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Controlling QoS by Integrated Power Control and Link Adaptation in Broadband Wireless Networks *

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Abstract. We propose and analyze the performance of an algorithm for integrated power control and adaptive modulation/coding to achieve a specified range of packet error rate for real-time applications in broadband wireless packet-switched networks. The algorithm applies the Kalman-filter method [1] for power control, and adapts packet transmission to an appropriate modulation level, according to the packet error requirement, and the radio and interference conditions. A new criterion for maintaining stable transmission power is derived. Based on the criterion, the proposed technique performs the link adaptation and adjusts transmission power to achieve the specified packet error rate. The effectiveness of the proposed method is demonstrated by several numerical examples.

1 INTRODUCTION

Customers' demand for broadband network services has been growing significantly as telecommuting and Internet access become increasingly popular. In the very near future, broadband services are also expected to support real-time, multimedia services such as voice, image and video. Today, researchers and engineers are actively exploring the feasibility of many new technologies such as asymmetrical digital subscriber loop (ADSL), hybrid fiber-coax (HFC), and wireless access for such broadband services. Although the wireless approach is not expected to provide a data rate as high as the wired counterparts, wireless networks can support very desirable features such as ubiquitous service and user mobility.

Another important trend is the use of packet-switching technology to replace traditional circuit-switching networks. Packet switching offers many advantages such as efficient use of communication resources and coding techniques. However, a major shortcoming of current Internet Protocol (IP) networks is their inability to guarantee quality of service (QoS), which is needed for real-time applications such as voice and video. In particular, due to unreliable radio links, it is difficult to ensure QoS (e.g., packet error rate, throughput and coverage) in wireless packet networks. As the third generation wireless networks [2] will be based on packet switching, it is important to address the QoS issue. The purpose of this paper is to propose and analyze an algorithm for integrated power control and link adaptation to achieve a specified QoS in the wireless networks.

Let us briefly review previous research work on the subject of power control and link adaptation. Dynamic transmission power control has been widely studied to combat interference in circuit-switched wireless networks; see e.g., [3, 4, 5]. Recently, [1] proposes a Kalman-filter method for power control in packet-switched time-division-multiple-access (TDMA) networks.

For a radio system with multiple modulation and/or coding levels, link adaptation is a technique to adapt the modulation and coding levels according to the channel condition and interference power 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. Much work on link adaptation by use of adaptive modulation has been done for fading channels (without co-channel interference); see for example, [6, 7]. By considering interference-limited

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systems, [8] shows that the overall network throughput can be maximized by adaptive modulation and iterative power control.

As for wireless packet networks, link adaptation has become an active research area as the ETSI is in the process of establishing the protocol and system standards for the Enhanced Data rates for GSM Evolution (EDGE) system. 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 [9] (a later proposal has two modulation and four coding levels [10]), where the highest data rate can exceed 550 Kbits/sec. Recently, [11] and [12] 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 [11] and [12], can be integrated with link adaptation for performance improvement.

The rest of this paper is organized as follows. We first present the assumptions for the wireless packet networks under consideration in Section 2. Next, we discuss the tradeoffs among QoS measures in Section 3. A new stability criterion for integrated power control and adaptive modulation is derived in Section 4. Then, the integrated algorithm is proposed in Section 5. In Section 6, we study the performance of the proposed algorithm by simulation. Finally, Section 7 presents our conclusion and future work.

2 NETWORK OPERATIONS AND ASSUMPTIONS

We consider a broadband, 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 such 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. As in the EDGE system, each transmitter chooses one of M combinations of modulation and coding levels for 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 signal-to-interference-plus-noise ratio (SINR) requirement for correct data reception. Thus, for brevity, we refer to the adaptation of modulation and coding levels simply as adaptive modulation. 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.

The Kalman-filter method [1] is used to control transmission power in this network. The method assumes:

1. The path gain between a terminal and its base station (i.e., the path loss plus shadowing) can be estimated accurately.
2. As for uplink transmission, the medium-access control (MAC) protocol in use allows one terminal in each sector or cell to transmit at a time. In addition, the base station knows which terminal is scheduled to transmit at different times. Clearly, typical polling schemes satisfy this assumption.
3. Interference power in each time slot can be measured quickly but possibly with noise and errors at each base station.
4. Base stations do not exchange information pertinent to traffic conditions and power control.
5. Actual transmission power can be communicated from the receiver (e.g., base station) to its transmitter (e.g., mobile terminal) efficiently. This may require a fast control channel to carry the power-control information.

According to the Kalman-filter method, the transmission power for time slot n is set to be

$$p(n) = \gamma^* \tilde{I}(n)/g(n) \quad (1)$$

where γ^* is the SINR target for the user, $\tilde{I}(n)$ is the interference plus noise power (mW) in slot n predicted by the Kalman filter, and $g(n)$ is the estimated path gain between the terminal that transmits in slot n and its base station. Readers are referred to [1] for details of the method.

It is noteworthy that the predicted $\tilde{I}(n)$ is not always accurate. As a result, adjusting transmission power according to (1) does not guarantee meeting the target γ^* at the receiving end. To increase the probability of the receiving SINR exceeding a threshold γ_{dB} in dB (to achieve a packet error rate below a given level), a margin δ in dB should be included in γ^*. That is, we set

$$\gamma^*_{dB} = \gamma_{dB} + \delta \quad (2)$$

where γ^*_{dB} is the dB equivalent of γ^*. The selection of appropriate δ will be discussed in Section 5.

3 TRADEOFFS AMONG QoS MEASURES

We believe that the key QoS measure for the wireless packet network is *packet error rate* (PER). For real-time applications such as voice and video, the PER has to be satisfactorily low to maintain the QoS because retransmission is infeasible due to excessive delay. If a network can provide a certain level of PER to its users, their throughput or bandwidth requirement can be met by assigning adequate time slots to them. (Of course, when too many active users generate an excessive amount of traffic, additional bandwidth is needed and/or call admission control should be exercised to guarantee satisfactory services for the admitted users.) On the other hand, when PER cannot be controlled, it will be difficult to meet the bandwidth requirements for various applications. Packet delay could be another issue. However, if the network provides satisfactory PER and bandwidth to users, the delay issue can be resolved readily.

Since non-real-time data service can tolerate certain degree of delay, efficient mechanisms such as that in [12] can be utilized to postpone certain packet transmissions until the associated radio conditions improve to a satisfactory level. In addition, retransmission also becomes feasible in case of errors. Nevertheless, the PER for the data service should still be kept below some threshold, which perhaps can be somewhat higher than that for real-time services, in order to keep delay and retransmission within an acceptable level.

Coverage in cellular networks is strongly related to the PER in the following way. Coverage in the packet-switched network can be defined as the fraction of sector or cell area where the terminals' PER is below a given threshold. It is clear that coverage is improved if the PER requirement can be relaxed and the opposite is also true.

It is important to understand the tradeoffs between PER and overall network throughput in a wireless network with link adaptation. As an extreme case, one can increase the throughput drastically by allowing terminals at "good" (in terms of radio link quality) locations to transmit at high modulation levels, while requesting terminals at many relatively "bad" locations to transmit at very low modulation levels or simply not to transmit at all. Thus, this improves the overall throughput at the expense of worsening coverage performance. In other words, the PER is very poor at many locations throughout the cell. On the other hand, if the PER over most of the cell area (including locations at the cell boundary) needs to be kept extremely low, the link-adaptation algorithm in use is expected to force transmission at low modulation levels with heavy coding, thus reducing the overall data throughput.

Fortunately, the tradeoff between PER (and related coverage) and network throughput can be resolved because, as mentioned above, the PER is a more fundamental QoS measure for real-time applications. Hence, our primary objective is to meet the PER requirement and improving throughput becomes a secondary concern. This is exactly the purpose of our integrated power-control and link-adaptation algorithm.

In the following, we explain why joint power control and adaptive modulation can be efficient for achieving a specified PER. When the channel condition is poor, transmitters can lower modulation levels to decrease SINR requirements 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 shown below, the complementary roles of power control and adaptive modulation give us a very efficient approach to providing the required QoS to users.

There are two issues for integrated power control and adaptive modulation for QoS. The first one is how to ensure the stability of power control in an adaptive modulation system. More specifically, the PER performance can be improved by transmitting at a higher power, which in turn increases interference to others. As a result, each transmitter may keep on increasing its power indefinitely while packets cannot be received successfully. This stability issue has been studied for systems with fixed modulation. However, it is an open issue for adaptive modulation systems. The second issue is how to integrate power control and adaptive modulation to deliver the specified QoS. In the following, let us first examine two special cases to gain some insight into the stability issue before presenting the integrated algorithm.

4 STABILITY OF POWER CONTROL FOR ADAPTIVE MODULATION

Assume that a simple power-control algorithm, instead of the Kalman method, is used. Using the simple algorithm, the base station instructs the terminal to transmit in slot n with power

$$p(n) = \gamma(n) I(n-1)/g(n) \qquad (3)$$

where $g(n)$ is the signal path gain as defined for (1), $\gamma(n)$ is the SINR target associated with the modulation level for transmission in slot n, and $I(n-1)$ is the actual interference plus noise power measured in the last slot $n-1$. The key difference between (3) and (1) is that $\tilde{I}(n)$ in (1) is predicted by the Kalman filter, while $I(n-1)$ in (3), the actual value for slot $n-1$, is used as an estimate of interference power in the next slot n. Otherwise, the simple power control operates in the same way as the Kalman method. Assume that there are N co-channel sectors or cells, each of which has at most one terminal transmitting in a time slot (e.g., by a polling scheme), as assumed by the Kalman method.

We note that the notion of "convergence" of power control does not apply well in the wireless packet networks because interference power can change drastically in time due to bursty packet traffic. Rather, our main concern is on whether the transmission powers of all terminals remain finite (or even remain below some threshold) at steady state. Thus, we define that the power control in (3) is *stable*, if $\lim\limits_{n\to\infty} p(n) < \infty$ for each transmitting terminal in all co-channel sectors.

4.1 STABILITY FOR SYNCHRONOUS ADAPTIVE MODULATION

In this case, terminals in all co-channel sectors are assumed to transmit at an identical modulation level synchronously, although the level changes from one time slot to the next. Correspondingly, let $\gamma(n)$ be the SINR target for all transmissions in time slot n. For $i, j = 1$ to N, assume that g_{ij} denotes the path gain from a transmitting terminal in sector j to the base station receiver of sector i. Let G be the path-gain matrix $[g_{ij}/g_{ii}]_{\mathbf{N\times N}}$ with elements in the diagonal replaced by zeros. The message length is assumed to be sufficiently long that the matrix G does not change in time. Furthermore, suppose that the constant receiver noise power at the base station of sector i is η_i. We use η to denote the vector of η_i/g_{ii} for $i = 1$ to N. Let the power vector for all terminals transmitting in slot n be denoted by $\mathbf{p(n)} = (p_1(n), ..., p_N(n))$.

For sector i, $I(n-1)$ in (3) is given by $\sum\limits_{j\neq i} g_{ij} p_j(n-1) + \eta_i$. Based on this, the power control in (3) can now be expressed in the following matrix form:

$$\mathbf{p}(n) = \gamma(n)\left[\mathbf{G}\mathbf{p}(n-1) + \eta\right] \quad . \tag{4}$$

Now let the eigenvalues of $\mathbf{G}$ be denoted by λ_1, λ_2, ..., λ_N with $|\lambda_1| \geq |\lambda_2| ... \geq |\lambda_N|$. Let the eigenvector associated with each such λ_i be $\mathbf{v_i}$. To consider stability, it is appropriate to consider the l_∞ norm of a vector $\mathbf{x} = (x_1, ..., x_N)^{\mathbf{T}}$, denoted by $||\mathbf{x}||_\infty \equiv \max\limits_{1\leq i\leq N} |x_i|$. We assume that $||\mathbf{v}_i||_\infty < \infty$ for all $i = 1$ to N, to exclude very extreme cases. As for the power vector $\mathbf{p}(n)$, $||\mathbf{p}(n)||_\infty \equiv \max\limits_{1\leq i\leq N} |p_i(n)|$.

Lemma 1: *For any finite, initial power vector* $\mathbf{p(0)} \geq 0$ and $\gamma(n) \geq 1$ for each n, if

$$\lim_{n\to\infty} \prod_{k=1}^{n} \gamma(k)|\lambda_1|^n = 0, \tag{5}$$

then the power control in (4) is stable, i.e., $\lim_{n\to\infty} ||\mathbf{p}(n)||_\infty < \infty$.

Proof: Based on the eigenvectors for $\mathbf{G}$, an initial power vector $\mathbf{p(0)}$ can be expressed as

$$\mathbf{p(0)} = \sum_{i=1}^{N} \alpha_i \mathbf{v}_i \tag{6}$$

where α_i's are constant. Similarly, the noise vector η is

$$\eta = \sum_{i=1}^{N} \beta_i \mathbf{v_i} \tag{7}$$

for some constants β_i's. Using (6) and (7), and the property of eigenvectors that $\mathbf{G}\mathbf{v_i} = \lambda_i \mathbf{v}_i$, recursively expanding (4) yields

$$\begin{aligned} \mathbf{p}(n) \;\; = \;\; & \prod_{k=1}^{n} \gamma(k) \sum_{i=1}^{N} \Bigg[\alpha_i \lambda_i^n + \beta_i \lambda_i^{n-1} + \frac{1}{\gamma(1)} \beta_i \lambda_i^{n-2} \\ & + ... + \frac{1}{\gamma(n-1)\gamma(n-2)...\gamma(1)} \beta_i \Bigg] \mathbf{v}_i \quad . \end{aligned} \tag{8}$$

Since the SINR requirement is much greater than 1 for typical modulation techniques, the premise that $\gamma(n) \geq 1$ for all n is reasonable. Thus, we obtain

$$\begin{aligned} ||\mathbf{p}(n)||_\infty \;\; \leq \;\; & \prod_{k=1}^{n} \gamma(k) |\lambda_1|^n \sum_{i=1}^{N} \Bigg[|\alpha_i| \cdot \frac{|\lambda_i|^n}{|\lambda_1|^n} \\ & + \frac{|\beta_i|}{|\lambda_i| - 1} \cdot \frac{|\lambda_i|^n}{|\lambda_1|^n} \\ & + \frac{|\beta_i|}{|\lambda_i| - 1} \cdot \frac{1}{|\lambda_1|} \Bigg] ||\mathbf{v}_i||_\infty \quad . \end{aligned} \tag{9}$$

Recall that $||\mathbf{v}_i||_\infty < \infty$ for each $i = 1$ to N. Further, since $|\lambda_1| \geq |\lambda_i|$ for all $i = 1$ to N, the summation term in (9) is bounded as n grows. In addition, when (5) holds, the product of $\gamma(k)$'s and $|\lambda_1|^n$ in (9) is finite and in fact becomes zero when n approaches infinity. Hence, $\lim\limits_{n\to\infty} ||\mathbf{p}(n)||_\infty < \infty$, i.e., the power control is stable at steady state for the adaptive modulation with the SINR target sequence $\gamma(k)$ satisfying (5). □

Define that an SINR target is *feasible*, if it yields a stable power control. One can determine a feasible target γ^* in (1), or equivalently γ^*_{dB} in (2), for a wireless packet network with fixed modulation by simulation or field testing. Since there exists many feasible combinations of targets for the same network with adaptive modulation, it is difficult to identify all of them. Without knowing all the combinations, the following theorem can determine the stability of power control in the network with adaptive modulation.

Theorem 1: *For any feasible SINR target γ^*_{dB} for the fixed-modulation system, a sufficient condition to guarantee stability of power in the corresponding system with adaptive modulation is*

$$\gamma^*_{dB} > \sum_{i=1}^{M} a_i \gamma_i^{dB} \tag{10}$$

where M is the number of distinct modulation levels, γ_i^{dB} is the SINR target in dB for modulation level i, and a_i is the long-term fraction of packets transmitted at modulation level i in each co-channel sector.

Proof: It is known that the stability condition for the fixed-modulation system is $|\lambda_1| < 1/\gamma^*$ [5]. Using this and for sufficiently large n,

$$\begin{aligned} |\lambda_1|^n \prod_{k=1}^{n} \gamma(k) &< \frac{\prod_{k=1}^{n} \gamma(k)}{(\gamma^*)^n} \\ &= \frac{\prod_{i=1}^{M} \bar{\gamma}_i^{n a_i}}{(\gamma^*)^n} \\ &= \left(\prod_{i=1}^{M} \bar{\gamma}_i^{a_i} / \gamma^* \right)^n \end{aligned} \tag{11}$$

where $\bar{\gamma}_i$ is the mW equivalent of γ_i^{dB}. We note that the conversion of the product of a time sequence of $\gamma(k)$ into a product of $\bar{\gamma}_i^{a_i}$ over all M possible modulation levels in (11) makes use of the fact that a_i is the long-term fraction (i.e., sufficiently large n) of packets transmitted at modulation level i. Thus, given that (10) holds, the ratio in parentheses on the right-hand side of (11) is less than 1. As n grows, raising that to a power of n makes the inequality in (5) hold. Consequently, by Lemma 1, $\lim_{n\to\infty} ||\mathbf{p}(n)||_\infty < \infty$. □

4.2 STABILITY FOR ASYNCHRONOUS ADAPTIVE MODULATION

In this case, assume that there are only two co-channel sectors in the system, each of which has one terminal transmitting in a time slot. However, the terminals in both sectors can transmit at different modulation levels in each slot and the selection of modulation level in one sector is independent of that in the other sector. For this reason, we refer this as the *asynchronous adaptive modulation*. Since our main interest is on interference-limited systems, the noise η is neglected in this case. On the other hand, the message length is now assumed to be finite and random, as in typical IP networks. Thus, as various terminals are scheduled to transmit according to the MAC protocol in use, the path-gain matrix changes in time correspondingly. Let $\mathbf{G}(n)$ be that matrix for slot n and

$$\mathbf{G}(n) = \begin{pmatrix} 0 & \frac{g_{21}(n-1)}{g_{22}(n)} \\ \frac{g_{12}(n-1)}{g_{11}(n)} & 0 \end{pmatrix} \tag{12}$$

where for $i, j = 1$ and 2, $g_{ij}(n)$ is the path gain from the terminal in sector j that transmits in slot n to the base station receiver of sector i. Note that $g_{ij}(n)$ depends on the radio environment, the transmission schedule, message length, etc. Further, for $i = 1$ and 2, let $\gamma_i(n)$ be the SINR target for the terminal in sector i transmitting in slot n. We define

$$\mathbf{\Gamma}(n) \equiv \begin{pmatrix} \gamma_1(n) & 0 \\ 0 & \gamma_2(n) \end{pmatrix}. \tag{13}$$

Based on this notation, the power control in (3) can be expressed in a matrix form for the asynchronous adaptation as follows.

$$\mathbf{p}(n) = \Gamma(n)\mathbf{G}(n)\mathbf{p}(n-1). \tag{14}$$

Recursively expand (14) yields

$$\mathbf{p}(n) = \Gamma(n)\mathbf{G}(n)\Gamma(n-1)\mathbf{G}(n-1)...\Gamma(1)\mathbf{G}(1)\mathbf{p}(0). \tag{15}$$

Now, let us first establish a necessary and sufficient condition for power stability in the fixed-modulation system where $\gamma_1(n) = \gamma_2(n) = \gamma^*$ for all n.

Lemma 2: *For a given SINR target γ^* in the fixed-modulation system, the power control in (14) is stable if and only if*

$$\lim_{2n\to\infty} (\gamma^*)^{2n} \frac{g_{12}(2n-1)g_{21}(2n-2)...g_{12}(2)g_{21}(1)}{g_{11}(2n)g_{22}(2n-1)...g_{11}(3)g_{22}(2)} < \infty \tag{16}$$

and

$$\lim_{2n\to\infty} (\gamma^*)^{2n} \frac{g_{21}(2n-1)g_{12}(2n-2)...g_{21}(2)g_{12}(1)}{g_{22}(2n)g_{11}(2n-1)...g_{22}(3)g_{11}(2)} < \infty. \tag{17}$$

Proof: Let us prove that (16) and (17) are the sufficient conditions for stable power. For the fixed-modulation system, $\gamma_1(n) = \gamma_2(n) = \gamma^*$ for all integer n. Substituting this and (12) into (15), we obtain

$$\mathbf{p}(2n) = (\gamma^*)^{2n} \begin{pmatrix} b_1 & 0 \\ 0 & b_2 \end{pmatrix} \cdot \mathbf{p}(0) \tag{18}$$

where

$$b_1 = \frac{g_{12}(2n-1)g_{21}(2n-2)...g_{12}(2)g_{21}(1)}{g_{11}(2n)g_{22}(2n-1)...g_{11}(3)g_{22}(2)}$$

and

$$b_2 = \frac{g_{21}(2n-1)g_{12}(2n-2)...g_{21}(2)g_{12}(1)}{g_{22}(2n)g_{11}(2n-1)...g_{22}(3)g_{11}(2)}$$

Given that $||\mathbf{p}(0)||_\infty$ is finite, one can readily observe from (18) that $\lim_{2n\to\infty} ||\mathbf{p}(2n)||_\infty < \infty$ if (16) and (17) hold. The proof for the converse follows the same arguments. □

The time sequence of $g_{ij}(n)$'s in (16) and (17) can be interpreted as a sample path in a simulation model. Thus, a given value of γ^* is a feasible SINR target for the fixed-modulation system with probability one, if both inequalities in (16) and (17) are satisfied for *almost every* sample path. Now we can obtain a sufficient condition for power stability in the system with asynchronous adaptive modulation as follows.

Theorem 2: *For any feasible SINR target γ^*_{dB} for the fixed-modulation system with two co-channel sectors, a sufficient condition to guarantee stability of power in (14) in the corresponding system with adaptive modulation is*

$$\gamma^*_{dB} > \sum_{i=1}^{M} a_i \gamma_i^{dB} \tag{19}$$

where M, γ_i^{dB} and a_i have been defined for Theorem 1.

Proof: By definition, $\mathbf{p}(2n) = (p_1(2n), p_2(2n))^{\mathbf{T}}$. Similar to the proof for Lemma 2, expanding (14) yields

$$p_1(2n) = \gamma_1(2n)\gamma_2(2n-1)...\gamma_1(2)\gamma_2(1) \frac{g_{12}(2n-1)g_{21}(2n-2)...g_{12}(2)g_{21}(1)}{g_{11}(2n)g_{22}(2n-1)...g_{11}(3)g_{22}(2)} p_1(0) \tag{20}$$

and

$$p_2(2n) = \gamma_2(2n)\gamma_1(2n-1)...\gamma_2(2)\gamma_1(1) \frac{g_{21}(2n-1)g_{12}(2n-2)...g_{21}(2)g_{12}(1)}{g_{22}(2n)g_{11}(2n-1)...g_{22}(3)g_{11}(2)} p_2(0). \tag{21}$$

Since γ^*_{dB} is feasible, (16) and (17) hold according to Lemma 2. Then, by comparing (20) and (21) with (18), one can verify that both $|p_1(2n)|$ and $|p_2(2n)|$ are finite (i.e., $||\mathbf{p}(2n)||_\infty < \infty$) as $2n$ increases to infinity if

$$\lim_{2n\to\infty} (\gamma^*)^{2n} > \lim_{2n\to\infty} \gamma_2(2n)\gamma_1(2n-1)...\gamma_2(2)\gamma_1(1). \tag{22}$$

Similar to (11) in the proof for Theorem 1, the product of the time sequence $\gamma_1(.)$ and $\gamma_2(.)$ in (22) can be converted into the product of $\bar{\gamma}_i$'s over all M modulation levels with a_i being the fraction of packets transmitted at each modulation level i in a long run. Finally, taking the logarithm on both sides, we obtain (19) from (22). □

Clearly, both cases of synchronous and asynchronous adaptive modulation examined above are special cases. Coincidentally, the same sufficient condition in (10) and (19) to guarantee power stability applies to both cases. However, due to analytic difficulty, we are not able to extend the stability criterion for general settings where transmitting terminals in multiple co-channel sectors can choose modulation levels asynchronously and message length is finite but random, as one would expect in reality. Furthermore, the analysis is performed for the simple power control in (3). In any event, we apply (10) to a setting with multiple co-channel sectors and the Kalman-filter power control in Section 5. Our numerical experience reveals that the criterion indeed guarantees power stability.

5 INTEGRATED POWER CONTROL AND ADAPTIVE MODULATION

Before presenting the algorithm, it is instructive to understand the major causes of high PER and remedial actions that are available. As outlined in Table 1, the first major cause for high PER is due to excessive *intersymbol interference* (ISI). The ISI problem depends on among many factors, such as the terminal speed, the radio propagation conditions, and the modulation level currently used for transmission. Although various techniques are available to mitigate the problem (see e.g., [13]), an effective one is to lower the modulation level; that is, to transmit at a reduced data rate to suppress the ISI. The second cause for high PER may be that the SINR at the receiving end is too low for successful detection. A low SINR can be due to a combination of strong interference and weak signal strength. A remedial action is to lower the SINR requirement by lowering the modulation level.

Lastly, when the PER performance is unsatisfactory, it can be due to the imperfection of the Kalman-filter method. As pointed out earlier, the power control in (1) does not guarantee the SINR γ^* at the receiver. Thus, a "safety" margin δ can be included in γ^*_{dB}, as indicated in (2). Depending on the PER performance, δ is increased or decreased as described in the following.

Table 1: Causes and Remedial Actions for High Packet Error Rate

Causes for High Packet Error Rate	Remedial Actions
Excessive Intersymbol Interference (Speed, Fading)	Lower Modulation Level to Reduce ISI Impacts
Low SINR	Lower Modulation Level to Reduce SINR Requirement
Imperfection of Power Control Algorithm	Increase Margin for SINR Target

5.1 ADJUSTMENT OF SAFETY MARGIN FOR SINR TARGET

Assume that the required PER performance is specified by a high and low threshold denoted by P_H and P_L, respectively. When the PER is higher than P_H, the safety margin δ should be increased periodically as a way to control the PER. On the other hand, when the PER is below P_L, δ can be decreased to reduce interference to others. In either case, δ should be changed once every T time slots with $T >> 1$ so that enough packet error measurements can be collected to maintain statistical confidence. Without loss of generality, let us assume that δ is an integer between 0 and K dB in this study. For the system with M modulation levels and γ_i^{dB} as their associated SINR targets, the inclusion of the margin factor δ in the SINR target means that the total number of distinct SINR targets is as large as MK. Let there indeed be MK targets in our discussion. Further, let γ_{ij}^{dB} be the SINR target in dB for modulation level i with $\delta = j$. That is,

$$\gamma_{ij}^{dB} = \gamma_i^{dB} + j \tag{23}$$

for $i = 1$ to M and $j = 1$ to K, where γ_{ij}^{dB} takes the place of γ_{dB}^* in (2) for power control.

Note that despite the SINR target margin δ, the power stability criterion in (10) and (19) is still valid because it considers only the actual SINR targets used in the transmission. The only difference is that we now have MK, instead of M, SINR targets. For this reason, let us define a_{ij} to be the long-term fraction of packets transmitted with SINR target γ_{ij}^{dB} for $i = 1$ to M and $j = 1$ to K. For easy reference later, (10) is now replaced by

$$\gamma_{dB}^* > \sum_{i=1}^{M}\sum_{j=1}^{K} a_{ij}\gamma_{ij}^{dB}. \tag{24}$$

5.2 COMPUTATION OF a_{ij}'s AND PER FOR EACH SECTOR

Since each base station is involved in controlling the transmission power and the use of SINR targets for various transmissions is readily known to the base station, it can use an exponential-smoothing technique to approximate the a_{ij}'s. Specifically, let us define $a_{ij}(n)$ as the approximation of a_{ij} up to slot n. For $0 < \omega < 1$, the base station computes

$$a_{ij}(n) = \begin{cases} \omega a_{ij}(n-1) + 1 - \omega & \text{if slot } n \text{ uses target } \gamma_{ij}^{dB} \\ \omega a_{ij}(n-1) & \text{otherwise} \end{cases} \tag{25}$$

for $i = 1$ to M and $j = 1$ to K for each slot n. The appropriate choice of ω will be discussed later.

Similarly, each base station can obtain the PER for each of its serving sectors in every time slot n. Let $P(n)$ be the approximate PER for a given sector at slot n. With $0 < \phi < 1$, the base station computes

$$P(n) = \begin{cases} \phi P(n-1) & \text{if sucessful reception in slot } n \\ \phi P(n-1) + 1 - \phi & \text{otherwise.} \end{cases} \tag{26}$$

5.3 INTEGRATED ALGORITHM

Assume that a feasible, SINR target γ_{dB}^* for the system with fixed modulation has been pre-determined by simulation techniques and/or field measurements. In the corresponding system with adaptive modulation, the following algorithm for integrated power control and adaptive modulation is executed for each sector at the end of time slot $n-1$.

1. Use (25) and (26) to obtain the approximate, long-term fractions $a_{ij}(n-1)$'s of packets transmitted with various SINR targets and PER $P(n-1)$ for slot $n-1$.
2. If T slots have elapsed since the last update of SINR target margin δ, perform the following:
   (a) If $P(n-1) \geq P_H$ and $\delta < K$ (e.g., 5 dB), increase δ by 1 dB. That is, increase the target margin, as the PER is excessive.
   (b) If $P(n-1) < P_L$ and $\delta > 0$, decrease δ by 1 dB. That is, decrease the target margin, as the PER is lower than required.
3. Determine the initial modulation level i, where $1 \leq i \leq M$, for the terminal that is scheduled to transmit in the next slot n in the sector.
4. If $P(n) > P_H$ and $i > 1$, reduce i by 1. That is, lower the modulation level by one, if possible, when the PER is too high.

5. Let the current value of δ be j. Assume that the packet in slot n is transmitted with SINR target γ_i^{dB} for modulation level i and the target margin of j dB. Obtain γ_{ij}^{dB} from (23) and use the Kalman-filter method to compute the transmission power $p(n)$ for the next slot n according to (1) with $\gamma^*(n)$ replaced by the linear-scale equivalent of γ_{ij}^{dB}.

6. If $p(n)$ is larger than a pre-specified maximum power $p_{\max}$ and $i > 1$, reduce the modulation level i by 1 and continue with step 5. Otherwise, continue with step 7.

7. With the packet assumed to be transmitted with the SINR target γ_{ij}^{dB} in slot n, compute the $a_{ij}(n)$'s from (25). Using these $a_{ij}(n)$'s in the place of a_{ij}'s in (24), check whether or not the stability criterion is satisfied.

8. If (24) is not satisfied and $i > 1$, reduce the modulation level i by 1 and continue with step 5. (Otherwise, the adaptation of modulation levels is completed because either the chosen level and the SINR target margin meet the stability criterion to guarantee power stability, or the lowest modulation level has been chosen.)

9. The base station instructs the associated terminal via the downlink to transmit at power $p(n)$ and modulation level i in the next slot n, as in the Kalman-filter method.

Note that depending on the choice of the network operator, there are many ways for determining the initial modulation level in step 3 of the algorithm. For example, a network can allow each terminal, regardless of its location and channel condition, to request any desirable modulation level for transmission. (Of course, the final selection of modulation level is selected by step 4, 6 and 8.) This method may be needed if the network prefers to try its best to accommodate the bandwidth demand of various applications for terminals located anywhere in the network. The price of such a best-effort approach is that transmitting at high modulation level, likely at high power, at bad terminal locations can cause excessive interference to others, thus degrading the overall network throughput. Alternatively, the determination of the initial modulation level can be based on the signal path gain for the associated terminals. More specifically, terminals with high signal-path gain, which likely have good radio links with their base stations, are allowed to choose high, initial modulation level. Otherwise, they can only specify a low modulation level as the initial level in step 3. As will be discussed below, this approach typically yields better throughput and PER performance, at the expense of restricting the use of high modulation levels to certain terminal locations.

6 PERFORMANCE STUDY

6.1 SIMULATION MODEL

The cell layout and interleaved channel assignment (ICA) with a frequency reuse factor of 2 [14] 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 [15] 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 randomly located terminals 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, 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 because it is appropriate for wireless packet networks [16]. Let L and H_i be the average message length and the probability of a message consisting of i packets, respectively. We have

$$H_i = 1 - \left(\frac{k}{i}\right)^{\alpha} \quad \text{for } i \geq k \in Z^{+} \text{ and } \alpha > 1 \qquad (27)$$

where k is set to be the smallest integer greater than or equal to $\frac{L}{2}$ (to keep the variance of message length finite) and α is selected to match the given average message length of L. In this study, we assume $L = 10$.

Our simulation model assumes that the maximum transmission power, $p_{\max}$, is 30 dBm. Two adjustable parameters for the Kalman-filter method, W and η defined in [1], 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 $M = 6$ modulation levels. The SINR detection requirements and the corresponding data throughput for each modulation level are given in Table 2. 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. Parameters in Table 2 are adapted from Table 3 and estimated from Figure 20 of

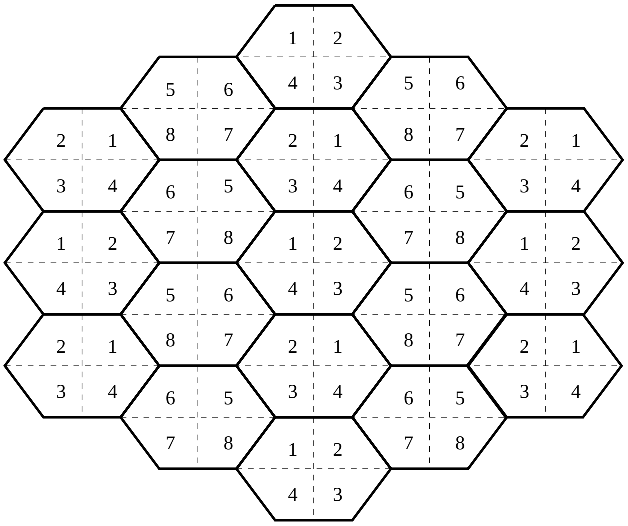

Figure 1: A 4-Sector Cell Layout and Interleaved Channel Assignment

[9]. For the integrated algorithm, the margin for the SINR target δ lies between 0 to 5 dB, as denoted by K in (24). Depending on the PER performance, the margin is increased or decreased by a step size of 1 dB once every 500 time slots. Based on simulation, it has been pre-determined that the cell layout and ICA scheme in Figure 1 can support a fixed SINR target γ^*_{dB} of 17 dB that yields stable and satisfactory use of transmission power. Finally, the weighting factors ϕ and ω in (25) and (26) are set to be 0.998, which are approximately equivalent to a sliding-window size of 500 time slots.

6.2 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 2. For example, when the measurement lies between 12 and 16 dB, modulation level 2 is used. Every sector makes such selection for its transmitting terminal in each time slot independently. For brevity, this SINR scheme is referred to as *method* A. The second method, to be referred to as *method* B below, is our proposed algorithm with the modulation level determined by method A above as the initial modulation level in step 3 of the algorithm (See Section 5.3). The modulation level is finalized by the subsequent steps of the algorithm.

We define *goodput* as the corresponding throughput times the probability of successful reception. Table 3 presents the goodput, the PER for packets transmitted

Table 2: SINR Requirement and Throughput for Various Modulation Levels.

Modulation Level	SINR Detection Requirement (dB)	Throughput (Kbps)
1	10	22.80
2	12	34.30
3	16	41.25
4	19	51.60
5	23	57.35
6	28	69.20

at different modulation levels, and the overall PER averaged over all levels of methods A and B with two settings of the PER requirements, P_H and P_L. As shown in the table, the PER performance for method A is not satisfactory for real-time applications (e.g., voice service, which requires a couple percent of PER [17]). In particular, modulation level 1 has extremely high PER. This is so because without power control, many terminal locations in Figure 1 simply cannot support a SINR of 10 dB. The PER for other modulation levels is not sufficient for real-time applications either. This reflects a fundamental inadequacy of method A; that is, previous SINR measurements may not accurately predict SINR performance in future time slots because the burstiness of packet transmission in the wireless packet environment. As a result, the chosen modulation level may not lead to successful packet transmission as the radio and interference conditions change drastically in time. In contrast, according to the specified PER requirements P_H and P_L, the proposed algorithm automatically adjusts the SINR target margin δ and adapts the modulation levels while preserving the stability of power. Consequently, method B is able to control and deliver the desired PER performance, at least for modulation level 2 to 6. As shown in Table 3, the PER performance for method B generally falls between the specified P_H and P_L. The ability to control the PER to meet the specified targets for the proposed algorithm comes at a price and that is a reduced goodput relative to method A. In this example, method A provides about 1/3 more goodput than method B. Nevertheless, these results reveal that the integrated power control and adaptive modulation can achieve a desirable tradeoff between the PER and throughput, to meet the application requirements.

A couple of other methods for link adaptation are examined. In a method to be called *method* C, the modulation level for a packet transmission is selected based on the signal strength (SS) received at the intended base station from a transmitting terminal with fixed transmission power. This method is simulated as follows. The signal path gain for all terminals served by each sector is first sorted in a descending order at

Table 3: Performance Comparison of Link-Adaptation Methods

Methods	PER for Modulation Levels						Overall PER	Goodput (Kbps)
	1	2	3	4	5	6		
SINR-Based Methods								
A) without PC	0.61	0.059	0.090	0.10	0.12	0.10	0.17	44.4
B) PC & Adapt (P_H, P_L)=(10%, 5%)	0.13	0.054	0.060	0.058	0.060	0.063	0.075	34.3
B) PC & Adapt (P_H,P_L)=(5%, 1%)	0.14	0.021	0.020	0.021	0.031	0.028	0.032	32.8
Signal Strength (SS) Based Methods								
C) without PC	0.35	0.18	0.20	0.16	0.15	0.059	0.18	38.6
D) PC & Adapt (P_H,P_L)=(10%, 5%)	0.089	0.072	0.071	0.078	0.078	0.068	0.076	36.5
D) PC & Adapt (P_H,P_L)=(5%, 1%)	0.052	0.023	0.031	0.045	0.045	0.028	0.029	32.7

the beginning of each simulation run. Terminals with the highest one-sixth of the signal path gains are assigned with modulation level 6; that is, modulation level 6 is always used when these terminals are scheduled to transmit. Similarly, terminals with the second highest one-sixth of the signal path gains are allocated with modulation level 5 and so forth. The main idea of such assignment of modulation levels to terminals is that the SINR at a base station from its transmitting terminal with strong signal is likely (although not guaranteed) to be satisfactory for high modulation transmission. Performance results for method C are also included in Table 3. It is clear from these results that the PER for method C (without power control) still remains at an unacceptable level of 15 to 20%. This is so because a strong signal does not imply good SINR at the receiver due to large time fluctuation of interference power.

In *method* D, the modulation level assigned to a terminal in method C is simply used as the initial level in step 3 of the proposed algorithm when the terminal is scheduled for transmission. Depending on the current interference condition, the consideration of stability criterion and the specified PER requirements, the modulation level is finalized by step 8. This way, the modulation and power control can truly adapt to the radio condition with an aim of meeting the PER requirements. As shown in Table 3, the PER for transmission at all modulation levels for method D typically fall between P_H and P_L. Of course, as one would intuitively expect, the goodput for the case of $(P_H, P_L) = (5\%, 1\%)$ is lower than that for the case of $(P_H, P_L) = (10\%, 5\%)$. It is so because low modulation levels are used more often in order to meet the more stringent PER requirements.

It is interesting to compare the performance of method B and D with the same (P_H, P_L) requirements. In particular, results in Table 3 clearly show that both methods with $(P_H, P_L) = (5\%, 1\%)$ provide similar network goodput and overall PER. The key difference between them is on the PER for modulation level 1, which can be explained as follows. Table 4 presents the probability distribution of final modulation levels for actual packet transmissions in method B, given the initial modulation level determined based on the last SINR measurement in step 3 of the algorithm. Similarly, Table 5 shows the corresponding results for method D. We have several observations. First, as a verification, these results confirm that the integrated algorithm indeed is capable of adapting the link starting with the initial modulation level to enforce the stability criterion and to meet the PER requirements. For example, the SINR measurements in method B identify modulation level 3 as the initial level with probability of 0.638 (row sum), which is reasonable for the radio environment in Figure 1. Then, this initial level is modified by step 4 and 8 of the algorithm, resulting into actual transmission at level 3, 2 and 1 with probability 0.023, 0.612 and 0.002, respectively, as indicated in Table 4. A similar observation can be made for other initial modulation levels and method D in Table 5.

Second and more importantly, the tables show that packets are actually transmitted at modulation level 1 with probability of 0.09 and 0.183 for method B and D, respectively. On the other hand, method B has many more packets transmitted at level 2 (with probability 0.86) than method D does (with probability of 0.703). Although method D has packet transmissions at higher modulation levels with slightly larger probability when compared to method B, those terminals transmitting at high modulation levels tend to trans-

Table 4: Probability of Transmission at Various Modulation Levels for Method B with (P_H, P_L)=(5%, 1%)

Initial Modulation Level	Final Modulation Level					
	1	2	3	4	5	6
1	0.051	0	0	0	0	0
2	0.036	0.157	0	0	0	0
3	0.002	0.612	0.023	0	0	0
4	0*	0.074	0.011	0.004	0	0
5	0*	0.013	0.003	0.004	0.002	0
6	0*	0.003	0*	0.001	0.001	0.001
column sum	0.090	0.860	0.038	0.009	0.003	0.001

*These figures are less than 0.001.

Table 5: Probability of Transmission at Various Modulation Levels for Method D with (P_H, P_L)=(5%, 1%)

Initial Modulation Level	Final Modulation Level					
	1	2	3	4	5	6
1	0.171	0	0	0	0	0
2	0.010	0.152	0	0	0	0
3	0.001	0.137	0.032	0	0	0
4	0*	0.137	0.016	0.014	0	0
5	0*	0.142	0.013	0.006	0.009	0
6	0*	0.137	0.012	0.001	0.005	0.006
column sum	0.183	0.703	0.074	0.021	0.015	0.006

*These figures are less than 0.001.

mit at reasonably low power in method D because their signal to the base stations is strong. Combining these factors, transmission power for method B is typically higher than that for method D, as can be verified from the cumulative probability function for transmission power in Figure 2. As a result, method B causes more interference than method D. Especially when terminals at "bad" locations (e.g., at the cell boundary) are scheduled for transmission, higher interference results in the PER of 0.14 for packet transmission at modulation level 1 for method B, when compared with the corresponding PER of 0.052 for method D, as shown in Table 3. Evidently, this comparison reveals that the signal path gain between a transmitting terminal and its base station should be considered in link adaptation to meet the PER requirements.

As pointed out above, the weighting factors ω and ϕ for computation of $a_{ij}(n)$'s and PER in (25) and (26) need to be sufficiently large. In addition to using $\omega = \phi = 0.998$ for the above results, other values are also tested. We find that for $\omega = \phi = 0.995$ (approximate window size of 200 slots), the algorithm tends to adapt low modulation levels because the stability criterion is strictly enforced as ω and ϕ decrease. (In the

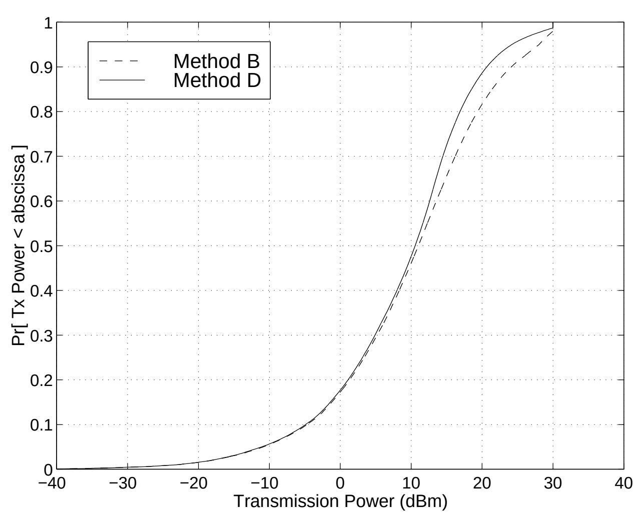

Figure 2: Transmission Power for Method B and D with (P_H, P_L)=(5%, 1%).

most stringent case, when ω and ϕ approach 0, only modulation levels 1 to 3 will be used for transmission as $\gamma^*_{dB} = 17$dB.) As a result, network throughput is reduced, but similar PER performance can be obtained. On the other hand, when ω and ϕ are increased to

0.999, we obtained performance results very similar to those for $\omega = \phi = 0.998$ reported above.

7 CONCLUSIONS AND FUTURE WORK

An algorithm for integrated power control and adaptive modulation/coding has been proposed to control and achieve a specified range of packet error rate for real-time applications in broadband wireless networks. The algorithm applies the Kalman-filter method [1] for power control, and adapts packet transmission to an appropriate modulation or coding level, according to the packet error requirement, and the radio and interference conditions. A new criterion for maintaining stable transmission power has been derived for wireless IP networks with adaptive modulation and/or coding. Based on the stability criterion, the proposed technique performs the link adaptation and adjusts transmission power to achieve the specified packet error rate, while ensuring that transmission power does not increase indefinitely, which would otherwise lead to unacceptable packet error and throughput performance. The new method can serve as a useful tool for achieving a desirable tradeoff among throughput, packet error rate and coverage in the networks. The effectiveness of the proposed method has been demonstrated for several numerical examples by simulation.

As for our future work on the subject, we plan to enhance the proposed algorithm so that the network throughput can be further maximized, while meeting the required packet error rate. Second, with guaranteed error performance by the algorithm, it is desirable to understand and explore the interactions and possible tradeoffs between the use of adaptive modulation/coding and assignment of multiple time slots to meet the bandwidth requirements of various applications in the wireless packet networks. Third, although the proposed algorithm is intended for the TDMA wireless netwoks, it is well possible that the algorithm can be modified for wideband CDMA networks because adaptive modulation in the TDMA system is equivalent to variable processing gain in the CDMA networks. Lastly, an issue strongly related to providing adequate bandwidth to users is call admission control. As reported in the literature, call admission control in wired IP and ATM networks is typically based on the concept of *effective bandwidth* (see e.g., [18, 19]). In the wireless packet networks, the new stability criterion can be viewed as a new constraint on how adaptive modulation/coding can be used properly. For this reason, combining the notion of effective bandwidth and the stability constraint to admit calls with different bandwidth requirements in broadband wireless networks is an open issue that deserves our research attention.

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