시변 페이딩 채널하에 CDMA 시스템을 위한 예측 폐루프 전력제어

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Predictive Closed-Loop Power Control for CDMA Systems in Time-Varying Fading Channels

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요 약

본 논문에서는 시변 페이딩 채널에 적합한 멀티스텝 LS 선형예측기를 갖는 새로운 예측 CDMA 폐루프 전력 제어 방식을 제안한다. 제안된 방식은 다중 전력 제어 그룹 지연을 효과적으로 보상하여 주며 단일 스텝 예측기를 갖는 기존의 예측 CLPC 방식이나 비예측 CLPC 방식에 비하여 우수한 성능 이득을 갖는다.

Key Words : Closed-loop power control (CLPC), predictive power control, least squares (LS) linear predictor, time-varying fading, CDMA..

ABSTRACT

In this paper, we present a novel predictive CDMA closed-loop power control (CLPC) method with a multi-step least squares (LS) linear predictor for time-varying fading channels. The proposed method effectively compensates multiple power control group delays and provides significant performance gains over nonpredictive CLPCs as well as conventional predictive CLPCs with one-step linear predictor.

Ⅰ. Introduction

In a wireless communication system, the transmitted signal is typically subject to path loss, shadowing and multipath fading. Path loss and shadowing are long-term effects and vary slowly over time. To compensate the resulting relatively slow fluctuations, mobile stations (MSs) can measure the averaged received power from the base station (BS) and adjust their transmit power accordingly realizing open loop power control. On the other hand, multipath fading varies faster and results in rapid fluctuations over much shorter durations. This requires the implementation of closed-loop power control (CLPC) where the BS manages the transmit power levels of MSs through feedback channels. First, the received signal-to-interference power ratio (SIR) is measured at the BS for each MS over a short time interval, which is usually defined as the power control group (PCG). The BS then compares each measured value to a preset threshold value and sends a power control command bit (PCB) per PCG to its managing MSs via feedback. Besides the basic delay of one PCG

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논문번호 : KICS2005-09-376, 접수일자 : 2005년 9월 16일
※ This work was supported by the Research Fund, 2005 of The Catholic University of Korea. This work was also supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) R05-2004-000-11860-0.

for every power control update, the PCB typically experiences an additional delay (d_A) within power control loop due to the processing delay, the round-trip delay, and the frame delay [1]. The overall loop delay is then given by $d = d_A + 1$. In current cellular systems, this is typically greater than 2~3 PCG units [1]. Traditional nonpredictive CLPC methods may not trace well the fast fading channel fluctuations in the presence of such loop delays resulting in excessive power control errors. Thus, predictive CLPCs have been proposed in the literature to effectively compensate the PC loop delay [2], [3]. These works assume one-step linear predictor which provides a predicted estimate for the next channel sample based on the current channel sample and $L-1$ preceding channel samples where L denotes the order of prediction filter. Thus, if one-step predictor is used for p-step ($p \geq 2$) prediction, the previously-predicted $p-1$ samples are needed which incur error propagation[4]. These algorithms are therefore typically limited to compensate only one PCG delay within CLPC loop.

This paper presents a predictive CLPC algorithm with a multi-step least squares (LS) linear predictor to effectively compensate the fading fluctuations due to the loop delay of multiple PCGs. This paper chooses LS filter rather than MMSE (minimum mean square estimation) filter since the former is easy to get the auto-correlation function for practical time-varying fading channels and has a lower complexity[5]. The proposed method eliminates the error propagation and outperforms conventional predictive CLPCs with one-step linear predictor.

Ⅱ. CLPC for CDMA Systems

For an uplink of CDMA system with K users, the BS receiver SIR for user i is given as

$$\gamma^i = \frac{g^{ii}x^i}{\theta\left(\sum_{j\neq i} g^{ij}x^j + \eta^i\right)} = \frac{g^{ii}x^i}{\xi^i + \eta'^i}, \quad (1)$$

for $i,j \in \{1,2,\cdots,K\}$

where $g^{ij} > 0$ is the link loss from the transmitter of user j to the access point (BS) of user i, x^i is the transmit power of user i and θ is the inverse of CDMA processing gain [6]. From now on, the user index i is dropped for simplicity. Furthermore, we assume that the interference power ξ is stationary and the noise power is negligible, i.e., $\eta' \ll \xi$. In general, the link loss g consists of the path loss, the shadowing effect, and the short-term fading. Assuming that the open loop power control perfectly compensates the path loss and the shadowing effect, g in (1) can be attributed only to short-term fading. In our work, we assume a Rayleigh fading channel with Bessel autocorrelation following the Jakes model [7]. If the measured SIR is higher than the preset threshold, the BS issues a command to the MS to lower its transmission power for the next PCG and vice versa. In the following, we first provide a brief review of nonpredictive CLPC, then present the details of our proposed algorithm.

2.1 Review of Nonpredictive CLPC

A nonpredictive CLPC has the same block diagram as in Figure 1(a) excluding the linear predictor. The capital characters in Figure 1(a) denote logarithmic versions (unit dB) of the corresponding lower-case ones, i.e. $X = 10\log_{10}x$, and their subscript n denotes the index of the PCG in the CLPC loop. For the nth PCG, the nonpredictive CLPC relies on the following state equation[6]:

$$\begin{aligned} X_n &= X_{n-1} + \Delta\Psi(\Gamma_{TH} - X_{n-d} - G_{n-d} + \Xi) \\ &= X_{n-1} + \Delta\Psi(\Gamma_{TH} - \Gamma_{n-d}) \\ &= X_{n-1} + \Delta\Psi(Z_{n-d}), \end{aligned} \quad (2)$$

where Γ_{TH} is the preset threshold, Ξ denotes the interference term and the link loss is given by $G_m = 10\log_{10}g_m = 20\log_{10}|a_m|$. Here, a_m is the mth complex fading signal sample. In (2), Δ is the fixed power control step size in dB and $\Psi(\cdot)$ denotes the the signum function given by

$$\Psi(x) = \begin{cases} 1 & \text{if } x \geq 0, \\ -1 & \text{otherwise.} \end{cases}$$

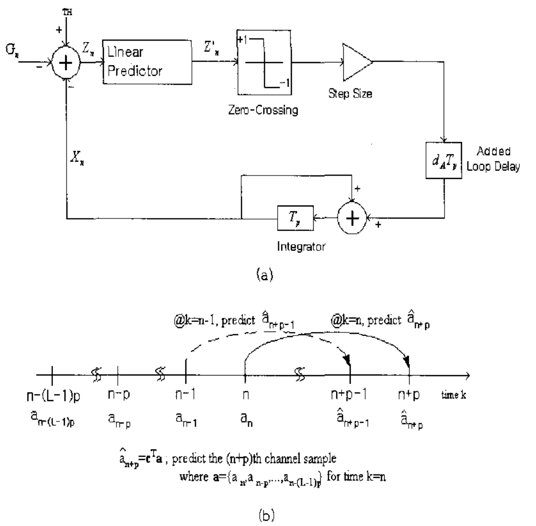

Figure 1. (a) Block diagram of predictive CLPC with a linear predictor. (b) p-step channel prediction

Based on the loop error statistics Z_n, the CLPC adjusts the PCB by $\pm\Delta$ dB. The PC loop delay d (unit PCG, 1 PCG = 1 T_p where T_p is the PC period) incurs a delayed fading channel estimate, G_{n-d}, and therefore a delayed SIR estimate, Γ_{n-d}, which, in return, increases the power control error standard deviation σ_Z. The more the loop delay increases, the greater σ_Z becomes.

2.2 Proposed Predictive CLPC Algorithm

In order to reduce the power control error due to the loop delay d of multiple PCGs, we propose a predictive power control scheme with a p-step linear predictor. The block diagram of the proposed CLPC is shown in Figure 1(a). After the linear predictor, Z_n converts into its corresponding output

$$Z'_n = \Gamma_{TH} - \Gamma'_n \tag{3}$$

where Γ'_n is the predicted estimate of receiver SIR for the $n+p$th PCG which is defined as

$$\Gamma'_n = \hat{X}_{n+p-1} + \hat{G}_{n+p} - \Xi. \tag{4}$$

Γ'_n is used to obtain the p-step predicted MS transmit power $\hat{X}_{n+p}$ by the following state equation

$$\hat{X}_{n+p} = \hat{X}_{n+p-1} + \Delta\Psi(\Gamma_{TH} - \Gamma'_n). \tag{5}$$

which is recursively used in (4) to generate the receive SIR Γ'_{n+1} for the next PCG. Here, $\hat{X}_{n+p-1}$ is the $(p-1)$-step predicted MS transmit power and $\hat{G}_{n+p}$ is the p-step predicted fading channel loss given by $\hat{G}_{n+p} = 20\log_{10}|\hat{a}_{n+p}|$. $\hat{a}_{n+p}$ denotes the predicted complex fading sample.

In (2), by replacing Z_k with Z'_k (where $k = n-d$) of (3), the state equation of the proposed predictive CLPC becomes

$$X_n = X_{n-1} + \Delta\Psi(\Gamma_{TH} - \hat{X}_{n-d+p-1} - \hat{G}_{n-d+p} + \Xi), \tag{6}$$

where the prediction step size p is chosen as d to fully compensate the loop delay. It should be noted that p is equal to 1 for conventional one-step predictive CLPC [2], [3]. For the prediction, an LS filter is employed whose details are given in the Appendix.

The prediction operation with the prediction step size p is also graphically described in Figure 1(b). The proposed scheme predicts $\hat{a}_{n+p}$ based on the current channel sample and $L-1$ previous ones which are separated from each other by p samples. The prediction filter coefficients are periodically updated through the use of a training (pilot) symbol sequence. The CLPC sampling rate $f_p = 1/T_p$ is chosen as to satisfy the Nyquist criteria for the p-step prediction of the fading signal, i.e. $f_p \geq 2pf_D$, where f_D is the maximum Doppler frequency [4]. In our scheme, the previously predicted channel samples $\hat{a}_{n+p=m}$, $m = 1, ..., p-1$ are not required for prediction. Therefore, unlike one-step prediction the proposed scheme has no error propagation. Assuming the same filter order L, the size of prediction window (buffer) in the proposed scheme is d times larger than that of one-step scheme, but such a complexity increase is marginal since d is 2 or 3 for cellular systems.

The proposed power control algorithm can be then summarized as follows:

[Step 1] Initialize the linear predictor coefficient vector based on the input data matrix D (see Appendix). Initialize a transmit power sample $\hat{X}_{p-1} = \Gamma_{Th} + \Xi$. Start the time index n with 0.

[Step 2] Update the channel sample vector and get the $n+p$th predicted fading channel sample $\hat{a}_{n+p}$ by (7) of Appendix.

[Step 3] Obtain the predicted estimate of receive SIR Γ'_n by (4) and generate (and transmit to MS) the PCB decided by (3) to adjust the MS transmit power.

[Step 4] Obtain the $n+p$th predicted MS transmit power $\hat{X}_{n+p}$ by (5).

[Step 5] Set $n = n+1$. Repeat Step 2 to 5 unless training sequence is received or 'release mode' (i.e. algorithm termination) is called. When the training sequence is received, go to Step 1.

Ⅲ. Numerical Results

In this section, we investigate the performance of the proposed predictive CLPC with multi-step linear predictor ($p = d$) and compare it to nonpredictive CLPC ($p = 0$) and conventional predictive CLPC with one-step linear predictor (p = 1). In the simulation study, we assume a carrier frequency f_c of 2 GHz, a data rate R_b of 10 Kbps, and a PCG rate f_p of 2 KHz. We consider uncoded BPSK transmission over a frequency-flat Rayleigh fading channel in the presence of a Gaussian-distributed interference term with a fixed variance of $I_0/2$, where I_0 is the interference power spectral density. Power control step Δ is chosen as 1 dB, and the employed LS linear prediction filter has an order L of 20. Assume overall loop delay $d = 3$ and perfect channel estimation.

Figure 2 illustrates the bit error rate (BER) performance versus E_b (bit energy) $/I_0$ (dB) for various mobile speeds, e.g. 20 km/h (f_D = 37 Hz), 60 km/h (f_D = 111 Hz), and 100 km/h (f_D = 185 Hz). It is observed that conventional one-step predictive CLPC has only a slight BER performance gain of 0.2~0.3 dB over nonpredictive CLPC. On the other hand, the proposed multi-step predictive CLPC achieves significant performance gains over its conventional counterparts. Specifically, at 5×10^{-3} BER we observe 2 dB gain at low speed (20 km/h) and 3 dB gain at medium or high speed (60 or 100 km/h).

Figure 3 illustrates σ_Z (lognormally-fitted) as a function of the mobile speed. It is observed that

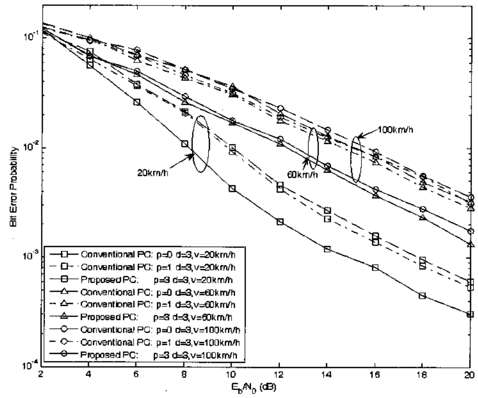

Figure 2. BER performance for conventional nonpredictive CLPC ($p = 0$), conventional one-step predictive CLPC ($p = 1$), and proposed multi-step predictive CLPC ($p = d$)

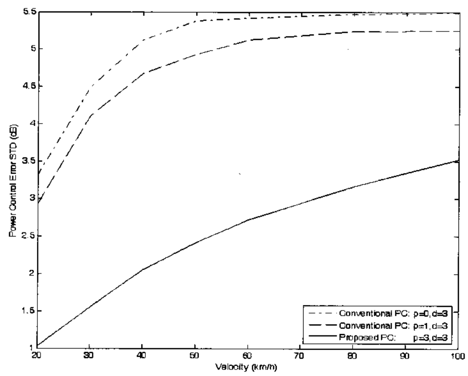

Figure 3. Power control error standard deviation (dB) versus mobile speed for conventional nonpredictive CLPC ($p = 0$), conventional one-step predictive CLPC ($p = 1$), and proposed multi-step predictive CLPC ($p = d$).

σ_Z of conventional one-step predictive CLPC reduces about 0.4 dB compared to the nonpredictive CLPC. The proposed multi-step CLPC brings significant further reductions, e.g. 1.95 dB (at 100 km/h) in comparison to the nonpredictive counterpart. This σ_Z difference among the three CLPC methods in Figure 3 supports our observations in Figure 2 and demonstrates the robustness of the proposed scheme for a wide range of mobile speeds.

Ⅳ. Conclusion

In this paper, we have proposed a novel predictive CLPC with multi-step LS linear predictor which effectively compensates multiple CLPC loop delays over time-varying fading channels. Its Monte-Carlo simulation results have also presented to demonstrate the superiority of the proposed CLPC over conventional nonpredictive CLPCs and conventional predictive CLPCs with one-step linear predictor in both low and high speed.

APPENDIX

The considered linear predictor employs an LS filter to predict the future fading channel samples

$$\hat{a}_{n+p} = \sum_{l=1}^{L} c_l a_{n-(l-1)p} = c^T a, \tag{7}$$

where $a = [a_n, a_{n-p}, \cdots, a_{n-(L-1)p}]^T$ 1) is the channel sample vector and $c = [c_1, c_2, \cdots, c_L]^T$ is the linear predictor coefficient vector. Assuming least-squares solution, c can be obtained as

$$c = R^{-1} r,$$

where R is the autocorrelation matrix of size $L \times L$ and r is the cross-correlation vector of size $(L \times 1)$. The autocorrelation matrix is constructed as $R = D^H D$ based on the input data matrix D of size $((N_c + L) \times L)$ relying on $(N_c + 1)$ p-step complex channel samples as follows:

$$D = \begin{bmatrix} a_0 & 0 & 0 & \cdots & 0 \\ a_p & a_0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ a_{(L-1)p} & a_{(L-2)p} & \vdots & \cdots & a_0 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ a_{N_c p} & a_{(N_c-1)p} & \cdots & \cdots & a_{(N_c-L+1)p} \\ 0 & a_{N_c p} & a_{(N_c-1)p} & \cdots & a_{(N_c-L+2)p} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & 0 & a_{N_c p} \end{bmatrix},$$

where $N_c \geq 2 \times L$. The cross-correlation vector is calculated as $r = D^H r_1$ where the $((N_c + L) \times L)$-vector $r_1 = [a_p, a_{2p}, \cdots, a_{N_c p}, 0, \cdots, 0]^T$.

1) $(\cdot)^T$ and $(\cdot)^H$ denote transpose and Hermitian (transpose conjugate) operators, respectively.

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