[24] F. Vogelbruch and S. Haar, "16-QAM turbo equalization based on minimum mean squared error linear equalization," in *Proc. IEEE 36th Asilomar Conf. Signals, Syst., Comput.*, Nov. 2002, pp. 1943–1947.
[25] B. M. Hochwald and S. ten Brink, "Achieving near-capacity on a multiple-antenna channel," *IEEE Trans. Commun.*, vol. 51, no. 3, pp. 389–399, Mar. 2003.
[26] M. Sellathurai and S. Haykin, "TURBO-BLAST for wireless communications: Theory and experiments," *IEEE Trans. Signal Process.*, vol. 50, no. 10, pp. 2538–2546, Oct. 2002.

Power Control for Multirate DS-CDMA Systems With Imperfect Successive Interference Cancellation

Shirin Jalali and Babak H. Khalaj

***Abstract*—In this paper, the problem of power allocation and optimal decoding order of users for the uplink channel of a multirate direct-sequence code-division multiple-access system with linear successive interference cancellation (IC) is addressed. First, the closed-form expressions of the required received powers at the base station for providing all users with their demanded rates and signal to interference-plus-noise ratios (SINRs) are derived. Then, it is shown that, unlike the case when the IC is perfect, in this case, optimum ordering of users at the receiver, which minimizes the total transmitted power, is a function of both their requested SINRs and path gains. Finally, in searching for the optimal ordering of users, an upper bound is found for the ratio between the path gain of the user with a higher requested SINR to the path gain of the user with a lower demanded SINR, which should be greater than the value which would assure that decoding the user with a higher SINR prior to the other one would be energy-conserving.**

***Index Terms*—Direct-sequence code-division multiple-access (DS-CDMA), interference cancellation (IC), multiuser detection, power control.**

I. Introduction

One of the most robust suboptimal multiuser interference cancellation (IC) methods is the so-called successive IC (SIC) [8]–[10]. In the SIC, the users are sequentially decoded; therefore, in such systems, placing the users in order while minimizing the total transmitted power is problematic. In [2], the problem of power control for a multirate code-division multiple-access (CDMA) system with SIC is considered, and it is shown that, when the IC is perfect, users should be decoded in a descending order of their path gain. The case of a linear imperfect SIC for a single-rate CDMA system is addressed in [3], and the power distribution required at the base station for each user is derived. The problem of power allocation for a multirate direct-sequence CDMA (DS-CDMA) system with SIC is examined in [6], and it is suggested that, under certain conditions, even when IC is imperfect, users should be decoded in descending order of their channel gains. The problem of finding optimal decoding order of users for a multirate CDMA system is also investigated in [7], and it is proposed that, under some conditions, the optimal ordering of the users remains the same under perfect and imperfect ICs.

Manuscript received September 25, 2004; revised November 28, 2005, May 30, 2006, December 13, 2006, and December 16, 2006. The review of this paper was coordinated by Prof. J. H. Cho.

S. Jalali is with the Electrical Engineering Department, Stanford University, Stanford, CA 94305 USA (e-mail: shjalali@stanford.edu).

B. H. Khalaj is with the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran (e-mail: khalaj@sharif.edu).

Digital Object Identifier 10.1109/TVT.2007.904536

In this paper, as an extension of the work done by Buehrer in [3], the multirate scenario is examined. It is shown that finding the optimal ordering of users for a multirate DS-CDMA system with imperfect IC is not straightforward. In addition, it is proved that, in this case, user path gains and requested signal to interference-plus-noise ratios (SINRs) should be both considered and that, in many situations, the effect of the SINR dominates.

II. System Model and Power Control

Consider a DS-CDMA system with K active users communicating with a common base station. By ignoring the interference caused by the users of other cells, the received signal at the base station can be written as

$$r(t) = \sum_{k=1}^{K} \sqrt{P_k} b_k(t-\tau_k) a_k(t-\tau_k) e^{j\phi_k} + n(t) \tag{1}$$

where P_k is the received power from the kth transmitter, $b_k(t)$ and $a_k(t)$ denote its bit stream and spreading waveform, and finally, τ_k and ϕ_k are its relative delay and phase. In addition, let $n(t)$ denote the received thermal noise signal, which is assumed to be a complex white Gaussian random process with double-sided power spectral density of N_0.

In a linear SIC, after decoding the first $k-1$ users, the signal used in decoding the information of user k is given by

$$r^{(k)}(t) = r(t) - \sum_{i=1}^{K-1} \hat{s}_i(t-\tau_i) \tag{2}$$

where $\hat{s}_i(t-\tau_i)$ is a linear estimate of $s_i(t) = \sqrt{P_i} b_i(t) a_i(t) e^{j\phi_i}$, as in the following:

$$\hat{s}_i(t-\tau_i) = \sum_{m=-\infty}^{\infty} z_{k,m} \Pi_{T_k}(t-mT_k) a_k(t) \tag{3}$$

where T_k is the bit duration of user k and is equal to $N_k T_c$. T_c is the common chip duration of all the users, and N_k is the spreading gain of user k. $\Pi_{T_k}(t)$ represents a unit pulse on $[0,\ T_k)$, and $z_{k,m}$ is the decision statistics used by the receiver to decide on bit m of user k and is equal to

$$z_{k,m} = \frac{1}{T_k} \int_{(m-1)T_k+\tau_k}^{mT_k+\tau_k} r^{(k)}(t) a_k^*(t-\tau_k) dt. \tag{4}$$

Combining (2) and (4) yields

$$z_{k,m} = \sqrt{P_k} b_{k,m} e^{j\phi_k} + \sum_{i=1}^{k-1} \tilde{I}_{k,i,m} + \sum_{i=k+1}^{K} I_{k,i,m} + N_{k,m} \tag{5}$$

where $\tilde{I}_{k,i,m}$ represents the effect of imperfect removal of previously canceled signals, and $I_{k,i,m}$ represents the effect of the signals that have not yet been canceled. $N_{k,m}$ is the thermal noise component, which is a Gaussian random variable with a zero mean and a variance of

$$\frac{N_0}{T_k} = \frac{N_0}{N_k T_c} := \frac{\sigma^2}{N_k} \tag{6}$$

where σ^2 is defined to be equal to N_0/T_c. The received SINR of user k, which is denoted as γ_k, is given by

$$\gamma_k = \frac{E^2\{z_{k,m}|b_{k,m}\}}{\mathrm{var}\{z_{k,m}|b_{k,m}\}} \tag{7}$$

where

$$E\{z_{k,m}|b_{k,m}\} = \sqrt{P_k}b_{k,m} \tag{8}$$

$$\mathrm{var}\{z_{k,m}\} = \frac{\sigma^2}{N_k} + \sum_{i=1}^{k-1}\mathrm{var}\{\tilde{I}_{k,m,i}\} + \sum_{i=k+1}^{K}\mathrm{var}\{I_{k,m,i}\}. \tag{9}$$

To this point, the derivation of the equations was similar to the case when all users required the same rate and quality of service. In order to go further and compute the variances given in (9), the diversity between user requests must be taken into account. Note that, if low-rate users employ pseudorandom sequences to mask their repetition codes, then, the other users would not be able to sense their spreading gains, and hence, the results in [3]–[5] for $\mathrm{var}\{\tilde{I}_{k,m,i}\}$ and $\mathrm{var}\{I_{k,m,i}\}$ could be applied to the multirate situation by just replacing the spreading gain of the user of interest in the place of the common spreading gain used in the single-rate scenario. Therefore

$$\mathrm{var}\{\tilde{I}_{k,m,i}\} = P_i\frac{l}{N_k} \tag{10}$$

and

$$\mathrm{var}\{I_{k,m,i}\} = \mathrm{var}\{z_{i,m}\}\frac{l}{N_k} \tag{11}$$

where, for rectangular pulses, l is defined as follows:

$$l = \begin{cases} 1, & \text{chip synchronous, zero phase} \\ 2/3, & \text{chip asynchronous, zero phase.} \end{cases} \tag{12}$$

When the phases are random, l should be multiplied by 1/2 [5], [6]. By defining $\eta_k \triangleq \mathrm{var}\{z_{k,m}|b_{k,m}\}$, from (9)–(11), it follows that

$$\eta_k = \frac{\sigma^2}{N_k} + \frac{l}{N_k}\sum_{i=1}^{k-1}\eta_i + \frac{l}{N_k}\sum_{i=k+1}^{K}P_i. \tag{13}$$

Multiplying both sides of (13) with N_k, rewriting it for $k-1$, and then subtracting both sides of the two equations from each other would yield

$$N_k\eta_k - N_{k-1}\eta_{k-1} = \eta_{k-1} - P_k. \tag{14}$$

Now, by substituting $\eta_k = P_k/\gamma_k$ and $\eta_{k-1} = P_{k-1}/\gamma_{k-1}$ in (14), it follows that

$$P_k = \frac{(N_{k-1}+l)/\gamma_{k-1}}{l + N_k/\gamma_k}P_{k-1} \tag{15}$$

which is a recursive formula in calculating P_k. By solving these recursive equations, which is easily done by replacing (15) with (13), the required power profile at the base station would be derived as follows:

$$P_1 = \frac{\sigma^2}{\frac{N_1}{\gamma_1} - l\sum_{k=1}^{K}\prod_{i=1}^{k-1}\frac{(N_{k-i}+l)/\gamma_{k-i}}{l+N_{k-i+1}/\gamma_{k-i+1}}} \tag{16}$$

and

$$P_k = P_1\prod_{i=1}^{k-1}\frac{(N_{k-i}+l)/\gamma_{k-i}}{l+N_{k-i+1}/\gamma_{k-i+1}} \tag{17}$$

for $2 \le k \le K$.

III. Optimizing Decoding Order

It is expected that, in order to minimize the total transmitted power in a system with SIC, it would be beneficial to decode users with higher requested SINRs prior to the others. The reason for this is that this would reduce the amount of residual interference to the remaining users more. However, as shown in the sequel, this is not always the case for a system where different users have different SINR requirements. In such a system, the optimal ordering of users, which minimizes the total transmitted power, depends both on their requested SINR and their channel qualities.

In order to find the optimal arrangement of users, we propose the following algorithm: queue users in decreasing order of their requested SINRs. Then, starting from user one, at each step, consider two consecutive users, for example, users $k-1$ and k. Compute the difference between the total required powers for the arrangement obtained after exchanging the place of these two users and the current setup. If the difference is positive, leave them in their current position; otherwise, exchange their places. When all successive user pairs are considered, the first pass of the algorithm is completed. Complete the consecutive passes in the same manner as the first one: Consider every two successive users, place them such that the first one has a greater required SINR, and then, based on the difference between the required powers of the two possible ordering of these two users, exchange their positions if it is energy-conserving. Stop at pass L if the arrangement of users at passes L and $L-1$ are the same.

Obviously, computing the difference between the total transmitted power at each step of the algorithm makes it too complex. In order to resolve this problem, we try to find some inequalities for user-requested SINRs and path gains, which can help us decide on their position, without requiring computation of the powers.

Let $\tilde{\mathbf{P}} = [\tilde{P}_1, \tilde{P}_2, \ldots, \tilde{P}_K]$ be the required power profile at the receiver, which meets the user required rates and SINRs, after exchanging the decoding order of users $k-1$ and k. Moreover, assume that the demanded SINR of all the users is greater than one, which makes sense from a practical point of view. From (15), for the new setup

$$\tilde{P}_k = \frac{(N_{k-1}+l)/\gamma_{k-1}}{l + N_k/\gamma_k}\tilde{P}_{k-1} \tag{18}$$

for $0 \le i \le k-1$ and $k+2 \le i \le K$. By dividing both sides of (15) by the both sides of (18) as in the following:

$$\frac{\tilde{P}_1}{P_1} = \frac{\tilde{P}_2}{P_2} = \cdots = \frac{\tilde{P}_{k-2}}{P_{k-2}} \triangleq r \tag{19}$$

$$\begin{aligned}\Delta &= \sum_{i=1}^{K}\tilde{P}_{tx,i} - \sum_{i=1}^{K}P_{tx,i} \\ &= (r-1)\left(\sum_{i=1}^{K}P_{tx,i} + \frac{\sigma^{2l}}{\frac{1}{\gamma_k} - \frac{1}{\gamma_{k-1}}}\right. \\ &\qquad \left.\times\left(\frac{1}{h_k}\left(1-\frac{1}{\gamma_{k-1}}\right) - \frac{1}{h_{k-1}}\left(1-\frac{1}{\gamma_k}\right)\right)\right). \end{aligned} \tag{20}$$

We observe that exchanging the decoding order of users k and $k-1$ changes the required power by $k-2$ preceding users by a constant factor r. For user $k+1$

$$\begin{aligned}\frac{\tilde{P}_{k+1}}{P_{k+1}} &= \frac{(N_{k-1}+l)/\gamma_{k-1}}{(N_{k+l})/\gamma_k}\frac{\tilde{P}_k}{P_k} \\ &= \frac{(N_{k-1}+l)/\gamma_{k-1}}{(N_k+l)/\gamma_k}\frac{(N_k+l)/\gamma_k}{l+N_{k-1}/\gamma_{k-1}}\frac{l+N_k/\gamma_k}{(N_{k-1}+l)/\gamma_{k-1}}\frac{\tilde{P}_{k-1}}{P_{k-1}}\end{aligned}$$

$$
\begin{aligned}
&= \frac{l + N_k/\gamma_k}{l + N_{k-1}/\gamma_{k-1}} \frac{\tilde{P}_{k-1}}{P_{k-1}} \\
&= \frac{l + N_k/\gamma_k}{l + N_{k-1}/\gamma_{k-1}} \frac{(N_{k-2} + l)/\gamma_{k-2}}{l + N_k/\gamma_k} \frac{l + N_{k-1}/\gamma_{k-1}}{(N_{k-2} + l)/\gamma_{k-2}} \frac{\tilde{P}_{k-2}}{P_{k-2}} \\
&= r
\end{aligned}
$$

and, therefore, similar to (19)

$$\frac{\tilde{P}_{k+1}}{P_{k+1}} = \frac{\tilde{P}_{k+2}}{P_{k+2}} = \cdots = \frac{\tilde{P}_K}{P_K} = r. \tag{21}$$

Let h_k denote the channel power gain of user k, and let $P_{tx,k}$, which is equal to P_k/h_k, be its transmitted power. The total transmitted power of the new setup would be

$$
\begin{aligned}
\sum_{i=1}^{i=K} \tilde{P}_{tx,i} &= \sum_{i=1}^{i=K} \frac{\tilde{P}_i}{h_i} \\
&= r \cdot \sum_{\substack{i=1 \\ i \neq k, k-1}}^{K} \frac{P_i}{h_i} + \frac{\tilde{P}_k}{h_{k-1}} + \frac{\tilde{P}_{k-1}}{h_k} \\
&= r \sum_{i=1}^{i=K} P_{tx,i} + \frac{\tilde{P}_k}{h_{k-1}} + \frac{\tilde{P}_{k-1}}{h_k} - r\left(\frac{P_k}{h_k} + \frac{P_{k-1}}{h_{k-1}}\right) \\
&= r \sum_{i=1}^{i=K} P_{tx,i} + rl \frac{P_{k-1}}{l + N_k/\gamma_k} \left(\frac{1}{h_k}\left(1 - \frac{1}{\gamma_{k-1}}\right) \right. \\
&\qquad \left. - \frac{1}{h_{k-1}}\left(1 - \frac{1}{\gamma_k}\right)\right).
\end{aligned} \tag{22}
$$

On the other hand, by equalizing the definition of γ_1 for the two cases

$$\gamma_1 = \frac{N_1 P_1}{\sigma^2 + \sum_{i=2}^K P_i} = \frac{N_1 \tilde{P}_1}{\sigma^2 + \sum_{i=2}^K \tilde{P}_i}. \tag{23}$$

Now, by combining (22) and (23), we can find the following equation, which is linear in r:

$$(r-1)\sigma^2 = rlP_{k-1} \frac{\frac{1}{\gamma_k} - \frac{1}{\gamma_{k-1}}}{l + \frac{N_k}{\gamma_k}}. \tag{24}$$

Finally, let Δ be the difference between the total transmitted power of the second arrangement of users and the first one. From (22) and (24), we conclude that (20) holds.

As mentioned before, at each step, the sign of Δ determines whether the two users should be left in their current positions or not. From our initial assumption, at each step of each pass of the algorithm, the two users of interest are first sorted such that $\gamma_k < \gamma_{k-1}$. From (24), it can be seen that r is greater than one in this case, and hence, $(r-1)$, which is the first term on the right-hand side of (20), is positive. Hence, if

$$0 \leq \frac{1}{h_k}\left(1 - \frac{1}{\gamma_{k-1}}\right) - \frac{1}{h_{k-1}}\left(1 - \frac{1}{\gamma_k}\right) \tag{25}$$

or equivalently

$$\frac{1 - \frac{1}{\gamma_k}}{1 - \frac{1}{\gamma_{k-1}}} h_k \leq h_{k-1} \tag{26}$$

then, the second term in (20) would also be positive, and as a result, Δ would be positive. Equation (26) implies an upper bound on the values of h_{k-1}/h_k, which assure that decoding the user with a higher requested SINR before the other one would preserve the total transmitted power.

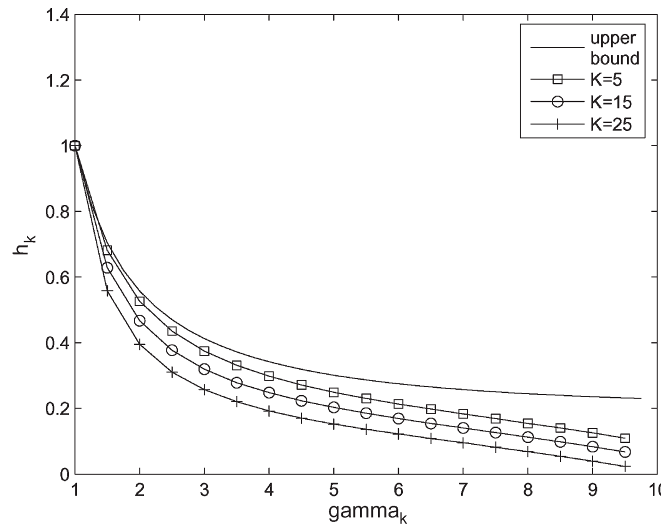

Fig. 1. Comparison between the upper bound derived from (26) for the critical value of the path gain of the distinct user in a system with K active users, with $K-1$ of them requiring $\gamma_1 = 1$ dB and experiencing $h_1 = 1$; if above the upper bound, the distinct user should be decoded earlier than the others versus its SINR requirement γk.

For the special case when $\gamma_{k-1} = \gamma_k \triangleq \gamma$, from (24), it follows that $r = 1$, and so, from (22), the difference between the powers would be given by

$$\Delta = \frac{P_{k-1}}{1 + N_k/\gamma_k}(1 - 1/\gamma)\left(\frac{1}{h_k} - \frac{1}{h_{k-1}}\right). \tag{27}$$

Since $\gamma \geq 1$, by our initial assumption, in order to get $\Delta \geq 0$, we should have

$$\frac{1}{h_k} - \frac{1}{h_{k-1}} \geq 0 \rightarrow h_{k-1} \geq h_k. \tag{28}$$

Equation (28) states that, if two users have equal required SINRs, then, the one with a better channel quality should be decoded in advance.

IV. Numerical Results

Consider a system with K active users, where $K-1$ of them require an SINR of $\gamma_1 = 1$ dB and experience a path gain of $h = 1$, and one of them requires $\gamma_k > 1$ dB and experiences a path gain of $h_k < 1$. Two possible arrangements of the users are the following: decoding the distinct user first or decoding it after decoding all the other users. From (26), we can find a value of $h_k < 1$, which would assure that decoding the distinct user earlier than the others is power-preserving. On the other hand, from (20), for $h_k \ll 1$, we expect Δ to be negative, which means that the distinct user should be decoded after decoding all the other users. The exact value of h_k, in which the distinct user should be decoded earlier, can numerically be computed. Fig. 1 shows this result versus the value of γ_k for a number of different values of K, along with its upper bound found from (26). It can be observed that, as the value of K or γ_k increases, the difference between the upper bound and the actual value becomes more significant. This result is expected from (20). Since adding extra users increases the total transmitted power, which appears in the second term of (20), hence, the first term, which reflects the effect of SINRs, becomes more dominant in determining the sign of (20).

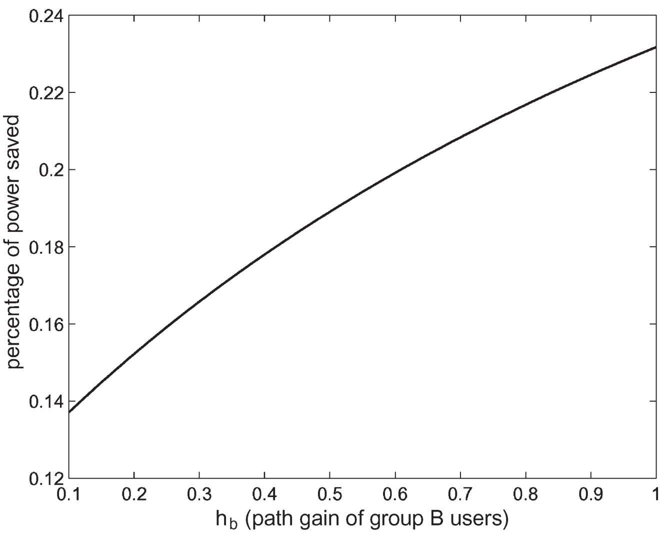

Fig. 2. Percentage of power saved by selecting optimal decoding order of users versus h_B, which is the path gain of the group of users with lower path gain (synchronous, with $K = 30$ and $N = 64$).

As a second example, consider a system with $K = 30$ active users, with half of them requiring $\gamma_A = 1$ dB and the rest requiring $\gamma_B = 4$ dB. To highlight the dichotomy between sorting users based on their path gains or SINR requirements, assume that all users in group A experience a path gain of $h_A = 1$ and that all users in group B see a path gain of $h_B < 1$. Fig. 2 shows the percentage of power that can be saved by decoding users of group B that have a higher SINR requirement but lower path gain earlier than users of group A for different values of h_B.

V. Conclusion

In this paper, we addressed the power control issue for the uplink channel of a multirate DS-CDMA system with imperfect SIC. We first derived the user-required power allocation in order to meet their SINR and bit rate demands. In addition, we showed that optimal ordering of users, which minimizes the total transmitted power, depends on their required SINRs, as well as channel gains. We also derived an upper bound on the ratio of the path gain of the user with a higher requested SINR to the path gain of the one with a lower requested SINR; if greater than the upper bound, it should be decoded earlier.

References

[1] S. Verdu, *Multiuser Detection*. Cambridge, U.K.: Cambridge Univ. Press, 1998.

[2] S. M. Shum and R. S. Cheng, "Power control for multirate CDMA systems with interference cancellation," in *Proc. IEEE Global Telecommun. Conf.*, 2000, vol. 2, pp. 895–900.

[3] R. M. Buehrer, "Equal BER performance in linear successive interference cancellation for CDMA systems," *IEEE Trans. Commun.*, vol. 49, no. 7, pp. 1250–1258, Jul. 2001.

[4] M. B. Pursley, "Performance evaluation for phase-coded spread-spectrum multiple-access-communication—Part I: System analysis," *IEEE Trans. Commun.*, vol. COM-25, no. 8, pp. 795–799, Aug. 1977.

[5] R. K. Morrow, "Accurate CDMA BER calculations with low computational complexity," *IEEE Trans. Commun.*, vol. 46, no. 11, pp. 1413–1417, Nov. 1998.

[6] F. Berggren and S. B. Slimane, "Power allocation for a simple successive interference cancellation scheme in a multi-rate DS-CDMA system," in *Proc. IEEE ICC*, New York, NY, 2002, vol. 1, pp. 351–355.

[7] A. Agrawal, J. Andrews, J. Cioffi, and T. Meng, "Iterative power control for imperfect successive interference cancellation," *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 878–884, May 2005.

[8] P. Patel and J. Holtzman, "Analysis of a simple successive interference cancellation scheme in a DS/CDMA system," *IEEE J. Sel. Areas Commun.*, vol. 12, no. 5, pp. 796–807, Jun. 1994.

[9] P. Kempf, "On multi-user detection schemes for synchronous coherent CDMA systems," in *Proc. Veh. Technol. Conf.*, 1995, pp. 479–483.

[10] R. Muller and J. Huber, "Capacity of cellular CDMA systems applying interference cancellation and channel coding," in *Proc. IEEE Global Telecommun. Conf.*, Nov. 1997, pp. 179–184.

Generalized Joint Power and Rate Adaptation in DS-CDMA Communications Over Fading Channels

Ye Hoon Lee, *Senior Member, IEEE*, and
Sang Wu Kim, *Senior Member, IEEE*

***Abstract*—We propose a generalized joint power and rate adaptation scheme in direct-sequence (DS) code-division multiple-access (CDMA) communications over Nakagami fading channels. The transmission power allocated to user i is proportional to G_i^P, where G_i is the channel gain of user i and p is a real number, and the data rate (i.e., spreading gain) is jointly adapted so that a desired QoS is maintained. We analyze the average data rate of the proposed adaptation scheme subject to fixed average and peak transmission power constraints. Our results show that the proposed joint adaptation scheme provides a significant performance improvement over power-only and rate-only adaptation.**

***Index Terms*—Adaptive systems, direct-sequence code division multiple access (DS-CDMA), joint power and rate, Nakagami fading.**

I. Introduction

When the transmitter is provided with channel state information, the transmission schemes can be adapted to this information, enabling more efficient use of the channel. Optimal adaptation of the transmission power was considered in [1], together with peak and average power constraints in [2]. Adaptive variations of data rate [3], constellation size [4], [5], coding scheme [6], and any combination of these parameters [7]–[10] were studied, all for narrow-band systems. Information theoretic approaches have been done in [11]–[13] for single-user channels, and it was claimed that optimal power and rate adaptation yields a small increase in Shannon capacity over just rate adaptation, and this increase diminishes as the number of diversity branches increases.

For current code-division multiple-access (CDMA) cellular systems, a power adaptation is employed to maintain the received power of each mobile at a desired level [14], [15]. The power adaptation, however, requires a large amount of transmission power to compensate for deep fading. It was shown in [16] that the rate adaptation provides a higher average data rate than the power adaptation, when the average transmission power and quality-of-service (QoS) requirements are identical. An optimal rate adaptation scheme with perfect power control was considered in [17] to maximize the throughput

Manuscript received February 24, 2005; revised January 12, 2006, December 27, 2006, and May 15, 2007. The review of this paper was coordinated by Prof. J. H. Cho.

Y. H. Lee is with the Department of Electronic and Information Engineering, Seoul National University of Technology, Seoul 139-743, Korea (e-mail: yhlee@ieee.org).

S. W. Kim is with the Department of Electrical and Computer Engineering, Iowa State University, Ames, IA 50011 USA (e-mail: swkim@iastate.edu).

Digital Object Identifier 10.1109/TVT.2007.905345