A SEMIBLIND ADAPTIVE BEAMFORMER USING A PARALLEL PILOT SIGNAL FOR WCDMA SYSTEMS

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ABSTRACT

A semiblind beamformer using a parallel pilot signal in the adaptive algorithm is investigated for wideband code-division multiple-access (WCDMA) systems. Although the pilot signal and traffic channels are designed to be transmitted using orthogonal codes in the downlink direction, time dispersion and frequency-selective fading in the transmission channel severely degrade this orthogonality at the receiver. As a result, the traffic signal of a target base station appears as interference coming from the same direction as the pilot signal, and causes poor performance of a pilot-only training-based beamformer. In order to mitigate this effect, we propose a semiblind beamforming algorithm that jointly exploits the pilot signal and the traffic channel signals. A modified version of the semiblind beamformer simultaneously suppresses self-interference and cochannel interference from other base stations. The proposed semiblind techniques outperform the conventional pilot-only approach as demonstrated via computer simulations.

1. INTRODUCTION

Third generation (3G) cellular mobile communication systems based on code-division multiple access (CDMA), such as WCDMA and cdma2000 [1], [2], allow multiple users to simultaneously occupy the same spectrum. In the downlink of a WCDMA system, a base station (BS) modulates several data sequences onto different physical channels by spreading them with distinguishable codes. Since the common pilot channel (CPICH) and the traffic channels are transmitted in parallel, this approach circumvents problems that arise for beamformers in time-division multiple-access (TDMA) systems where the pilot and traffic channels are time-multiplexed, and thus encounter different transmission channels due to the time-varying wireless environment. As a result, minimum mean-square-error (MMSE) and least-squares (LS) criteria are more readily applied to beamformers in CDMA systems [3]. However, multipath propagation destroys the orthogonality between the physical channels at the receiver, which in turn causes the signals transmitted from the same BS to interfere with each other. This self-interference is not adequately handled by MMSE or LS beamformers using only the CPICH in a training-based algorithm.

Semiblind approaches for channel estimation and beamforming using parallel pilot and traffic signals have been of interest recently (see, e.g., [4], [5], [6], [7]). Channel estimation in [8] is implemented by utilizing the predefined pilot signal and statistical models of the unknown traffic data, including deterministic and Gaussian maximum-likelihood (ML) methods. Although these techniques offer a substantial performance improvement over pilot-only algorithms, the computational complexity is relatively high. Related iterative algorithms derived in [4] are based on similar semiblind formulations.

In this paper, a semiblind beamformer is presented for the downlink of WCDMA systems that exploits the CPICH to estimate the data on different physical channels by suppressing self-interference (SI). Moreover, the approach in [9] based on the blind minimum output-energy (MOE) technique is incorporated to mitigate the cochannel interference (CCI) from other BSs. A new semiblind beamformer is thus developed by combining and extending these two techniques to consider SI and CCI rejection at the same time. The proposed semiblind techniques have a lower complexity than previous approaches and provide better performance than a conventional pilot-only method.

The rest of this paper is organized as follows. Section 2 describes the WCDMA downlink, including a composite transmitted signal model. The semiblind beamformers are discussed in Section 3. Computer simulations are provided in Section 4, and conclusions are summarized in Section 5.

2. WCDMA DOWNLINK SIGNAL MODEL

We consider M synchronous cochannel BSs where each BS is assumed to have the CPICH $s_p$ and $K$ code-multiplexed physical traffic channels, including the primary common control physical channel (P-CCPCH). The data on the physical channels are represented using the binary alphabet $\{0, 1\}$, which are mapped to non-return-to-zero (NRZ) symbols defined as follows:

$$d(n) \triangleq \begin{cases} +1, & \text{if binary symbol is 0} \\ -1, & \text{if binary symbol is 1}. \end{cases} \quad (1)$$

A physical channel passes through a serial-to-parallel converter which splits the signal into in-phase (I) and quadrature (Q) branches. A QPSK symbol can thus be represented as $b(n) = d(2n) + jd(2n+1)$ which is spread by a channelization code. The channelization codes are generated by the orthogonal variable spreading factor (OVSF) technique, and are denoted by $c_k = [c_k(1), \ldots, c_k(SF)]^T$ where $k$ is the code number and $c_k(n) \in \{-1, +1\}$. $SF$ is the spreading factor, which for convenience is fixed at 256 throughout this paper.

As shown in Figure 1, the transmitted signal for the $n$th spread QPSK symbol of the $m$th BS can be written as

$$s_{h}^{(m)}(n) = \left( \sum_{k=1}^{K} b_k(n)c_k \right) \odot c_{sc}^{(m)}(n) + s_{p}^{(m)}(n) \quad (2)$$

where $m \in [0,511]$ is the scrambler number, and $\odot$ denotes the Schur product. $c_{sc}^{(m)}$ is the primary scrambling code with a period of 38, 400 chips (one frame), and $s_{p}^{(m)}$ is the CPICH, both for the
Fig. 1. Downlink WCDMA transmitter model for the $m$th BS.

For the $m$th BS, $c_{sc}^{(m)}(n) \triangleq [c_{sc}^{(m)}((n - 1)256 + 1), \ldots, c_{sc}^{(m)}(n256)]^T$ is a partial vector of $c_{sc}^{(m)}$; a partial vector $s_p^{(m)}(n)$ is similarly defined for $s_p^{(m)}$. The transmitted signal for one frame is given by $s^{(m)} = [s_1^{(m)}T, \ldots, s_{150}^{(m)}T]^T$.

In order to more easily describe the semiblind techniques, we combine the channelization code $c_k$ and the scrambling code $c_{sc}^{(m)}$ to generate the composite spreading sequence $v_k^{(m)}(1), \ldots, v_k^{(m)}(150))^T$ for one frame, as illustrated in Figure 2. Thus, the spreading sequence for a QPSK symbol is defined as

$$v_k^{(m)}(n) \triangleq c_k \odot c_{sc}^{(m)}(n).$$

Next, we rewrite the transmitted signal in (2) for the $m$th BS as follows:

$$s^{(m)} = \sum_{k=1}^{K} v_k^{(m)} b_k^{(m)} + s_p^{(m)}$$

where $b_k^{(m)} = [b_k^{(m)}(1), \ldots, b_k^{(m)}(150)]^T$ is the data sequence of the $k$th physical channel for one frame, and

$$v_k^{(m)} = \begin{bmatrix} v_k^{(m)}(1) & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & v_k^{(m)}(150) \end{bmatrix}$$

is a composite spreading matrix of size 38, 400 $\times$ 150.

The received signal vector with $M$ synchronous cochannel BSs at a single antenna can be written as

$$x = \sum_{m=1}^{M} s^{(m)} + n$$

where $n$ is zero-mean additive white Gaussian noise (AWGN) with variance $\sigma^2$. In order to compute the LS beamformer for a receiver with $N$ antennas, the following received data matrix of size $N_T \times N$ is generated:

$$X_j \triangleq \begin{bmatrix} x_1((l - 1)N_T + 1) & \ldots & x_N((l - 1)N_T + 1) \\ \vdots & \ddots & \vdots \\ x_1(lN_T) & \ldots & x_N(lN_T) \end{bmatrix}$$

where $N_T = 2560$ is the size of the observation period ($\approx 0.67$ ms), $l$ is the observation set number, and $x_m$ is the received signal at the $m$th antenna element.

3. SEMIBLIND BEAMFORMERS

The first beamformer is designed to suppress SI from other code-multiplexed physical channels, and the second beamformer is designed to simultaneously reduce SI and CCI from other BSs.

3.1. Semiblind Beamformer for Self-Interference (Semiblind A)

Each data stream is modulated to a particular physical channel with a unique code so that several channels can be simultaneously transmitted. The specific traffic channel is then demodulated using a deserializer with the appropriate code at the receiver. A conventional pilot-only trained beamformer can be used in the receiver to suppress CCI arriving from different directions. The goal of a pilot-only beamformer for the $j$th BS is to achieve the condition

$$Xw - s_p^{(j)} = 0$$

where $w$ is the beamformer weight vector, and $0$ is a column vector of zeros. In this manner, all physical channels transmitted from the same BS are assumed to propagate through the same transmission channel and still retain their orthogonality. However, since multipath destroys this orthogonality, these code-multiplexed physical channels become interference to the CPICH. Therefore, the beamformer is designed to approximate the transmitted signal of the target $j$th BS, so that (8) becomes

$$Xw - s^{(j)} = 0.$$ (9)

Substituting (4) yields

$$Xw - \sum_{k=1}^{K} V_k^{(j)} b_j^{(j)} - s_p^{(j)} = 0.$$ (10)

Note that $b_j^{(j)}$ is the unknown data sequence on the $k$th physical channel; it is estimated by passing the beamformer output through a despreader which is implemented via multiplication with the spreading matrix $V_k^{(j)}$. The soft estimated data sequence of the $k$th physical channel is $\hat{b}_j^{(j)} = V_k^{(j)H}Xw$ where the superscript $H$ denotes complex conjugate transpose. Substituting this into (10) yields the following cost function for the first semiblind beamformer:

$$J_A(w) = \left\| Xw - \sum_{k=1}^{K} V_k^{(j)} V_k^{(j)H} Xw - s_p^{(j)} \right\|^2$$

$$= \left\| (I - \sum_{k=1}^{K} V_k^{(j)} V_k^{(j)H}) Xw - s_p^{(j)} \right\|^2$$ (11)
where $I$ is the identity matrix. The resulting weight vector (denoted Semiblind A) is obtained as

$$w_A = \arg \min_w J_A(w)$$

$$J_A(w) = \left( X^H X \right)^{-1} X^H s_p^{(j)}$$

(12)

where $X^\dagger \triangleq (I - \sum_{k=1}^{K} V_k^{(j)} V_k^{(j)H}) X$. Defining the symmetric matrix $P_V^{(k)} \triangleq V_k^{(j)H} V_k^{(j)}$, we see that $P_V^{(k)} = V_k^{(j)}$ because $V_k^{(j)} V_k^{(j)H} = I \delta_{k,k'}$, where $\delta_{k,k'}$ is the Kronecker delta function. Thus, $P_V^{(k)}$ is a projection matrix onto the subspace spanned by the composite spreading code $v_k$. Defining $P_V^{(k)} \triangleq \sum_{k=1}^{K} P_V^{(k)}$, we see that $X^\dagger$ is orthogonal to the projection of $X$ onto the column subspace of $P_V$.

3.2. Semiblind Beamformer for Self-Interference and Cochannel Interference (Semiblind B)

Next, the MOE blind technique is incorporated to suppress the CCI from other active BSs. In WCDMA systems, the output of the beamformer projected onto the subspace of the interfering spreading matrices should be forced to zero. Since the CPICH $s_p^{(m)}$ of the $m$th interfering BS can be obtained after BS detection, we define the interference CPICH matrix $S_{p,i} \triangleq [s^{(1)}, ..., s^{(m)}]$, where $m = 1, ..., M$ and $m \neq j$ (recall that $j$ denotes the target BS). The beamformer weights are designed to minimize the output energy as follows:

$$w = \arg \min_w ||s_p^{(m)H} X w||^2.$$  

Combining (13) with the cost function in (11) yields the following composite cost function for the second beamformer:

$$J_B(w) = \lambda ||X^\dagger w - s_p^{(j)}||^2$$

$$+ (1 - \lambda) \sum_{m=1, m \neq j}^{M} ||s_p^{(m)H} X w||^2$$

(14)

where $0 < \lambda \leq 1$ is a scalar whose value is chosen depending on the transmission environment. The first term in (14) is designed to mitigate SI, and the second term is designed to suppress CCI from $M - 1$ BSs (thus, a small value for $\lambda$ is preferred for high CCI environments). The beamformer weights of this composite cost function are obtained as (denoted Semiblind B)

$$w_B = \left( \lambda X^\dagger X + (1 - \lambda) \sum_{m=1, m \neq j}^{M} X^H s_p^{(m)} s_p^{(m)H} X \right)^{-1}$$

$$\times \lambda X^\dagger s_p^{(j)}.$$  

(15)

4. COMPUTER SIMULATIONS

4.1. Simulation Scenario

The computer simulations assume $M = 15$ synchronous cochannel BSs. The target BS with scrambler 54 (BS-54) transmits $K = 17$ physical channels, including the CPICH, the P-CCPCH, and fifteen traffic channels. Each interfering BS propagates through an independent two-path transmission channel, and the target BS passes through a four-path transmission channel. The signals from these BSs arrive at an $N = 8$-element antenna array with angles of arrival (AOAs) uniformly distributed in $[0^\circ, 180^\circ]$.

4.2. Base Station Detection

Base station detection, which is also known as the cell search procedure, provides slot and frame synchronization for each BS. It detects every cochannel BS signal by computing the cross-correlation between the received signal and the $512$ primary scrambling codes. For the proposed semiblind techniques, the BSs need to be identified since their scrambling code numbers (scrambler indexes) are used to derive the beamformer weights. Figure 3 shows the results of BS detection where each peak represents a specific BS. Their relative signal powers and AOAs are summarized in Table 1.

4.3. Performance Comparison

The output signal-to-interference-plus-noise ratio (SINR) and the bit error rate (BER) for each of the proposed semiblind beamformers were evaluated using Monte-Carlo simulations and $50$ data frames in the observation time interval. The output SINR is computed ac-
\[
\text{SINR} = \frac{w^H S^{(j)} S^{(j)H} w}{\sigma^2 w^H w + \sum_{m=1, m \neq j}^M w^H S^{(m)} S^{(m)H} w}
\]  

where \( S^{(j)} = \begin{bmatrix} s_{1}^{(j)} \ldots s_{N}^{(j)} \end{bmatrix}^T \) is the received signal matrix for the \( j \)th BS. The simulation results are compared with that of a conventional pilot-only beamformer as well as the ideal beamformer (i.e., with full knowledge of the transmitted signal, referred to as the known data case). As shown in Figs. 4 and 5, the proposed semiblind beamformers provide performance gains over that achieved by a conventional pilot-only beamformer. The semiblind beamformer (Semiblind B) for combined SI/CCI rejection performs better than that designed only for SI rejection (Semiblind A) at high SNRs where CCI dominates.

5. CONCLUSION

We have presented a new semiblind beamformer for the downlink of WCDMA systems that employs the CPICH and estimated signal data in a least-squares cost function. This semiblind beamformer was extended to simultaneously suppress self-interference caused by the code-multiplexed channels as well as the cochannel interference from other active base stations by incorporating a minimum output energy technique. Computer simulation results show that the proposed semiblind beamformers improve the output SINR and BER performance of a WCDMA receiver compared to that using a conventional pilot-only beamformer.

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7. REFERENCES