The Maximum Throughput and the Maximum Balanced Throughput of Mobile Slotted ALOHA Networks

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Abstract–The performance of mobile slotted ALOHA networks with finite population is analyzed by a multi-group model. Using this model, the group performance of a multi-group system can be interpolated to obtain the approximate user performance as a function of the distance relative to the central station. For a network approximated by a multi-group system in heavy traffic, the maximum throughput and the maximum balanced throughput problems are formulated as constrained optimization problems. These two objectives approximate the network capacity and help achieve the fairness between the close-in and distant users. In the general case, these optimization problems can be solved by numerical optimization algorithms. Faster solutions based on recursion, however, are derived for a specific system with multi-level dominating power. An application of the multi-group model to a slotted ALOHA network with a linear topology in a Rician fading channel is demonstrated. Computer simulation is used to validate the results obtained from the analytical model.

Keywords: mobile radio networks, S-ALOHA, capture, near-far effect, maximum throughput, fairness, multi-group, analytical models

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1. Introduction

In the literature performance evaluation of finite-population slotted ALOHA (S-ALOHA) radio networks has centered on total network throughput and the average packet delay [1]-[3]. These performance measures are appropriate in the case of a "homogeneous" system, i.e., the receiving power at the central station from all users is approximately equal and the network throughput is equally shared by the users. These measures, however, are not useful for a "heterogeneous" system such as a mobile S-ALOHA network where the receiving power at the central station varies from one user to another. For example, close-in users can reach the central station with a much higher level of power than distant users because of the rapid decay of the strength of electromagnetic signals in a radio channel. Without proper control on the channel access, the radio channel can be completely saturated by the close-in users. In order to study the issue of fair sharing of the common radio channel, we need a more elaborate network model that explicitly considers the performance of the users whose signals at the station have different power levels.

Goodman and Saleh [4] considered the near-far effect in a S-ALOHA network in a non-fading channel. They found that the near-far effect can improve the throughput and delay of the system as a whole. Plas and Linnartz [2] considered a mobile S-ALOHA network with Rayleigh fading, shadowing, and the near-far effect. Although a more realistic channel model is used, their model does not differentiate the performance of the close-in and far-off users. Liu, Silvester and Polydoros [5] proposed a multi-group analytical model for mobile S-ALOHA networks with capture. The multi-group model can be used to evaluate the throughput, delay, and stability of each group in a heterogeneous network with general channel and capture models.

In the present study, we extend the work in [5] to address the capacity (i.e., the maximum throughput) and the fairness (i.e., the maximum balanced throughput) aspects of mobile S-ALOHA networks. Section 2 briefly reviews the multi-group model and introduces the principle to approximate a mobile S-ALOHA network by a multi-group system. Two optimization problems for a multi-group network in the heavy traffic scenario are studied: the maximum throughput problem and the maximum *balanced* throughput problem. The maximum throughput problem, which is to maximize the total network throughput, is discussed in Section 3. The maximum balanced throughput problem, that is to maximize the network throughput under the constraint that all users have the same throughput, is treated in Section 4. Both problems are concerned with finding transmission probabilities that achieve optimality for the network in the heavy traffic scenario. A S-ALOHA network with a linear topology in a Rician channel is considered in Section 5, where numerical results are also presented and discussed.

2. Multi-group S-ALOHA with Capture

2.1 The Model

A. Terminal Model

Consider a S-ALOHA system with K groups of terminals (or users), labeled as G_1, G_2,..., G_K. For group i, $i = 1, 2,..., K$, G_i consists of M_i single-buffered terminals that are identical and independent. 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. If the transmission is successful, the terminal will receive a 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. When it is in the backlogged state, it will transmit the packet with probability

q_i in each slot until it succeeds.

B. General Capture Model

In general, the probability that the central station can successfully receive a packet in a slot depends on the activities of all the K groups. Define the activity vector $\vec{a} = (a_1, a_2,..., a_K)$, where a_i, $i = 1, 2,..., K$, 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 the factors such as modulation, coding, propagation law, channel characteristics, etc. We can think of $P_i(\vec{a})$ as a parameter that depends on the operating environment and the physical modem structure. $P_i(\vec{a})$ serves as input parameter when the network performance is evaluated.

C. Network Model

For a given terminal and capture model, the network can be modeled by a K-dimensional Markov chain with the state being the number of backlogged users in each group. A decoupling approximation can be used to avoid having to solve this K-dimensional Markov chain. The equilibrium state probabilities of the decoupled Markov chains can be used to compute the throughput, delay, and stability of each group. The details of the computation procedure can be found in [5].

D. Network Throughput in Heavy Traffic Scenario

In the heavy traffic scenario (σ=1 for all users), a user in group i will transmit in a slot with probability q_i. The probability that a_i users in group i transmit in a slot is therefore

$\binom{M_i}{a_i} q_i^{a_i} (1-q_i)^{M_i - a_i}$ denoted by $B(M_i, a_i, q_i)$. The throughput of group i, S_i, is given by

$$S_i = \sum_{a_1=0}^{M_1} \dots \sum_{a_K=0}^{M_K} P_i(a_1, \dots, a_K) \prod_{j=1}^{K} P_r[a_j \text{ users in group } j \text{ transmit}]$$

$$= \sum_{a_1=0}^{M_1} \dots \sum_{a_K=0}^{M_K} P_i(a_1, \dots, a_K) \prod_{j=1}^{K} B(M_j, a_j, q_j) .$$

The throughput of a user in group i is thus S_i / M_i. The sum of the throughput of all groups is the network throughput S, which is given by

$$S = \sum_{i=1}^{K} S_i$$

$$= \sum_{a_1=0}^{M_1} \dots \sum_{a_K=0}^{M_K} \left[\sum_{i=1}^{K} P_i(a_1, \dots, a_K) \right] \prod_{j=1}^{K} B(M_j, a_j, q_j) .$$

Let $P_s(a_1, \dots, a_K) = \sum_{i=1}^{K} P_i(a_1, \dots, a_K)$. S can be further simplified as

$$S = \sum_{a_1=0}^{M_1} \dots \sum_{a_K=0}^{M_K} P_s(a_1, \dots, a_K) \prod_{j=1}^{K} B(M_j, a_j, q_j) . \quad (1)$$

2.2 Parameter Selection

The parameters K, $\vec{M} = (M_1, M_2, \dots, M_K)$, and $\{P_i(\vec{a})\}_{i=1}^{K}$ need to be determined before the network performance can be evaluated. The first parameter to be determined is K, the number of groups. A larger K will give higher accuracy of the performance estimates at the cost of the higher complexity of the resulting model and the higher computational cost in determining $\{P_i(\vec{a})\}_{i=1}^{K}$. After K is determined, users in the network can be put in the same group if they have similar capability to capture the receiver at the central station. One way is to divide the range of the mean receiving power 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. After the performance of the groups is found, the user performance as a function of the distance relative to the central station can be obtained by interpolating group performance.

3. The Maximum Throughput Problem

3.1 Problem Formulation

For a K-group S-ALOHA network with given $\vec{M} = (M_1, M_2, \ldots, M_K)$ and $\{P_i(\vec{a})\}_{i=1}^{K}$ in the heavy traffic scenario, the network throughput is a function of the transmission probabilities $\vec{q} = (q_1, q_2, \ldots, q_K)$. Therefore the network throughput S, Eq. (1), can be maximized by an optimal choice of $\vec{q}$. This problem can be written as a multivariate nonlinear constrained optimization problem given by

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

subject to

$$0 \le q_i \le 1, \; i = 1, \ldots, K.$$

There exist many numerical algorithms [6] that can solve the above optimization problem. In the following, we will consider a special case where analytical solutions exist.

3.2 Multi-group S-ALOHA with Multi-level Dominating Power

In the K-group S-ALOHA network, the users in different groups are assumed to be able to reach the central station with different levels of power such that higher power always dominates lower power. In other words, the central station can capture the transmission from a user in group i if there is no other transmission from groups $1, 2, \ldots, i$. Therefore we have the throughput of each group and the overall network throughput given by

$$S_1 = B(M_1, 1, q_1),$$

$$S_2 = B(M_2, 1, q_2)\, B(M_1, 0, q_1),$$

$$\vdots$$

$$S_K = B(M_K, 1, q_K) \prod_{j=1}^{K-1} B(M_j, 0, q_j),$$

$$S = \sum_{i=1}^{K} S_i.$$

To find the optimal $\vec{q}$, we need to solve the following system of K simultaneous equations $\frac{\partial S}{\partial q_i} = 0$, $i = 1, \ldots, K$. It turns out that the K equations can be solved recursively starting from $\frac{\partial S}{\partial q_K} = 0$, which gives $q_K = 1/M_K$. Then, $\frac{\partial S}{\partial q_{K-1}} = 0$ can be used to find the optimal q_{K-1}. By repeating this process, the optimal $\vec{q}$ can be obtained as follows.

$$q_i = \begin{cases} \dfrac{1}{M_K} & \text{if } i = K \\ \dfrac{1 - B(M_K, 1, q_K)}{M_{K-1} - B(M_K, 1, q_K)} & \text{if } i = K-1 \\ \dfrac{1 - B(M_{i+1}, 1, q_{i+1}) - \sum_{j=i+2}^{K} B(M_j, 1, q_j) \prod_{l=i+1}^{j-1} B(M_l, 0, q_l)}{M_i - B(M_{i+1}, 1, q_{i+1}) - \sum_{j=i+2}^{K} B(M_j, 1, q_j) \prod_{l=i+1}^{j-1} B(M_l, 0, q_l)} & \text{if } 1 \le i \le K-2. \end{cases}$$

It is not difficult to see that as M_i approaches infinity ($i = 1, \ldots, K$), the above recursion will match the one given in [10], where the maximum throughput of a multi-group S-ALOHA networks with infinite population and multi-level dominating power was considered.

4. The Maximum Balanced Throughput Problem

4.1 Problem Formulation

The optimal transmission probabilities $\vec{q} = (q_1, q_2, \ldots, q_K)$ that maximize the network throughput do not guarantee that the throughput per user is the same for all users, which is a desirable feature for some applications. 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

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

Note that there are $(K - 1)$ more constraints here than the maximum throughput problem introduced in the previous section. Because of the additional constraints, we can expect that the maximum balanced throughput is always smaller than or equal to the maximum throughput for a given network. The reduction in throughput is the cost paid for the fairness of the system.

Similar to the maximum throughput problem, the maximum balanced throughput problem can also be solved by many numerical algorithms [6]. In what follows, we will consider a special case which is the same as the one in Section 3.2 except for the additional $(K - 1)$ constraints.

4.2 Multi-group S-ALOHA with Multi-level Dominating Power

With the addition of the $(K - 1)$ constraints to the maximum throughput problem considered in Section 3.2, we have the maximum balanced throughput 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 $$S_1 = B(M_1, 1, q_1),$$

$$S_i = B(M_i, 1, q_i) \prod_{j=1}^{i-1} B(M_j, 0, q_j), \; 2 \le i \le K,$$

and $$S = \sum_{i=1}^{K} S_i.$$

By the method of Lagrange multipliers, we define

$$T = \sum_{i=1}^{K} S_i + \lambda_1 \left(\frac{S_1}{M_1} - \frac{S_2}{M_2} \right) + \lambda_2 \left(\frac{S_2}{M_2} - \frac{S_3}{M_3} \right) + \ldots + \lambda_{K-1} \left(\frac{S_{K-1}}{M_{K-1}} - \frac{S_K}{M_K} \right),$$

where $\lambda_1, \lambda_2, \ldots, \lambda_{K-1}$ are Lagrange multipliers. The optimal $\vec{q} = (q_1, q_2, \ldots, q_K)$ can be obtained by solving the following system of equations

$$\begin{cases} \dfrac{\partial T}{\partial q_i} = 0 & i = 1, \ldots, K \\ \dfrac{\partial T}{\partial \lambda_j} = 0 & j = 1, \ldots, K-1. \end{cases}$$

From $\dfrac{\partial T}{\partial \lambda_j} = 0$, we have $\dfrac{S_j}{M_j} = \dfrac{S_{j+1}}{M_{j+1}}$. After some simplification, we get

$$q_j = \frac{q_{j+1}(1-q_{j+1})^{M_{j+1}-1}}{1+q_{j+1}(1-q_{j+1})^{M_{j+1}-1}} \qquad 1 \le j \le K-1.$$

From $\dfrac{\partial T}{\partial q_K} = 0$, we have $q_K = \dfrac{1}{M_K}$. Therefore the optimal $\vec{q}$ can be obtained by the recursive formula

$$q_i = \begin{cases} \dfrac{1}{M_K} & \text{if } i = K \\ \dfrac{q_{i+1}(1-q_{i+1})^{M_{i+1}-1}}{1+q_{i+1}(1-q_{i+1})^{M_{i+1}-1}} & \text{if } 1 \le i \le K-1. \end{cases}$$

5. Application

In this section, we will consider a mobile S-ALOHA network with a linear topology in a Rician fading channel. Two K-group systems which approximate the linear network are considered: one with Rician fading the other with multi-level dominating power. For both systems, the selection of K and the population of each group $\vec{M}$ are discussed. For the K-group system with Rician fading, the computation of the conditional capture probabilities $\{P_i(\vec{a})\}_{i=1}^{K}$ is sketched.

5.1 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 fact that users cannot approach the receiver at the central station without any limit. 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.

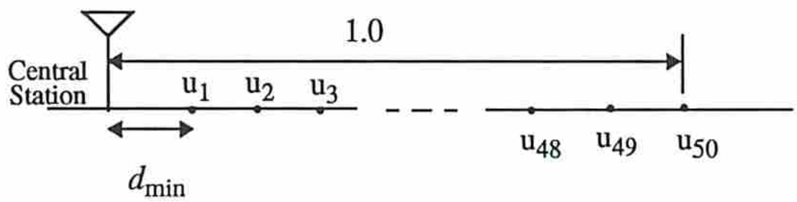

Fig. 1. The topology of a S-ALOHA network with 50 users equally spaced in $[d_{min}, 1.0]$.

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 [7]. 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 [9]

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

where P is the mean signal power (equal 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 [8]. In our study, K_r is chosen to be 10 dB. The instantaneous signal power is assumed to be constant in 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 the interfering power is greater than a threshold R, called the capture threshold. The value of R [9] depends on the modulation and coding schemes used and is chosen to be 4 (6 dB) in the present study.

5.2 Approximation by *K*-group Systems

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 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 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 power 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 being 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 a 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.

5.3 Numerical Results and Discussion

The unbalanced user throughput as a function of the distance relative to the central station in the heavy traffic scenario ($\sigma = 1$) for the network given in Section 5.1 is shown in Fig. 2*a*-2*d*. In these figures, the close-in users have significant higher throughput than the distant users, although all users transmit with the same probability ($q = 0.02$). These figures demonstrate that the prediction of the user throughput by the multi-group model (with Rician fading) closely matches simulation. Note that the accuracy of the multi-group model increases as K increases.

The numerical results for the maximum throughput and the maximum balanced throughput of the two K-group systems which approximate the network given in Section 5.1 are summarized in Tables 1 and 2, respectively. The maximum throughput and the maximum balanced throughput are searched by the optimization routines in the IMSL library [6] for the K-group system with Rician fading, and computed by the recursive formulae for the K-group system with dominating power.

Table 1 shows that the maximum throughput of the system with multi-level dominating power is closer to that of the system with Rician fading when K is smaller. This is because the difference of the mean power is so large that a close-in group can almost completely dominate a distant group when K is small. In the case of larger K, the tendency that a close-in group can dominate a distant group becomes weaker, which makes the maximum throughput with Rician fading smaller than that with multi-level dominating power. It is also observed that the maximum throughput of both systems increases as K increases with the help of the near-far effect. Nevertheless, as the total network throughput is maximized, the user throughput is extremely unbalanced for both systems. For example, in the case of $K = 5$ for the system with Rician fading, the maximum throughput is achieved when groups 2 and 4 have zero throughput. Note that the zero throughput of some groups indicates a relation between power levels and number of groups. In this example, the fact that the 5-group system which degenerates to a 3-group system due to the zero throughput of group 2 and 4 has higher maximum throughput than that of the genuine 3-group system ($\vec{M}$ =(4, 11, 35)) can be attributed to the effect of the larger difference between the power levels of groups at the central station. In order to maximize the total network, it is better to require the groups have dominating power levels than have non-dominating power levels that may interfere with each other. To achieve maximum throughput, there exists a trade-off between number of groups and power levels of a system.

Similar to Table 1, Table 2 shows that the maximum balanced throughput of the system with multi-level dominating power is closer to that of the system with Rician fading when K is smaller. As expected, the maximum balanced throughput increases as K increases. Compared to the maximum throughput in Table 1, the maximum balanced throughput in Table 2 is smaller. This confirms a trade-off that the balanced user throughput is obtained at the cost of some reduction in the total network throughput.

During the search for the optimal $\vec{q}$ in the maximum throughput and the maximum balanced throughput problems, it is found that the recursive formulae for the system with multi-level dominating power can be used to obtain a reasonable initial guess of $\vec{q}$, which is crucial for the convergence of the numerical algorithms.

The maximum balanced user throughput of the 5-group system with Rician fading (i.e., $\vec{q}$ = (0.0097, 0.0105, 0.0132, 0.0222, 0.03111)) is illustrated in Fig. 3. It is compared to simulation where the transmission probabilities are set to values that achieve the maximum balanced throughput in the 5-group approximation, i.e., users 1-2 transmit with probability 0.0097, users 3-5 transmit with probability 0.0105, users 6-12 transmit with probability 0.0132, users 13-24 transmit with probability 0.0222, and users 25-50 transmit with probability 0.0311. It can be seen that the throughput imbalance between users is less severe compared to Fig. 2*d*. It is expected that this unfairness can be further alleviated if more groups are used to approximate the network performance computation.

6. Conclusion

An analytical multi-group model is used to evaluate the performance of mobile S-ALOHA networks. The user performance as a function of the distance relative to the central station is approximated by interpolating the group performance of a multi-group system. The maximum throughput and the maximum balanced throughput of mobile S-ALOHA networks in heavy traffic are analyzed by the multi-group model. The validity of the model is verified by a hypothetical system with multi-level dominating power and computer simulation. Although a linear network in a Rician channel is considered as an example, other network topologies and channel models can be considered by computing the corresponding conditional capture probabilities. The issue of optimal power control for enhancing the capacity of a mobile slotted ALOHA network needs further investigation.

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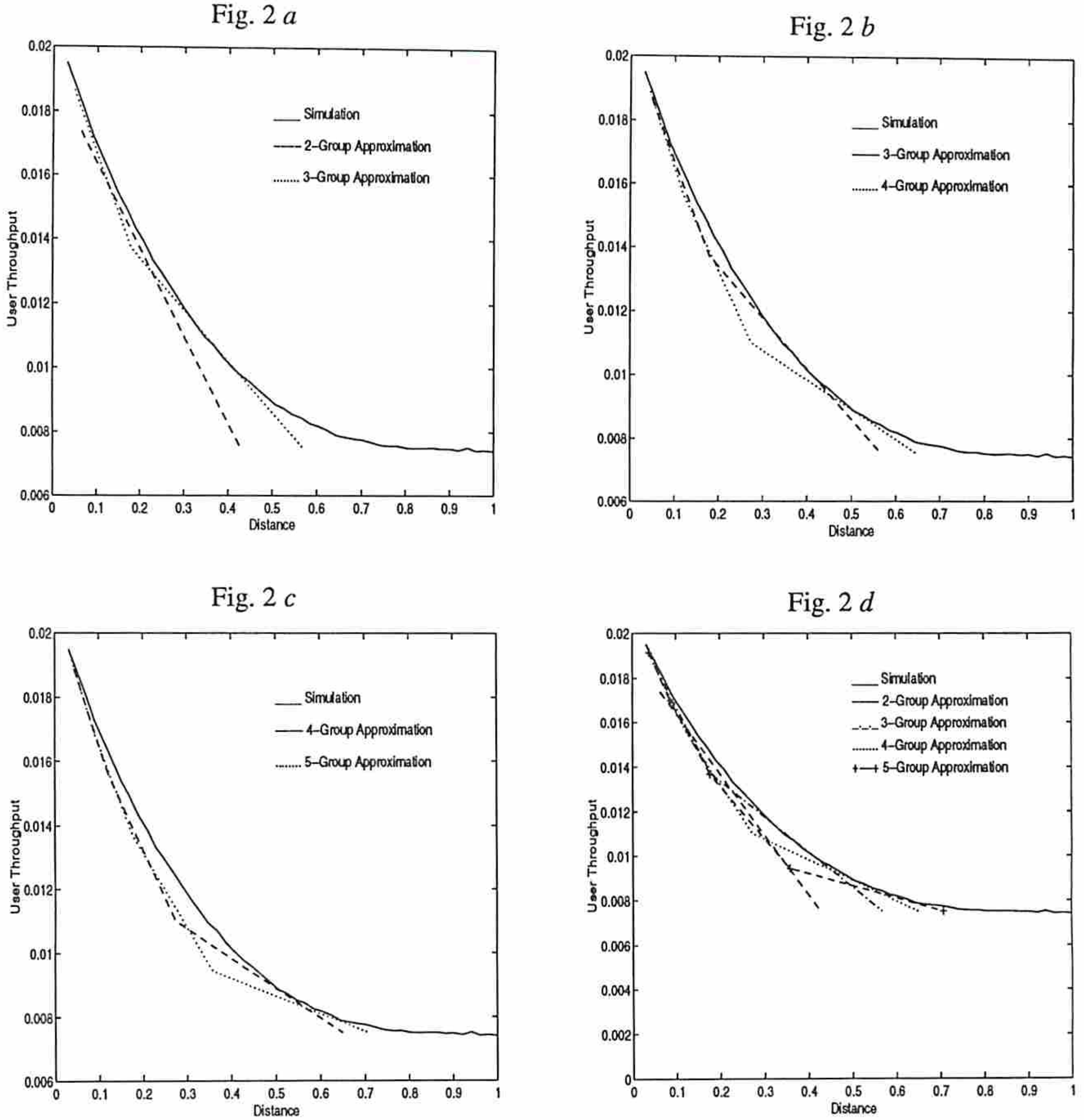

Fig. 2*a*-2*d*. The user throughput as a function of the distance relative to the central station for the slotted ALOHA network with Rician fading given in Section 5.1. The transmission probability $q = 0.02$ and the Rician factor $K_r = 10$ for all users.

Table 1: The maximum throughput of two K-group S-ALOHA networks, one with Rician fading and the other with multi-level dominating power

	Rician Fading			Dominating Power		
	Transmission Probability $\hat{q}$	User Throughput	Maximum Throughput	Transmission Probability $\hat{q}$	User Throughput	Maximum Throughput
K=2 $\vec{M}$=(8, 42)	.0831 .0239	.0456 .0045	.5542	.0823 .0238	.0451 .0045	.5482
K=3 $\vec{M}$ =(4, 11, 35)	.1409 .0464 .0226	.0871 .0141 .0034	.6224	.1318 .0590 .0286	.0863 .0182 .0031	.6544
K=4 $\vec{M}$ =(3, 5, 12, 30)	.1767 .0748 .0153 .0278	.1115 .0281 .0036 .0039	.6353	.1492 .1023 .0538 .0333	.1080 .0409 .0105 .0023	.7239
K= 5 $\vec{M}$ = (2,3,7,12,26)	.3195 .0000 .0857 .0000 .0339	.2166 .0000 0223 .0000 .0036	.6826	.2181 .1509 .0706 .0538 .0385	.1705 .0665 .0170 .0066 .0017	.7819

Table 2: The maximum balanced throughput of two K-group S-ALOHA network, one with Rician fading and the other with multi-level domonating power

	Rician Fading			Dominating Power		
	Transmission Probability $\hat{q}$	User Throughput	Maximum Throughput	Transmission Probability $\hat{q}$	User Throughput	Maximum Throughput
K=2 $\vec{M}$=(8, 42)	.0090 .0242	.0084	.4202	.0088 .0238	.0083	.4130
K=3 $\vec{M}$ =(4, 11, 35)	.0094 .0125 .0280	.0091	.4549	.0094 .0106 .0286	.0091	.4569
K=4 $\vec{M}$ =(3, 5, 12, 30)	.0096 .0112 .0175 .0300	.0094	.4682	.0101 .0106 .0123 .0333	.0099	.4942
K= 5 $\vec{M}$ = (2,3,7,12,26)	.0097 .0105 .0132 .0222 .0311	.0095	.4735	.0107 .0110 .0120 .0142 .0385	.0106	.5285

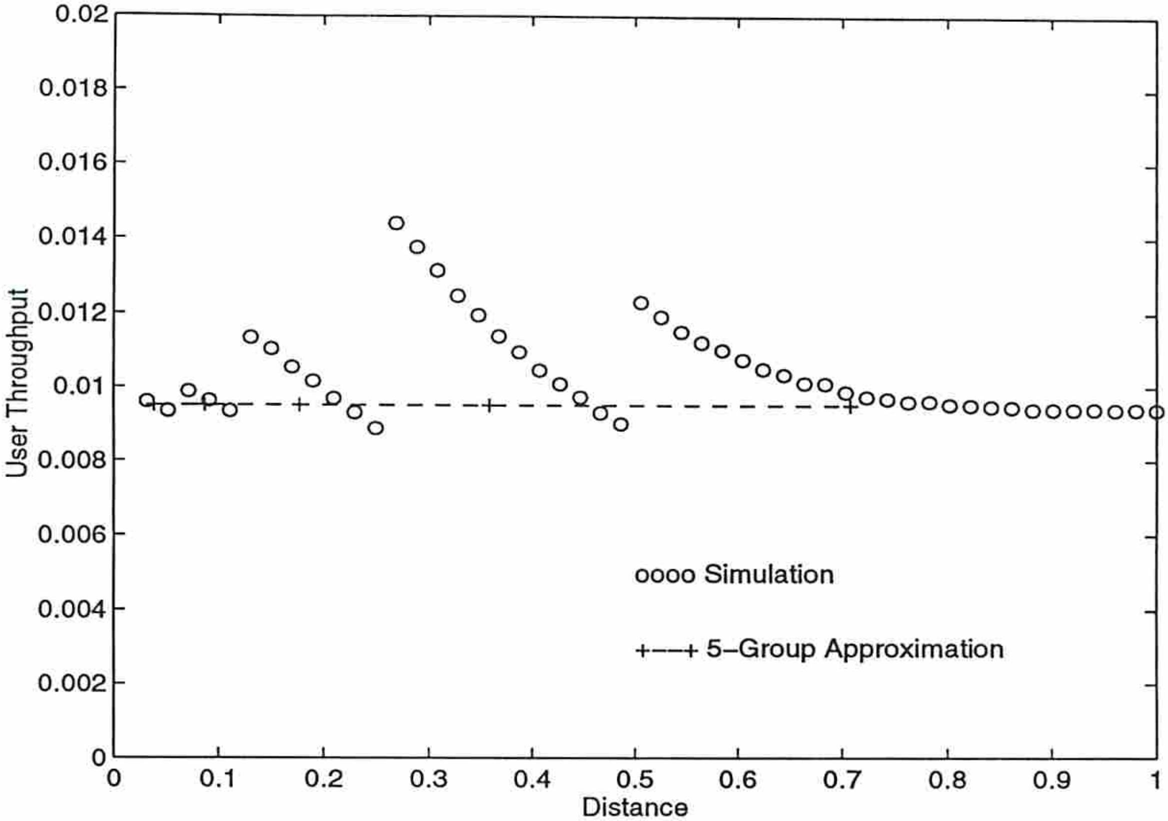

Fig. 3. The user throughput as a function of the distance relative to the central station for the network with Rician fading given in Section 5.1. Users transmit with different probabilities to achieve more balanced throughput, i.e., users 1-2 transmit with probability 0.0097, users 3-5 transmit with probability 0.0105, users 6-12 transmit with probability 0.0132, users 13-24 transmit with probability 0.0222, and users 25-50 transmit with probability 0.0311.