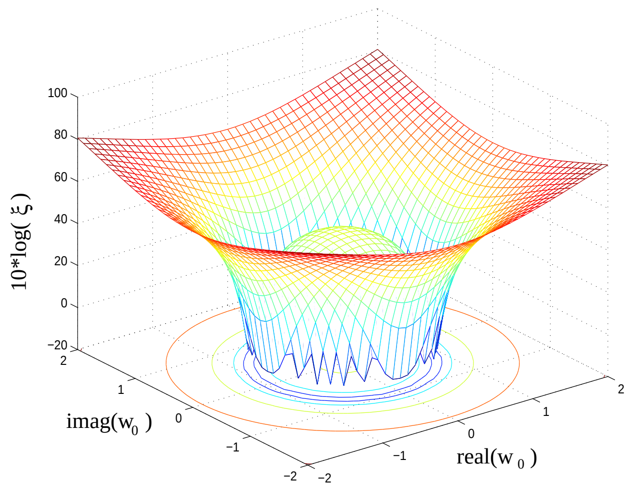

Fig. 3. Cost function ξ in dependency of a single complex valued coefficient w_0,for a fully loaded system with $N = 16$ users.

adapt the equaliser weights and potentially track any channel variations. Note that the remaining $N - K - N_p$ inactive users should be taken into consideration, otherwise the equalisation criterion is under-determined and the correct signals would not necessarily be extracted in the despreading operation. It was found to be best in terms of convergence speed, steady state error and transmit power to force the inactive users to zeros in the MSE sense, thus ensuring that the overall system is fully determined [15].

Therefore the proposed cost function consists of three terms and is formulated as ξ,

$$\xi = \mathcal{E}\left\{\sum_{l=0}^{K-1}(\gamma^2 - |\hat{u}_l[n]|^2)^2\right\} + \mathcal{E}\left\{\sum_{l=0}^{N_p-1} |p_l[n] - \hat{p}_l[n]|^2\right\} + \\ + \mathcal{E}\left\{\sum_{l=K+N_p}^{N-1} |\hat{u}_l[n]|^2\right\} \quad , \qquad (3)$$

where $\mathcal{E}\{\cdot\}$ denotes the expectation operator. The equaliser coefficients in $\mathbf{w}$ can be determined such that the above cost function is minimised,

$$\mathbf{w}_{\mathrm{opt}} = \arg\min_{\mathbf{w}} \xi \quad . \qquad (4)$$

Note that in the absence of any pilot signals, a manifold of solutions exists for (4) due to the indeterminism of the CM criterion to rotations in phase.

4.3. Phase ambiguity

Since an ambiguity with respect to a complex rotation $e^{j\varphi}$ ($\varphi \in [0; 2\pi]$) cannot be resolved by CM criteria, the rotation invariance can be overcome by exploiting the presence of a pilot, or in its absence by loading at least one inactive user

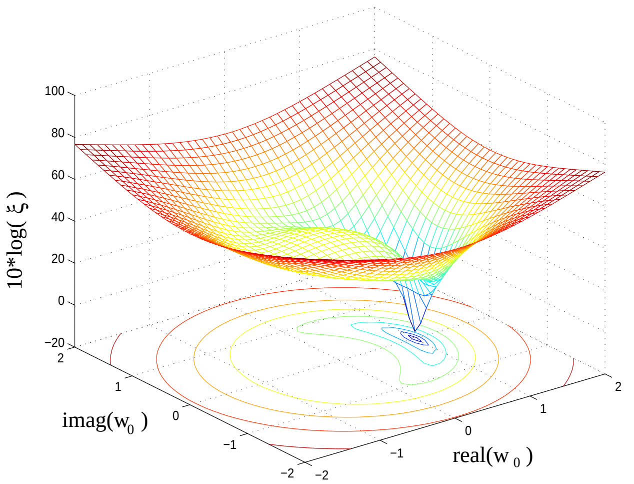

Fig. 4. Cost function ξ in dependency of a single complex valued coefficient w_0, for a partially loaded system with 10 active users and 6 pilots.

with a pilot signal. However, this solution is valid only for partially loaded scenarios and issues such as the use of differential encoding or the transmission of a synchronisation word may still persist.

Example. In order to give an idea of the cost function and to show pilots remove the phase ambiguity, the following example is presented. Firstly, we assume a fully loaded system with $N = 16$ users employing QPSK with $\gamma = 1$ over a distortionless and delayless channel $g[m] = \delta[m]$ with a signal to noise ratio (SNR)of 20 dB. Fig. 3 shows the cost function ξ in dependency of an equaliser $\mathbf{w}$ with a single complex coefficient w_0. The cost function shows that there is a manifold of optimal solutions satisfying $|w_{0,\mathrm{opt}}| = 1$. Secondly, we assume that the system is partially loaded by $K = 10$ active users and 6 pilots. Thus, as shown in Fig. 4, the cost function ξ reduces to a single global optimum $w_{0,\mathrm{opt}} = 1$ and the phase ambiguity has been removed.

5. SEMI-BLIND ADAPTATION

Simple adaption rules for the equaliser can be obtained by considering a stochastic gradient descent technique, whereby an iterative update rule is utilised for the equaliser coefficient vector $\mathbf{w}_n$ at time n,

$$\mathbf{w}_{n+1} = \mathbf{w}_n - \mu \nabla \hat{\xi} \qquad (5)$$

where μ is the algorithm step size, and ∇ the gradient operator applied to an instantaneous cost function $\hat{\xi}[n]$. The latter is obtained from (3) by dropping the expectation operation. The gradient term of the instantaneous cost functions can be derived by using equations (3) and (2), yielding

$$\begin{aligned}\frac{\partial \hat{\xi}}{\partial \mathbf{w}^*} &= -2 \sum_{l=0}^{K-1} (\gamma^2 - |\hat{u}_l[n]|^2)\, \mathbf{H}_l[nN]\, \mathbf{r}_{nN}\, \hat{u}_l^*[n] - \\ &\quad - \sum_{l=0}^{N_p-1} \mathbf{H}_l[nN]\, \mathbf{r}_{nN}\, (p_l[n] - \hat{p}_l[n])^* + \\ &\quad \sum_{l=K+N_p}^{N-1} \mathbf{H}_l[nN]\, \mathbf{r}_{nN}\, \hat{u}_l^*[n]. \qquad (6)\end{aligned}$$

The first term in (6) is equivalent to a blind version of this algorithm for a fully loaded system [7], which differs from the standard CM algorithm [17] or its extension in [13] by the inclusion of a code filtered term $\mathbf{H}_l[nN]\ \mathbf{r}_{nN}$ rather than just the equaliser input $r[n]$. The resulting structure is known as a filtered-X [18] or a filtered-error filter-regressor structure [11] in the context of LMS-type algorithms. The additional two terms in (6) are due to pilot signals and to force the output of inactive code filters to zero.

6. SIMULATION RESULTS

The stochastic gradient algorithm derived in Sec. 5 is experimentally tested and evaluated below for the $N = 16$ UMTS-TDD physical channel presented in Sec. 2, by using both burst types 1 and 2. Simulations are performed over one frame of 10 ms, whereby all 15 bursts are dedicated to downlink mode only. The dispersive channel is considered static over this frame with frequency response given by in Fig. 5. The length of the equaliser is $L = 10$, and the step size is experimentally chosen to be about an order of magnitude below the onset of divergence. In Sec. 6.1 we assume a fully loaded scenario and compare the proposed scheme with a basic strategy based on a chip rate equalisation performed in the training period, in terms BER and

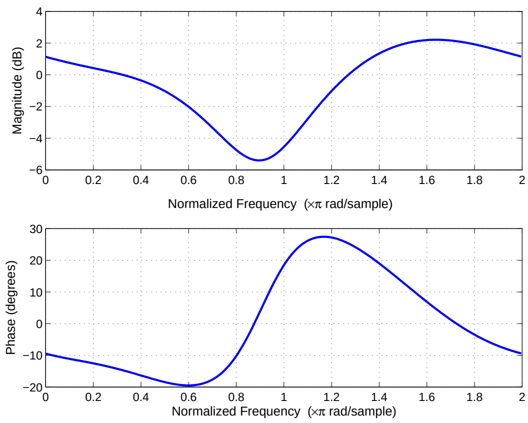

Fig. 5. Channel frequency responce (top)magnitude (bottom) phase

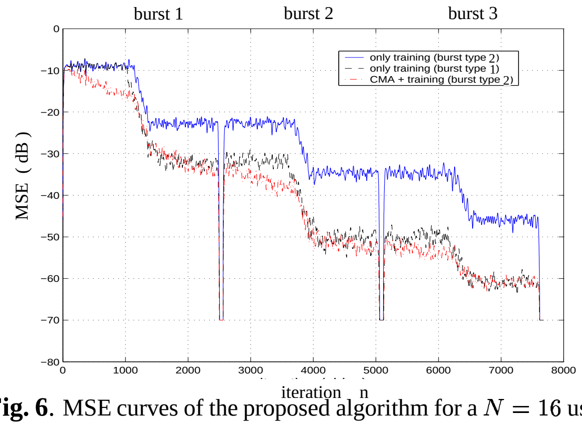

Fig. 6. MSE curves of the proposed algorithm for a $N = 16$ users UMTS-TDD system over a duration of three bursts for the shorter burst type 2, compared to an LMS-type training based method for both burst types.

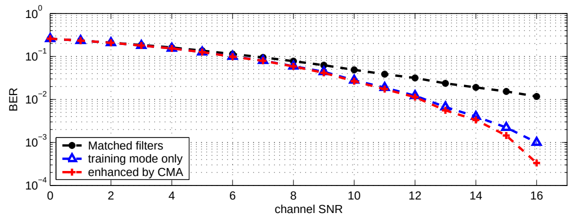

Fig. 7. BER performance of the proposed algorithm in burst type 2 mode, compared to training based equalisation for burst type 2, and a receiver without equalisation only based on code-matched filtering.

MSE performance. Later in Sec. 6.2 we evaluate the performance enhancement achieved by the introduction of pilots in the partially loaded system.

6.1. Fully loaded Scenario

For the fully loaded UMTS TDD system all possible 16 QPSK user signals are transmitted and no pilots are used. In order to achieve an optimum response, the adaptation is initialised with the first coefficient in the weight vector set to unity. The proposed adaptation scheme is implemented in a noise-free channel by using bursts of type 1, which have the shortest training period (256 chips). As it is shown in Fig. 6, the proposed algorithm outperforms the two other schemes when the equalisation is performed in both burst types but only over the training period. The remaining error floor is due to model truncation. This means that by using the proposed scheme the spectral efficiency could be raised by approximately 13% by using burst type 2 instead of burst type 1 at a similar MSE performance albeit a somewhat higher computational cost. Fig. 7 exhibits the BER performance of the proposed algorithm, matched filters with no equalisation, and the training equalisation with type 2 bursts. It can be noticed that for low SNRs there is no benefit from using equalisation, however for medium or relatively high SNRs the proposed scheme shows increasing benefit compared to the two other methods.

6.2. partially loaded scenario

For a partially loaded system with $K = 10$ user signals, either 4 or 6 pilots are transmitted under similar channel conditions presented in Sec.6.1. Note that with the introduction of pilots, no phase correction is needed and the choice of the initial weight vector is not crucial. In the following, the second coefficient is set to unity. The MSE curves represented in Fig. 8 are obtained over a noise-free channel. It can be seen that the introduction of 6 pilots exhibits a faster convergence than either schemes where 4 pilots or none are used. In noisy channels, the introduction of pilots enhances the BER performance of the system for relatively medium to high SNRs, as shown in Fig. 9.

7. CONCLUSIONS

A semi-blind equalisation approach for a UMTS-TDD downlink scenario has been presented, with the aim of enforcing CM conditions on the various active user signals and MSE criteria on either introduced pilots or the remaining inactive users. The algorithm presents better convergence behaviour over the basic training equalisation even with longer training periods, whereby a gain of data rate and spectrum efficiency can be achieved. It has been shown through various simulations that the implementation of pilots enhances the system performance in terms of MSE and BER and resolves the typical CM phase ambiguity.

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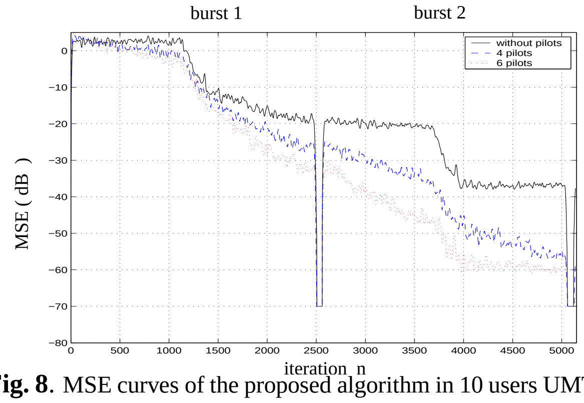

Fig. 8. MSE curves of the proposed algorithm in 10 users UMTS-TDD environment with or without pilots over two bursts of type 2.

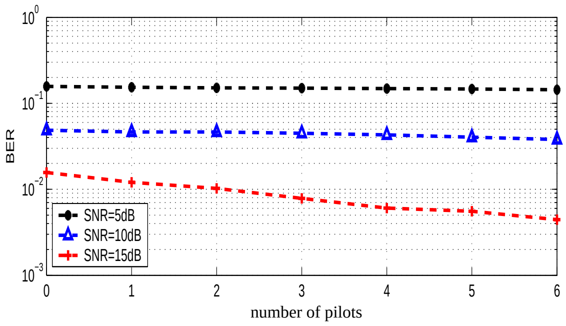

Fig. 9. effect of the number of pilots on the BER performance corresponding to the case of 10 active users.

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