As we have seen, multiple-access schemes based on spread-spectrum techniques, especially CDMA, are promising candidates for future LEO satellite communications systems. As already mentioned, the reason that the wide bandwidth of spread-spectrum waveforms introduces frequency diversity, which can mitigate multipath and interference [1–6]. In addition, with CDMA it is possible to use the same carrier frequency in all service areas, so when a user leaves the service area of a satellite and enters the next area, switching the user’s connection to a new satellite, a process referred to as hand-off, requires a simpler process than the parallel process in TDMA or FDMA. In this chapter, CDMA will be employed on the uplinks (i.e., users-to-satellites links) of our LEO satellite system, and performance of that scheme in uniform and nonuniform traffic distributions will be evaluated. In some literature, uplink is referred to as reverse link; throughout this text, however, we
refer to it as uplink, because that name better indicates the physical direction of the link.

This chapter investigates the performance of a LEO satellite system for two types of traffic information scenarios. The first scenario is a general CDMA system designed to service analog-type terminals [7,8]. After that, we discuss the performance of CDMA in a LEO satellite system when an integrated voice/data traffic scenario is involved [9]. Examination of the first situation is made analytically, whereas the second system is described by simulation. Future LEO satellite-based PCNs are expected to support different types of information; hence, such an integrated information analysis is necessary.

This chapter will show that in analog systems 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. As a result of that phenomenon, the performance of each user becomes a variable of location and the satellite with which the user is connected, not a proper feature in a communications system. To make the dependency weaker, a traffic assignment scheme, which makes the traffic load of the satellite over the dense traffic area smaller, is proposed and its performance improvement is estimated.

In the integrated traffic scenario, according to the simulation results, traffic nonuniformity affects the performance of the system almost in the same manner as for nonintegrated systems. It will be shown that the ratio of the population of data users to that of voice users has little effect on the performance of system. By modeling the satellite system during the movement of the satellites, the change in signal quality during peak traffic load in their route is also determined, and the worst case from the viewpoint of performance is derived.

The chapter is organized as follows. Section 3.1 considers an analog scenario. The mathematical model for the traffic nonuniformity and the calculations on SIR with a number of numerical examples are given in that section. Through the examples, we find the situation in which the traffic nonuniformity has the largest effect on the performance of the system and name it the worst case. At the end of the section, we propose a traffic assignment control method, which equalizes the traffic loads of
service areas to some degree, and investigate its capability with numerical examples.

Section 3.2 continues the discussion of CDMA for an integrated voice/data scenario. We first explain the integrated voice/data system and the extension of the traffic model. The calculation of SIR and simulation environment also are given in this section. The performance of the system in both situations of the worst case and during the movement of the satellites is evaluated. The section finishes by proposing a modified power control scheme, very similar to the traffic assignment control scheme explained in Section 3.1.

### 3.1 Performance evaluation of analog systems

In this section, a general direct-sequence CDMA scheme is employed on the uplinks of the LEO satellite system, and its performance in uniform and nonuniform traffic distributions are discussed by the measure of SIR. Because in CDMA all users send their information with the same carrier frequency, the dominant factor that affects the signal quality is the interference from other users, rather than simple background (mostly thermal) noise, as in channel-assignment schemes such as TDMA or FDMA. Therefore, we use the expression “signal-to-interference” ratio instead of the conventional “signal-to-noise” ratio, although the background thermal noise is considered part of total interference.

We introduce the traffic model and then derive the SIR at individual satellites. In considering the movement of the satellites, we discuss the effect of relative locations of the satellites to the peak of the traffic load on SIR. We also investigate the performance variation according to the degree of the traffic nonuniformity.

#### 3.1.1 Traffic modeling

Section 2.2 explained the existence of the traffic-nonuniformity problem in LEO satellite systems. According to the conclusions given there, we can expect the distribution of communications traffic loads on the globe to be a combination of heavily populated areas, lightly populated areas, and areas with very small population [10]. To model such geographic traffic nonuniformity mathematically, there might be different kinds of
assumptions; for example, simply a rectangular pulse-shape traffic model in which the levels of the pulses show the levels of the traffic load at given parts of the globe. Another simple model may be a triangular-pulse model, in which the peaks of the triangles show densely populated areas. It seems that such a triangular model is much more realistic than the rectangular one, because sharp changes in the levels of the traffic load or in the number of users are not the case in the real world. The linear changes in the level of traffic that appear in the triangular model also seem not very realistic. If we accept having peaks of communication traffic load in some parts of the globe, much more realistic changes in the level of the traffic loads can be thought as normal or Gaussian shaped. These three possible shapes for a traffic model are shown in Figure 3.1. From the viewpoint of the total traffic load in a large-enough area, the triangular and normal models can offer the same results; however, from the viewpoint of the traffic loads in small areas, the normal model seems more familiar.

Another viewpoint in establishing a traffic model is its degree of simplicity during mathematical interpolations. Although a complex multipeak traffic model may show the real traffic-load distribution of the globe, the mathematics due to such model become complicated. A simpler single-peak traffic model can exhibit the most important effects of the traffic nonuniformity on the performance of a system. Moreover,
we can have a clearer discussion of the reason(s) for such effects and on
the method(s) that can weaken those effects. With such an idea, we
consider an area on the Earth equal in size to the summation of the
interference areas of three successive satellites in the same orbit with a
single peak of traffic load, as mentioned in Section 2.3.

Consider the circular LEO satellite system model explained in
Section 2.3 and repeated here for convenience in Figure 3.2. To analyze
the influence of the geographical nonuniformity of the traffic correspond-
ing to the distribution of the users of the satellite system, total traffic load
is modeled by a single-peak normal distribution of the population of the
users in the observed area. The location of that single peak of the traffic
load is assumed as the origin, and the location of any user is calculated
according to this origin. The distribution of the users is assumed to have
the following function [8,9]:

\[
\rho(\alpha) = \frac{h}{\theta_{\min}} \left( \frac{\alpha}{\theta_{\min}} \right) - \frac{\beta_i}{\theta_{\min}} + \beta_{i+1}
\]

\[
\alpha = 0
\]

\[
(\text{Origin})
\]

\[
\text{Center of the Earth}
\]

\[
\text{SAT } i
\]

\[
\text{SAT } i - 1
\]

\[
\text{SAT } i + 1
\]

\[
\theta_{\min}
\]

\[
h
\]

\[
R
\]

\[
\alpha
\]

\[
\beta_i
\]

\[
\beta_{i-1}
\]

\[
\beta_{i+1}
\]

\[
\rho(\alpha)
\]

\[
\text{Coverage Area}
\]

\[
\text{Interference Area}
\]

\[
\text{Figure 3.2} \quad \text{Typical shape of the normal nonuniform traffic model used in analysis.}
\]
where $\alpha$ is the angular distance of any user from the origin measured by the angle at the center of the Earth in radians, $\omega$ is a parameter representing the degree of uniformity of traffic, and $A$ is a factor related to the total traffic load (total number of users) in the observed area (this factor will be explained later). With that definition, the traffic nonuniformity is expressed by $\omega$; that is, larger values of $\omega$ expand the normal function more and an infinite value of $\omega$ realizes a uniform traffic distribution. A typical shape of $p(\alpha)$ is shown in Figure 3.2.

To investigate the effect of traffic nonuniformity with this model, the total traffic load for the satellites under consideration should be kept fixed when $\omega$ or the number of satellites in each orbit, $N_s$, changes. For that purpose, 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

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

(3.2)

The ratio of the traffic loads of two adjacent natural service areas, when the peak of traffic is located at the origin, as shown in Figure 3.2, can be found from

$$\text{traffic ratio} = \frac{\int_{-\pi/3N_s}^{\pi/3N_s} p(\alpha) d\alpha}{\int_{-\pi/N_s}^{\pi/N_s} p(\alpha) d\alpha}$$

(3.3)

The traffic ratio for different numbers of satellites in an orbit, $N_s$, is shown in Figure 3.3.

### 3.1.2 SIR: The measure of performance

#### 3.1.2.1 CDMA as multiple-access method and SIR calculations

This section evaluates the effects of traffic nonuniformity on the performance of the uplinks of a LEO satellite system. Direct-sequence CDMA is utilized as the multiple-access scheme in this direction.
An important issue in multiple-accessing methods based on CDMA is the equalization of powers of receiving signals at each base station, referred to as reverse link power control [11–13]. With that control, the signals of all users reach the base stations with the same power regardless of their distances to the base stations. Without such control, the probability of successful transmission for users near the base stations is much higher than the ones far from the base stations. This phenomenon is referred to as the near-far problem, and it is said that power control is an effective method to remedy the problem. Moreover, it is said that power control can realize equal channel sharing and maximize the capacity of the CDMA.

Figure 3.3 Ratio of traffic in the service area of two adjacent satellites (the first one is over the traffic peak) for different number of satellites in one orbit.
In a LEO satellite system, this requirement can be satisfied if each Earth station has the knowledge of the required transmitting power levels to all visible satellites, by measuring the power of pilot signals received from the satellites [11]. Therefore, we assume that each satellite continuously transmits a pilot signal whose power level is known by all users. Comparing the received power level of this pilot signal with the referenced one, users can calculate their distance to all visible satellites and also can transmit their information with controlled power to allow reception at the connecting satellite with equal power to other users connecting to that satellite.

In the case of LEO satellite systems compared with terrestrial systems, because of relatively small effects of shadowing and Rayleigh fading, it is reasonable to assume that the radio signal power is attenuated in proportion to the second power of propagation distance [14,15]. (Shadowing and Rayleigh fading problems in the case of LEO satellite systems are discussed in Chapter 6.) Under that assumption, when the location of the Earth station (equipped with isotropic antenna) is \( \alpha \), the required transmitting power level to the \( i \)th satellite equals

\[
P_i(\alpha) = \kappa S_i \cdot l_i^2(\alpha) \quad i = 1, 2, \ldots, N_s \quad (3.4)
\]

where \( S_i \) is the designed receiving power level of the signals at the \( i \)th satellite, and \( l_i(\alpha) \) is the distance (measured in meters) between the \( i \)th satellite and the Earth station at the angular offset \( \alpha \). \( \kappa \) is a constant with the dimension of \( m^2 \), but, as will be seen later, in final equations of SIR the ratio of powers rather than their absolute values are involved. Then \( \kappa \) can be assumed as unity, and hence we neglect it in the next equation for simplicity. (Note that if the background noise level is negligible compared to the level of multiple-access interference, \( \kappa \) can be completely neglected in the evaluation of SIR; however, if we consider the background noise as a part of total interference, \( \kappa \) cannot be neglected.)

At the moment, we assume different power levels at satellites (e.g., \( S_i \) for the \( i \)th one) and derive a general form of SIR equations. However, by assuming \( S_i = S \) for all \( i \), an equal power scenario can be simply derived.

If the location of the \( i \)th satellite is \( \beta_i \), the distance \( l_i(\alpha) \) becomes
where $R$ is the average radius of the Earth, about 6,378 km, and $h$ is the altitude of the satellites. When two or more satellites are visible at the same time for an Earth station, the user compares the required transmitting power to each of them and connects to the satellite that requires lower power. Note that, at the instant shown in Figure 3.2, $\beta_i$ is equal to zero, while the other two satellites have nonzero (positive and negative) values equal to the separation of the satellites.

When the uplink is designed to operate at an adequate power level, in CDMA systems, the effect of thermal noise generally is smaller than that of interference; hence, SIR is a proper measure of the system performance. Note that there is a simple relation between SIR and $E_b/N_0$; the ratio of signal energy per bit to interference plus noise energy (which sometimes is referred to as required SIR to achieve a specified error rate performance) is as follows [15]:

$$\text{SIR} = \left( \frac{E_b}{N_0} \right) \left( \frac{2R_b}{W_{ss}} \right)$$

where $R_b$ is the data bit rate, and $W_{ss}$ is the spread-spectrum bandwidth. Then one can derive the error rate performance easily.

For a given user of the $i$th satellite, the transmitted signal arrives at that satellite with the power $S_i$, and signals of all other simultaneous transmissions from the users located in the service area and interference area of that satellite appear as additive interference. Thus, the SIR at the $i$th satellite becomes

$$\text{SIR}_i = \frac{S_i}{I_i}$$

where $I_i$ is the total power of the interference at the $i$th satellite, described as
\[ I_i = \int p(\alpha) \cdot \min[P_i(\alpha)] \cdot l_i^{-2}(\alpha) d\alpha, \quad i = 1, 2, \ldots, N_s \quad (3.8) \]

where \( \min[x] \) is the minimum value of \( x \) and describes the connection of any user to the satellite that requires the lowest transmitting power. The interval of the integration in (3.8) should be determined for each area separately, as discussed next.

As a result of sphericity of the Earth, if the angular distance between a satellite and a user is larger than \( \beta_i \), the transmitting signal of that user does not reach that satellite, where

\[ \beta_i = \cos^{-1}\left(\frac{R}{R + h}\right) \quad (3.9) \]

is the interference limit angle. The interference limits are shown in Figure 3.2 for the \( i \)th satellite. Let all \( N_s \) satellites on an orbit request the same required transmitting powers, and thus users connect to the nearest satellite: natural service area configuration will be realized. In that case, from (3.8), the interference reached at the \( i \)th satellite at \( \beta_i \) can be determined from

\[ I_i = \int_{\beta_i - \pi/N_s}^{\beta_i + \pi/N_s} p(\alpha) d\alpha + S_i - 1 \int_{\beta_i}^{\beta_i - \pi/N_s} p(\alpha) l_i^{-2}(\alpha) d\alpha + S_i + 1 \int_{\beta_i + \pi/N_s}^{\beta_i + \pi/N_s + 1} p(\alpha) l_{i+1}^{-2}(\alpha) d\alpha \quad (3.10) \]

where \( S_i, S_i - 1, \) and \( S_i + 1 \) are the designed receiving signal powers at the \( i \)th and its adjacent satellites, which are now assumed to be the same values. The first term in (3.10) is the interference reached from the users located in the service area of the \( i \)th satellite; however, two other terms show the interferences from the users of neighboring satellites in the interference area of the \( i \)th satellite. If the designed receiving power differs for each satellite, the service area and the interference area will be
different from those in (3.10). (The performance control that results from changing these powers is discussed in Section 3.1.3.)

3.1.2.2 The effect of satellite position on SIR
Because in a LEO satellite system the satellites are on nongeostationary orbits, they are in continuous motion, with relatively high ground speed, which is determined according to the altitude of the satellites and which was shown in Section 1.2 [16]. Here we examine the changes in SIR characteristics according to the travel of satellites, assuming that a non-uniform traffic distribution as (3.1), with a predefined value of $\omega$ in a specified area within the satellites’ path, exists. In this analysis, we assume that the satellites are on circular orbits. The circular orbits usually are used in LEO satellite system constellations and simplify the control of the system considerably.

Figure 3.4 shows the changes in the SIR characteristics of two adjacent satellites, the $i$th and the $(i+1)$st ones, as a function of $\beta_i$, that is, the angular position of the $i$th satellite, for typical constellation parameters of $h = 800$ km, $N_s = 11$ [17,18], and $\omega = 0.2$, when $S_i = S$ for all satellites. According to Figure 3.3, in this case, the number of users of the $i$th satellite is about twice those of its neighbor satellites, the $(i-1)$st and the $(i+1)$st ones. Assuming counterclockwise rotation of the satellites, $\beta_i = -2\pi / N_s$ is the instant when the $i$th satellite is far from the peak of the traffic by equal angle as the separation of the satellites, $2\pi / N_s$, and the $(i+1)$st one is just over this peak. They rotate in their circular orbit with a constant angular velocity, until the $i$th satellite reaches a symmetrical position to the traffic peak as the start point, that is, $\beta_i = 2\pi / N_s$. At the halfway point, when $\beta_i = 0$, the $i$th satellite is located just above the traffic peak. If we define the worst situation of system performance as the case when the signal quality at a satellite has the lowest value, from this calculation, this is the case where the peak of the traffic load lies just under one of the satellites, that is, $\beta_i = 0$ and $\beta_i = -2\pi / N_s$. Figure 3.4 shows that at those points the satellite above traffic peak has low signal quality; however, its neighbor satellite has a large value of SIR.

An important point drawn from Figure 3.4 is that there are large variations in signal quality at each satellite when a nonuniform distribution of users exists. That phenomenon may be acceptable while the level of SIR is higher than a threshold that ensures an acceptable error rate;
however, it means that the users of the communications system have to accept large tolerances in their service quality performance, even during short periods of time, which is not good behavior for a reliable communications system.

3.1.2.3 SIR and Traffic Nonuniformity

According to the definition of the worst case given in the Subsection 3.1.2.2, here we examine how the degree of traffic nonuniformity affects the performance of the system. In the case where one satellite, say, the ith one, is above the traffic peak, SIR at the ith satellite and at its neighbor, the (i + 1)st satellite, become

**Figure 3.4** Changes in SIR characteristics of two neighboring satellites as a function of their angular locations.
\[
SIR_i = \frac{1}{2} \left[ \int_0^{\pi/N_s} p(\alpha) d\alpha + \int_{\pi/N_s}^{\beta_1} p(\alpha) \cdot l_i^2 + 1(\alpha) \cdot l_i^{-2}(\alpha) d\alpha \right]
\]

\[
SIR_i + 1 = \frac{1}{2} \left[ \int_0^{3\pi/N_s} p(\alpha) d\alpha + \int_{\pi/N_s}^{3\pi/N_s} p(\alpha) l_i^2(\alpha) l_i^{-2}(\alpha) d\alpha + \int_{2\pi/N_s - \beta_1}^{2\pi/N_s} p(\alpha) l_i^2(\alpha) l_i^{-2}(\alpha) d\alpha \right]
\]

again with the assumption that the satellites have the same designed receiving power levels, S. For the sake of simplicity, let us name the ith satellite above the peak of the traffic with a large number of users as the dense traffic satellite (DTS) and its neighbors with smaller numbers of users as sparse traffic satellites (STSSs). Figure 3.5 shows the SIR characteristics at the DTS and each STS as a function of traffic nonuniformity for \(h = 800\) km and \(N_s = 11\). As can be seen in the figure, in large traffic nonuniformity (i.e., small \(\omega\)), there are large differences between the signal qualities at the satellites, one above the dense traffic area and another above the area with sparse traffic. Also, the result of the case when more satellites exist in each orbit is shown in Figure 3.6. When the number of satellites in each orbit is increased, the service area and hence the number of users connecting to each satellite is decreased. It seems that the increase in the number of satellites can improve the performance of satellites with high communications traffic; although such methods increase the total cost of the satellite system. However, from Figure 3.6, we can conclude that the increase in the number of satellites gives negligible performance improvement for the DTS when the degree of traffic nonuniformity is large. For the case in which the number of satellites is 11 but the satellites have a higher altitude (i.e., \(h = 1,500\) km), almost the same result as Figure 3.6 can be achieved; thus, the same kind of conclusion on the effect of the altitude on SIR can be drawn.
at DTS

at STS

$B = 100$

$h = 800 \text{ km}$

$N_s = 11$

Signal-to-Interference Ratio (dB)

Measure of Uniformity in Traffic, $\omega$

Figure 3.5. SIR characteristics at DTS and STS with the same required transmitting power levels, for $N_s = 11$.

$B = 100$

$h = 800 \text{ km}$

$N_s = 15$

Signal-to-Interference Ratio (dB)

Measure of Uniformity in Traffic, $\omega$

Figure 3.6. SIR characteristics at DTS and STS with the same required transmitting power levels, for $N_s = 15$. 

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As mentioned in Chapter 2, in the LEO satellite systems, some regions are in the coverage area of two or more satellites at the same time. Those areas, conventionally referred to as double coverage areas, are the result of the altitude and the number of satellites in each orbit. In a system with satellites higher in altitude or with a larger number of satellites in each orbit, the portion of the users located in double coverage areas becomes larger; hence, we observe some performance improvement. Note that a user in a double coverage area has the choice to connect to any the satellites that cover the area, if the protocol used in the system permits such selection to its users. The existence of such double coverage areas in LEO satellite systems suggests that there should be some flexibility in the definition of a service area other than natural method. It also suggests the possibility of performance improvement with other methods of assignment to users to satellites.

3.1.3 Traffic assignment control

3.1.3.1 Optimum control

Subsection 3.1.2 assumed that the required receiving powers of all satellites are the same and, hence, that service areas of all satellites are equal in size, referred to as 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. There needs to be a method that can change the size of service areas according to the offered traffic loads. As an example of such a method, 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. Obviously, in the case of uniform traffic, the size of service areas would be returned to the areas that appear in a natural service area configuration.

In this manner, let us first assume that the peak of the traffic is located under the ith 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 (the 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 DTS. This method is realized by changing the ratio of designed receiving power of the DTS to that of its neighbors on both sides, say, increasing the ratio \( \gamma = S_i/S_{i-1} = S_i/S_{i+1} \) (which was unity in the last section). Each satellite counts the number of its users in a given period of time and by the means of intersatellite links, for example, the numbers of users of individual satellites are compared with each other, and then the proper ratio of \( \gamma \) in each area for the next period of time is selected and established. Figure 3.7 shows an example of the change in SIR as a function of the ratio \( \gamma \) in a relatively large traffic nonuniformity situation of \( \omega = 0.2 \). By increasing the ratio \( \gamma \) from 1, the number of users of the DTS and STSs is increased and decreased, respectively. Therefore, the performance of the DTS gradually improves and those of STSs degrade. As shown in Figure 3.7, as the ratio of the designed receiving powers, \( \gamma \), increases, the SIR curves reach to a cross-point. Increasing the powers ratio more, makes the performances

![Figure 3.7](image-url)
of STSs worse than that of the DTS. From the viewpoint of service quality for a given user, it is desirable to establish the same signal qualities when the connecting satellite of a given user is changed. Therefore, if we define the optimum control as one that makes all the satellites have the same SIR characteristics, the cross-point exhibits the optimum control.

3.1.3.2 Measuring the optimum capability
Taking appropriate powers ratios that achieve the optimum control for each traffic nonuniformity situation (i.e., for each $\omega$) gives the SIR characteristics shown in Figure 3.8 and Figure 3.9 for $N_s = 11$ and $N_s = 19$, respectively. These figures show the changes in SIR characteristics at DTS and STS before and after applying the control scheme, where the solid lines show the SIR at both the DTS and the STS when optimum control

![Figure 3.8](image)

**Figure 3.8** Effect of controlling the required transmitting powers of satellites in its optimum case, for $N_s = 11$. 

- **Optimum control**
- **at DTS, equal required powers**
- **at STS, equal required powers**

$B = 100$
$h = 800 \text{ km}$
$N_s = 11$
is employed. As the figures illustrate, by applying this method, we are able to improve the performance of the DTS, that is, the satellite with heavy traffic load. There are two reasons for that improvement. First, by increasing the required transmitting power of the DTS, the service area of the DTS becomes smaller, and thus interference from its own users decreases. Second, lower transmitting powers of the users of STSs make the interference power from their users smaller. The latter occurs for every case, and if the double coverage area becomes large, the former effect also can be expected. Thus, as in the case in Figure 3.9, in which a larger number of satellites in each orbit is considered and then all areas on the ground are covered by at least two satellites, it is possible to improve the performance of the DTS even for a very small value of $\omega$, such as 0.1.

**Figure 3.9** Effect of controlling the required transmitting powers of satellites in its optimum case, for $N_s = 19$. 
Let us now change the relative position of satellites to the peak of the traffic load or the origin. Figure 3.10 shows another example, where the peak of the traffic is not just under one satellite: the \(i\)th and the \((i + 1)\)st satellites are at \(\beta_i = -\frac{1}{4}(2\pi/N_s)\) and \(\beta_{i+1} = \frac{3}{4}(2\pi/N_s)\), respectively. In this case, even with the small double coverage area as occurred in the case of \(N_s = 11\) and with small \(\omega\), the optimum control can improve the performance of the satellite that has the larger traffic load. It should be mentioned that any improvement in performance of a satellite requires a large degradation in performance of its neighbor satellites; however, with a trade-off between the achievable performance improvement and the related numbers of users of the satellites, the method becomes more attractive. That is, with this method, we improve the signal qualities for

![Figure 3.10](image)

**Figure 3.10**  Effect of controlling the required transmitting powers of satellites in its optimum case, for \(N_s = 11\) and different satellite positions.
a large population of users at the expense of degrading the performance of a smaller population of users. The important point is that we can maintain the performance for all users at an acceptable level; establishing the same signal quality at all service areas is much easier.

3.2 Performance of integrated voice/data systems

In Section 3.1, the effect of traffic nonuniformity on the signal quality and performance of a LEO satellite communications system was determined. That analysis made no distinctions on the information type. In this section, we plan to examine the problem of traffic nonuniformity in an integrated voice/data scenario, which is of much interest in future PCNs [19,20].

To follow the calculations given in Section 3.1, in this section we determine the SIR characteristics at LEO satellites through simulation in two steps [9]. First, the case in which the satellites are assumed to be fixed with respect to the heavy traffic area in a short period of time is considered, and the relation between their performances and the intensity of traffic nonuniformity is estimated. After that, the investigation is generalized to the real case, that is, during the movement of satellites. Although the main purpose here is the estimation of the performance of LEO systems in nonuniform traffic situations, a modified power control method with the aim of remedying the effects of traffic nonuniformity also are discussed.

3.2.1 System considerations

Consider again the LEO satellite system model explained in Section 3.1.1. For such a system, we consider the effects of traffic nonuniformity on the performance of the system according to its uplinks. In this direction for multiple accessing by users to the satellite channel to transmit their packets, a packet CDMA scheme is used. We assume a simple CDMA protocol, in which all user information is transmitted in the form of a sequence of fixed-length packets on the channel. Access to the satellite channel is completely unconstrained (i.e., random access), so that any given users begin transmission whenever they are ready to
send data. Moreover, assume there is no restriction on the transmitted-
information type, which can be either voice or data. Data traffic is sent
out as a single contiguous burst at the available peak CDMA channel
speed, as in Aloha channels [5,21], packets not received successfully at
the satellite are retransmitted repeatedly (after appropriate random
delay) until an acknowledgment eventually is received. On the other
hand, constantly generated bit-stream traffic such as voice is sent as a
periodic sequence of packets with the duty cycle adjusted to match the
requirements of the constant bit-rate source. Stream traffic normally
cannot be retransmitted, so the receiver has to accept the packet loss rate
caused by multiuser interference. More details about realizing this kind
of mixed voice/data traffic scenario can be found in some papers (e.g.,
see [19,20,22,23]) and explained in the following.

In CDMA, in contrast to circuit-switching methods, integration of
circuit-mode and packet-mode traffic requires no special protocol struc-
ture. On the other hand, in CDMA, users’ transmitter powers should be
controlled in such a manner that the received powers at the satellite
become constant, avoiding the inbound channel receiver by close-in
transmitters. As mentioned, in LEO satellite systems after the signal at
the satellite is despreaded, all the simultaneous transmissions from the
users located in the interference area of the satellite appear as additive
interference. In this section, it is assumed that this kind of power control
has been perfectly employed. It also is assumed that the uplink is designed
to operate at an adequate power level, so that thermal noise effects need
not be considered in the capacity and performance model.

Voice and data messages are formatted into packets as illustrated in
Figure 3.11. As can be seen in the figure, each voice packet contains, in
addition to its information bits, a synchronization preamble, network
header, and bit error correcting code. The continuous bit stream of voice
is broken up into periodically spaced packets, each with header, synchro-
nization and error correction overheads. Here, it is assumed briefly that
the channel transmission speed, $R_t$, exceeds the voice encoder bit rate,
$R_v$; hence, the required duty cycle for transmission will be about $R_v / R_t$.
The actual packet size depends on which error correction method has
been used. For example, with Bose-Chaudhuri-Hocquenghem (BCH) cod-
ing, which is capable of correcting $n$ bits of error, the packet size, $L$, and
the number of the bits of information, including the network header,
residing in data field, \( N \), satisfies the relation of \( N = L - n \log_2 L \) \([15,22]\), where \( n \log_2 L \) gives the number of bits of the error correction field of the transmitting packet.

In the case of data packet transmission, because the data message is transmitted as a contiguous sequence of \( L \) bit packets, the header and the synchronization bits are necessary to transmit only at the beginning of the messages. Therefore, in this case, only the data field of the first packet contains the network header bits, and, similar to voice packets, all the data fields of the packets have \( N \) bits of data. Unless the acknowledge signal for correct reception of entire packets of message is received by the user, a data message is assumed to be in error; hence, after an

---

**Figure 3.11** Formatting of (a) voice and (b) data packets for transmission on uplinks.
appropriate time-out, an Aloha-type retransmission procedure is executed by the transmitter. This procedure executes until the message is successfully received and acknowledged by the connected satellite.

Because the connection to LEO satellites for any ground user is temporary due to the relative movement of satellites, if during the transmission of packets or before receiving acknowledgment the user is forced to change connection to a new satellite, the information on the past connection is forwarded to the new satellite. After that, the new satellite should handle the process of transferring the user’s packet from the old satellite or the transmission of an acknowledgment packet to the user. Such a mechanism should be prepared in the hand-off process. In the case of satellite systems with intersatellite links, the information can be easily exchanged via those links. In systems without intersatellite links, the information might be exchanged via ground gateways.

3.2.2 Extension of the traffic model

To apply the calculations given in Section 3.1 to an integrated voice/data scenario, we extend the traffic model of the system, keeping the nonuniform distribution of the users same as before. The population of the users is divided into two sets: voice users, \( N_v(t) \), and interactive data users, \( N_d(t) \), where the subscript \( i \) denotes their relation to the \( i \)th satellite, measured at the time of process, \( t \). Each user lies in only one of these two sets, not in both simultaneously. The call (message) generation rates of the users of the two sets are \( \lambda_v \) (calls/s/user) for voice users and \( \lambda_d \) (messages/s/user) for data users, both with exponential interarrival time and independent of the satellite to which they connect. At any instant, a user is assumed to be in only one of two states, that is, busy or idle, according to the involvement in a call (data message) transfer. New arrivals are generated only by the idle users, that is, the users that have completed their calls (i.e., have had their data messages acknowledged). A voice call is assumed to originate a continuous bit stream at a constant rate of \( R_v \) (Kbps), with an average holding time (exponential distribution) of \( T_c \) (s). A data user also is assumed to generate packets from an exponential message length distribution with average length of \( M \) kbit. The information is transmitted on a satellite channel with a transmission speed of \( R_t \) (Kbps).
In the case of data transmission, packets that fail reception at the destination or are received with uncorrectable errors are not acknowledged; hence, with a random delay, they are retransmitted. Retransmitted packets enter the channel at the rate of $\lambda_r$ (messages/s). Because the probability of successful transmission is a function of the packet length, the average length of retransmitted messages differs from M for generated messages and has the value of $M'$; however, its distribution can be assumed to be the same as generated messages, that is, exponential message length. Appropriate selection of retransmission delay in packet CDMA channel using Aloha protocol is an important factor that ensures stability [24]. The equilibrium value of $\lambda_r$, the retransmission packet rate, depends on that delay and also on the rate of collision on the channel. At equilibrium, the total packet inflow and outflow rates should be equal. With that fact and with a procedure similar to the one used in [25], the average length of the retransmitted message $M'$ and the retransmitted packet rate $\lambda_r$ are searched numerically throughout the simulation. Figure 3.12 summarizes the traffic load offered to the channel at the time of process.

To apply the equilibrium condition, it first is necessary to find the probability of packet success. At each satellite and in the absence of thermal noise, the packet error is caused by the interference from all users lying in the interference area of that satellite. At the network analysis level in many spread-spectrum schemes, it is possible to model the channel interference by summing the interference powers and treating the sum as Gaussian noise [26].

---

**Figure 3.12** Offered traffic load to CDMA channel.
When the interference is assumed as Gaussian noise, we can define the equivalent bit energy-to-noise ratio at the ith satellite, $\mu_i$. By this model, the probability of bit error can be approximated by

$$p_e = 0.5 \operatorname{erfc}(\sqrt{\mu_i})$$

(3.13)

where

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-\tau^2} d\tau$$

is the complementary error function. The probability of packet success conditioned on $\mu_i$ is defined as

$$P[\text{success of observed packet } | \mu_i] = s(\mu_i)$$

(3.14)

In spread-spectrum systems, the function $s(\cdot)$ is a smooth function of signal-to-interference ratio. It depends on the adoption of error-correcting code; with powerful error-correction codes, it approaches a step function at some threshold value of SIR at the satellite. The unconditional packet success probability can be calculated by integrating $s(\cdot)$ with respect to the probability density function of $\mu_i$ over all possible values of $\mu_i$.

Because for any value of SIR the probability of packet success and, hence, the expected number of successfully transmitted packets (i.e., throughput) can be evaluated, in this chapter only SIR characteristics as the performance measure of the system are employed. The throughput performance in a more specified system is discussed in Chapter 4.

### 3.2.3 Simulation environment

To estimate the SIR characteristics of a LEO satellite system in the presence of nonuniform and time-dependent traffic, a simulation model based on the traffic model explained in Section 3.2.2 is used. In this model, a typical LEO satellite system with 11 satellites at the altitude of
1,500 km is assumed. In each processing interval period of the simulation program, T, the traffic uniformity parameter $\omega$ changes by the equal steps of $\Delta \omega$ from a maximum value (for nearly uniform traffic load situation) to a minimum value (for a peaked traffic case).

In the simulation model, the multiuser interference power faced by each packet transmitted to the satellite under process is the sum of two parts. The first part is due to the existing packets generated by the users who are in the coverage area of this satellite and who select it as a connecting satellite; the second part is the interference from external users in adjacent satellites’ coverage areas and in line of sight of the satellite under process. Both those interferences are determined as a function of the number of new generated packets, retransmitted packets, and continued packets from last trials, in every trial according to duration time of their connections. Without restricting the discussion to hand-off performance of the system, here we assume that a perfect hand-off procedure for the users has been done; that is, any active user (a user in a busy state) at any instant communicates with the satellite in whose coverage area that user lies that offers minimum required transmitting power to that user. Table 3.1 summarizes the simulation parameters used for evaluation of the performance of our LEO satellite system.

### Table 3.1
Simulation Parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel transmission speed (Kbps)</td>
<td>$R_t$</td>
<td>20</td>
</tr>
<tr>
<td>Voice encoder bit rate (Kbps)</td>
<td>$R_v$</td>
<td>8</td>
</tr>
<tr>
<td>Packet size (bits)</td>
<td>$L$</td>
<td>256</td>
</tr>
<tr>
<td>Max. number of correctable errors per packet (bits)</td>
<td>$n$</td>
<td>10</td>
</tr>
<tr>
<td>Synchronization overhead per packet (bits)</td>
<td>—</td>
<td>10</td>
</tr>
<tr>
<td>Call generation rate of voice users (calls/s/user)</td>
<td>$\lambda_v$</td>
<td>0.0005</td>
</tr>
<tr>
<td>Message generation rate of data users (messages/s/user)</td>
<td>$\lambda_d$</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Although it is said that the spatial reuse of frequencies and voice activity are important points to increase the capacity of CDMA [11], here we do not explicitly include them in the model. The reason for no consideration of voice activity is that the low bit-rate speech coding under consideration here indirectly exploits short-term burst effects to some degree. On the other hand, the efficiency of spatial reuse in CDMA depends on a number of factors, including the multiplexing efficiency of the CDMA code and the modulation technique employed, which are not necessary to express precisely here for the purpose of our comparison.

### 3.2.4 Performance measurement

The calculations given in Section 3.1 can be directly used in the case of integrated voice/data traffics, if we change the distribution function of the packets $p(\alpha)$ in (3.8) to $p_1(\alpha)$, which is the composite distribution of the packets transmitted at the time of process by users, including distributions of new generated packets, retransmitted packets, and continued packets. Then, (3.8) in the case of integrated voice/data traffic situation becomes

$$I_i = \int p_1(\alpha) \cdot \min(P_i(\alpha)) \cdot l_1^{-2}(\alpha) \, d\alpha \quad i = 1, 2, \ldots, N_s \quad (3.15)$$

Similar to Section 3.1, the power of interference at the $i$th satellite, that is, the DTS, is

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average holding time of voice users (minutes)</td>
<td>$T_c$</td>
<td>3</td>
</tr>
<tr>
<td>Average length of message (kbit)</td>
<td>$M$</td>
<td>1</td>
</tr>
<tr>
<td>Retransmission time-out limit (s)</td>
<td>$T_o$</td>
<td>60</td>
</tr>
<tr>
<td>Processing interval time (s)</td>
<td>$T$</td>
<td>10</td>
</tr>
</tbody>
</table>
\[
I_{\text{DTS}} = I_i = 2 \left[ S_i \int_0^{\pi/N_s} p_1(\alpha) \cdot l_i^2(\alpha) \cdot l_i^{-2}(\alpha) d\alpha \\
+ S_i - 1 \int_{\pi/N_s}^{\beta_i} p_1(\alpha) \cdot l_i^2(\alpha) \cdot l_i^{-2}(\alpha) d\alpha \right]
\]

(3.16)

where the first term inside the brackets denotes the (half) interference from the users of the DTS, and the second is that from the users of the STS. In (3.16) we have used the symmetry of the model, which results in the factor of 2 in the equation. Similarly, interference at the STS can be found as

\[
I_{\text{STS}} = I_i - 1 = I_i + 1 \\
= S_i + 1 \int_{\pi/N_s}^{3\pi/N_s} p_1(\alpha) d\alpha + S_i \int_{2\pi/N_s - \beta_i}^{\pi/N_s} p_1(\alpha) l_i^2(\alpha) l_i^{-2}(\alpha) d\alpha \\
+ S_i + 2 \int_{3\pi/N_s}^{2\pi/N_s + \beta_i} p_1(\alpha) l_i^2(\alpha) l_i^{-2}(\alpha) d\alpha
\]

(3.17)

where the first term is the interference from its own users, and the second and third terms are from the users of the satellites on both sides. It should be noted here that since the effects of the other satellites are out of the interference area of the satellite under process, only the first-order neighboring satellites’ users are considered here.

To examine the change in performance of the satellites according to the change in the level of traffic nonuniformity, we change the value of \( \omega \) as a linear function of time during the simulation. According to Figure 3.3, for our traffic model a value of \( \omega = 0.2 \) can show a high nonuniformity distribution and a value of \( \omega > 5 \) can exhibit the uniform distribution. Therefore, in the simulation we consider the change of \( \omega \) in such a margin. The time duration will be 21 minutes, which is derived according to the following consideration.
According to the law of Newton, explained in Section 1.2, the angular velocity, $\omega_{vs}$, of each satellite can be found from

$$\omega_{vs} = \left(\frac{gm}{r^3}\right)^{1/2}$$

(3.18)

where $(gm)^{1/2} = 631.3482 \text{ km}^{3/2}/\text{s}$; $g$ is gravity constant; $m$ is the mass of the Earth; and $r$ is the radius of the satellite orbit, equal to $R + h$. From (3.18) and simple calculations, at the altitude used in our numerical examples, 1,500 km, the period of a complete rotation of the satellites will be about $T_s = 116$ minutes. Because we assume 11 satellites in each circular orbit, a simulation period equal to 21 minutes, that is, $2 \cdot T_s/N_s$, will be a good trial. This period is equal to the time necessary for a satellite to move above the observed area. Figure 3.13 shows the change of $\omega$ according to the time considered in the simulation.

![Figure 3.13](image-url) **Figure 3.13** Relation between the traffic nonuniformity parameter $\omega$ and time during the simulation.
Let us assume that all satellites request the same power levels to the users; thus, \( S_i = S \) for \( i = 1, 2, \ldots, N_s \). Then the assumption of connecting a given Earth station to the lowest required power satellite results in connection to the nearest satellite from that station. Figure 3.14 shows the simulation result of SIR characteristics at both the DTS and the STS for a minimum elevation angle of \( \theta = 10^\circ \), \( h = 1,500 \) km, and \( N_s = 11 \) as a function-processing time, assuming equal populations of voice and data users. In Figure 3.14, the simulation procedure starts at \( t = 0 \) with a large value for \( \omega (\omega > 5) \) as a relatively uniform traffic case and finishes at \( t = 1,260 \) s with a nonuniform peaked traffic (\( \omega = 0.2 \)). From Figure 3.14, we can find large difference between the signal qualities of the DTS and the STS. At high traffic nonuniformity, the SIR of the DTS degrades notably, while the STS marks superfluous quality. We conclude that the large traffic nonuniformity (e.g., \( \omega = 0.2 \)) decreases the system efficiency, significantly. It should be noted that the traffic nonuniformity

![Figure 3.14](image-url)

**Figure 3.14** SIR characteristics at DTS and STS as a function of traffic nonuniformity for equal populations of voice and data users.
of \( \omega = 0.2 \) still is not such large nonuniformity; that is, with respect to Figure 3.3, the ratio of traffic under the DTS to traffic of the STS for this value of \( \omega \) is some value around 10; however, the difference in the SIR performances becomes about 6 dB. Although not shown here, with lower altitudes of satellites, the difference becomes larger (e.g., with \( h = 800 \) km, the difference increases to 13 dB). That large difference is a direct result of the necessity of connecting users to the nearest satellite. In addition, because for the users located in the coverage area of a single satellite there is no other choice for connecting to the other satellites at a given period of time, they have to accept this large multiuser interference and its consequences.

Figures 3.15 and 3.16 show the SIR characteristics at DTS and STS with the same satellite system constellation parameters as Figure 3.14; but for different ratio of population of data users to voice users. Comparing these three figures, it is concluded that by increasing the ratio of the

![Graph showing SIR characteristics at DTS and STS](image.png)

**Figure 3.15** SIR characteristics at DTS and STS as a function of traffic nonuniformity for the ratio of data users to voice users equal to 2.
data users to voice users, keeping the total number of users fixed, the performance of the system even in uniform traffic case degrades. One reason is the retransmission permission given to the data users. However, the ratio of data users to voice users seems not to be considerably effective on large divergence in the characteristics of DTS and STS in nonuniform traffic situations.

3.2.5 Dynamic nonuniform traffic concepts

3.2.5.1 Dynamic features of LEO satellite systems

We have analyzed the effect of traffic nonuniformity in LEO satellite systems by defining a nonuniform traffic probability density function, which had a single peak through the coverage areas of three adjacent satellites. In that analysis, it was assumed that at the instant of the process,
the single peak is just under one of the satellites, making its traffic load dense. That assumption leads the analysis to an investigation of a special situation that may have a particular role at the design procedure time. Although LEO satellites are in continuous motion in their orbits and hence their network topology is highly dynamic, the assumption that the system constellation is static for a small period of time is reasonable; in some papers, this situation is referred to as a quasi-stationary arrangement of the LEO satellites \[27,28\].

More exactly speaking, we should note that the traffic loads in coverage areas of LEO satellites are not only nonuniform but also changing as a function of time, as result of two phenomena. The first one is the natural feature of telecommunications systems, that is, the changes in the total number of the users during different hours in a day at the same area, nonuniformity in call arrival and call arrival density, and so on. The second phenomenon is a direct result of the moving property of LEO satellites, from the viewpoint of a fixed object on the Earth. Speaking more precisely, such an object should not be called fixed, when we remember the high speed of the LEO satellites (e.g., with a typical value of \( h = 1,500 \) km, each LEO satellite has a linear ground speed of about \( 7.1 \) km/s), not comparable to the speed of any known vehicles on the ground or in the air. Therefore, any fixed or mobile stations can be viewed as fixed stations in LEO satellite system. Moreover, in the case of a LEO satellite communication system, the latter phenomenon, that is the change in traffic loads according to the movement of satellites, is rapid, compared with the change related to different hours in a day. Hence it is reasonable to consider that rapid change only in the calculations, made the other constant during measurement. That way, we can apply the same LEO satellite system model. Again, to make the effect of traffic nonuniformity clearer and the calculations simpler, only one orbit of the LEO satellite system is considered.

3.2.5.2 Simulation model
To estimate the changes in characteristics of a LEO satellite communications system employing CDMA when the satellites experience nonuniform traffic distribution during their travels, a modified version of the model in Section 3.2.2 is used. In this model, it is assumed that a nonuniform traffic distribution as (3.1) with a predefined value of \( \omega \) in a
specified area within the satellites’ path exists. Assuming counterclockwise movement of the satellites, two satellites, namely, the ith satellite and its first neighbor satellite to the right, the (i + 1)st satellite, subsequently experience service to the users distributed according to that distribution function. The start point of simulation is when the ith and its first neighbor satellite to the right are in $\alpha = 2\pi/N_s$ and $\alpha = 4\pi/N_s$, respectively, far from the peak of the traffic distribution located at $\alpha = 0$. They rotate in their circular orbit with the constant angular velocity until the ith and its first neighbor satellite to the right reach $\alpha = -2\pi/N_s$ and $\alpha = 0$, respectively. During this period, the ith satellite experiences three specific states of traffic of the STS, the DTS, the STS again, and, of course, their intermediate states, subsequently; however, the first right neighboring satellite before reaching the STS and DTS states starts from a very low traffic state, even less than the STS’s state.

Except for the traffic nonuniformity measure, $\omega$, which is fixed in this simulation model, other parameters in Section 3.2.3, including the simulation period of 21 minutes, stand for this simulation too. Figure 3.17 shows the changes of SIR characteristics at the ith satellite and its first neighbor satellite to the right as a function of the processing time for $\omega = 0.2$, assuming equal populations of voice and data users. As the figure illustrates, even in the case of not-so-large traffic nonuniformity as much as $\omega = 0.2$ (compared with $\omega < 0.1$), in not-so-short periods of time large degradation in SIR at the satellites occurs. That is just when the neighbor satellites, whose facilities generally can be accessed by the users to some degree, have large SIR values. If we again assume that the worst situation in system performance is the case in which the signal quality at a satellite has the lowest value, from the figure this is the case where the peak of the traffic load lies just under one of the satellites; that is, the result derived in Section 3.1 is reconfirmed. Figure 3.14 suggests we apply the facilities of the low-traffic neighbor satellites more optimally.

3.2.5.3 Modified power control scheme

The results shown to this point were based on the assumption that all satellites request the same receiving power levels and thus that users connect to the nearest satellite. That means that without paying attention to the number of simultaneous transmissions and the current packet-loss
rate of the system any user must always connect only to the nearest satellite. However, for users located in areas covered by two satellites, there is the choice to connect to the satellite that has a lower traffic load than the closest satellite, even if its distance is larger. This section considers the scheme in which the required uplink power levels to the satellites are changed according to their traffic loads.

In this method, in each processing interval period, T, the traffic load of all satellites distributed in their coverage area, is measured. According to the current value of the required uplink power level to each satellite, its permitted service area and, consequently, the value of SIR at that satellite also are determined. The required uplink power level to any given satellite is changed if the SIR value at it is less than a lower threshold.

![Figure 3.17](image-url)

**Figure 3.17** Changes in SIR characteristics at the main satellite and its first neighbor satellite to the right as a function of processing time with equal required transmitting power levels.
level and at its neighbor satellite is more than an upper threshold level, or vice versa. The change is performed according to the ratio of the traffic loads of that satellite and its neighbors adaptively and is reported to other satellites through the intersatellite network, for example. Because the users located in the coverage area of each satellite and out of its double coverage areas have to connect to that satellite only, the maximum change in required uplink power level to each satellite is limited to the point where that change can affect to the decision of the users in double coverage areas. Any further changes in uplink power levels will only decrease the performance of both light and heavy traffic satellites.

By applying this method, the required uplink power levels to the satellites with heavier traffic load become larger; on the other hand, the required uplink power levels of light-traffic ones decrease. That results in a decrease in the service area of the satellite with the higher traffic load. With the same parameters as in Subsection 3.2.5.2, Figure 3.18 shows

![Figure 3.18](image_url)

**Figure 3.18** Changes in SIR characteristics at the main satellite and its first neighbor satellite to the right as a function of processing time after applying the modified power control scheme.
the simulation results the same as Figure 3.17, hereafter applying the above explained modified power control method. For this case, it is assumed as an example that the upper and lower threshold levels are $-23.0$ and $-24.5$ dB, respectively.

Although the performance improvement due to the modified power control is not well exhibited in Figure 3.18, the method can equalize the traffic load offered to each satellite to some degree. If more satellites exist in each orbit or if their height becomes higher, we can expect that the method gives more performance improvement. Chapter 5 discusses this method in more detail and shows that the method can improve the performance of LEO satellite systems that suffer from geographic traffic nonuniformity.

### 3.3 Summary

This chapter modeled the situation of nonuniformity in traffic loads of a LEO satellite–based communications system and investigated the performance of the system with a CDMA scheme by the measure of signal-to-interference ratio (SIR). Both analog and integrated voice/data traffic scenarios were considered. With the same required uplink power levels requested by the satellites, it was shown that the performance of the LEO satellite system, measured by the value of SIR at each satellite, degrades as a direct result of nonuniformity in distribution of users. It also was shown that the worst case in the performance of the satellite system happens when the peak of the traffic load lies just under one of the satellites.

To have better characteristics near to the case where the traffic distribution is uniform, new traffic assignment and modified power control schemes have been proposed for analog and integrated voice/data systems, respectively, in which weights are given to the required receiving powers of the satellites. By applying those schemes, it has been shown that in nonuniform traffic situations it is possible to improve the performance of the dense-traffic satellite at the expense of degrading the superfluous performance of its neighboring satellites, which have lighter traffic loads. If either the number of satellites on each orbit or the altitude of the satellites becomes higher, we can expect the schemes to exhibit better performances.
References


