A Novel Uplink Receiver for GSM/EDGE Systems with Orthogonal Sub Channel Feature

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Abstract— **The increasing demand for traffic capacity of the GSM/EDGE Radio Access Networks (GERAN) induced the Third Generation Partnership Project (3GPP) to examine the Orthogonal Sub Channel (OSC) transmission scheme. This new feature aims at doubling the cell capacity by multiplexing two co-cell users on the same radio resource. This work presents a new two-stage receiver specifically designed for the uplink GSM-OSC system. The proposed strategy relies on two optimum interference mitigation filters jointly derived for the multiplexed users. The filtered signals are then processed by a multi user detector that recovers the transmitted sequences. The proposed algorithm shows a significant performance gain with respect to existing interference cancellation receivers.**

I. INTRODUCTION

Despite of many previsions, the Global System for Mobile Communications (GSM) is far from being a dead technology. Voice traffic, in particular, is expected to grow nearly threefold all over the world by 2012 [1]. Mobile operators are pushed to find new solutions for improving the efficiency of current GSM networks with low impact on existing hardware equipments, to reduce as much as possible the upgrading costs. A well known approach for improving the traffic capacity is reducing the cellular reuse factor; the drawback, however, is the increase of co-channel interference and the consequent performance degradation. To face this problem, the Third Generation Partnership Project (3GPP) has recently investigated the use of Single/Double Antenna Interference Cancellation (SAIC/DAIC) algorithms [2]-[7]. Performance specifications for mobile stations (MS) equipped with interference cancellation have been provided by the Downlink Advanced Receiver Performance (DARP) phase I-II requirements. New DARP handsets are already on the market.

Relying on the improved co-channel interference robustness of the new GSM mobiles, the 3GPP is now examining the feasibility of allocating different users to a same radio resource in the cell. Among the proposed solutions, the Orthogonal Sub Channel (OSC) multiplexing scheme [8] aims at doubling the voice capacity with negligible impact on the existing handsets by enabling the transmission of two GMSK streams on the same time slot. The increased capacity of GSM-OSC networks can be exploited in the future either to serve more users in the given bandwidth (e.g. in highly loaded markets) or to group the voice traffic into a portion of the available bandwidth leaving free resources for services of data transmission. In the OSC downlink (DL), in order to minimize the mutual interference, the two GMSK signals are generated with a phase offset (using two QPSK subsets of the 8-PSK EDGE constellation) and they are recovered at the two MSs through DARP receivers. On the other hand, in the uplink (UL), the two signals are transmitted independently by two normal GMSK MSs and have to be detected at the BS by multi-user detection (MUD). New processing techniques are required at the BS to handle the interference generated both from out-of-cell and in-cell users.

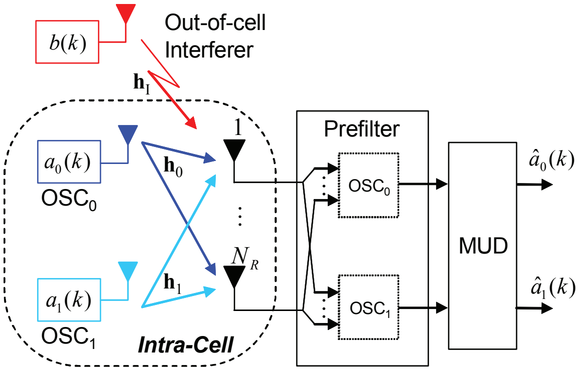

Fig. 1. UL GSM layout with OSC feature. Two MSs are sharing the same frequency: the proposed Joint OSC receiver applies a prefilter for each OSC user to mitigate the out-of-cell interferer and performs a MUD to recover the desired sequences.

The *contribution* of this work is the design of a new two-stage UL receiver: the Joint OSC Receiver (JOR) combines a front-end prefiltering stage for the mitigation of the out-of-cell interference, with a MUD that optimally handles the mutual interference between the two in-cell users (Fig. 1). Differently from conventional SAIC/DAIC, here prefilters are optimized *jointly* for the two OSC users, so as to minimize the interference from neighboring cells while preserving the two multiplexed signals. The second stage is a MUD that jointly estimates the two transmitted sequences: joint maximum likelihood sequence estimation (JMLSE) is considered as optimal non-linear solution, while linear detection (L-MUD) is proposed as a good trade-off between performance and computational complexity. The proposed scheme is shown to outperform all the existing receivers, in particular the interference filtering schemes based on conventional SAIC/DAIC and

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the Serial/Parallel Interference Cancellation (SIC/PIC) MUD algorithms suggested for the OSC feature [8].

This work is organized as follows: Sec. II introduces the adopted GSM with OSC system model, Sec. III recalls the state of the art receivers applied to the OSC context whereas Sec. IV describes the proposed receiver. Numerical simulations are discussed in Sec. V where a realistic GSM system has been designed. Finally the conclusions are drawn in Sec. VI.

II. SYSTEM MODEL

The uplink of a synchronous multicell GERAN environment is modelled adopting the OSC feature as prescribed in [8]: two in-cell mobile stations (MSs) share the same radio resource transmitting two GMSK modulated signals [9] while an out-of-cell interferer is impairing the transmissions (see the example in Fig. 1).

At each MS a sequence of information bits is convolutionally encoded, mapped over different bursts according to the adopted channel coding scheme and finally differentially encoded. Each burst is composed by $K = 148$ symbols made up of: 114 data (divided into two semibursts of $M = 57$ each), 8 guards and 26 training symbols placed in the midamble. The training sequences (TSC) of the in-cell OSC users are known at the BS, while no information is available about the out-of-cell MS. We denote the kth transmitted symbol as $a_i(k)$ for the ith OSC user and $b(k)$ for the out-of-cell interferer, with $\{a_i(k), b(k)\} \in \{\pm 1\}$, $k = 1, \ldots, K$, and $i = 0, 1$.

We suppose that all the MSs employ a single antenna (see Fig. 1) whereas the BS is equipped with an array of N_R antennas that are sufficiently spaced apart so that the received signals can be considered uncorrelated. The $N_R \times 1$ complex-valued signals at the output of the receiver's filter (before sampling) can be written as:

$$\bar{\mathbf{y}}(t)=\sum_{i=0}^{1}\sum_{k=1}^{K}\bar{\mathbf{h}}_i(t-kT)j^k a_i(k)+\sum_{k=1}^{K}\bar{\mathbf{h}}_{\mathrm{I}}(t-kT)j^k b(k)+\bar{\mathbf{n}}_{\mathrm{bn}}(t), \tag{1}$$

where $1/T$ is the baud rate, the $N_R \times 1$ vector $\bar{\mathbf{h}}_i(t)$ gathers the N_R channel impulse responses of the ith OSC user, while $\bar{\mathbf{h}}_{\mathrm{I}}(t)$ refers to the out-of-cell interferer. Channel responses comprise the pulse shaping filter (i.e., the linearized GMSK pulse waveform), the multipath fading channel and the receiver's filter. The term j^k represents the periodic symbol rotation prescribed by the GMSK linearized model [9]. Finally, $\bar{\mathbf{n}}_{\mathrm{bn}}(t)$ models the additive white Gaussian noise (AWGN) filtered by the receiver's filter, with zero mean and covariance $\mathrm{E}[\bar{\mathbf{n}}_{\mathrm{bn}}(t)\bar{\mathbf{n}}_{\mathrm{bn}}^{\mathrm{H}}(t+\tau)] = \sigma_{\mathrm{bn}}^2 \mathbf{I}_{N_R} G(\tau)$, where σ_{bn}^2 is the noise variance and $G(\tau)$ is the autocorrelation of the filter impulse response.

A. Real-valued discrete-time signal model

According to [4]-[5], in order to boost the performance of linear interference cancellation, the received signals (1) are sampled with time interval $T/2$ and re-organized into an equivalent real-valued discrete-time domain, through the real-valued processing procedure summarized in the sequel (see [3] for details).

The two signal samples associated with the kth symbol time are first stacked into the $2N_R \times 1$ hybrid space-time (S-T) vector $\bar{\mathbf{y}}_s(k) = \left[\bar{\mathbf{y}}^{\mathrm{T}}(kT), \bar{\mathbf{y}}^{\mathrm{T}}(kT + T/2)\right]^{\mathrm{T}}$. This signal is then derotated in order to transform each GMSK stream into a BPSK-like modulated signal. The derotated signal is obtained as $\bar{\mathbf{y}}_d(k) = \mathbf{J}(k)\bar{\mathbf{y}}_s(k)$, using the $2N_R \times 2N_R$ diagonal matrix $\mathbf{J}(k) = \mathrm{diag}\left\{j^{-k}, j^{-(k+1/2)}\right\} \otimes \mathbf{I}_{N_R}$ where $\otimes$ denotes the Kronecker product. Finally, real and imaginary parts are separated leading to the $4N_R \times 1$ vector representation of the signal sampled at the baud rate: $\mathbf{y}(k) = [\mathrm{Re}\{\bar{\mathbf{y}}_d^{\mathrm{T}}(k)\}, \mathrm{Im}\{\bar{\mathbf{y}}_d^{\mathrm{T}}(k)\}]^{\mathrm{T}}$.

The signal vector $\mathbf{y}(k)$ can be written as a function of the $4N_R \times 1$ discrete-time real-valued channel responses $\{\mathbf{h}_0(k), \mathbf{h}_1(k), \mathbf{h}_{\mathrm{I}}(k)\}$ that are obtained from the continuous-time complex-valued responses $\{\bar{\mathbf{h}}_0(t), \bar{\mathbf{h}}_1(t), \bar{\mathbf{h}}_{\mathrm{I}}(t)\}$ by applying the same procedure of sampling, derotation, and real/imaginary separation as described above. Assuming a channel response length of L symbol times, we can arrange all the resulting channel samples into the $4N_R \times (L + 1)$ matrices $\{\mathbf{H}_0, \mathbf{H}_1, \mathbf{H}_{\mathrm{I}}\}$, with $\mathbf{H}_i{=}[\mathbf{h}_i(0) \cdots \mathbf{h}_i(L)]$, for $i = 0, 1$, and $\mathbf{H}_{\mathrm{I}}$ defined accordingly.

The overall $4N_R \times (K + L)$ received samples are:

$$\mathbf{Y} = [\mathbf{y}(1) \cdots \mathbf{y}(K + L)] = \mathbf{H}_0\mathbf{A}_0 + \mathbf{H}_1\mathbf{A}_1 + \underbrace{\mathbf{H}_{\mathrm{I}}\mathbf{B} + \mathbf{N}_{\mathrm{bn}}}_{\mathbf{N}}, \tag{2}$$

where $\mathbf{A}_i$ and $\mathbf{B}$ are the $(L{+}1) {\times} (K{+}L)$ convolution matrices for, respectively, the ith OSC user and the out-of-cell interferer symbols. The convolution matrices have elements $[\mathbf{A}_i]_{m,n} = a_i(m - n)$ and $[\mathbf{B}]_{m,n} = b(m - n)$, for $m = 1, \ldots, L + 1$, and $n = 1, \ldots, K + L$. The matrix $\mathbf{N}$ collects the samples of all the impairments due to the out-of-cell interference and the background noise $\mathbf{N}_{\mathrm{bn}} = [\mathbf{n}_{\mathrm{bn}}(1) \cdots \mathbf{n}_{\mathrm{bn}}(M + L)]$.

The filters for interference mitigation and the channel impulse responses for data detection are estimated within each burst using the training signals received during the midamble. Let $N_t + L$ be the training sequence length, the $4N_R \times N_t$ submatrix of (2) containing the midamble signals can be represented as:

$$\mathbf{Y}_t = [\mathbf{H}_0, \mathbf{H}_1] \begin{bmatrix} \mathbf{A}_{t,0} \\ \mathbf{A}_{t,1} \end{bmatrix} + \mathbf{N}_t = \mathbf{H}\mathbf{A}_t + \mathbf{N}_t. \tag{3}$$

where $\mathbf{A}_{t,i}$ is the $(L + 1) \times N_t$ convolution matrix of the training symbols of the ith OSC user, and $\mathbf{N}_t$ denotes the noise-plus-inter-cell-interference samples. Notice that the first L symbols of the received midamble are discarded due to the ISI generated by the tail of the first semi-burst of data.

III. OVERVIEW OF EXISTING RECEIVERS

The OSC feature of GSM has been designed so as to ensure compatibility with standard GSM receivers that are equipped with interference cancellation capabilities (here referred to as single-user interference cancellation, SU-IC). In the UL, the receiver at the BS may employ well-known linear filters for SU-IC (e.g., conventional SAIC/DAIC algorithms) and/or MUD schemes for a more effective in-cell interference cancellation (e.g., the SIC solution suggested within 3GPP for

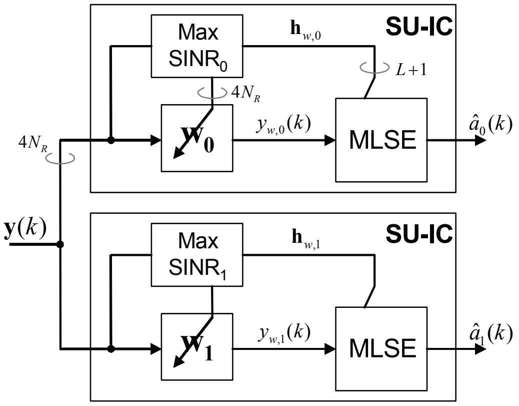

Fig. 2. SU-IC receiver block diagram. A prefilter is applyed to the received signal maximizing the SINR of a single OSC channel.

the OSC feature or other linear/no-linear solutions widely studied for CDMA system). In this section, some of these existing algorithms are recalled and combined into possible receiving architectures for the specific GSM-OSC framework. These solutions will be used as performance reference in the numerical analysis in Sec. V.

JMLSE Equalizer. Joint detection of the OSC sequences $\{a_0(k), a_1(k)\}$ is obtained by the optimal multi-antenna JMLSE equalizer, without any prefiltering stage. JMLSE can be implemented by a Viterbi Algorithm (VA) with 2^{2L} states using as input the complex-valued signals (1) sampled at baud-rate (see [11] for details). Signals incoming from the N_R antennas are optimally combined in the branch metric of the trellis.

SU-IC. The BS detects one OSC user at a time (Fig. 2) by means of conventional SU-IC algorithms developed for the DARP I-II GSM evolution, such as SAIC for $N_R = 1$, DAIC for $N_R = 2$ or their direct extension to any number of antennas (see, e.g., [6], [7]). We remark that no standardized versions of these receivers are available, only different vendor solutions. For the ith OSC sequence, a linear prefilter is designed by maximizing the Signal to Interference plus Noise Ratio (SINR):

$$\mathrm{SINR}_i = \frac{\left\|\mathbf{h}_{w,i}\mathbf{A}_{t,i}\right\|^2}{\left\|\mathbf{w}_i^{\mathrm{T}}\mathbf{Y}_t - \mathbf{h}_{w,i}\mathbf{A}_{t,i}\right\|^2}, \quad (4)$$

obtaining the filter $\mathbf{w}_i$ and the relative filtered channel $\mathbf{h}_{w,i}$. Notice that the interference term at the denominator includes both the out-of-cell *and* the other OSC user. The two filtered signals $y_{w,i}(k) = \mathbf{w}_i^{\mathrm{T}}\mathbf{Y}(k)$, $i = 0, 1$, are then processed by separate MLSE equalizers.

SIC. We consider a successive cancellation receiver (see Fig. 3-a) as suggested within 3GPP for the OSC feature [8]: the strongest OSC signal is detected first, then the detected sequence is re-modulated, convolved with the estimated channel response and subtracted from the received signals for detection of the other OSC sequence. A variety of interference mitigation receivers can be used for the SIC implementation, here we have used the SU-IC algorithm applied twice.

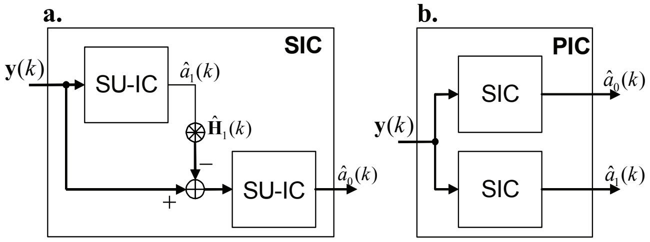

Fig. 3. Block diagram of the SIC (a) and PIC (b) algorithm.

PIC. A parallel cancellation approach is designed as the combination of two SIC receivers (Fig. 3-b).

IV. JOINT OSC RECEIVER

We propose a new receiving strategy specifically designed for the OSC-aware system, as the combination of a front-end filtering stage with a MUD, as sketched in Fig. 4. Two linear filters $\{\mathbf{w}_0, \mathbf{w}_1\}$ are applied to the received signal (2) generating the following filtered streams for the two users:

$$\begin{cases} \mathbf{y}_{w,0}^{\mathrm{T}} = \mathbf{w}_0^{\mathrm{T}}\mathbf{Y} = \mathbf{h}_{w,00}^{\mathrm{T}}\mathbf{A}_0 + \mathbf{h}_{w,01}^{\mathrm{T}}\mathbf{A}_1 + \mathbf{n}_0^{\mathrm{T}} \\ \mathbf{y}_{w,1}^{\mathrm{T}} = \mathbf{w}_1^{\mathrm{T}}\mathbf{Y} = \mathbf{h}_{w,10}^{\mathrm{T}}\mathbf{A}_0 + \mathbf{h}_{w,11}^{\mathrm{T}}\mathbf{A}_1 + \mathbf{n}_1^{\mathrm{T}} \end{cases} . \quad (5)$$

The coefficients of the filters $\{\mathbf{w}_0, \mathbf{w}_1\}$ and the relative filtered channel responses $\{\mathbf{h}_{w,00}, \mathbf{h}_{w,11}\}$ are jointly optimized during the training phase so as to minimize the out-of-cell interference at the filter output, as described in Sec. IV-A. These signals are then used in the second stage for joint detection of the symbol sequences $\{a_0(k), a_1(k)\}$, taking into account the mutual interference due to the cross-channels $\mathbf{h}_{w,01}^{\mathrm{T}} = \mathbf{w}_0^{\mathrm{T}}\mathbf{H}_1$ and $\mathbf{h}_{w,10}^{\mathrm{T}} = \mathbf{w}_1^{\mathrm{T}}\mathbf{H}_0$, and the residual noise $\mathbf{n}_i^{\mathrm{T}} = \mathbf{w}_i^{\mathrm{T}}\mathbf{N}$ (see Sec. IV-B).

A. Optimal design of JOR prefiltering

The $4N_R \times 1$ filters $\{\mathbf{w}_0, \mathbf{w}_1\}$ and the corresponding filtered channels $\{\mathbf{h}_{w,00}, \mathbf{h}_{w,11}\}$ are the parameters to be optimized. They are calculated jointly for the two OSC mobiles using the midamble signals $\mathbf{Y}_t$ in (3) and the knowledge of the training sequences (TSC) $\{\mathbf{A}_{t,0}, \mathbf{A}_{t,1}\}$. The optimization is carried out by maximizing the signal-to-noise-plus-out-of-cell-interference ratios $\{\mathrm{SINR}_0, \mathrm{SINR}_1\}$ at the filters' output. The SINR for user $i = 0$ (and similarly for user $i = 1$) can be written as:

$$\mathrm{SINR}_0 = \frac{\left\|\mathbf{h}_{w,00}^{\mathrm{T}}\mathbf{A}_{t,0}\right\|^2}{\left\|\mathbf{w}_0^{\mathrm{T}}\mathbf{Y}_t - \mathbf{w}_0^{\mathrm{T}}\hat{\mathbf{H}}_1\mathbf{A}_{t,1} - \mathbf{h}_{w,00}^{\mathrm{T}}\mathbf{A}_{t,0}\right\|^2}, \quad (6)$$

where $\hat{\mathbf{H}}_1$ denotes the least square estimate of the user-1 channel, obtained as $[\hat{\mathbf{H}}_0, \hat{\mathbf{H}}_1] = \mathbf{Y}_t\mathbf{A}_t^{\mathrm{T}}(\mathbf{A}_t\mathbf{A}_t^{\mathrm{T}})^{-1}$. It is important to notice that, differently from conventional SU-IC, the power on the denominator includes *only the out-of-cell* interference, *not the in-cell* one, as the aim of this first stage is to exploit all the available space dimensions to cancel as much as possible the interference from other cells.

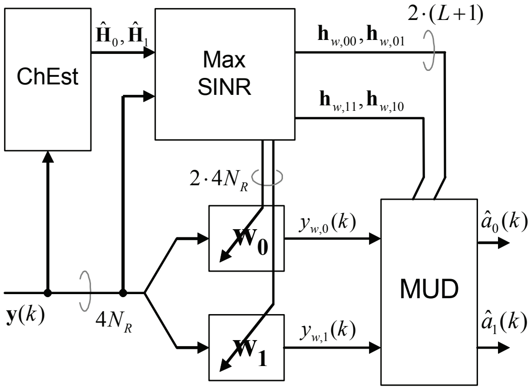

Fig. 4. JOR block diagram: the filters are designed to provide the maximum SINR for each OSC user.

The solutions can be carried out as described in [10] for the rank-one receiver derivation accounting for $\mathbf{Z}_0 = \mathbf{Y}_t - \hat{\mathbf{H}}_1 \mathbf{A}_{t,1}$ as the received signal, so that:

$$\mathbf{w}_0 = \mathbf{R}_{zz,0}^{-1} \mathbf{R}_{za,0} \mathbf{h}_{w,00} \tag{7}$$

$$\mathbf{h}_{w,00} = \mathbf{R}_{aa,0}^{-1} eig_{\max} \left(\mathbf{R}_{aa,0}^{-\mathrm{T}/2} \mathbf{R}_{az,0} \mathbf{R}_{zz,0}^{-1} \mathbf{R}_{za,0} \mathbf{R}_{aa,0}^{-1/2} \right) \tag{8}$$

where the covariance matrices are defined as $\mathbf{R}_{zz,0} = \mathbf{Z}_0 \mathbf{Z}_0^{\mathrm{T}} / N_t$, $\mathbf{R}_{az,0} = \mathbf{A}_{t,0} \mathbf{Z}_0^{\mathrm{T}} / N_t$, and similarly for $\mathbf{R}_{aa,0}$ and $\mathbf{R}_{za,0}$. For the other user (i.e. $i = 1$) the solutions $\{\mathbf{w}_1, \mathbf{h}_{w,11}\}$ are dually defined.

Intuitively the application of the optimal filter $\mathbf{w}_i$ performs a whitening through the covariance $\mathbf{R}_{zz,i}^{-1}$ of the signal $\mathbf{Z}_i$ (where the other OSC user is excluded) and then extracts the dominant component of the channel by projecting the signal over the eigenvector associated with the maximum SINR.

B. MUD for joint detection of the two OSC users' data

We can rewrite the $2 \times (K + L)$ signal (5) at the input of the detection stage as:

$$\mathbf{Y}_w = [\mathbf{y}_{w,0}, \mathbf{y}_{w,1}]^{\mathrm{T}} = \mathbf{H}_{w,0} \mathbf{A}_0 + \mathbf{H}_{w,1} \mathbf{A}_1 + \mathbf{N}_w, \tag{9}$$

where the $2 \times (L + 1)$ matrices $\mathbf{H}_{w,0} = [\mathbf{h}_{w,00}, \mathbf{h}_{w,10}]^{\mathrm{T}}$, $\mathbf{H}_{w,1} = [\mathbf{h}_{w,11}, \mathbf{h}_{w,01}]^{\mathrm{T}}$ gather the filtered channels for the two in-cell users while the residual interference can be expressed as $\mathbf{N}_w = [\mathbf{n}_0, \mathbf{n}_1]^{\mathrm{T}}$.

MUD is the best choice to recover the two sequences from (9). In this section we consider both the optimal non-linear JMLSE and the linear detection, as a good trade-off between performance and computational complexity [12]. Detection is carried out over half a burst at a time, estimating the $2M$ symbols associated with each semi-burst. For optimal detection, a pre-whitening of the noise $\mathbf{N}_w$ has to be performed on the signal (9) using the noise covariance $\mathbf{R}_n = \mathrm{E}[\mathbf{N}_w \mathbf{N}_w^{\mathrm{T}}]/(K + L)$. This matrix can be estimated from the training signals $\mathbf{Y}_{w,t}$ (i.e., the submatrix of $\mathbf{Y}_w$ relative to the midamble) as $\hat{\mathbf{R}}_n = \frac{1}{N_t} \hat{\mathbf{N}}_{w,t} \hat{\mathbf{N}}_{w,t}^{\mathrm{T}}$ with $\hat{\mathbf{N}}_{w,t} = \mathbf{Y}_{w,t} - \mathbf{H}_{w,0} \mathbf{A}_{t,0} - \mathbf{H}_{w,1} \mathbf{A}_{t,1}$. The pre-whitening is given by

$$\tilde{\mathbf{Y}}_w = [\tilde{\mathbf{y}}_{w,0}, \tilde{\mathbf{y}}_{w,1}]^{\mathrm{T}} = \hat{\mathbf{R}}_n^{-\mathrm{T}/2} \mathbf{Y} = \tilde{\mathbf{H}}_{w,0} \mathbf{A}_0 + \tilde{\mathbf{H}}_{w,1} \mathbf{A}_1 + \tilde{\mathbf{N}}_w. \tag{10}$$

The corresponding whitened channel responses have been denoted as $\tilde{\mathbf{H}}_{w,i} = \mathbf{R}_n^{-\mathrm{T}/2} \mathbf{H}_{w,i}$.

1) Non-linear MUD: Joint maximum likelihood estimation of the two users' sequences can be obtained by a VA (see, e.g., [11]). The estimate is:

$$\hat{\mathbf{a}} = \arg\min_{\hat{\mathbf{a}}} \underbrace{\sum_{k=1}^{K} \underbrace{\left| \tilde{\mathbf{Y}}_w(k) - \tilde{\mathbf{H}}_{w,0} \mathbf{a}_0(k) - \tilde{\mathbf{H}}_{w,1} \mathbf{a}_1(k) \right|^2}_{\Delta J_k(\hat{\mathbf{a}}(k))}}_{\text{Path metric}}, \tag{11}$$

where $\mathbf{a}_0(k) = [a_0(k), ..., a_0(k - L)]^{\mathrm{T}}$ and $\mathbf{a}_1(k) = [a_1(k), ..., a_1(k - L)]^{\mathrm{T}}$ collect the symbols associated to the selected trellis state. The path metric is the overall cost for a given sequence $\hat{\mathbf{a}}$ while $\Delta J_k(\hat{\mathbf{a}}(k))$ is the branch metric, i.e. the distance between the kth noisy observation and the possible transmitted symbols $\hat{\mathbf{a}}(k) = [\hat{a}_0(k), \hat{a}_1(k)]$. Using the VA, the path metric can be calculated recursively as: $J_k(\hat{\mathbf{a}}(k)) = J_{k-1}(\hat{\mathbf{a}}(k - 1)) + \Delta J_k(\hat{\mathbf{a}}(k))$. The resulting number of states in the JMLSE trellis is 2^{2L}.

2) Linear MUD: Let us re-arrange the samples of (10) associated with a single semi-burst into the $2(M + L) \times 1$ vector:

$$\tilde{\mathbf{y}}_w = \tilde{\mathcal{H}}_w \mathbf{a} + \tilde{\mathbf{n}}_w, \tag{12}$$

where $\mathbf{a} = [a_0(1), ..., a_0(M), a_1(1), ..., a_1(M)]^{\mathrm{T}}$ collects the $2M$ transmitted symbols, $\tilde{\mathcal{H}}_w$ is the $2(M+L) \times 2M$ convolution matrix obtained from the filtered channels $\{\tilde{\mathbf{H}}_{w,0}, \tilde{\mathbf{H}}_{w,1}\}$ and $\tilde{\mathbf{n}}_w = [\tilde{\mathbf{n}}_0^{\mathrm{T}}, \tilde{\mathbf{n}}_1^{\mathrm{T}}]^{\mathrm{T}}$ is the overall residual noise/interference. Minimum mean square error (MMSE) estimation of the data vector $\mathbf{a}$ is obtained as [13]:

$$\hat{\mathbf{a}} = (\tilde{\mathcal{H}}_w^{\mathrm{T}} \tilde{\mathcal{H}}_w + \mathbf{I}_M)^{-1} \tilde{\mathcal{H}}_w^{\mathrm{T}} \tilde{\mathbf{y}}_w, \tag{13}$$

followed by a threshold detector.

V. NUMERICAL RESULTS

The performance of the proposed receiver is assessed through Montecarlo simulations of a standard compliant GSM-OSC uplink scenario with $N_R = 2$ antennas and subcarrier frequency 900 MHz. Two in-cell and one out-of-cell MSs are simulated. One of the in-cell mobiles employs a conventional TSC, the other one uses a new TSC as specified in [14]. According to the ideal frequency hopping and receiving diversity assumptions, independent realizations of the Typical Urban (TU) channel model [12] are generated for each burst, user and receiving antenna. The vehicular speed is fixed to 3 km/h for all the MSs. The estimated channel has length $L = 4$ taps. The receiver employs a root raised-cosine filter with roll-off $\alpha = 0.3$ and 3dB bandwidth equal to 240 kHz.

The average performance of the generic OSC user is evaluated in terms of raw Bit Error Rate (BER) at the detection output and the Frame Error Rate (FER) for an Adaptive Full Speech (AFS) coded transmission with 5.9 kbit/s. The performance is

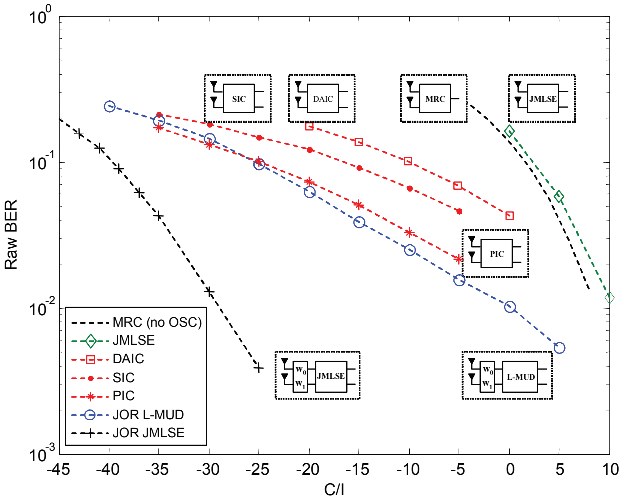

Fig. 5. Raw BER vs C/I for all the uplink receivers.

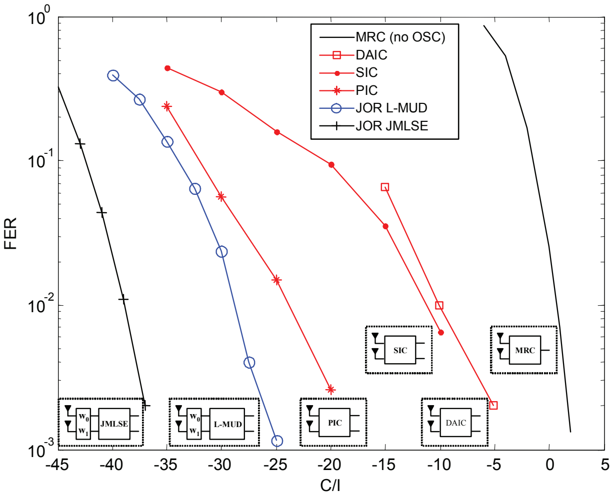

Fig. 6. FER as a function of C/I for all the uplink receivers.

drawn as a function of the carrier-to-interference ratio defined as $\mathrm{C/I} = P/P_\mathrm{I}$, where $P = \mathrm{E}[\|\mathbf{h}_i(k)\|^2]$, $i \in \{0,1\}$, denotes the average received power of each OSC user and $P_\mathrm{I} = \mathrm{E}[\|\mathbf{h}_\mathrm{I}(k)\|^2]$ refers to the interferer. The proposed JOR algorithm is compared with all the conventional receivers presented in Sec. III. A standard uplink GSM receiver, with Maximum Ratio Combining (MRC) of signals at different antennas, is considered as well as performance reference, assuming a conventional cellular scenario where only one user is active in the cell (no OSC).

Fig. 5 and 6 give, respectively, the raw BER and FER results. From the comparison between the two figures we can see the gain introduced by the coded transmission with the diversity provided by the block fading model. Among all receivers, the JMLSE equalizer experiences the worst performance, as this receiver optimally handles the mutual interference between the two OSC users, but no prefiltering is performed to mitigate the out-of-cell impairments. Both SIC and PIC offer good performance, even though the SIC algorithm shows performance comparable with the conventional DAIC approach. The JOR filter with the JMLSE detection outperforms all the other solutions, but the 256 states of the VA can be a strong limitation for the hardware implementation. A better trade-off between computational cost and performance is reached by the JOR with linear MUD which guarantees good performance with reasonable computational complexity.

VI. CONCLUSION

The 3GPP is evaluating the new OSC feature as the next solution to improve the cell capacity in the existing GERAN networks. In this work we have developed a new uplink receiver with a prefiltering stage that has been optimized to mitigate the out-of-cell interference and a MUD stage that has been designed to jointly decode the two in-cell users' streams. Simulation results corroborated the performance gain provided by the proposed receiver with respect to other conventional receivers.

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