Integrated Link Adaptation and Power Control to Improve Error and Throughput Performance in Broadband Wireless Packet Networks

Kin K. Leung, *Fellow, IEEE,* and Li-Chun Wang, *Member, IEEE*

***Abstract*—In this paper, we prove that the problem of maximizing data throughput by adaptive modulation and power control while meeting packet error requirements is NP-complete. A heuristic algorithm for integrated link adaptation and power control is, thus, proposed to achieve specified error rates and to improve overall throughput for real-time applications in broadband wireless packet networks. The algorithm divides terminals into groups according to their signal path gains and periodically adapts transmissions based on the required error rates, actual error statistics, and average transmission power of each terminal group. Transmission power is adjusted by an enhanced Kalman-filter method to ensure successful reception. Extensive simulation results reveal that the algorithm consistently delivers the specified error performance and attempts to maximize network throughput for a wide range of parameter settings.**

***Index Terms*—Adaptive Kalman filtering, adaptive modulation, cochannel interference, error analysis, land mobile radio cellular systems, packet switching, power control, radio communication, time division multi-access.**

I. Introduction

AS TELECOMMUTING and Internet access become increasingly popular, customers' demand for broadband network services has been growing significantly. In the near future, broadband services are also expected to support real-time, multimedia services such as voice, image, and video. Wireless access is one of the approaches to providing such services. In particular, the European Telecommunications Standards Institute (ETSI) is establishing the protocol standards for the enhanced data rates for GSM evolution (EDGE) system [18] as the third-generation wireless network for high-speed services.

Using packet-switching technology and multiple modulation and coding levels, the EDGE system employs a link-adaptation technique to adapt packet transmission to one of six coding levels [5] (a current proposal has nine modulation and coding levels [6]), where the highest data rate can exceed 550 kb/s. The main idea of link adaptation is to adapt the modulation and coding levels according to the channel and interference conditions in order to improve data throughput. When the channel condition is poor, a low modulation level (i.e., few data bits per symbol) and/or heavy coding should be used in a packet transmission to enable correct signal detection. On the other hand, if the channel situations are favorable, high modulation level and/or light coding can be used to increase data rate.

Due to unreliable radio links, it is challenging to ensure quality-of-service (QoS) in terms of packet error rate (PER) in the wireless networks. For real-time services such as Internet protocol (IP) voice, music and video, stringent delay requirements severely limits or even precludes retransmission of lost packets. Thus, tight delay requirements often translate into stringent requirements for PER. As a result, in order to support such real-time services, it is important to design the wireless networks such that the required QoS can be delivered to users.

Evidently, link adaptation is helpful in delivering QoS. Specifically, when the channel condition is poor, transmitters can lower modulation levels to decrease the requirements of signal-to-interference-plus-noise ratio (SINR) for correct signal detection. Lowering SINR requirements increases the probability of successful reception, thus, helping to meet the PER objective. However, especially for interference-limited systems with sufficient traffic load, adapting even to the lowest modulation level may not always guarantee meeting the specified PER. In this case, increasing transmission power can improve signal strength and, thus, the SINR at the receivers. Hence, one can view power control as performing an active role in delivering the expected PER to users, while adaptive modulation plays a passive (or reactive) role. As discussed further below, the complementary roles of power control and link adaptation give us a very efficient approach to providing the required QoS to users. With this understanding, a key design problem for a wireless packet network like the EDGE system is: *how to maximize the overall network throughput over the choice of modulation and coding levels and transmission power, subject to meeting given PER requirements*. Here, we propose and analyze an integrated algorithm of link adaptation and power control for the problem.

Our recent work [13] (and early results in [12]) on integrated power control and link adaptation, represents our initial attempts in solving the problem. In particular, the proposed algorithm in [13] chooses the modulation and power level according to a power-stability criterion (to maintain stable transmission power in a long run). In this work, we find that the use of the stability criterion is actually unnecessary, when link adaptation and

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K. K. Leung was with AT&T Labs—Research, Middletown, NJ 07748 USA. He is now with Bell Labs, Lucent Technologies, Murray Hill, NJ 07974 USA (e-mail: kkleung@ieee.org).

L.-C. Wang was with AT&T Labs—Research, Middletown, NJ 07748 USA. He is now with the Department of Communications Engineering, National Chiao Tung University, Taiwan.

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power control operation is based on the measured PER at the receivers and their requirements, provided that a feasible setting of modulation and power levels exists to support the required PER in the network under consideration. This is because monitoring and controlling PER performance by the link adaptation and power control implicitly force transmission power to fall within a given dynamic range. The algorithm proposed here is based on monitoring PER performance.

Let us briefly review other work on power control and link adaptation. Power control has been widely studied to combat interference in wireless networks; see, e.g., [17], [19], and [21]. Recently, [9] proposes a Kalman-filter method for power control in packet-switched time-division multiple-access (TDMA) networks. An enhanced version of the Kalman-filter method is used to control transmission power here. Much work on link adaptation by adaptive modulation has been done for fading channels; see for example [1] and [7]. For cellular systems, [14] proposes iterative algorithms to maximize the overall network throughput by adaptive modulation and power control. Unfortunately, the formulation in [14] does not consider the PER requirements (constraints). Evidently, it is difficult to extend the algorithms for real-time services with specific PER requirements. In [3] and [15], new adaptation schemes are proposed to improve overall data throughput for nonreal-time data services. However, the use of link adaptation to deliver the specified PER for real-time multimedia applications is an open issue, which is the topic to be addressed in this paper. Further, we examine how power control, which is not considered in [3] and [15], is integrated with link adaptation for performance improvement.

This paper is organized as follows. We first present the operations and power control for the wireless networks under consideration in Section II. In Section III, we prove that the problem of maximizing network throughput while meeting the given PER requirements is NP-complete. That is, no efficient algorithm for the problem exists. Then, a new algorithm for integrated link adaptation and power control based on monitoring PER performance is proposed in Section IV. In Section V, we study the performance of the proposed algorithm by simulation. Finally, Section VI is our conclusion.

II. Network Operations and Power Control

Consider a packet-switched TDMA network with data rates up to several megabits per second, link lengths (or cell radius) typically less than 10 km and operating frequency in the range of 1–5 GHz. Assume that each data message (e.g., an email) is divided into a number of packets, each of which can be transmitted in one time slot. When a transmitter (either a mobile terminal or a base station) sends a message, all its packets are transmitted in successive time slots. (For example, such corresponds to transmission in the same time slot of the consecutive TDMA frames [16] in the GSM/EDGE system providing single time-slot service.) Similar to the EDGE system, the network under consideration allows transmitters to choose one of M combinations of modulation and coding levels for transmission in each time slot, according to the link-adaptation algorithm in use. In this study, the key effect of using different modulation and coding levels is a change of SINR requirement for correct data reception. Thus, for brevity, we refer to the adaptation of modulation and coding levels simply as adaptive modulation here. Further, although the algorithm to be proposed is applicable to both uplink (from terminal to base station) and downlink (from base station to terminal), our discussion will focus on the up-link transmission.

An enhanced Kalman-filter method is used to control transmission power. Using this method, each terminal continuously measures the interference power for its assigned radio channel, regardless of whether or not the base station associated with the terminal is transmitting data and whether or not the data being transmitted is intended for the terminal. The measurements are fed into a Kalman filter to predict future interference power. Let $\tilde{i}_n$ and $\tilde{I}_n$ denote the predicted interference power for slot n in mW and dBm, respectively. The time and measurement update equations for the Kalman filter for interference predictions are

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

$$\tilde{P}_{n+1} = \hat{P}_n + Q_n \tag{2}$$

$$K_n = \tilde{P}_n \left(\tilde{P}_n + R_n\right)^{-1} \tag{3}$$

$$\hat{I}_n = \tilde{I}_n + K_n \left(Z_n - \tilde{I}_n\right) \tag{4}$$

$$\hat{P}_{n+1} = (1 - K_n)\,\tilde{P}_n \tag{5}$$

where $\tilde{I}_n$ and $\hat{I}_n$ are the *a priori* and *a posteriori* estimate of interference power in dBm for slot n, $\tilde{P}_n$ and $\hat{P}_n$ are the *a priori* and *a posteriori* estimate-error variance, K_n is the Kalman gain, Z_n is the measured interference power (i.e., actual interference plus measurement error) and Q_n and R_n are the variance for the process noise (i.e., change of interference power of one slot relative to the previous one) and the interference measurement noise (or error), respectively. Based on measurements up to slot n, $\tilde{I}_{n+1}$ in (1) gives the predicted interference power for slot $n+1$.

Let $\bar{Z}_n$ be the average interference measurements over W frames prior to slot n. Thus

$$\bar{Z}_n = \frac{1}{W} \sum_{i=n-W+1}^{n} Z_i. \tag{6}$$

We can estimate Q_n by

$$Q_n \approx \frac{1}{W-1} \sum_{i=n-W+1}^{n} \left(Z_i - \bar{Z}_n\right)^2. \tag{7}$$

Note that Q_n in (7) is an estimate of the sum of the variances for the interference power and measurement noise because the measurement Z_i in (6) is the sum of the actual interference power and measurement error. However, since the fluctuation of interference power can reach tens of decibels, which is much higher than typical measurement errors, (7) represents a good estimate for Q_n.

It is also worth noting that R_n depends on the actual error characteristics of interference measurements. To illustrate our ideas without considering details of the measurement error characteristics, we assume for simplicity in this paper that R_n is given by

$$R_n = \eta Q_n \tag{8}$$

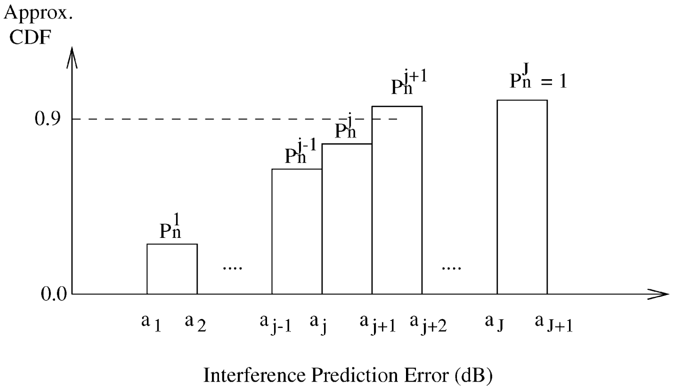


Fig. 1. Approximate CDF for interference prediction error.

where η is a given constant between zero and one. This range is appropriate because as mentioned before, Q_n in (7) includes the measurement-error variance. For a given η, we effectively consider the corresponding value for the variance of measurement errors.

The predicted interference $\tilde{i}_n$ in (1) is used to control transmission power p_n for slot n

$$p_n = \min\left[\frac{\gamma^* \tilde{i}_n \delta_n}{g_n},\, p_{\max}\right] \tag{9}$$

where γ^* is the SINR target for the chosen modulation level, $\tilde{i}_n$ is the interference-plus-noise power (mW) in slot n predicted by the Kalman filter, δ_n is an error margin (to be discussed below), and g_n is the estimated path gain between the transmitting terminal in slot n and its base station.

The error margin δ_n is obtained by tracking the accuracy of interference power predicted by (1). Precisely, let Δ (a random variable in decibels) be the error of the Kalman-filter prediction and the error for slot n be

$$E_n = Z_n - \hat{I}_n \tag{10}$$

where Z_n and $\tilde{I}_n$ are the measured and predicted interference power in dBm for slot n, respectively. Based on the E_ns, we approximate the cumulative probability function (CDF) for Δ. Toward this end, let there be J intervals of prediction error and the range of the jth interval be $(a_j, a_{j+1}]$, as shown in Fig. 1. To cover the full range of possible errors, one may need to set $a_1 = -\infty$ and $a_{J+1} = \infty$. For each time slot $n > 0$ and each $j = 1$ to J, compute

$$P_n^j = \begin{cases} \phi P_{n-1}^j, & \text{if } E_n > a_{j+1} \\ \phi P_{n-1}^j + 1 - \phi, & \text{otherwise} \end{cases} \tag{11}$$

where P_n^j is the approximate probability of $\Delta \le a_{j+1}$ based on the error sequence E_n up to slot n with $P_0^j = 1$ for all $j = 1$ to J initially and ϕ is a properly chosen parameter between zero and one.

To provide a physical interpretation for (11), let us assume $\phi = 1 - 1/m$ where m is a positive integer. Without loss of generality, we consider the probability for $\Delta \le a_2$ (i.e., the probability mass associated with the first error interval) based on prediction errors E_n's in a sliding window of last m slots. Furthermore, suppose that $E_n \le a_2$ for all $n = 1$ to m. As a result, (11) yields $P_m^1 = 1$, since $P_0^1 = 1$ initially. Now, E_{m+1} becomes available for slot $m+1$. If $E_{m+1} > a_2$, then $P_{m+1}^1 = (1 - 1/m)$ according to (11). The interpretation of this is that among the E_n for $n = 2$ to $m+1$, only E_{m+1} is greater than a_2. So, by definition of P_n^j, $P_{m+1}^1 = (m-1)/m$, which is identical to that by (11). On the other hand, if $E^{m+1} \le a_2$, (11) yields $P_{m+1}^1 = 1$, which is also consistent with the probability definition. In essence, given that the prediction errors become available one at a time, (11) uses an exponential-smoothing technique to handle prediction errors over a sliding window of time slots and to approximate the CDF for Δ.

Let Δ_n be a specified ωth percentile (e.g., for 90th percentile, $\omega = 0.9$) of Δ based on the error statistics up to slot n. We approximate $\Delta_n \approx a_{k+1}$ where k is the smallest from one to $J-1$ such that $P_n^k \ge \omega$. For the example in Fig. 1, the 90th percentile for Δ based on statistics up to slot n is approximated by a_{j+2} as $P_n^j < 0.9$ and $P_n^{j+1} \ge 0.9$. Let δ_n and $\tilde{i}_n$ be the linear-scale equivalent of Δ_n and $\tilde{I}_n$, respectively. The corresponding percentile of interference power in mW is the product of $\tilde{i}_n$, predicted by (1) and δ_n. Accordingly, the transmission power for slot n is determined by (9).

We note that δ_n actually 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 γ^* regardless of the actual message length and control delay (see [9] and [10]). It is also worth noting that the power control requires periodic exchange of control information between the receiver and the transmitter; see e.g., [4].

III. Problem Complexity

In this section, we prove that a simple form of the problem of maximizing network throughput subject to meeting a given PER requirement posed in Section I is NP-complete [8]. More precisely, let the system have N terminals in N different co-channel sectors concurrently transmitting packets to their base stations (i.e., having N radio links) at each time slot. The modulation level and power for link i at a given slot are denoted by $L(i)$ and $p(i)$, respectively. Let there be M modulation levels, indexed by one to M and K discrete levels of transmission power, denoted by real numbers t_i for $i = 1$ to K. As a result, for each link i, $L(i) \in \{1, 2, \ldots, M\}$ and $p(i) \in \{t_1, t_2, \ldots, t_K\}$. In general, one can represent the data rate and the required SINR detection threshold associated with each modulation level as nonlinear functions of the level index. However, we show below that even if the functions are linear, the optimization problem is already difficult to solve. Specifically, the data rate and the detection threshold for link i are assumed to be $\alpha L(i)$ and $\beta L(i)$, respectively, where α and β are proportionality constants. Let $\mathbf{L} = (L(1), L(2), \ldots, L(N))$ and $\mathbf{p} = (p(1), p(2), \ldots, p(N))$. Using this notation, the problem of maximizing the overall throughput λ for each time slot is

$$\max_{\mathbf{L}, \mathbf{P}} \lambda = \sum_{i=1}^{N} \alpha L(i) \tag{12}$$

subject to

$$\frac{g_{ii}p(i)}{\sum\limits_{j\neq i} g_{ij}p(j)+\sigma} \geq \beta L(i) \quad \text{for all } i = 1 \text{ to } N \qquad (13)$$

where g_{ij} is the path gain from the transmitter of link j to the receiver of link i and σ is the receiver noise power. We note that the above SINR constraints in (13) are used to represent the PER requirement for the chosen modulation level. Further, the throughput is maximized for each time slot. For the packet-switching networks under consideration, the values of g_{ij}'s in (13) and, thus, the optimal $\mathbf{L}$ and $\mathbf{p}$ change from one time slot to another. However, the optimization in (12) is also valid for circuit-switching wireless networks where these quantities are independent of time.

Theorem 1: The problem of maximizing the overall throughput in (12) subject to the SINR (or equivalently PER) requirement in (13) is NP-complete.

Proof: The optimization problem (12) is nonlinear due to the products of $p(j)$'s and $L(i)$'s in (13). Let $Q_{ij} = L(i)p(j)$ for all $i, j = 1$ to N. Thus, $Q_{ij} \in \{t_1, \ldots, t_K, 2t_1, \ldots, 2t_K, \ldots, Mt_1, \ldots, Mt_K\}$. Since Q_{ij}'s are finite, real numbers, we can express each Q_{ij} in terms of binary (zero or one) variables X_{ijk}'s as $Q_{ij} = \sum_{k=a_{ij}}^{\bar{a}_{ij}} X_{ijk}2^k$ where a_{ij} and $\bar{a}_{ij}$ are properly chosen integers according to the accuracy tolerance of the binary representation. Similarly, we express $L(i) = \sum_{k=b_i}^{\bar{b}_i} Y_{ik}2^k$ and $p(i) = \sum_{k=c_i}^{\bar{c}_i} Z_{ik}2^k$. Consequently, (12) becomes a nonlinear zero-one integer programming problem. Now, we apply the technique in [2] to linearize the problem by introducing new variables to replace the cross-product terms. Then, the proof is completed by using the fact that the resultant, linear integer programming is NP-complete [8, p. 245]. □

As the optimization is NP-complete, efficient algorithms are unlikely to exist. Thus, we devise a heuristic approach in the following with a primary goal of delivering the specified PER, while attempting to maximize the network throughput as a secondary objective.

IV. Integrated Link Adaptation and Power Control

There are two key factors for efficient link-adaptation schemes. First, to maximize the network throughput, it is desirable to have a link-adaptation technique that adapts quickly to changes of radio conditions. On the other hand, to guarantee the required PER, it is advantageous to adapt the link according to the actual error performance (where packet error can be identified by use of cyclic-redundancy code). Since error statistics require a long time to accumulate, especially for meeting stringent PER requirements, link adaptation based on per-user error performance will be too slow in responding to changes of channel conditions. As a compromise, we propose to divide all terminals in each co-channel sector into groups and to perform link adaptation on a per-terminal-group basis according to the error performance of each group. This way, by monitoring the error performance of all traffic associated with a terminal group, the statistics collection time can be shortened significantly, thus, enabling quick link adaptation to improve data throughput while meeting the error requirements.

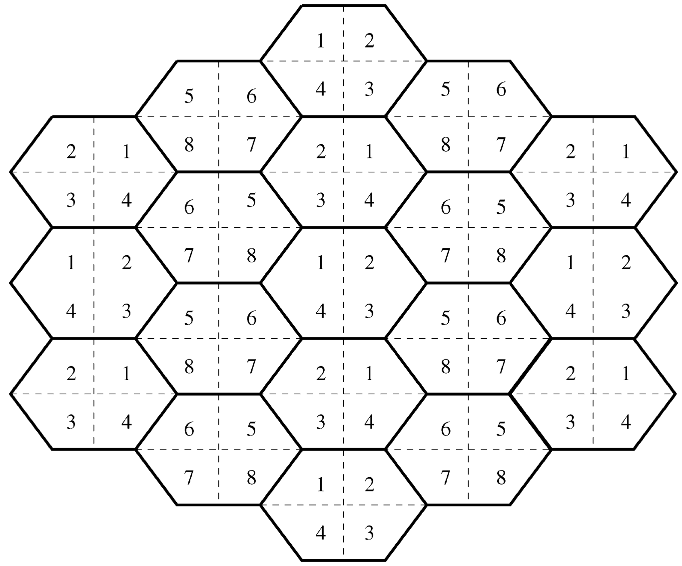


Fig. 2. Four-sector cell layout and interleaved channel assignment.

A. Terminal Grouping by Signal Path Gains

The quality of a radio link between a terminal and its associated base station can typically be characterized by three parameters: the signal path gain (including shadow fading) and signal transmission and interference power. In the wireless packet networks, both transmission and interference power change constantly. In our view, signal path gain is the most intrinsic parameter for link quality. So, we propose to use the signal path gain as a criterion for the terminal grouping. Terminals of the same group are expected to have similar link quality.

Another supporting reason for using signal path gain as the grouping criterion is that signal and interference path gains are almost uncorrelated. To illustrate our idea, consider the cellular layout and channel assignment of frequency reuse factor of two in Fig. 2 [20], where 2,000 terminals are randomly populated at fixed locations in each cell. With typical radio propagation assumptions (see Section V for details), Fig. 3 shows the relationship between the signal path gain (shadowing included) from a terminal to its associated base station and the sum of path gains from the terminal to all other co-channel base stations, which receive interference from the terminal for uplink transmission. The sum of interfering path gains reflects the potential impacts of interference caused by the terminal. It is found that the signal path gain and the sum of interfering path gains have a very small correlation coefficient of 0.018. Such uncorrelated relationship is desirable for our purposes. Otherwise, if it were a strong positive correlation, the link adaptation based on such a terminal group basis would make unstable changes of modulation level.

One way to perform the terminal grouping is to determine the range of the signal path gain for a given network. Then, the range is divided into several (not necessarily uniform) regions, according to a given set of region parameters. Terminals with corresponding signal path gain in each region form a group. To speed up the collection of error statistics uniformly for various terminal groups, it is desirable to have a roughly equal number of terminals in each group, based on an assumption that each terminal has similar traffic load characteristics. As a natural

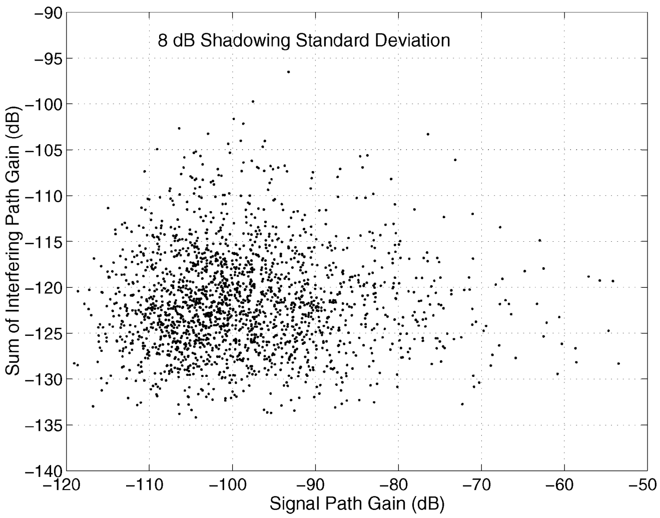


Fig. 3. Interference versus signal path gain.

TABLE I
SINR REQUIREMENT AND THROUGHPUT

Modulation Level	SINR Detection Requirement (dB)	Throughput (Kbps)
1	10	22.8
2	12	34.3
3	16	41.25
4	19	51.6
5	23	57.35
6	28	69.2

candidate, the number of terminal groups can be chosen to be equal to the number of modulation levels in the system such that each group may be transmitting or receiving at a distinct modulation level. Of course, the number of groups should be selected based on the number of active terminals; too few terminals per group will defeat the purpose of terminal grouping in terms of shortening the statistics collection time.

It is worth noting that depending on mobility, a given terminal may belong to different terminal groups in a dynamic way. Each terminal periodically estimates its signal path gain (e.g., by use of the control channel for handoff purposes in GSM system [16]). One approach to reducing unnecessary group reassignment is to feed the periodic estimates of signal path gain for each terminal into a low-pass filter. Then, comparing the "smoothed" signal-path gain against the region parameters determines the affiliated terminal group for the terminal. Based on this method, unless a terminal is extremely mobile, the smoothed quantity provides a reasonable representation of the signal-path gain.

B. Adaptation Algorithm by Terminal Grouping

The new algorithm for link adaptation and power control for uplink transmissions is outlined as follows (while similar operations apply to downlink).

1) For each co-channel sector, its base station continuously collects the error statistics and computes the PER P_E for every K packet transmissions from terminals of each group. In addition, it keeps track of the average transmission power $\bar{p}$ of the K packet transmissions, regardless of their modulation levels, for each terminal group.
2) This step is taken every time after K packets have been transmitted by terminals of the same group. If P_E is higher than the required value P_R, adjust the modulation level down by one level for the next K packet transmissions by terminals in the group. The purpose of stepping down the modulation level is to lower the required SINR for correct reception, thus, improving the PER when needed. Further, if $\bar{p}$ is less than a given threshold p_t (e.g., 15 dBm), step up the modulation level by one level for the next K transmissions from the terminal group. The idea there is to utilize unused power to increase data rate, if possible.
3) To achieve the PER requirement, the enhanced Kalman-filter power control in Section II is used to adjust the transmission power for each time slot according to (9) to achieve the SINR target for the adapted modulation level.
4) Due to different fading conditions for various terminals, using the same γ^* for a given modulation level in (9) may not necessarily guarantee the required PER performance for each terminal in the same group. To ensure that, each terminal is allowed to use slightly different values of γ^* as follows. Each modulation level has a nominal SINR target γ and each terminal maintains an adjustment parameter, denoted by Θ and θ in dB and linear scale, respectively. Initially, each terminal sets $\Theta = 0$ and $\theta = 1$. Each terminal monitors its PER for every K packets transmitted by the terminal. If the updated PER fails to meet the required P_R, Θ is increased by a prespecified, fixed quantity (e.g., 0.5 dB). Otherwise, Θ is decreased by the same quantity, unless Θ is zero. Then, for the next K packet transmissions by the terminal, the linear-scale equivalent θ is used to obtain the SINR target for the chosen modulation level by substituting $\gamma^* = \gamma\theta$ into (9) for power control. (The same θ is applicable to determining γ^* for any modulation level chosen for the terminal.) The key idea here is to slightly increase the SINR target by Θ dB for achieving the required error performance for individual terminals.

The choice of K in Step 1 should be large enough to ensure statistical significance of the measured error rate relatively to a given PER requirement P_R. A reasonable choice is to set K to be 10 or 20 times of $1/P_R$. For example, when $P_R = 0.02$, choose $K = 500$ or 1,000 to ensure the accuracy of the measured PER performance.

It is worth noting that Step 2 steps down the modulation level due to unsatisfactory PER performance and moves it up in case of under-utilized power. In special cases, it is possible that the PER does not meet the required performance and the average transmission power is also below the threshold p_t. We expect that such is probably due to the fact that the Kalman filter cannot

TABLE II
PERFORMANCE COMPARISON OF LINK-ADAPTATION METHODS FOR $L = 10$ PACKETS/MESSAGE

Cases	PER for Modulation Levels						Overall	Throughput
	1	2	3	4	5	6	PER	(Kbps)
SINR-Based Adaptation Method								
1) Without PC	0.61	0.061	0.092	0.10	0.12	0.10	0.17	44.15
2) Kalman PC ($P_R = 2\%$)	0.59	0.067	0.098	0.10	0.12	0.11	0.16	45.67
3) Kalman PC ($P_R = 5\%$)	0.52	0.050	0.076	0.073	0.090	0.12	0.11	46.87
4) Kalman PC ($P_R = 10\%$)	0.13	0.076	0.088	0.090	0.093	0.083	0.093	39.19
Terminal-Grouping Method for Adaptation								
5) Without PC ($P_R = 2\%$)	0.14	0.012	0.010	0.007	0.018	0.025	0.10	26.88
6) Without PC ($P_R = 5\%$)	0.15	0.026	0.026	0.011	0.017	0.060	0.10	29.55
7) Without PC ($P_R = 10\%$)	0.19	0.045	0.060	0.052	0.026	0.060	0.11	33.34
8) Kalman PC ($P_R = 2\%$)	0.051	0.027	0.023	0.022	0.022	0.018	0.027	35.60
9) Kalman PC ($P_R = 5\%$)	0.061	0.052	0.055	0.050	0.055	0.041	0.053	38.74
10) Kalman PC ($P_R = 10\%$)	0.12	0.097	0.10	0.10	0.10	0.075	0.099	38.79
11) Method D in [12]	0.052	0.023	0.031	0.045	0.045	0.028	0.029	32.7

predict interference-plus-noise power accurately enough. Since the power control in (9) includes the error margin δ_n, which possibly changes from one time to the next, slight increase in δ_n because of the inaccurate predictions (thus, using a small fraction of unused power) may be enough to meet the PER requirement. Thus, the modulation level remains unchanged in Step 2 for those cases, with a hope that the PER becomes satisfactory for the next K packet transmissions by power control. We also remark that the dynamic adjustment for γ^* according to the measured and required packet error rate in Step 4 is similar to the outer-loop power control for code-division multiple-access (CDMA) systems [11].

V. PERFORMANCE STUDY

A. Simulation Model

We use computer simulation to study the performance of the proposed algorithm for link adaptation and power control based on the terminal grouping, which is referred to as the terminal-grouping method below. The cell layout and interleaved channel assignment (ICA) with a frequency reuse factor of two [20] in Fig. 2 is simulated. In this ICA scheme, there are four sets of channels and sectors with the same label in the figure share the same channel set. Each cell is divided into four sectors, each of which is served by a base station antenna at the center of the cell. The beamwidth of each base station antenna is 60°, while terminals have omnidirectional antennas. Each radio link between a terminal and its base station is characterized by a path-loss model with an exponent of four 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 at the receiver is fixed and equal to -110 dBm. Each sector is populated with 500 terminals randomly and each of them selects the base station that provides the strongest signal power. Terminals are assumed to remain stationary throughout the simulation. For convenience, terminals in all cells are assumed to be synchronized at the slot boundary for transmission. Furthermore, unless stated otherwise, we assume 100% traffic load in this study; that is, there are always terminals ready for transmission in each co-channel sector. Message length is assumed to have a discrete form of Pareto distribution [9] with average length denoted by

L. More precisely, each time a terminal transmits a message, i, the number of slots used in the message transmission, is characterized by the following cumulative distribution function

$$H_i = 1 - \left(\frac{k}{i}\right)^{\alpha} \quad \text{for } i \geq k \in Z^{+} \text{ and } \alpha > 1 \tag{14}$$

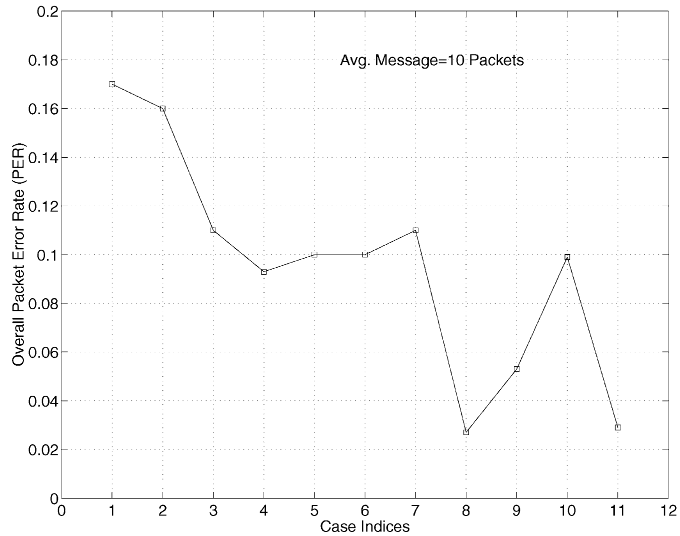
where k and α are given parameters. Then, the probability that a message consists of i packets is given by $h_i = (k/i)^{\alpha} - (k/(i+1))^{\alpha}$ for $i \geq k \in Z^{+}$ and the average message length is

$$L = k + \sum_{i=k+1}^{\infty} \left(\frac{k}{i}\right)^{\alpha}. \tag{15}$$

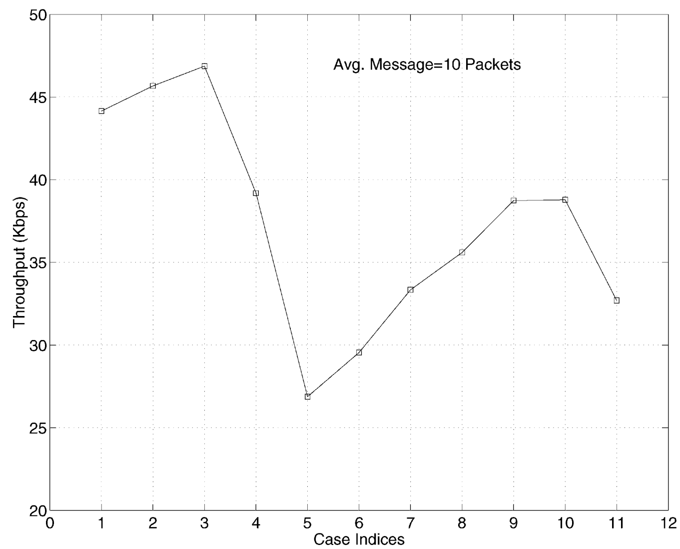
Since the Pareto distribution has an infinite variance if $\alpha \leq 2$, such values should be avoided. Otherwise, our simulation cannot reach a steady state and results will not have statistical significance. Thus, to guarantee finite variance, for a given L, we set $k = \lceil L/2 \rceil$ to ensure $\alpha > 2$, where $\lceil y \rceil$ is the smallest integer greater than or equal to y. Using this k value, α can be solved from (15) for the given L. Remark that $\alpha > 2$ may make effects of traffic burstiness somewhat less evident. However, our results below show that system performance strongly depends on L. For a fixed L, impacts of variation in k and α require further study.

The enhanced Kalman-filter method is used to control transmission power for each time slot in each co-channel sector in Fig. 2. For tracking the CDF of the prediction error Δ, ϕ in (11) is set to be 0.999 (approximately equal to tracking the error over a sliding window of 1,000 slots) and the number of error intervals J is 100. For a given PER requirement P_R, the ωth percentile of the prediction error with $\omega = 1 - P_R$ is used in determining the error margin δ_n for adjusting power in (9). For example, when $P_R = 0.02$, δ_n is the 98th percentile of the prediction error. In any event, transmission power is limited between 0–30 dBm. The average power threshold, p_t, for determining stepping up the modulation level in Step 2 of the algorithm is 15 dBm. As illustrative examples, W and η in (6) and (8) are set to be 30 and 0.5, respectively. The model also assumes that interference power in one time slot can be measured and used to determine the power for the next slot.

We assume that the system has six modulation levels. The SINR detection requirements and the corresponding data throughput for each modulation level are given in Table I. For example, for a packet transmission using modulation level 1, if the SINR at the receiver is greater than 10 dB, the packet is received successfully and the associated data throughput is 22.8 kb/s. Naturally, the SINR requirements are also used as the targets γ^* for various modulation levels to control power in (1). For simplicity, slow adjustment of SINR targets for individual terminals in Step 4 of the algorithm is not considered in the simulation. Parameters in Table I are actually adapted from Table III and estimated from Fig. 20 of [5]. With six modulation levels, all 500 terminals in each sector are divided into six groups of equal size according to their signal path gain. Initially, the group with the weakest to the strongest signal path gain uses modulation level 1 to 6 for transmission, respectively. Then, according to the algorithm, the modulation level is readapted every $K = 1{,}000$ packets transmitted by each terminal group. For each parameter setting, the simulation model was run for 0.4 million time slots and performance results presented below were obtained for the middle cell in Fig. 2.



(a)



(b)

Fig. 4. (a) Comparison of packet error rate for various link-adaptation methods for $L = 10$ packets/message (b) Throughput comparison for various link-adaptation methods for $L = 10$ packets/message.

B. Performance Results and Discussions

To set up a basis for comparison, we consider a simple link-adaptation scheme without power control (PC) that chooses the modulation level according to the SINR measurement of the previous time slot. Specifically, the scheme compares the SINR measurement with the detection requirements in Table I. For example, when the measurement lies between 12–16 dB, modulation level 2 is used for transmission in the next time slot. Every sector makes such selection for its transmitting terminal independently. This SINR scheme is referred to as *Case 1* in Table II. Cases 2–4 are identical to Case 1, except that the enhanced Kalman method is now used to control transmission power according to the various

TABLE III
PROBABILITY OF TRANSMISSION AT VARIOUS MODULATION LEVELS FOR THE TERMINAL-GROUPING METHOD WITH 100% TRAFFIC LOAD AND $L = 10$ PACKETS/MESSAGE

Terminal Group	Target PER	Modulation Level					
		1	2	3	4	5	6
1	0.05	1.0	0.0	0.0	0.0	0.0	0.0
1	0.10	1.0	0.0	0.0	0.0	0.0	0.0
1	0.15	1.0	0.0	0.0	0.0	0.0	0.0
2	0.05	0.834	0.166	0.0	0.0	0.0	0.0
2	0.10	0.646	0.354	0.0	0.0	0.0	0.0
2	0.15	0.367	0.550	0.083	0.0	0.0	0.0
3	0.05	0.180	0.603	0.218	0.0	0.0	0.0
3	0.10	0.065	0.456	0.479	0.0	0.0	0.0
3	0.15	0.033	0.423	0.544	0.0	0.0	0.0
4	0.05	0.017	0.257	0.548	0.178	0.0	0.0
4	0.10	0.0	0.103	0.542	0.338	0.017	0.0
4	0.15	0.017	0.069	0.399	0.454	0.062	0.0
5	0.05	0.0	0.0	0.033	0.562	0.372	0.033
5	0.10	0.0	0.0	0.0	0.215	0.652	0.133
5	0.15	0.0	0.0	0.0	0.149	0.600	0.251
6	0.05	0.0	0.0	0.0	0.0	0.017	0.983
6	0.10	0.0	0.0	0.0	0.0	0.0	1.0
6	0.15	0.0	0.0	0.0	0.0	0.0	1.0

PER requirements P_R. To help us understand the algorithm characteristics, Cases 5–7 correspond to the link-adaptation method by terminal grouping without power control, while Cases 8–10 represent our proposed algorithm. Table II presents the throughput, the PER for packets transmitted at different modulation levels and the overall PER averaged over all levels for these cases.

First of all, we observe from the table that when power control is not used, Cases 1 and 5–7 for both the SINR and terminal-grouping methods cannot control the PER effectively. For the SINR method, it is so because the previous SINR measurements may not accurately predict SINR performance in future time slots because of the burstiness of packet transmission in the wireless packet environment. As a result, the chosen modulation level may not lead to successful packet reception as the radio conditions can change drastically in time. As for Cases 5–7, the terminal-grouping method adapts the modulation level according to the requirement P_R. However, the scheme is not effective in delivering the PER performance because the link adaptation takes place only periodically and the radio conditions can vary significantly from one time slot to another during the adaptation period.

As the results for Cases 2–4 show, the SINR scheme with the enhanced Kalman power control is still not quite effective in achieving the specified error performance because SINR measurements may not accurately reflect future link quality. In contrast, according to the specified PER requirement P_R, the proposed algorithm adapts transmissions at appropriate modulation levels and adjusts transmission power to meet the SINR detection threshold. Consequently, as shown in Table II, the PER performance for Cases 8–10 generally comes very close to the PER target P_R. One can observe that the PER for transmission at modulation level 1 in Case 8 is noticeably higher than the required 2% PER. This reveals that the radio conditions may not support the very stringent PER performance for a very small fraction of terminals. In any event, the overall PER of 2.7% is very close to the target of 2% in that case. As expected, when P_R becomes stringent, the throughput is reduced in Cases 8–10.

We also compare the performance of the terminal-grouping method with that reported in [12]. The latter algorithm chooses modulation level and transmission power according to a power-stability criterion to maintain stable transmission power in a long run. As mentioned earlier, such use of the stability criterion is unnecessary as the new algorithm monitors and operates based on the measured PER. To show a comparison between their performance, we include results for Method D in Table II of [12] as Case 11 in Table II here. Despite differences in the link-adaptation algorithms, the error performance for Case 11 is very similar to that of Case 8. However, our new algorithm yields about 10% more throughput than the one in [12]. Furthermore, our extensive testing shows that the new algorithm is more robust in delivering desirable performance for a wide range of settings than the previous one.

It is important to point out that the ability to control the PER to meet the specified targets by the proposed algorithm comes at a price of reduced throughput. In fact, this represents

TABLE IV
PER PERFORMANCE OF THE TERMINAL-GROUPING METHOD (WITH POWER CONTROL)

Traffic Load (%)	Target PER	Measured PER ($L = 5$)	Measured PER ($L = 10$)	Measured PER ($L = 20$)
100	0.02	0.028	0.027	0.023
100	0.05	0.053	0.053	0.052
100	0.10	0.099	0.099	0.097
100	0.15	0.145	0.144	0.146
100	0.20	0.191	0.188	0.171
80	0.02	0.021	0.023	0.025
80	0.05	0.049	0.050	0.054
80	0.10	0.095	0.094	0.099
80	0.15	0.141	0.136	0.142
80	0.20	0.184	0.176	0.183
60	0.02	0.022	0.023	0.026
60	0.05	0.051	0.052	0.054
60	0.10	0.097	0.097	0.100
60	0.15	0.142	0.138	0.143
60	0.20	0.183	0.171	0.185
40	0.02	0.022	0.023	0.028
40	0.05	0.051	0.050	0.054
40	0.10	0.096	0.093	0.099
40	0.15	0.139	0.128	0.142
40	0.20	0.179	0.161	0.185

an interesting tradeoff between maximizing throughput and controlling PER performance. To illustrate this, Fig. 4(a) and 4(b) portray the overall PER and throughput for all cases reported in Table II. One can see from the figures that the SINR method in Cases 1–3 yields relatively high throughput than other cases, while the PER for Cases 1–3 is also higher than that of other cases. Although Cases 5–7 provide similar PER in Fig. 4(a), their throughput is low relative to other cases, as shown in Fig. 4(b). On the other hand, for Cases 8–10, which correspond to the proposed terminal-grouping method with required PER P_R of 0.02, 0.05, and 0.1, respectively, the measured PER comes very close to the PER requirement without reducing their throughput to the level of Cases 5–7.

Table III presents the probability distribution of the modulation levels for actual packet transmission for the proposed algorithm for various target PER. For example, for terminal group 4, the probability of packet transmission using modulation level 4 is 0.178, 0.338, and 0.454 for the target PER of 5%, 10%, and 15%, respectively. This confirms the expected operations of the proposed algorithm because for less stringent PER requirement, the algorithm will tend to step up the modulation level for transmission.

Finally, we study the packet error and throughput performance of the proposed algorithm with partial traffic loading. For a given loading, after a terminal completes a message transmission, its associated sector remains idle for a random number of time slots before a next terminal in the sector is allowed to start a new message transmission. The duration

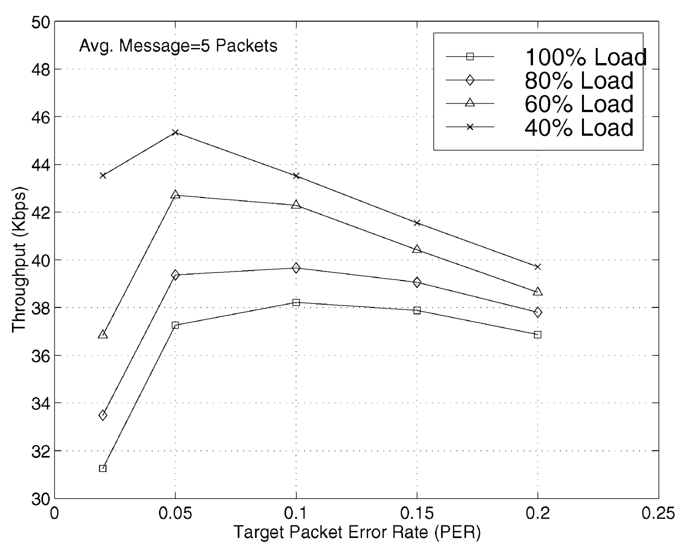


Fig. 5. Throughput performance of the terminal-grouping method (with power control) for $L = 5$ packets/message.

of an idle period is geometrically distributed and its average is determined according to the average message length and the traffic loading. Table IV presents the measured PER of the proposed algorithm for various target (required) PER, traffic load conditions and average of 5, 10, and 20 packets per message (denoted by $L =$ 5, 10, and 20). We observe that the proposed algorithm indeed can deliver the required PER

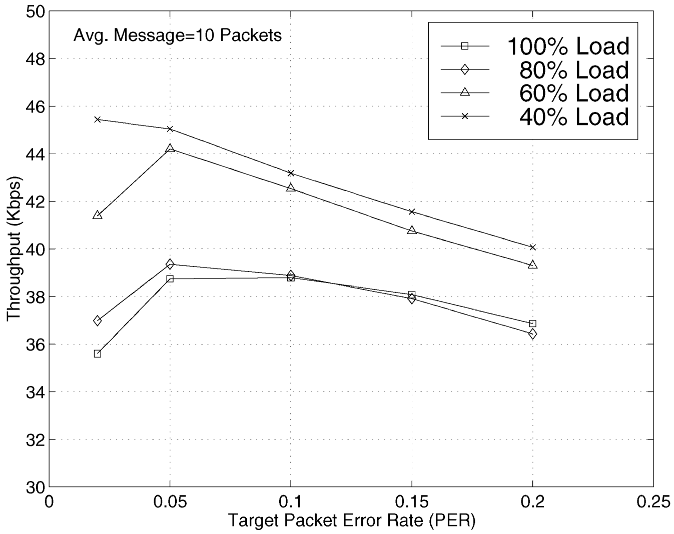


Fig. 6. Throughput performance of the terminal-grouping method (with power control) for $L = 10$ packets/message.

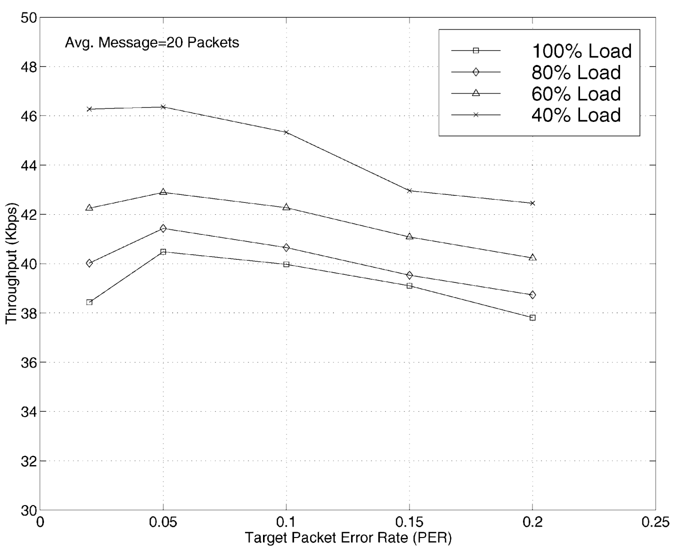


Fig. 7. Throughput performance of the terminal-grouping method (with power control) for $L = 20$ packets/message.

performance as the measured PER comes very close to the target values in all cases considered.

Figs. 5–7 show the corresponding throughput performance as a function of target PER for $L = 5$, 10, and 20, respectively. It is interesting to note for these figures that for a given L value, the throughput generally increases as traffic load decreases. This is a very desirable feature because the power control in the proposed algorithm will detect reduced interference power when traffic load decreases, thus, lowering the transmission power needed to yield the SINR target γ^* in (9). In turn, comparing the average transmission power with a fixed threshold p_t by Step 2 of the algorithm in Section IV-B will likely step up the modulation level for transmission, which results into increased data throughput.

Second, Figs. 5–7 reveal that for a given traffic load and L value, the throughput does not always improve as the target PER is increased (relaxed). Evidently, for very stringent PER requirement, the algorithm will force most of the transmissions using the more robust modulation, which yields a low throughput. On the other hand, when the required PER is too high, the algorithm tends to allow too many packets transmitted using high modulation levels, which can result into unsuccessful reception and lowered throughput. For a given traffic load and message length characteristics, there appears to be an "optimal" target PER that can maximize the network throughput.

VI. Conclusion

The problem of maximizing data throughput by adaptive modulation/coding and power control while meeting requirements of PER has been shown to be NP-complete. A heuristic algorithm for integrated link adaptation and power control has been proposed to achieve specified error rates while improving overall throughput for real-time applications in broadband wireless networks. The algorithm divides terminals into groups according to their signal path gains and adapts the transmissions based on the required error rates, actual error statistics, and the average transmission power of each terminal group. Transmission power is adjusted by an enhanced Kalman-filter method to ensure correct reception.

The performance of the proposed algorithm has been studied by computer simulation. Our results reveals that the algorithm delivers the required error performance and attempts to improve network throughput at the same time. It can take advantage of reduced interference for decreased traffic load to further improve throughput by transmitting at high modulation levels. Extensive testing shows that the algorithm is very robust and efficient. By having various packet error requirements, the algorithm is applicable to real-time multimedia services. The new algorithm can also serve as a useful tool for achieving a desirable tradeoff among throughput, PER and coverage in the networks.

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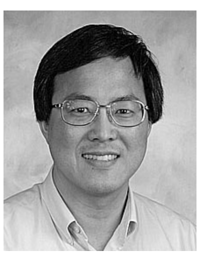
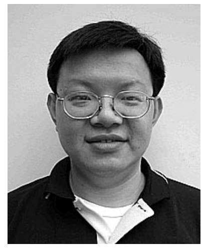


Kin K. Leung (S'78–M'85–SM'93–F'01) received the B.S. degree in electronics from the Chinese University of Hong Kong, Hong Kong, in 1980 and the M.S. and Ph.D. degrees in computer science from University of California, Los Angeles, in 1982 and 1985, respectively.

He joined AT&T Bell Labs, Holmdel, NJ, in 1986. He was with AT&T Labs from 1996 to 2002. Recently, he rejoined Bell Labs, Lucent Technologies, Murray Hill, NJ. His research interests include radio resource allocation, power control, adaptive modulation, spread spectrum, MAC protocols, teletraffic issues, and mobility management in broadband wireless networks.

Dr. Leung received the Distinguished Member of Technical Staff Award from AT&T Bell Labs in 1994 and shared with his colleagues the 1997 Lanchester Prize Honorable Mention Award. He actively serves on the Technical Program Committees for international conferences, including committee Co-Chair for the Multiaccess, Mobility, and Teletraffic for Wireless Communications (MMT'98) and the committee Vice-Chair for the ICC 2002. He was a Guest Editor for the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS. Currently, he is an Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS and TRANSACTIONS ON WIRELESS COMMUNICATIONS.



Li-Chun Wang (S'93–M'96) received the B.S. degree from National Chiao Tung University, Taiwan, in 1986, the M.S. degree from National Taiwan University, in 1988, and the M.Sci. and Ph.D. degrees from Georgia Institute of Technology, Atlanta, GA, in 1995 and 1996, respectively, all in electrical engineering.

From 1990 to 1992, he was with the Telecommunications Laboratories of Ministry of Transportations and Communications, Taiwan (currently the Telecom Labs of Chunghwa Telecom Company). In 1995, he was with Bell Northern Research of Northern Telecom Inc., Richardson, TX. From July 1996 to 2000, he was a Senior Technical Staff Member in the Wireless Communications Research Department, AT&T Laboratories, Middletown, NJ. Since September 2000, he has been the Associate Professor in the Department of Communications Engineering, National Chiao Tung University. His current research interests are in the area of cellular architectures and radio resource management techniques for heterogenerous wireless networks.

Dr. Wang was a Co-Receipent of the 1997 IEEE Jack Neubauer Memorial Award for the Best System Paper of the year, published in the IEEE TRANSCTIONS ON VEHICULAR TECHNOLOGY. Currently, he is an Associate Editor of IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS.