Transmit Permission Control on Spread ALOHA Packets in LEO Satellite Systems

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***Abstract*—A transmit permission control method for improving the throughput characteristics of a low earth orbit (LEO) satellite communication system employing spread-slotted ALOHA multiple-access scheme is proposed. Both nonfading and fading satellite links are considered. The basic idea of the proposed scheme is to decrease the level of interference at each satellite and, hence, to increase the probability of packet success, by prohibiting the packet transmission from the users with relatively high propagation loss to their connecting satellites. It is shown that the method has the ability to improve the throughput performance in heavy traffic loads and the peak value of the throughput, significantly. It is also shown that the average delay performance of the system employing the proposed scheme is superior to that of the conventional system at heavy traffic loads.**

I. INTRODUCTION

CONSIDER the problem of selecting a multiple-access scheme which can be applied on reverse links, from users to satellites, of a low earth orbit (LEO) satellite communication system. There are some proposals on the usage of spread-spectrum techniques, such as [1] and the combination of spread spectrum with the slotted ALOHA scheme [2], which are expected to provide higher capacity than other conventional schemes. The enhanced capacity of the spread-spectrum scheme in addition to its well known advantages, such as immunity to external interference and jamming, in combination with the simplicity that offers by slotted ALOHA schemes, make the spread-slotted ALOHA attractive for use in LEO satellite systems.

In spread-spectrum multiple-access schemes, the equalization of the received powers from the users, referred to as power control, is an important issue [3]. When such a power control is employed, all the received signals at the base station, here at the satellite, have the same power levels, in spite of their distance to the satellite. Without such power control, other problems such as the near–far problem appears. In either case, with or without power control, the attempt of a large number of users to send their signals results in a high level of interference and a low probability of capture, and consequently, low throughput of the system. To decrease the level of interference at each satellite, in this paper we focus on a system employing power control and propose a method in which a user far from a satellite may not be allowed to transmit whenever its propagation loss is more than a predefined value. Since LEO satellites are in continuous movement, the distance of a user to a satellite and, hence, its propagation loss has a periodic variation, thus making the proposed scheme practical.

The assumed spatial distribution of users on the earth enables us to evaluate the performance of the method in both uniform and nonuniform traffic situations. In the following section, we introduce the LEO satellite system model and the traffic distribution employed in this analysis. Section III describes the idea of the proposed scheme, transmit permission control. Section IV involves the throughput analysis followed by the average delay performance analysis in Section V. Section VI shows the performance of the proposed scheme via numerical examples. From Section II through Section VI, a nonfading channel is assumed; however, in Section VII, a faded land mobile satellite link with both signal shadowing and multipath fading will be introduced and the performance of the system and the proposed scheme will be shown. Section VIII concludes the paper.

II. SYSTEM MODEL—NONFADING CHANNEL

Consider a global communication network comprising LEO satellites which are on a multiple-orbit constellation. The total number of orbits and the number of the satellites in each orbit are designed such that any area on the earth is covered by, at least, one satellite. Any user of this communication network has the possibility to communicate with its visible satellite(s) directly.

According to mobility feature of the LEO satellites, the connection of a user to a satellite is a temporary connection, and by the means of hand-off schemes, a continuous communication can be realized. In this paper (without taking care of the performance of hand-off schemes), we analyze the performance of the system on an average basis during a short period of time in which the mobility of the satellites can be neglected.

The protocol which we use in this paper aims to improve the performance of the communication system on its reverse links (uplinks), i.e., from users to satellites. In fact, in forward links from satellites to users, the satellite, same as the base station in a cellular system, can take care of all the transmissions in its service area and any conventional multiple-access scheme such as time-division multiple-access (TDMA) can be applied.

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To be more specific, assume that there are N_s equally spaced satellites in each orbit. Each satellite continuously sends out a signal at a constant predefined power level S. Every user, say the jth one, receives at least one attenuated form of this signal, for example from the ith satellite where $i = 1, 2, \cdots, N_s$, with the power

$$R_{i,j} = \kappa S \, d_{i,j}^{-\beta} \tag{1}$$

where κ is a constant with dimension m^{-2}, $d_{i,j}$ is the distance of the jth user to the ith satellite, and β is the power loss factor. For the satellite links, the value of $\beta = 2$ is usually assumed. We use the predefined signal for three purposes. First, by monitoring this signal every user becomes able to determine its distance to all visible satellites and, hence, to find the nearest one and can connect to that satellite. With the assumption of connecting the users to their nearest satellites, equal-size circular service areas for all satellites is realizable. The remaining two purposes are related to the realizations of the power control and the transmit permission control schemes, respectively, and will be described in the next section.

The remaining problem on describing the system model is on defining the spatial distribution of the users. The geographical contribution of the users on the globe makes the distribution of the communications traffic loads have different levels of high traffic load peaks over the dense populated areas and also flat and low traffic load over nonpopulated areas. For conventional geostationary satellites, in which every satellite covers about one-third of the surface of the globe, the unbalanced traffic load can be managed carefully by each satellite. However, for LEO satellite systems in which a satellite may cover a small fraction of the globe, this problem results in nonoptimal usage of the communication facilities (as, e.g., described in [4]–[6]). Although the purpose of this paper is to introduce a multiple-access method which improves the performance of the system in high traffic situations and not to discuss the traffic nonuniformity problem, we assume a spatial distribution model which includes the traffic nonuniformity and show that the method can improve the performance of the system in both uniform and nonuniform traffic situations.

To make the problem and the performance of the proposed method clear, in this paper, we consider the performance of one part of communication system including the area in which the signal of users can be reached at any of three succeeding satellites on the same orbit. It is assumed that the locations of different users are statistically independent. The spatial density of population of the users in this area forms a bell-shaped density function to be centered at the second satellite. The projection of this bell-shaped density function on the plane including the three satellites determines the density of population of users which is used in the analysis. (Note that because of small difference between distances of different users in the same service area to the satellite, this two-dimensional (2-D) traffic model results in a good approximation with mathematical tractability.) The total population of the users in this area is assumed to be finite and equals N_u. The location of any user on this plane is assumed to be a random variable with probability density function (pdf)

$$p(x) = \frac{A}{\omega} \exp\left(-x^2/2\omega^2\right) \tag{2}$$

where x is the relative distance of the users from origin, which is assumed to be under the center satellite, ω is the traffic uniformity parameter, and A is a factor which makes the total probability of existence of a user in this area equal to one. With this model, we can evaluate the performance improvement achieved by our multiple-access method in both uniform and nonuniform traffic situations. Also note that small values of ω make the users concentrate in service area of the second satellite and realize a high traffic situation for it, thus enabling us to see the characteristics of the multiple-access scheme in this case.

III. TRANSMIT PERMISSION CONTROL METHOD

As stated in the previous section, in this paper we are interested in the performance of the reverse links. The basic multiple-access scheme assumed in this direction is direct-sequence spread-slotted ALOHA (DS/SSA) scheme, which allows multiple transmissions simultaneously and is known as a scheme that increases the capacity of mobile satellite systems [1], [2]. In conventional DS/SSA systems (which, for example, were used in [6]), a user transmits its information in the form of packets, whenever it has a packet, in the next slot, regardless of the behavior of the other users. The purpose of the transmit permission control method is to modify the DS/SSA scheme in such a way that permissions for transmission are given only to the users whose interference have a smaller effect in capture probability of the other packets.

In multiple accessing methods based on spread-spectrum techniques, including the DS/SSA scheme, the equalization of the received powers from the users is an important issue (e.g., see [7]). In our LEO satellite system, any user may send its packet with proper power level by monitoring the predefined signal received from the nearest satellite. Therefore, it is assumed that all received signals for any given satellite, say the ith one, reach the satellite by the same power level, S. (This is the second usage of the predefined signal mentioned in previous section.) According to (1), the transmitted power level of the jth user, where $j = 1, 2, \cdots, N_u$, to the ith satellite will be

$$T_{i,j} = \kappa^{-1} S \, d_{i,j}^{\beta}. \tag{3}$$

Hence, it is assumed that the network operates under perfect power control. It should be noted that, from the viewpoint of a given packet, all other signals transmitted from users either in same service area or in different ones act as interference. The packets of the users in the same service area have the same power S, however, the ones from different service areas have different power levels based on their distances.

The probability of packet success or capture probability for a given packet is decreased as the number of simultaneous transmitted packets increases. Specifically, if the given packet, namely the tagged packet, is in the service area of the ith satellite, the interference from other packets in the same

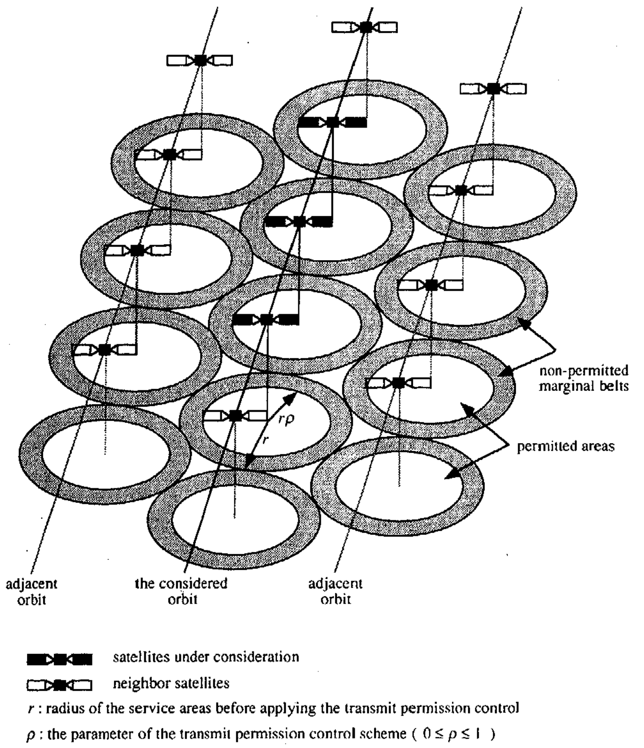

Fig. 1. Configuration of the service of the satellites before and after applying the transmit permission control scheme.

service area and the packets in marginal areas of the adjacent service area are the dominant factors that decrease the capture probability for the tagged packet and, hence, the total throughput of the system. Our proposed transmit permission control reduces the number of simultaneous transmissions, especially by avoiding the transmissions of the users in marginal areas of service areas.

The realization of the method is based on the third usage of the predefined signal sent by the satellites mentioned in Section II. Since the power levels of these signals are known by all users, any user can determine the propagation loss from its place to the visible satellites. In transmit permission protocol, if a user has propagation loss more than a predefined value, $l_{\max}$, it is not allowed to transmit packets. This means that the users in marginal belts of service areas are prohibited from transmitting.

This scheme may seem to be unfair for the users with relatively large values of propagation loss to their nearest satellites. However, if we allow all users to transmit at all times the large interference reduces the capture probability and consequently decreases the total throughput. Larger success probability for the permitted users results in higher total throughput than low success probability for all users, which of course depends on the proper design of the predefined value of propagation loss. On the other hand, since the satellites are in continuous movement, unpermitted users are allowed to transmit after a short period.

By applying this method, the radius of the service area of each satellite is reduced by some factor ρ, where $0 \leq \rho \leq 1$. The value of ρ depends on and has the same information as $l_{\max}$, with simpler tractable meaning. Fig. 1 shows the changes in service areas of the satellites after applying the transmit permission control. It is clear that selecting small values of ρ makes most of the users have no permission at most of time; on the other hand, the values of ρ close to one make the system have characteristics almost the same as the system without such control. We will discuss the selection of ρ later.

IV. THROUGHPUT PERFORMANCE

In the previous section, we proposed our transmit permission control protocol and discussed on the expectation of improvement in throughput of the system without any exact definition of throughput. In this section, we define and calculate the normalized total throughput of three succeeding satellites as the first performance measure in our analysis.

We start the definition of the normalized total throughput for three satellites by defining the throughput of one satellite as the expected number of successfully received packets at the satellite per time slot. We assume here that the size of a slot and packet length are equal. If we denote the throughput of the ith satellite by ξ_i, the normalized total throughput for three succeeding satellite in an orbit can be defined as the summation of the throughputs of these three satellites divided by the total number of users as

$$\xi_{\text{norm}} = \frac{\xi_{i-1} + \xi_i + \xi_{i+1}}{N_u}. \tag{4}$$

At each LEO satellite, the capture probability of the tagged packet not only depends on the level of interference caused by simultaneous transmissions from the users in the same service area, but also depends on the level of interference caused by transmissions of the users of adjacent satellites, as well. The reason is that all users use the same frequency spectrum and the signal of any user can be received at any satellite if the user is in line-of-sight (LOS) of that satellite, and increased the level of interference at that satellite. The only difference between these two kinds of interference is their power levels: The power of the interference from the users in same service area are the same as the power of signal S, and the powers of the interference of the other users depend on their distances.

To find the throughput of each satellite, say the ith one, let us assume that any user that has the propagation loss to its nearest satellite less than $l_{\max}$ sends a packet in every time slot with the probability q. Also assume that the number of such users in service area of the ith satellite is n_i and the total number of the transmitting users whose signals reach at the ith satellite, including n_i users, is m_i. In [5], it is shown that under these conditions the throughput of the ith satellite can be calculated by averaging the throughput for all possible values of n_i and m_i, i.e.,

$$\xi_i = \sum_{M=1}^{N_u} P[M_i = M] \sum_{m=1}^{M} f(m;M) \cdot \sum_{n=1}^{M} P[n_i = n | m_i = m] n P_{C,i} \tag{5}$$

where M_i is the number of the users whose their signals reach at the ith satellite, $f(m;M)$ is the binomial density function of the simultaneously transmitted packets with the parameters q and M, and $P_{C,i}$ is the probability of success for the tagged packet when $n_i = n$, $m_i = m$, and when the fading is neglected. Two other event probabilities in (5) can be calculated from the pdf of the location of the users, defined in (2), and are derived in [5].

To find the probability of packet success, $P_{C,i}$, we model the channel interference by summing the interference powers, both the interference from the users whose their signals reach the ith satellite and the additive white Gaussian noise (AWGN) of two-sided power spectral density $N_0/2$, treat the sum as Gaussian noise [8], and denote the equivalent bit energy-to-noise ratio at the ith satellite by μ_i. If the packets are modulated by the direct-sequence scheme with binary phase shift-keying (BPSK) with a rectangular chip pulse, μ_i can be formulated by [9]

$$\mu_i = \left(\frac{2I_i}{3LS} + \frac{1}{\mu_0}\right)^{-1} \tag{6}$$

where L is the bandwidth expansion factor, I_i is the total power of interference at the ith satellite, and μ_0 is the ratio of bit energy-to-power spectral density of the background white Gaussian noise.

With such a model, we can have the conditional probability of packet success, conditioned on μ_i, which is a smooth function of the signal-to-noise ratio (SNR), depend on the level of coding. With the assumption of a highly coded system, this function can be well fitted to a step function at some threshold value μ_c and, hence, the unconditional probability of success can be derived by integrating the pdf of μ_i, $f_{\mu_i}(\mu)$, as

$$P_{C,i} = \int_{\mu_c}^{\infty} f_{\mu_i}(\mu)\, d\mu = 1 - F_{\mu_i}(\mu_c) \tag{7}$$

where $F_{\mu_i}(\mu)$ is the cumulative distribution function (CDF) of μ_i. In [8], it is shown that for the purpose of calculating the probability of packet success, this threshold assumption gives close enough results.

With respect to the relation of I_i and μ_i in (6), it can be seen that

$$\begin{aligned} F_{\mu_i}(\mu) &= \mathrm{Prob}\left[\mu_i \le \mu\right] \\ &= \begin{cases} 1 - F_{I_i}\left(\dfrac{3LS}{2}\left(\dfrac{1}{\mu} - \dfrac{1}{\mu_0}\right)\right), & \mu \le \mu_0 \\ 0, & \mu > \mu_0 \end{cases} \end{aligned} \tag{8}$$

where $F_{I_i}(I)$ is the CDF of I_i and its analytic expression is derived in [5]. By substitution of (8) in (7), and simple mathematics, we have

$$P_{C,i} = \begin{cases} F_{I_i}(K(\mu_c) \cdot S), & \mu \le \mu_c \\ 0, & \mu > \mu_c \end{cases} \tag{9}$$

where

$$K(\mu_c) = \frac{3L}{2}\left(\frac{1}{\mu_c} - \frac{1}{\mu_0}\right). \tag{10}$$

Note that $K(\mu_c)$ gives the possible number of simultaneous transmissions excluding the tagged packet in the absence of background noise and interference. We denote this parameter, because of its meaning mentioned above, as multiple-access capability.

V. AVERAGE DELAY PERFORMANCE

Another important measure of performance in a packet communication system is the average delay performance, which shows the average required time for successfully delivering a packet in the system. If the spread-slotted ALOHA scheme is employed in a communication system with negligible value of propagation delay, such as in microcellular system, the average delay is mainly due to the number of retransmissions of collided packets because of the high level of interference experienced by those packets. After the occurrence of a packet collision, the sender of that packet should retransmit the packet repeatedly after a randomly selected period until an acknowledgment is eventually received. In a low throughput situation, the number of such collisions increases and, hence, the average delay becomes longer.

In the LEO satellite system, although the propagation delay between users and satellites is much smaller than that of a geostationary satellite system, if the number of retransmitted packets increases the total propagation delay becomes on the order of the packet length and, hence, it is not negligible. If we improve the probability of packet success, the number of collisions decreases and we expect an improved average delay performance of the system as well. The proposed transmit permission control scheme, as shown later, improves the probability of packet success and the throughput performance and, hence, it may improve the delay performance too. However, since by applying this method another delay time, i.e., the delay due to the waiting time to get the permission for transmission for part of users, is added, we should consider the average delay performance in the evaluation of the method in addition to the throughput performance. A trade-off between the average delay and the throughput performance may determine the optimum degree of the transmit permission control scheme.

Average delay is defined as the average time elapsed from the moment a packet is generated by a user to the moment the entire packet is received successfully at a satellite. We consider two kinds of the average delay. The first one is the average delay for the packets generated by the users in the service area of each satellite, say the ith satellite for which it is denoted by $\overline{\Delta}_i$. Since the expected number of users and the throughput in service areas of satellites in nonuniform traffic distribution are different, the average delays in different service areas are also different. Therefore, we define the normalized average delay, $\overline{\Delta}_{\mathrm{norm}}$, as the average delay for the packets generated in all service areas, for example, considering three satellites we have

$$\overline{\Delta}_{\mathrm{norm}} = \frac{\overline{\Delta}_{i-1}E\{N_{i-1}\} + \overline{\Delta}_i E\{N_i\} + \overline{\Delta}_{i+1}E\{N_{i+1}\}}{N_u} \tag{11}$$

where $E\{N_i\}$ is the expected number of users in the service area of the ith satellite. Obviously, in uniform traffic distribution $\overline{\Delta}_{\mathrm{norm}}$ will be equal to the average delay in any of service areas.

In Section IV, it is assumed that any user with the propagation loss less than l_{max} to its nearest satellite sends a packet in each time slot with the probability q. This assumption leads a binomial composite arrival distribution, including both the new originated packets and retransmitted ones. That is, we have assumed that the new originated packets and the retransmitted packets have the same packet generation statistics. Although in general, for practical implementation the probability of transmitting a new originated packet, p_0, is smaller than that of a retransmitted packet, p_r, in [10] it is shown that the assumption of $p_0 = p_r = q$ gives major simplifications and close results. The need for retransmission occurs due to the loss of the packet because of the excessive interference level, as is considered in the calculations of the probability of packet success in Section IV.

Any user wishing to transmit a packet should first check the permission for transmission according to the protocol of the transmit permission control scheme. If a user is in an unpermitted area, it should wait until a satellite comes close enough to it so that its propagation loss to that satellite becomes less than $l_{\max}$. The probability of being a user in unpermitted areas of each service area is related to the percentage of the permitted areas in that service area and also to the pdf of location of users and for the ith satellite is denoted by p_{np_i}. Note that without employing the transmit permission control $p_{\mathrm{np}_i} = 0$ for all satellites. The waiting time for obtaining the permission is denoted by τ_{wp} and can have any value between zero and $2r(1-\rho)/\nu$, where r is the radius of service areas and ν is the linear speed of satellites, and for practical values of ρ it is assumed that the average value of τ_{wp} is $\overline{\tau}_{\mathrm{wp}} = r(1-\rho)/\nu$. Therefore, the average waiting time related to the transmit permission control in the service area of the ith satellite is $\overline{\tau}_{\mathrm{wp}} p_{\mathrm{np}_i}$.

Any user waits for an acknowledgment from the destination satellite before it clears the packet. Since a slotted case is considered, the packet can be generated at any point during a slot, yet it has to wait until the beginning of the next slot before a transmission is attempted. The time between packet generation and starting of the next slot is represented by τ_{pg} and can have any value between zero and τ_p, the packet duration, with equal probability. Hence, the average time from the generation of the packet until entering the entire packet to the channel equals $\overline{\tau}_{\mathrm{wp}} p_{\mathrm{np}_i} + \tau_p/2 + \tau_p = \overline{\tau} p_{\mathrm{np}_i} + 3/2\tau_p$. For the purpose of comparing the average delay performance in the conventional DS/SSA system and in the system which employs the transmit permission control scheme and for the sake of simplicity in calculations, zero-guard time is assumed here.

The packet travels through the uplink satellite channel and is subjected to the one-hop satellite delay T_d. Although T_d differs according to the location of the transmitting user in a service area, since for a satellite system its variance is very small, an average value of T_d is used in numerical examples. In the case of successful reception of the packet by the satellite, on average $\tau_d = \overline{\tau}_{\mathrm{wp}} p_{\mathrm{np}_i} + 3/2\tau_p + T_d$ seconds are elapsed between generation of the packet and its full acceptance by the satellite. In this case, the satellite sends an acknowledgment packet with the duration of τ_{ack} and the user receives this packet after $T_d + \tau_{\mathrm{ack}}$ seconds. Here we assume that τ_{ack} is negligible compared to other time durations. From the moment the user sends a packet, it waits for another T_d seconds, expecting to receive the acknowledgment packet. If the attempt is successful, it clears the packet. If acknowledgment packet is not received, the user considers the packet lost and enters into the process of reattempting transmission. We assume that the probability of losing the acknowledgment packet is very small. If the packet is lost, the user waits for τ_w seconds, a random retransmission delay time with an average of $\overline{\tau}_w$. The retransmission procedure is repeated until an acknowledgment received by the user. Note that in any steps of the retransmission, the user may find the unpermitted condition and then should wait until the permission is obtained.

For the scenario described above, the average delay of the packet in the service area of the ith satellite can be expressed as

$$\begin{aligned}\overline{\Delta}_i &= \tau_d p_{\mathrm{suc}_i} + (\tau_d + \overline{\tau}_{\mathrm{tw}})(1 - p_{\mathrm{suc}_i}) p_{\mathrm{suc}_i} + (\tau_d + 2\overline{\tau}_{\mathrm{tw}}) \\ &\quad \cdot (1 - p_{\mathrm{suc}_i})^2 p_{\mathrm{suc}_i} + \cdots \\ &= \sum_{k=0}^{\infty} (\tau_d + k\overline{\tau}_{\mathrm{tw}})(1 - p_{\mathrm{suc}_i})^k p_{\mathrm{suc}_i} \\ &= \tau_d + \overline{\tau}_{\mathrm{tw}} \left(\frac{1}{p_{\mathrm{suc}_i}} - 1 \right) \end{aligned} \tag{12}$$

where $\overline{\tau}_{\mathrm{tw}}$ is the average time elapsed between the end of the first transmitted packet and the end of the first retransmitted packet, or, between the ends of any two successive retransmitted packets, at the satellite, equals to $\overline{\tau}_{\mathrm{tw}} = T_d + \overline{\tau}_w + \tau_d$, and p_{suc_i} is the average of the probability of packet success in the service area of the ith satellite.

VI. PERFORMANCE OF THE TRANSMIT PERMISSION CONTROL SCHEME—NONFADING CHANNEL

In this section, we examine, via numerical examples, the performance of the proposed scheme in both uniform and nonuniform traffic situations. We will show first that in both situations the method can improve the peak of the total throughput, and after that by focusing on a nonuniform traffic situation which realizes a heavy traffic situation for the central satellite, we will show the ability of the method to improve the throughput of that satellite and hence the total throughput performance. Finally, we discuss on the selection of the maximum propagation loss, $l_{\max}$, or its consequent parameter, ρ. Throughout these examples, a typical circular-orbit LEO satellite system with 11 satellites in each orbit flying at the altitude 800 km is assumed. For analytical limitations, also N_u is assumed to be 100. As mentioned before, for the nonfading channel the power loss factor β is assumed to be two.

Fig. 2 shows the normalized total throughput as a function of offered traffic load in uniform and two nonuniform traffic situations with $K(\mu_c) = 10$. In this figure, the value of ρ is set to one to disable the transmit permission control. As shown in this figure, by increasing the nonuniformity in traffic distribution (i.e., decreasing the value of ω), since the number of simultaneous transmissions in service area of one of the satellites becomes very large, the total throughput considerably degrades. With higher values of multiple-access capability, such as $K(\mu_c) = 30$, the large interference made the performance of the system in nonuniform traffic situations

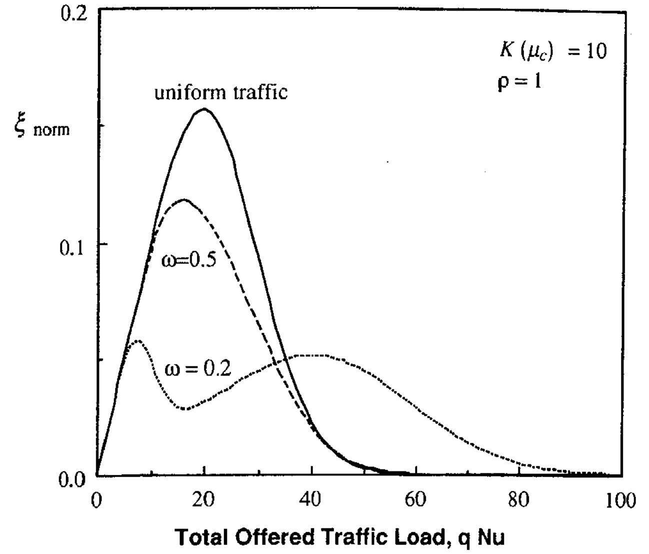

Fig. 2. The throughput performance without the transmit permission control method and with small multiple-access capability.

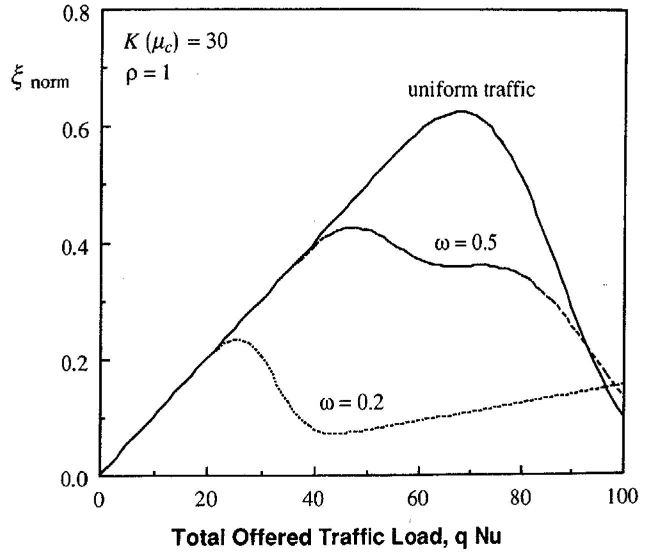

Fig. 3. The throughput performance without the transmit permission control method and with medium multiple-access capability.

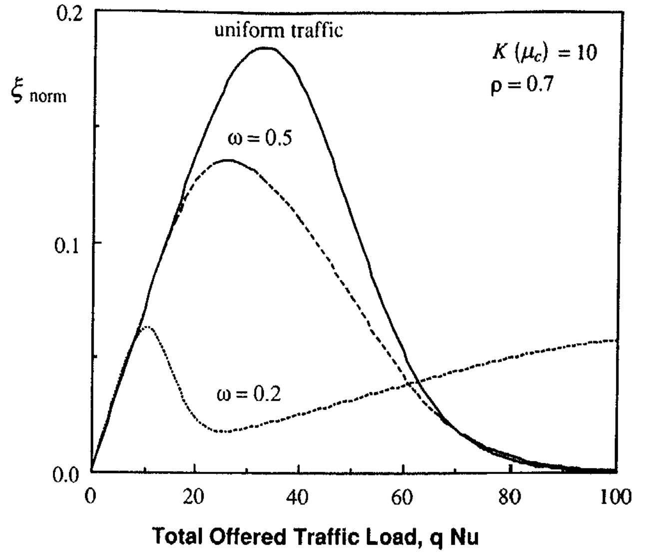

Fig. 4. The throughput performance with the transmit permission control method ($\rho = 0.7$) and with small multiple-access capability.

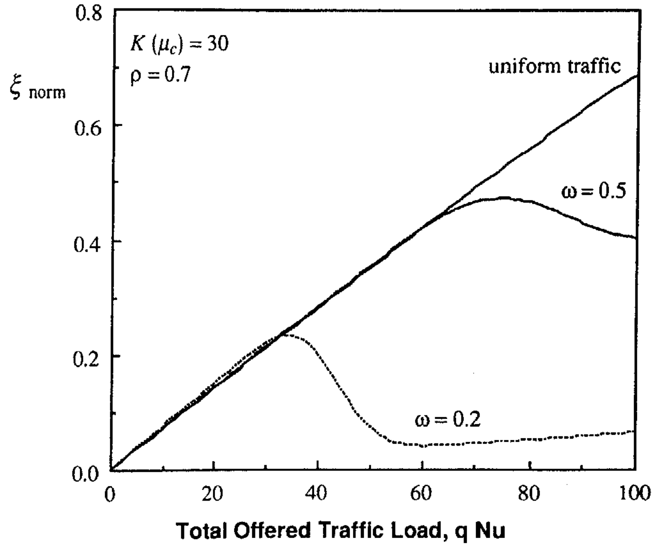

Fig. 5. The throughput performance with the transmit permission control method ($\rho = 0.7$) and with medium multiple-access capability.

significantly less than the uniform traffic situation, as shown in Fig. 3. These figures show that the traffic nonuniformity has a significant effect on the throughput performance of the system.

Let us assume an arbitrary value for ρ and see the performance of the system with transmit permission control method. Figs. 4 and 5 show the normalized total throughput characteristics for uniform and nonuniform traffic situations with $K(\mu_c) = 10$ and $K(\mu_c) = 30$, corresponding to Figs. 2 and 3, respectively, after applying the transmit permission control with $\rho = 0.7$. Although on average about 70% of the users in each service area are only allowed to transmit their packets, applying the proposed method exhibits higher peak throughputs in both cases. In either case, the method shows the improvement not only in enhancing the peak of the throughput curves, but also in expanding the curves on the offered traffic load axis—a factor of improving the system stability.

The improvements achieved by this scheme are due to some different reasons. The prohibition of a portion of the users in the same service area of the satellite which its throughput is considered, is the main factor, since the power of interference of these users are the same as the power of signal, S. The omission of interference from part of users of the neighbor satellites is the second reason. The powers of interference of these latter users depend on the power loss factor β and their distances to the satellites.

The selection of ρ in previous examples was arbitrary. An optimum selection of ρ can be made by a trade-off between the amount of traffic load and the performance improvement. By decreasing the value of ρ, the number of the users which are permitted to transmit in each service area are also decreased. This means that the number of simultaneous transmitting packets decreased, which is not necessary at light traffic loads.

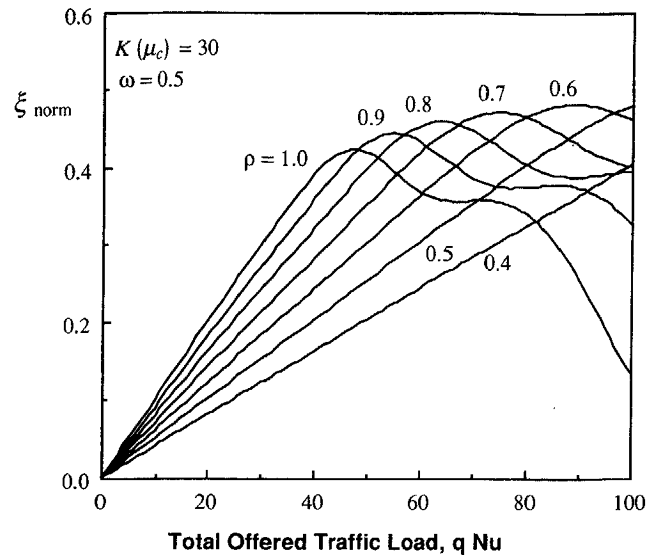

Fig. 6. Effect of selection of ρ on total throughput performance.

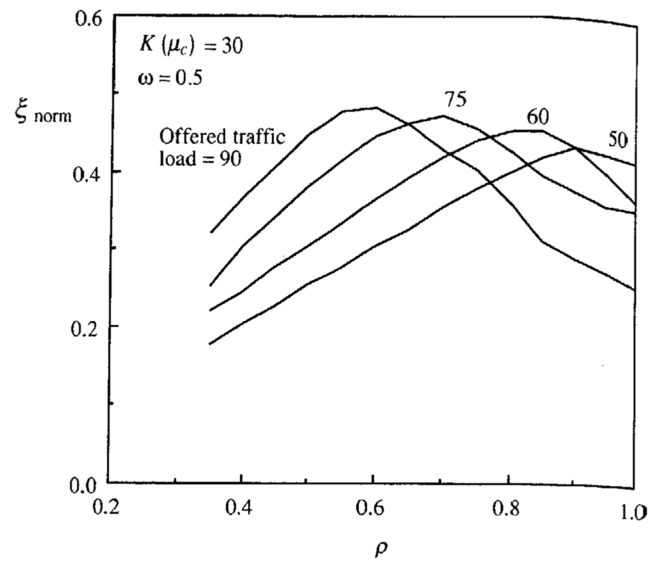

Fig. 7. Effect of selection of ρ on total throughput performance in different offered traffic loads.

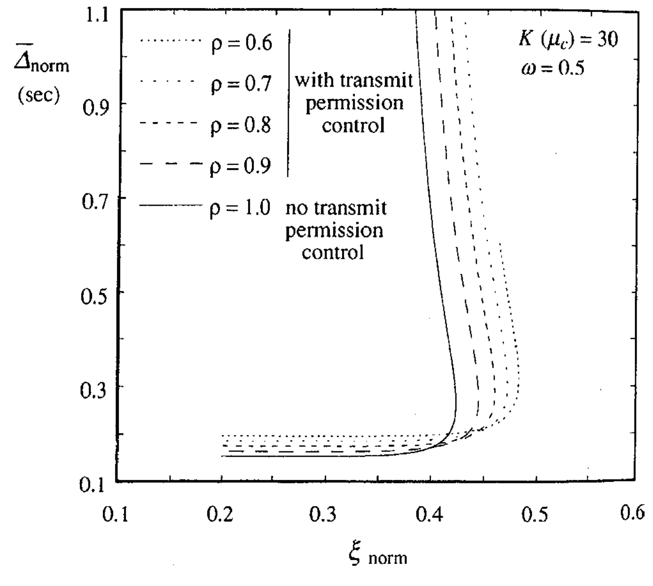

Fig. 8. Comparison between the average delay-throughput performance of the systems with and without the transmit permission control scheme.

On the other hand, at heavy traffic loads, denying some users from transmission improves the probability of packet success and thus the total throughput. From the definition of total normalized throughput which includes all users, permitted and unpermitted, it is possible to find the proper value of ρ. To show the effect of the selection of ρ on performance of the system, here we focus our examples on a special case of $K(\mu_c) = 30$ and $\omega = 0.5$ which realizes a heavy traffic situation and, hence, low capture probability in the service area of one of the satellites.

Fig. 6 shows the effect of changing the parameter of the transmit permission control method ρ on the normalized total throughput of the system. Decreasing the value of ρ from one (no transmit permission control) to about 0.5 shows improvement in the peak value of throughput curves; however, for traffic loads less than 50, the system without the proposed method shows better characteristics. At light traffic loads, all the transmissions can be serviced and prohibiting some users from transmission does not improve the probability of packet success of the others and only decreases the total number of the packets on air and, hence, the throughput. On the other hand, for traffic loads higher than 50, this prohibition increases the probability of packet success for the permitted users, so that higher throughput is achieved. Small values of ρ can have improvement only at large offered traffic loads.

Fig. 7 compares the normalized total throughput for different values of offered traffic load $q \cdot N_u$ as a function of ρ. The point which is illustrated by this figure is that according to the throughput performance for each traffic load, there is an optimum value for ρ which can improve the throughput performance. This means that, there is a tight relation between the selection of ρ and the offered traffic load region in which the system works: A system working at heavy traffic load requires smaller values of ρ and for a system in which a light offered traffic region is designed, the values of ρ near one is enough. Also this figure illustrates, using small values of ρ at high offered traffic situations improves the performance of the system significantly. We conclude that an adaptive selection of ρ can maintain improved throughput characteristics at a wide range of the offered traffic load.

Let us now examine the effect of the transmit permission control scheme on the average delay performance of the system. Throughout the following examples, $\tau_p = 0.1$ s and $\overline{\tau}_w = 0.3$ s are assumed. Fig. 8 shows the normalized average delay $\overline{\Delta}_{\text{norm}}$ versus the normalized total throughput under the same conditions as Fig. 6, again with ρ as a parameter. At the initial low throughput region, which corresponds to light offered traffic loads, employing the transmit permission control enlarges the average delay, similar to the discussion given for Fig. 6, because of the prohibition from transmission of the parts of the users which can be serviced successfully. However, at higher throughput regions, the average delay

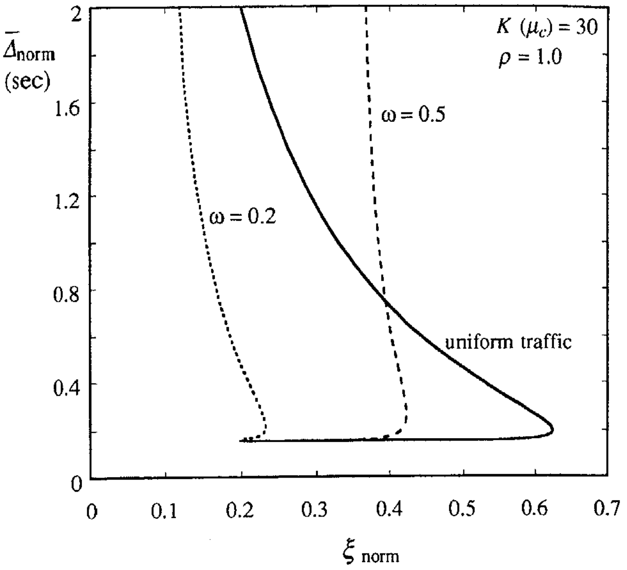

Fig. 9. Average delay-throughput performance of the system without the transmit permission control at different traffic conditions.

performance of the system employing the transmit permission control becomes superior to that of the system without this scheme. In this latter region, employing the proposed scheme decreases the large number of retransmissions and, hence, shortens the average delay. This figure again suggests that an adaptive selection of ρ can offer improved average delay, similar to the suggestion given for the throughput performance, in a wide range of change in offered traffic load. Note that employing the transmit permission control with a fixed value of $\rho = 0.7$ enlarges the average delay at most on the order of half a packet length.

Fig. 9 shows how the traffic nonuniformity affects the average delay performance of the system. In this figure, a system which does not employ the transmit permission control is considered. This figure illustrates that in uniform traffic situations, the system exhibits much more stability than in nonuniform traffic situations. This is in addition to the higher total throughput that the system can handle in uniform traffic condition. The reason for having more stable system in uniform traffic is that, at nonuniform traffic situations the expected number of users in service area of one of the satellites is large, and, hence, the number of retransmitted packets is large. Therefore, the increase in the average delay after collisions in these traffic situations becomes sharp compared to the uniform traffic situation. We conclude, by examining the throughput or the average delay performances, i.e., that the traffic nonuniformity affects the performance of the system significantly. The same conclusion is derived for the system employing the transmit permission control.

VII. PERFORMANCE OF THE TRANSMIT PERMISSION CONTROL SCHEME—FADING CHANNEL

In Section II, a nonfading land mobile satellite channel was assumed. This assumption is a proper simplification specially for the satellite systems with relatively high elevation angles. However, in the case of LEO satellite systems, low elevation angles are often considered. Therefore, to have more accurate results, it is necessary to compute the performance of the LEO satellite system and the transmit permission control scheme with a channel that suffers from variations of the received signal power due to fading.

Shadowing and multipath fading are the two problems that affect the level of the received signal powers. Shadowing of the signal from users to the satellites, caused by the obstacles in the path between users and satellites, reduces the power of the received signal over the total signal bandwidth and its effects become larger as the elevation angle decreases. The reception of the signals being reflected from the objects around the user, or multipath signals, results in a deep fade due to the different propagation distances. To express this fading, we employ the channel model proposed in [11]. This model is described by the time-share of shadowing B, i.e., the fraction of time that the signal is shadowed. During the shadowed interval, the channel is modeled as log-normal frequency nonselective Rayleigh fading. In unshadowed period, $1 - B$, the channel is modeled as frequency nonselective Rician. The resulting pdf of the received signal power normalized to the power of the signal in the absence of either fading or shadowing is then given by the mixture density

$$f_V(V) = (1 - B)ce^{-c(V+1)}I_0(2c\sqrt{V}) + Bce^{-cV} \qquad (13)$$

where c is the direct-to-multipath signal power ratio (Rice-factor) and $I_0(\cdot)$ is the modified Bessel function of the first kind and zeroth order. The parameter V can be thought as the factor that shows the effects of fading: In a nonfading channel, it is a unity constant value and in a fading channel it is a random variable with the pdf given in (13). Note that the expected value of the normalized received power in the absence of either fading or shadowing is unity. Although this channel model can be used for both directions, uplinks and downlinks, in order to make the effect of fading on uplinks clear, here we assume nonfading downlink channels; hence, making users know the exact value of their distances to the satellites and transmit with the proper power level given in (3). In [11], there is a complete discussion on the parameters c and B for different satellite elevations and different environments. In this paper, we consider the $c = 10$ as a typical value in a LEO satellite channel, and the $B = 0.3$ case, as used in [12] and [13].

According to (3), a user, namely the jth one, in the service area of the ith satellite and in the distance $d_{i,j}$ from it, transmits its packet by the power $T_{i,j}$ to ensure the received power level S at that satellite in the absence of fading. However, because of the fading the level of the received signal from this user at the ith satellite may be different from the level S according to the level of fading. In this case, the signal of the jth user reaches at the ith satellite with the level

$$S_{i,j} = T_{i,j}\kappa d_{i,j}^{-\beta} V_{i,j} \qquad (14)$$

where $V_{i,j}$ is a random variable with the pdf given in (13). The signals of the users in service areas of the neighbored satellites and in the LOS of the ith satellite reach at the ith satellite with power levels related to the distances of each user from two satellites and also the level of fading. Without lack of generality, assume that the kth user in the service area of the $(i+1)$st satellite is one of these users, and has the distance $d_{i,k}$ to the ith satellite and $d_{i+1,k}$ to the $(i+1)$st satellite. It transmits packets by the power $T_{i+1,k}$ to ensure the received power level S at the $(i+1)$st satellite in the absence of fading. Because of the fading channel, its signal is reached at the ith satellite with the power

$$S_{i,k} = T_{i+1,k} \kappa d_{i,k}^{-\beta} V_{i,k} \tag{15}$$

where again $V_{i,k}$ is a random variable with the pdf given in (13).

As in Section IV, it is necessary to find the probability of packet success in the service area of each satellite to calculate the throughput. This probability was derived in Section IV for nonfading satellite links. With fading uplink channels defined in (13), now we should find the probability of packet success $P_{C,i}$ for the fading environment. In the nonfading environment discussed in the previous section, the power level of the target packet is the fixed value S, which appears in (6), (8), and (9). On the contrary, in the fading environment, it is a random variable according to the random variable $V_{i,j}$ as is described by (14). On the other hand, the total power of the interfering packets, I_i, is a random variable even without fading, as the locations, and thus the powers at the satellite, of $m - n$ users of the neighbor satellites, are the random variable. When fading is considered, the total power of the $m - n$ users are still random variables, but not only by the locations of the users but also because of fading as is denoted in (15). In addition to these $m - n$ users outside the service area, the level of the interference from each of the remaining interfering users inside the service area is also not the constant but random by the fading, as in (14). Considering those difference in the fading environment, we derive numerically the packet success probability $P_{C,i}$ and find the throughput characteristics with (5). Note that, in the calculation, with the assumption of performing the analysis during a short period of time and a reasonably high bit rate, we assumed that the fading varies slowly compared to the bit rate and, hence, the received signal power is considered constant during one symbol interval.

Fig. 10 compares the normalized total throughputs before and after applying the transmit permission control scheme in the fading channel for $K(\mu_c) = 30$ and $\omega = 0.5$. For the transmit permission control case, two values of $\rho = 0.7$ and $\rho = 0.6$ are shown. As seen in this figure, the performance of the system at heavy traffic loads can be improved by means of the transmit permission control method. If we compare the results shown for the fading channel with the ones for the nonfading channel, we can observe some throughput enhancements at heavy traffic loads in the fading channel with or without transmit permission control. The reason is that at heavy traffic loads the effect of fading acts positively to improve the probability of the packet success by decreasing the level of interference power, and hence improves the throughput. On the other hand, at light traffic loads fading decreases the total throughput slightly. At light offered traffic loads, the effect of fading on the desired signal is much more effective than on the level of interference, since in this case the number of interferers is small. After applying the transmit permission control, since the number of transmitting users decreases, the achievable enhancement due to fading in the transmit permission control case becomes less than the case without transmit permission control. In both fading and nonfading channels, an adaptive selection of the maximum allowable propagation loss $l_{\max}$ may result in maximum improvement at all traffic loads.

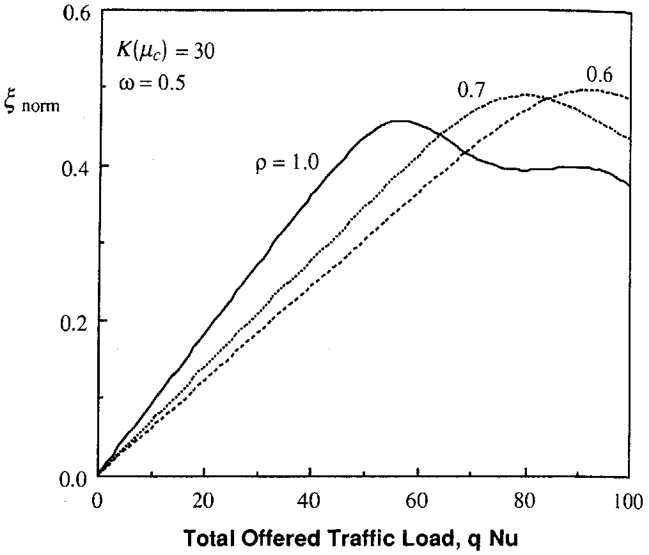

Fig. 10. The throughput performance with and without the transmit permission control scheme in the fading channel.

VIII. CONCLUSION

In this paper, a transmit permission control protocol applicable in (DS/SSA) multiple-access systems is proposed. It is shown that with a proper choice of the maximum propagation loss, beyond which a user is not allowed to transmit, the method can improve the throughput performance of the LEO satellite communication system, in both uniform and nonuniform traffic situations, significantly. For the fading channels, it is shown that the fading decreases the power of interference received at each satellite and, hence, enhances the throughput characteristics at heavy traffic loads. Although the method seems to enlarge the average delay of the system, it is shown that at heavy offered traffic loads the method decreases the number of packet retransmissions and hence exhibits better average delay performance at those traffic regions. The mobility feature of the LEO satellites makes the method practical here, but the method can be applied in, for example, cellular mobile communication systems, in which the base stations are fixed but the mobiles move around.

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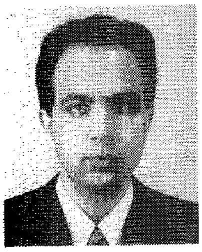

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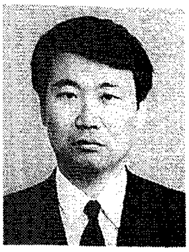

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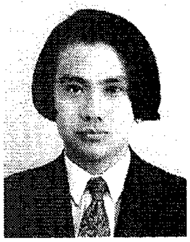

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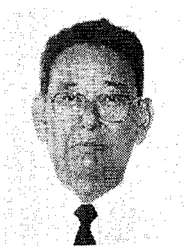

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