INTERNATIONAL JOURNAL OF ADVANCED ENGINEERING AND BUSINESS SCIENCES (IJAEBS)
Journal homepage: https://ijaebs.journals.ekb.eg

IMPROVEMENT OF THE PERFORMANCE OF LEOS SYSTEMS

Sherif S. Emam *[a] ,Ahmed A. Azam [a]

[a] Electronics and communication Dept., Higher Engineering Institute, Thebes Academy, Cairo, Egypt,

*Corresponding author: sherifsamyzow9@gmail.com

Received: 26-02-2025 **Accepted:** 27-04-2025 **Published:** 30-04-2025

ABSTRACT

The throughput performance of Low Earth Orbit Satellite (LEOS) communication systems is analyzed, with a focus on the impact of Multiple Access Interference (MAI) in a direct sequence spread spectrum (DSSS) network operating under a non-uniform traffic model. The study examines how MAI affects system efficiency and evaluates performance improvements for both Dense Traffic Satellites (DTS) and Sparse Traffic Satellites (STS). Various interference mitigation techniques, including advanced power control, adaptive coding, and interference cancellation strategies, are explored to enhance throughput performance. Simulation results demonstrate that optimizing these techniques significantly improves network reliability, reduces packet loss, and maximizes spectral efficiency under varying traffic conditions. The findings provide valuable insights into designing robust LEOS systems capable of handling dynamic traffic distributions while maintaining high service quality.

Keywords

Low Earth Orbit Satellite Communication, Throughput Performance, Multiple Access Interference, Direct Sequence Spread Spectrum, Non-uniform Traffic, Dense Traffic Satellite, Sparse Traffic Satellite, Interference Mitigation

1 INTRODUCTION

This paper investigates the performance of a CDMA-LEOS system designed for voice communication services. We will show that when CDMA is applied on the uplinks, traffic nonuniformity causes large differences in the signal qualities at succeeding satellites; a satellite above a heavily loaded (dense) traffic area has a low signal-to-interference ratio (SIR), while its neighbor satellites over lightly loaded (sparse) traffic areas have a high level of SIR.

Although mobile communication terrestrial system coverage is rapidly growing, they are limited to populated areas. Large areas of the Globe are rarely populated. LEOS systems are entitled for those rarely populated areas. So, LEOS systems are not competitor to mobile communication systems, but they are complementary to them. The performance of any communication system is best illustrated by its throughput. The throughput of a communication system is defined as the average number of packets that are successfully delivered to receivers from the total number of transmitted packets. In this paper we consider the throughput analysis of the Globalstar system. We assume a flexible traffic distribution, which cover both uniform and non-uniform traffic models. Throughput of both Dense Traffic Satellite (DTS) and Sparse Traffic Satellite (STS) as well as that of three consecutive satellites are calculated.

The throughput performance of Geostationary satellites are already existing in a lot of text books and papers [1-4]. However the study of LEOS has two main difficulties: the nonuniformity of the traffic and the dynamic of the system since the satellites are in continuous motion with respect to the Earth station. These two problems were investigated in [5,6]. It has also been recognized that CDMA offers random access channel sharing with low delay, along with spread spectrum advantages such as:-

1. Immunity to external interference and jamming.

2. Antennas on board mobile earth stations are usually very small and hence their beams are very broad, which may result in considerable amount of interference to and from existing satellite systems. Spectrum spreading is effective to solve the problem of interference.

3. Broad antenna beam of the mobile earth station is likely to be affected by multi path interferences. Spectrum-spreading is one of the measures to reduce the multipath effect.

4. To achieve the radio termination with a sufficiently high resolution, it is necessary to adopt a sequence of code with excellent autocorrelation characteristics.

Multiple access procedures from mobile earth stations to the satellites have to be as simple as possible. Asynchronous access based on direct-sequence spread-spectrum is considered to be one of the promising schemes in this respect [7]. Thus one of the best solutions to global

Personal Communication Network (PCN) is the use of CDMA-LEOS. In section 2 the system model is organized. Section 3 explains the performance measure (throughput) for three adjacent satellites. In section 4 the techniques employed for improvement of the performance are surveyed. Section 5 includes the conclusions.

2 THE SYSTEM MODEL

Because of small coverage area of LEOS, compared with geostationary ones, for a global communication network it is necessary to organize the LEOS on a multiple orbit configuration. In this model [8], an area on the earth is represented by an arc as shown in Fig. 1. In this figure, we distinguish between the coverage area of a satellite and the interference area of it. The coverage area is specified by the minimum value of the elevation angle, θmin, that an earth station is assumed to be able to access to the satellite while the interference area is determined by the final line of sight of that satellite. The service area is defined as a limited area within a coverage area where users can connect to the satellite. The double coverage area is an area commonly located between two or more adjacent coverage areas.

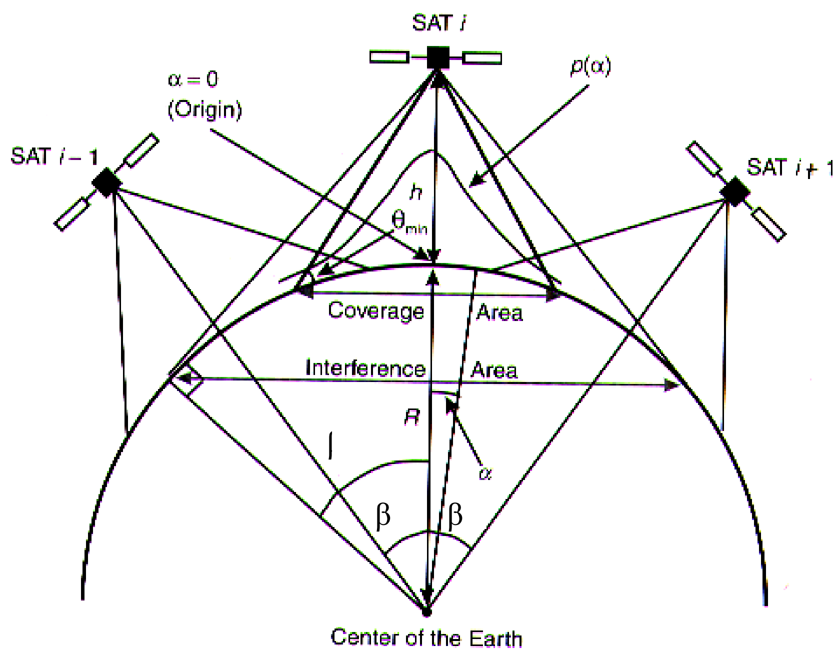

Fig.1. Typical shape of the normal non-uniform traffic model used in analysis

It should be noted that if an earth station lies in the interference area but out of the coverage area of a satellite, it would not be allowed to connect to that satellite, but still its signal reaches that satellite as interference. In order to analyze the influence of the non-uniformity in traffic, we focus on a series of three satellites and their users. Assume that the total numbers of users, N_u, are distributed randomly in a given area, the size of which is equal to the service areas of three adjacent satellites and their interference areas. For a LEOS system in which the satellites have the altitude h (km), the geometric interference limit for each of them in a smooth spherical earth assumption is given by the angle.

$$\beta_I = \cos^{-1}\left(\frac{R}{R+h}\right) \qquad (1)$$

Where R is the average radius of the earth and it is equal to 6378 Km. The distribution of the users is assumed to have the following function [6]:

$$P(\alpha) = \frac{A}{\omega}\exp\left(-\alpha^2/2\omega^2\right), \qquad |\alpha| \le \pi \qquad (2)$$

where α is the relative location of a user, measured by the angle at the center of the earth; ω is the parameter representing the uniformity of the traffic, and A is a factor related to the total traffic load (total number of users) in the observed area. Since the total traffic load for the satellites under consideration should be kept fixed when ω or the number of satellites in each orbit; N_s changes, we assume that the total traffic load of three natural service areas, when the peak of the traffic is located at the origin, is constant and equal to B and thus

$$A = B / \int_{-3\pi/N_s}^{3\pi/N_s} \exp\left(-\alpha^2/2\omega^2\right) d\alpha \qquad (3)$$

The ratio of the traffic loads of two adjacent natural service areas, when the peak of the traffic is located at the origin, is defined as:

$$TR = \int_{-\pi/N_s}^{\pi/N_s} P(\alpha) d\alpha \; l \int_{\pi/N_s}^{3\pi/N_s} P(\alpha)\, d\alpha \qquad (4)$$

3 THE THROUGHPUT

In this section, the performance measure namely the throughput will be derived for LEOS systems [8].

3.1 Distribution of the Users

We can say that N_u users are distributed in an area whose size A_r, is given as:

$$A_r = \frac{4\pi}{N_s} + 2\beta_I \qquad (5)$$

Which is the size of the interference areas of the three succeeding satellites. In that area, it is assumed that the location of every user is a random variable with probability density function p (α) as [6, 9].

Finally, it is assumed that each user sends a packet, including newly generated and retransmitted packets, with probability q [10]. If we assume M users in the specific area under consideration, the distribution of the number of packets that are sent simultaneously to the channel becomes binomial with the parameters q and M as [11]

$$f(m;M)=\begin{cases}\binom{M}{m}q^{m}(1-q)^{M-m} & m\le M\\ 0 & m>M\end{cases} \qquad (6)$$

where m is the number of transmitted packets. Here, we consider the LEOS system with six orbits and eleven satellites on each orbit.

3.2 Throughput Analysis

In the case of LEOS systems with non-uniform traffic distribution, the expected number of users and hence the composite packet arrival rate are different in each service area. Thus, we normalize the throughput for each satellite by the expected number of users in its service area, $E\{N_i\}$, namely, the normalized throughput for the i^{th} satellite, as

$$\xi_{i,norm}=\frac{\xi_i}{E\{N_i\}}\quad (packet/slot/user),\quad i=1,2,.....,N_s \qquad (7)$$

where ξ_i is the expected number of successfully transmitted packets of the i^{th} satellite.

We can calculate the value of multiple access capability, $K(\mu_c)$, and we can obtain the possible number of simultaneous transmissions, except for the tagged packet, in the absence of background noise and interference[9-12]. Having the probabilities of packet success at the satellite(s) covering the equivalent service area, now we can calculate the throughput. If the expected number of users in the equivalent service area and the total throughputs of the satellites

$$\zeta_{norm}=\frac{\zeta}{E\{N\}}\quad (packet/slot/user) \qquad (8)$$

covering this area (relating to the users in this area) are denoted by $E\{N\}$ and ξ, respectively, we normalize ξ by $E\{N\}$ to obtain the normalized throughput, defined as:

4 TECHNIQUES EMPLOYED FOR IMPROVEMENT OF THE PERFORMANCE

To improve the performance of a communications system employing such a multiple-access scheme, it is necessary to keep the level of multiple-access interference as low as possible. So, we can improve the performance by one of the following methods: Modified power control (MPC), transmit permission control (TPC), adaptive transmit permission control (ATPC) and packet admission control (PAC). These techniques will be described in this section respectively.

4.1 Modified Power Control (MPC) Scheme

It was assumed that the required receiving powers of all satellites are the same and, hence, that the service areas of all satellites are equal in size, which is the case of natural service area configuration. That configuration, although natural in the case of uniform traffic, no longer has merit when the nonuniform distribution of users is involved. It will be better to change the size of service areas according to the offered traffic loads using different schemes. This section proposes a scheme in which the designed receiving powers of the satellites are not equal. The proposed method would control the size of service areas according to their local traffic loads; that is, the service areas with light traffic loads are expanded, and the ones with heavier traffic loads are decreased.

Let us first assume that the peak of the traffic is located under the i^{th} satellite, that is, the DTS. Because the users communicate with the satellite that needs the smallest transmitting power, by increasing the required transmitting power of the DTS compared with its adjacent satellites on both sides (STSs), it is possible to increase the tendency of the users in a double coverage area to connect to the STS, not to the DTS, thus decreasing the traffic load of the DTS. This method is realized by changing the ratio of the designed receiving power of the DTS to that of its neighbors on both sides, say, increasing the ratio $\gamma = S_i / S_{i-1} = S_i / S_{i+1}$ [12]. Each satellite counts the number of its users in a given period of time and by the means of inter-satellite links, for example, the numbers of users of individual satellite are compared with each other, and then the proper ratio of γ in each area for the next period of time is selected and established. By increasing the ratio γ from 1, the number of users of the DTS and STSs are decreased and increased respectively. Therefore, the performance of the DTS gradually improves and that of STSs degrades. As the ratio of the designed receiving powers, γ, increases the SIR curves reach to a cross- point. Increasing the powers ratio more makes the performances of STSs worse than that of the DTS.

There are different ways to realize the MPC. One way is to keep the required receiving powers at the $(i+1)^{th}$ and the $(i-1)^{th}$ satellites fixed and increase the power S_i by the factor γ. Another way is to keep the S_i constant and decrease the powers S_{i-1} and S_{i+1} by γ. Finally we can consider an intermediate way: decreasing S_{i-1} and S_{i+1} and increasing S_i. Although from the viewpoint of the analysis all three ways result in the same performance, consideration of practical factors, such as limited transmitting power of the hand-held terminals, and limited power variations, makes one way more attractive. For example, from the viewpoint of the limitation in the power supply of the terminals, keeping S_i constant and decreasing $S_{i-1}$and S_{i+1} would be the best.

4.1.1 *Measuring the Optimum Capability*

Applying the modified power control will also improve the throughput. Fig. 2 shows the discrepancy between the throughput of the i^{th} and the $i+1^{th}$ satellite, showing the existence of an optimum value of γ. Fig. 3 illustrates the amelioration in the system performance when we apply the modified power control.

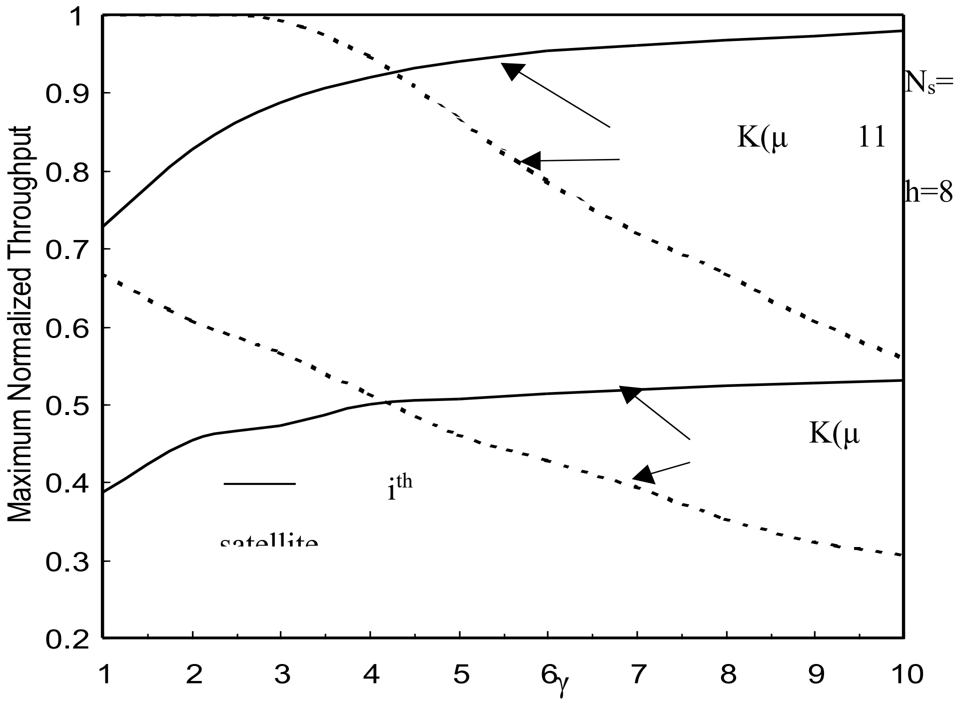

Fig.2. Change in the maximum normalized throughput according to the change in γ for ω=0.5 and different levels of the multiple access capability, K(μc)=30 and 50

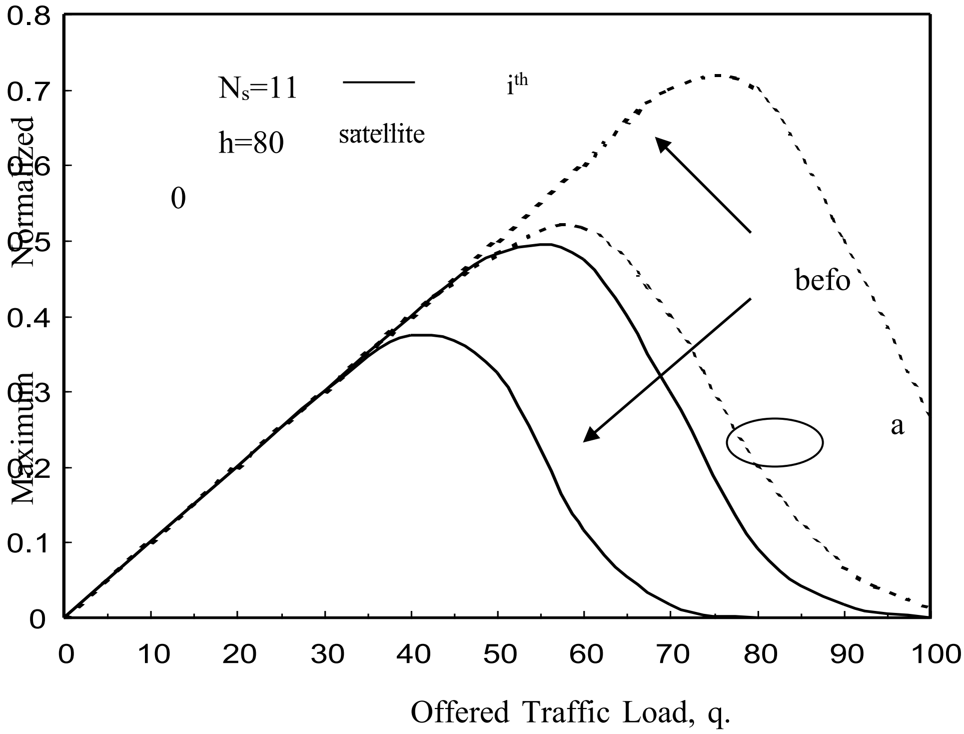

Fig.3. Normalized throughputs of the individual satellites for ω=0.5 and K(μc)=30, before and after applying the modified power control scheme with a fixed value of γ=4

4.1.2 Some Practical Notes on the Realization of the Modified Power Control Scheme

We provide some practical considerations on the realization of the modified power control scheme in LEOS systems. The first point is the selection of the proper value of the ratio of the receiving powers of the satellites, γ. That value can be calculated according to the statistics of the packet transmissions to the satellite channels. In a LEOS network, to realize the modified power control effectively, the satellite should have some communication control channels to each other, which can be provided by inter-satellite links, proposed in some global LEOS systems. Each satellite can inform other satellites of the statistics of its traffic load via the intersatellite links, then the calculation of γ can be performed either globally for all satellites in a central control station (in space or on the ground) or for a group of satellites. After the calculation, the results on selection of relative values of γ are passed to all satellites, which then can manage the transmitting powers of their users according to the selected value of γ [12,13].

Each satellite, according to the updated value of γ, changes the transmitting power of, for example, its pilot signal and sends the control signal over the forward links to all users in the services area. This step is completely executed in the same manner as for the case of conventional power control scheme.

Another point in a realistic system is the range of the offered traffic load in which the system is operating or is designed to operate. The modified power control scheme does not have good performance when the offered traffic load is very high. For that reason, we propose a system in which the value of γ is reset to one to disable the modified power control scheme at heavy offered traffic loads. Actually, in an Aloha or a spread Aloha system, the system is designed to operate at the offered traffic loads near the one that corresponds to the peak of the throughput curves. Operating the system above that point makes the stability of the system sensitive to the changes of the offered traffic load and, hence, lets the system go to unstable situations easily. Theoretically, there is no need for trying to improve the performance of the system in those areas.

4.2 Transmit Permission Control (TPC)

The idea of the proposed TPC is nothing more than the following simple instruction: Users can send packets if they are located at distance less than a certain value. Without specifying what determines that distance value at the moment, we can conclude that this method reduces the number of simultaneous transmission: that is, the level of multiple access interference, especially by avoidance of the transmission by users in marginal service areas [14,15].

Let us have physical representation of the TPC method. Assume a fixed and same value for the maximum allowable propagation loss, Imax, in the service area of all satellites. After applying the method, the radius of service area of each satellite, r_0, is multiplied by some factor λ, where $0 \le \lambda \le 1$, resulting in a reduction of $1- \lambda$ in the radius of service areas. The parameter λ depends on and has the same information as Imax with simpler tractable meaning, that is large values of Imax make the decrement of service area of satellites small, which means a nearly unity value of λ and vice versa. Fig. 4 illustrates the change in service areas of the satellites before and after application of the TPC scheme. In the figure, it is assumed that minimum numbers of satellites and orbits are considered for global coverage.

In each circular service area of the satellites in Fig. 4, assume the largest hexagon that can be inscribed in it. The area of such a hexagon can be calculated, considering the spherical shape of the earth.

It should be clear that selecting small values of λ means most users have no permission most of the time; on the other hand, values of λ close to unity make the system have the characteristics almost the same as those of the system without such a control. Therefore, there should be an optimum value of λ that provides the largest improvement in the system performance. We will discuss the performance of the system employing the TPC scheme and selection of λ; after that, we show the existence of such an optimum value.

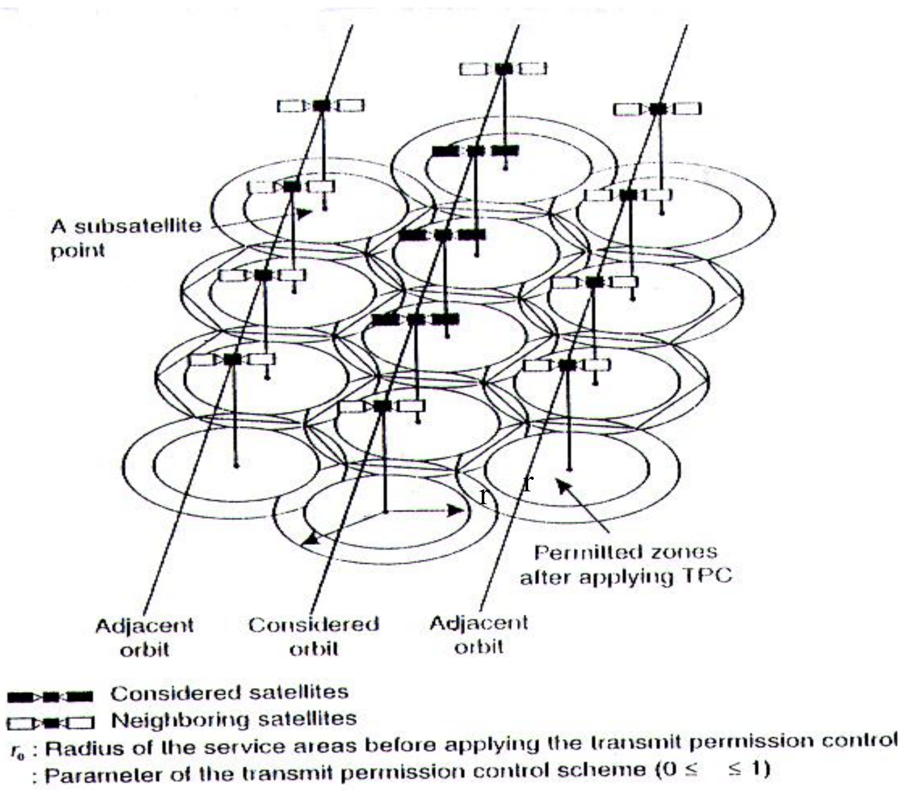

Fig.4. Configuration of the service areas of the satellites before and after application of the TPC scheme

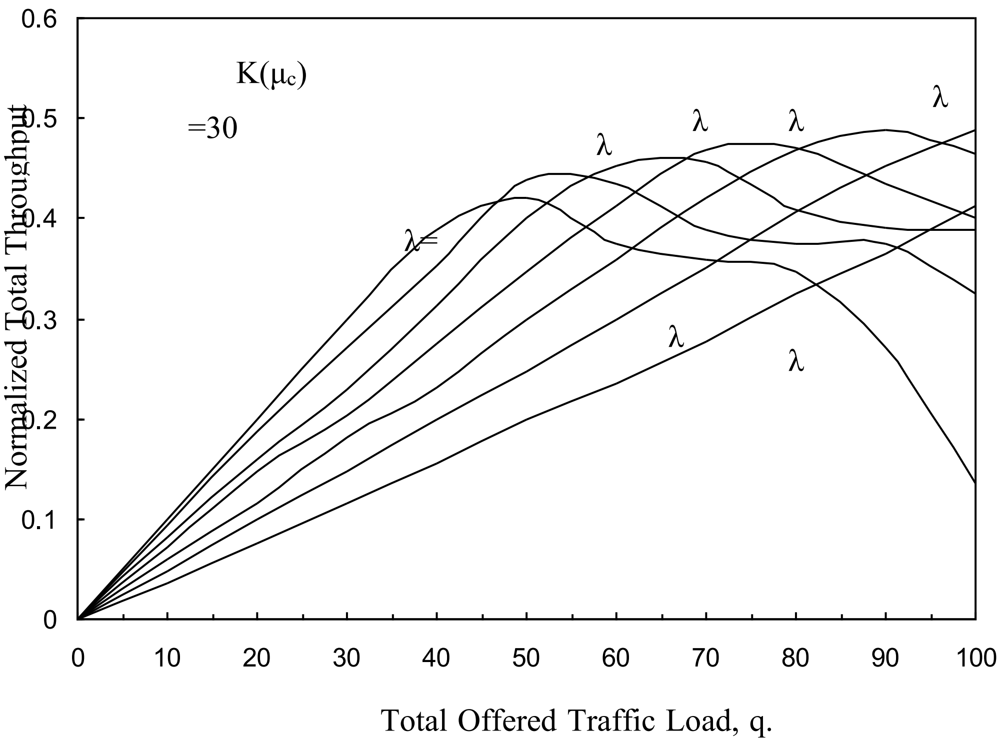

Fig.5. Effect of selection of λ on normalized total throughput performance

The improvements achieved by the scheme are due to different reasons. The prohibition from transmission of a portion of the users in the service area of each satellite is the main factor, since the power of interference of those users is the same as the power of the signal, S. The omission of interference from a portion of users of the adjacent satellites is the second reason.

An optimum selection of λ, however, can be made by a trade-off between the level of traffic load and degree of performance improvement. A decrease in the value of λ results in a decrease in the number of users permitted to transmit in each service area. That means the number of simultaneous transmitting packets decreases, which is not necessary in light traffic loads. On the other hand, in heavy traffic loads restricting some portion of users from transmission improve the probability of packet success and thus the total throughput. Since in calculation of the total normalized throughput, the total number of users, including both permitted and non-permitted users, is considered, it is possible to find a proper value of λ.

To show the effect of the selection of λ on the performance of the system, let us focus the evaluation on a special case of $K(\mu_c)=30$ and $\omega=0.5$, which is a heavy traffic situation and hence a low-capture probability for one of the satellites.

Fig. 5 shows the effect of changing the parameter of the TPC method λ on the normalized total throughput of the system. As shown in the figure, decreasing the value of λ from 1(i.e., no transmit denials) to about 0.5 shows improvement in the maximum value of throughput curves. For traffic loads less than about 50, however, the system without the proposed method shows better characteristics. The reason is that in light traffic loads all the transmissions can be serviced with high probability of success, 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 total throughput. On the other hand, for traffic loads higher than 50, the probability of packet success is relatively low, and this prohibition increases the probability of packet success for the permitted users, so that larger throughput is achievable. Small values of λ can give improvement only in heavy offered traffic loads.

4.3 Adaptive Transmit Permission Control (ATPC) Schemes

Since we saw the results that illustrate the dependency of the effectiveness of the TPC method on the level of the offered traffic load: higher offered traffic loads need smaller values of λ to have better performance, and lighter traffic loads require larger values of λ. That fact implies that an adaptive selection of λ according to the total offered traffic load can improve the throughput performance of the system. In addition, in the case of nonuniform traffic distribution, if we see the throughput characteristics of individual satellites, for example, the satellite over the dense traffic area and its neighbor satellites over the sparse traffic areas, we can expect to find better performance by adaptive selection of λ for each satellite according to its level of the offered traffic load [14].

The idea behind these two typical examples, that is, the selection of λ according to the traffic loads of individual satellites, in addition to the idea that is, the selection of λ according to the total offered traffic load, introduce two possible adaptive methods for the selection of λ. We refer to these techniques as adaptive TPC (ATPC) methods. In the following subsections, the two ATPC will be described.

4.3.1 ATPC method 1

The first method considers the selection of λ according to the change of the total offered traffic load of the three satellites. Similar to the basic TPC method, the reduction in the service areas of all satellites is the same by the factor λ. However, different from the basic method, the value of the λ is not constant but changes according to the change of the total offered traffic load. In this method according to the total offered traffic load statistics, which are estimated from the statistics of the previous time slots, the optimum value for λ is calculated, so the maximum total throughput can be achieved and the users are informed via down link information channels. This value of λ is common in all service areas and is updated regularly, depending on how often the level of the traffic load changes. The result is the equal reduction or enhancement of the service areas compared to the ones established in the last time slots. In this scheme, regardless of the different traffic load offered to the satellites, the sizes of the service area of all satellites are kept the same even after the methods is applied.

4.3.2 ATPC method 2

The second method considers the selection of λ according the change in the offered traffic load of individual satellites. Similar to the first method, the statistics of the traffic load are used for determining the optimum value for λ. However, different from the first method, the decision is not common for all satellites and is performed by each one and is valid only for that satellite. The optimum value for λ in this method is the value that makes the throughput of each satellite maximum. That makes the satellite with lighter traffic loads select larger values for λ. This method is especially effective for the case of nonuniform traffic situations, in which different satellites have different total traffic loads. After this method is applied, the service area of the satellite with the higher traffic load becomes smaller than that of the satellite with the lighter traffic load.

4.3.3 Performance of ATPC methods

Let us compare the performance of the system without the TPC method with the ones employing ATPC methods 1 and 2. Fig. 6 shows the performance of the system under the same conditions as Fig. 5. Employing the first adaptive method maintains good performance at light offered traffic load by disabling the TPC (i.e., selecting λ=1) and improves the throughput at higher offered traffic loads by gradually decreasing the value of the λ. As the offered traffic load increases, the value of λ decreases equally for all three satellites. However, a decrease in λ according to the total traffic load is proper mostly for the satellite with high traffic load; a large decrease in the value of λ is not suitable for the light traffic satellites. Contrarily, by employment of the second method, the value of λ can be determined for each satellite independently; hence, the performance of the system by the measure of the normalized total throughput improves more compared with the first adaptive method. In the latter method we improve the throughput of each satellite separately; hence, the method exhibits better total throughput at the whole range of the offered traffic load. In other words, in the ATPC method 2, we assign a traffic load to each satellite near to the traffic level that can be serviced by that satellite. This is the reason for its better performance.

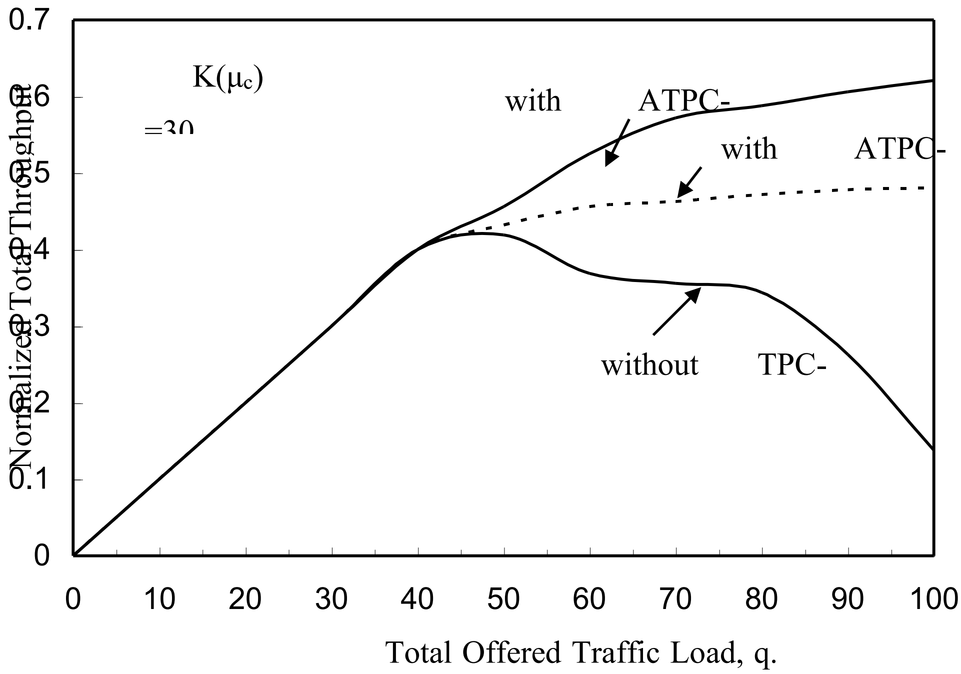

Fig.6. Comparison of the performance of the systems without the TPC method, with ATPC-method 1 and with ATPC- method 2

Although the improved characteristics of the second adaptive method are much more attractive than the first one, the implementation of the second method requires much more complexity. In the first method, the decision on the optimum value of λ is based on the offered traffic load in the area serviced by a group of satellites, for example, in the model of three satellites, which changes slowly; hence, the change in λ also should perform slowly. However, for the second method, especially in a nonuniform traffic situation, the offered traffic load to each satellite changes rapidly, and then λ must be changed often. A trade-off between such complexities and the differences in their performance improvement may determine the best method to be utilized in a real system.

4.4 Packet admission control (PAC)

We propose another scheme, PAC, in which, unlike the TPC, there is no prespecified un-permitted area, but the following two constraints are applied [15]:

- Users with shorter propagation distances to their connecting satellites are honored with higher probability for transmission.
- The degree of priority for transmission of closer users over distant users is moreover controlled according to the traffic distribution of users in the area under consideration.

The first constraint aims to provide a higher probability of transmission to the users who require low-power transmitting signals, to decrease the total power of interference at each satellite. On the other hand, the second constraint is necessary to control the degree of priority given to the closer users by the first constraint. In the absence of the second constraint, even with a small number of users with short propagation distances, their priorities for transmission are high. The second constraint biases those priorities to ensure more transmission from area with more users in the case of nonuniform distribution of users.

There should be several approaches consistent with those two constraints. For an example of the PAC method that provides those two constraints, assume that in each slot each user may transmit a packet with probability $q\varepsilon$ instead of the simple probability of transmission, q, considered before. The parameter ε is a random variable between [0,1] with the probability density function $f_E(\varepsilon)$, which is calculated by each user at the time of transmitting a packet according to the traffic information provided by satellites on downlinks. A simple form of the random variable ε that supports the two constraints of the PAC is a linear function of the location of users, r_u, which is itself a random variable, such as:

$$\varepsilon(r_u) = 1 - \frac{r_u}{r_0} \tag{9}$$

where r_0 is the radius of the equivalent service area and $r_u \leq r_0$. From (9), the probability distribution function of ε can be determined from that of the random variable r_u, in the from of

$$F_E(\varepsilon) = P[E \leq \varepsilon] = F_R[r_0(1-\varepsilon)] \tag{10}$$

The linear relation of ε to r_u in (9) provides higher probability of transmission for closer users in uniform traffic situations because of capture of the traffic by the close satellite. Moreover, in nonuniform traffic distribution, larger values of ε are given to users located in the dense traffic areas.

Let us now evaluate the throughput performance with the random packet transmission of the PAC method. Throughout the following examples, a typical LEOS system with 6 orbits and 11 satellites on each orbit is considered. The orbit height, h, is 800 km, and the minimum elevation angle, θ_{min}, is 10. The total number of users, N_u, in the area under consideration is 100. Fig. 7 shows the normalized throughput as a function of the composite packet transmission, q, with ω as a parameter, for $k(\mu_c) = 30$, in an unfading channel assumption as shown in the figure, assignment of higher packet admission probabilities to users with short propagation distances significantly improves the throughput characteristics in all traffic situations. In the case of ω = 0.2, however, the performance improvement is rather small, since in that highly nonuniform traffic situation, the number of users with almost the same propagation distances to their connecting satellites at any time is large.

With the PAC, however, we can improve or maintain the performance of each satellite in different traffic distributions. Regarding the performance of the PAC under fading conditions, for the LEOS channels it requires a more specific model than the one presented here however, as the PAC decreases the number of users with low elevation angles, it will exhibit better performance under fading situation.

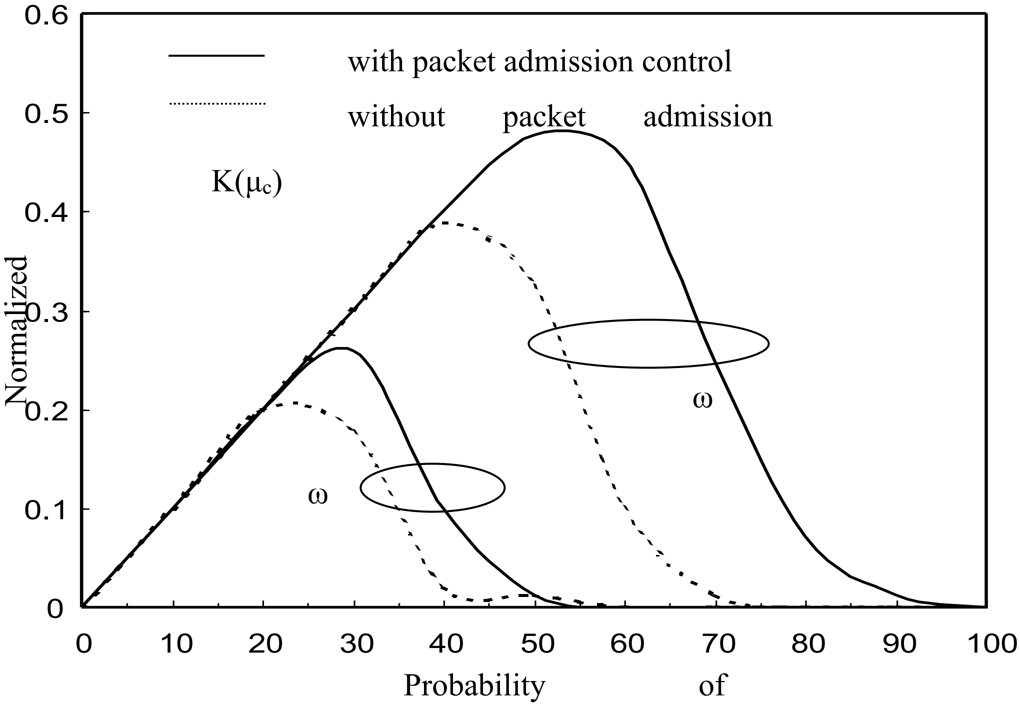

Fig.7. Throughput performance of PAC scheme at different traffic situations

5 CONCLUSIONS

This paper models the nonuniformity of the traffic loads in a satellite based communication system employing LEOS and analyzes the performance of the system. We compare the performance of DTS and STS. It is shown that the throughput of the STS is better than throughput of DTS where the MAI is larger. This suggests that some of the users under DTS could be transferred to STS.

Also, it is shown that the worst case in the performance of the satellite system happens when the peak of traffic load lies just under one of the satellite. In addition, a modified power control method which changes the required transmitting power levels, according to the traffic load in coverage area of satellites, is examined and is shown that this method can remedy the performance degradation of the system to some degrees.

Finally, we employed different techniques to improve the performance. The larger difference in throughput between the DTS and STS in non-uniform traffic in case one is that when applying MPC, a higher ratio of γ is needed in order to get the same throughput for DTS and STS. Thus the need for TPC is more essential, since the discrepancy in throughput of the DTS and the STS is more pronounced.

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