A Hybrid access protocol for multiple access satellite communication network

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Abstract - *A* new hybrid protocol for multiple access in satellite communications is proposed. Its stability is proved under general stationary assumptions. Also, we show the continuity of the system distributions as a function of the input distributions and obtain some stochastic comparison results. A dynamic decentralized algorithm is developed to obtain efficient partitioning of the set of users. Some simulation results are presented to demonstrate the usefulness of these algorithms.

1 Introduction

Multiple access communication networks form an important class of communication networks. Whenever several users have to share a communication channel the question arises how to use it efficiently. Over the years several algorithms have been provided for this important practical problem [1],[2],[3]. The access schemes proposed fall into four major groups : fixed assignment, random assignment, demand assignment, adaptive assignment. In fixed assignment, access, subchannels are derived from a channel by allocating portions of the channel in time, frequency or code giving rise to TDMA, FDMA and CDMA respectively . Each sub channel is pre assigned in a fixed manner to stations, which occupy available bandwidth whether or not they are actively generating network traffic. The lack of flexibility of these systems in allocating bandwidth resources and their inefficiencies in handling of bursty traffic make them unsuitable for packet network. At the other extreme from this is the random access schemes. The entire bandwidth of the channel is used by any of the multiple stations at times determined by themselves without any coordination between the stations. Thus collisions are possible ([3] - [4]). The demand assignment access is a class of collision free schemes in which access to the channel is scheduled to the stations either in cyclic order or in an acyclic order, The scheduling may be centrally controlled or may be distributed ([1]). Adaptive assignment access combines the advantages of random access mode when the channel is lightly loaded with the advantages of fixed assignment as the channel load increases, thereby avoiding the disadvantages of both the schemes. There are a large number of these protocols proposed in the literature ([2] ,[5]). But many of them use reservatian slots or control subframes, which would result in a large overhead at light loads and also in satellite networks where the propogation delay is large this would result in large overall delays. We also propose a new efficient multiple access algorithm for satellite networks. One of the first issues that has to be settled for an algorithm to be usefui is its stability. The usual assumptions in the literature made on the arrival traffic to answer this question are not satisfied in practice (see [6] for a survey). We prove the stability of our algorithm , under weaker assumptions.

It has been intuitively known that the slotted ALOHA with a finite number of users should be optimal under low traffic conditions. We have proved this result in ([7],[8]), under Bernoulli input traffic conditions. Also, in some sense it has been argued in [14] that TDMA should be optimal in a class of multiple access algorithms. The assumptions and the system considered in [14] for this are peculiar and unrealistic. We argue in ([7],[8]) that TDMA is optimal in a large class of multiple access algorithms under heavy traffic when there are $M < \infty$ number of users each with a finite or infinite buffer and the arrival traffic to each user is iid. It is also known that at intermediate loads both slotted ALOHA and TDMA perform poorly [2]. Therefore a large number of algorithms have been discussed in literature to improve the channel efficiency under these load conditions. Our new algorithm is, motivated by the above optimality results. It becomes slotted ALOHA under light loads, TDMA under heavy loads and outperforms both at intermediate loads for unsymmetric traffic which is the most common situation in practical systems. For this algorithm we prove the stability when the input traffic is stationary ergodic. We have shown in ([6],[7]) the stochastic continuity for the distributions of the queue length process as a function of the distributions of the input process. It is important to demonstrate this for the theoretical performance results to be practically relevant. We also show some stochastic comparison results for this algorithm.

The algorithm has to be tuned properly according to the arrival rates for it to perform well. For this we propose an online dynamic algorithm which based on the channel feedback properly adjusts the grouping in the algorithm to provide good performance. We present some simulation results to show the usefulness of our algorithm.

The paper is planned as follows. We present our new multiple access algorithm in Section 2. We also show its periodic stationarity in this Section. In Section 3 we show stochastic continuity and prove two stochastic comparison results for this algorithm. A dynamic decentralized algorithm is provided in Section **4** *to* obtain a good partition of users for our multiple access algorithm. Section **5** presents simulation results for our multiple access algorithm and also for the dynamic scheme of Section **4.**

2 A new multiple access algorithm and its stability

We assume **there** are $1 < M < \infty$ users each having an infinite buffer to store packets. These users share a common communication channel. The packets to be transmitted on the channel are of equal lengths. The time axis is divided into slots. The length of the slots is such that a packet can be transmitted in one slot. The transmission of packets can start only at the beginning of a slot. **A** user sends at most one packet in a slot if it has something to transmit. If the transmission times of two packets overlap then there is a collision and those packets will have to be transmitted again. The users can detect whether in a slot there was a successful transmission or a collision.

The M users are divided into L groups G1,G2,. ..,GL. These groups don't have to be disjoint. Each slot is assigned to a group in a periodic fashion. We take the period as d slots. In the slot assigned to a group all the users which have packets to transmit at the beginning of that slot transmit a packet with a certain probability. If more than one packet gets sent then there is a collision and those packets will be tried again in the next assigned slot.

The general stability result of Loyne [9] will be used to show the stability of this system.

We **use** the following notation:

kth slot = time interval (k, k+1)

x_k(i) = number of new packets generated in the (k-1) slot at the user i.

t_k(i) = 1 if ith user would transmit a packet in the kth slot if it has a packet at time **k.**

= 0 otherwise.

z_k(i) = queuelength at the ith user at time k without including x_k(i).

1_A = indicator function of set A.

y_k(i) = 1 if ith user has a successful transmission in the kth slot.

= 0 otherwise.

Then the system equation can be written as

$$z_{k+1} = z_k + (x_k - y_k)$$

where $z_k = (z_k(1), z_k(2), \ldots, z_k(M))$ and similarly for x_k and y_k. We can write this equation as $z_{k+1} = f(z_k, x_k, t_k)$

The random variables t_k take care of the assignment of the slots to different groups.

Theorem 1: *If the sequence $\{(x_k, t_k)\}$ is periodic stationary and ergodic, $E[x_k] < \infty$ and $E[(x_k - y_k)] < 0$, then periodic stationary and ergodic distributions of $\{z_k\}$ exist. When the system starts at $t = 0$ with $z_o = 0$, the finite dimensional distributions of $\{z_k\}$ converge to the periodic stationary distribution. Also if the system starts with z_o finite a.s., the random variables remain bounded a.s.*

Proof: It is easy to see that f is monotonically non decreasing in z. Then as explained in [8], using the results of [9] we obtain the existence of periodic stationary distributions of $\{z_k\}$. The a.s. finiteness of z_k under stationary distribution can be proved just as in [10]. Other results can be proved in the same way.

□

It is easy to see that if $\{t_k\}$ is stationary then the above system becomes slotted ALOHA with periodic input, if $\{(x_k, t_k)\}$ is stationary then it is slotted ALOHA with stationary input, if $\sum_{i=1}^{M} t_k(i) = 1$ for all k and t_k is deterministic then it is TDMA with periodic input

These stability results, in the case of periodic input are new even for the TDMA and the slotted ALOHA system. For earlier work on these systems see [1],[11].

The algorithm presented above is actually a class of algorithms. How well it performs depends upon the groups formed. For different traffic patterns different groups may have to be formed. In this paper we address the problem of appropriate grouping via simulations. We develop a decentralized algorithm, which users can use, without knowing each others arrival rates, based on the channel feedback to arrive at a good grouping. We show its usefulness via simulations.

3 Continuity and comparison for the multiple access systems

In this section we first show that the (prestationary) distribution of $\{z_k\}$ is a continous function of the distribution of the input sequence $\{(x_k, t_k)\}$. We have also shown the continuity of the stationary distributions for TDMA and slotted ALOHA in ([7],[8]). We also provide two stochastic comparison results for our system in this section.

We denote by $\{(z_o^{(m)}, x_k^{(m)}, t_k^{(m)}), k \geq 0\}$ a sequence of input sequences. The corresponding queue lengths in the multiple access system are denoted by $\{z_k^{(m)}\}$. For the theorems 2 and 3 we don't need stationarity of input sequences. We denote the distance between sequences $\{z_o^{(m)}, (x_k^{(m)}, t_k^{(m)})\}$ and $\{z_o, (x_k, t_k)\}$ as

$$\|\{(z_o^{(m)}, (x_k^{(m)}, t_k^{(m)})), k \geq 0\} - \{(z_o, (x_k, t_k)), k \geq 0)\}\|$$

$$= \|z_o^{(m)} - z_o\| + \Sigma_{k=0}^{\infty} (\|x_k^{(m)} - x_k\| + \|t_k^{(m)} - t_k\|).2^{-k}/Den(k)$$

where Den(k) is given by

$$Den(k) = 1 + \|x_k^{(m)} - x_k\| + \|t_k^{(m)} - t_k\|$$

With respect to this distance, we have the following.

Theorem 2: *If $\{z_o^{(m)}, (x_k^{(m)}, t_k^{(m)}), k \geq 0\} \rightarrow \{z_o, (x_k, t_k)\}$ in probability, then $\{z_k^{(m)}\} \rightarrow \{z_k\}$ in probability.*

The proof of this theorem follows, as in [10].

With respect to the above distance measure we can also have

Theorem 3: *If the $\{z_o^{(m)}, (x_k^{(m)}, t_k^{(m)})\}$ and $\{z_o, (x_k, t_k)\}$ are sequence of independent random variables and $z_o^{(m)} \xrightarrow{w} z_o$, $x_k^{(m)}(i) \xrightarrow{w} x_k(i), t_k^{(m)}(i) \xrightarrow{w} t_k(i)$ for $i = 1, \ldots, M$, then $z_k^{(m)} \xrightarrow{w} z_k$ where $\xrightarrow{w}$ denotes convergence in distribution. Also, $\{z_k^{(m)}, k \geq 1\} \xrightarrow{w} \{z_k, k \geq 1\}$.*

Proof: In TDMA and in slotted ALOHA it is easy to see that z_{k+1} depends upon only $\{z_o, x_m, t_m, 0 \leq m \leq k\}$. Therefore we have convergence $z_k^{(m)} \xrightarrow{w} z_k$. For the general system, the result follows by these two results and the independence assumption. The result for the whole sequence $\{z_k, k \geq 1\}$ follows because of the metric chosen.

□

Now we consider the stochastic comparison problem. We consider two arrival sequences $\{(x_k, t_k)\}$ and $\{(x'_k, t'_k)\}$. Let us have $t_k = t'_k$ and $x_k \leq_{st} x'_k$ where $x \leq_{st} x'$ denotes that if f is any measurable real valued nondecreasing function on the state space with finite means $E[f(x)]$ and $E[f(x')]$ then $E[f(x)] \leq E[f(x')]$. Let the two systems start at $k = 0$ with initial conditions $z_o \leq_{st} z'_o$ respectively. Then we have the following

Theorem 4: *If $x_k \leq_{st} x'_k, z_o \leq_{st} z'_o, t_k = t'_k, \{x_k\}$ and $\{x'_k\}$ are independent of each other and formed of independent random variables and x_k and x'_k are independent of t_k then $z_k \leq_{st} z'_k$ and if z_k and z'_k converge to stationary distributions, then the stationary distributions also satisfy this inequality. This inequality holds for joint finite distributions of sequences $\{z_k\}$ and $\{z'_k\}$ also.*

Proof: We can form on another probability space r.v.s $\tilde{z}_o, \tilde{z}'_o, \tilde{x}_k, \tilde{x}'_k$ and $\tilde{t}_k$ s.t. $\tilde{x}_k \leq \tilde{x}', z_o \leq \tilde{z}'_o$, a.s. [15] and $\{\tilde{x}_k\} \stackrel{d}{=} \{x_k\}$, $\tilde{z}_o \stackrel{d}{=} z_o$, $\tilde{z}'_o \stackrel{d}{=} \tilde{z}_o$, $\{\tilde{x}'_k\} \stackrel{d}{=} \{x'_k\}$, Then for our system we can easily show that $\tilde{z}_k \leq \tilde{z}'_k$ a.s. Now, $\tilde{z}_k \stackrel{d}{=} z_k$ and $\tilde{z}'_k \stackrel{d}{=} z'_k$, therefore we obtain $z_k \leq_{st} z'_k$ for all k. If $z_k \xrightarrow{w} z$ and $z'_k \xrightarrow{w} z'$ then we also obtain $z \leq_{st} z'$.

The above argument can be repeated to obtain the results for finite dimensional distribution also.

□

From the proof of the above theorem, we can obtain similar results for the delay distribution also. If we also change the distribution of t_k from t'_k then we can give counter examples to show that even when $t_k \leq_{st} t'_k, x_k = x'_k, z_o = z'_o$ we may not obtain $z_k \leq_{st} z'_k$ or $z_k \geq_{st} z'_k$. Now we obtain the above stochastic inequality results for convex ordering also [12]. For this we only have to show that if we denote

$$z_{k+1} = f(z_k, x_k, t_k) \qquad (1)$$

then f is convex in (z_k, x_k). This we show in

Lemma 1: *The mapping* f *defined in* (1) *is convex in* (z_k, t_k).

Proof: See ([7],[8]).

In the following we denote convex ordering by $\leq_c$. The above lemma gives us

Theorem 5 : *If $z_o \leq_c z'_o, t_k = t'_k, x_k \leq_c x'_k$ and all these random vectors are andependent of each other (the components of random vectors need not be andependent) then $z_k \leq_c z'_k$. If $z_k \xrightarrow{w} z$, $z'_k \xrightarrow{w} z'$ and also $E[z_k] \rightarrow E[z]$, $E[z'_k] \rightarrow E[z']$ then $z \leq_c z'$.*

□

The result implies that our system is yet another example of the fact the determinism minimizes queue lengths.

The results in Theorem 4 and 5 also provide the following fact. If z_k and z'_k converge weakly to periodic distributions ie; if $z_{dk+l} \xrightarrow{w} y_l$ and $z'_{dk+l} \xrightarrow{w} y'_l$ as $k \rightarrow \infty$ for some $0 \leq l \leq d$, then $y_l \leq_{st} y'_l$ or $y_l \leq_c y'_l$ in the corresponding cases.

4 A Dynamic multiple access scheme

In section 2 we have proposed a multiple access scheme and showed that it would out-perform slotted ALOHA and TDMA at intermediate arrival rates. This supremacy in performace is obtained only if the system is run using the optimal partition. Also, the users in each group should use the optimal retransmission probabilities. The optimal partition and the optimal retransmission probabilities depend among other factors on the arrival rate at each node. Thus in order to implement the above protocol it is necessary for each node to know the arrival rate at every other node in the network for it to implement the algorithm in a decentralized way. But in the real world, the nodes have no information of the arrival rate; atmost each node can in some way estimate its own arrival rate. This is of course not sufficient . One simple way of achieving this would be to allow each station to estimate its rate and then transmit this to every station until all stations have the rate of every other station. But it is certainly of interest if the users have a decentralized algorithm which uses only the information directly available from the channel feedback. Thus in this section we develop algorithms which use the channel feedback for varying the partition and finally converge to an optimal partition.

Before we go over to the dynamic algorithm for forming optimal partitions] we have to find the optimal retransmission probabilities for slotted ALOHA protocol. In [13] optimal retransmission probabilities are calculated when the arrivals have a binomial distribution. In our multiple access scheme the arrivals to a node do not have a binomial distribution when the number of groups is more than 1, even when the input distribution to each node is binomial. Thus in order to find optimal retransmission probabilities we develop a dynamic scheme (algorithm 1 below) by which each node varies the retransmission probability, based on the number of collisions, idle slots and successes, so as to increase the number of successes and decrease the number of co lisions The convergence behaviour of the algorithm is shown in figs. 5,6.

We now present the dynamic scheme to obtain the optimal partition and in this, we use the above alg.1 to obtain the optimal retransmission probabilities. We propose two different schemes. In the first scheme we start the system using the TDMA protocol and run it for N number of slots where N is called the estimation interval. During this interval each node counts the number of transmissions made by each of the other nodes (there can be no collisions since the system is being run as TDMA). An estimate of the arrival rate is obtained as follows : $a_i = tr_i/N'$ where $N' = N/M$, M = no. of users, tr_i =the number of transmissions by the ith node in the estimation interval and a_i =estimated arrival rate at the ith node.

If the estimation interval is sufficiently large then a good estimate of the arrival rate is obtained. Using these arrival rates the optimal partition is obtained. At the moment we do not have analytical results for the problem of obtaining an optimal partition for given arrival rates when they are different for different users. This is because the delay and queue length distributions are not available even for the slotted ALOHA case with general arrivals. But in the next section via simulations we provide some guidelines. Each of the groups use the dynamic scheme proposed above for slotted ALOHA to obtain the optimal retransmission probability. This scheme would work very well if the arrival rates at the users do not vary with time. If the arrival rates vary then each time the system has to run as TDMA and the optimal partition obtained. The other scheme which we propose overcomes this drawback.

In the second scheme, to find the optimal partition we start in any particular partition and go through a number of iterations to converge to the optimal partition. In each iteration, every group in the partition uses Alg 1 to converge to the optimal retransmission probability ; this forms the first phase of the algorithm. In the second phase of the algorithm, the optimal retransmission probability so obtained are used to repartition the users, if necessary. This is done as follows : if the retransmission probablity of any group lies below a lower threshold [thresh 1] the group is split into two groups and on the other hand if the retransmission probability is greater than a threshold [thresh 2] then the group is merged with some other group having a retransmission probability higher than thresh 2,if at all such a group exists; otherwise the group is retained as before. Thus the new groups are identified and their slot assignments are fixed. This completes one iteration. The algorithm is said to have converged at the end of an iteration if the new partition obtained is the same as one used in the previous iteration. We refer to this scheme as Alg 2 and below we present this algorithm. This scheme was incorporated in simulation and was found to do well. Simulation was done with all the users having equal arrival rates as well as with the users having unequal arrival rates. These results are shown in figs. 1 to 6.

(i) Algorithm to converge to the optimal retransmission probability for a slotted ALOHA system

Alg 1 :

At iteration n :

let retransmission probability $= p_n$, no. of collisions in its cycle $= c_n$, no. of successes in its cycle $= s_n$

If

$s_{n-1} > s_n$ or $c_n > c_{n-1}$

then

$p_{n+1} = p_n - \epsilon_n$

else

$p_{n+1} = p_n + \epsilon_n$

endif

Comment : The step size ϵ_n is slowly decreased as n increases.

(ii) Algorithm **for** finding the optimal partition

Alg **2** :

step **1:** At each partition run algorithm 1 to obtain optimal retransmission probabilities.

step **2:** If number of users in a group > 1 and optimal retransmission probabilities < 1 /(no. of users in the group), then split the group into equal subgroups (if no. of users is odd then one of the subgroups will have one user more than the other).

step **3:** If optimal retransmission probability > thresh2, then merge two such groups.

step **4:** If the grouping does not change in step **2** or step **3** then stop the algorithm; else reassign the slots to the new groups - one slot to each group in a frame. The initial retransmission prob allotted to a group is 1/(no. of users in the group) . Then repeat step 1.

5 Simulation results

It has been mentioned in the previous section that our multiple access scheme results in better performance only if we run the system using a good partition. The optimal partition depends among other factors on the arrival rate to each user. In order to get some information on the optimal partitions, we have run the system as slotted ALOHA,TDMA and using different groups (partitions) and we have a comparison of the system's mean delay per packet. These results are plotted in fig.3 and fig.4. Figure **3** corresponds to the symmetric case with binomial input to each user and it can be seen that in this case, slotted ALOHA does best till 0.06 arrival rate and beyond which TDMA is optimal. Figure **4** corresponds to the users having trinomial input. Similar results were obtained with 8 symmetric users. Thus we beiieve that in the case of symmetric users slotted ALOHA is optimal at (total) rates less than $1/M$ and TDMA is optimal at rates beyond this. Grouping does not seem to do better at any of the rates. In table 1 we give the results of the asymmetric case with binomial arrival distribution at each user. We observe that grouping helps when some users have high arrival rate while the others have low arrival rates.

Since in the asymmetric case grouping the users does much better than slotted ALOHA or TDMA we have proposed algorithms to obtain optimal retransmission probabilities as well as optimal partitions. We have used Alg.1 to obtain optimal retransmission probabilities. Figure 1 gives a comparison of the optimal retransmission probabilities obtained, for a set of 6 symmetric users, numerically (using the technique given in [13]), by simulation and using Alg.1. Figure 2 gives a comparison of the mean delay per packet obtained for slotted ALOHA numerically, by simulation and by using Alg.1 using the corresponding optimal retransmission probabilities. Figures 5 and 6 give the convergence of this algorithm at different arrival rates.

We use Alg.2 to obtain optimal partitions. The results are presented in table 2. In this case the convergence occures in less than 40,000 slots.

Although we do not have theoretical results which would provide us with optimal partition, for different arrival rates, we compared the partition obtained by this algorithm with several other partitions via simulation and this partition gives lowest mean delay among all of them.

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Table 1 : Comparison of slotted ALOHA, TDMA and lowest among other groupings via simulation (asymmetric)

No.	arrival rates to different users						Total system mean delay per packet			opt. group
	1	2	3	4	5	6	ALOHA	TDMA	lowest gpg.	
1	0.1	0.005	0.005	0.005	0.005	0,005	1.42	6.66	1.84	ALOHA
2	0.1	0.1	0.1	0.005	0.005	0.005	6.60	7.10	3.35	{1,4},{2,4},{3,6}
3	0.1	0.1	0.1	0.1	0.005	0.005	17.56	7.18	3.47	{1,5},{2,6},{3},{4}
4	0.1	0.1	0.1	0.1	0.1	0.005	1494	7.28	6.1	{1},{2},{3},{4},{5,6}
5	0.1	0.03	0.03	0.005	0.005	0.005	1.75	5.91	2.2	ALOHA
6	0.1	0.07	0.07	0.005	0.005	0.005	2.81	5.96	3.06	ALOHA

Table 2 : Results of partitioning for dynamic scheme

initial partition : slotted ALOHA

Arrival rates of different users						Final partition
0.1	0.005	0.005	0.005	0.005	0.005	slotted ALOHA
0.1	0.1	0.1	0.1	0.005	0.005	{1},{2},{3},{4,5,6}
0.4	0.005	0.005	0.005	0.005	0.005	slotted ALOHA
0.1	0.1	0.1	0.005	0.005	0.005	{1},{2},{3},{4,5,6}

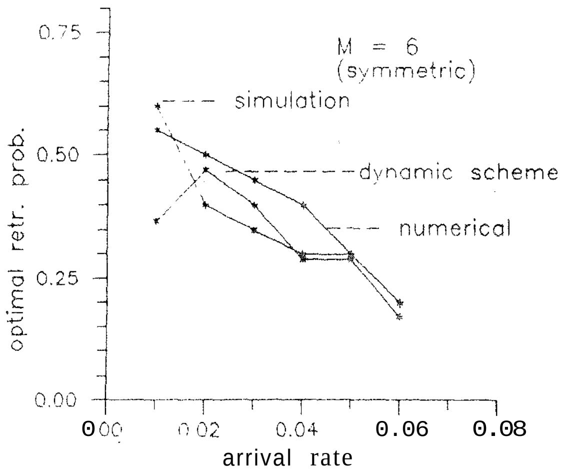

fig. 1 optimal retrans. probs for slotted ALOHA (numerical, simulation and dynamic scheme)

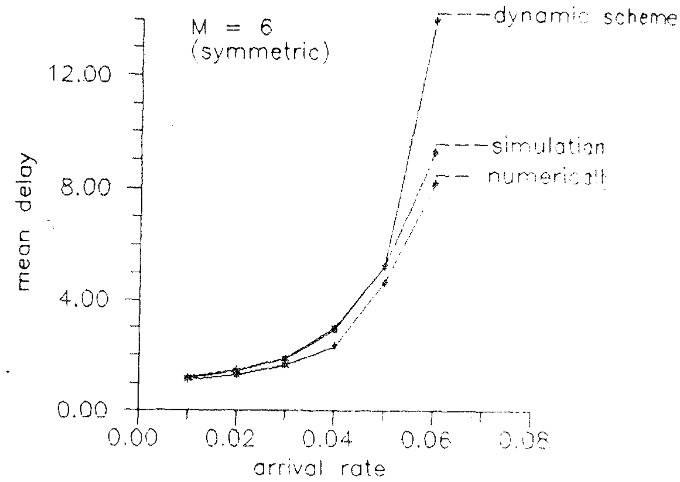

fig. 2 comparison of mean delays for slotted ALOHA

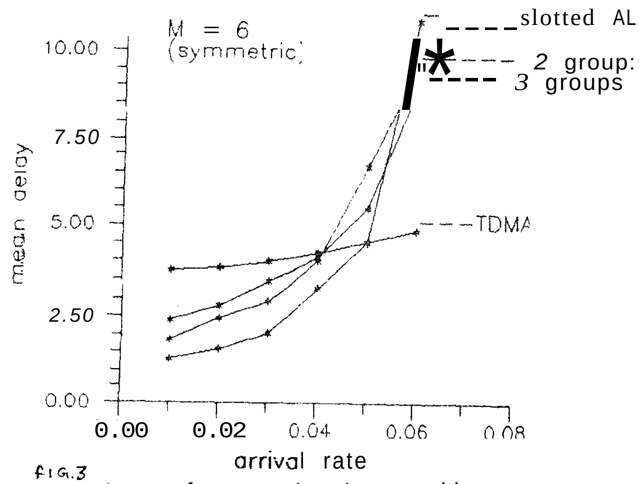

FIG.3
comparison of grouped scheme with slotted ALOHA, and TDMA

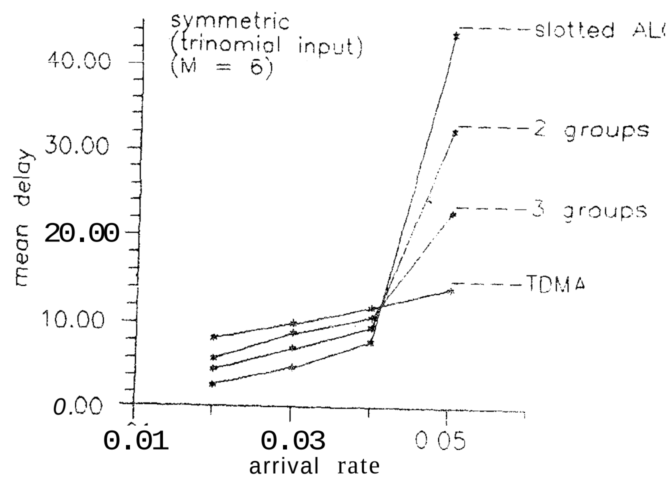

fig. 4 comparison of grouped scheme, slotted ALOHA AND TDMA

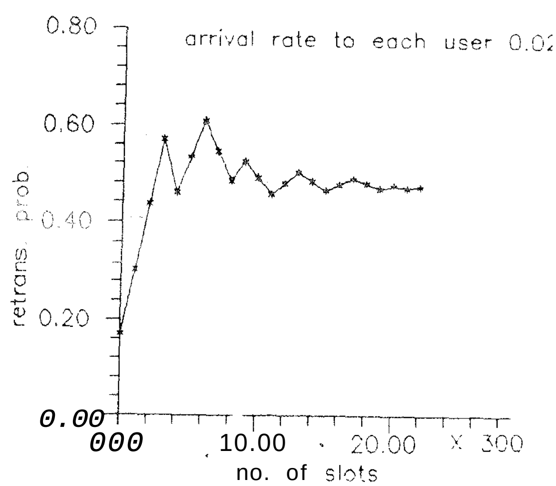

fig. 5 convergence of retransmission probability

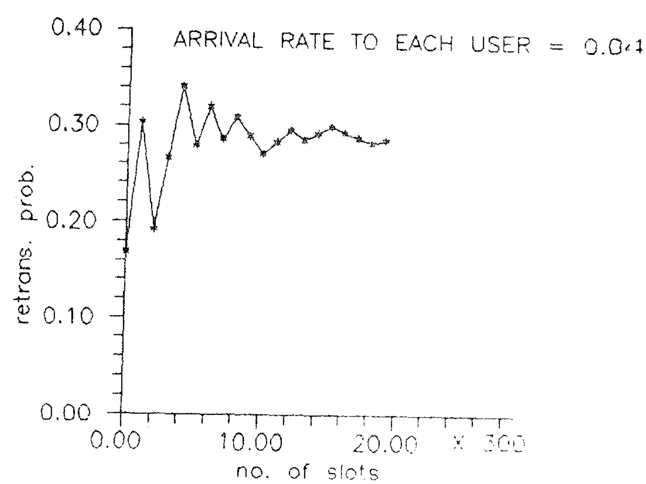

fig. 6 convergence of retransmission probability