Integrated Link Adaptation and Power Control for Wireless IP Networks

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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 wireless IP 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. 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.

1. INTRODUCTION

As telecommuting and Internet access become increasingly popular, customers' demand for broadband network services has been growing significantly. In the very 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 ETSI is in the process of establishing the protocol standards for the Enhanced Data rates for GSM Evolution (EDGE) system 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 [E98] (a current proposal has nine modulation and coding levels [E99]), where the highest data rate can exceed 550 Kbits/sec. 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. For example, when the channel and interference conditions are poor, a low modulation level (i.e., few information 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 IP voice, music and video, stringent delay requirements severely limits or even precludes re-transmission 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 the 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.* In this paper, we propose and analyze an integrated algorithm of link adaptation and power control for the problem.

Our recent work [LW99] and [LW00] on integrated power control and link adaptation represent our initial attempts in solving the problem. In particular, the proposed algorithm in [LW00] 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 the link adaptation and power control operate 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 so because monitoring and controlling the PER performance by the link adaptation and power control implicitly force transmission power to fall within a given dynamic range. Indeed, the algorithm proposed in this paper is based on monitoring the 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., [Z92], [RZ98] and [UY98]. Recently, [L99] 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, [GC97] and [AG98]. By considering interference-limited systems, [QC99a] shows that the overall network throughput can be maximized by adaptive modulation and power control. Recently, [C99] and [QC99b] propose new adaptation schemes to improve overall data throughput for non-real-time data services. However, the use of link adaptation to deliver the specified QoS for real-time, multimedia applications is an open issue, which is the topic to be addressed in this paper. Furthermore, we examine how power control, which is not considered in [C99] and [QC99b], is integrated with link adaptation for performance improvement.

The rest of this paper is organized as follows. We first present the operations and power control for the wireless packet networks under consideration in Section 2. In Section 3, we prove that the problem of maximizing network throughput while meeting the given PER requirements is NP-complete. That is, no efficient algorithm for solving the problem exists. Then, a new algorithm for integrated link adaptation and power control based on monitoring PER performance is proposed in Section 4. In Section 5, we study the performance of the proposed algorithm by simulation. Finally, Section 6 presents our conclusion.

2. 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 kilometers and operating frequency in the range of 1 to 5 GHz. Assume that the TDMA network supports IP in a way 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. Similar to other IP networks, when a transmitter (either a mobile terminal or a base station) sends a message, all its packets are transmitted in contiguous time slots. 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 for integrated power control and adaptive modulation to be proposed below is applicable to both uplink (from terminal to base station) and downlink (from base station to terminal), our discussion will focus on the uplink transmission here.

The enhanced Kalman-filter method [L00] is used to control transmission power. That is, the transmission power for time slot *n* is set to be

$$p(n) = \gamma^* \delta(n) \tilde{i}(n) / g(n) \tag{1}$$

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, $\delta(n)$ is an error margin (to be discussed further below), and $g(n)$ is the (estimated) path gain between the terminal that transmits in slot *n* and its base station.

The error margin $\delta(n)$ is obtained by tracking the accuracy of the interference power predicted by the Kalman filter. More precisely, let Δ (a random variable in dB) be the error of the Kalman-filter prediction and the error for slot *n* be

$$E(n) = I(n) - \tilde{I}(n) \tag{2}$$

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

$$P_n^j = \begin{cases} \phi P_{n-1}^j & \text{if } E(n) > a_{j+1} \\ \phi P_{n-1}^j + 1 - \phi & \textit{otherwise} \end{cases} \tag{3}$$

where ϕ is a properly chosen parameter between 0 and 1, and $P_0^j = 1$ for all $j = 1$ to *J*. Let $\Delta(n)$ be a specified ω^{th} percentile (e.g., for 90th percentile, $\omega = 0.9$) of Δ based on the error statistics up to slot *n*. We approximate $\Delta(n) \approx a_k$ where *k* is the smallest from 1 to *J* such that $P_n^k \geq \omega$. Let $\delta(n)$ and $\tilde{i}(n)$ be the linear-scale equivalent of $\Delta(n)$ and $\tilde{I}(n)$, respectively. The corresponding percentile of the interference-plus-noise power in mW is the product of $\tilde{i}(n)$ (predicted by the Kalman filter) and $\delta(n)$. Accordingly, the transmission power for slot *n* is determined by (1).

In essence, the term $\delta(n)$ 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 [L00] and [L99] for details of the Kalman method.

3. 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 1 is NP-complete [GJ79]. 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 1 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 i, $L_i \in \{1,2,...,M\}$ and $p_i \in \{t_1,t_2,...,t_K\}$. For simplicity, the data rate and the required SINR detection threshold for link i are assumed to be αL_i and βL_i, respectively, where α and β are proportionality constants. Let $\mathbf{L}=(L_1,L_2,...,L_N)$ and $\mathbf{p}=(p_1,p_2,...,p_N)$. Using this notation, the problem of maximizing the overall throughput λ for each time slot is:

$$\max_{\mathbf{L},\mathbf{P}} \ \lambda = \sum_{i=1}^{N} \alpha L_i \tag{4}$$

$$\text{subject to} \quad \frac{g_{ii} p_i}{\sum_{j \neq i} g_{ij} p_j + \sigma} \geq \beta L_i \quad \text{for all } i=1 \text{ to } N \tag{5}$$

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 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 (5), and thus the optimal $\mathbf{L}$ and $\mathbf{p}$ change from one time slot to another. However, the optimization in (4) 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 (4) subject to the SINR (or equivalently PER) requirement in (5) is NP-complete.*

Proof. The optimization problem (4) is nonlinear due to the products of p_j's and L_i's in (5). Let $Q_{ij}=L_i p_j$ for all $i,j=1$ to N. Thus, $Q_{ij} \in \{t_1,...,t_K,2t_1,...,2t_K,...,Mt_1,...,Mt_K\}$. 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, (4) becomes a nonlinear zero-one integer programming problem. Now, we apply the technique in [C69] 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 [GJ79, p.245]. □

As the optimization problem is NP-complete, it is unlikely that any efficient algorithm may exist. Thus, we choose to devise a heuristic approach in the following with a primary goal of delivering the specified PER and maximizing the network throughput as a secondary objective.

4. 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. Since error statistics require a long time to accumulate, 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, the statistics collection time can be shortened significantly, thus enabling quick link adaptation to improve data throughput while meeting the error requirements.

4.1 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 packet networks under consideration, 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, and cause similar amount of interference to others.

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 2 in Figure 1 [WL99], where 2,000 terminals are randomly populated at fixed locations in each cell. With typical radio propagation assumptions (see Section 5 for details), we examined 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 is a strong positive correlation, the link adaptation based on such a terminal group basis may 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. Terminals with corresponding signal path gain in each region form a group. To speed up the collection of error statistics uniformly, it is desirable to have a roughly equal number of terminals in each group. As a natural 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.

4.2 Adaptation Algorithm by Terminal Grouping

The new algorithm for link adaptation and power control for uplink transmissions is outlined below (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 $\overline{p}$ 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 is to lower the required SINR for correct reception, thus improving the PER when needed. Further, if $\overline{p}$ 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, each modulation level is associated with a nominal SINR target. Using the enhanced Kalman-filter power control in Section 2, adjust the transmission power for each time slot to achieve the SINR target for the adapted modulation level.
4. For each terminal, the SINR target is adjusted periodically and relatively slowly (i.e., similar to the CDMA outer-loop power control) to ensure required error performance for individual terminals.

5. PERFORMANCE STUDY

5.1 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 2 [WL99] in Figure 1 is simulated. Each cell is divided into 4 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^o, while terminals have omni-directional antennas. Each radio link between a terminal and its base station is characterized by a path-loss model with an exponent of 4 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 100m 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. 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 be Pareto distributed with an average of 10 packets [L99].

The enhanced Kalman-filter method outlined in Section 2 is used to control transmission power for each time slot. For tracking the CDF of the prediction error Δ, ϕ in (3) 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 ω^{th} percentile of the prediction error with $\omega = 1 - P_R$ is used in determining the error margin $\delta(n)$ for adjusting power in (1). For example, when $P_R = 0.02$, $\delta(n)$ is the 98th percentile of the prediction error. In any event, transmission power is limited between 0 to 30 dBm. The average power threshold, p_t, for determining stepping up the modulation level in Step 2 of the algorithm is 15 dBm. Two adjustable parameters for the Kalman-filter method, W and η, are set to be 30 and 0.5, respectively. The model also assumes that interference power in one time slot can be measured accurately and used to determine the power for the next slot.

We assume that the system has 6 modulation levels. The SINR detection requirements and the corresponding data throughput for each modulation level are given in Table 1. 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 data throughput is 22.8 Kbps. 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 1 are actually adapted from Table 3 and estimated from Figure 20 of [E98]. With 6 modulation levels, all 500 terminals in each sector are divided into 6 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 re-adapted 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 Figure 1.

5.2 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 1. For example, when the measurement lies between 12 and 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 A* in Table 2. Cases B to D are identical to Case A, except that the enhanced Kalman method is now used to control transmission power according to the various PER requirements P_R. To help us understand the algorithm characteristics, Cases E to G correspond to the link-adaptation method by terminal grouping without power control, while Cases H to J represent our proposed algorithm. Table 2 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 A and E to G 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 E to G, 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 B to D show, the SINR scheme with the enhanced Kalman power control is still not quite effective 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 2, the PER performance for Cases H to J generally comes very close to the PER target P_R. One can observe that the PER for transmission at modulation level 1 in Case H 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 intuitively expected, when P_R becomes stringent, the throughput is reduced in Cases H to J. For comparison, we also include results for Method D in Table 2 of [LW99] as Case K here. Despite differences in the link adaptation algorithms, the error performance for Case K is very similar to that of Case H. However, the new algorithm proposed here yields about 10% more throughput than that reported in [LW99]. 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 an interesting tradeoff between maximizing throughput and controlling PER performance. For example, one can see from Table 2 that the SINR method in Cases A to D yields almost 1/3 more throughput than Cases H to J of the terminal-grouping method. Nevertheless, to meet the PER requirements for specific applications, network designers can use the integrated algorithm for power control and link adaptation to achieve a desirable tradeoff between the PER and throughput.

Finally, we studied 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 of an idle period is geometrically distributed and its average is determined according to the average message length and the traffic loading. We measured the actual PER and throughput of the proposed algorithm for various target (required) PER and traffic load conditions. Although these results are not presented here due to space limitation, they allow us to make several observations. First, we find that the proposed algorithm indeed can deliver the required PER performance as the measured PER comes very close to the target values. Second, it is interesting to note that the throughput 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 (1). In turn, comparing the average transmission power with a fixed threshold p_t by Step 2 of the algorithm in Section 4.2 will likely step up the modulation level for transmission, which results into increased data throughput. Third, for a given traffic load, 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 result into unsuccessful reception and lowered throughput. For a given traffic load, there appears to be an "optimal" target PER that can maximize the network throughput.

6. CONCLUSIONS

The problem of maximizing data throughput by adaptive modulation/coding and power control while meeting requirements of packet error rate 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 [L00] 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 maximize network throughput. It can further improve throughput when interference is reduced for decreased traffic load. Extensive testing shows that the algorithm is very robust and efficient. By having various packet error requirements, the algorithm is applicable to real-time, multi-media services. The new algorithm can also serve as a useful tool for achieving a desirable tradeoff among throughput, packet error rate and coverage in the networks.

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Table 1. SINR Requirement & 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

Fig.1. A 4-Sector Cell Layout and ICA

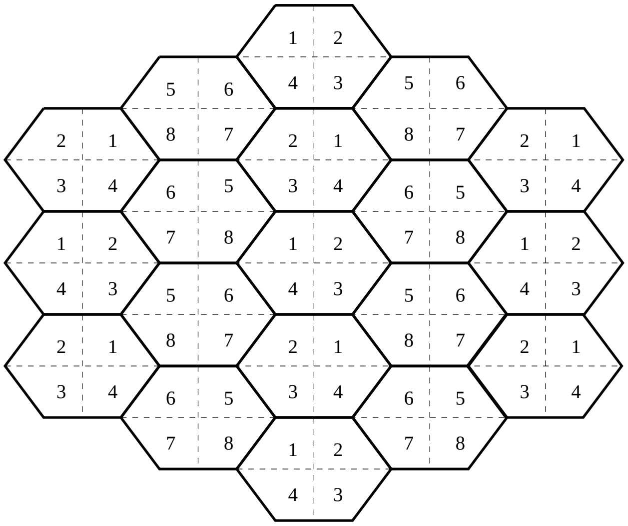

Table 2. Performance Comparison of Link-Adaptation Methods.

Cases	PER for Modulation Levels						Overall PER	Throughput (Kbps)
	1	2	3	4	5	6		
SINR-Based Adaptation Method								
A) Without PC	0.61	0.061	0.092	0.10	0.12	0.10	0.17	44.15
B) Kalman PC $(P_R = 2\%)$	0.59	0.067	0.098	0.10	0.12	0.11	0.16	45.67
C) Kalman PC $(P_R = 5\%)$	0.52	0.050	0.076	0.073	0.090	0.12	0.11	46.87
D) 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								
E) Without PC $(P_R = 2\%)$	0.14	0.012	0.010	0.007	0.018	0.025	0.10	26.88
F) Without PC $(P_R = 5\%)$	0.15	0.026	0.026	0.011	0.017	0.060	0.10	26.88
G) Without PC $(P_R = 10\%)$	0.19	0.045	0.060	0.052	0.026	0.060	0.11	33.34
H) Kalman PC $(P_R = 2\%)$	0.051	0.027	0.023	0.022	0.022	0.018	0.027	35.60
I) Kalman PC $(P_R = 5\%)$	0.061	0.052	0.055	0.050	0.055	0.041	0.053	38.74
J) Kalman PC $(P_R = 10\%)$	0.12	0.097	0.10	0.10	0.10	0.075	0.099	38.79
K) Method D in [LW99]	0.052	0.023	0.031	0.045	0.045	0.028	0.029	32.7