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Physical Channel Modeling, Adaptive Prediction and Transmitter Diversity for Flat Fading Mobile Channel[1]

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Abstract

The deterministic nature of flat fading wireless channels is demonstrated with realistic physical models. The models identify typical and worst-case channel parameter variation rates and yield datasets of channel strength vs. position, which are used to test a previously proposed long-range adaptive prediction algorithm. Our physical insights and unique long-range prediction capability for the fast fading can be used in conjunction with space diversity -- including novel transmitter diversity schemes for a single receiving antenna -- or adaptive power adjustment to significantly reduce or eliminate the effects of deep fades in wireless communications.

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1. Introduction

Signal fading due to the presence of several Doppler frequency shifted components is a dominant source of impairment in wireless communication. The greatest bit-error rate (BER) loss and the associated high-power requirements result from "deep fades," which are the result of destructive interference between the component radio waves [1, 2]. Since the channel changes rapidly, the transmitter and receiver are not generally optimized for current channel conditions, and thus fail to exploit the full potential of the wireless channel. The greatest potential lies in the exploitation of prior-knowledge of when the waves interfere constructively, so the channel is much better than in the absence of fading. Novel perspectives of propagation studies show that the interference pattern formed by the direct signal and the reflected signal components is *deterministic* [3]. The superposition of these *deterministic* sinusoidal components changes rapidly as the vehicle moves, producing the familiar fast-fading signal envelope observed in practice. However, the amplitude, frequency and phase of each component change on a much slower time scale. This insight allows us to accurately predict the channel far ahead with a previously proposed long-range channel prediction method [4, 5]. This capability will potentially result in signal optimization at the transmitter for reduction of the power requirements and increased reliability for wireless channels. In this paper, we will concentrate on the description of the physical insights into the deterministic nature of the fast fading channels, and tests of the adaptive prediction method on the realistic physical model rather than the simple simulation models (e.g. three-scatterer or Jakes model)

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[4, 5]. We also describe a novel transmitter diversity approach based on the proposed prediction method.

2. Deterministic nature of the fast fading channels

The fading signal is often modeled as a random process [1, 2], arising from an infinite number of scatterers. However, propagation studies in a variety of environments show that the fading signal consists primarily of a small number of discrete sinusoidal components (often 10 or fewer) and the interference pattern is formed from the superposition of these components [3, 6]. Generally, we can observe this process from two different frames of reference.

(a) The first frame of reference is the ground. In this case, we assume that all reflectors are stationary and the receiver moves, so there are no Doppler shifts in this frame. The receiver passes through this interference pattern. Models of the interference pattern give insights to relative importance of scatterers, and the parameter variation rates of the component signals. The positions of destructive interference are the deep fades.

(b) A different physical picture of this scenario derives from the frame of reference of the mobile rather than the ground. In this frame, the component signals are Doppler shifted, and interfere with each other in time rather than position. At the mobile, the received flat fading signal is given by

$$c(t) = \sum_{n=1}^{N} A_n e^{j(2\pi f_n t+\phi_n)} \qquad (1)$$

where (for the n^{th} scatterer) A_n is the amplitude, f_n is the Doppler frequency, and ϕ_n is the phase. The Doppler frequency is determined by the mobile's speed and the angle of the incident radio wave relative to mobile direction. There are two important observations regarding the fading signal c(t):

First, in contrast to the fast variation of fading signal c(t) envelope, the parameters A_n, f_n and ϕ_n vary on much slower time scale, e.g. on the order of 100 times the coherence time of the signal envelope. This assumption can be justified from the physics based on the method of images combined with diffraction theory. In typical environments such as a rural highway, suburban and urban areas, it appears that most situations (but not all – base station siting is still important) would be adequately handled by a system which could respond to changes in Doppler frequency and amplitude on the 0.1 second time scale (assuming 1 GHz carrier frequency). The rate of component phase change is slow, and is not expected to be important at all in most scattering objects realizations.

The second property of the fading signal is that typically the number of significant scatterers N in (1) is modest. A signal is important in the interference pattern only when its strength is of comparable to the strongest component present. According to this observation, small scatters like cans, people, road signs will not be important if the direct signal or reflections from large or medium-sized scatterers like buildings, hillsides or cars, are present, since their amplitudes remain large over a broad area. The number of significant scatterers (large and medium scatterers) in a specific environment is modest. The treatment of reflections from large and medium-sized objects as virtual sources diffracted through a ‘slit’ the size of the object in the object plane gives immediate qualitative insights to typical and worst-case rates of parameter variation. These physical insights into the nature of the fast fading provide limits on the speed of adaptation needed for an algorithm which can predict the channel significantly into the future, i.e., to reveal the timing of future deep fades and future periods with better than average channel conditions.

3. Adaptive prediction of the flat fading channel

A novel linear prediction (LP) method of the flat fading channel was proposed in [4, 5]. It is different from the conventional channel estimation at two aspects. First, the novel LP method focuses on predicting the future behavior of the fading coefficients rather than estimating its current value. Second, in contrast to conventional channel estimation employed

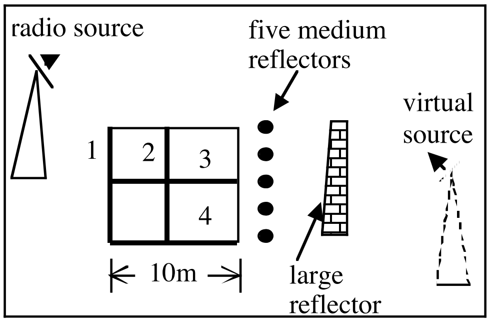

Figure 1: Generation of interference pattern of realistic physical model

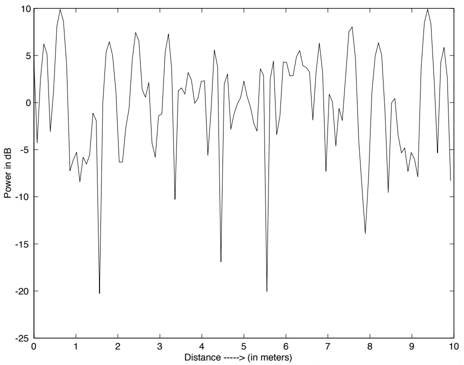

Figure 2: Power level of realistic physical model

at the high sampling rate (usually at the data rate, e.g. [7]), the novel method used the considerable lower sampling rate (on the order of twice the maximum Doppler frequency), which allows the long range channel behavior to be captured. The LP method is based on All-Pole modeling. In this model, the estimate of the future channel sample $\hat{c}_n$ is based on p previous channel samples $c_{n-1}, \cdots, c_{n-p}$:

$$\hat{c}_n = \sum_{j=1}^{p} d_j c_{n-j} \qquad (2)$$

Since the channel observations are not available beyond the observation interval, channel estimates can be used as described in [5]. These estimates are updated adaptively in conjunction with the channel inversion with threshold power adjustment method [5]. Due to the channel time-varying characteristics which are mainly reflected in the LP coefficients d_j in (2), the adaptive tracking method was used to update the model parameters as follows [5]:

$$\underline{d}(n+1) = \underline{d}(n) + \eta e_n \underline{\tilde{c}}_n^* \qquad (3)$$

where η is the step-size, $\underline{d}(n)=(d_1(n), ...d_p(n))$ is the time-dependent vector of channel model parameters (see (3)), $\underline{\tilde{c}}(n)=(\tilde{c}_{n-1}, ..., \tilde{c}_{n-p})$ is the vector of updated channel estimates, and the error signal, $e_n = c_n - \hat{c}_n \approx \tilde{c}_n - \hat{c}_n$. In this summary, we set $\tilde{c}_n = c_n$ in the computation of e_n. This approximation is justified by the results in [5]. Application of this adaptive tracking method significantly reduces the propagation error and maintains the robustness of long range prediction as the physical channel parameters vary.

4. Testing the proposed algorithm on realistic physical channel models

As an example of deterministic modeling, suppose one large and five medium-sized reflecting objects create an interference pattern with the source. The source is 109.2 m above the track center shown in Figure 1. A large object 10.8 m below the track does not run perpendicular to it, so its effective source is 130.8 m below the left end of the track — think of it as a hill or building. Its amplitude reflection coefficient is 2/3. The five medium reflectors are evenly spaced on a 10 m long line parallel to the track and with effective sources 1.8 m below. Think of them as five spherical cars parked along the road. The interference pattern shown in Figure 2 is complex with narrow, deep fades which are ~1/100 the average power. This curve is not that different from what is observed in the field, giving further credence to the expectation that several reflectors are sufficient to produce such an interference pattern. Not shown in the figure are the variations in Doppler shifts and amplitudes with position for each of the scattering components, which we can use to estimate required adaptive tracking performance. In general, the rate of Doppler frequency variation will be larger if one passes closer to the virtual source, so the routes 3 and 4 represent a near-worst-case scenario. The amplitude variation is also strong along these paths, since it drops with distance from such a reflector.

The proposed linear prediction method was tested on the realistic physical channel models. Here, we predict the power variation of fading channels rather than channel fading gains, as has been done in [5]. In practice, the power (or magnitude) is the much more important parameter to predict, since it can directly reveals the location of deep fades. We choose route 1 as typical case and route 3 as the worst case in Figure 1 to be tested. The observation interval was 80 samples, and the model order p=30. The simulation results are shown in Figure 3 and Figure 4. We see that the channel power variation can be predicted very closely for the typical situation. However, the prediction becomes more difficult for the route 3 due to the very large power variation.

5. A transmitter diversity scheme for a single receiving antenna

The slow variation of fading channel parameters allow us to accurately predict future channel properties far ahead, as shown above. This prior knowledge can be used for transmitter optimization, and is especially important for the downlink since usually only one antenna is used at mobile. For example, transmitter diversity in the downlink can be provided by adaptively selecting the transmission antenna at the base station with the best channel, using our channel prediction. In order to illustrate how and why this scheme works, suppose that just two antennas A and B spaced at half wavelength apart are used at base station. The driving configuration is: (1) predict the future channel when transmitting from antenna A; (2) predict the future channel when transmitting from antenna B; (3) select and use the antenna which results in the larger signal at the receiver. This is a time-varying strategy and requires channel prediction for each transmitter antenna. It provides transmitter space diversity and essentially eliminates deep fades in the downlink with only a single antenna on the mobile. In modeling this transmitter diversity system, it is important to take into account that shifting the source antenna does not simply shift the interference pattern, since the positions of the effective sources for the reflected light will also change for flat objects. Many questions related to this approach are still open and are under investigation.

6. Conclusions

Realistic physical models are studied and it is observed that channel parameters vary slowly enough for tracking and long range prediction. This was examined through the channel power prediction of a realistic model. Such capability will engender transmitter optimization using simple space diversity.

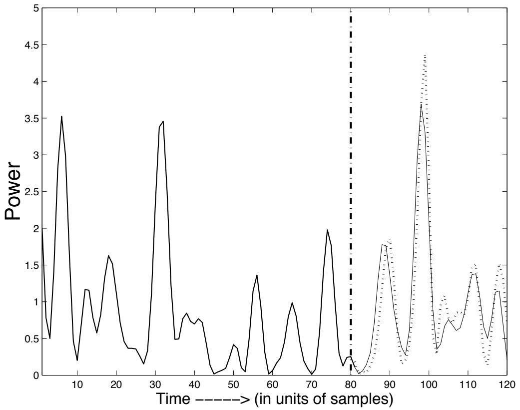

Figure 3 Parallel to and far from the reflectors (route 1). First half: the actual fading channel envelope (solid line) is observed. Second half: the actual future (solid) and predicted (dotted) fading channel envelopes.

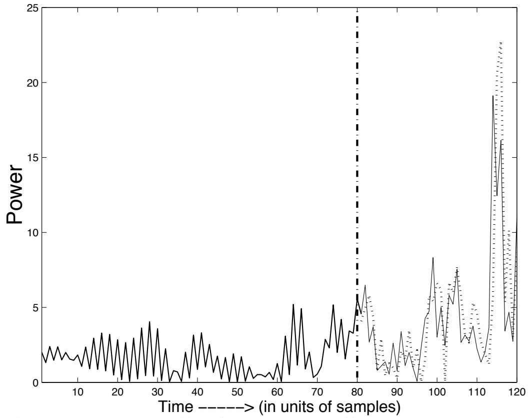

Figure 4 Perpendicular to the reflectors (route 3). First half: the actual fading channel envelope (solid line) is observed. Second half: the actual future (solid) and predicted (dotted) fading channel envelopes.

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