Hybrid Adaptive Channel Estimation in WCDMA Downlink Systems

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Abstract - **The receiver performance of DS-CDMA systems is significantly affected by the accuracy of channel estimate. In WCDMA downlink systems, the channel information can be estimated using a common pilot channel (CPICH). Since this pilot signal is transmitted to all users in the cell with constant power, we consider the improvement of channel estimate by additionally using power-controlled data signal in the dedicated physical channel (DPCH). Since decision errors are unavoidable in the DPCH decoding process, we combine the channel estimate from the CPICH and DPCH, considering the DPCH data decision error. For further improvement of channel estimate, we also employ an adaptive channel estimation filter (CEF). Numerical results show that the proposed channel estimator outperforms the conventional pilot channel aided estimator, particularly when the channel condition becomes worse.**

I. INTRODUCTION

In the third generation WCDMA systems, coherent detection is used in both the uplink and downlink. Coherent receiver inherently requires the knowledge on the channel impulse response (CIR). There have been proposed a number of methods to estimate the CIR [1-6]. One conventional method is to use a pilot channel which is available to all the receivers [1]. Continuous pilot symbols are sent through a common pilot channel (CPICH) in the WCDMA downlink system, making it possible to estimate the CIR more accurately. The other method is to use a pilot signal which is time-multiplexed with data signal. This method is quite applicable to the uplink that has no common pilot channel. It is also possible to combine these two methods to improve the channel estimation performance in the downlink [2].

While the above two methods use known pilot signals, it is also possible to use data signals for channel estimation. Removing the modulated data part from the received signal, it is possible to get the CIR from a dedicated physical channel (DPCH). Since the CPICH is transmitted to all the users in the same cell without transmit power control, it may be useful for more accurate channel estimation to additionally use the DPCH which is dedicated to each user with power control. Since this method utilizes the decoded data signal, it is called decision-directed (DD) method. However, the estimation performance can significantly be degraded due to unavoidable decision error. To alleviate this problem, the DD method can be combined with the pilot-aided scheme, resulting in a so-called hybrid channel estimation method [3-6].

There have been several studies on the DD and hybrid methods. The DD method was studied in conjunction with the use of differential encoding [3]. A DD scheme is combined with a pilot-channel-aided scheme [4], where these two channel estimates are combined based on the minimum mean squared error (MMSE) criterion. Since the optimum MMSE solution requires the knowledge on the channel statistics, it may not be applicable to real situation. Another DD scheme is combined with a pilot-symbol-aided scheme [5], but it provides little advantage over other schemes since the CPICH is available in the WCDMA downlink system. The use of a multistage DD scheme is considered [6], but it may not be feasible for real applications due to high implementation complexity.

In this paper, we consider a hybrid method that combines a DD scheme with a pilot-channel-aided scheme. Improved channel estimate can be obtained by appropriately combining the two channel estimates from the CPICH and DPCH. The combining weight is analytically designed so as to maximize the signal-to-interference power ration (SIR) of the combined channel estimate. It is shown that the combining weight can be determined in some practical manner at the receiver without the *a priori* knowledge on the channel statistics. The idea of adaptive channel estimation (ACE) [1] is applied to DPCH channel estimation for improved estimation performance.

Following Introduction, a conventional channel estimation method is described in Section Ⅱ and the proposed hybrid ACE is described in Section Ⅲ. The performance of the proposed scheme is evaluated in terms of the BER performance in Section Ⅳ. Finally, conclusions are summarized in Section V.

II. CONVENTIONAL CHANNEL ESTIMATOR

We consider a WCDMA downlink receiver as depicted in Fig. 1, where the structure of the *l*-th branch of a conventional rake receiver is shown. Let L be the number of resolvable channel paths and hence be the number of branches in the rake receiver. The received signal of the *l*-th path at time $t = nT_c$ can be represented as

$$r_l[k\psi_{dp} + n] = (h_l^{CP}[k]p_{cp}c_{cp}[n] + h_l^{DP}[k]m[k]c_{dp}[n])c_{scr}[n] + I[n] \quad (1)$$

where T_c denotes the chip time, ψ_{dp} is the spreading factor of the DPCH, p_{cp} is the CPICH pilot symbol, $m[k]$ is the *k*-th DPCH data symbol, $c_{cp}[n]$ and $c_{dp}[n]$ are the channelization code for the CPICH and DPCH, respectively, $c_{scr}[n]$ represents the cell-specific scrambling code, $I[n]$ is the interference term including the multipath interference, inter-cell interference and background thermal noise, and $h_l^{CP}[k]$ and $h_l^{DP}[k]$ are the complex-valued channel gain multiplied by the transmit gain of the CPICH and DPCH, respectively, i.e., $h_l^{CP}[k] = \sqrt{P_{cp}}h_l[k]$ and $h_l^{DP}[k] = \sqrt{P_{dp}}h_l[k]$. Here, $h_l[k]$ is the complex-valued channel gain of the *l*-th path in the *k*-th symbol duration, and P_{cp} and P_{dp} denote the transmit power of the CPICH and DPCH, respectively. Thus, $h_l^{CP}[k] = \alpha h_l^{DP}[k]$ where $\alpha = \sqrt{P_{cp}/P_{dp}}$.

A. Pilot-channel-aided channel estimation

To obtain a channel estimate using the CPICH, the received signal is first descrambled and despread using $c_{scr}[n]$ and $c_{cp}[n]$, respectively. Then, the despread signal $\tilde{r}_l^{CP}[k]$ can be written as

$$\begin{aligned}\tilde{r}_l^{CP}[k] &= \frac{1}{\psi_{cp}}\sum_{n=0}^{\psi_{cp}-1} r_l[k\psi_{dp} + n]c_{scr}^*[n]c_{cp}[n] \\ &= h_l^{CP}[k]p_{cp} + \eta[k]\end{aligned} \quad (2)$$

where the superscript " ∗ " denotes the complex conjugate, ψ_{cp} is the spreading factor of the CPICH and $\eta[k]$ represents the interference term.

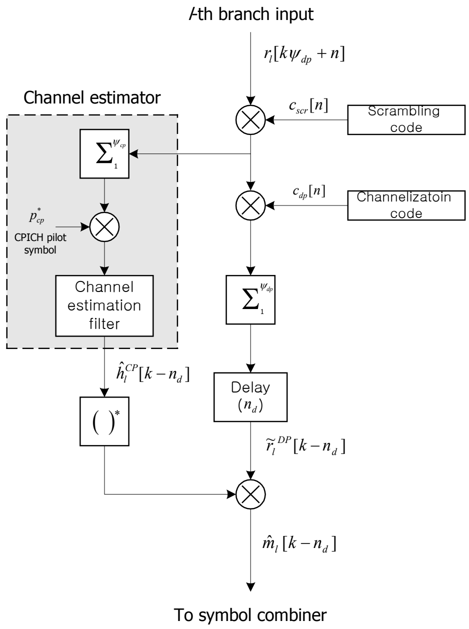

Fig. 1. The *l*-th branch of conventional rake receiver in the WCDMA downlink.

Since the pilot symbol p_{cp} is known, an instantaneous estimate of $h_l^{CP}[k]$ can be extracted from $\tilde{r}_l^{CP}[k]$ by multiplying both sides of (2) by p_{cp}^*. Then the resulting signal is low-pass filtered to reduce the interference effect using a channel estimation filter (CEF). The CEF is usually realized in the form of a moving average (MA) finite impulse response (FIR) filter or one-pole infinite impulse response (IIR) filter. Note that the MA FIR filter can provide performance comparable to an optimally designed FIR filter, while requiring significantly reduced complexity [1]. In this paper, we consider the use of an MA FIR filter as the CEF for ease of analysis. Then, the estimated channel gain for the *l*-th path can be obtained as

$$\hat{h}_l^{CP}[k] = \frac{1}{N_l}\sum_{j=-N_l/2}^{N_l/2-1}\tilde{r}_l^{CP}[k + j]p_{cp}^* \quad (3)$$

where N_l is the tap size of the MA FIR CEF for the CPICH.

B. Decision-directed channel estimation

The DPCH data signal can also be used for channel estimation. The procedure is similar to the use of the CPICH. The only difference is that the decoded data symbol is utilized instead of known pilot symbol. The DPCH despread signal $\tilde{r}_l^{DP}[k]$ can be written as

$$\tilde{r}_l^{DP}[k] = \frac{1}{\psi_{dp}} \sum_{n=0}^{\psi_{dp}-1} r_l\,[k\psi_{dp} + n] c_{scr}^*[n] c_{dp}[n] \\ = h_l^{DP}[k] m[k] + \eta'[k] \tag{4}$$

where $\eta'[k]$ represents the interference term. Denoting the decision data by $\hat{m}[k]$, the estimated channel gain $\hat{h}_l^{DP}[k]$ can be obtained as

$$\hat{h}_l^{DP}[k] = \frac{1}{M_l} \sum_{j=-M_l/2}^{M_l/2-1} \tilde{r}_l^{DP}[k+j] \hat{m}^*[k+j] \tag{5}$$

where M_l is the tap size of the MA FIR CEF for the DPCH.

III. PROPOSED HYBRID CHANNEL ESTIMATOR

Fig. 2 depicts the structure of the proposed hybrid channel estimator. In the proposed hybrid method, the channel is first estimated using a pilot-channel-aided method as (3), which is used for combining the received data signal. Then the data signal is tentatively obtained by making a hard decision on the symbol combiner output. With this hard-decoded data signal, the channel is re-estimated using the DPCH signal as (5). Finally, we obtain the final channel estimate by combining the two channel estimates with appropriate combining coefficient w_{cp} and w_{dp}.

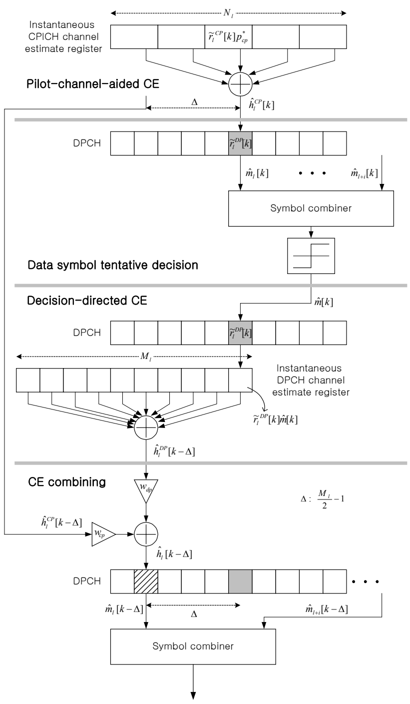

Fig. 2. Structure of the hybrid channel estimator.

It is shown that the optimum tap size N_l of the MA CEF for the CPICH based ACE is determined by various channel condition factors such as the SNR, Ricean factor of the propagation path and maximum Doppler frequency [1]. Since the maximum Doppler frequency is the most influencing factor in determining the optimum tap size and the DPCH and CPICH experience the same Doppler spread, the tap size M_l can be obtained by making the averaging time intervals of the two CEFs equal, i.e.,

$$M_l = N_l \cdot \frac{\psi_{cp}}{\psi_{dp}}. \tag{6}$$

Since decision errors are unavoidable in the DD method, it is desirable to consider the effect of these errors on combining $\hat{h}_l^{DP}[k]$ with $\hat{h}_l^{CP}[k]$. Let P_e be the probability of bit errors due to tentative decision. Assuming that these errors occur uniformly and that the data signal $m[k]$ is QPSK modulated, it can be shown that

$$E\{\tilde{r}_l^{DP}[k]\hat{m}^*[k]\} = P_e(1-P_e)\cdot(h_l^{DP}[k]\cdot e^{j\frac{\pi}{2}}) + P_e(1-P_e)\cdot(h_l^{DP}[k]\cdot e^{-j\frac{\pi}{2}}) \\ + P_e^2\cdot(-h_l^{DP}[k]) + (1-P_e)^2\cdot(h_l^{DP}[k]) \\ = (1-2P_e)\cdot h_l^{DP}[k] \tag{7}$$

where $E\{X\}$ denotes the expectation of X. Thus, $\tilde{r}_l^{DP}[k]\hat{m}^*[k]$ in (5) can be represented as

$$\tilde{r}_l^{DP}[k]\hat{m}^*[k] = (1-2P_e)\cdot h_l^{DP}[k] + \eta'[k]\hat{m}^*[k] + \varepsilon[k] \tag{8}$$

where

$$\varepsilon[k] = (m[k]\hat{m}^*[k] - 1 + 2P_e)\cdot h_l^{DP}[k]. \tag{9}$$

Note taht $\varepsilon[k]$ is an additional interference term due to tentative decision errors whose variance is $4P_e(1-P_e)\cdot\left|h_l^{DP}[k]\right|$.

Since $\hat{h}_l^{DP}[k]$ from (5) can be rewritten as

$$\hat{h}_l^{DP}[k] = \frac{1}{M_l}\sum_{j=-\frac{M_l}{2}}^{\frac{M_l}{2}-1} \tilde{r}_l^{DP}[k+j]\hat{m}^*[k+j] \\ = (1-2P_e)\cdot h_l^{DP}[k] + \frac{1}{M_l}\sum_{m=-\frac{M_l}{2}}^{\frac{M_l}{2}-1}\left(\eta'[k+j]\hat{m}^*[k+j] + \varepsilon[k+j]\right), \tag{10}$$

the SNR ρ_{dp} of $\hat{h}_l^{DP}[k]$ is

$$\rho_{dp} = \frac{(1-2P_e)^2\cdot\left|h_l^{DP}[k]\right|^2}{\frac{\sigma_{\eta'}^2}{M_l} + \frac{4P_e(1-P_e)\cdot\left|h_l^{DP}[k]\right|^2}{M_l}} \tag{11}$$

where $\sigma_{\eta'}^2$ is the variance of $\eta'[k]\hat{m}^*[k]$. If $\left|h_l^{DP}[k]\right|^2$ is much larger than $\sigma_{\eta'}^2$, there will be few decision errors, i.e.,

P_e is very close to zero. On the other hand, if $\left|h_l^{DP}[k]\right|^2$ is much less than $\sigma_{\eta'}^2$ due to deep fading, the second term of the denominator of (11) can be neglected. Then, ρ_{dp} can be approximated as

$$\rho_{dp} \cong \frac{(1-2P_e)^2 \cdot \left|h_l^{DP}[k]\right|^2}{\sigma_{\eta'}^2} M_l \cdot \qquad (12)$$

Similarly, the SNR ρ_{cp} of $\hat{h}_l^{CP}[k]$ can be calculated from (3) and (6),

$$\rho_{cp} = \frac{\left|h_l^{CP}[k]\right|^2}{\sigma_\eta^2} N_l = \frac{\left|h_l^{CP}[k]\right|^2}{\sigma_{\eta'}^2} M_l \qquad (13)$$

where σ_η^2 is the variance of $\eta[k]p_{cp}^*$, equal to $\sigma_{\eta'}^2 N_l / M_l \cdot$

In the proposed hybrid channel estimation scheme, the channel estimate $\hat{h}_l[k]$ is obtained by

$$\hat{h}_l[k] = w_{cp} \cdot \hat{h}_l^{CP}[k] + w_{dp} \cdot \hat{h}_l^{DP}[k] \qquad (14)$$

where w_{cp} and w_{dp} are the combining weight. It can easily be shown that the SNR ρ_{hyb} of $\hat{h}_l[k]$ is

$$\begin{aligned} \rho_{hyb} &= \frac{\left[w_{cp} + \frac{w_{dp}\cdot(1-2P_e)}{\alpha}\right]^2 \cdot \left|h_l^{CP}[k]\right|^2}{(w_{cp}^2 + w_{dp}^2)\cdot \frac{\sigma_{\eta'}^2}{M_l}} \\ &= \frac{\left[\alpha w_{cp} + w_{dp}\cdot(1-2P_e)\right]^2}{\alpha^2 (w_{cp}^2 + w_{dp}^2)} \cdot \rho_{cp} \\ &\le \frac{(w_{cp}^2 + w_{dp}^2)\cdot\left[\alpha^2 + (1-2P_e)^2\right]}{\alpha^2 (w_{cp}^2 + w_{dp}^2)} \cdot \rho_{cp} \end{aligned} \qquad (15)$$

by using Cauchy-Schwartz inequality. Thus, the optimum combining weight maximizing ρ_{hyb} is given by

$$\hat{w}_{dp} = \frac{1}{\alpha}(1-2P_e)\hat{w}_{cp} \qquad (16)$$

and the corresponding maximum SNR is

$$\rho_{hyb,\max} = \left[1 + \left(\frac{1-2P_e}{\alpha}\right)^2\right] \cdot \rho_{cp}. \qquad (17)$$

The SNR gain by the use of the hybrid method increases as P_e decreases. In particular, when P_e is fixed, the achievable SNR increases as the power ratio of the DPCH and CPICH increases.

It can be shown from (3) and (10) that

$$\frac{E\left\{\hat{h}_l^{DP}[k]\right\}}{E\left\{\hat{h}_l^{CP}[k]\right\}} = \frac{1}{\alpha}(1-2P_e) = \frac{\hat{w}_{dp}}{\hat{w}_{cp}} \cdot \qquad (18)$$

Thus, the optimum weight $\hat{w}_{cp}$ and $\hat{w}_{dp}$ can be determined in practice using $\hat{h}_l^{CP}[k]$ and $\hat{h}_l^{DP}[k]$ which are available at the receiver without the *a priori* knowledge on the channel statistics.

IV. PERFORMANCE EVALUATION

To verify the performance of the proposed hybrid ACE scheme, the receiver performance is examined under two extreme channel environments: one is when P_{cp}/I_{or} =-13dB and I_{or}/I_{oc}=-3dB, and the other is when P_{cp}/I_{or}=-10dB and I_{or}/I_{oc}=9dB, where I_{or} is the total transmit power from the desired base station and I_{oc} is the interference power from other cells. Table 1 summarizes the simulation condition. The former channel environment corresponds to the case when the user resides near the cell boundary and the CPICH is transmitted with relatively low power. This implies that α in (17) becomes small due to the transmit power control and thus significant performance improvement can be expected. On the other hand, the latter channel environment corresponds to the case when the user is near the base station and the CPICH is transmitted with relatively high power. In this case, it can be expected little additional gain with the use of the hybrid scheme because α becomes large.

Fig. 3 depicts the BER performance of the proposed adaptive hybrid scheme compared to other channel estimation methods, such as the pilot-channel-aided scheme with a fixed CEF, hybrid scheme with a fixed CEF and pilot-channel-aided scheme with an adaptive CEF. Here, the term “fixed” means the use of an MA FIR CEF whose tap size is fixed to one slot time interval (= 0.667ms). The ideal case (i.e., known CIR) is also presented for reference. It can be seen that the proposed hybrid scheme outperforms other schemes particularly in the former (i.e., poor) channel environment. The performance improvement decreases as the CPICH power increases high enough to produce an accurate channel estimate without additional use of the DPCH. When the CPICH power is so high and the interference power is relatively low, the bandwidth adaptation of the CEF becomes less effective.

Fig. 4 depicts the required DPCH power to obtain 10^{-3} BER in terms of the maximum Doppler frequency. It can be seen that the proposed adaptive hybrid scheme works well for a wide range of Doppler frequency. Note that these results are obtained under the two-path Case-1 channel condition [7], but similar results are obtained even when the channel has more paths, e.g., in the four-path Case-3 channel.

As shown in Fig. 2, the hybrid scheme requires an additional symbol delay Δ due to the CEF in the DD channel estimation. This problem can be alleviated with the use of an asymmetric CEF with zero group delay with little performance degradation [1]. The additional computation of the hybrid scheme compared to that of the pilot-channel-aided scheme is mainly due to the use of the DD scheme: hard-decision, multiplication and MA filtering. The multiplication is the most affecting process to increase the computational complexity among these. Since the hard-decoded data bits in the DD scheme take a value of 1 or –1, the multiplication process can be realized using an addition process. Thus, the proposed hybrid scheme can be realized without significantly increasing the computational complexity.

V. CONCLUSION

We have proposed an adaptive hybrid channel estimation scheme that uses both the CPICH and DPCH for channel estimation. The optimum combining weight is analytically designed considering the tentative decision error. For further performance improvement, the bandwidth of the CPICH CEF and DPCH CEF is adaptively controlled according to the channel condition. Numerical results show that the proposed scheme outperforms the adaptive pilot-channel-aided scheme as well as the conventional fixed schemes. The performance improvement of the proposed hybrid scheme increases as the channel condition becomes worse. The proposed scheme can easily be applied to real situation without significantly increasing the receiver complexity.

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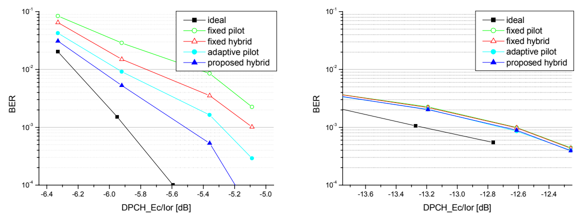
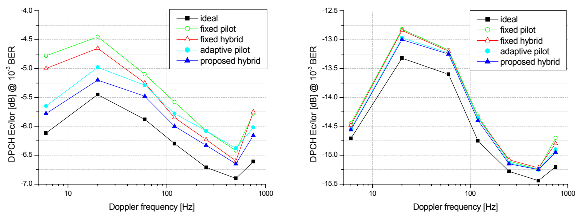
Table 1. Simulation condition.

DPCH	144 Kbps (ψ_{dp} =16)
CPICH	-13dB, -10dB
I_{or} / I_{oc}	-3dB, 9dB
Channel	Rayleigh (classic), 3GPP model (Case-1)
CEF	MA FIR
Power control	Step size: 1dB, Control period: 1 slot (0.667ms)



(a) Ior/Ioc=-3dB, CPICH Ec/Ior=-13dB **(b) Ior/Ioc=9dB, CPICH Ec/Ior=-10dB**

Fig. 3. BER performance when f_d =20Hz.



(a) Ior/Ioc=-3dB, CPICH Ec/Ior=-13dB **(b) Ior/Ioc=9dB, CPICH Ec/Ior=-10dB**

Fig. 4. Required Ec/Ior at 10^{-3} BER.