Sensitivity of downlink transmission methods to the channel time variations in UMTS/TDD systems

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ABSTRACT

In cellular mobile radio systems, transmit beamforming can be used to reduce the interference in the downlink. In a Time Division Duplex (TDD) system with sufficiently short duplex period, the uplink channel estimation can be used to design the downlink beamformer. The purpose of this paper is to analyse the sensitivity of several transmit techniques to the channel variations between uplink and downlink time-slots. This analysis is done using experimental data obtained from real environments.

I. INTRODUCTION

Multiple Access Interference (MAI) and Inter Symbol Interference (ISI) are limiting factors of a CDMA system. In UMTS one of the most important concern is to cancel or to reduce all these forms of interference. To do so, several downlink beamforming methods have been proposed [1], [2], [3], [4]. All of these methods assume the availability of channel estimations. In the case of a Time Duplex Division (TDD) systems [5], [6] they can be deduced from the uplink receiver. As part of the European project SATURN (Smart Antenna Technology in Universal bRoadband wireless Network), multi-sensor signals have been recorded during an uplink measurements campaign. The testbed used during field trials was jointly developed by THALES, University of Nantes and FTR&D. Data provide time-slot by time-slot channel estimations during 40 frames, i.e. 600 time-slots which were used to evaluate the sensitivity of the transmission method to the channel time variation.

In the following, we begin by presenting the three multi-antenna transmit algorithms studied in this work. The performance of these algorithms will be shown in the case of perfect reciprocity, i.e. when the uplink and downlink communications take place at the same time. Then, an imperfect reciprocity of the channels will be studied. In this case, the downlink time-slot occurs several time-slots after the last uplink time-slot with which the channel has been estimated. In these two parts, both indoor and outdoor cases will be considered.

The conclusions will be drawn about the algorithm robustness to the channel time variations.

II. ALGORITHMS

In a CDMA system, the most used method at the downlink reception (at the mobile station) is the RAKE receiver. The configuration of a RAKE receiver with a simple transmission (one antenna) at the base station (BS), is considered as the reference of this work because a priori channel knowledge is not required at the BS. This reference, named simple transmission, will be compared to the three following algorithms.

A. Conventional beamforming

The objective of the conventional beamforming method [2], [4] is to reduce the MAI by maximizing the signal power intended for the specific receiver. It can be seen as a form of maximum ratio combining. The signal vector transmitted at the array output is given by:

$$\mathbf{x}(t) = \sum_{j=1}^{K} \mathbf{w}_j(t) \ast s_j(t)$$

(1)

where $s_j$ is the data sequence intended for the $j^{th}$ user, $K$ is the number of co-channel users allocated to the base station and $\mathbf{w}_j$ is the antenna array weight vector (for the $j^{th}$ user) to be determined. The star denotes the convolution product.

The frequency selective channel can be described using a baseband representation as a tapped delay line $\mathbf{h}(t)$. So, the total received signal at the mobile $k$ is given by:

$$r_k(t) = \mathbf{h}_k^T(t) \ast \mathbf{x}(t) + n_k(t)$$

(2)

$$r_k(t) = \sum_{j=1}^{K} \mathbf{h}_k^j(t) \ast \mathbf{w}_j(t) \ast s_j(t) + n_k(t)$$

(3)

where $\mathbf{h}_k$ is the vector of channel impulse response from the base station to mobile $k$ and $n_k$ is an additive Gaussian white noise.
This received signal can be decomposed into three parts:

\[ r_k(t) = h_k(t) \ast w_k(t) \ast s_k(t) + \sum_{j \neq k} h_k(t) \ast w_j(t) \ast s_j(t) + n_k(t) \]  

(4)

Desired signal

Interference (MAI)

Noise

It is considered that the channel is described by \( L_k + 1 \) taps and the beamformer by \( L_k + 1 \) taps. Then, the beamformer taps are stacked into a vector \( w_k = [w_k^T(0), w_k^T(1), \ldots, w_k^T(L_k)]^T \) and the channel taps are put into a convolution matrix \( H_k \).

It follows that the received SINR at mobile \( k \) is :

\[ \text{SINR}_k = \frac{w_k^H R_k w_k}{\sum_{j \neq k} w_j^H R_j w_j + \sigma_n^2} \]  

(5)

with \( R_k = E[H_k^H H_k] \)  

(6)

For the conventional beamforming, the weight vectors is determined as follows :

\[ w_j = \operatorname{arg \ max} \frac{w_j^H R_j w_j}{w_j^H w_j} \]  

(7)

where \( R_k \) is the correlation matrix of the channel impulse response between the user \( k \) and the antenna array (obtained thanks to the uplink data), and \( w_k \) is the beamforming weight vector at the antenna array for the user \( k \).

The solution of this method is given by the eigenvector with the largest eigenvalue of \( R_k \).

B. Generalised beamforming

The objective of the generalised beamforming method [2] is to reduce the (MAI) by maximizing the ratio between the signal power intended for the specific receiver and the transmitted interference to the other receivers. This quantity, known as the Signal to Transmitted Interference Ratio (STIR) for mobile \( k \) is given by :

\[ \text{STIR}_k = \frac{w_k^H R_k w_k}{w_k^H \left( \sum_{j \neq k} R_j \right) w_k} \]  

(8)

It is necessary to introduce a factor \( \alpha \) (which can be seen as a regularisation factor). Note that this factor is essential to reduce the excess power transmitted in the system. Thus, \( \alpha \) determines the trade-off between low side-lobes in general and signal suppression towards the interfering mobiles known by the base station. Then we obtain the following generalised eigenvalue problem,

\[ w_k = \arg \ max \frac{w_j^H R_j w_j}{w_j^H \left( \sum_{j \neq k} R_j + \alpha \mathbf{I} \right) w_j} \]  

(9)

The parameter \( \alpha \) was arbitrarily set to :

\[ \alpha = \frac{0.1}{M} \text{Tr} \left( \sum_{j \neq k} R_j \right) \]  

(10)

i.e. 10 % of the total interference power. \( M \) corresponds to the number of antennas of the array.

The solution of this method is obtained by using the eigenvector with the largest eigenvalue of the generalised eigenvalue problem.

C. Pre-equalisation

The pre-equalisation method [3], consists in doing a form of zero forcing (ZF) technique at the base station. It is possible if the downlink channel is known precisely. The objective of this method is to cancel both MAI and ISI. Consequently, the data detection effort will be considerably reduced, because no channel estimation and no equalisation are necessary at the mobile station.

In this section, the pre-equalisation algorithm is described from a time discrete system model.

All \( K \) data vectors (\( K \) is the number of co-channel users allocated to the base station) are stacked to form the total data vector :

\[ d = [d_1^T \ldots d_K^T]^T \]  

(11)

A CDMA code of length \( Q + 1 \) is assigned to each user. The code assigned to the user \( k \) is given by :

\[ c_k = [c_k(0) \ldots c_k(Q)]^T \]  

(12)

Each code \( c_k \) is arranged to a matrix \( C_k \). The \( K \) code matrices obtained are combined to the block diagonal matrix \( C \) described as follows :
The mobile radio channel is characterised by $KM$ channel impulse response ($M$ is the number of antennas), each one is associated with the propagation channel between one of the base station antenna element and one of the mobile antenna. The channel is described by $L_B + 1$ taps. Those taps are stacked into a vector for the user $k$ and the antenna $m$:

$$h_{km} = [h_{km}(0) \ldots h_{km}(L_B)]^T$$

(14)

The base station is assumed to transmit a signal $s$ at each antenna. In this case, the total transmit signal is the combined transmitted signal from all antenna elements expressed by:

$$s = [s_1^T \ldots s_M^T]^T$$

(15)

A Toeplitz matrix $H_{km}$ is formed with each channel impulse response $h_{km}$. Then, all Toeplitz matrices are arranged to:

$$H = \begin{bmatrix} H_1^T & \ldots & H_K^T \end{bmatrix}^T$$

(16)

with

$$H_k = \begin{bmatrix} H_{k1} & \ldots & H_{kM} \end{bmatrix}$$

(17)

Using the channel impulse matrix $H$ and the transmit signal $s$, the total received signal at all $K$ mobile stations can be written as:

$$r = Hs$$

(18)

The following condition is now considered:

$$C^H r = d$$

(19)

It means that the decoded received signal is exactly the transmit data vector. By substituting $r$, the last expression can be rewritten as:

$$C^H Hs = d$$

(20)

The transmitted signal is obtained by the standard Lagrange optimisation techniques from the condition (20):

$$s = H^\dagger C(C^H H H^\dagger)^{-1} d$$

(21)

III. TDD FRAME STRUCTURE FOR DIFFERENT SERVICES

The TDD frame has a duration of 10 ms and is subdivided into 15 time slots of $2560*T_c$ duration (i.e. a time slot contains 2560 chips). Each time slot is allocated to either the uplink or the downlink as shown in figure 1. With such a flexibility, the TDD mode can be adapted to different services and deployment scenarios. However, it must be noticed that in any configuration, at least one time slot has to be allocated for the downlink and at least one time slot has to be allocated for the uplink [5].

![Figure 1: The TDD Frame structure](image1)

Hence, two extreme TDD frame configurations can be obtained. The first configuration (figure 2) corresponds to the most favorable case. This configuration is a multiple-switching-point configuration (symmetric DL/UL allocation). Each downlink time slot is directly preceded by an uplink time slot. So, the delay between a downlink time slot and the previous uplink time slot is minimum.

![Figure 2: The TDD frame structure in the most favorable case of channel reciprocity assumption](image2)

The second configuration (asymmetric DL/UL allocation, figure 3) corresponds to the least favorable case. There are 14 time slots between the last downlink time slot and the previous uplink time slot.

![Figure 3: The TDD frame structure in the least favorable case of channel reciprocity assumption](image3)

These two different configurations are used to study the stationarity of the channel on the uplink.
IV. TIME STATIONARY CHANNELS

In this section, simulations are based on the channels estimated during the uplink measurement campaign. It is considered that the channel is reciprocal and perfectly estimated: the channel estimated by the uplink receiver and the one used for the downlink are strictly identical. For the pre-equalisation, the conventional beamforming and the generalised beamforming methods, four users (with two spreading codes) and four antennas are considered.

A. Outdoor simulations

For the outdoor experimentations, the antenna array were put on the roof of a suburban building, and the mobile station were placed in a vehicle. This vehicle wandered through the streets of a suburban environment.

Figure 4 gives the bit error rate estimations obtained by the considered methods using the experimental channels.

It appears that, when the downlink channel is exactly known, the pre-equalisation method is very efficient contrary to the reference method, the conventional beamforming and the generalised beamforming methods. In fact, there is a BER floor for these last three methods due to ISI. ISI exists because the channel is frequency selective. However, the MAI is reduced by the methods based on beamforming techniques (especially for the generalised beamforming) unlike the simple transmission (the reference method).

B. Indoor simulations

For the indoor experimentations, the antenna array were put on a girder of a metallic hangar. Then, the mobile station was set in different places in this hangar. The mobile station did not move during the recording. Figure 5 shows the simulations results for the four algorithms.

The same conclusions as in the outdoor simulations could be made. The pre-equalisation method is more efficient than the conventional beamforming method. But, the observed BER floor with the other methods is less important. This result is totally logical because the channel is less frequency selective in the indoor environment than in the outdoor environment (the delay spread is shorter), so the ISI is reduced.

V. TIME VARYING CHANNELS

In real cases, the uplink and downlink time slots can be separated by a delay which depends on the service reciprocity. In this section, we consider that the uplink channel is estimated during an uplink time slot and used for the downlink filter design one time slot later (k=1 in the most favourable case, figure 2) or fourteen time slots later (k=14 in the least favourable case, figure 3) as it is shown in figure 6.
A. Outdoor simulations

For the outdoor simulations, the configuration is unchanged, the same uplink data being used. The results of algorithms simulations for the most favourable case are presented in figure 7.

![Figure 7: Outdoor simulations for a time varying channel (one time-slot delay between uplink and downlink channels).](image)

Figure 8 represents the results for the least favourable case.

![Figure 8: Outdoor simulations for a time varying channel (14 time-slot delays between uplink and downlink channels).](image)

It appears in figure 7 and 8, that, for a small time variation (one time slot), the channel variations have not many influence on the beamforming methods (conventional and generalised) contrary to the pre-equalisation method, which is very sensitive to the channel variations. For an important time variation, the advantages provided by the beamforming methods reduce rapidly and the performance of these methods are close to the one of the simple transmission case, while the performances of the pre-equalisation method degrade dramatically.

B. Indoor simulations

The results shown in figure 9 are obtained for the most favourable case using indoor data as described in section IV.B.

![Figure 9: Indoor simulations for a time varying channel (one time-slot delay between uplink and downlink channels).](image)

The results for the least favourable case are presented in figure 10.

![Figure 10: Indoor simulations for a time varying channel (14 time-slot delays between uplink and downlink channels).](image)

In the indoor case, the beamforming methods are no longer sensitive to the delay between the uplink and the downlink time slots. Indeed the two beamforming methods are sensitive to direction of arrival that is a slow varying parameter that can be considered as static in an indoor environment. Pre-equalisation is very sensitive to phase variation. Even in a stationary environment as the indoor one, phases are changing, degrading in a significant way the pre-equalisation performance. This method is too sensitive to the channel variation to be practically used.
MAI and ISI, due to the frequency selective channel are two limiting factors of a CDMA system. Several transmission methods, which can be used to reduce all these forms of interference, based on uplink estimated channels have been studied and tested using real signals recorded in outdoor and indoor environments.

Theoretically, pre-equalisation method is very efficient, but the results have shown that this method is very sensitive to the channel time variations even in the most favourable conditions namely in indoor environment (slowly varying channel) and for the minimal duplex delay (one slot), performance degradation due to no-stationarity of the channel is still very sensitive. So, the pre-equalisation method can not be used practically.

The beamforming methods are more robust in the case of limited channel variations and are well matched to indoor environments.

REFERENCES


