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Prediction of Received Signal Power for Mobile Cellular Systems

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ABSTRACT

In this subproject, prediction of signal power received from a mobile station by a base station is investigated. The motivation for this work arises from the power control requirements essential to Direct Sequence Code Division Multiple Access (DS-CDMA) systems. The results are also applicable to other non-frequency-hopping systems as well. This paper gives a short overview to some main aspects and results of the work.

A class of finite-impulse-response (FIR) type polynomial predictors is investigated with simulations employing two urban mobile radio channel models. The simulations show that FIR polynomial predictors can provide the controller smoothed signal power samples with the signal-to-noise ratio (SNR) improved by ca. 5 dB, without any delaying of the signal.

INTRODUCTION

In a CDMA system each user is simultaneously exploiting the same frequency band. This is possible by assigning each user a specific pseudo-noise code with which the user's bits are coded and identified. The need for the power control arises from the fact that although the codes may be theoretically orthogonal, and thus perfectly separable, the prefect orthogonality is not achieved in practise. The resulting cross-talk between users degrades the quality of speech finally introducing a capacity limit to the system. The interuser interference can be reduced by keeping the transmitter power as low as possible [1] and the power received from each user equal in average, thus improving the speech quality and increasing the system capacity. A power control loop is illustrated in Fig. 1. The predictive filtering is

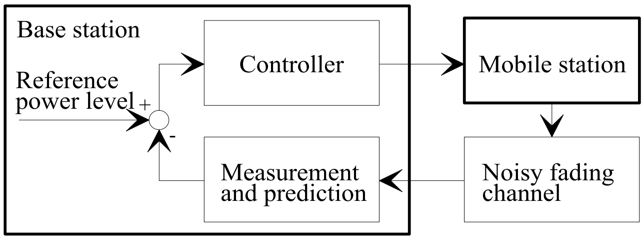

Fig. 1: Power control loop in a CDMA system.

proposed for both *prediction of power levels* and for *delayless smoothing* of power signals as it is usually not desirable for the controller to try to compensate too fast fades.

This work is reported in my Master's Thesis [6], and the main results have also been accepted for presentation and publication [4], [5].

FADING POWER SIGNAL

Two different single path propagation Rayleigh fading channel models were used for simulations described in more detail in [4] and [5]. The Jakes' Rayleigh fader [2] consists of sums of sinusoids at appropriately chosen Doppler frequencies. In the other simulator, Rayleigh fading signal is generated by shaping zero mean white Gaussian noise according to the receiver antenna geometry. At demodulation the received high-frequency real-valued signal is transformed into a complex-valued base-band-equivalent signal. The simulators generate this complex-valued signal whose power is computed as the sum of squares of the components. The components were independently contaminated by zero mean white Gaussian noise before the power calculations. Channel responses of both simulators visually resemble low degree polynomials. Output power signal from the Jakes' fader with and without noise is shown in Fig. 2.

In the simulations the applied carrier frequency was 1800 MHz, the sampling rate of the unmodulated in-phase and quadrature components was 1 kHz, and the applied vehicle speeds were 5 km/h and 50 km/h. The input SNRs used within components were 10 dB and 0 dB, corresponding to good and bad channels, respectively.

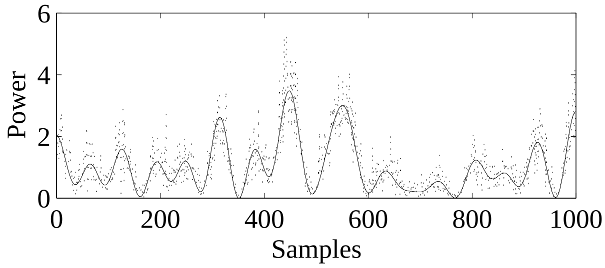

Fig. 2: Noisy (dotted) and noiseless (solid) power signal simulations of one second at 5 km/h using Jakes' Rayleigh fading channel model.

OVERVIEW OF POLYNOMIAL PREDICTION

With reference to the noiseless power signal in Fig. 2, it is easy to see that a piecewise polynomial model can be expected to suit well for modeling of the narrow-band power signal. The polynomial signal model is given by

$$\tilde{y}(n) = \nu_0 + \nu_1 n + \ldots + \nu_{L-1} n^{L-1} + \nu_L n^L + e(n) \qquad (1)$$

where n is the index of a discrete-time sequence, $\tilde{y}(n)$ is the value of the polynomial at n, $e(n)$ is an additive noise term, ν_i are the weighting coefficients with i=0, 1, ..., L, and L is the degree of the polynomial model selected. In polynomial prediction signals are approximated with low degree polynomials whose future values are estimated from a measured sample history. Generally, a one-step-ahead predicted signal value at time n is given by a finite sum of weighted past signal values as

$$\hat{y}(n) = \sum_{i=1}^{k} h(i) y(n-i) \,. \qquad (2)$$

The noise gain of this predictor is defined in both time and frequency domains as

$$NG = \sum_{i=-\infty}^{\infty} |h(i)|^2 = \frac{1}{2\pi} \int_{-\pi}^{\pi} \left| H\left(e^{j\omega}\right) \right|^2 d\omega \qquad (3)$$

where $H(e^{j\omega})$ is the predictor transfer function.

The results in this paper are obtained using Heinonen-Neuvo (H-N) polynomial predictors [3]. They are FIR type low-pass predictors which minimize the noise gain (3) of the filters given a polynomial signal of a given degree. They are derived to provide for unbiased prediction. Also, closed form solutions for the optimal low-degree H-N one-step-ahead predictor coefficients exist [3]. Since H-N predictors are optimized for polynomial signals, they were expected to perform equally well with both Jakes' and noise shaping channel models.

Magnitude responses for the first and second degree H-N predictors of lengths 20 and 50 are plotted in Fig. 3. The lowpass nature of H-N predictors is clearly visible with the passband bandwidth and the passband gain decreasing along with the increasing predictor length.

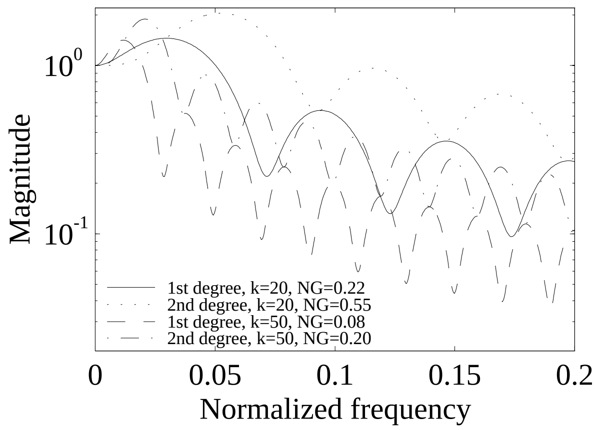

Fig. 3: Magnitude responses of some H-N predictors.

POWER PREDICTION CONCEPTS

First, prediction of fading signals as such was simulated. On the other hand, it is usually not desirable for a power control system to follow all the fast fading, and the power control system itself may also introduce some physical performance limits. This suggested prediction of a low-pass part of the power signal, i.e., intentional smoothing out of the deep fast fades of the power signal. The maximum Doppler shift encountered at the mobile speed of 5 km/h was chosen as the highest frequency to be predicted, and the reference power signals for per-

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formance measures were filtered accordingly. The results presented here are for the latter case.

As a received demodulated signal is a complex-valued low-pass signal, there exist two approaches for the power signal prediction: 1) direct prediction of the noisy power signal computed from the components, Fig. 4(a), and 2) independent prediction of the components before computing the power, Fig. 4(b). In Fig. 4, y_c and y_s are the noisy in-phase and quadrature components, respectively. The computational costs of the first and second approach may be different since they demand one or two predictors, respectively.

In the first approach, the prediction could result in negative values. This is unnatural for the feedback loop. In the second approach, the predictive power estimate is guaranteed to be strictly positive because of the final squaring operations. Detailed statistical analysis of these schemes is done in the subproject described in [7]. It is worth mentioning that simulation results of predicting a constant signal in noise exactly match the results derived analytically in the companion subproject.

SIMULATION RESULTS

Simulation results presented here are based on one-step-ahead predictions of both the power signal and its in-phase and quadrature components.

Several H-N predictors were used with the Jakes' and the noise shaping channel model with the parameters mentioned earlier. SNR gain of the predictor was chosen as the performance measure. The input power signal SNR was defined to be equal to the output power signal SNR without filtering and prediction. They were estimated from the sample sequences as

$$SNR_{out} = \frac{\sum_n \left[\left(f\left(x_c(n+1)^2 + x_s(n+1)^2\right)\right)^2\right]}{\sum_n \left[\hat{y}(n) - \left(f\left(x_c(n+1)^2 + x_s(n+1)^2\right)\right)^2\right]} \qquad (4)$$

$$SNR_{in} = \frac{\sum_n \left[\left(f\left(x_c(n)^2 + x_s(n)^2\right)\right)^2\right]}{\sum_n \left[\left(y_c(n)^2 + y_s(n)^2 - f\left(x_c(n)^2 + x_s(n)^2\right)\right)^2\right]} \qquad (5)$$

where $\hat{y}(n)$ is an output power sample, n spans over the sample sequence used for computing the SNRs,

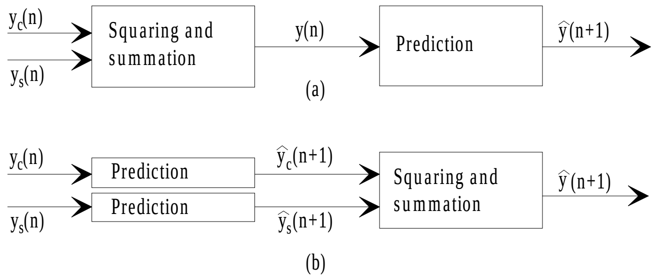

Fig. 4: Block diagrams of the two prediction schemes.

$x_c(n)$ and $x_s(n)$ are noiseless component input samples, and f produces the lowpass filtered sample of the signal whose corresponding sample is the argument of f. $f(\cdot)$ provides for the SNR measure that takes the desired smoothing of the fast fading into account. Predicting the un-band-limited power signal, $f(\cdot)$ is replaced by its argument. The SNR gains, shown in Figs. 5 and 6 for 5 km/h Jakes' Rayleigh fading using band-limited-reference prediction, were calculated as

$$\text{SNR gain}\,(dB) = SNR_{out}(dB) - SNR_{in}(dB) \qquad (6)$$

For each case least-squares optimal (LS) FIRs were designed to give some "upper bound" for fixed-coefficient predictor performance. The calculation of LS FIR coefficients is very much more tedious than computing the H-N coefficient, since it requires knowledge of the signal spectrum, and solving of a possibly large system of equations.

From Fig. 5, it can be seen that in low noise conditions at slow speeds the prediction in components requires longer predictors to reach the same SNR gain as the direct prediction of the power signal. In such cases, the prediction should be done directly from the power signal. It is also noticed that the output SNR gain gets worse after reaching a maximum as the filter length increases. This is due to the fact that while high-order predictors have smaller noise gains, they also have a narrower prediction bandwidth than low-order predictors. Also, longer filters are needed to match the narrower signal bandwidth in the case of component prediction than in the direct power prediction.

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Under high noise conditions at low speeds, Fig. 6, prediction in components exhibits clearly better noise attenuation than the direct prediction of the power signal. In these cases the prediction should be done in components. As in the component prediction the signal to be predicted is of narrower bandwidth, the actual signal is better preserved than with the direct power prediction. Also, with much higher noise content, it is easier to improve the overall SNR than in the low noise conditions. At 50 km/h the noise content affects the selection of the prediction scheme as presented here for 5 km/h.

CONCLUSIONS

The conclusion is that with simple 10 - 20 tap polynomial predictors the SNR of the power signal can be improved by upto 5 - 9 dB, while introducing no delay in the signal. At higher speeds, suitable H-N predictors may be successfully used to average out short-term fading. In the presence of considerable noise, the power estimate is more accurate if it is calculated from the separate predictions of in-phase and quadrature components. In these cases implementation cost may be reduced by predicting the components even though two predictors are needed instead of one as shorter predictors are required in order to achieve the same SNR gain.

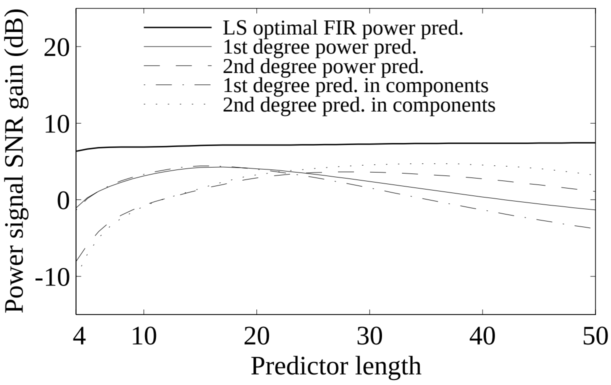

Fig. 5: Output SNR gains of H-N predictions as functions of the predictor length using Jakes' fader and band-limited reference signals. (Theoretical component input SNR 10 dB, speed 5 km/h)

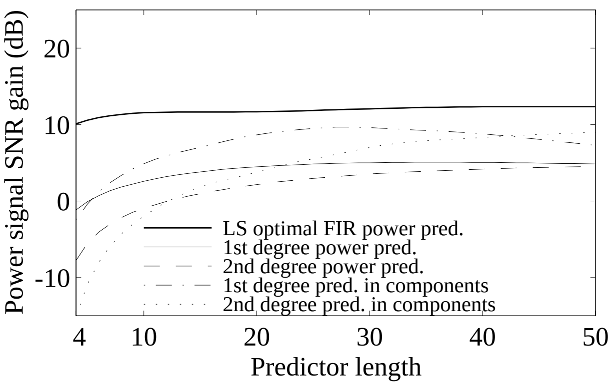

Fig. 6: Output SNR gains of H-N predictions as functions of the predictor length using Jakes' fader and band-limited reference signals. (Theoretical component input SNR 0 dB, speed 5 km/h)

In summary, predictive filtering is a highly potential tool for power control in the uplink transmission of CDMA systems. The results encourage to analyze the proposed prediction schemes with power control loop simulations. Apart from the advantages for short-term power control, predictive techniques may also be useful in forecasting the longer-term power level for control of handovers from one base station to another.

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