

Robust H_∞ Power Control for CDMA Systems in User-Centric and Network-Centric Manners

Nan Zhao, Zhilu Wu, Yaqin Zhao, and Taifan Quan

In this paper, we present a robust H_∞ distributed power control scheme for wireless CDMA communication systems. The proposed scheme is obtained by optimizing an objective function consisting of the user's performance degradation and the network interference, and it enables a user to address various user-centric and network-centric objectives by updating power in either a greedy or energy efficient manner. The control law is fully distributed in the sense that only its own channel variation needs to be estimated for each user. The proposed scheme is robust to channel fading due to the immediate decision of the power allocation of the next time step based on the estimations from the H_∞ filter. Simulation results demonstrate the robustness of the scheme to the uncertainties of the channel and the excellent performance and versatility of the scheme with users adapting transmit power either in a user-centric or a network-centric efficient manner.

Keywords: CDMA, power control, distributed algorithms, H_∞ filter, robustness.

I. Introduction

Power control has been extensively studied in recent years, especially for wireless code division multiple access (CDMA) communication systems. It has mainly been used to reduce co-channel interference and to guarantee the signal-to-interference ratio (SIR) of ongoing connections, resulting in a better quality of service (QoS). From the viewpoint of practical applications, distributed power control schemes are of special interest and importance. One of the most well-known distributed algorithms was originally proposed in [1], and has been further studied and expanded upon in a number of works [2]-[7]. The power control schemes in these works may be deemed greedy or user-centric in that a user updates its own transmit power with the sole purpose of maintaining a target QoS metric during communication.

Achieving satisfactory QoS is important for users, and it benefits the user-centric objective; however, users may not be willing to achieve it at arbitrarily high power levels, because power is itself a valuable commodity. Cutting power consumption not only prolongs the life of the battery and alleviates health concerns about electromagnetic emission but also decreases the interference to other users in the network. In addition, different users may have different views of power consumption. For example, a handset user is more concerned about the power than a user with a vehicle-mounted device. Recent works [8]-[12] have focused on devising utility-based policies which allow users to consider multiple objectives rather than a sole QoS metric. The algorithm of [8] reformulated the problem using a softened SIR requirement and adding a penalty on power consumption. In [9], a joint network- and user-resource control as a form of a Stackelberg game was proposed. In this scheme, the network decides the

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unit price, and users decide the transmitter power according to the price. In [10], a distributed utility maximization power control scheme was solved by Lagrangian dual decomposition. In [11], a distributed approach for solving the multiobjective power optimization problem was presented, and the obtained solution is parameterized so that a tradeoff can be made between power consumption and QoS. However, it is not suitable and lacks robustness when channel fading is severe. An estimator-based distributed power control algorithm was presented in [12] which can adapt power in either a greedy or energy efficient manner; nevertheless, its power updating equation is very complex for practical use.

Traditional power control schemes using power iterations [1]-[4], [11] are not appropriate to compensate Rayleigh channel fading, because all the schemes require a rather long time to converge. Usually, they assume that the link gains and fading conditions are not changed much during the whole power control period. Therefore, filtering techniques which can estimate interference have been used in power control to combat channel fading. Leung [13] and Leung and Wang [14] used the Kalman filter to predict interference, assuming that the interference signal and its measurements are corrupted by additive white Gaussian noise (AWGN) in a TDMA system. Having obtained the predicted value for the interference, they used a simple scheme based on the defining formula for the SIR for mobile power updates. In [15], dynamic channel and power allocation algorithms using the Kalman filter were developed to provide predicted measurements for both gains and interference under the assumption that they are corrupted by AWGN. These power control schemes using the Kalman filter are effective only if the fluctuation of channel variation and the measurement noise are Gaussian distributed. However, in general the fluctuation of channel variation is not Gaussian distributed. Thus, a more appropriate choice is the H_∞ filter [16]-[18]. In contrast to the Kalman filter, the H_∞ filter considers the system filtering regardless of the nature of the system and measurement disturbances, as long as the power of the disturbance is bounded [19], [20].

In this paper, we propose a simple estimator-based distributed power control scheme employing the H_∞ filter, which can act in either a user-centric or network-centric manner depending on a user's application and the network dynamics. The remainder of this paper is organized in four sections. In section II, the system model of the CDMA wireless communication system is introduced, and some preliminaries about power control are also reviewed. In section III, the estimator-based distributed power control scheme considering both user-centric and network-centric objectives is proposed and analyzed. In section IV, the H_∞ filter is introduced and applied to the proposed power control scheme as an estimator.

Section V provides simulation results which demonstrate the effectiveness and efficiency of the proposed power control scheme with the H_∞ filter. The various approaches of the scheme are also illustrated in the uplink of a wireless CDMA communication system with users having heterogeneous service requirements.

II. System Model

In a cellular wireless network, a certain QoS should be maintained for all active users. The SIR is a quantity that measures a user's QoS. Consider the uplink (mobile to base) power control problem with N active users in a wireless CDMA communication system, and the SIR of an active link from mobile station i (user i) to base station n defined by

$$\gamma_{ni}(k) = \frac{Lg_{ni}P_i(k)}{\sum_{j=1, j \neq i}^N g_{nj}P_j(k) + \sigma^2}, \quad i = 1, 2, \dots, N, \quad (1)$$

where $P_i(k)$ is the transmission power for mobile station i at discrete-time instant k , g_{nj} is the link gain from mobile station j to base station n , and σ^2 is the background noise at the base station n . Assuming that a mobile only transmits to one base station during the time of power control, $\gamma_{ni}(k)$ can be simplified as $\gamma_i(k)$. Here, L is the processing gain in spread spectrum wireless systems. That is, in CDMA 2000, $L=64, 128, \text{ or } 256$. Let us denote the denominator in (1) by I_i , which represents the received interference plus the background noise. Then, the SIR described in (1) can be rewritten as

$$\gamma_i(k) = \frac{Lg_{ni}P_i(k)}{I_i(k)}, \quad i = 1, 2, \dots, N. \quad (2)$$

Let

$$\delta_i(k) = \frac{Lg_{ni}}{I_i(k)}, \quad i = 1, 2, \dots, N, \quad (3)$$

where $\delta_i(k)$ denotes the channel variation (introduced in [21]), and it will be estimated by the H_∞ filter in the proposed power control scheme.

The goal of traditional power control schemes [2]-[7] is that every mobile should achieve the value of its own SIR above a certain target value. That is,

$$\gamma_i \geq \gamma_i^{\text{tar}}, \quad i = 1, 2, \dots, N. \quad (4)$$

It is a greedy or user-centric approach, and may cause arbitrarily high energy consumption. Although there is a distributed constrained power control (DCPC) which can constrain the transmit power to be less than a certain maximum [4], it may also cause severe performance degradation.

III. Utility-Based Distributed Power Control

1. User-Centric and Network-Centric Objectives

Within the problem of distributed power control, a user's user-centric objectives are defined as benefits that a user may seek in disregard of other network users. Conversely, a user's network-centric objectives are defined as benefits experienced by other network users, or the network as a whole, due to the user's actions [8], [9].

To achieve user-centric objectives, the greedy approach can be adopted. It updates the user's transmit power according to channel states with the goal of maintaining the SIR value above a target SIR threshold. A user may be best suited to use the strategy when supporting an application which has a continuous stream of delay sensitive traffic, such as voice-based applications. To achieve network-centric objectives, the energy efficient approach can be adopted. It updates the user's transmit power relative to the channel state and the special application. In other words, a user would increase transmit power during good channel conditions, and decrease power for poor channel conditions or with a delay insensitive application, such as data-based applications and applications in a vehicle-mounted device.

2. Proposed Algorithm

The SIR error of user i is defined by

$$E_i(k) = \gamma_i^{\text{tar}} - \gamma_i(k), \quad (5)$$

which may be viewed as a user-centric metric since it represents the deviation between the user's target QoS of γ_i^{tar} and the received QoS of $\gamma_i(k)$ at time k . A user's adaptation of transmit power so as to minimize its SIR deviation is perceived as an action which only benefits that user. On the contrary, a user's transmit power may be viewed as a network-centric metric since the higher the power is, the more it contributes to the interference introduced into the network by that user. Thus, a user's adaptation of transmit power so as to reduce interference introduced by itself shall be interpreted as an action which benefits other network users, or equivalently, the network. Accordingly, we propose a performance criterion of user i as

$$J_i(k) = E_i^2(k+1) + a_i P_i^2(k+1), \quad (6)$$

which considers both the user-centric objective and the network-centric objective. The nonnegative a_i in (6) defines the difference in the levels of importance of the user-centric metric and network-centric metric. For different applications, different a_i may be chosen. Only the user-centric metric is concerned when $a_i=0$. Conversely, a network-centric metric is addressed

by regulating the amount of interference introduced into the network by user i when $a_i > 0$.

Suppose that the transmit power of user i can be updated according to the following distributive linear control law:

$$P_i(k+1) = P_i(k) + u_i(k), \quad i = 1, 2, \dots, N, \quad (7)$$

where the control variable $u_i(k)$ has to be chosen as the one which can minimize the cost function described as (6).

Applying the necessary conditions for the Nash equilibrium [22], we have

$$\begin{aligned} \frac{\partial J_i(k)}{\partial u_i(k)} &= \frac{\partial \left(a_i (P_i(k) + u_i(k))^2 + (\gamma_i^{\text{tar}} - \gamma_i(k+1))^2 \right)}{\partial u_i(k)} \\ &= 2a_i (P_i(k) + u_i(k)) + \frac{\partial (\gamma_i^{\text{tar}} - \delta_i(k+1)P_i(k+1))^2}{\partial u_i(k)} \\ &= 2a_i (P_i(k) + u_i(k)) + \frac{\partial (\gamma_i^{\text{tar}} - \delta_i(k+1)(P_i(k) + u_i(k)))^2}{\partial u_i(k)} \\ &= 2a_i (P_i(k) + u_i(k)) - 2\delta_i(k+1)(\gamma_i^{\text{tar}} - \delta_i(k+1)(P_i(k) + u_i(k))) \\ &= 0, \end{aligned} \quad (8)$$

and from (8), we obtain

$$u_i^{\text{opt}}(k) = -P_i(k) + \frac{\gamma_i^{\text{tar}}}{\frac{a_i}{\delta_i(k+1)} + \delta_i(k+1)}, \quad (9)$$

which is the optimal value of $u_i(k)$ that can minimize the value of the criterion described in (6).

Taking the second derivative, we obtain

$$\frac{\partial^2 J_i(k)}{\partial^2 u_i(k)} = 2\delta_i^2(k+1) + 2a_i > 0, \quad (10)$$

which confirms the globality of the minimum. Thus, the corresponding optimized power updating function is given by

$$\begin{aligned} P_i(k+1) &= P_i(k) + u_i^{\text{opt}}(k) \\ &= \frac{\gamma_i^{\text{tar}}}{\frac{a_i}{\delta_i(k+1)} + \delta_i(k+1)}, \end{aligned} \quad (11)$$

where $\delta_i(k+1)$ should be estimated at every time instant so that it can adapt the transmit power instantaneously.

An important assumption behind the power iterative algorithms in [1]-[6] is that power updates occur quickly enough and the link gains can be assumed to be fixed. On the contrary, our power control scheme is not an iterative algorithm. The assumption that the link gains do not change during power evolution is not required in the proposed scheme. However, the proposed power control scheme is suitable for the situations of fast channel fading due to the immediate decision of the

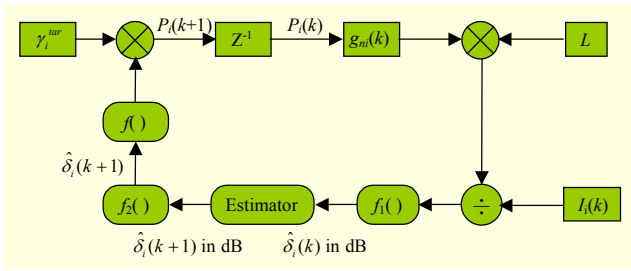


Fig. 1. Proposed distributed power control scheme with an estimator.

optimal power allocation of the next time step based on the predictions of the channel variation $\delta_i(k+1)$ at the next time instant $k+1$. With a good estimator (namely, the discrete-time H_∞ filter), all the effects, including path loss, shadow fading, and Rayleigh fading, are taken into consideration, and the proposed scheme would achieve much better performance than iterative schemes. The algorithm in [7] is also based on an estimator and is suitable for situations of fast channel fading. However, it only considers user-centric objectives, and it does not consider network-centric objectives. Our proposed algorithm considers both user-centric and network-centric objectives.

A block diagram of the proposed power control scheme with an estimator is shown in Fig. 1. We define $f(\cdot)$ as

$$f(x) = \frac{1}{\frac{a_i}{x} + x}, \quad (12)$$

and $f_1(x) = 10 \log_{10}(x)$ and $f_2(x) = 10^{x/10}$ are converting functions between W and dBW.

As seen in Fig. 1, the performance of the estimator has a direct impact on the performance of the power control scheme. Here, $\hat{\delta}_i(k+1)$ denotes the estimated value of $\delta_i(k+1)$, and the power updating function of (11) can be reformed as

$$P_i(k+1) = \frac{\gamma_i^{\text{tar}}}{\frac{a_i}{\hat{\delta}_i(k+1)} + \hat{\delta}_i(k+1)}. \quad (13)$$

IV. H_∞ Filter as an Estimator

The celebrated Kalman filter has been widely used in noise signal processing to estimate system states using past measurements. It is based mainly on the minimization of the L_2 -norm of the corresponding estimation error. This type of estimation assumes that the message generating process has a known dynamic and that the exogenous inputs have known statistical properties. The Kalman filter offers an optimal filtering algorithm when the system model parameters are known and the system and measurement noise is represented by white Gaussian processes with known statistics (power

spectral density). However, these assumptions may limit the application of the Kalman filter as an estimator since in many situations, only approximate signal models are available and/or the statistics of the noise sources are not white Gaussian or are even unavailable. Moreover, the Kalman estimator may not be robust against parameter uncertainty of the signal models.

In contrast to Kalman filter, the H_∞ filter considers the system filtering regardless of the nature of the system and measurement disturbances, as long as the power of the disturbance is bounded [19], [20].

In the proposed power control scheme, $\delta_i(k+1)$ must be estimated. The fluctuations of $\delta_i(k+1)$ do not have normal distributions in general. Hence, the Kalman filter is not appropriate for the problem under consideration. The H_∞ filter, however, does not require any knowledge of the statistics of system and measurement disturbances, which makes the H_∞ filter an appropriate estimator for the proposed power control scheme.

The dynamics of δ_i (in dB) is described by

$$\delta_i(k+1) = \delta_i(k) + \omega_i(k), \quad (14)$$

where $\omega_i(k)$ represents the process noise (disturbance). Let $y_i(k)$ be the measurement of $\delta_i(k)$:

$$y_i(k) = \delta_i(k) + v_i(k), \quad (15)$$

where $v_i(k)$ is the measurement noise. Due to the scalar nature of the problem, it is obvious that the system controllability and observability conditions are met. These conditions are needed for the existence of the appropriate solution of the algebraic Riccati equation.

The measurement of the H_∞ filter is given by

$$\sup_{Q_i, W_i, V_i} \frac{\sum_{k=0}^{N-1} \|\delta_i(k) - \hat{\delta}_i(k)\|_{Q_i}^2}{\|\delta_i(0) - \hat{\delta}_i(0)\|_{R_i^{-1}(0)}^2 + \sum_{k=0}^{N-1} \{\|\omega(k)\|_{W_i^{-1}}^2 + \|v(k)\|_{V_i^{-1}}^2\}} < \frac{1}{\lambda}, \quad (16)$$

where Q_i , W_i , and V_i are positive weighting parameters chosen by the designer, and λ is a prescribed level of noise attenuation. The discrete-time H_∞ filter is given by

$$\hat{\delta}_i(k+1) = \hat{\delta}_i(k) + K_i(k)(y_i(k) - \hat{\delta}_i(k)), \quad (17)$$

where $K_i(k)$ is the optimal gain of the H_∞ filter. It is computed by

$$K_i(k) = R_i(k) \left(I - \lambda Q_i R_i(k) + V_i^{-1}(k) R_i(k) \right)^{-1} V_i^{-1}(k). \quad (18)$$

Since, in our problem, $R_i(k)$, Q_i , and V_i are all scalars, the gain in (18) can be found as

$$K_i(k) = \frac{R_i(k)}{\left(1 - \lambda Q_i R_i(k) + \frac{R_i(k)}{V_i} \right) V_i}, \quad (19)$$

where $R_i(k)$ is the unique positive solution of the following scalar difference Riccati equation:

$$R_i(k+1) = R_i(k) \left(I - \lambda Q_i R_i(k) + V_i^{-1}(k) R_i(k) \right)^{-1} + W_i. \quad (20)$$

Again, since $R_i(k)$, Q_i , W_i , and V_i are all scalars, (20) can be written as

$$R_i(k+1) = \frac{R_i(k)}{1 - \lambda Q_i R_i(k) + \frac{R_i(k)}{V_i}} + W_i. \quad (21)$$

The initial condition of the system is $\delta_i(0) = \delta_{i0}$. The initial condition of the H_∞ filter is $R_i(0) = R_{i0}$. These initial conditions are arbitrary positive quantities. It can be shown that the steady-state value of $R_i(k)$ satisfies

$$R_{i,ss} = \frac{W_i \left(\frac{1}{V_i} - \lambda Q_i \right) \pm \sqrt{\left(W_i \left(\frac{1}{V_i} - \lambda Q_i \right) \right)^2 + 4W_i \left(\frac{1}{V_i} - \lambda Q_i \right)}}{2 \left(\frac{1}{V_i} - \lambda Q_i \right)}. \quad (22)$$

Only the positive value is the steady-state solution of $R_i(k)$. It is obvious that the choice of the optimization parameters λ , Q_i , W_i , and V_i has an impact on the filter performance. In this paper, they are set as $Q_i=20$, $W_i=1$, $V_i=0.1$, and λ can be 0.2, 0.1, or 0.01. In addition, δ_{i0} and R_{i0} are positive random numbers using random number generators.

V. Simulation Results and Discussion

In this section, several simulations in a wireless one-cell CDMA communication system are presented to demonstrate effectiveness and efficiency of the proposed distributed power control scheme. A hexagonal cell with a diameter of 2 km is considered with a base station centered at the origin and mobile locations which are chosen randomly from a uniform distribution. Background receiver noise power within the user's bandwidth of $\sigma_i^2=0.05$ mW is used in the simulations. It is assumed that the link gains have the following form:

$$g_{ni}(k) = d_{ni}^{-4}(k) S_{ni}(k), \quad (23)$$

where $d_m(k)$ is the distance from mobile station i to base station n at time instant k , and S_{ni} is a log-normal distributed stochastic process with its standard deviation of 8 dB. The processing gain L is set to 128, and $SIR_i^{\text{tar}}=5$ for all users. A maximum transmit power level of $P^{\text{max}}=500$ mW is set, and initially each user will transmit with a power level of $P_i(0)=P^{\text{min}}=0$ mW.

A widely known and accepted power control scheme called DCPC [4] is given by

$$P_i(k+1) = \min \left\{ \frac{\gamma_i^{\text{tar}}}{\gamma_i(k)} P_i(k), P^{\text{max}} \right\}, \quad (24)$$

and we use it as a traditional iterative power control scheme to compare with our proposed estimator-based scheme.

We also consider the Nash game power control scheme proposed in [6] for comparison in the simulation. The iterative function of the scheme is given by

$$P_i(k+1) = \begin{cases} \gamma_i^{\text{tar}} \left(\frac{P_i(k)}{\gamma_i(k)} \right) - \frac{b_i}{2c_i} \left(\frac{P_i(k)}{\gamma_i(k)} \right)^2, & \text{if positive,} \\ 0, & \text{otherwise.} \end{cases} \quad (25)$$

In the simulation, $b_i/(2c_i)$ is set 2.5.

First, the performance of the proposed power control scheme with $a_i=0$ (user-centric manner), the Nash game scheme, and DCPC are compared and analyzed ignoring the stochastic detriments giving rise to measurement noise and channel fading in a cell of 20 users. In this case, the channel fading only depends on the distance from the mobile station to the base station, and it can be expressed as

$$g_{ni}(k) = d_{ni}^{-4}(k). \quad (26)$$

As seen in Figs. 2 and 3, both the average SIR and the average transmit power of the proposed scheme converge much more quickly than those of the DCPC scheme. In particular, the larger λ is, the faster the proposed scheme converges. The Nash game scheme converges faster than the proposed scheme with $\lambda=0.1$ but much more slowly than the proposed scheme with $\lambda=0.2$. The DCPC scheme and the Nash game scheme, as iterative algorithms, converge rather slowly, and it takes more than 10 steps to get close to the target SIR. However, as the H_∞ filter is applied, the proposed scheme

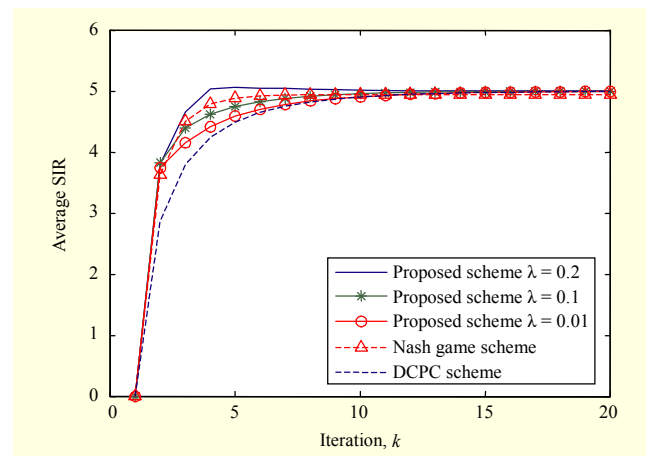


Fig. 2. Comparison of the average SIR of the proposed scheme with various λ values, the Nash game scheme, and DCPC scheme without channel fading.

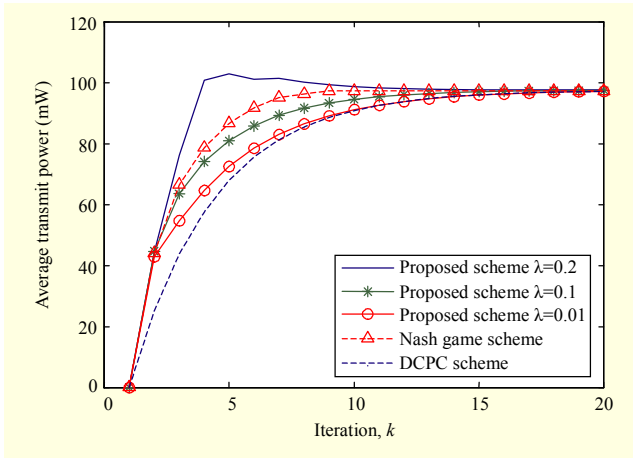


Fig. 3. Comparison of average transmit power of the proposed scheme with various λ values, the Nash game scheme, and the DCPC scheme without channel fading.

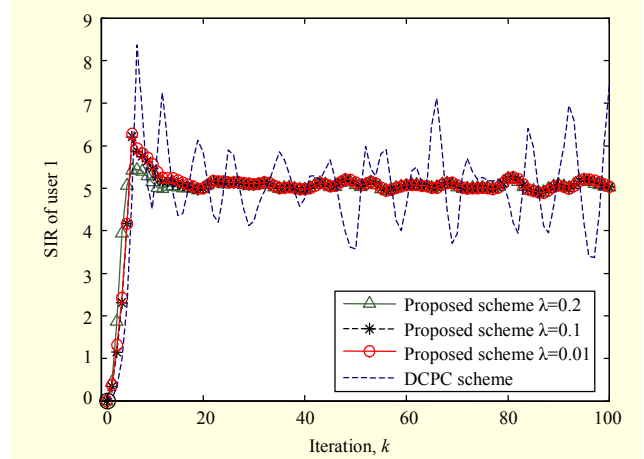


Fig. 6. Comparison of SIR of a single user of the proposed scheme with various λ values and the DCPC scheme with severe channel fading.

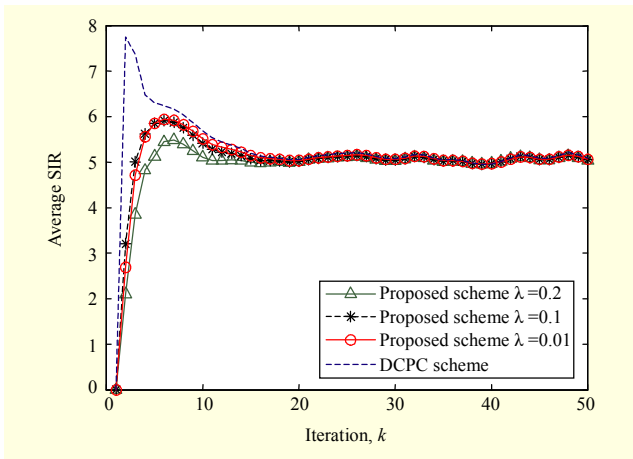


Fig. 4. Comparison of average SIR of the proposed scheme with various λ values and the DCPC scheme with severe channel fading.

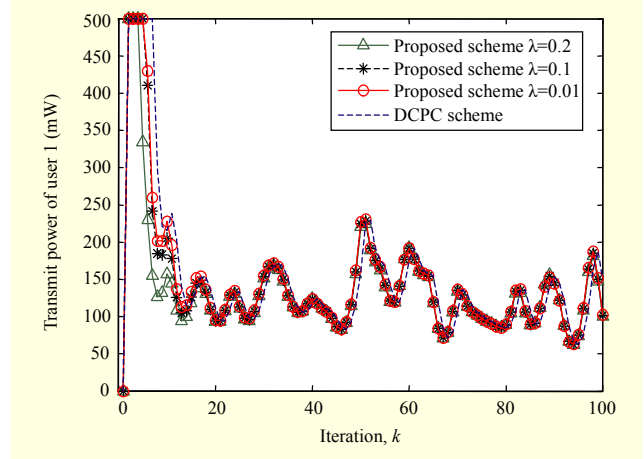


Fig. 7. Comparison of transmit power of a single user of the proposed scheme with various λ values and the DCPC scheme with severe channel fading.

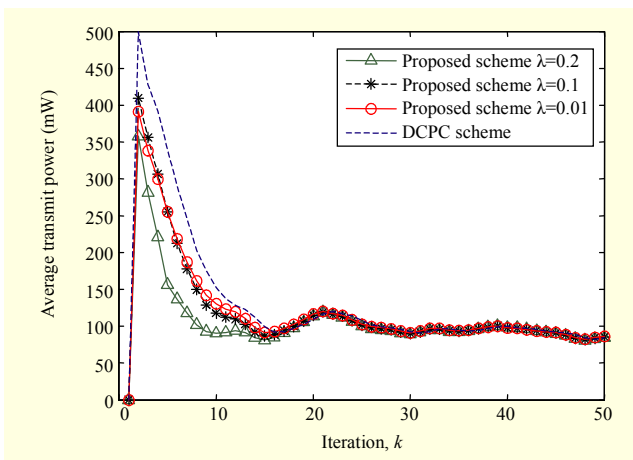


Fig. 5. Comparison of average transmit power of the proposed scheme with various λ values and the DCPC scheme with severe channel fading.

adapts the transmit power instantaneously. It merely takes 3 steps to converge when $\lambda=0.2$. In addition, we have found that λ should not be larger than 0.25 with these parameters or it will never converge.

Next, we investigate the robustness of the proposed power control scheme to channel fading. The network-centric metric is also ignored with $a_i=0$, and it will be demonstrated later. We assume that the channel fading is severe and the link gains follow (23). Also, there are 20 users in the cell. As DCPC and the Nash game scheme are both iterative algorithms and their performance is poor and almost the same when channel fading is severe, only the DCPC scheme is compared with the proposed scheme in the following simulation.

As seen in Figs. 4 and 5, when the proposed robust H_∞ power control scheme is applied, both the average SIR and the average transmit power converging curves are much more

stationary than those of the DCPC scheme. Especially when $\lambda=0.2$, the fluctuation of the curves is much smaller than for other cases in the initial few steps, and the curves become much closer when further iterations are carried out. However, there are more obvious advantages of the proposed robust H_∞ power control scheme as seen in Fig. 6. Though the converging curves of a single user's transmit power using various schemes are almost the same in Fig. 7, the SIR curves are extremely different. In Fig. 6, the converging curves of the first user's transmit power do not fluctuate much and stay around the target SIR of 5 with severe fading when the proposed scheme is applied, and they are almost the same with other λ values. The proposed power control scheme can combat the degradation of the channel with excellent performance due to the immediate decision of optimal power allocation based on the estimations of the channel variations from the H_∞ filter. On the other hand, when applying the DCPC scheme, it can hardly converge and the fluctuation is extremely large because it operates in an iterative manner and converges slowly. The largest value of SIR is over 8, and the smallest is close to 3; therefore, it is not suitable for practical use because of channel fading.

Last, we demonstrate the user-centric and network-centric metric of the proposed power control scheme. The channel fading is ignored for clarity in that only the different working manners of the proposed power control policy are examined. We set λ in the H_∞ filter to 0.01.

The SIR and power evolution of a cell containing 20 users in a wireless CDMA system is shown in Figs. 8 and 9. For the first 40 iterations, each user adapts power in a user-centric manner through assigning $a_i=0$. All the users attain their target SIR value upon convergence of the transmit power. In fact, the proposed distributed power control scheme with $a_i=0$ is equal to the algorithms proposed in [7]. For $40 < k \leq 80$, the two users with the most power (users 5 and 10) autonomously choose to act in a network-centric manner by selecting $a_5=a_{10}=0.0002$. In particular, a_5 and a_{10} can be dynamically assigned by the network due to congestion, a change in the user's application, or as a way of prioritizing the QoS of various users. Alternatively, they can also be decided by users 5 and 10 themselves during transmission in accordance with changes in application, traffic, battery state, or channel state. A resultant saving of 44.6 percent and 36.8 percent in transmission power is experienced by user 5 and user 10, respectively, and it causes a mean power savings of 9.5 percent to be experienced by the other 18 greedy users at no sacrifice to their QoS. This is due to users 5 and 10 addressing their network-centric objective of decreasing the interference which they introduce into the network and therefore reducing the power dissipation of the other network users. Energy efficient users like users 5 and 10

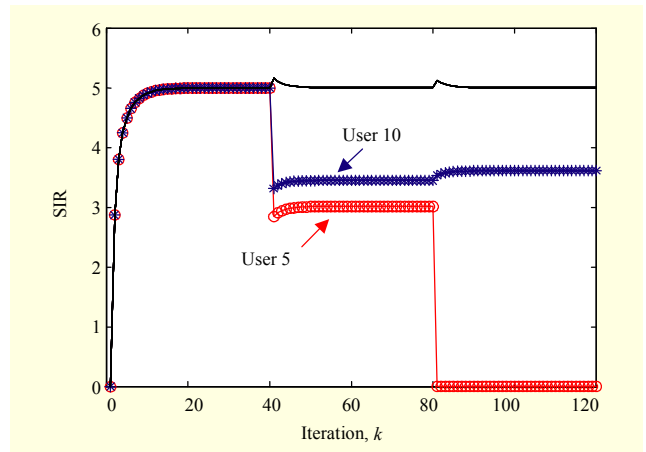


Fig. 8. Dynamics of SIRs of $N=20$ users with the proposed scheme with user-centric and network-centric approaches.

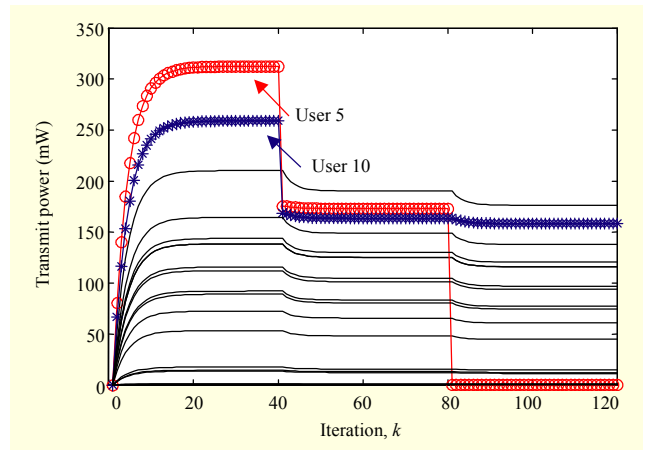


Fig. 9. Dynamics of the transmit powers of $N=20$ users with the proposed scheme with user-centric and network-centric approaches.

experiencing $SIR_i(k) < SIR_i^{\text{tar}}$ may still fulfill their application-specific QoS requirement with a sacrifice in delay. Such users would require excessive retransmissions at the link layer, or increased redundancy at the physical layer to compensate for its degraded SIR. Finally, user 5 chooses to further address energy efficiency via an assignment of $a_5=1$ during the interval $80 < k \leq 120$. This results in user 5 opting out via a converged transmit power of $P_5(k) = P^{\text{min}} = 0$ mW for $80 < k \leq 120$. As seen in Figs. 8 and 9, user 5 will only start transmission in response to an improved channel state. In response to the increased network-centric performance of user 5, an additional mean power savings of 6.9 percent is experienced by the other 19 transmitting users at no loss to their SIR performance.

The SIR and power evolution with a larger number of users $N=25$ is shown in Figs. 10 and 11. For $0 < k \leq 100$, all users update their power in a user-centric manner with $a_i=0$, and their SIRs all reach the target SIR at the cost of extremely high

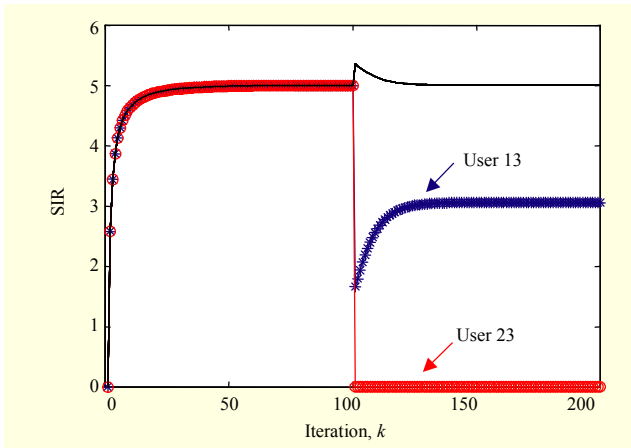


Fig. 10. Dynamics of the SIRs of $N=25$ users with the proposed scheme with user-centric and network-centric approaches.

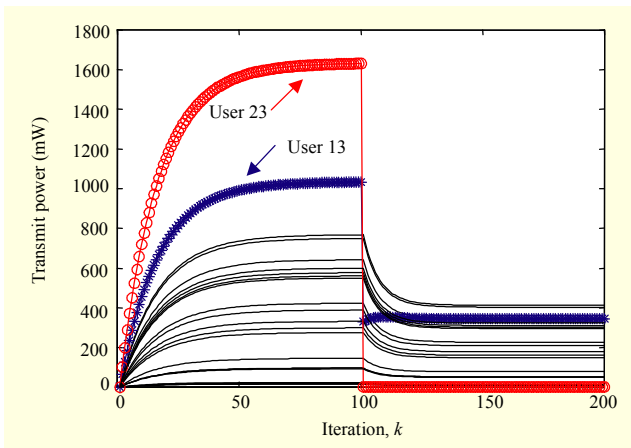


Fig. 11. Dynamics of the transmit powers of $N=25$ users with the proposed scheme with user-centric and network-centric approaches.

energy expenditures. There are even 9 users whose transmit power exceeds the maximum power level of $P^{\max}=500$ mW. To keep the transmit power of all users below P^{\max} , the two users dissipating the most power (users 13 and 23) autonomously choose to act in an energy efficient manner by setting $a_{13}=0.00005$ and $a_{23}=1$ for $100 < k \leq 200$. User 13 with $a_{13}=0.00005$ achieves $\text{SIR}_{13}(k) < \text{SIR}_{13}^{\text{tar}}$, and it may still fulfill its application-specific QoS requirement with a sacrifice in delay. A resultant saving of 66.6 percent in transmission power is experienced by user 13. User 23 chooses to further address energy efficiency with $a_{23}=1$, and it may make this user opt out with its transmit power equal to 0 mW. A mean power saving of 46.2 percent is experienced by the other 23 greedy users. The transmit power of all the users converges far below the $P^{\max}=500$ mW, and this is due to the network-centric approach adopted by users 13 and 23, which greatly reduces the power dissipation of the other network users.

These two examples also demonstrate that the more congested the system is, the more efficient the network-centric approach is.

VI. Conclusion

A novel robust H_{∞} distributed power control scheme has been presented for wireless CDMA networks. In the scheme, each user adapts its power either in a user-centric manner or a network-centric manner according to a simple updating function. It may be best for a user to perform in a user-centric manner when the channel state is good or when it is supporting an application which has a continuous stream of delay sensitive traffic, such as voice-based applications. At other times, it may be better for a user to act in a network-centric manner when the channel state is bad or with a delay insensitive application such as data-based applications and applications in a vehicle-mounted device. Another critical feature of the scheme is that the power adapts instantaneously due to predictions of the channel variations at the next time instant from the H_{∞} filter. Thus, it is robust to the channel fading, and is more suitable than iterative algorithms for practical use with severe fading. Several simulations have been carried out, and the results demonstrate the effectiveness and efficiency of the proposed scheme.

References

- [1] G.J. Foschini and Z. Miljanic, "A Simple Distributed Autonomous Power Control Algorithm and Its Convergence," *IEEE Trans. Veh. Technol.*, vol. 42, no. 4, Nov. 1993, pp. 641-646.
- [2] S.A. Grandhi, R. Vijayan, and D.J. Goodman, "Distributed Power Control in Cellular Radio Systems," *IEEE Trans. Commun.*, vol. 42, no. 2/3/4, Feb./Mar./Apr. 1994, pp. 226-228.
- [3] R.D. Yates, "A Framework for Uplink Power Control in Cellular Radio Systems," *IEEE J. Sel. Areas Commun.*, vol. 13, no. 7, Sept. 1995, pp. 1341-1348.
- [4] S. Grandhi, J. Zander, and R. Yates, "Constrained Power Control," *Wirel. Pers. Commun.*, vol. 1, no. 4, Dec. 1995, pp. 257-270.
- [5] C.C. Chai et al., "A Unified Framework for Transmitter Power Control in Cellular Radio Systems," *ETRI J.*, vol. 26, no. 5, Oct. 2004, pp. 423-431.
- [6] S. Koskie and Z. Gajic, "A Nash Game Algorithm for SIR-Based Power Control in 3G Wireless CDMA Networks," *IEEE ACM Trans. Netw.*, vol. 13, no. 5, Oct. 2005, pp. 1017-1026.
- [7] D. Skataric, Z. Gajic, and L. Qian, "Optimal Linear and Bilinear Algorithms for Power Control in 3G Wireless CDMA Networks," *Eur. Trans. Telecomm.*, vol. 18, no. 4, Jun. 2007, pp. 419-426.
- [8] M. Xiao, N.B. Shroff, and E.K.P. Chong, "A Utility-Based Power-Control Scheme in Wireless Cellular Systems," *IEEE*

ACM Trans. Netw., vol. 11, no. 2, Apr. 2003, pp. 210-221.

- [9] N. Feng, S. Mau, and N.B. Mandayam, "Pricing and Power Control for Joint Network-Centric and User-Centric Radio Resource Management," *IEEE Trans. Commun.*, vol. 52, no. 9, Sept. 2004, pp. 1547-1557.
- [10] S. Han, S. Kim, and Y. Han, "Distributed Utility-Maximization Using a Resource Pricing Power Control in Uplink DS-CDMA," *IEEE Commun. Lett.*, vol. 12, no. 4, Apr. 2008, pp. 286-288.
- [11] M. Elmusrati, R. Jantti, and H.N. Koivo, "Multiobjective Distributed Power Control Algorithm for CDMA Wireless Communication Systems," *IEEE Trans. Veh. Technol.*, vol. 56, no. 2, Mar. 2007, pp. 779-788.
- [12] S. Sorooshiyari and Z. Gajic, "Autonomous Dynamic Power Control for Wireless Networks: User-Centric and Network-Centric Consideration," *IEEE Trans. Wirel. Commun.*, vol. 7, no. 3, Mar. 2008, pp. 1004-1015.
- [13] K.K. Leung, "Power Control by Interference Prediction for Broadband Wireless Packet Networks," *IEEE Trans. Wirel. Commun.*, vol. 1, no. 2, Apr. 2002, pp. 256-265.
- [14] K.K. Leung and L. Wang, "Integrated Link Adaptation and Power Control to Improve Error and Throughput Performance in Broadband Wireless Packet Networks," *IEEE Trans. Wirel. Commun.*, vol. 1, no. 4, Oct. 2002, pp. 6196-29.
- [15] K. Shoarinejad, J. Speyer, and G. Pottie, "Integrated Predictive Power Control and Dynamic Channel Assignment in Mobile Radio Systems," *IEEE Trans. Wirel. Commun.*, vol. 2, no. 5, Sept. 2003, pp. 976-988.
- [16] K. Zhou and J. Doyle, *Essentials of Robust Control*, Prentice Hall, 1998.
- [17] L. Qian and Z. Gajic, "Optimal Distributed Power Control in Cellular Wireless Systems," *Dynamics of Continuous, Discrete and Impulsive Systems*, vol. 10, no. 4, Aug. 2003, pp. 537-559.
- [18] B.K. Lee, Y.H. Chen, and B.S. Chen, "Robust H_∞ Power Control for CDMA Cellular Communication Systems," *IEEE Trans. Signal Process.*, vol. 54, no. 10, Oct. 2006, pp. 3947-3956.
- [19] X.M. Shen and L. Deng, "Game Theory Approach to Discrete H_∞ Filter Design," *IEEE Trans. Signal Process.*, vol. 45, no. 4, Apr. 1997, pp. 1092-1095.
- [20] M.J. Grimble and A. El Sayed, "Solution of the H_∞ Optimal Linear Filtering Problem for Discrete-Time Systems," *IEEE Trans. Acoust. Speech Signal Process.*, vol. 38, no. 7, July 1990, pp. 1092-1104.
- [21] S. Ariyavisitakul and L.F. Chang, "Signal and Interference Statistics of a CDMA System with Feedback Power Control," *IEEE Trans. Commun.*, vol. 41, no. 11, Nov. 1993, pp. 1626-1634.
- [22] J. Nash, "Noncooperative Games," *Ann. Math.*, vol. 54, no. 2, 1951, pp. 286-295.



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