Paper

Linear quadratic power control for CDMA systems

Michael D. Anderson, Sylvie Perreau, and Langford B. White

Abstract — In this paper, we present a robust decentralized method for jointly performing channel estimation and closed loop power control for the reverse link of CDMA networks. Our method, based on linear quadratic Gaussian (LQG) control systems theory and Kalman filtering, does not require any training symbols for channel or signal to interference ratio (SIR) estimation. The main interest of this new scheme is that it improves the performance of current SIR based power control techniques while avoiding the problem of power escalation, which is often observed in current systems.

Keywords* — *CDMA systems, power control, Kalman filtering, channel estimation, linear quadratic control systems.

1. Introduction

Up-link power control (PC) is a crucial element in multi user CDMA systems. In order to maximize capacity and quality of service (QoS), all mobile station (MS) transmissions should be received at the base station (BS) with equal power [1, 2]. Since CDMA systems are interference limited, much work concentrates on the signal to interference ratio as a measure to control MS powers [3–6].

In theory, assuming perfect knowledge of the SIR, SIR based PC outperforms signal strength based PC. This is because the power of the received signal is in fact the sum of the power of the desired and the interference signals. Therefore, in a situation where the received signal power is strong because the interference is significant, a signal strength based power control algorithm would wrongly instruct the MS to decrease its transmit power. Therefore, SIR seems to be a more natural parameter to control interference limited systems. However, SIR based PC is associated with 2 major drawbacks. Firstly, SIR is difficult to estimate accurately [7]. UMTS [8] specifies simultaneous transmission of the DPCCH control channel with DPDCH data channel. SIR is estimated using pilot bits transmitted on DPCCH. System capacity is obviously reduced accordingly. Centralized schemes, where the BS has information for all MS, can determine SIR more accurately than distributed systems [5]. However, centralized methods are difficult to implement due to their high computational complexity.

The other major downfall of SIR based PC is the problem of power escalation. SIR, as the name suggests, is a ratio between signal and interference. As one MS increases its power to compensate for interference from other MS's, its signal interferes more on all other MS's which will in turn increase their transmit power. Instability and power escalation (also defined as positive feedback) can result while the SIR for each MS remains the same. This is particularly prevalent when the system is operating at or near the capacity limit. Therefore, an SIR based PC scheme should be used in conjunction with a perfect call admission control mechanism, which is very difficult to guarantee in real systems.

Zhang et al. [9] address the power escalation problem with a joint signal strength and SIR based PC scheme that compares both quantities to thresholds and adjusts power in the MS with a simple adaptive step size algorithm. The positive feedback potential is of course eliminated with the use of the signal strength constraint. This approach may stop the escalation problem but it still does not minimize the MS transmit power. Ratanamahatana et al. [10] propose a simple method for extracting from the received signal, the desired and interfering signal strengths using pilot symbols. This method, however, reduces system capacity and has potential problems when PC bits are in error on the forward channel.

Qain and Gajic [11] take the power escalation problem further by applying stochastic control systems theory to SIR estimation and PC. SIR error and MS transmit power are jointly minimized and an $H\infty$ filter/estimator is used to track the channel variations. They extend their work by applying constrained optimization techniques to include maximum and minimum allowed MS transmit power. This work is followed up in [12] where the SIR error variance and sum of the variance of MS transmission power are jointly minimized. Linear quadratic control theory is applied. However, this method is not suitable for tracking channel variations due to the mobile speed, which is a crucial issue to be addressed for fading channels.

In this paper, we present a robust decentralized method for jointly performing channel estimation and close loop power control for the reverse link of CDMA networks. We base our approach on optimal control systems theory. The novelty of our approach is that while it aims at maintaining the SIR of each MS close to the SIR targets, its implementation does not rely on the actual calculation of the SIR. In other words, our approach takes *implicitly* into account the interference component of each signal but is not affected by a positive feedback. Another important feature of our proposed method is that it does not rely on any pilot or training sequence thus increasing the system capacity. The general structure of this algorithm is similar to the one already implemented in the IS95 system. It is therefore very easy to implement in practical systems. Finally, being an adaptive method, it allows taking into account fading characteristics of wireless channels. This adaptivity to the channel conditions is further improved by a multi step size approach, which allows compensating for deep fades. In order to achieve this, a quantized 3-bit PC command on the feedback (forward) channel is proposed. The paper is organized as follows: we first present the problem formulation and the general linear quadratic gain controller. Then, the channel estimation is addressed using a Kalman filter. Finally, simulations comparing the conventional IS95 power control device with our proposed scheme are presented.

2. Problem formulation

In this paper, we use the following notations and assumptions:

- $p_k(n)$ is the transmit power of mobile user k during the frame n.
- $\Gamma_k(n)$ is the squared absolute value of the average (over frame n) of the up-link channel gain (for user k).
- The spreading codes are long random sequences such that the cross correlations between users averaged over a frame are approximately $1/N$, where N is the spreading gain.
- σ^2 is the variance of the thermal noise process (modeled as a zero mean Gaussian random variable).
- $P_k(n) = p_k(n)\Gamma_k(n)$ is the power of the signal, received at the base station, after despreading for user k.

3. Perfect power control

Using the above notations, we can write the signal to interference (plus noise) ratio for user k over frame n:

$$SIR_k(n) = \frac{P_k(n)}{\frac{1}{N}\sum_{j\neq k} P_j(n) + \sigma^2}\,. \tag{1}$$

Assuming that perfect power control is feasible, we want to find $P_k(n)$ for every user k in the system which satisfies

$$SIR_k(n) = \beta\,, \tag{2}$$

where β is the SIR target, assumed to be identical for all users in the system (this condition can be relaxed).
This will be achieved when all user signals will be received with the same power denoted by P^* expressed as:

$$P^* = \frac{\beta\sigma^2}{1 - \frac{\beta(K-1)}{N}}\,, \tag{3}$$

where K is the total number of users in the system. In this paper, we perform power control so that the received powers for all users approach this optimal value P^*. Note that in order to obtain P^*, it is necessary that $1 - \frac{\beta(K-1)}{N}$ be positive which leads to the classical condition on the capacity:

$$K_{\max} < 1 + \frac{N}{\beta}\,. \tag{4}$$

As mentioned in the introduction, it is well known that this capacity limit must be ensured for the power control scheme implemented in IS95 to be stable. Our proposed method can be more flexible: when the call admission control momentarily allows more users than $K_{\max}$ in the system, our algorithm assumes that the capacity has reached its limit ($K = K_{\max}$) and this does not affect the stability of the system.

4. Robust power control formulation on the logarithmic scale

Let us denote by $w_k(n)$ the average over frame n of the power of the CDMA signal despread by the spreading sequence of user k. Then $w_k(n)$ is written as:

$$w_k(n) = P_k(n) + \frac{1}{N}\sum_{j\neq k} P_j(n) + \sigma^2 + v_k(n)\,. \tag{5}$$

Here, $v_k(n)$ is the measurement noise due to the limited number of samples involved in the average operation.
In the decentralized case, we do not have access to the received powers $P_j(n)$ for $j \neq k$. However, it is reasonable to assume that for each j we have:

$$P_j(n) = P^* + e_j(n)\,. \tag{6}$$

In other words, even though each user's signal is power controlled so that Eq. (3) is respected, the power control is not perfect and each user's signal is received with a power which differs from P^* by a value $e_j(n)$.
Therefore Eq. (5) can be rewritten as:

$$w_k(n) = P_k(n) + \frac{K}{N}P^* + \sigma^2 + v'_k(n)\,, \tag{7}$$

where $v'_k(n) = v_k(n) + \frac{1}{N}\sum_{j\neq k} e_j(n)$. Note that $\frac{K}{N}P^* + \sigma^2 = = \frac{1}{\beta}P^*$. Also, since $P_k(n) = P^* + e_k(n)$, we can write:

$$\begin{aligned} w_k(n) &= P_k(n) + \frac{1}{\beta}P^* + v'_k(n) = \\ &= \left(\frac{1}{\beta}+1\right)P_k(n) - \frac{1}{\beta}e_k(n) + v'_k(n) = \\ &= \left(\frac{1}{\beta}+1\right)P_k(n) + v''_k(n)\,, \end{aligned} \tag{8}$$

where $v''_k(n) = v'_k(n) - \frac{1}{\beta}e_k(n)$.

Let us recall that the usual IS95 power control algorithm is performed on a logarithmic scale. It would be thus useful to write this observation equation on a logarithmic scale. Let us denote by $X_{dB_k}(n)$ the value of $X_k(n)$ on the logarithmic scale, i.e. $X_{dB_k}(n) = 10\log_{10}(X_k(n))$.
We then have:

$$\begin{aligned} w_{dB_k}(n) &= 10\log_{10}\left(\frac{1}{\beta}+1\right)+ \\ &\quad +10\log_{10}\left(P_k(n)(1+\frac{v_k''(n)}{P_k(n)})\right) = \\ &= 10\log_{10}\left(\frac{1}{\beta}+1)+10\log_{10}(P_k(n)\right)+ \\ &\quad +10\log_{10}\left(1+\frac{v_k''(n)}{P_k(n)}\right) = \\ &= P_{dB_k}(n)+\lambda^2+\xi_k(n)\,, \end{aligned} \tag{9}$$

where $\lambda^2 = 10\log_{10}\left(\frac{1}{\beta}+1\right)$ and the measurement noise $\xi_k(n) = 10\log_{10}\left(1+\frac{v_k''(n)}{P_k(n)}\right)$.
We thus have the following observation equation on the logarithmic scale:

$$w_{dB_k}(n) = P_{dB_k}(n)+\lambda^2+\xi_k(n)\,. \tag{10}$$

Recall that the received power $P_{dB_k}(n)$ is in fact written as:

$$P_{dB_k}(n) = \Gamma_{dB_k}(n)+p_{dB_k}(n)\,, \tag{11}$$

where $\Gamma_{dB_k}(n)$ is the channel gain and $p_{dB_k}(n)$ the transmit power at frame n.
The aim of this paper is to properly adjust $p_{dB_k}(n)$ so that the SIR of each user is close to its target value (i.e. so that the receive power of each user is close to P^*). We propose to do so by deriving the infinite horizon linear quadratic Gaussian controller as detailed in the next section. More precisely, our aim is to design $u_k(n)$ such that:

$$p_{dB_k}(n+1) = p_{dB_k}(n)+u_k(n)\,. \tag{12}$$

5. The linear quadratic controller

From now on, for simplification, we will omit the subscripts k and dB, bearing in mind that all quantities are expressed in dBs and that each user performs the same operations in a decentralized way.
In this section, we assume that the channel gain $\Gamma(n)$ is exactly known to the base station. In the next section, we will explain how to estimate these quantities using the Kalman filter.
The aim of this section is to design the control command $u(n)$ in an LQG framework, i.e. which minimizes the following linear quadratic cost function:

$$J = E\{\lim_{N\to\infty}\sum_{n=0}^{N} q_c\|P(n)-P^*\|^2+r_c\|u(n)\|^2\}\,, \tag{13}$$

where q_c and r_c are quantities to be determined. This cost function is a weighted combination of the squared error between the received power and the optimum received power P^*, and the power of the control command $u(n)$. Indeed, while the ultimate aim is to meet the SIR requirements, it is also important to keep the control command as small as possible for implementation purposes. It is obvious that in some circumstances, imposing too much constraint on the control command will make it impossible to achieve the main objective (i.e. minimize $\|P(n)-P^*\|$). There is hence a trade off in the choice of the cost minimization weighting factors r_c and q_c. A discussion on the respective importance of these two parameters is provided in the next section.
It is well know that a static feedback law determined by the solution to an algebraic Ricatti equation (ARE) gives the solution to the minimization of the cost function J.
In other words, the optimal control $u(n)$ is given by:

$$u(n) = K^pP(n)+K^rP^*, \tag{14}$$

where

$$K^p = -(P^{(1)}+r_c)^{-1}P^{(1)} \tag{15}$$

$$K^r = -(P^{(1)}+r_c)^{-1}P^{(2)} \tag{16}$$

with $P^{(1)}$ given by the solution to the ARE:

$$P^{(1)} = P^{(1)}-P^{(1)}(P^{(1)}+r_c)^{-1}P^{(1)}+q_c \tag{17}$$

and $P^{(2)}$ obtained by:

$$\begin{aligned} P^{(2)} &= \frac{q_c}{K^p} = \\ &= -\frac{q_c(P^{(1)}+r_c)}{P^{(1)}}\,. \end{aligned} \tag{18}$$

One can easily see that

$$K^r = \frac{q_c}{P^{(1)}} = -K^p \tag{19}$$

and that

$$P^{(1)} = \frac{1+\sqrt{1+4r_c}}{2}\,. \tag{20}$$

Finally, the command $u(n)$ is computed as

$$\begin{aligned} u(n) &= K^p(P(n)-P^*) = \\ &= -K^r(p(n)+\Gamma(n)-P^*)\,. \end{aligned} \tag{21}$$

As mentioned previously, the control command $u(n)$ depends on the channel gain $\Gamma(n)$ which is usually not known at the base station. In the next section, we show how to estimate this quantity using the Kalman filter.

6. Kalman filtering estimation of the channel gain

Recall that the observation process on the logarithmic scale is written as:

$$w(n) = p(n) + \Gamma(n) + \lambda^2 + \xi(n), \tag{22}$$

where the transmit power $p(n)$ given by

$$p(n) = p(n-1) - K^r(p(n-1) + \Gamma(n-1) - P^*) \tag{23}$$

is known to the receiver.
In this section, we assume that due to the Doppler effects, the channel coefficients are correlated in time. We therefore model the (unknown) channel gain on the logarithmic scale as an auto regressive (AR) process as:

$$\Gamma(n) = \left[\Gamma(n-1)\ \Gamma(n-2)\ \cdots\ \Gamma(n-L)\right]\mathbf{h} + b(n), \tag{24}$$

where $\mathbf{h} = [h_1\ h_2\ \cdots\ h_L]^T$ is supposed to be known at the base station. A method for estimating these coefficients in conjunction with the method presented in this paper can be found in [13].
Using this time dependency, we can easily write a state equation for vector $\underline{\Gamma}(n) = [\Gamma(n)\ \Gamma(n-1)\ \cdots \Gamma(n-L+1)]$ as follows:

$$\underline{\Gamma}(n) = A\underline{\Gamma}(n-1) + [b(n)\ 0\ \cdots\ 0]^T, \tag{25}$$

where

$$A = \begin{bmatrix} h_1 & h_2 & \cdots & h_L \\ 1 & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ 0 & \cdots & 1 & 0 \end{bmatrix}. \tag{26}$$

The observation Eq. (22) can be written as a function of the model state $\underline{\Gamma}(n)$ as:

$$w(n) = C\underline{\Gamma}(n) + p(n) + \lambda^2 + \xi(n) \tag{27}$$

with $C = [1\ 0\ \cdots 0]$.

Using Eqs. (25) and (27), we can easily derive the Kalman filter estimate of state $\underline{\Gamma}(n)$, i.e. $\hat{\underline{\Gamma}}(n|n)$:

$$\hat{\underline{\Gamma}}(n|n) = \mathcal{F}A\hat{\underline{\Gamma}}(n-1|n-1) + M(w(n) - p(n) - \lambda^2), \tag{28}$$

where $\mathcal{F} = I - MC$. The filter gain M is given by:

$$M = \Sigma C^T (C\Sigma C^T + R_0)^{-1} \tag{29}$$

and Σ is obtained by solving the Ricatti equation:

$$\Sigma = A(\Sigma - \Sigma C^T (C\Sigma C^T + R_0)^{-1} C\Sigma)A^T + Q_0, \tag{30}$$

where $R_0 = cov(b(n))$ and $Q_0 = cov(\xi(n))$.

7. The proposed PC algorithm

Let us recall the major steps involved in our proposed method. At frame n:

1. Evaluate $w(n)$, the logarithm of the average over the frame of the users' signal power.
2. Compute the Kalman filtering estimation of channel gain state $\Gamma(n)$ using Eq. (28).
3. Using the Kalman estimate of the channel gain for frame n, compute $u(n+1)$, the control command for next frame using the LQG controller (Eq. (21)).
4. Quantize and encode the control command and transmit the control bits on the feedback channel.
5. At the mobile station, upon reception of the control command bits, compute the transmit power $p(n+1)$ using Eq. (12).

8. Numerical issues

We have seen that the scheme derived in the previous sections depends on the 4 following parameters: r_c and q_c for the LQG controller and R_0 and Q_0 for the Kalman filter. In this section, we provide a preliminary discussion on the choice of these parameters. A more exhaustive study is left for future work.

Choice of q_c. In the particular framework we deal with in this paper, there is no other constraint on q_c than $q_c > 0$. In fact, what really matters is the ratio between q_c and r_c. Therefore, we will assume that $q_c = 1$ and emphasize on the choice of r_c.

Choice of r_c. It is well known that by taking r_c close to zero, the LQG performs a *loop transfer recovery*. In this case, it can be shown that the LQG behaves like a Kalman filter predictor. The advantage of loop transfer recovery is that we do know its good robustness property to modelization errors. While this is desirable, the drawback is that there is no constraint on the amplitude of the control command $u(n)$ (the controller only minimizes the variance of the receive power). In the case of power control, it is important to keep $u(n)$ as small as possible. Indeed, errors can occur during the transmission of the control bits on the feedback channel (these bits are not protected by any error control scheme). Therefore, by keeping $u(n)$ as small as possible, this also ensures that if an error occurs on the control command bits, this error will also be small. Another determining factor in the choice of r_c is the velocity of the mobile: indeed, for high speeds, deep fades are likely to occur. Therefore, $u(n)$ needs to be big enough to properly track those fades. To summarize, r_c must be chosen as small as possible consistent with limiting the control action. An analytical study is needed in order to properly determine this parameter.

Choice of Q_0. By definition, $Q_0 = var(\xi(n))$ where $\xi(n)$ is the measurement noise. Clearly, $\xi(n)$ depends on the number of users in the system.

Choice of R_0. R_0 is by definition the variance of the input noise to the state model. This parameter in fact depends on the velocity of the mobile: for large speeds, R_0 is large and vice versa. The choice of R_0 is important for the tracking performance of the Kalman filter: if chosen too small, the Kalman estimate is not able to track the variations of the channel. On the other hand, if chosen to large, the Kalman estimate will be too noisy. However, with R_0 depending only on the mobile velocity, it is possible to derive it (this is not addressed in the paper and is left for future work). An interesting point is that this parameter will help determining analytically r_c which also depends on the mobile speed.

9. Simulation results

We developed a simulation environment corresponding to the proposed UMTS guidelines. For simplicity we assigned a single up-link channel per user at a continuous data rate of 60 kbit/s (uncoded). All users' signals passed through a fast fading Rayleigh channel. The Rayleigh fading channel was computed using the Jakes method [14]. Table 1 shows the simulation parameters. We used 3-bit quantized PC commands and optimized step sizes for both our proposed method and the IS95 power control device.

Table 1
Simulation parameters

Parameter	Value
PC command rate	1 500 Hz
Frame length	10 ms
Slots per frame	15
Channel bandwidth	5 MHz
Chip rate	3.84 Mc/s
Processing gain	64
Data rate (uncoded)	60 kbit/s
Filter length	10

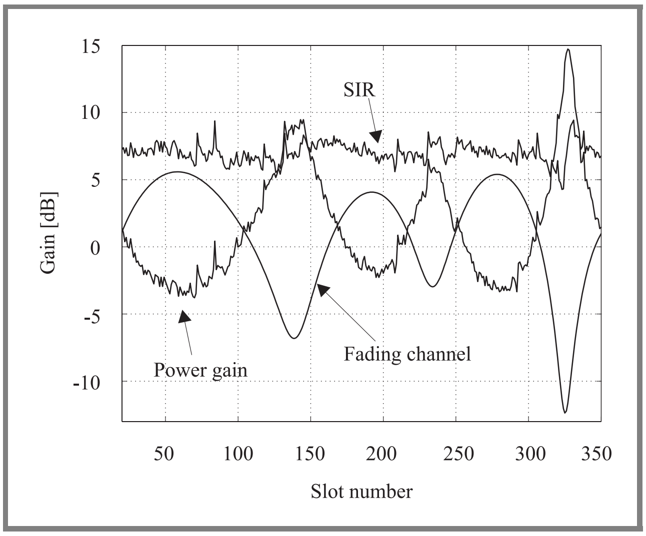

Fig. 1. Transmit power and channel gain variations.

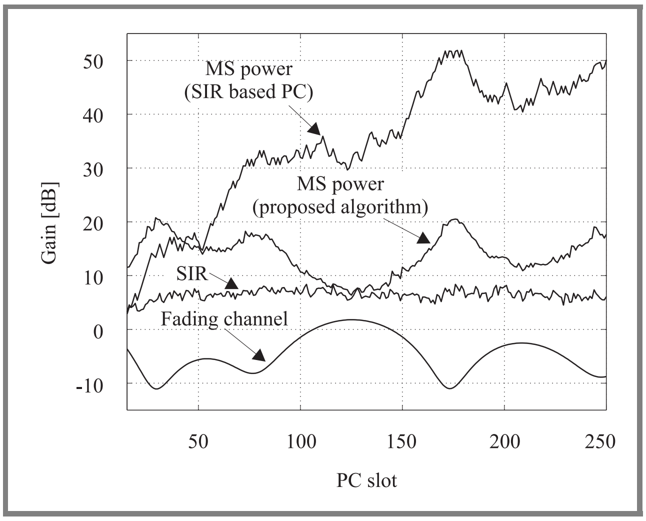

Fig. 2. Example of power escalation – power escalation in SIR based power control.

In Fig. 1, we show how the transmit power, derived with our proposed scheme, follows the variations of the channel.

Figure 2 highlights the main advantage of our proposed scheme as compared to the IS95 power control device: our proposed approach is not subject to positive feedback, which occurs when all users in the system unnecessarily increase their transmit power. Given the spreading gain of 64 and the SIR target of 7 dB, one can easily see that the maximum number of users allowed in the system is 14. In our simulation, the number of users was set to $K = 13$. Therefore, we operated just under the capacity limit. One can see that the IS95 power control device is subject to instability from frame number 50. One can see that even though the capacity limit is not exceeded, the transmit power is unnecessarily high, compared to our scheme.

In Fig. 3, we show that the performance of our scheme in terms of bit error rate (BER) is slightly better than the IS95 performance. In this simulation, the number of users was set to 10 (which eliminates the power escalation issue of the IS95 scheme) and we assumed that the SIR has been estimated using the technique in [7]. It is important to recall the fact that SIR based power control techniques outperform signal strength based schemes. Our scheme, even though based on signal strength, implicitly takes into account the interference component. This explains why, even though based on signal strength, it does not perform badly compared to SIR based methods. The fact that it actually performs better than IS95 is due to the fact that the SIR estimate used in the IS95 scheme does

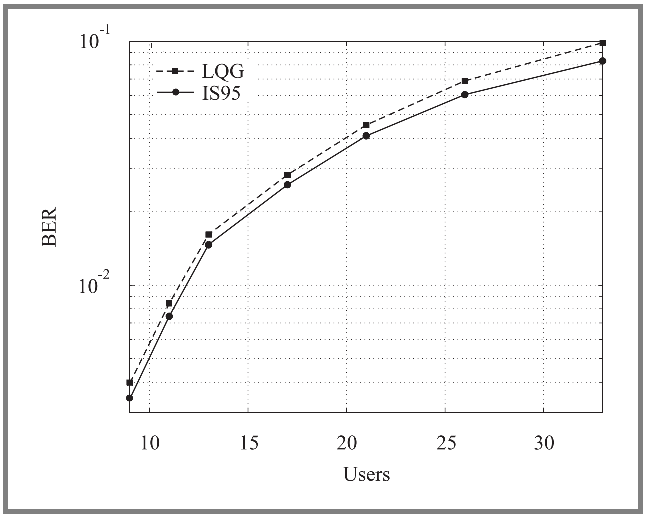

Fig. 3. Bit error rate versus users.

not match exactly the actual SIR. Also, since the Kalman filter estimate takes explicitly into account the channel gain dynamics, the control commands showed better tracking performance, especially in deep fade situations.

10. Conclusion

In this paper, we have proposed a new scheme for power control in a CDMA system, based on a linear quadratic Gaussian controller and using Kalman filtering for channel estimation purposes. The main feature of this method is that it ensures that the SIR requirements for each user are met without the usual drawback of SIR based power control techniques, i.e. positive feedback. Our method does not require any SIR estimation, which is usually difficult to accurately perform without training or pilot symbols. Essentially based on signal strength, it implicitly takes into account the interference component of the signal, without any knowledge of the other users' signal strength and without any training sequence for estimation purposes. Simulations show that this method provides a better performance than SIR based techniques, without the risk of power escalation, which can occur in IS95 based systems when approaching the capacity limit. We have shown in this paper that our method relies on a set of parameters that are crucial for the robustness and the tracking abilities of the Kalman filter estimate and the controller. We have qualitatively discussed the choice of these key parameters. However, further analytical work is needed in order to clarify how they should be expressed as a function of the mobile velocity.

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References

[1] J. G. Proakis, *Digital Communications*. McGraw-Hill, 1995, 3 ed.

[2] A. J. Viterbi, *CDMA: Principles of Spread Spectrum Communications*. Addison-Wesley, 1995.

[3] S. Nourizadeh, P. Taaghol, and R. Tafazolli, "A novel closed loop power control for UMTS", in *First Int. Conf. 3G Mob. Commun. Technol.*, 2000, pp. 56–59.

[4] F. Ye, Q. T. Zhang, and C. C. Ko, "A simple adaptive up-link power control algorithm for DS/CDMA system", in *IEEE/AFCEA EUROCOMM'2000, Inform. Syst. Enhan. Publ. Saf. Secur.*, 2000, pp. 16–19.

[5] F. C. M. Lau and W. M. Tam, "Novel predictive power control in a CDMA mobile radio system", in *IEEE 51st Veh. Technol. Conf. Proc.*, 2000, vol. 3, pp. 1950–1954.

[6] S. Gunaratne, S. Nourizadeh, T. Jeans, and R. Tafazoli, "Performance of SIR-based power control for UMTS", in *Second Int. Conf. 3G Mob. Commun. Technol.*, 2001, pp. 16–20.

[7] A. Kurniawan, "SIR-estimation in CDMA systems using auxiliary spreading sequence", *Mag. Electr. Eng.*, vol. 5, no. 2, pp. 9–18, 1999.

[8] H. Holma and A. Toskala, Eds., *WCDMA for UTMS*. Wiley, 2001.

[9] D. Zhang, Q. T. Zhang, and C. C. Ko, "A novel joint strength and SIR based CDMA reverse link power control with variable target SIR", in *IEEE Int. Conf. Commun.*, 2000, vol. 3, pp. 1502–1505.

[10] S. Ratanamahatana and H. M. Kwon, "Channel estimation for power controlled 3G CDMA", in *IEEE 51st Veh. Technol. Conf. Proc.*, 2000, vol. 3, pp. 2429–2433.

[11] L. Qian and Z. Gajic, "Joint optimization of mobile transmission power and SIR error in CDMA systems", in *Proc. 2001 Am. Contr. Conf.*, 2001, vol. 5, pp. 3767–3772.

[12] L. Qian and Z. Gajic, "Variance minimization stochastic power control in CDMA systems", in *IEEE Int. Conf. Commun.*, 2002, vol. 3, pp. 1763–1767.

[13] S. Perreau, M. Anderson, and L. White, "Adaptive power control for CDMA systems using linear quadratic Gaussian control", in *Thirty Sixth Asil. Conf. Sig., Syst. & Comput.*, Nov. 2002.

[14] W. C. Jakes, Ed., *Microwave Mobile Communications*. IEEE Press, 1994.

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