A Study of the Robustness of a New Spatio-Temporal Receiver Against Coherence in Multipath Adverse Channels for CDMA Systems

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Abstract. The performance of tremendous beamforming methods degrades when the desired signal and interferences are correlated. This correlation results primarily in signal cancellation. The method proposed up to now using spatial smoothing result in a serious increasing of hardware or software complexities. Another technique based on the generalized sidelobe canceller (GSC) has been proposed and its efficiency for reducing interferences has been outlined. However, this algorithm robustness against desired signal cancellation remains weak. To remedy this problem, a new spatio-temporal interference suppression scheme for demodulation of DS-CDMA signals is proposed. It is based on the simultaneous combination of a spatial GSC algorithm and a temporal GSC filter bank to process the received signals. The resultant receiver is shown to be quite suitable for non-coherent mobile environments and allowed to achieve a viable performance. The impingement of user coherence is also studied and the robustness of the proposed design is accordingly outlined.

1 Introduction

The majority of array processing methods lose their optimality in coherent environments, which can lead to beamforming efficiency reduction. The coherence is almost an inherent phenomenon in multipath environments, and its unwanted effect should be eliminated in order to achieve high performances. This coherence results not only in partial or all cancellation of the desired signal but also in the failure of deep nulls formation in correlated interference directions. To reach better performances in such cases, increasing of the adaptive antenna array size seems to be a quite suitable solution. However, this approach results in high computational complexity, low convergence speed and increased array sensitivity to imperfections [1].

To avoid cancellation of the desired signal and break the correlation between the desired and interference signals, conventional approaches perform averaging over the space or frequency domains prior to the beamforming [2],[3]. However, these two approaches have some drawbacks. For instance, the space averaging method is limited only to uniform array structures; whereas the frequency averaging needs an estimate of signal and interference directions.

The spatial smoothing is another technique that can be used to reduce the signal intercorrelation [4]. The Toeplitz structure of the covariance matrix destroyed by the inter-signal correlation can be recovered by the spatial smoothing through averaging overlapping sections of the main array. An insight into the resultant array shows that the
previous method involves high array dimensions in a correlated-signal environment to perform in the same way as a smaller array in an uncorrelated-signal environment. In addition, this method suffers from limit cycle phenomenon that reduces the performance of the receiver. In order to avoid desired signal cancellation, some relatively new work has shown that combining the code filtering feature of CDMA modulation and the Generalized Sidelobe Canceller (GSC) structure [5]-[9] is particularly suitable. However, in these approaches, the multipath diversity was solely exploited [10]-[13]. In addition, the robustness of the proposed schemes against coherence was limited and the number of cochannel users small comparatively to the capacity objectives of the actual and future wireless systems. To overcome these limitations, we propose a new spatio-temporal scheme using spatial and temporal processing algorithms. This has been made possible through the preliminary extraction of the strongest paths of the desired user using a spatial filtering algorithm based on GSC scheme [14]. This first step aims to maximize the rate of interference cancellation, and ensures the presence of the desired signal in one path or more, which minimizes the probability of signal cancellation. The spatially-filtered signals corresponding to the most powerful desired user paths are then processed by a temporal GSC block to further reduce multiple access interference via a code filtering procedure. In this work, the effect of coherence between signal and interferences on the effectiveness of the spatio-temporal processings is studied. The least mean square (LMS) algorithm is retained for the spatial part of the receiver whereas the recursive least square with quadratic constraint Tolerance (RLSC) is adopted for the temporal part.

This paper is organized as follows: next section describes the model of the received signals at the cell site assuming multipath and multiple access interferences. In section 3, the new receiver design is summarized and the related algorithms are presented. In order to illustrate the effectiveness and the limitation of the proposed approach, Section 4 discusses the simulation results as well as the effect of coherence on the system performance. Finally, conclusions are presented in Section 5.

1 Signal model

This section introduces the signal model used for this work. As shown in Fig.1, a DS-CDMA cell site system using a linear antenna array with \( M \) antenna elements and the presence of \( N \) users communicating simultaneously in the cell, are considered. Multipath environment is assumed and each of the multipath component is assigned a time delay that is an integer multiple of the chip duration. In this environment, a line-of-sight signal that propagates between the transmitter and the receiver is allocated a unity amplitude whereas all other path amplitudes are selected from a uniform distribution in the interval \([0.5, 1]\). In addition, the users transmit Hadamard code modulated bit streams, and the code sequence has a period of \( L_c = T_b/T_c \) so that there is one code period per data symbol, where \( T_b \) corresponds to the data symbol duration, \( T_c \) to the chip duration and \( L_c \) to the processing gain. Considering all the assumptions stated above, the \( M \times 1 \) received baseband signal within one bit observation interval can be expressed as

\[
x(t) = \sum_{k=1}^{K} \sum_{l=1}^{L_c} A_k \exp(j2\pi f t - \theta_k) A_l \exp(j2\pi f t - \theta_l) + n(t)
\]  

(1)
where \( M \) is the number of elements in the array, \( K \) is the number of users communicating in the same cell, \( L_k \) is the number of multipath components relative to the \( k \)th user, \( N(t) \) is the \( M \times 1 \) background Gaussian noise vector, and \( \tau_{k,l} \) is the delay spread of the \( l \)th path. \( \mathbf{A}(\theta_{k,l}) \), \( \phi_{k,l} \) and \( a_{k,l} \) denote the steering vector, the angle of arrival, and the amplitude response of the \( l \)th path of the \( k \)th user, respectively.

The steering vector \( \mathbf{A}(\theta_{k,l}) \) of the \( l \)th path of the \( k \)th user can be formulated in terms of its components at each element as follows

\[
\mathbf{A}(\theta_{k,l}) = [a_1(\theta_{k,l}) \ldots a_M(\theta_{k,l})]
\]

and each component can be expressed as

\[
a_m(\theta_{k,l}) = e^{-j \frac{2\pi}{\lambda} md \sin(\theta_{k,l})}, \quad m = 1 \ldots M
\]

where \( \lambda \) is the wavelength at the operating frequency and \( d \) is the inter-element spacing, which is chosen equal to \( \lambda / 2 \).

The transmitted signal \( s_k(t) \) given in equation (1), emanating from the \( k \)th user is a DS-CDMA sequence coded by a BPSK modulation, which can be written as

\[
s_k(t) = b_k[i] c_k(t - iT_b)
\]

where \( T_b \) is the data symbol duration, \( b_k[i] \in \{-1,1\} \) is the \( i \)th BPSK symbol, and \( c_k(t) \) is the Walsh-Hadamard spreading waveform that is expressed as

\[
c_k(t) = \sum_{j=-\infty}^{\infty} d_k[j] \pi(t - NT_c)
\]

where \( d_k[j] \in \{-1,1\} \) is the \( j \)th element of the code sequence for the \( k \)th user, and \( \pi(t) \) is usually a rectangular waveform of unit amplitude and chip duration \( T_c \).

In this work, the spatial and temporal processing are chip-synchronized, and at each chip duration \( T_c \) the input signals corresponding to the \( l \)th data chip are collected in a \( M \times 1 \) vector \( \mathbf{X}(l) \) as follows

\[
\mathbf{X}(1) = [x_1(1) \quad x_2(1) \ldots \quad x_M(1)]
\]

The beamformer input vector is then adaptively filtered using the corresponding weight vector that is expressed as

\[
\mathbf{W} = [w_1 \quad w_2 \ldots \quad w_M]
\]

where \( w_i \) is the weight component at the \( i \)th array element.

It is well known that in the case of correlated signals, the spatial filtering can cause the partial or complete cancellation of the desired signal \([15],[16],[2],[3]\). To overcome this situation, a new algorithm using spatial and temporal GSC...
2 Beamformer and temporal GSC structures

For correlated signal environments, a new structure that significantly alleviates the signal cancellation problem at the cost of a slight signal processing complexity addition is proposed and described. The block diagram of the proposed spatio-temporal receiver is shown in Fig.1. First, the beamformer (spatial part), which is based on the GSC structure, tracks the three strongest multipath components of the desired user. The data acquisition and the weight adaptation are performed at each chip duration. The weights are then updated using the least mean square algorithm (LMS) in the GSC structure, and the constraint matrix is constructed with the steering vectors of the corresponding paths. It is worthwhile to notice that this preliminary spatial filtering acts on the spread CDMA signals, which results in better filtering performances within the bit duration. The target task now is to temporally filter the desired-user-path signals and optimally combine them. Following the same procedure described previously, the resultant signals corresponding to the strongest spatially filtered paths are processed by the temporal GSC scheme, which is based on the recursive least squares algorithm with quadratic tolerance constraint. As a result, the signal-to-interference-plus-noise-ratio (SINR) of the signal associated with each resolved path is accordingly maximized.

The constraint matrix of the temporal GSC is shaped with the path code vectors, which ensures a decorrelating solution to extract the desired signal component and excludes a trivial solution (all zero) in the design of the temporal filter.

Fig. 1. Structure of the proposed receiver
2.1 Spatial GSC filter

This module aims essentially to create main beams in the direction of the desired three strongest path signals and produce nulls in the interference direction. Referring to Fig.1, it consists of three parts: a conventional beamformer, a signal blocking processor, and an adaptive noise canceller. The adaptive noise canceller receives the conventional beamformer outputs and the signal blocking processor outputs as the primary inputs and the reference signals, respectively. Indeed, the spatial GSC exploits the combined efficiencies of the conventional beamformer in selecting only the desired signal and the adaptive noise canceller in eliminating the interferences to optimize the system output using the LMS algorithm. The $M \times L$ weight vector at the adaptive noise canceller input, where $L$ is the number of resolved paths, is designed so that the energy of the output of the filter can be written as:

$$y(n) = W^H X(n)$$  \hspace{1cm} (6)

and it is minimized under the following constraint

$$C^H W = g$$  \hspace{1cm} (7)

where $n$ is the iteration index which corresponds to the chip index and $(.)^H$ is the conjugate (Hermitian) transpose operation. For each chip duration, $C$ is a $M \times L$ constraint matrix and $g$ is an identity matrix of dimension $L \times L$. The $i^{th}$ column of $C$, $C_i$, consists of the steering vector corresponding to the $i^{th}$ path. The weight vector in equation (6) is defined as:

$$W(n) = w_q - Bw_a(n)$$  \hspace{1cm} (8)

where $w_a$ is the adaptive weight vector resulting from the conventional beamformer processing and lies to the subspace spanned by the basis formed by the columns of the constraint matrix, $w_q$ is the quiescent weight vector that lies to the orthogonal subspace, and $B$ is the $M \times (M-L)$ blocking matrix, which is orthogonal to the constraint matrix $B^H C = 0$. The $M \times 1$ quiescent term relative to the $m^{th}$ path in the conventional beamformer can be expressed as

$$w_{m,q} = C^T(CC^T)^{-1}g_m$$  \hspace{1cm} (9)

where $g_m$ is the $m^{th}$ column of $G$. Ideally, the $m^{th}$ quiescent weight allows to pass only the desired signal component from the $m^{th}$ path. The goal of the adaptive weight component is then to minimize the overall output power in order to reduce the multi-user interference and the noise levels in the beam domain. The complete signal cancellation, which is a major problem in the conventional approaches, is avoided through not only the orthogonality of the quiescent and the adaptive terms but also by using the individual filtering of each path. This orthogonality is achieved by generating the blocking matrix $B$ in the left null space of $C$. The implementation of the LMS algorithm [17],[18],[19] for the spatial part becomes then an easy task and involves the following steps:
\[
    w_a(0) = 0
\]
\[
e(n) = w^{H}_q x(n) - w^{H}_a(n-1)B^H u(n)
\]
\[
w_a(n) = w_a(n-1) + \mu(n-1) e^*(n)
\]

where \( \mu \) is a parameter that aims to control the speed of convergence of the algorithm. If \( \mu \) is chosen too large, the algorithm may diverge, and if it is chosen too small, the convergence time increases and the approach may no longer be applicable to real-time processing. Due to these reasons, an optimum value of the step size needs to be chosen through a proper investigation and \( 1/2M \) seems to be a convenient value, where \( M \) is the number of antenna elements.

### 2.2 Temporal GSC filter

As explained previously, three sequences of the spatially filtered spread signals corresponding to the strongest paths of the desired user are introduced into the temporal GSC module to be further processed. The constraint matrix \( C_t \) is generated by assigning the spreading code coefficients of the \( m \)th path to the \( m \)th line preceded by zeros, whose number is equal to the path delay. In this case, the timing of the locally generated spreading code replica is locked to time delay of the resolved propagation paths. The temporal weight \( w_t \) is decomposed into two orthogonal components, the constrained part \( w_{t,q} \) and the unconstrained one \( w_{t,a} \). The quiescent term is given by the same expression as in eqn. (9) except that the constraint matrix \( C \) is replaced by \( C_t \) and \( f_m \) by \( f_m,t \) where \( f_m,t \) is the \( m \)th column of the \( Lc \times Lc \) identity matrix \( I \). The adaptive part of the temporal weight is processed using the recursive least square algorithm with quadratic constraint tolerance (RLSC) [17], [18], [19]. In the temporal processing, the step size is taken as \( 1/(2Lc) \) and the resultant signal in a bit duration is a \( Lc \times 1 \) vector corresponding to the combination of the three multipath signals. The RLSC algorithm involves the following relations:

\[
w^{*}_q = 0
\]
\[
P(0) = \frac{1}{\delta}
\]
\[
k(n) = \frac{B^{-1}P(n-1)B^H y(n)}{1 + \beta^{-1}B^H y(n)P(n-1)C^H y(n)}
\]
\[
P(n) = \beta^{-1}(P(n-1) - k(n)y^H(n)B^H P(n-1))
\]
\[
e(n) = w^{*}_q y(n) - w^{*}_{t,a}(n-1)B^H y(n)
\]
\[
w_{t,a}(n) = w_{t,a}(n-1) + k(n)e^*(n)
\]

where the memory factor \( \delta \) is typically chosen close to 1 and it is set to 0.999 in these simulations while the value of \( d \) for presetting the initial value is fixed at 0.1. The quadratic constraint tolerance is then defined by the following equations:
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\[
\begin{align*}
\text{If} & \quad \| w_{\chi_\alpha}(n) \|^2 \geq \alpha^2 \\
\nu_{\chi_\alpha}(n) &= P(n) w_{\chi_\alpha}(n) \\
a &= \| \nu_{\chi_\alpha}(n) \|^2 \\
b &= -2 \Re \left( \nu_{\chi_\alpha}(n)^* w_{\chi_\alpha}(n) \right) \\
c &= \| w_{\chi_\alpha}(n) \|^2 - \alpha^2 \\
\eta &= -b - \Re \left( b^2 - 4ac \right)^{1/2} \\
w_{\chi_\alpha}(n) &= w_{\chi_\alpha}(n) + \eta \nu_{\chi_\alpha}(n)
\end{align*}
\]

with \( \alpha^2 = T_0 - w_{r_\alpha} H w_{r_\alpha} \), where \( T_0 \) is the quadratic constraint tolerance chosen equal to 0.2.

3-Simulation results

Computer simulations were carried out to evaluate the influence of the coherence between the desired and interference signals on the resultant antenna array beampatterns. For this purpose, a processing gain of 128 for the Walsh-Hadamard codes is considered, and eight omnidirectional array elements are assumed, unless mentioned otherwise. In this work, an SNR of 10 dB is also considered. Furthermore, three path signals are assigned for each user and they are chosen comparatively high. The terms coherent and non-coherent in our analysis are directly related to the situation where a certain number of co-channel users own the same arrival angles as the desired-user-path signals, and the one where the DOAs are completely different for all users.

In the non-coherence scenario simulations, arrival angles of 0\(^\circ\), -20\(^\circ\), 40\(^\circ\) are assigned to the three signals of the desired user while other users are given arrival angles uniformly distributed on [60, 150]; so that the user angle are distinct.

First, a set of resultant beampatterns for the direct path generated in the non-coherent environment are represented in Fig. 2 when the number of receive antenna is varied.

![Fig. 2. The resultant beampattern with the antenna number variation](image-url)
From this figure, it is seen that the direction $0^\circ$ is pointed whatever is the number of antennas. However, when the receive diversity order increases, the beampattern narrows removing a higher amount of interference and allowing for a better quality of beamforming and the sidelobe levels are more efficiently attenuated. This is due to the fact that more antennas offers additional degrees of freedom to preserve the desired signal and provides a more accurate pointing of desired direction. With 2 antennas, the filtering is quite inefficient as the main lobe extends over the entire displayed angle range. In the following eight antenna elements are assumed placed at the base station side.

The non-coherence case seems to be an ideal scenario for real application communication systems. To emphasize the coherence impact on the system performance, two more adverse profiles are considered in Fig. 3. The medium-coherence case is simulated by choosing DOAs of $0^\circ$, $-20^\circ$ and $40^\circ$ for the desired user three paths whereas 5 other user multipath DOAs are chosen randomly so that to coincide with the desired user's ones. A more pessimistic scenario is simulated to reproduce the strong coherence scenario, and 36 users' DOAs are divided into three equal sets $[-30^\circ, -10^\circ]$, $[0^\circ, 10^\circ]$, $[20^\circ, 60^\circ]$, respectively so as to ensure that the desired DOAs are fully drowned in the interferences' DOAs. The resultant beampatterns for the direct path corresponding to the three different environments are shown in Fig. 3. This figure highlight the receiver reliability with the MAI increase in case of non-coherence. The results indicate also that in such case the modified B removes efficiently the desired signal multipath components from the blocking matrix block so that the adaptive noise and MAI block works only on the orthogonal subspace and desired signal cancellation is avoided. In addition, while the desired direction is well pointed in case of non-coherence, a deviation from direction $0^\circ$ proportional to the coherence increase, is noted. Moderate coherence does not affect the beamforming efficiency and only remanent spatial interference is observed in the desired direction, however the high coherence impinges drastically on the beamformer performance. Fortunately, the strong-coherence case is very pessimistic and the most practical transmissions fortunately do not fit to this profile. Furthermore, even pointing errors are present in one branch (one of the three processed paths), it is still possible to obtain a main lobe in the desired direction from other paths. Note also that the sidelobe level is less than 0.1 in case of non-coherence, but increases in the presence of coherence, because the MAI is higher and the beamformer is unable to totally cancel it.
The temporal block aims to remedy the critical cases, where the spatial part is no more able to alleviate the harmful MAI effects on the beampattern deviation (for example in case of strong coherence). It redresses the system performance via code filtering by using a RAKE-receiver-despreading-like procedure. First the influence of temporal step size variation on the BER performance is investigated in Fig. 4. According to this figure, it appears that maintaining this parameter as small as possible introduces an improvement in BER performance, resulting in higher capacity in terms of users supported in the cell. We noted, however that below the value $1/(2L_c)$, a negligible gain is reached (other values are not represented in the figure). The dual influence of spatial step size variation of the mixed GSC receiver in ensuring high beamforming quality has been assessed in [5]. Note that regardless is the temporal step size value, this receiver allows to reach a significant gain over the single antenna case. The value of the spatial step size is maintained to $1/(2L_c)$ in the following.
So far, we study the BER performance enhancement according to coherence, and the system robustness to its increase. To evaluate the reliability of the proposed scheme, the average BER in terms of the number of users is shown in Fig.5 in a non-coherent profile, compared to the alone application of the beamforming and the temporal processing. It can be stated according to the obtained results that the proposed design introduces a sensible enhancement in BER performance. If the required BER is $10^{-2}$, the whole 60 users can be supported in the cell by adopting the proposed scheme, while less than 40 users and 30 users can be supported by the temporal and spatial processors alone, respectively.

![Fig. 5. Performance comparison of the different schemes in case of non coherence](image_url)

To address the system efficiency in combating the coherence increase when the proposed scheme is incorporated, the BER performance is studied in the strong coherence scenario against the BER performance resulting from the application of the spatial and temporal processing alone. In such case, the behavior of the spatial processor is drastically altered and it tends to perform similarly to the single element scheme. The slight difference results from the processing of each path separately, and the combination of the filtered path signals. Remember that this scheme is pessimistic as it assumes that the three desired path directions are contaminated by a large amount of MAI. As mentioned before, the receiver relies on the temporal part to adequately perform the filtering. Due to this fact, the temporal processor and the proposed scheme perform analogously with a little gain exhibited by the latter coming from the prior spatial processing. It follows that this scheme can adapt to various channels and can be fully exploited if operating in a switching mode. In case of non and medium coherences, one can benefit from the whole architectures encompassing spatial and temporal parts. For channels showing adverse behaviors (extending between medium and strong coherence cases), the spatial processor can be switched, thus introducing a precious complexity saving.
5- Conclusion

In this paper, the performance of a new efficient technique for adaptive array in multiple access CDMA environment has been presented. The proposed structure combines temporal and spatial GSC schemes to ensure accurate filtering of the desired signal and avoid the cancellation problem. The effect of the coherence between received signals on the system performance has also been addressed. The receiver robustness has been considered in the proposed design. It is shown that despite losing of beamforming efficiency in a strong coherence environment, the receiver is still able to reach quite viable performance. The scheme allows to boost capacity and is highly recommended for practical applications in adverse channels.

Fig. 6. Performance comparison of the different schemes in case of strong coherence

References

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