Adaptive Channel Estimation Exploiting Pilot Diversity with SINR Estimation for WCDMA Downlink Receivers

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\textbf{ABSTRACT}

This paper addresses the issue of channel phaser estimation in WCDMA, in which both the Common Pilot Channel (CPICH), which is not power controlled, and the Dedicated Physical Control Channel (DPCCH), having pilot symbols with power control, are available. Depending on the user’s location, either the CPICH or DPCCH may have better SINR and hence, yield more reliable channel estimates. The proposed channel estimator estimates the channel gain by adaptively combining the estimates from common pilot channel and pilot symbols. We derive the optimum weights (SINR-based) for combining using Minimum Mean Square Error (MMSE) criterion. A subspace based SINR estimation method is also presented.

\section{I. INTRODUCTION}

For 3G wireless communications Wideband Code Division Multiple Access (WCDMA) has been accepted as a world wide standard \cite{1,2}. WCDMA is based on Direct Sequence Code Division Multiple Access (DS-CDMA) with coherent detection on downlink. In WCDMA, a Common Pilot Channel (CPICH) is transmitted for phase reference, so that channel estimates required for coherent detection can be estimated from CPICH.

Along with CPICH, in WCDMA, the Dedicated Physical Control Channel (DPCCH) also has pilot symbols in every slot. The main difference between CPICH and DPCCH is, that the CPICH is transmitted at fixed rate (30 Kbps, $SF = 256$) \cite{3} and its power is usually at a fixed percentage, e.g., 10\% of the total power form base station, while pilot symbols in DPCCH are power controlled. However, the pilot symbols are fewer in number, according to transmission data rate \cite{3}. The reason for the provision of CPICH and pilot symbols in DPCCH is to enable the use of smart antenna techniques, i.e., beamforming applied to DPCCH. If CPICH and DPCCH are transmitted using the same antenna radiation pattern, the mobile can take advantage of both CPICH and DPCCH for channel estimation.

Conventional methods for channel estimation are based on using either pilot channel CPICH \cite{4} or pilot symbols in DPCCH with interpolation \cite{5,6} over data part of the slot.

In this paper, it is shown that, it is advantageous to exploit the pilot diversity, i.e., availability of pilot symbols in CPICH and DPCCH for channel estimation. One method of channel estimation exploiting pilot diversity is discussed in \cite{7}, which assumes the channel is constant for one slot and uses fixed weights (heuristic) for combining channel estimates from pilot channel and pilot symbols. This assumption is not valid for channels with high Doppler and the weights cannot be kept constant since the channels CPICH and DPCCH see a rapid variation in Signal to Interference plus Noise Ratio (SINR) in a multi-cellular environment, i.e., when user is closer to base station like U 2 and moves away to the edge of cell like U 1 as shown in Fig. 1.

In this paper we propose a channel estimation scheme exploiting pilot diversity with optimum adaptive weights for combining channel estimates from pilot channel and pilot symbols which are shown to be a function of Signal to Interference plus Noise Ratio (SINR) in a multi-cellular environment.
Interference plus Noise Ratio (SINR) in DPCH and CPICH respectively.

This paper is organized as follows. The system model is given in section II. The principle of pilot diversity, the proposed algorithm are presented Section III and SINR estimation algorithm is given in section IV. Numerical results are given in Section V.

II. WCDMA SIGNAL MODEL

This section models the Wideband CDMA downlink signal under the frequency selective multipath Rayleigh fading channel in Additive White Gaussian Noise (AWGN) along with multiple users.

A. The Transmitter

Consider a Wideband CDMA communication system with K users and denote the signature sequence of the $k^{th}$ user in $m^{th}$ symbol as $s_k[n]$ for $k = 1, ..., K$, and signature sequence of common pilot channel in $m_p^{th}$ symbol as $s_p[p]$.

$$s_k[mSF + n] = c_k[n]d[n + mSF], 0 \leq n \leq SF - 1, \quad s_p[mSF + p] = c_p[p]d[p + mSF], 0 \leq p \leq SF_p - 1$$  \hspace{1cm} (1)

where $SF$ is the spread factor, $c_k[n] = \pm 1, n = 0, ..., SF - 1$ is the channelization code assigned to the $k^{th}$ user, $SF_p$ and $c_p[p]$ are spread factor and the channelization code of common pilot channel respectively, $d[n]$ is the cell or sector dependent complex scrambling code having much longer repetition period than the symbol duration, $T_c = T/\text{SF} = T_p/\text{SF}_p$ the chip duration where $T$ and $T_p$ are the symbol durations of traffic and pilot channels respectively, and the sequences $s_k[n]$ and $s_p[p]$ represent a combination of channelization and scrambling codes.

$$q_k(t) = \sum_{j=0}^{SF} s_k[j]\psi(t - jT_c), 0 \leq t \leq T$$

$$q_p(t) = \sum_{j=0}^{SF_p} s_p[j]\psi(t - jT_c), 0 \leq t \leq T_p$$  \hspace{1cm} (2)

where $q_k(t)$ and $q_p(t)$ are the signature waveforms after matched filtering for traffic and pilot channels respectively, and $\psi(t)$ the pulse shaping waveform. Then the total transmitted signal can be denoted as

$$r(t) = \sum_{k=1}^{K} A_k b_k q_k(t - mT) + A_p b_p q_p(t - m_p T_p) + \eta(t)$$  \hspace{1cm} (3)

where $A_k$ is the transmitted amplitude of the $k^{th}$ user’s traffic signal, $A_p$ is the amplitude of common pilot channel, $b_k \in \{ \pm 1 \pm j \}/\sqrt{2}$ the symbol transmitted by the $k^{th}$ user, $b_p$ is the symbol in common pilot channel which is always equal to one, $\beta = A_p/A_k$ is the ratio of amplitudes of pilot channel to traffic channel, and $\eta(t)$ the zero mean complex Gaussian noise with power spectral density $\sigma_n^2$.

B. The Channel

The channel considered is a multipath channel exhibiting frequency selective Rayleigh fading with AWGN. In the downlink every user has the same number of multipaths, say $L$ and let $h_i(t)$ and $\tau_i$ represent the channel response and the propagation delay of $i^{th}$ path. Then the time-variant impulse response of the channel for $m^{th}$ symbol can be given as

$$g(t) = \sum_{i=1}^{L} h_i(t)\delta(t - \tau_i)$$  \hspace{1cm} (4)

C. The Receiver

The received signal at the input of matched filter in the Mobile Station (MS) end is the convolution of the transmitted signal and the fading channel response, given by

$$r(t) = \sum_{k=1}^{K} A_k b_k \sum_{i=1}^{L} h_i(m)q_k(t - mT - \tau_i) + A_p b \sum_{i=1}^{L} h_i(m)q_p(t - m_p T_p - \tau_i) + \eta(t)$$  \hspace{1cm} (5)

The received signal $r(t)$ is passed through a matched filter which is a square root raised cosine filter with roll off factor $\alpha = 0.22$ in WCDMA system. Also, we assume that the path delays are multiples of $T_c$, and are known at the receiver. Then the received signal after filtering and sampling can be modeled as a discrete signal as follows

$$y[n] = \sum_{k=1}^{K} A_k b_k \sum_{i=1}^{L} s_k[n - mT - d_i] h_i[n] + A_p b \sum_{i=1}^{L} s_p[n - m_p T_p - d_i] h_i[n] + \eta[n]$$  \hspace{1cm} (6)

where $y[n] = y[nT_c], d_i = \tau_i/T_c$ is the normalized path delay, $\eta[n]$ is the Gaussian noise with zero mean and variance $\sigma_n^2$.

III. CHANNEL ESTIMATION EXPLOITING PILOT DIVERSITY

In this section we propose the channel estimation algorithm exploiting pilot diversity. Consider a user moving towards the edge of the cell, i.e. when the received pilot power is getting reduced. We derive a combining metric for channel estimates from the DPCCH channel and CPICH channel to improve the channel estimation accuracy. We describe how channel coefficient for each path is estimated.

The algorithm minimizes the error in channel estimates in the MMSE sense. The combining metrics are shown to be a function of Signal to Interference plus Noise Ratios (SINR) in the DPCH and CPICH channels. So this is an adaptive algorithm which requires a estimate of SINR and ratio of amplitudes between the pilot channel and traffic channel, $\beta = A_p/A_k$. The algorithm for estimating SINR is described in section IV.
A. Principle of Pilot Diversity

The channel coefficient estimate $\hat{h}_l(n)$ for the $l^{th}$ path at symbol time $n$, obtained by the proposed scheme, may be expressed as

$$\hat{h}_l(n) = a_p \hat{h}_{lp}(n) + a_t \hat{h}_{lt}(n)$$  \hspace{1cm} (7)

where $\hat{h}_{lp}(n)$ and $\hat{h}_{lt}(n)$ are respectively the channel coefficient estimates from pilot and traffic channels for the symbol $n$ after normalizing to $\beta$, the ratio of amplitudes between the pilot channel and traffic channel ($= A_p/A_t$), and $a_p$ and $a_t$ are respectively combining coefficients for pilot and traffic channels under the constraint $a_p + a_t = 1$. The variation in SINR of DPCH and CPICH as a user moves away from BTS, i.e., users U 1 and U 2 in BTS (B) is shown in Fig. 2.

![Variation of SINR in DPCH and CPICH as user moves away from BTS](image)

Fig. 2. Variation of SINR in DPCH and CPICH as user moves away from the BTS-B

The channel coefficient estimates $\hat{h}_{lp}(n)$ and $\hat{h}_{lt}(n)$ can be written as

$$\hat{h}_{lp}(n) = h_l(n) + \eta_p$$
$$\hat{h}_{lt}(n) = h_l(n) + \eta_t$$  \hspace{1cm} (8)

where $\eta_p$ and $\eta_t$ are the impairments (interference plus noise) in CPICH and DPCH respectively.

B. Determination of Combining Coefficients

Channel estimation accuracy is a function of combining coefficients $a_p$ and $a_t$, and may be expressed in terms of channel coefficient estimation Mean Squared Error (MSE)

$$MSE = J = E \left[ |h_l - \hat{h}_l|^2 \right]$$
$$= E \left[ |h_l - (a_p \hat{h}_{lp} + a_t \hat{h}_{lt})|^2 \right]$$  \hspace{1cm} (9)

Since the channel estimation MSE is a quadratic function of $a_p$ and $a_t$, the minimum channel estimation MSE, $J_{min}$, is obtained by finding $a_p$ and $a_t$, which satisfy the following equation

$$\nabla J = \left[ \frac{\partial J}{\partial a_p} \frac{\partial J}{\partial a_t} \right]^T = [0 \ 0]^T$$  \hspace{1cm} (10)

From equation (10), the optimal $a_p$ and $a_t$ are found to be

$$a_p = \frac{\sigma_{nl}^2 - \sigma_{nc}^2}{(1 + \sigma_{nl}^2)(1 + \sigma_{np}^2) - (1 + \sigma_{nc}^2)^2}$$
$$a_t = \frac{\sigma_{nt}^2 - \sigma_{nc}^2}{(1 + \sigma_{nt}^2)(1 + \sigma_{np}^2) - (1 + \sigma_{nc}^2)^2}$$  \hspace{1cm} (11)

where $\sigma_{nl}^2$ and $\sigma_{nt}^2$ are the variances of interference plus noise terms in traffic channel and pilot channel respectively and $\sigma_{nc}^2$ is the variance term of common interference plus noise, i.e., the Multi User Interference (MUI) and noise terms present in both the channels.

The denominator in $a_p$ and $a_t$ can be simplified and these expressions can be rewritten as follows

$$a_p = \frac{\sigma_{nl}^2}{\sigma_{nl}^2 + \sigma_{np}^2 - 2\sigma_{nc}^2}$$
$$a_t = \frac{\sigma_{nt}^2}{\sigma_{nt}^2 + \sigma_{np}^2 - 2\sigma_{nc}^2}$$  \hspace{1cm} (12)

Since $a_p + a_t = 1$ these can be written as

$$a_p = \frac{\sigma_{nl}^2}{\gamma_p}$$
$$a_t = \frac{\sigma_{nt}^2}{\gamma_t}$$  \hspace{1cm} (13)

From this we can observe that $a_p$ and $a_t$ are inversely proportional to the interference plus noise terms in their own channels or it can be said that they are directly proportional to the SINR in the channels. Hence these terms can be simplified in terms of the SINR as follows

$$a_p = \frac{\gamma_p}{\gamma_t + \gamma_p}$$
$$a_t = \frac{\gamma_t}{\gamma_t + \gamma_p}$$  \hspace{1cm} (14)

where $\gamma_p$ and $\gamma_t$ are the signal to interference plus noise terms in the pilot channel and traffic channel respectively [8].

C. Algorithm

Channel estimation exploiting pilot diversity can be described in the following steps:

1) Estimate the channel gain from CPICH $\hat{h}_{lp}$ using the optimum Channel Estimator [4], which controls the filter bandwidth according to SINR and Doppler.
2) Estimate the SINR $\gamma_p$ in CPICH.
3) Estimate the channel gain from DPCCH $\hat{h}_{lt}$ using some interpolation methods such as [6].
4) Estimate the SINR $\gamma_t$ in DPCH.
5) Estimate the ratio of amplitudes $\beta$ between CPICH and DPCCH.
6) Normalize $\hat{h}_{lt}$ by the estimated ratio $\beta$.
7) Determine the combining weights $a_p$ and $a_t$ as given in equation (14), using the estimated $\gamma_p$ and $\gamma_t$. 

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8) Combine the channel estimates $\hat{h}_{t,p}$ and $\hat{h}_{t,t}$ using $a_p$ and $a_t$ to get the final channel estimate $\hat{h}_t$.

In the algorithm described above the amplitude ratio $\beta$ is estimated using all symbols in one slot of Dedicated Physical Channel (DPCH) and CPICH. The SINR in DPCH and CPICH, i.e., $\gamma_t$ and $\gamma_p$ are estimated using the algorithm in section IV. The SINR estimates $\gamma_t$ and $\gamma_p$ can be used recursively for each power control group (one slot length), i.e., $\gamma(i) = \gamma(i-1)$ for both CPICH and DPCH where $i$ is the slot index or can be fixed for one frame length. In this paper Wiener interpolation [6] is used for channel estimation using pilot symbols in DPCCH.

IV. SINR ESTIMATION

In this section we describe the SINR estimation [9] used to calculate the adaptive weights $a_p$ and $a_t$ for pilot diversity channel estimation.

Assuming the channel condition does not vary significantly over the duration $SF + D$ chips, where $D$ is the maximum multipath delay in multiples of $T_c$, we can write the received signal in equation 6 in vector form as

$$\mathbf{y} = \sum_{k=1}^{K} b_k \mathbf{s}_k \mathbf{h}_k + \mathbf{\eta}$$  \hspace{1cm} (15)

where $\mathbf{y} = [y[mSF], y[mSF + 1], ..., y[mSF + SF - 1]]^T$ is a observation vector of $SF$ chips, $\mathbf{h}_k$ is the channel response vector of $(D + 1)$ chips of the $k^{th}$ user, and $\mathbf{\eta} = [\eta[mSF], \eta[mSF + 1], ..., \eta[mSF + SF - 1]]^T$ the noise vector. $\mathbf{s}_k$ is a $SF \times (D + 1)$ matrices formed by $s_k$ which is a combination of channelization and scrambling codes of the $k^{th}$ user defined as,

$$
\begin{pmatrix}
    s_k[mN] & \ldots & s_k[mN - D] \\
    s_k[mN + 1] & \ldots & s_k[mN + 1 - D] \\
    \vdots & \ddots & \vdots \\
    s_k[mN + N - 1] & \ldots & s_k[mN + N - 1 - D]
\end{pmatrix}
$$

For user $k$, $\mathbf{s}_k$ is known both at the transmitter and the receiver. From (15) we have

$$\mathbf{y} = b_k \mathbf{s}_k \mathbf{h}_k + \sum_{i \neq k} b_i \mathbf{s}_i \mathbf{h}_i + \mathbf{\eta}$$  \hspace{1cm} (16)

Let $\mathbf{w}_k$ denote the last two terms of (16),

$$\mathbf{w}_k = \sum_{i \neq k} b_i \mathbf{s}_i \mathbf{h}_i + \mathbf{\eta}$$  \hspace{1cm} (17)

Note that $\mathbf{w}_k$ is equal to the Interference plus Noise (I+N), To calculate the power of $\mathbf{w}_k$, we first find the left null space of $\mathbf{s}_k$, denoted by $\mathbf{N}(\mathbf{s}_k^T)$, let $\mathbf{s} \in \mathbf{N}(\mathbf{s}_k^T)$ be a vector. Because

$$\mathbf{s}^T \mathbf{y} = 0$$  \hspace{1cm} (18)

Project $\mathbf{w}_k$, onto the whole vector space of $\mathbf{N}(\mathbf{s}_k^T)$. Let $\mathbf{N}(\mathbf{s}_k^T)$ be spanned by the orthonormal basis $\{\mathbf{e}_1, \mathbf{e}_2, ..., \mathbf{e}_p\}$, then we have

$$\sum_{p=1}^{P} E[|\langle \mathbf{e}_p, \mathbf{w}_k \rangle|^2] = \sum_{p=1}^{P} \sum_{i=1}^{N} \sum_{j=1}^{N} e_{p,i} e_{p,j} E[w_{k,i} w_{k,j}^*]$$

$$= \sum_{p=1}^{P} \sum_{i=1}^{N} |e_{p,i}|^2 \sigma^2_{(I+N)}$$

$$= P \sigma^2_{(I+N)}$$  \hspace{1cm} (19)

since

$$\langle \mathbf{e}_p, \mathbf{y} \rangle = \langle \mathbf{e}_p, b_k \mathbf{s}_k \mathbf{h}_k + \mathbf{w}_k \rangle$$

$$= \langle \mathbf{e}_p, b_k \mathbf{s}_k \mathbf{h}_k \rangle + \langle \mathbf{e}_p, \mathbf{w}_k \rangle$$

$$= \langle \mathbf{e}_p, \mathbf{w}_k \rangle$$  \hspace{1cm} (20)

the $(I + N)$ can be estimated by

$$\sigma^2_{I+N} = \frac{1}{P} \sum_{p=1}^{P} |\langle \mathbf{e}_p, \mathbf{y} \rangle|^2 - \frac{1}{P} \sum_{p=1}^{P} |\langle \mathbf{e}_p, \mathbf{y} \rangle|^2$$  \hspace{1cm} (21)

and the SINR is given by

$$\text{SINR} = \frac{1}{P} \sum_{p=1}^{P} |\langle \mathbf{e}_p, \mathbf{y} \rangle|^2 - \bar{1}$$  \hspace{1cm} (22)

To estimate $\gamma_t$ the SINR in traffic channel of user $K$, $s_k$ the combination of channelization code of length $SF$ of user $k$ and scrambling code is used and for $\gamma_p$ the SINR in pilot channel, $s_k$ in equation 16 is replaced with $s_p$, the combination of channelization code of length $SF_p$ (256) of pilot and scrambling code as defined in equation 1 is used.

V. NUMERICAL RESULTS

Fig. 3 shows the Mean Square Error (MSE) performance of pilot diversity scheme. In this simulation there are two multipaths spaced at [0 4] chips with relative powers of [0 0](dB) and vehicular velocity $v=120$ Km/h. The setup for this problem is illustrated in Fig. 1.

As can be seen from the illustration a 3 cell environment is considered with a vehicular user in cell B moving from his Base Station (BTS B) to the boundary of the cell, i.e., the power received from his BTS is getting reduced. We assumed a closed loop power control, so that the received power in the Dedicated Physical Channel (DPCH) is constant and the received power of CPICH is more when user is closer to BTS B and gets reduced when he moves to the boundary of the cell. The inter-cell interference is increased at the boundary of the cell. This effect is simulated by varying power ratio of pilot channel to traffic channel by keeping SNR at 0 dB and distributing rest of the power between inter-cell and intra-cell interference as a function of user’s position in the cell. The intra-cell interference (MUI) is simulated using Orthogonal Channel Noise Simulator (OCNS) [10]. As can be seen from Fig. 3 MSE of the channel estimator is less when the estimates from both pilot channel and pilot symbols are combined by a SINR based metric as described in section. III. In Fig. 3 PSAE refers to pilot symbol assisted estimation, i.e., channel estimation using DPCCH and PCAE refers to pilot channel assisted estimation, i.e., channel estimation using CPICH.
VI. CONCLUSION

In this paper, we proposed a channel estimator for WCDMA receivers exploiting pilot diversity present in the system. Adaptive weights for combining estimates from pilot symbols and pilot channel are derived based on MMSE criterion and they were shown to be a function of the SINR in the channels. A novel way of SINR estimation in the channels (traffic and pilot) exploiting the code sequences of the channel is also given to determine the combining weights. It is also shown that the algorithm considerably reduces the MSE in the channel tap estimates.

REFERENCES


