On the choice of the best linear multi-antenna receiver to combat downlink adjacent channel interference in WCDMA networks

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Abstract — In this paper we consider some linear multi-antenna receivers to combat inter-operator interference in non-coordinated WCDMA networks. Adjacent channel interference creates dead zones where the QoS target cannot be reached. We first characterize the importance of this phenomenon by evaluating the dead zone area and probability of finding a given number of users in it. We then derive specific reception schemes from the space-time Wiener receiver in order to get the best trade-off between performance and complexity. As a third step we discuss the importance of adjacent channel interference regarding the propagation environment and handover strategy.

I. INTRODUCTION

In this paper we consider non-coordinated WCDMA cellular networks, which means in particular that competing operators base stations are not co-located. In this context adjacent channel interference (ACI) is due to the presence of several operators in the same geographical area. Adjacent band operators generate out-of-band emissions because of transmit filter imperfections and transmit power amplifier (PA) non-linearities. Additionally, the receiver filter has a finite frequency selectivity, which makes it sensitive to in-band emissions of adjacent band operators. As 3GPP specifications have been designed taking into account cost and design constraints, there are situations where ACI can have a considerable impact on the receiver performance. The position of the mobile station within the main cell plays an important role regarding the influence of ACI. ACI power can be stronger than the useful signal when the mobile station of interest is very close to an adjacent band operator base station (BS) and distant from the useful BS. Note that ACI also exists in non-CDMA networks (e.g. GSM) but is not influential because frequency reuse is high (e.g. 21) while in CDMA networks it equals 1. Making a simple link budget analysis shows the existence of dead zones (DZ) in which the adjacent band operator blinds the mobile station under consideration.

Throughout this paper we assume a network deployment based on 3GPP parameters. Because mobile stations are generally the limiting factor of cellular network performance, we only consider the downlink case. It turns out that ACI is thought to be an influential source of interference in 3GPP-compliant networks. Under these conditions a possible way of combating ACI is to use several antennas at the mobile station. This paper aims precisely at knowing to what extent low-complexity multi-antenna signal processing algorithms can compensate for transmit and receive devices imperfections. For the problem under consideration in this paper, namely ACI suppression in WCDMA networks, the most useful contributions on ACI cancellation are [1] and [2]. Both of these papers still focus on filters imperfections in TDMA systems and out-of-band emissions are taken into account. Single-antenna algorithms proposed in [1] rely on adjacent channels knowledge, which is not available in the problem under investigation. In [2] a useful array processing technique is proposed to combat ACI but would require major changes in order to be used to our context (CDMA, multipath channels, limited MS complexity). Interference cancellation schemes proposed in this paper are closer to those presented in [3] where the problem of combating intracell interference in WCDMA networks with reduced-complexity versions of the space-time MMSE receiver.

This paper is structured as follows. In section II we describe our signal model, which includes power amplifier non-linearities and filters imperfections. Section III characterizes the importance of the dead zone problem by providing a geometrical characterization of dead zones and evaluating the probability of finding a given number of users in a dead zone. In section IV we present the reception schemes under consideration namely the space-time Wiener filter, generalized 2D Rake, spatial matched filter, whitened 2D Rake and the conventional 2D Rake. The performance of these receivers in different propagation scenarios is assessed in section V. The main contributions of the paper are summarized in section VI.

II. SIGNAL MODEL

Unless stated otherwise we will always consider the hard handover strategy. When hard handover is assumed we will consider two base stations: one useful base station (associated with the subscriber of interest) and another one belonging to an adjacent band operator. When soft handover is assumed we will consider three base stations: two useful base stations and one adjacent band operator base station. As mentioned in the introduction, ACI stems both from the adjacent band BS out-of-band emissions and finite receive filter frequency selectivity. In the following two subsections we show how these imperfections can be taken into account in the signal model. We will introduce notations associated with the useful base(s) station(s) only and give the corresponding signal, since the adjacent band signal is generated in the same way up to a frequency offset (5 MHz in the UMTS - FDD mode).

A. Transmit signal model

In this paper the downlink case is considered. No assumption is made on the number of antennas used by the useful base station. But we assume that the mobile station of interest is equipped with “Q” sensors. Four sources of reception performance degradation are taken into account: the thermal noise, the interchirp interference (ICI), the multiple access interference (MAI) and, of course, the adjacent channel interference generated by the adjacent band operator. To be
more realistic, intercell should be accounted for. We will see that in the area of interest, which is in and around the dead zone, neglecting intercell interference does not prevent us from drawing useful interpretations from the presence of ACI in cellular networks.

Transmit filter output: denoting by $P_k$ the power allocated to user “$k$”, $c_i(n)$ its spreading code, $b_i(n)$ its QPSK symbols, $s(n)$ the useful base station scrambling code and $g(t)$ the equivalent transmit filter allows us to express the baseband signal at the output of the transmit filter:

$$x(t) = \sum_{n=Z}^{K} \sum_{k=1}^{\infty} \sqrt{P_k b_k(i)c_i(n)s(n)}g(t-nT_c)$$

where “$K$” is the number of active users in the cell covered by the considered base station, “$i$” is the symbol index, “$n$” is the chip index and $T_c$ is the chip duration. According to the UMTS-FDD mode specifications, the transmit filter is a root raised-cosine (RRC) filter with roll-off 0.22 and truncated to 8 chip durations (the purpose of this operation is to trade spectral performance against computational burden).

Power amplifier input: power amplification is the last stage of the transmitter, it has to amplify the in-phase plus in-quadrature signal (say $\tilde{X}(t)$), which writes as follows:

$$\tilde{x}(t) = \tilde{x}_r(t) + \tilde{x}_l(t) = \text{Re}[x(t)]\cos(\omega_0 t) + \text{Im}[x(t)]\sin(\omega_0 t)$$

where $\omega_0 = \frac{f_0}{2\pi}$ is the useful carrier frequency.

Power amplifier output: a good approximation of the power amplifier non-linearity is the polynomial model given in [4]. This approximation is often used by mobile and base stations manufacturers. Under this approximation, the PA output expresses as:

$$y(t) = \tilde{x}(t)\sum_{j=0}^{D} a_j |\tilde{x}(t)|^{2j}$$

where “$D$” is the approximation degree and $a_0 = 1$.

B. Receive signal model

Reception filter: the baseband filter is a discrete-time finite impulse response filter and is often chosen to be a RRC filter (roll-off 0.22). In 3GPP-compliant networks receiving mobile stations are sensitive to in-band emissions of adjacent band operators because the latter is truncated (as in the transmitter) to 8 chip durations. Assuming a white input for the RRC filter, it can easily shown that truncating the RRC filter at 8 chip durations instead of 32 leads to a 30 dB increase of the averaged power spectral density of out-of-band emissions.

Received signal (hard handover): although the received signal is generated through a non-linear device (PA), the receiver considers, for the baseband reception algorithms, a linear model of the transmission chain in the sense that the useful signal is separated from the ACI in an additive way. The discrete-time model that is used to the interference cancellation purpose is given in the following figure, where $y(n) = [y_1(n) \ldots y_L(n)]^T$ is the signal received by the $Q$-sensor MS antenna, “$L$” is the number of paths of the overall channel impulse response $g_i(.)$, $d_i(.)$ is the useful chip sequence defined in (1), $a_k$ corresponds to propagation losses over the useful link, $a_i$ corresponds to propagation losses over the ACI link. At last, notations $\tilde{e}^{out}(.)$ and $\tilde{e}^{jout}(.)$ stands for ACI received in and out of the theoretical MS frequency band $\left[ f_0 - (1+p) / T_c , f_0 + (1+p) / T_c \right]$, $\rho$ being the RRC roll-off factor.

$$y(n) = \alpha_0 \sum_{k=1}^{Q} \sum_{\ell=0}^{L-1} h(\ell) d_k(n-\ell)$$

$$+ \alpha_0 \sum_{k=1}^{Q} \sum_{\ell=0}^{L-1} h(\ell) d_k(n-\ell) + \frac{y(n)}{\text{ACI}} + \frac{y(n)}{\text{AWGN}}$$

Figure 1 clearly shows what we mean by in-band and out-of-band interference.

![Figure 2](image-url)  
Figure 1: two origins of ACI

Received signal (soft handover): the scenario under consideration in this paper is described in figure 2. In this case, the mobile station receives the same information bits from the two closest base stations. Channel estimation is performed with both stations and the more powerful paths are selected and combined, in order to achieve a better signal to interference ratio (see section IV).

![Figure 2](image-url)  
Figure 2: the soft handover situation under investigation

II. DEAD ZONE CHARACTERIZATION

In the previous section we have seen how ACI can be modelled. The purpose of this section is to discuss the importance of ACI in cellular networks. We want to know how often the dead zone (DZ) phenomenon occurs. To this end we first review 3GPP’s definition regarding ACI, then we give the propagation losses model we used in order to evaluate a typical dead zone radius. Making a simple analysis on the probability of the DZ phenomenon to occur concludes this section.
**A. Review of 3GPP’s definitions on ACI**

Out-of-band-emissions maximum power: in the UMTS – FDD mode [5], the maximum level of base stations out-of-band emissions has been specified through the adjacent channel leakage ratio (ACLR). It is defined by $\text{ACLR}_{\text{BS}} = P_{\text{TX}}(\text{in band})/P_{\text{TX}}(\text{out-of-band})$ and has to be greater than 45 dB.

Maximum of adjacent channel power: in the same way, the minimum frequency selectivity of receive mobile stations has been specified through the adjacent channel selectivity (ACS). It is defined by $\text{ACS}_{\text{MS}} = P_{\text{RX}}(\text{in band})/P_{\text{RX}}(\text{out-of-band})$ and has to be greater than 33 dB.

In order to measure the combined effects of transmission and reception in the adjacent band, the downlink adjacent carrier-to-interference ratio has been defined as $\text{ACIR}^{-1} = \text{ACLR}_{\text{BS}} + \text{ACS}_{\text{MS}}$. The dominant part of ACI is due to MS frequency selectivity since $\text{ACIR} ≈ 32.7$ dB.

Assuming a 3GPP typical NLOS urban micro-cell environment [8] for both the useful and ACI channels we find that the dead zone radius equals about 70 meters for a 0 dB SIR (voice service) and a $600 \text{ m}$ cell radius from the useful BS. In fact, this is not the worst case scenario since it can happen that the ACI propagation channel is less severe than the useful one and the SIR target can be higher than that (data service). In any case, compared to a typical micro-cell radius (about 600 m), the DZ radius is significant even for low rates transmissions.

**C. Probability for active users to be in a dead zone**

Given a dead zone radius, we want to know what are the chances of one user (or more) to be in a dead zone. To this end we assume that the active users can be anywhere in the useful cell with an equal probability. We always denote by $K$ the number of users in the cell under consideration. Let $k$ be the number of users in a dead zone. One can show that the probability of the event $k ≥ K$ to occur is roughly given by:

$P(k ≥ K) = 1 - \sum_{i=0}^{K} \binom{K}{i} \epsilon(K)^{i+1} \epsilon(K)^{K-i}$

$\epsilon(K) = \sum_{m=0}^{\infty} R_{\text{cell}}^{m} (K) / BR_{\text{cell}}^{m}$

To establish this relation we have considered a cluster comprising “B” useful base stations and “B” base stations belonging to an adjacent band operator. The index “B” indicates that the “dead zone radius”, which has to be thought of as a characteristic dimension of the dead zone, depends of the cell under consideration (propagation environment …). In particular, one can check that when the number of active users goes to the infinity, the probability of finding one user in the DZ tends to 1. Note that the dead zone radius depends on the user load because the QoS is MAI-dependent. For a 1D Rake, a 32 spreading factor and a 600 m cell radius we have obtained the following results:

<table>
<thead>
<tr>
<th>$K$</th>
<th>4</th>
<th>8</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(k ≥ 1)$</td>
<td>4%</td>
<td>10%</td>
<td>19%</td>
</tr>
</tbody>
</table>

Table 1: Probability of finding at least 1 user in a DZ

From this (worst case scenario) example we see that what could be at first glance considered as second-order effects can have a significant impact on the network performance, we propose studying different multi-antenna reception schemes in order to know to what extent signal processing can be of help to compensate for Tx and Rx imperfections.

**III. MULTIPLE ANTENNAS RECEPTION SCHEMES**

We want to know to what extent using several antennas at the mobile station can help to combat ACI. In order to keep the receiver complexity reasonable we only study linear reception schemes. In this case the receiver consists of a linear space-time equalizer, followed by descrambling and despreading operations. One can show that for these reception strategies, the symbol estimate of the user of interest (index $i$) has a generic expression:

$\hat{b}_i(i) = \sum_{n=0}^{K} \sum_{l=0}^{L} w_l(n+i) y(n+l) z_i(n)x^{*}(n)$

where $N$ is the spreading factor and $w_l(i)$ is the $Q$-dimensional weighting vector depending on the reception scheme.
The best linear scheme is the chip-rate space-time Wiener filtering (STWF). This filter is designed in order to minimize the mean square error between its output and a reference sequence (the pilot sequence $d_f(n)$ for instance); it is given by

$$w = \left( E[y(n) y^H(n)] \right)^{-1} E[y(n) d_f(n)]$$

(10)

where $w$ and $E[.]$ are obtained by stacking the $L$ successive chip-rate samples $w(t)$ and $y(n)$, $t = 0, ..., L-1$, in a vector. In practice, this filter is implemented by replacing the expectation operator in (10) with a discrete sum over $n$. Hence, implementing the STWF requires the inversion of a $QL \times QL$ matrix. The complexity of this operation is too high regarding the fact that RRC filters have been truncated to decrease complexity. That is why in this work, we focus on the following less complex reception schemes: conventional 2D RAKE, spatial matched filter (SMF) and whitened 2D Rake. Indeed the STWF is not a good candidate for WCDMA user equipment since large matrix inversions are involved. Furthermore the corresponding space-time matrix is in ill-conditioned in certain situations.

B. Conventional 2D Rake

In this case there is one Rake per antenna and antenna outputs are simply added. It follows that:

$$w(\ell) = h(\ell)$$

(11)

It is known that this strategy is optimum when the noise-plus-interference term is Gaussian, temporally and spatially white.

C. Spatial matched filter (SMF)

A spatial filter matched to the pilot sequence is first applied to the received signal, and it is followed by a 1D RAKE receiver. The coefficients of the RAKE receiver are the spatially filtered versions of channel coefficients. For a given delay denoted by $\ell_0$, the weighting vector writes:

$$w(\ell) = g(\ell_0) a^H(\ell_0) h(\ell)$$

(12)

with

$$a(\ell_0) = \arg\min_{\alpha} E[a^H y(n) - d_r(n - \ell_0)]^2 = R^{-1} h(\ell_0)$$

(13)

and $R = E[y(n) y^H(n)]$. The delay $\ell_0$ is chosen in order to maximize:

$$h^H(\ell_0) R^{-1} h(\ell_0)$$

(14)

D. Whitened 2D Rake (W2D-Rake)

The idea here is to approximate space-time Wiener filtering by assuming the space-time covariance matrix to be block diagonal, which is equivalent to assume temporally white the noise-plus-interference term. It is easy to show that under this assumption the STWF boils down to:

$$w(\ell) = R^{-1} y h(\ell)$$

(15)

E. Soft Handover

When soft handover is performed, the propagation channels corresponding to both stations are estimated. This provides the receiver with two sets of channels coefficients. Both stations are then independently demodulated are their outputs are added.

In practical implementation, only a few paths are selected (the RAKE fingers) with respect to a power criterion. The extension of this selection to the case of soft handover is straightforward: the receiver measures the power of the channel coefficients associated to both stations and keeps only the most powerful. The other coefficients are then set to zero. With this selection strategy, it can occur that, when one of the stations has temporally particularly good propagation conditions, the second station is not demodulated.

IV. SIMULATION RESULTS AND DISCUSSION

In this section we essentially want to ask two questions. First we want to know the influence of the receiver choice on the mobile station performance in the presence of ACI. Then we consider a soft handover scenario in order to know to what extent the dead zone area is reduced.

A. Simulation setup

The considered scenario is as follows (see figure 2). The distance between each useful base station and the interfering station is 290m. The distance between useful base stations is 500m. The mobile station is equipped with a linear antenna comprising 4 sensors equally spaced of 10cm. The MS is moving along a line between the useful and adjacent base stations. The thermal noise level is fixed to -110 dBm. The number of active users is 8, the spreading factor equals 32 and the useful channel is estimated thanks to the common pilot channel (2560 chips, 10% of the BS transmit power). The PA non-linearity is modelled by a 3-degree polynomial ($a_1 = 4/27$) and works at its 1 dB compression point. The power of each useful BS is 43 dBm. We assume that for each BS 35 dBm is allocated to the user of interest, which corresponds to the maximum power a user can be given. As a consequence the communication is dropped if the QoS target cannot be reached. The propagation channel power delay profile between the useful station and the terminal handset is chosen to be the Vehicular A channel and the chosen path loss model corresponds to microcell propagation environments [8] that is to say that $L_0 = 34.53, K_0 = 38$.

Two propagation scenarios are considered for the adjacent base band station. In the first one (best case), the transmit power of the interfering station is 40 dBm and propagation conditions are the same as for the useful station. In the second case (worst case), the mobile station is in line-of-sight with the interfering station, for which the transmit power is 43 dBm. In the latter case the interfering channel has one Rice component and the path loss model parameters are $L_0 = 30.18, K_0 = 26$. It is reasonable to think that the vast majority of typical propagation scenarios lie between these two cases in term of reception performance.

B. What is the most efficient receiver?

Figure 3 represents the raw BER of the 1D-RAKE, 2D-RAKE, SMF and W2D-RAKE as a function of the distance in meter ($r_0$) between the mobile station and interfering station antenna in both scenarios (best case and worst case). As hard handover is assumed here the signal coming from the second station is considered as an additional source of interference. We observe that with a conventional single-antenna receiver, for a 2.10^-5 BER target the dead zone radius equals 45m or 90m depending on the scenario under consideration (best case, worst case). It can be significantly reduced by using several antennas at the receiver. In the worst case, the dead zone radius is reduced to 45m when implementing the 2D-RAKE, and to 15m for the SMF or W2D-RAKE. In the best case, the dead zone radius equals 12m for the 2D-RAKE while the dead zone
The phenomenon is negligible when using the other receivers. We also notice that the 1D-Rake and 2D-Rake performance are totally degraded by the presence of a line-of-sight, while SMF and W2D-Rake still get excellent performance. This can be explained by the fact that in the LOS case, there is only one dominant path coming from the interfering station. Indeed the presence of a LOS changes the interfering channel power angle profile, the latter becomes sparse and mobile sensors become correlated. It turns out that only SMF and W2D-Rake are able to exploit this correlation to spatially reject the dominant interfering path whatever its power is.

C. What is the influence of Soft Handover?

When the mobile station is far enough from the useful base station, a soft handover situation is likely to occur. In this case the mobile station receives power from several (say the two closest) base stations. Channel estimation is performed for both useful channels and the more powerful paths are selected. In figure 4 we have compared the performance of the 1D-RAKE and 2D-RAKE in the two extreme propagation scenarios under investigation (best and worst cases) when soft handover is performed. We observe that in the worst case, the improvement due to soft handover is negligible (for a $2 \times 10^{-2}$ BER target the dead zone radius equals 85m with the 1D-RAKE, and 42m with the 2D-RAKE). In the best case, the dead zone radius is reduced to 17m by the 1D-RAKE and to 10m by the 2D-RAKE.

V. CONCLUSIONS

From the proposed theoretical analysis of the DZ phenomenon and simulation results, we see that, in most of the cases, dead zones can be reduced if a soft handover with two useful base stations is performed. In fact, the dead zone phenomenon is particularly significant when using only one antenna at the MS in a situation where the interfering power is strong. This happens for instance when the interfering channel has a Rice component, which is a realistic assumption taken into account the fact that the MS is close to the interfering BS. In this case, even soft handover is not able to cancel the ACI. On the other hand using suited multiple-antenna reception schemes such as spatial matched filter or a whitened 2D Rake leads to good MS performance whatever the propagation channels. Indeed the SMF and W2D Rake provide good performance even if the interfering channel power angle profile is sparse. As an important consequence we see that the use of efficient multi-antenna receivers allows reducing the use of soft handover since they are able to perform ACI cancellation very well, and by this way, to increase the cell capacity.

REFERENCES