Open-loop Power Control Error on a Frequency Selective CDMA Channel

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Abstract

In order to combat shadowing and distance losses in a land mobile satellite system, an adaptive power control (APC) scheme is essential. Such a scheme, implemented on the uplink, ensures that all users' signals arrive at the base station with equal average power as they move within the satellite spot beam.

Because of the lengthy round-trip delay on a satellite link, closed-loop power control systems are only of marginal benefit. Therefore, an *open-loop* APC scheme is proposed to counteract the effects of shadowing on a frequency-selective multipath fading channel. The power control scheme has been simulated. It has been found that the power control error can be approximated by a log-normally distributed random variable. To quantify the performance of the APC, the standard deviation of the power control error in decibels is presented as a function of the measurement time and vehicle velocity.

I Introduction

A land mobile satellite link suffers from fading, shadowing, and distance losses. To combat some of these effects, an adaptive power control (APC) scheme is desirable. The purpose of the APC is to reduce the above-mentioned effects, to maintain a constant average performance among the users, and to minimize the required transmit power for each user. In addition, in a direct-sequence (DS) code-division multiple-access (CDMA) system, the purpose of power control is to reduce the mulitple-access interference effect caused by users which interfere with one another. In [1], we have analyzed the performance of an APC scheme over a flat fading channel. In this paper, we simulate the effect of power control error (PCE) on the uplink of a frequency-selective fading channel, and include various effects which were ignored for the purposes of analytic simplicity in [1].

There are two forms of APC. In closed-loop implementations, the uplink channel state is estimated by the base station, which then transmits this information back to the mobile for use in the reverse link power control. In a terrestrial environment, such a scheme is feasible under most conditions; however, even with low earth orbit (LEO) satellites, the round trip delay is about 10ms for a 400 nautical mile satellite and up to 60ms for 800 nautical mile satellites at lower elevation angles [2]. Because closed-loop schemes are dependent on the round trip delay, their use is typically not feasible in a land mobile satellite system, since such a system suffers from rapid multipath fading.

An alternate, and simpler form of power control is an open-loop system. In such a scheme, the channel state on the downlink is estimated by the user, and this estimate is used as a measure of the channel state on the uplink. This technique is ideal if the uplink and downlink are perfectly correlated. However, due to multipath fading, this is not, in general, true. Nevertheless, open-loop APC can compensate for large scale variations such as shadowing, and it provides a fast, inexpensive method to equalize average received power at the base station. An open-loop APC algorithm should therefore attempt to minimize the effect of the multipath fading component by averaging it out.

The channel is modeled as a frequency selective fading multipath channel with log-normal shadowing. This might be the typical scenario in a land mobile satellite system when, for example, the user is under a tree or

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in the shadow of a tall building. The fading component on the forward link is assumed to be uncorrelated with that on the reverse link, and the shadowing components on the forward and reverse links, which are caused by blockage and distance, are assumed perfectly correlated. As a result, the primary purpose of the APC algorithm at the mobile is to provide an estimate of the shadowing component.

To quantify the performance of the APC, the standard deviation of the power control error in decibels is obtained from simulation. This is shown to be a critical function of both the measurement time used in the algorithm, and the vehicle velocity. The statistics of the power control error are analyzed and found to be closely approximated by a log-normal random variable.

The paper is organized as follows. The system model and various assumptions are described in Section II. In Section III, we examine the APC performance over a frequency-selective channel, and we present results on the performance of the APC. Section IV presents conclusions.

II System model

We model the channel as frequency-selective with exponentially decaying multipath intensity profile, and we consider the effect of multipath diversity on the APC by making use of a RAKE receiver. As in [3], we model the time-variant frequency-selective channel as a tapped delay line with tap spacing T_c, and tap coefficients $\{z_l(t)\}$ which are zero-mean, complex-valued stationary, mutually independent Gaussian random processes. Thus, the complex lowpass equivalent channel impulse response, in the presence of shadowing, is given by

$$h(\tau;t) = S(t)\sum_{l=0}^{L-1} z_l(t)\delta(\tau - lT_c), \qquad (1)$$

where $S(t)$ represents the amplitude of the shadowing component and is assumed to be log-normally distributed, i.e., $S(t) = e^{\zeta(t)}$, where $\zeta(t)$ is Gaussian distributed with mean $\overline{\zeta}$ (dependent on base-to-mobile distance) and standard deviation σ_ζ [1]. L is the number of resolvable paths, each spaced T_c apart (see Fig. 1). If the multipath spread is T_s, then the number of resolvable paths is $L = \lfloor T_s/T_c \rfloor + 1$. Using the standard wide sense stationary uncorrelated scattering (WSSUS) assumption implies that the $\{z_l(t)\}$ are mutually uncorrelated and thus statistically independent. We can also write $z_l(t) = \alpha_l(t)e^{j\phi_l(t)}$, where the $\{\alpha_l(t)\}$ are Rayleigh distributed and the phases $\{\phi_l(t)\}$ are uniformly distributed in $[0, 2\pi]$. The average path strength Ω_l is the second moment of α_l (i.e., $\Omega_l = \mathrm{E}[(\alpha_l)^2]$), and is assumed to be related to the second moment of the initial path strength by

$$\Omega_l = \Omega_0 e^{-\mu l}, \qquad \mu \geq 0. \qquad (2)$$

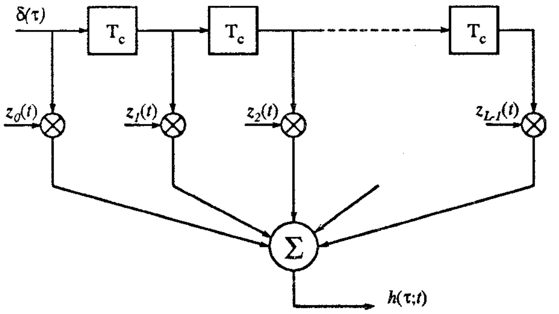

Figure 1: Tap-delay line model of the channel.

Equation (2) describes the decay of the average path strength as a function of path delay; the parameter μ reflects the rate at which this decay occurs. The shape of the decay function is referred to as the multipath intensity profile (MIP) [3]. In our study, the MIP is assumed to be exponential, and actual measurements indicate that this is fairly a good assumption for congested urban areas [4]. It is further assumed that the link is coherent. This is achieved by transmission of a pilot tone which consists of a pure spreading sequence (no data) at a sufficient power level. The second order statistics of the Rayleigh distributed tap weights are described below.

Using (1), the complex lowpass equivalent received signal is given by

$$r(t) = S(t)\sum_{l=0}^{L-1} \alpha_l(t)e^{j\phi_l(t)} \sum_{k=1}^{K} c_k(t - lT_c) + n(t), \quad (3)$$

where $c_k(t)$ is the spreading sequence of the kth user — a binary square waveform with chip time equal to T_c, and $n(t)$ is the complex valued low pass equivalent additive white Gaussian noise with two-sided power spectral density η_o. In (3), we have assumed that the shadowing is the same on each path. Also, it can be seen that the downlink is synchronous, since the gateway/base station has timing knowledge of all users' signals.

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[1] This mean and standard deviation are in units of nepers. To convert to the more commonly used unit of decibels, multiply by $20/\ln 10$.

We estimate the received power at the mobile as shown in Fig. 2. Also, we consider a single satellite spot beam. For simplicity, we assume that the received signal is essentially constant over one bit time, and can thus be replaced by its value at the midpoint of the bit interval. The accuracy of this approximation is examined in [5] and shown to be valid over the range of normalized Doppler bandwidths considered.

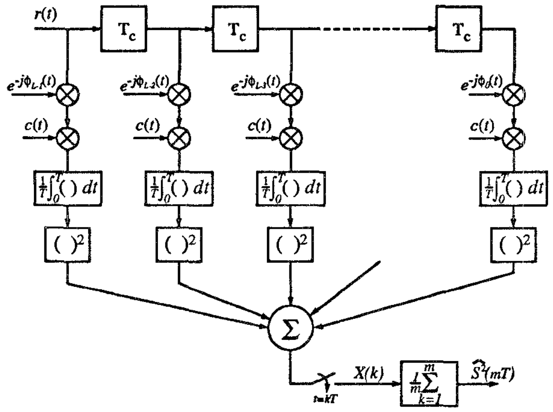

Figure 2: Power estimation using RAKE.

We need to know the second order statistics of $\alpha^2(t)$. Since such statistics are available for terrestrial mobile radio links, we will use these results, even though our goal is to apply them to a mobile satellite channel. In particular, it is known [6] that for a land mobile channel, with $\alpha(t)$ Rayleigh distributed, the correlation function of $\alpha^2(t)$ is given by

$$\begin{aligned} R_{\alpha^2}(\tau) &= \mathrm{E}\{\alpha^2(t)\alpha^2(t+\tau)\} \\ &= 4\sigma^4(\rho^2(\tau)+1), \end{aligned} \tag{4}$$

where $2\sigma^2$ is the power of the Rayleigh component. The quantity $\rho(\tau)$ is the normalized autocovariance function of the complex Gaussian random process whose envelope is the Rayleigh process. If the received waves are travelling only horizontally, i.e., there is no vertical component, then from [6]

$$\rho(\tau) = \mathrm{J}_0(2\pi f_d|\tau|), \tag{5}$$

where $f_d = v/\lambda$ is the Doppler bandwidth, v is the velocity of the mobile relative to the base station, and λ is the wavelength (we assume that the system bandwidth is much smaller than the absolute value of the carrier frequency). In [7], the more general case of angles of arrival in the vertical plane is examined for realistic distributions. It is found that for vertical angles of arrival less than 45°, $\rho(\tau)$ is quite close to (5). In our simulation, the Rayleigh distributed multipath fading envelope is generated as described in [8]. This technique assumes that the arrival angles of the multipath signals at the receiver are uniformly distributed in $[0,2\pi]$, implying that the power spectrum of the fading envelope is symmetric, and is given by

$$S(f) = \begin{cases} \frac{E^2}{2\pi f_d\sqrt{1-(\frac{f}{f_d})^2}} & |\,f\,| < f_d \\ 0 & \text{elsewhere,} \end{cases} \tag{6}$$

where E is the rms value of the signal envelope.

Relative to the rapid variations of the multipath fading, the shadowing effects are much slower. Here, we will assume that the shadowing is constant over the interval of observation.

III Power control error

In order to estimate the received power, the outputs of the taps of the RAKE receiver are first individually correlated with the despreading sequence over one bit time, then squared and summed to yield $X(k)$ at time kT. An estimate of the received power is then formed by summing $X(k)$ (see Fig. 2). The power estimate at time mT is given by $\widehat{S^2}(mT)$, and the mobile uses this estimate to transmit an amplitude that is inversely proportional to $(\widehat{S^2}(mT))^{1/2}$. Taking into account a round trip delay of Δ bits, the received signal at the base station will contain a term similar to (3), except weighted by the inverse of $(\widehat{S^2}(mT))^{1/2}$, i.e., the signal envelope at time $m'T = (m+\Delta)T$ is

$$\begin{aligned} r'(m'T) &= \frac{S(m'T)\sum_{l=0}^{L-1}\alpha_l'(m'T)e^{j\phi_l'(m'T)}c'(m'T-lT_c)}{(\widehat{S^2}(mT))^{1/2}} \\ &\quad + MAI(m'T) + n'(m'T) \\ &= \gamma\sum_{l=0}^{L-1}\alpha_l'(m'T)e^{j\phi_l'(m'T)}c'(m'T-lT_c) \\ &\quad + MAI(m'T) + n'(m'T), \end{aligned}$$

where γ is defined as the power control error. Notice that the Rayleigh fading terms on the reverse link are different from those on the forward link, since the uplink and downlink frequency bands are assumed separated by more than the coherence bandwidth of the channel. On the other hand, the shadowing terms on both links are assumed perfectly correlated.

A simulation of the power control scheme was performed. Figure 3 compares the cumulative distributions of the logarithm of the simulated power control error in nepers (with three equal strength multipath components, i.e., multipath delay profile exponent $\mu = 0.0$) with a Gaussian cumulative distribution function. The two c.d.f.'s are plotted versus each other, so that a Gaussian c.d.f. appears as a straight line. The simulated PCE lies quite close to the straight line. This implies that the distribution of the PCE is similar to a log-normal distribution.

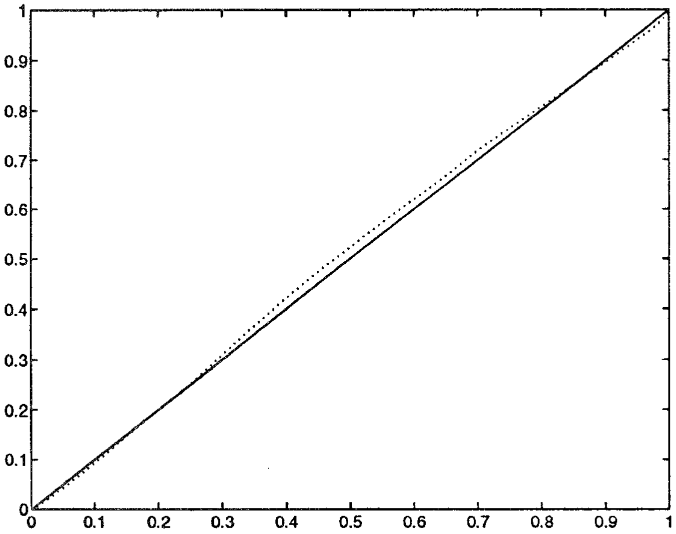

Figure 3: Comparison of the c.d.f. of the logarithm of the simulated power control error with a Gaussian c.d.f. - power estimation. $L = 3, \mu = 0, m = 40, f_dT = 0.05$.

III.A Discussion

The effect of downlink multiple access interference on the standard deviation of the power control error, σ_δ, in dB is studied through simulation. Randomly generated binary sequences are used as the spreading codes for different users. Interestingly, the results are found to be insensitive to the number of simultaneously active users. This observation is attributed to the low cross-correlation values among different users' spreading codes. In fact, for greater than 10 users, the performance is a consistent 10% worse than with a single user. Due to simulation time constraints, the results that follow are for the single user case, only, and should therefore be viewed as slightly optimistic by a factor of about 10%.

Figure 4 shows the effect of the measurement interval on the power control error standard deviation. The number of multipath components is $L = 3$, and the multipath delay profile exponent is $\mu = 0.2$. The curves are parameterized by the normalized one-sided Doppler bandwidth, f_dT. It is observed that as f_dT increases, corresponding to an increase in the vehicle speed, σ_δ decreases. The reason for this is that an increase in Doppler bandwidth results in an increase in the fading rate of the Rayleigh fading process (equivalently, a decrease in the correlation of the Rayleigh process). Heuristically, this means that we are trying to average out a signal which is fluctuating more rapidly (since it is less correlated), and thus the variance of our estimate will decrease. The same explanation is valid when the measurement interval increases, i.e., over the span of the measurement interval, we observe more fluctuations, which results in a reduced variance of the estimate.

Figure 5 shows the effect of increasing the number of taps in the RAKE receiver, in which we perform maximal ratio combining of all the resolvable paths. It is seen that as the number of RAKE receiver taps is increased, the power control error decreases. As can be seen from Fig. 5, the value of σ_δ decreases from 2.1 dB for the flat fading case ($L = 1$) to 1.67 dB for the frequency selective case with a 9 tap RAKE receiver when $f_dT = 0.05$, $m = 40$, and $\mu = 0.5$. This can result in significant improvement in the system capacity, as shown in [9].

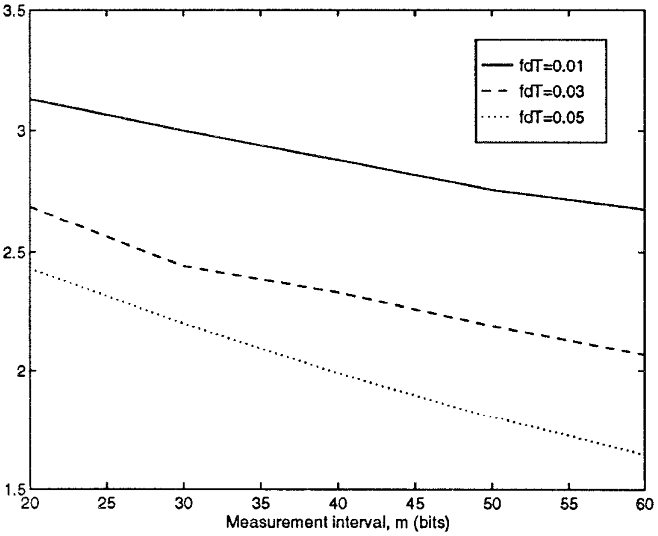

Figure 4: Variation of σ_δ (in dB) with measurement interval, m (bits). $L = 3$, $\mu = 0.2$, $E_b/N_o = 10$ dB.

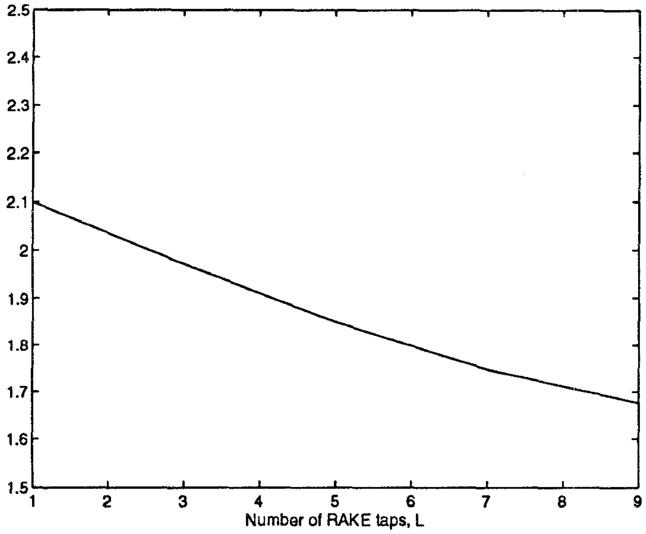

Figure 5: Variation of σ_δ (in dB) with number of RAKE taps, L. $f_d T = 0.05$, $m = 40$, $\mu = 0.5$, $E_b/N_o = 10$ dB.

IV Conclusions

We have simulated the performance of an adaptive open-loop power control scheme for use in a land mobile satellite system. The statistics of the power control error have been found to be well-approximated by a log-normal random process, and the APC performance has been quantified by examining the standard deviation of the power control error in terms of various parameters, such as Doppler frequency and measurement time. Since the APC scheme is open-loop, performance improvement is obtained by averaging out the fast fading fluctuations on the downlink. Results have been presented for frequency selective channels using a RAKE receiver. It has been seen that the downlink multiple access interference has marginal effect on the power control error, and increasing the measurement interval, or the Doppler bandwidth (equivalently, increasing relative vehicle speed), or the number of taps in the RAKE receiver, reduced the power control error.

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