Power Control by Kalman Filter With Error Margin for Wireless IP Networks

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ABSTRACT

A power-control method based on tracking of interference power by use of a Kalman filter, proposed earlier for packet-switched TDMA wireless networks, does not yield performance gain in case of short message length and/or moderate control delay. The major reason is that the interference prediction by the filter may not be accurate enough due to little interference temporal correlation. In this paper, we enhance the power-control method by introducing an error margin in determining the transmission power. The error margin is obtained based on tracking of interference prediction error, which automatically captures the impacts due to short message length and control delay.

Our performance results reveal that the enhanced power-control method is capable of providing a significant performance improvement even for short message and moderate control delay. Specifically, for the worst case where the message length $L=1$ (i.e., one packet per message), the 90 and 95 percentile signal-to-interference-plus-noise ratio (SINR) by the enhanced method are 2.69 and 2.96 dB above those for no power control in a system of 4-sector cells with a frequency reuse factor of 2/8. In contrast, the original Kalman-filter method with no error margin yields no SINR gain for $L=1$. For $L=10$, we also observe similar improvement by the enhanced method for control delay up to 3 time slots.

1. INTRODUCTION

With the proliferation of Internet and the convenience of user mobility in wireless networks, the demand for high-speed wireless access to the Internet is expected to grow tremendously in the near future. Such wireless access is needed to provide: a) efficient access to World Wide Web for information and entertainment, b) remote access for telecommuters to their computer systems, and c) multimedia services such as voice, image and video.

Dynamic transmission power control has been widely practiced to manage interference in wireless networks; see e.g., [Z92a], [FM93], [EKBNS96] and [RZ98]. Specifically, power control has been shown to be a useful technique to improve performance and capacity of time-division-multiple-access (TDMA) wireless networks. In this paper, we consider the power-control issue for packet-switched TDMA networks with user data rates up to several megabits per second, link lengths (or cell size) typically less than 10 kilometers and operating frequency in the range of 1 to 5 GHz.

In general, power control algorithms for wireless networks can be categorized into two classes: *signal-based* and *signal-to-interference-ratio (SIR) based* power control. Signal-based power control [W93] [HWJ97] adjusts the transmission power based on the received signal strength, which in turn depends on path loss, shadowing and fading of the radio link between the transmitter and receiver. In contrast, SIR-based control [Z92a], [Z92b], [FM93], [GVG94], [UY98] changes the power according to the ratio of signal and co-channel interference (possibly plus noise) power levels. (Since only co-channel interference is considered here, it is simply referred to as *interference* in the following.) It has been shown that SIR-based power control outperforms signal-based control.

Many SIR-based power control algorithms assume that calls have relatively long holding time and they base on the last SIR measurement to adjust power iteratively. However, they may not be efficient for packet-switching networks due to the burstiness of data packets. Recently, a power-control method based on interference tracking by use of a Kalman filter is proposed in [L99] for wireless packet networks. The power-control method is integrated with link adaptation to control error performance and enhance network throughput in [LW99] and [LW00].

Despite the performance gain of the Kalman-filter method, an outstanding issue remains as follows. Specifically, the gain of the Kalman method relative to the performance for no power control diminishes significantly when the average message length L in terms of the number of packets (or time slots) decreases. To illustrate our point, for the cellular layout [WL00] in Figure 1, Figure 2 shows such degradation of performance gain for the power-control method. (Note that Figure 2 is reproduced from that in [L99]. This example layout will be discussed in detail later.) The degradation is because the Kalman filter cannot predict the interference power accurately as short message yields little temporal correlation for the interference in the packet-switched networks. Similar degradation in performance gain also occurs for increased control delay, which is the delay incurred in measuring the interference power and passing the power-control information from the receiver to the transmitter (e.g., see Figure 5 in [L99]). The purpose of this paper is to enhance the Kalman-filter method so that the enhanced technique can provide significant performance improvement despite short message and moderate control delay.

The organization of the rest of this paper is as follows. In section 2, the system assumptions and the enhanced Kalman-filter method for power control are presented. In Section 3, we use simulation techniques to study the performance of the new method. In addition, we also explain and interpret the numerical results. Finally, we present our conclusions and future work in Section 4.

2. AN ENHANCED KALMAN-FILTER POWER CONTROL

Although the power-control method is applicable to both uplink (from terminal to base station) and downlink (from base station to terminal), our discussion will focus on the uplink here.

2.1 System Assumptions

1. Consider a cellular radio network where time is divided into *slots*. Let each data message be divided into a number of packets, each of which can be transmitted in one time slots. As in typical IP networks, the message length (in terms of the number of packets) varies randomly from message to message. Despite such randomness, the networks allow multiple, contiguous time slots to be used by the same transmitter for sending a message. As a consequence, the interference at a given receiver is correlated from one time slot to the next.
2. The signal path gain (e.g., the sum of the path loss and shadow fading for the radio link) between a terminal and its base station can be estimated accurately. This is a reasonable assumption, especially for the link quality not changing much in time when the terminal is moving at a very slow speed or stationary.
3. The medium-access control (MAC) protocol in use allows at most one terminal in each sector or cell to send data at a time; that is, no data contention occurs within the same sector or cell. In addition, the base station knows which terminal is scheduled to transmit at different times. (For example, typical polling and reservation schemes meet both requirements.) When a terminal transmits, it can send packets in multiple time slots contiguously.
4. Due to large volume of data involved, base stations do not exchange control information among themselves on a per packet basis in real time. Thus, it is extremely difficult to estimate how much interference one transmission causes to others in neighboring cells.
5. Interference power in each time slot can be measured quickly but possibly with errors at each base station. At a high level, the interference power is equal to the difference between the total received power and the power of the desired signal, where the latter can be measured by filtering based on the training symbols for the signal. In fact, such measurements can be involved and challenging, especially when time duration is short; see e.g., [AS95], [A97] and [AMY98].

2.2 Interference Prediction

Based on the temporal correlation of interference, we use a Kalman filter to predict interference power to be received at a base station in the immediate future. Let I_n be the actual interference-plus-noise power in dBm received in time slot n at a given base station. In other words, I_n is the "process state" to be estimated by the Kalman filter. We assume that the noise power, which depends on the channel bandwidth, is given and fixed. For brevity, unless stated otherwise, the interference plus thermal noise is simply referred to as *interference* in the following. The dynamics of the interference power is described by

$$I_n = I_{n-1} + F_n \tag{1}$$

where F_n represents the change of interference power for slot n relative to that in slot $n-1$ as terminals may start new transmissions and/or adjust their transmission power in the former slot. In the terminology of Kalman filter, F_n is the "process noise." In essence, changes of interference power are modeled by a Brownian-motion process in (1). Let Z_n be the measured interference power in slot n. Then,

$$Z_n = I_n + E_n \tag{2}$$

where E_n is the "measurement noise." Eq.(1) and (2) are commonly referred to as the *signal generation model.* By the Kalman filter theory [BH97], the time and measurement update equations are:

$$\tilde{I}_{n+1} = \hat{I}_n \tag{3}$$

$$\tilde{P}_{n+1} = \hat{P}_n + Q_n \tag{4}$$

$$K_n = \tilde{P}_n(\tilde{P}_n + R_n)^{-1} \tag{5}$$

$$\hat{I}_n = \tilde{I}_n + K_n(Z_n - \tilde{I}_n) \tag{6}$$

$$\hat{P}_n = (1 - K_n)\tilde{P}_n \tag{7}$$

where $\tilde{I}_n$ and $\hat{I}_n$ are the a priori and a posteriori estimate of I_n, $\tilde{P}_n$ and $\hat{P}_n$ are the a priori and a posteriori estimate error variance, K_n is the Kalman gain, and Q_n and R_n are the variance for the process noise F_n and measurement noise E_n, respectively.

Clearly, Q_n and R_n need to be estimated appropriately as input to (4) and (5). For that purpose, the following estimations based on the interference measurements in a sliding window of the last W slots are used:

$$\bar{Z}_n = \frac{1}{W} \sum_{i=n-W+1}^{n} Z_i \tag{8}$$

$$Q_n = \frac{1}{W-1} \sum_{i=n-W+1}^{n} [Z_i - \bar{Z}_n]^2 \tag{9}$$

$$R_n = \eta Q_n \tag{10}$$

where η is a constant between 0 and 1. Strictly speaking, Q_n in (9) is an estimate of the variance of the sum of the process and measurement noise because measurements Z_n's include the fluctuation of both interference and measurement errors. However, since the standard deviation of the interference power can reach as much as tens of decibels, which is much higher than typical measurement errors, (9) yields a good variance estimation for the process noise F_n. In addition, the choice of R_n according to (10) with η less than 1 is reasonable because the measurement noise (error) is likely to be smaller than the fluctuation of interference power. Furthermore, the sliding window size *W* should be at least several times the average message length so that multiple terminals are likely to have transmitted during the time window, thus capturing changes of interference power.

For each slot *n*, the interference measurements are input to (9) and (10) to estimate Q_n and R_n. Using these values and the current measurement, (5) to (7) yield the Kalman gain, and the a posteriori estimates for I_n and P_n, respectively. The a priori estimates for the next time slot are given by (3) and (4). In particular, $\tilde{I}_{n+1}$ in (3) is used as the predicted interference in slot $n+1$ for power control.

2.3 Tracking of Prediction Error & Power Control

As pointed out above, the interference prediction by (3) may not be accurate enough for the purpose of power control in case of short message length and/or control delay. For this reason, we propose to track the prediction error and include an error margin in determining transmission power as follows.

Let Δ (a random variable in dB) be the error of the interference prediction and the actual error for slot *n* be

$$\Delta_n = I_n - \tilde{I}_n \tag{11}$$

where I_n and $\tilde{I}_n$ are the measured and predicted interference power in dBm for slot *n*, respectively. Based on the Δ_n's, one can approximate the cumulative probability function (CDF) for Δ. Towards this end, let there be *M* possible intervals of prediction error and the range of the j^{th} interval be $(a_j, a_{j+1}]$. For each time slot $n > 0$ and each $j = 1$ to *M*, compute the following

$$P_n^j = \begin{cases} \alpha P_{n-1}^j & \text{if } \Delta_n > a_{j+1} \\ \alpha P_{n-1}^j + 1 - \alpha & \textit{otherwise} \end{cases} \tag{12}$$

where α is a properly chosen parameter and $P_0^j = 1$ for all $j = 1$ to *M*. It is worthnoting that as (12) characterizes the prediction error based on previous interference predictions and actual measurements, the CDF automatically captures the impacts due to reduced interference temporal correlation for short message length and/or control delay.

Let Δ_n^ω be a specified ω^{th} percentile (e.g., for 90th percentile, $\omega = 0.9$) of Δ based on the error statistics up to slot *n*. We approximate $\Delta_n^\omega \approx a_k$ where *k* is the smallest from 1 to *M* such that $P_n^k \geq \omega$.

Let δ_n^ω and $\tilde{i}_n$ be the linear-scale equivalent of Δ_n^ω and $\tilde{I}_n$, which have been obtained from the error tracking procedure and predicted by the Kalman filter, respectively. One can view that $\tilde{i}_n$ is the average predicted interference powe in mW, while the product of $\tilde{i}_n$ and δ_n^ω represents the ω^{th} percentile of the predicted interference power. Accordingly, the base station instructs via a downlink channel the terminal to transmit in slot *n* with power

$$p_n = \beta^* \frac{\delta_n^\omega \, \tilde{i}_n}{g_n}. \tag{13}$$

where β^* is the target SINR and g_n is the path gain from the transmitting terminal to the base station for slot *n*. (By Assumption 1, the base station can determine g_n accurately.) The goal of setting power according to (13) is to choose just enough power to achieve the target SINR β^*, thus minimizing interference to others without degrading one's link quality. The term δ_n^ω represents an error margin, which depends on the accuracy of the interference prediction by the Kalman filter and the specified confidence probability ω. Nevertheless, the error margin is chosen dynamically and appropriately with a goal of delivering the SINR target β^* regardless of the actual message length and control delay.

2.4 Steps for the Enhanced Kalman-Filter Method

The Kalman-filter method for controlling transmission power for each time slot *n* can be summarized as:

a. For each time slot *n*, each base station measures the interference power for the time slot.

b. Use (11) and (12) to compute the prediction error for slot *n* and to update the CDF for the prediction error, respectively.

c. The interference measurement for slot *n* is input to the Kalman filter in (3) to (10) to predict the interference power $\tilde{I}_{n+1}$ (or equivalently, $\tilde{i}_{n+1}$) in the next slot $n+1$. Record the predicted interference power $\tilde{I}_{n+1}$ for future reference.

d. Based on the MAC protocol in use (which satisfies Assumption 2), the base station tracks the path gain g_{n+1}, and selects the transmission power by (13) for the terminal that transmits in slot $n+1$.

e. The power level p_{n+1} is forwarded via the downlink to the terminal for actual transmission.

3. PERFORMANCE STUDY

3.1 Simulation Model

We simulate the cell layout and interleaved channel assignment (ICA) [WL00] in Figure 1. A total of 19 cells are simulated. Each cell is divided into 4 sectors, each of which is served by a base station antenna located at the center of the cell. The beamwidth of each base station antenna is 60^o, while terminals have omni-directional antennas. The radiation pattern for the base station antenna is assumed to be a parabolic shape; that is, a 3 dB drop occurs at the beamwidth half angle and any direction beyond a threshold angle in clockwise or anti-clockwise direction suffers a given, fixed attenuation relative to the gain at the front direction, which is called the *front-to-back* (FTB) ratio. Thus, given the beamwidth and the FTB ratio, the parabolic-shape antenna pattern can be fully specified. For the 60^o base station antenna with 20 dB FTB ratio, this pattern yields a 3 dB drop at the 30^o angle in clockwise or anti-clockwise direction from the front direction, the threshold angle is 77.5^o and the antenna gain at the front direction is 9.5 dBi. The ICA (static) scheme in Figure 1 is considered where the frequency reuse factor is 2/8 (i.e., reuse in every 2 cells or 8 sectors).

Each radio link between a terminal and its base station is characterized by a path-loss model with an exponent of 4 [R96] and lognormal shadow fading with a standard deviation of 8 dB. Fast fading is not considered in this study. Cell radius is assumed to be 1 Km and the path loss at 100 m from the cell center is -70 dB. Thermal noise power is fixed and equal to -115 dBm (to approximate a use of 1 MHz channel bandwidth).

To fully consider the effects of shadow fading and the antenna pattern, terminals are first placed randomly at $\pm 67.5^o$ from the front direction of the base station antenna and as much as 1.25 times the cell radius from the center of each cell. Then, each terminal selects the base station that provides the strongest signal power. The process is repeated until each sector serves 500 terminals. To provide accurate results, only statistics in the middle cell in Figure 1 are collected and reported below. In addition, each simulation is repeated with 5 different sets of random seeds (e.g., for populating terminals and selecting shadow fading) to ensure correctness and results presented below are aggregated results of all five sets.

Two adjustable parameters W and η for (8) to (10) are 30 and 0.5, respectively. Transmission power is limited between 0 to 30 dBm. The number of prediction error intervals M in (12) is 100. The minimum (a_1) and maximum error (a_{M+1}) are 0 and 10 dB, respectively, where all error intervals have equal range in dB.

For convenience, our simulation model assumes that terminals in all cells are synchronized at the slot boundary for transmission. Furthermore, we assume 100% traffic load in this study. That is, there are always terminals ready for transmission in co-channel sectors. Thus, after a terminal transmits a message with a random length according to a discrete form of Pareto distribution [L99], the base station immediately schedules another randomly chosen terminal in the same sector to start a new transmission in the next time slot.

3.2 Performance Results and Discussions

While assuming that interference power in one time slot can be measured and used to determine the power for the next slot (i.e., control delay $D = 0$), Figure 3 compares the SINR performance for the enhanced Kalman-filter method with that for no and optimal power control. For no power control, transmission power is fixed at 30 dBm. Results for the optimal power control, shown by solid line in the figure, are obtained by the method in [GVG94] that maximizes the minimum SIR among all the links without considering thermal noise. The method assumes precise knowledge of path gain for all combinations of terminals and base stations. By knowing the path-gain matrix for the transmitting terminals and receiving base stations, the iterative method is executed until convergence to determine the optimal transmission power for each time slot. The transmission power is scaled in each iteration to avoid numerical underflow and overflow.

As for the enhanced Kalman-filter method, we set the target SINR β^* in (13) to be 15 dB. In addition, the 90 percentile prediction error is used as the error margin δ_n^{ω} in (13); that is, $\omega = 0.9$. As shown by the dashed lines in Figure 3, even for the worst case where each message consists of one single packet (i.e., average message length $L = 1$), the enhanced method yields 2.69 and 2.96 dB gain for the 90 and 95 percentiles of the SINR above those for no power control. In contrast, the original Kalman-filter method without the error margin yields no SINR gain for $L = 1$ in Figure 2. As L increases, the enhanced method further improves the SINR performance, as shown in Figure 3.

Figure 4 shows the significant performance gain of the enhanced power-control method with moderate control delay D in terms of time slots. Specifically, for $L = 10$ and $D = 3$, these results reveal that the enhanced method provides 3.68 and 4.16 dB gain for the 90 and 95 percentiles of the SINR above those for no power control.

It is worthnoting that the SINR gain for the enhanced power control in Figures 3 and 4 is due to the error margin δ_n^{ω}. For short message or control delay, the interference prediction by the Kalman filter is inaccurate. However, the error margin captures how inaccurate the prediction is, thus allowing use of additional transmission power just enough to overcome the uncertainty. As one would expect, the amount of additional power is proportional to the degree of prediction inaccuracy. For the parameter settings in Figures 3 and 4, the corresponding distribution of the transmission power is presented in Figures 5 and 6, respectively. As shown in Figure 5, the transmission power increases as L decreases. This is so because short message yields little interference temporal correlation, thus causing large prediction error. As a result, a large error margin δ_n^{ω} in (13) makes transmission power relatively high. As L increases, additional correlation helps the Kalman filter predict interference fairly accurately, thus reducing the need of additional transmission power associated with the error margin. Similar comments also apply to Figure 6 where transmission power increases as control delay D increases.

4. CONCLUSIONS AND FUTURE WORK

The Kalman-filter power control [L99] proposed for packet-switched TDMA networks does not yield performance gain in case of short message length and/or moderate control delay. The major reason is that the interference prediction by the Kalman filter may not be accurate enough due to little interference temporal correlation. In this paper, we enhance the power-control method by introducing an error margin in determining the transmission power. The error margin is obtained based on tracking of previous interference prediction errors, which automatically capture the impacts due to short message length and control delay.

Our performance results reveal that the enhanced power-control method is capable of providing a significant performance improvement even for short message and moderate control delay. Specifically, for the worst case where the message length $L=1$ (i.e., one packet per message), the 90 and 95 percentile SINR by the enhanced method are 2.69 and 2.96 dB above those for no power control in a system of 4-sector cells with a frequency reuse factor of 2/8 [WL00]. In contrast, the original Kalman-filter method with no error margin yields no SINR gain for $L=1$. For $L=10$, we also observe similar improvement by the enhanced method for control delay up to 3 time slots.

For third generation wireless networks, network performance will depend on the design of dynamic channel assignment (DCA), power control, link adaptation and use of smart antenna. We have studied integrated algorithms of the enhanced power-control method and link adaptation in [LW99] and [LW00]. However, how the DCA and use of smart antenna can be combined with the former techniques for performance and capacity gain is still an open issue. We are in the process of addressing this issue, with a goal of achieving high spectral efficiency and capacity in practical networks.

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Fig.1. A 4-Sector Cell Layout and Channel Assignment

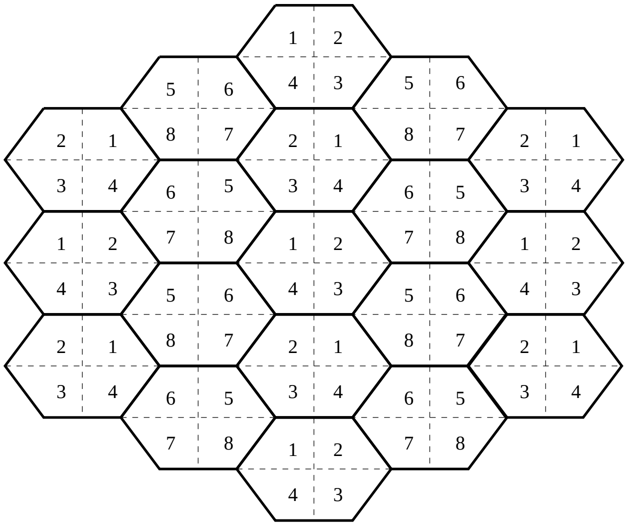

Fig.2. SINR Gain for the Original Kalman Method

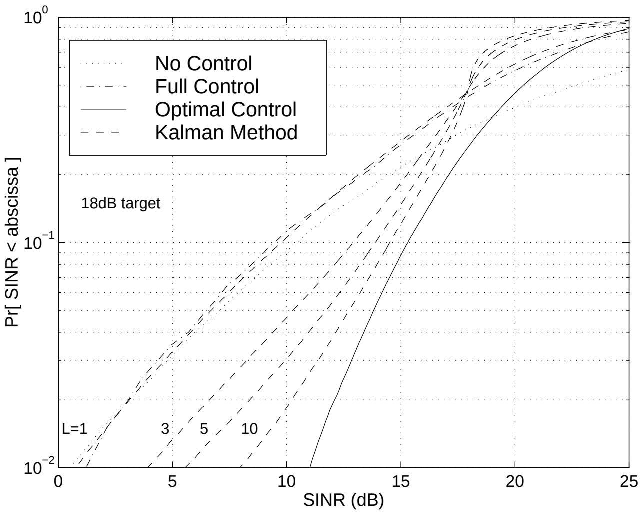

Fig.3. SINR Gain for Short Message by the Enhanced Method

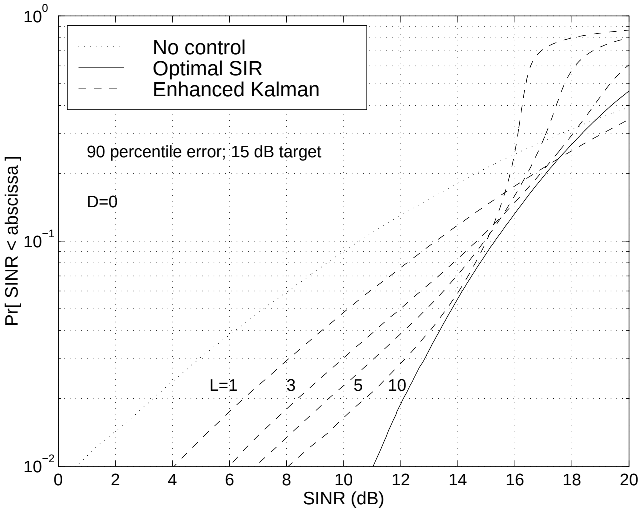

Fig.4. SINR Gain with Control Delay by the Enhanced Method

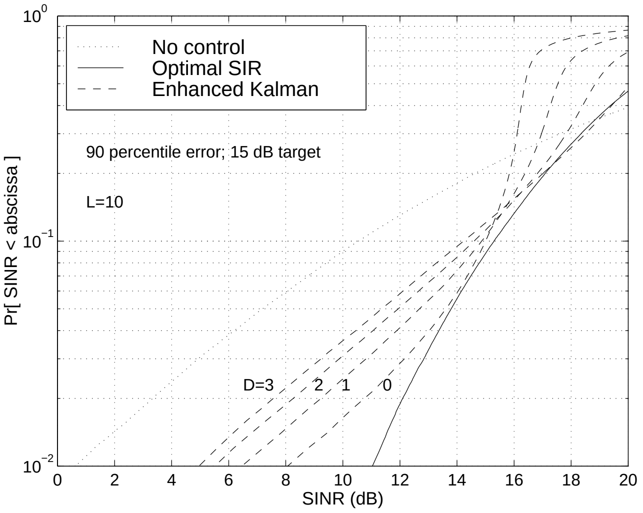

Fig.5. Transmission Power for Various Message Lengths

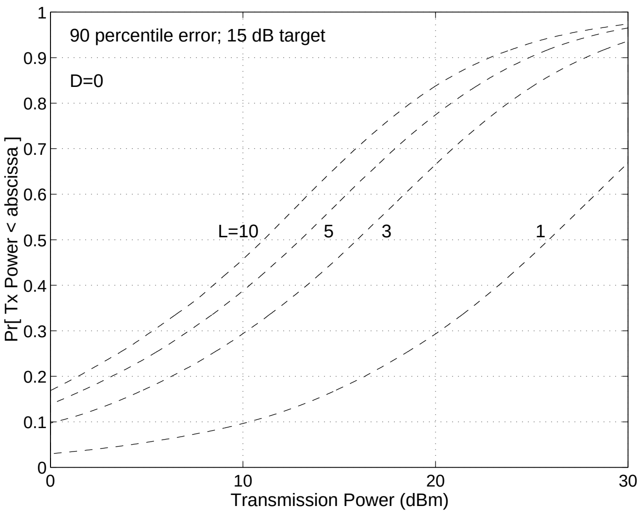

Fig.6. Transmission Power for Various Control Delay