Retransmission Control and Fairiness Issue in Mobile Slotted ALOHA Networks with Fading and Near-far Effect

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CENG Technical Report 96-02

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(213)740-4579

January 1996

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***Abstract*–**The effects of different retransmission control policies on the performance of a mobile data system employing the slotted ALOHA protocol are investigated, with the emphasis on the unfairness between close-in and distant users due to the near-far effect. An analytical multi-group model is developed to evaluate both the user and the network performance of the mobile slotted ALOHA network under two classes of retransmission control policies, namely the Uniform Policy and the Nonuniform Policy. The Uniform Policy requires that all users adopt the same retransmission probability, whereas the Nonuniform Policy allows more distant users to have larger retransmission probability in order to compensate for the unfairness caused by the near-far effect. The performance of a slotted ALOHA network with a linear topology in a Rician fading channel under the two policies is compared by the multi-group model and simulation. The Nonuniform Policy is found to be more effective in alleviating the unfairness of user throughput over a wider range of the data traffic load than the Uniform Policy, which is effective only when the data traffic load is very light. Thus, a mobile data network can enjoy the network performance improvement derived from the near-far effect while the unfairness between close-in and distant users can be greatly mitigated without resorting to power control.

1. Introduction

Mobile packet data networks have been attracting a lot of interest recently due to the flexibility and low cost of the services provided to users on the move. Typical mobile data services include paging and wireless electronic mail services. In addition to the services provided to human users, the signalling traffic generated for network control (e.g., tracking and registration of mobile users) also forms a major need for mobile data networks. Other innovative future systems such as Intelligent Vehicles Highway System (IVHS) require mobile data networks for the communication needs between vehicles and roadside base stations for vehicular traffic management and driver information services.

One of the major design issues in mobile data networks is the choice of the channel access protocol for the mobile-to-base station channel (uplink). The channel from the base station to mobile users (downlink) is not a multiple access channel; neighboring base stations can avoid the contention on the downlink by FDMA, TDMA, or other scheduling algorithms. Therefore, we will only consider the channel access problem on the uplink hereafter.

The bursty characteristics of the data traffic on the uplink lead us to consider random access schemes. Among the family of random access schemes, slotted ALOHA (S-ALOHA) [1] is a simple channel access protocol that has received a great deal of attention since it appeared in early seventies. The throughput-delay performance in a broadcast channel was considered in [2], [3], where simultaneous transmissions are assumed to be lost and a single transmission is assumed to be successful. In a mobile radio environment, the propagation path loss and multipath fading can make the received power of packets differ by orders of magnitude allowing advantage to be taken of the capture effect, the phenomenon that the packet with the strongest power is successfully received even in the presence of other interfering packets. On the other hand, co-channel interference and thermal noise make the probability of successful reception of a single transmission less than one. Therefore, the capture effect improves network performance, whereas co-channel interference and thermal noise degrade performance. Many capture models have been proposed to evaluate network performance, e.g., [4], [5], [6], [7]. Some of them take into account the fading channel, most of which use a Rayleigh fading model due to the analytical tractability.

Stability is another important issue with ALOHA systems [3]. A simple approach to stabilize an ALOHA system is by retransmission control. Many adaptive retransmission control schemes have been considered for broadcast channels (i.e., no capture); see [8] for a recent study. There are some papers considering static retransmission control for S-ALOHA with capture. For example, the stability of S-ALOHA with capture is considered in [6]; the stability condition for a 2-group S-ALOHA system with capture can be found in [9].

Almost all of the published work on S-ALOHA focuses on network performance, with some exceptions such as [4], [6], [10], and [11] where single user performance is considered. In those papers considering single user performance, the near-far effect is found to cause unfair user throughput. To alleviate the unfairness, it was concluded in [10] that some form of power control is necessary, which will inevitably weaken the capture effect and therefore degrade network performance. However, [11] suggests the use of retransmission control to level out the unfairness and yet keep the capture effect intact.

In this paper we will extend the work of [11] and investigate the effect of retransmission control on both single user and network performance, taking into account multipath fading and the near-far effect. The focus is on the inequity in user performance and the effectiveness of retransmission control to improve the fairness. The approach that we take is to abstract a mobile S-ALOHA network as a multi-group system where the user spatial distribution, channel fading characteristics, and physical layer parameters (such as modulation, coding, diversity, etc.) are matched properly to the system parameters of the analytical multi-group model. The accuracy of the analytical model is validated by a more detailed simulation model [12].

The paper is structured as follows. In Section 2, the system parameters of the multi-group model are introduced, and the principle of matching a mobile S-ALOHA network with a multi-group system is discussed. Section 3 investigates the problem of finding the optimal retransmission control strategy under different objectives and constraints. In Section 4, the numerical results of the performance of an example network are presented. Various performance measures such as single user performance, group performance, and network performance as functions of the retransmission control strategy are considered. Section IV provides some closing remarks.

2. The Multi-group System Model for Mobile S-ALOHA Networks

In this section, we first introduce the analytical system model, namely the multi-group S-ALOHA with capture, the objective of which is to represent a wide range of S-ALOHA networks. We then discuss how to set system parameters of the multi-group model for a given mobile S-ALOHA network, which could be a stand-alone network or a cellular structured network with co-channel interference.

2.1. The Multi-group Model

A. Terminal Model and Channel Access Control

Consider a S-ALOHA system with one central station and K groups of terminals (or users). Group i (i = 1, 2,..., K) consists of M_i single-buffered terminals that are identical and independent of each other. Each terminal is either in the idle state or in the backlogged state. When a terminal is in the idle state, a packet will be generated and transmitted in the next slot with probability σ_i, the *packet generation probability*. If the transmission is successful, the terminal will receive an error-free positive feedback right after the transmission and remain in the idle state. Whereas if the transmission is not successful, it will enter the backlogged state and retransmit the packet with probability q_i, the *retransmission probability*, in each of the following slots until it succeeds. Although the assumption about instantaneous and error-free feedback is to simplify the analysis, the performance obtained serves as an upper bound for the system performance. The effect of imperfect and delayed feedback in a mobile S-ALOHA system can be investigated by simulation but is beyond the scope of this study.

The terminal model described above is general enough for us to consider the effect of channel access control strategies under 2 scenarios: the heavy traffic and the normal traffic scenarios. In the heavy traffic scenario, the packet retransmission probability q_i and the packet generation probability σ_i of group i are set to be the same. This scenario is of interest if one wants to find the capacity (the maximum throughput) of a network. If one is interested in average packet delay or stability of the system, the system performance should be examined over various q_i for a given σ_i, which corresponds to our normal traffic scenario.

The flexibility of the possibly different packet generation/retransmission probabilities (σ_i/q_i) of the multiple groups allows us to investigate more general channel access control strategies which can improve the fairness of the system. We distinguish 2 channel access strategies: the

Uniform Policy and the Nonuniform Policy. Under the Uniform Policy, the packet generation probabilities and the retransmission probabilities are the same for all groups (i.e., $\sigma_i = \sigma \ \forall i\text{""and""}q_i = q \ \forall i$), but σ is not necessarily equal to q. For the Nonuniform Policy, σ_i and q_i can vary from group to group.

B. General Capture Model

Assuming that the radio channels from terminals in the same group to the central station are statistically the same and independent from each other, the probability that the central station can successfully receive a packet in a slot depends on the activity of all K groups, the interference that comes from the thermal noise, and any co-channel interference. Define the activity vector $\vec{a} = (a_1, a_2, \ldots, a_K)$, where a_i, $i = 1, 2, \ldots, K$, is the number of transmissions from group i in a slot. Given the activity vector in a slot, the probability $P_i(\vec{a})$ (called the *conditional capture probability* of group i) that one of terminals in group i successfully transmits a packet to the central station depends on factor such as fading characteristics, modulation, coding, diversity, and the statistics of the interference due to thermal noise and co-channel interference. We can think of $P_i(\vec{a})$ as a parameter that depends on the operating environment and the physical modem structure. For a given operating environment and a physical modem structure, $P_i(\vec{a})$ can be precomputed.

C. Network Performance Model

For a given normal traffic scenario[1], a channel access control policy (uniform or nonuniform), and a set of conditional capture probabilities, the network can be modeled by a K-

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1. In the heavy-traffic scenario, the network is memoryless from slot to slot, and therefore its performance can be evaluated without the effort of formulating a Markov chain [13].

dimensional Markov chain with the state being the number of backlogged users in each group. A decoupling approximation, which assumes that the state transition of the one-dimensional Markov chain for a group depends only on the equilibrium state occupancy probabilities of the other groups, can be used to avoid having to solve this K-dimensional Markov chain. The decoupling assumption was found to be sufficiently accurate when packets from stronger groups tend to successfully capture the receiver in the presence of the interfering packets from weaker groups [11]. The equilibrium state probabilities of the decoupled Markov chains can then be used to compute the throughput, delay, and stability of each group. Since the users in the same group are symmetric, the user throughput is just the group throughput divided by the number of users in the group; the packet average delay of a user is the same as the average packet delay of the corresponding group. The details of the computational procedure can be found in [11].

2.2. Model Parameter Selection

The system parameters K, $\vec{M} = (M_1, M_2, ..., M_K)$, and $\{P_i(\vec{a})\}_{i=1}^{K}$ need to be determined before network performance can be evaluated. The first parameter to be determined is K, the number of groups. A larger K allows us to see in more detail how user (or group) performance behaves at the cost of the higher complexity of the resulting model and the higher computational cost in determining $\{P_i(\vec{a})\}_{i=1}^{K}$, but K cannot be too large in order to keep the decoupling approximation accurate. After K is determined, users in the network can be put into the same group if they have similar likelihood of being captured at the central station. One way is to divide the range of the mean received powers at the central station into K (not necessarily equal) intervals and put the users that fall in the same interval into the same group. The distance of group

i relative to the central station after grouping is determined so that group i will produce the same average interference power at the central station as the sum of the power of the M_i individual users. For an inverse square power law, the distance between group i and the central station, r_{G_i}, satisfies

$$M_i \frac{1}{r_{G_i}^2} = \sum_{j=1}^{M_i} \frac{1}{r_j^2},$$

where $r_1, \ldots, r_{M_i}$ are the location of the users in group i before grouping.

It should be noted that the above grouping method (for determining $\vec{M}$ of the multi-group model) is independent of the actual spatial distribution (which can be linear, such as vehicles in highways, or planar, such as users in cities.) After the group performance is found, the individual user performance as a function of the distance relative to the central station can be obtained by interpolating group performance. Compared to the conventional approach for the analysis of a S-ALOHA system, where the spatial users distributions have to be restricted to some specific forms due to analytical tractability [6], the proposed grouping method is more general.

3. The Optimal Retransmission Control

For a mobile S-ALOHA network which is equipped with a particular physical modem structure and operating in a given environment, the system parameters (i.e., $\vec{M} = (M_1, M_2, \ldots, M_K)$ and $\{P_i(\vec{a})\}_{i=1}^{K}$) of the corresponding K-group S-ALOHA system can first be determined. Then, there is the question of how to set the retransmission probabilities of the K groups (q_i's) for given packet generation probabilities (σ_i's). Depending on the objective of the network design, we can formulate the appropriate optimization problem, some of which are discussed below.

3.1. The Maximum Throughput Problem

If the objective is to maximize the total network throughput, the retransmission probabilities $\vec{q} = (q_1, q_2, ..., q_K)$ should be set to the solution of the multivariate[1] nonlinear constrained optimization problem given by

$$\max_{q_1, ..., q_K} S$$

$$\text{subject to } 0 \le q_i \le 1 \,, i = 1, ... , K,$$

where S, the network throughput, is the sum of the throughputs of the K groups. In general, we are unable to solve this optimization problem due to the highly nonlinear relationship between $\vec{q}$ and S. However, in [13] we analytically solved a special case of the problem where the group with stronger power operates as if there were no other (weaker) groups, an assumption that has been used by other researchers for studying multi-group S-ALOHA with infinite population, e.g., [14]. In the numerical example presented later, numerical algorithms based on [15] are used to solve the above optimization problem.

The solution to this maximum throughput problem usually results in a scenario where most of the network throughput comes from the users in the close-in region of the central station. This phenomenon is acceptable if the data traffic is not delay-sensitive and users who are distant from the central station will move closer at some time. If the data traffic is delay-sensitive (i.e., the

1. For the Uniform Policy, the optimization problem degenerates to a univariate optimization problem.

packet cannot wait until users move to the neighborhood of the central station), we may want to consider the maximum balanced throughput problem below.

3.2. The Maximum Balanced Throughput Problem

To ensure that the user throughput is the same throughout the system while the network throughput is maximized, we need to solve another constrained optimization problem given by

$$\max_{q_1, \ldots, q_K} \; S$$

subject to $0 \le q_i \le 1$, $i = 1, \ldots, K$, and

$$\frac{S_1}{M_1} = \frac{S_2}{M_2} = \ldots = \frac{S_K}{M_K},$$

where S_i and M_i are the throughput and the population of group i, respectively. There are $(K - 1)$ more constraints here than in the maximum throughput problem, and so we can expect that the maximum balanced throughput will be smaller than the maximum throughput for the unbalanced case. The reduction in throughput is the cost paid to achieve fairness.

Similar to the maximum throughput problem, the maximum balanced throughput problem can also be solved by many numerical algorithms. In [13], we solve a special case which is the same as in Section 3.1 with the additional $(K - 1)$ constraints.

4. Application

Most of the work on the analysis of mobile S-ALOHA networks considers Rayleigh fading. In order to demonstrate the flexibility of our model, we consider a linear mobile S-ALOHA network in a Rician fading channel. In addition, the performance of the uniform and nonuniform retransmission control policies are also examined.

4.1. The Network

A. Topology

Consider a S-ALOHA network with 50 users equally spaced in an interval of $[d_{min}, 1]$ as shown in Fig. 1. d_{min}, which is greater than zero, reflects the reality that users cannot approach too close to the central receiver. Here d_{min} is chosen such that the maximum mean receiving power is 30 dB (i.e., $d_{min} = 0.0316$) with the power of user 50 as the reference.

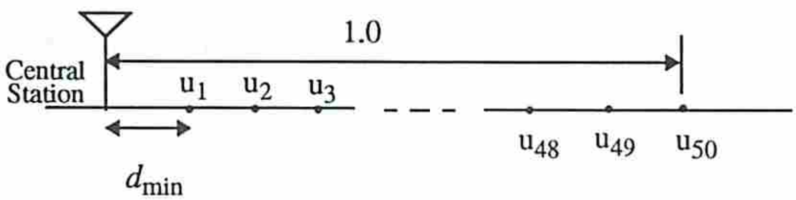

Fig. 1. The topology of a S-ALOHA network with 50 users equally spaced in $[d_{min}, 1.0]$.

B. Channel Model

All users transmit with the same power. The path loss exponent of the channel from mobile users to the central station ranges from 1.2 to 4.0 in micro cellular environments [16]. In the present study, the exponent is chosen to be 2. In addition to the path loss, the signals from mobile users to the central station suffer Rician fading with the instantaneous signal power following a noncentral chi-square distribution given by [18]

$$f(x|P, K_r) = \frac{(1+K_r)\, e^{-K_r}}{P} exp\left(-\frac{1+K_r}{P}x\right) I_0\left(\sqrt{4K(1+K_r)\frac{x}{P}}\right),$$

where P is the mean signal power (proportional to r^{-2}), K_r is the Rician factor, and I_0 is the modified Bessel function of the first kind of order zero. Measurement results show that K_r ranges from 7 dB to 12 dB [17]. In our study, K_r is chosen to be 10 dB. The instantaneous signal power is assumed to be constant over a packet, i.e., slow fading. Note that the shadowing effect is not considered here.

C. Capture Criterion

The receiver at the central station is assumed to be able to successfully receive a packet in the presence of other simultaneous transmissions if the ratio of the power of the desired signal and the sum of interfering powers is greater than a threshold R, called the capture threshold. The value of R depends on the modulation and coding schemes used [18] and is chosen to be 4 (6 dB) in the present study.

4.2. Approximation by a K-group System

A. Selection of K

The range of the mean receiving power is between 0 dB (from user 50) and 30 dB (from user 1). One way to group users is to divide the 30 dB range into K equal intervals (in dB) and then put the users falling in the same interval into the same group. For a 2-group approximation, users 1 to 8 are in group 1, whereas users 9 to 50 are in group 2, i.e., $\vec{M}$ = (8, 42). Similarly, we have $\vec{M}$ = (4, 11, 35) for a 3-group approximation, $\vec{M}$ = (3, 5, 12, 30) for a 4-group approximation, and $\vec{M}$ = (2, 3, 7, 12, 26) for a 5-group approximation. As K increases, the accuracy of the multi-group approximation increases (provided that decoupling approximation is still good) at the cost of the increasing complexity in the conditional capture probabilities.

B. Computation of the Conditional Capture Probabilities for Rician Fading

Given the activity vector $\vec{a} = (a_1, a_2, ..., a_K)$, the conditional capture probability of group i is $P_i(\vec{a}) = a_i \cdot P_r[X > R \cdot Y]$, where X is the received power of a particular packet of group i, and Y is the sum of the received powers of all other packets. Given $a_i \neq 0$, X is a noncentral chi-square random variable with parameters $P = 1/r_i^2$ and K_r. The probability density function (pdf) of Y is the convolution of the pdf's of all other transmissions, each of which is a noncentral chi-square random variable with the same K_r, but different P. The pdf of Y does not have a closed form expression. In our study, Y is approximated by a noncentral chi-square random variable with the same mean and variance as the sum of all interfering non-central chi-square random variables. With this approximation, $P_i(\vec{a})$ can be numerically evaluated by the double integral

$$\int_0^\infty \left[\int_0^{\frac{x}{R}} f_Y(y)\, dy \right] f_X(x)\, dx .$$

Note that this approximation is exact when there is only one interferer in a slot.

In this analysis, we have made 3 approximations: one being the grouping approximation, another being the decoupling approximation for the K-dimensional Markov chain, and the third being the chi-square approximation for the distribution of the sum of the power of all interfering packets. The accuracy of the system performance obtained by these approximations made here is validated by simulation results.

4.3. Numerical Results and Discussion

The unbalanced user throughput as a function of the distance relative to the central station in heavy traffic for the network given in Section 4.1 is shown in Fig. 2. It shows that close-in users have significantly higher throughput than distant users, although all users transmit with the same probability ($\sigma = q = 0.02$). The figure demonstrates that the prediction of the user throughput by the multi-group model closely matches simulation results, which shows that the grouping approximation and the chi-square approximation are good as far as system performance is concerned. Note that the ability of the multi-group model to predict the user throughput as a function of the distance relative to the central station improves as K increases.

To demonstrate the accuracy of the multi-group approach for a wide range of network loading, we plot, in Fig. 3, the network throughput as a function of the packet generation probability for various grouping approximations. This figure shows that the 2-group approximation is not as accurate as the 3-group or 5-group approximations. Note that all of these grouping approximation are good when the network is operating at a point below maximum capacity. The discrepancy between the multi-group models and the simulation model is primarily due to the grouping method that lumps together all users in a group, which results in a capture phenomenon weaker than in the real network. With the similarity between the 3-group and 5-group model results, the simpler 3-group model will be used for the rest of the numerical examples (unless mentioned otherwise.)

Fig. 4 shows the impact of the choices of packet generation probability and retransmission probability on the stability of the system. As expected, for a particular packet generation probability, there is a maximum retransmission probability, beyond which the network throughput will drop very fast–the *unstable region*. The figure shows that a smaller retransmission probability can ensure stability of the system for a wider range of packet generation probabilities at the cost of higher packet delay.

Fig. 5-10 explore the effect of the Uniform Policy on network and user throughput. We consider 3 retransmission probabilities: $q = 0.04$ in Fig. 5-6, $q = 0.08$ in Fig. 7-8, and $q = 0.12$ in Fig. 9-10. In Fig. 5, the network throughput increases monotonically as the packet generation probability σ increases, whereas the group-3 throughput shows a behavior of increase initially and then decrease. This indicates that higher overall network throughput does not necessarily mean that all users experience higher throughput. In fact, the weaker groups are sacrificed to the stronger groups when the channel load is high. Fig. 6 shows that the unfairness between user throughput deteriorates as σ increases. In fact, it can be seen that after σ exceeds some threshold (close to 0.01 in this case,) the group-3 user throughput starts to saturate and then decrease, whereas the group-1 user throughput continues to increase due to capture.

In Fig. 7-8, we increase q from 0.04 to 0.08. Now the network throughput does not increase monotonically as σ increases. From Fig. 7, we see that the network throughput drops because of the breakdown of group 3, which consists of most of the users in the network. But the network throughput picks up again later since the group-1 throughput keeps increasing and the group-2 throughput does not decrease too fast. Fig. 8 shows the behavior of the user throughput as σ increases. As in Fig. 6, the fairness of the user throughput begins to degrade when σ exceeds about 0.01. Fig. 9-10 show similar behavior as Fig. 7-8 except that the breakdown of group 3 is more dramatic because of the higher retransmission probability $q = 0.12$. From Fig. 6, 8, and 10, we find that the fairness of user throughput exhibits a threshold phenomenon, and that the unfairness beyond the threshold gets more critical for larger retransmission probabilities.

From the results in Fig. 5-10, we see that there is a trade-off between fairness and efficiency for a S-ALOHA network with the Uniform Policy. To show the trade-off, we define two indices: the fairness index and the efficiency index. The *fairness index* is defined as the ratio of the user throughput of the weakest group to the user throughput of the strongest group, which is always less than one for the Uniform Policy, and the *efficiency index* is defined as the ratio of the network throughput to the maximum network throughput for a given retransmission probability. To avoid clutter, Fig. 11 shows the design trade-off for only two values of the retransmission probability q. In both cases, as the packet generation probability σ increases, the fairness index decreases whereas the efficiency index increases up to the point where the maximum throughput is reached. The point where the two indices are equal suggests a good trade-off between the network efficiency and the fairness of the user throughput.

Fig. 12-13 explore the effect of the Nonuniform Policy on network and user throughput. The retransmission probabilities of the 3 groups, $\vec{q}$ = (2.8E-3, 2.3E-2, 0.1), are chosen to give the maximum balanced throughput for $\sigma = 0.01$. Although the total network throughput shown in Fig. 12 looks similar to the one in Fig. 7, the distribution of the network throughput for the 3 groups are different. In Fig. 13, with the smaller retransmission probability, the group-1 user throughput does not increase as fast as in the case of the Uniform Policy (see Fig. 6, 8 and 10.)

The comparison between the Uniform Policy and the Nonuniform Policy is highlighted in Fig. 14-15. Fig. 14 shows that the network throughput is not sensitive to the retransmission probability before the maximum throughput (which depends on the retransmission probability) is reached. As expected, a lower retransmission probability will give a larger maximum network throughput. Fig. 15 compares the fairness indices of different retransmission control policies. It shows that the Nonuniform Policy is able to maintain better fairness over a wider range of network loading compared to the Uniform Policy. Note that the fairness index of the Nonuniform Policy in Fig. 15 is slightly greater than 1.0 for σ smaller than 0.01. This indicates that the user throughput of group 3 is slightly larger than that of group 1 when σ is less than 0.01. We also observe that the fairness indices of the 4 cases considered are all above 0.8 as long as σ is smaller than 0.01, which means that the unfairness is not serious if the packet generation probability is always less than 0.01.

Having discussed the effect of the retransmission control policies, we compare the numerical results of the maximum throughput and the maximum balanced throughput of several multi-group systems that are derived from the S-ALOHA network introduced in Section 4.1 in heavy traffic (i.e., $\sigma_i = q_i$), see Table 1. These results are obtained by numerical optimization. Both the maximum throughput and the maximum balanced throughput increase as the number of groups (K) increases due to the improved capture capability under the near-far effect. This strongly suggests that it is very inefficient to achieve balanced throughput by perfect power control (corresponding to $K = 1$) where all users adjust their transmission power so that their packets will arrive at the central station with equal strength. On the other hand, retransmission control (corresponding to higher values of K) should be adopted to take the advantage of the capture phenomenon due to the near-far effect. In fact, it can be inferred that if each user can fine tune its retransmission probability by interpolating the optimal retransmission probabilities obtained by the 5-group system, the system performance can be further improved.

We also note that as the network throughput is maximized, the fairness is very poor among close-in and distant users. In order to enforce the fairness among users' throughputs, the network has to sacrifice some capacity. The difference between the maximum throughput and the maximum balanced throughput is the cost of the fairness of user throughput.

6. Conclusion

An analytical multi-group model is developed to evaluate the performance of mobile slotted ALOHA networks under two retransmission control policies. The effectiveness of the policies in improving the fairness of user performance in a mobile environment with fading and near far effects are examined. The Uniform Policy is simple and can achieve reasonable fairness if the packet generation probability is kept below a certain threshold (exceeding which will result in a highly unfair system.) The Nonuniform Policy, however, is able to provide better fairness over a wider range of packet generation probabilities.

The cost of applying retransmission control to achieve balanced user throughput is considered by comparing the numerical solutions of the maximum throughput problem and the maximum balanced throughput problem. The results indicate that power control is not as efficient as retransmission control for improving fairness of the system.

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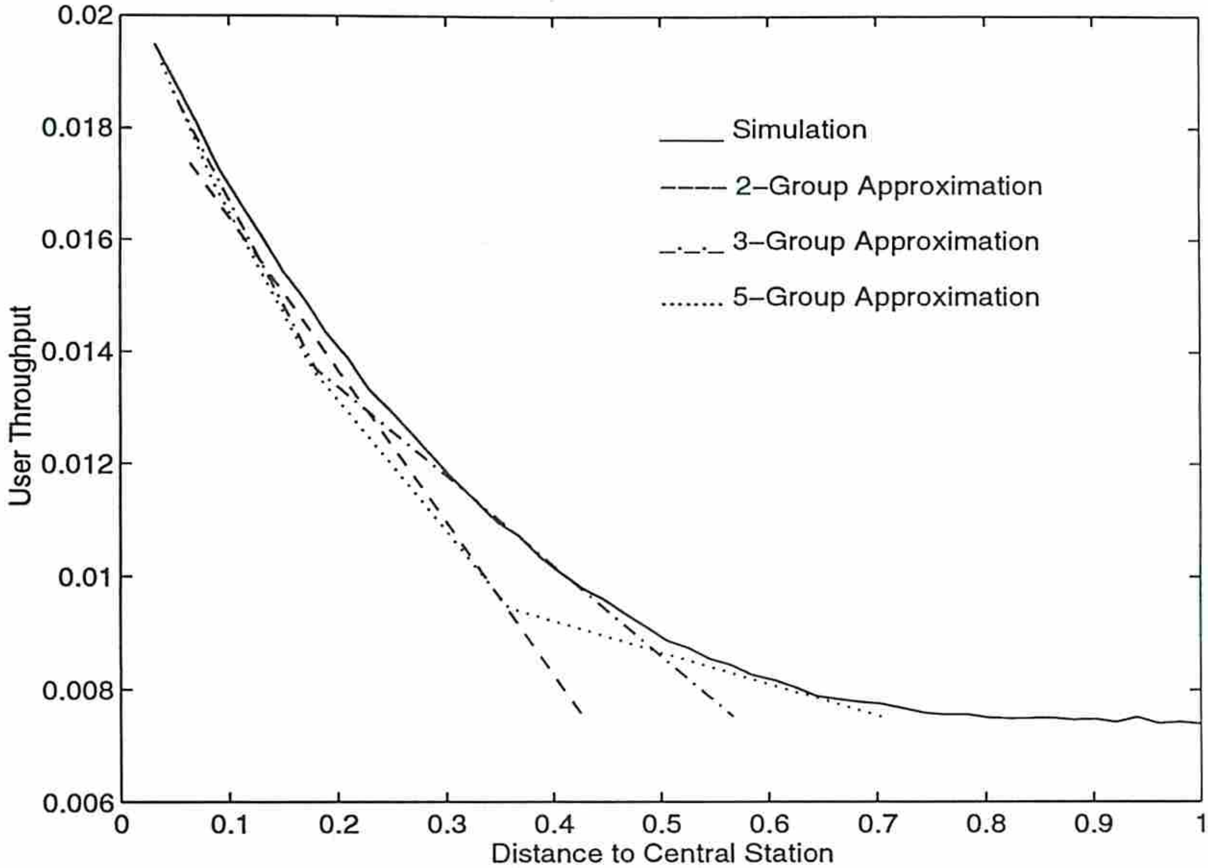

Fig. 2. The unfair user throughput as a function of the distance relative to the central station for the slotted ALOHA network with Rician fading given in Section 4.1. The transmission probability $\sigma = q = 0.02$ and the Rician factor $K_r = 10$ for all users.

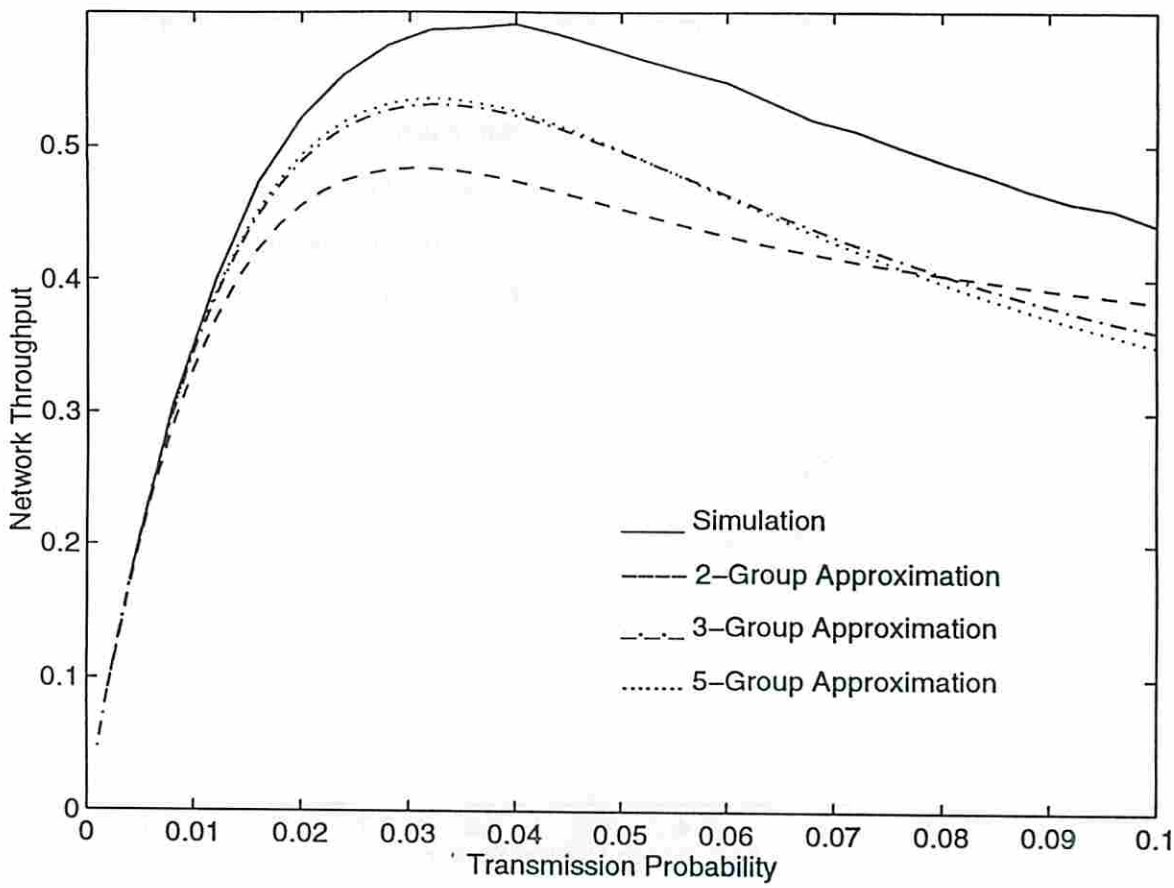

Fig. 3. Network throughput versus transmission probability in heavy traffic ($\sigma = q$) under the Uniform Policy for different grouping approximations compared against simulation.

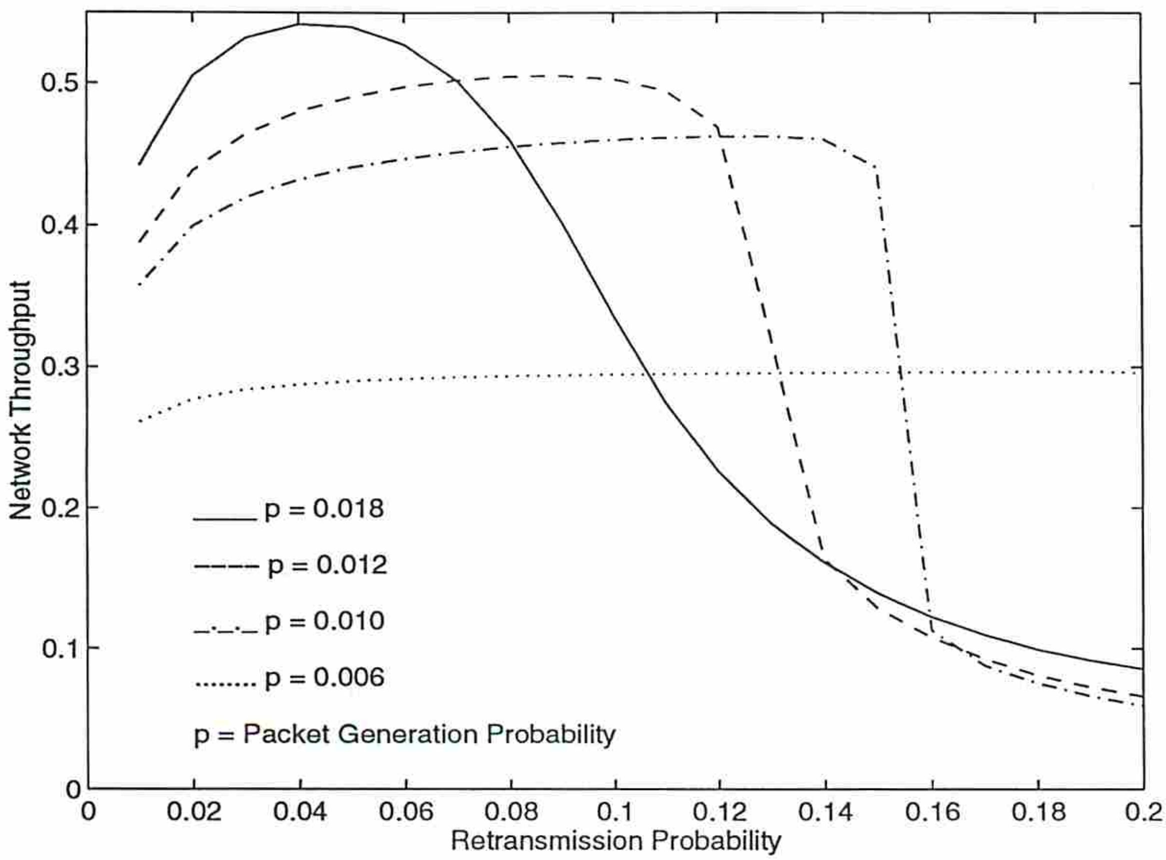

Fig. 4. Joint effect of σ and q on network throughput. The breakdown of network for q exceeding some threshold shows the unstable nature of S-ALOHA system.

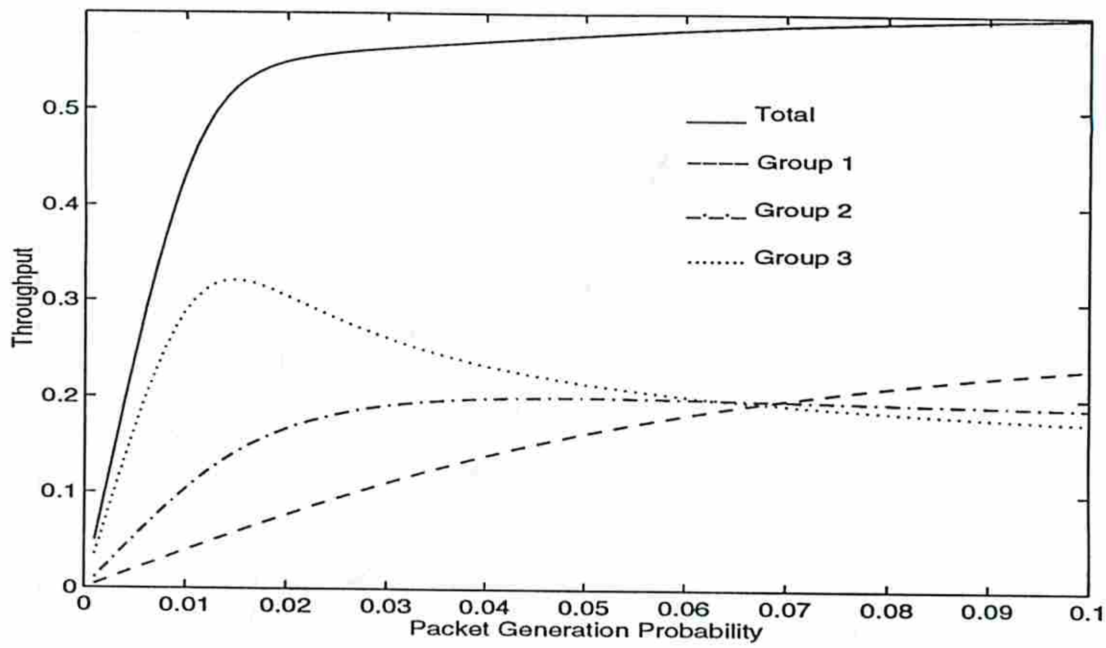

Fig. 5. Total/group throughputs versus σ when $q = 0.04$ under the Uniform Policy.

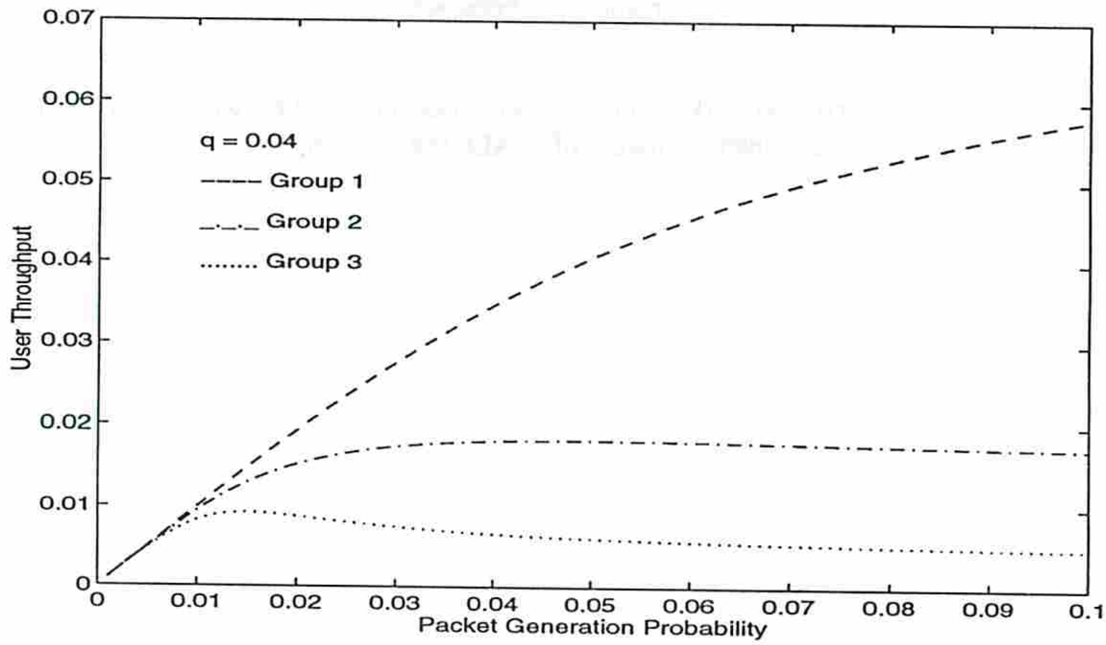

Fig. 6. Fairness of the user throughput under the Uniform Policy in normal traffic where $q = 0.04$.

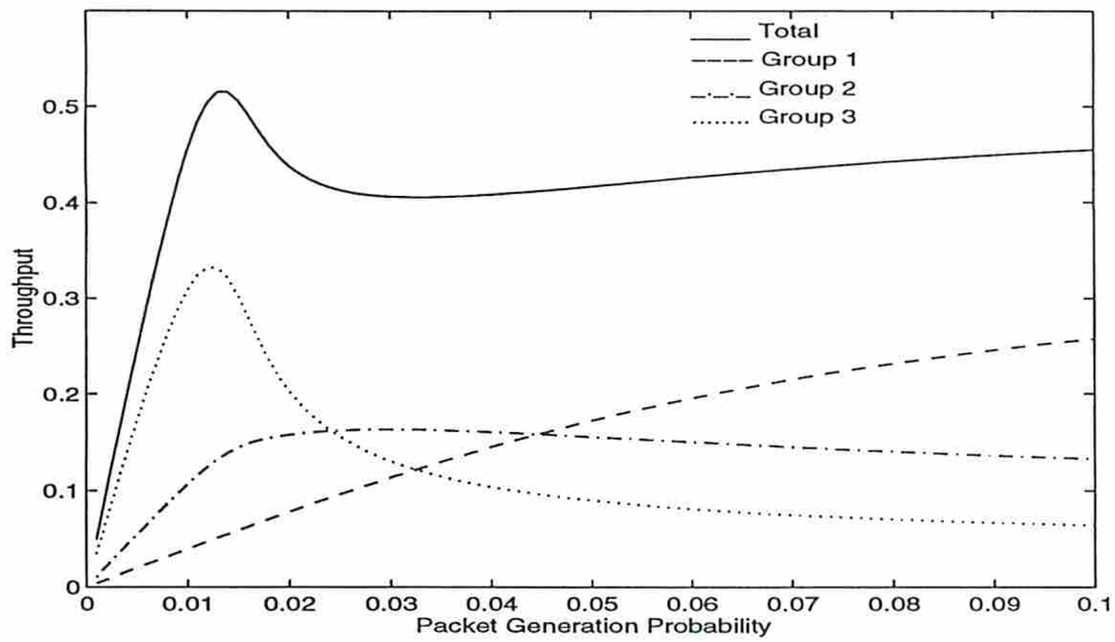

Fig. 7. Total/group throughputs versus σ when $q = 0.08$ under the Uniform Policy.

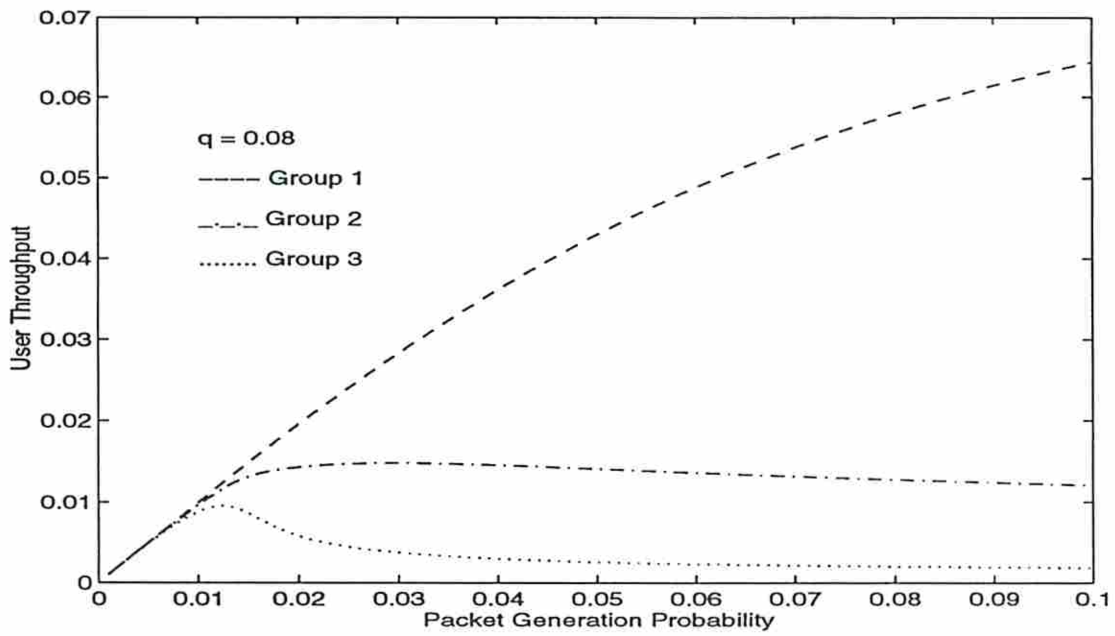

Fig. 8. Fairness of the user throughput under the Uniform Policy in normal traffic where $q = 0.08$.

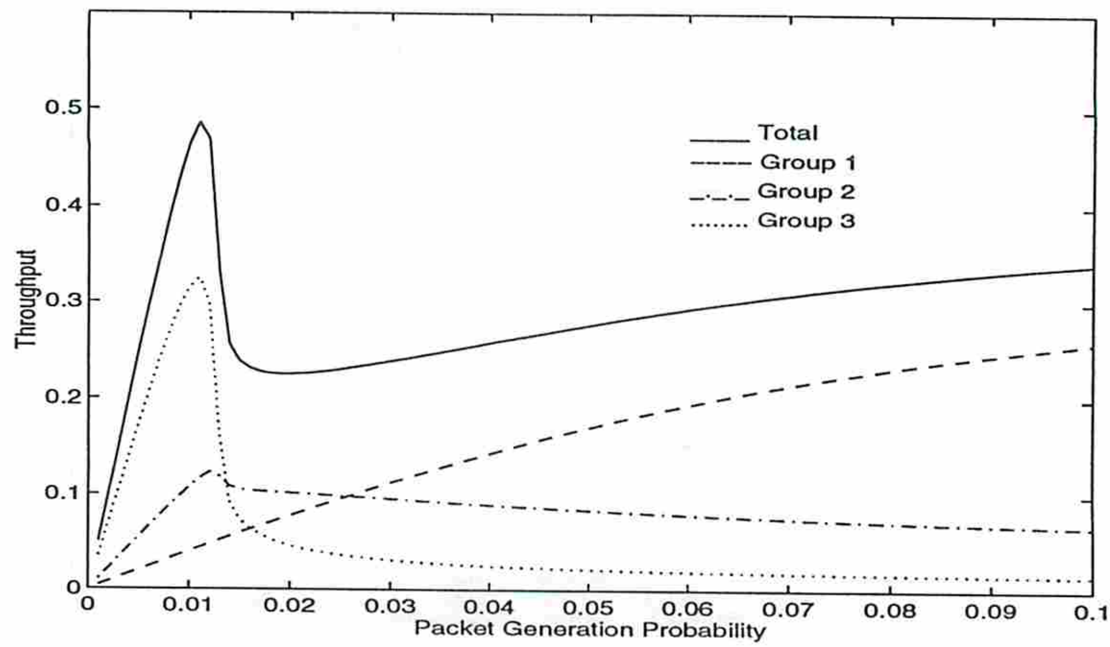

Fig. 9. Total/group throughputs versus σ when $q = 0.12$ under the Uniform Policy.

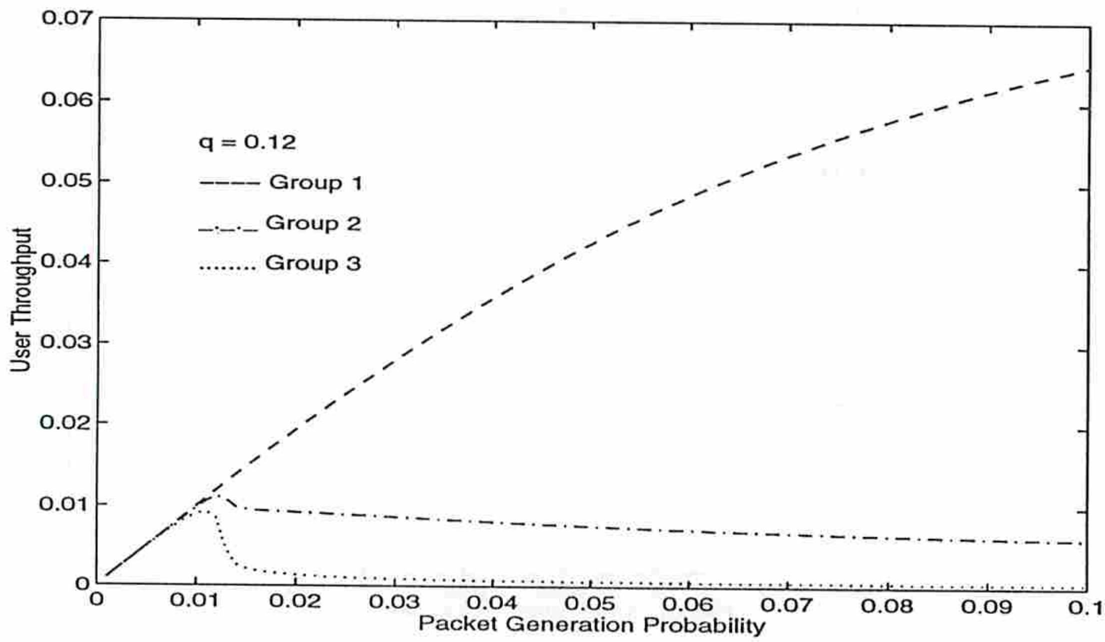

Fig. 10. Fairness of the user throughput under the Uniform Policy in normal traffic where $q = 0.12$.

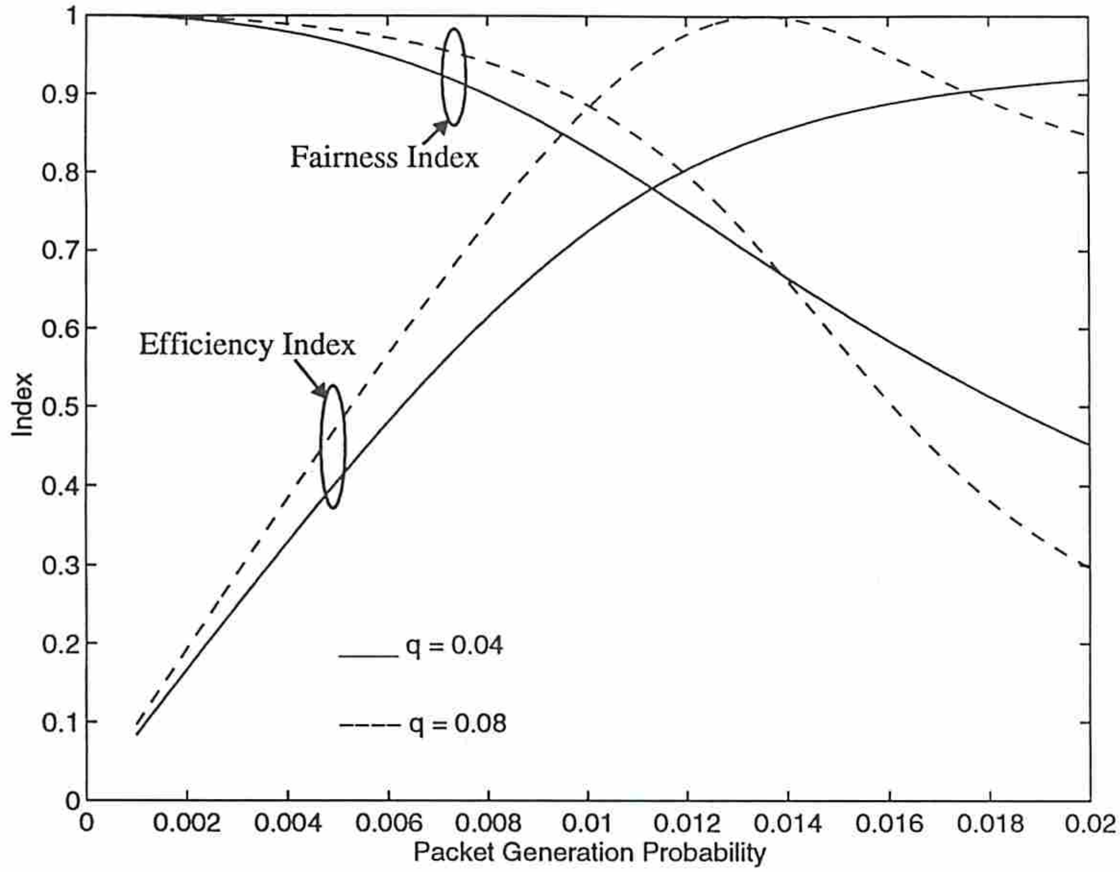

Fig. 11. Trade-off between user fairness and network efficiency.

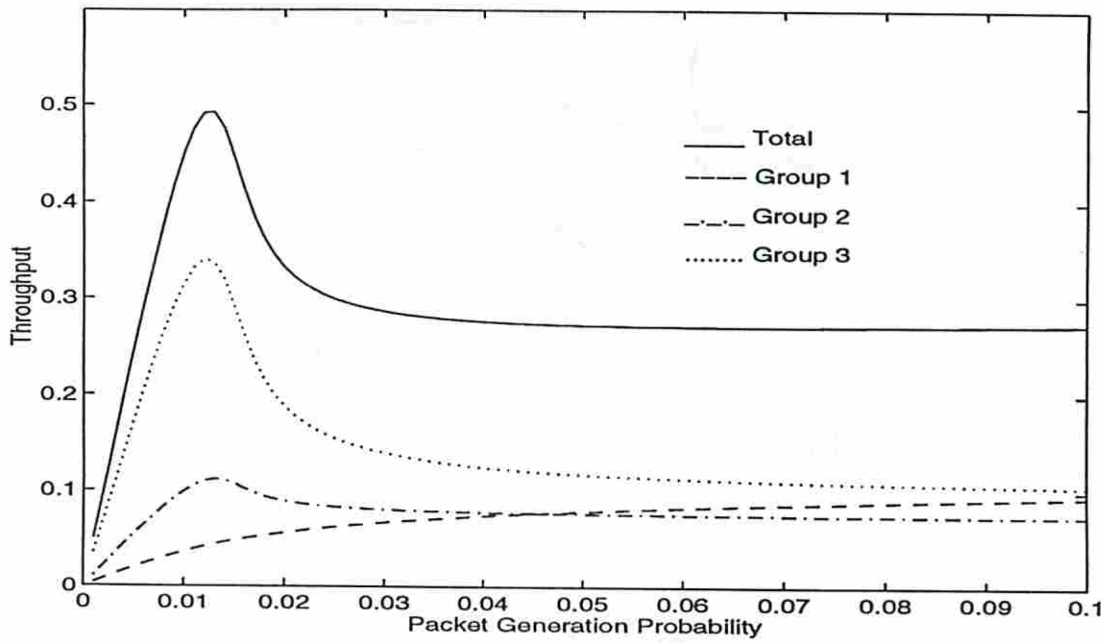

Fig. 12. Total/group throughputs versus σ under the Nonuniform Policy. $\vec{q} = (2.8E\text{-}3, 2.3E\text{-}2, 0.1)$ is the solution that achieves the maximum balanced throughput when $\sigma = 0.01$.

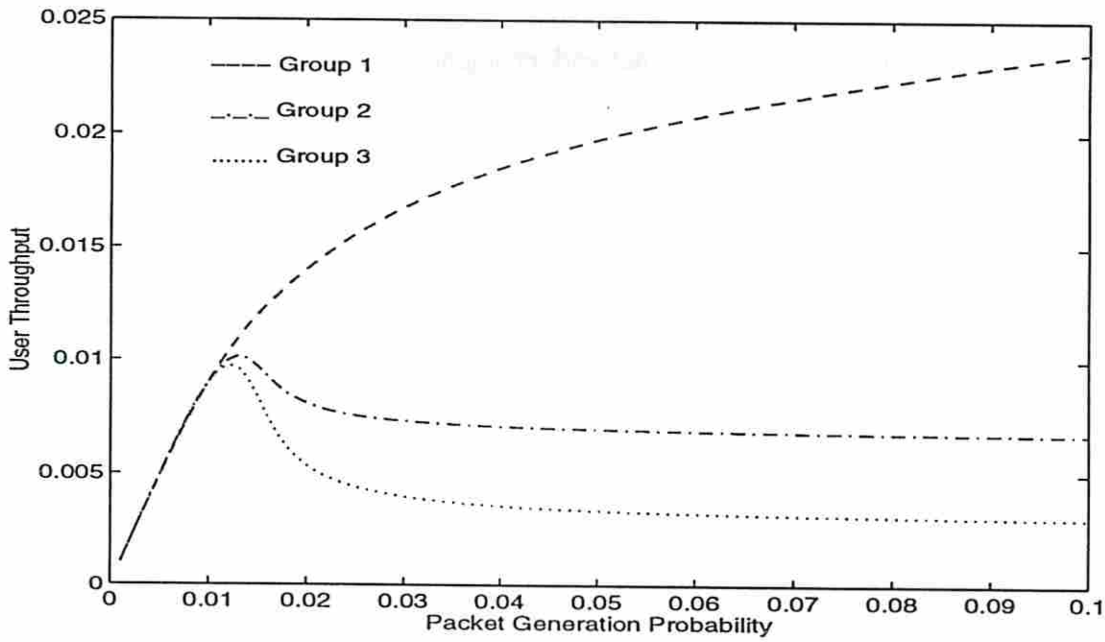

Fig. 13. Fairness of the user throughput under the Nonuniform Policy in normal traffic. $\vec{q}$ is the same as in Fig. 12.

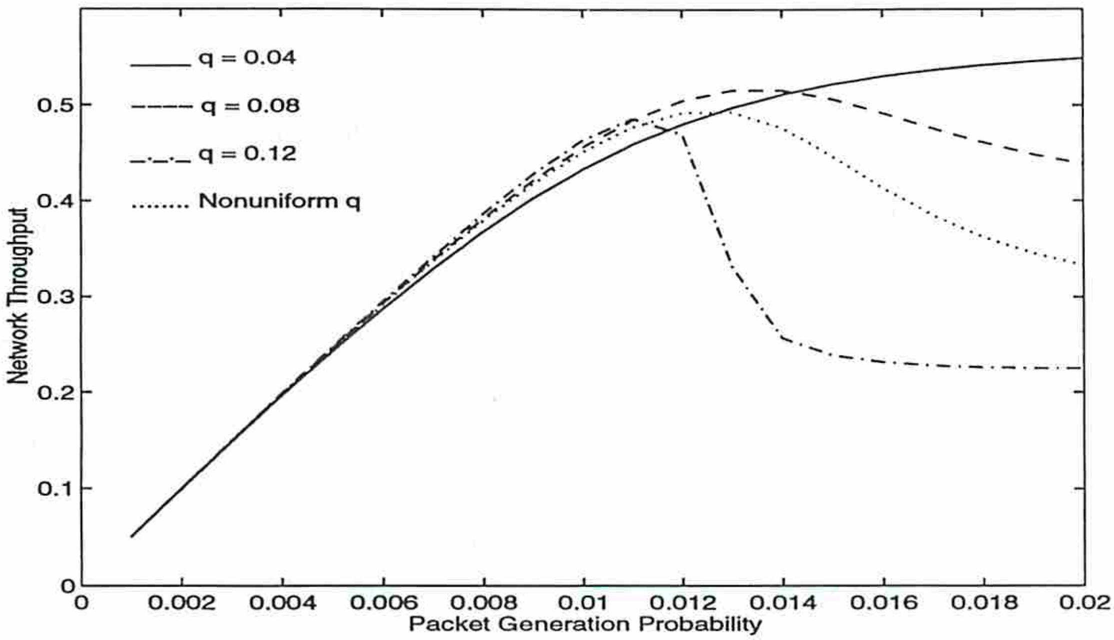

Fig. 14. Network throughput versus packet generation probability for various retransmission control policies.

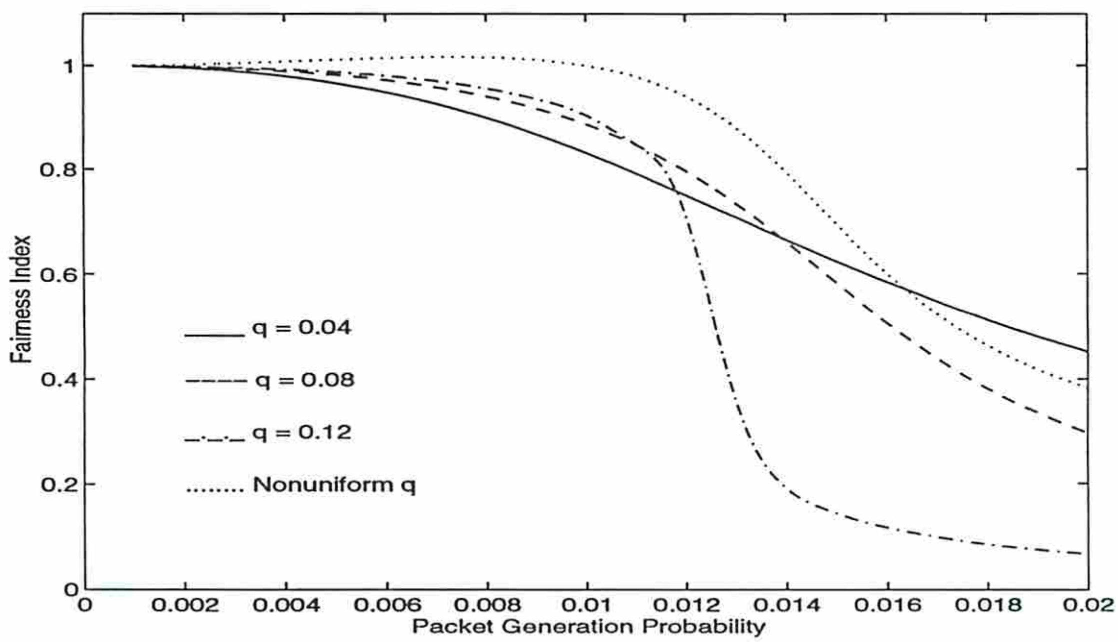

Fig. 15. Fairness comparison for various retransmission control policies.

Table 1: Comparison between the maximum throughput and the maximum balanced throughput of the K-group slotted ALOHA systems

	Maximum Throughput			Maximum Balanced Throughput		
	Transmission Probability $\vec{q}$	User Throughput	Network Throughput	Transmission Probability $\vec{q}$	User Throughput	Network Throughput
$K = 1$ $\vec{M} = (50)$	.0204	.0076	.3786	.0204	.0076	.3786
$K = 2$ $\vec{M} = (8, 42)$	.0831 .0239	.0456 .0045	.5542	.0090 .0242	.0084	.4202
$K = 3$ $\vec{M} = (4, 11, 35)$	.1409 .0464 .0226	.0871 .0141 .0034	.6224	.0094 .0125 .0280	.0091	.4549
$K = 4$ $\vec{M} = (3, 5, 12, 30)$	.1767 .0748 .0153 .0278	.1115 .0281 .0036 .0039	.6353	.0096 .0112 .0175 .0300	.0094	.4682
$K = 5$ $\vec{M} = (2,3,7,12,26)$	.3195 .0000 .0857 .0000 .0339	.2166 .0000 .0223 .0000 .0036	.6826	.0097 .0105 .0132 .0222 .0311	.0095	.4735