Comparison of CDMA and FDMA/TDMA in non-GEO Satellite Systems

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Abstract— **We compare CDMA and FDMA (or TDMA) schemes in multi-beam non-geostationary satellite systems, taking the effects of antenna patterns on inter-cell interference into consideration. The maximum acceptable number of users per cell in uplink is employed as a measure of the system capacity. We have found that in FDMA (or TDMA) systems the maximum acceptable number of users varies according to the altitude of the satellites, while the performance is insensitive to the altitude in CDMA systems. For this reason, the altitude of the satellites is found to be an important factor for selecting multiple access schemes in non-geostationary satellite systems.**

I. Introduction

In cellular communication systems, the choice of multiple access schemes is one of the most important issues, because it determines the acceptable number of users. We have compared the multiple access schemes, CDMA and FDMA (or TDMA), in the satellite communication systems.

Previous studies on terrestrial systems have shown that CDMA can offer the larger number of users than FDMA or TDMA [1]-[3]. However, it is not guaranteed that this conclusion stands for satellite systems, because the mechanism of the interference in satellite systems is different from that in terrestrial systems.

In terrestrial systems, every cell has a base station at its center. In uplink, the power of interfering signals from other users is mainly dominated by the propagation loss which is often modeled by the fourth power of the propagation distance. On the contrary in satellite systems, base stations are loaded into the same satellite and their corresponding cells are formed by multi-beams of the satellite. The interference power from other users depends on the radiation pattern of the beams.

Some studies have been made on the comparison between CDMA and FDMA (or TDMA) in satellite communication systems. Gilhousen et al. showed that CDMA systems are superior to FDMA systems [4]. However, they did not consider the interference from adjacent cells and the radiation pattern of the spot-beam antenna. In [5], Monsen drew the completely contrary conclusion, i.e., FDMA or TDMA accepts the larger number of users than CDMA if the amount of the interference from adjacent cells is taken into account. In this study, however, the channel reuse patterns are not analyzed for FDMA or TDMA. Fu et al. proposed the comprehensive model and calculated the interference accurately in [6]. They also showed that the number of FDMA or TDMA is comparable to that of CDMA. In their study, however, the discussion is made only for low earth orbital satellite systems with the particular beam pattern and only for the cell located at the subsatellite point.

Following these studies, in this manuscript, CDMA and FDMA (or TDMA) are compared for non-GEO satellite systems with the consideration of the effects of beams and the location of cells. As a measure of the system performance, the maximum acceptable number of users is employed.

This paper is organized as follows. In Sect. 2, the system model is presented and in Sect. 3 the acceptable maximum number of users is derived for CDMA and FDMA (or TDMA) systems. Sections 4 and 5 give numerical results and conclusions of this manuscript.

II. System Model

A. Overall Arrangement

In order to make our discussion simple, we use the two-dimensional model shown in Fig. 1. In this model, the earth is expressed by the circle with the radius R_e. The satellites are equally spaced with the altitude of H [km]. Let us focus on one of these satellite and name it as the reference satellite. The analysis of the system capacity is done on this satellite considering the interference from the user of its adjacent satellites in both side.

The area where a satellite serves is called the service area of the satellite. It is assumed that the service areas of satellites do not overlap. The elevation angle at the edge of its service area, α, is called the minimum elevation angle of this system.

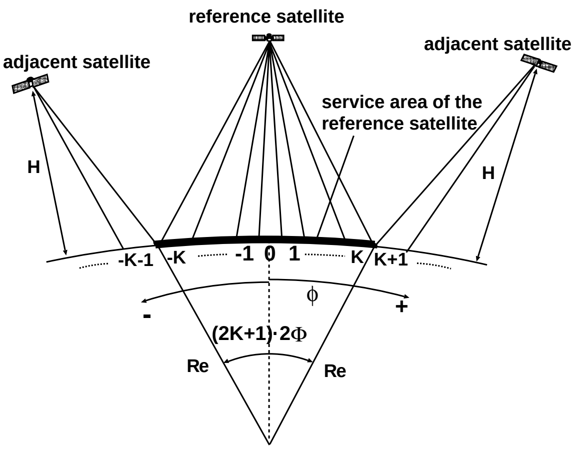

Fig. 1. The model of the satellite system.

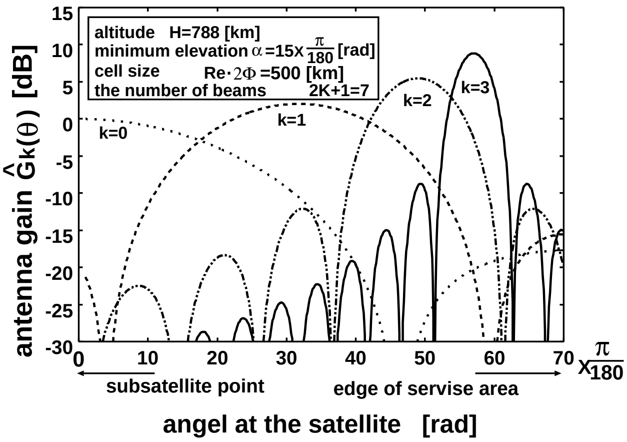

Fig. 2. An example of beam arrangement.

Each satellite has symmetrically arranged $2K+1$ spot-beams to illuminate its service area. The beams are numbered clockwise and the beam to the subsatellite point of the reference satellite is numbered as the 0-th. Let the location of a user be represented by the central angle of the earth from a subsatellite point of the reference satellite, ϕ.

B. Relation of beams and cells

Each spot-beam forms a cell on a ground. The shapes and arrangement of the spot-beams dominate the location and size of cells. In this manuscript, it is assumed that all cells have the same size with the central angle of the earth 2Φ, and the all beams and cells satisfy the following conditions.

- Adjacent cells do not overlap.
- The adjacent beams have the same gain at the direction of the boundary of the cells.
- At the direction of the boundary of the 0-th cell and its adjacent cells, the gains of the both beams are -3dB than its maximum.
- The center of a beam is directed to the center of its corresponding cell.

C. Radiation Pattern

The radiation pattern of the k-th spot-beam is modeled by that of an aperture antenna [7]:

$$\hat{G}_k(\theta) = G_{0k} \cdot \left[2\frac{J_1(\pi a_k \sin\theta)}{\pi a_k \sin\theta} \right]^2 \qquad (1)$$

where θ is the angle from the center of the beam, $J_1(\ )$ is the Bessel function of the first order, a_k is the ratio of the aperture diameter and the wave length, and G_{0k} is the maximum power gain which is chosen so that the radiation efficiency is 1, i.e.,

$$\frac{1}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \hat{G}_k(\theta)d\theta = 1. \qquad (2)$$

Figure 2 shows an example of the arrangement of the beams, where all beams are normalized by the maximum gain of the 0-th beam.

III. The Maximum Number of Users per Cell

In this manuscript, the maximum acceptable numbers of users in the uplinks of CDMA and FDMA (or TDMA) are compared.

In both schemes, it is assumed that the transmitted power of users is controlled perfectly i.e., the attenuation loss from the user to its own satellite and the antenna gain of its corresponding spot-beam are compensated perfectly. Then, the transmitted power of a user located at the position ϕ in the k-th cell, $P_k(\phi)$, is expressed as [8]

$$P_k(\phi) = \frac{[4\pi d(\phi)]^2}{\lambda^2 G_k(\phi)} S, \qquad (3)$$

where λ is the wave length, $G_k(\phi)$ is the antenna gain of the k-th beam expressed as the function of the position ϕ and S is the nominal received power. The function $d(\phi)$ is the distance from the user at the position ϕ to its corresponding satellite, which is described as:

$$d(\phi) = \begin{cases} d_-(\phi) & \text{if } -3(2K+1)\Phi \le \phi < -(2K+1)\Phi \\ d_0(\phi) & \text{if } |\phi| \le (2K+1)\Phi \\ d_+(\phi) & \text{if } (2K+1)\Phi < \phi \le 3(2K+1)\Phi, \end{cases} \qquad (4)$$

where $d_-(\phi)$ is the distance to the left adjacent satellite, $d_0(\phi)$ is the distance to the reference satellite and $d_+(\phi)$ is the distance to the right adjacent satellite.

A. CDMA

In CDMA systems, all users share a common spectral bandwidth, and the multiple access interference (MAI) dominates the quality of service. Thus, we first derive the interference level of the uplinks in the multi-beam CDMA satellite communication system.

We focus on a user in the k-th ($|k| \leq K$) cell of the reference satellite and derive the interference power from other users in the j-th cell which is expressed as $i_{k,j}$. The interference power can be classified into three types by the location of an interfering user.

When the desired user and the interfering user are in the same cell, under the perfect power control, the interference power from a user at position ϕ in the k-th cell, $i_{k,k}(\phi)$, is given by

$$i_{k,k}(\phi) = S. \tag{5}$$

Next, let us find interference from users in other cells served by the reference satellite, i.e., from the j-th ($j \neq k, |j| \leq K$) cell. As the transmitted power is controlled, the attenuation loss component is compensated. Then the interference power from a user at position ϕ in the j-th cell, $i_{k,j}(\phi)$, is derived as

$$i_{k,j}(\phi) = \frac{G_k(\phi)}{G_j(\phi)} S \quad (j \neq k, |j| \leq K). \tag{6}$$

The users visible from the reference satellite but served by the adjacent satellites also cause interference. In this case, the interference power from a user at position ϕ in the j-th cell, $i_{k,j}(\phi)$, is expressed as

$$i_{k,j}(\phi) = \frac{G_k(\phi)}{G_j(\phi)} \left[\frac{d(\phi)}{d'_0(\phi)} \right]^2 S \quad (K+1 \leq |j| \leq J), \tag{7}$$

where $d'_0(\phi)$ is the distance to the reference satellite from the user in the service area of an adjacent satellite at the position ϕ . The $\pm J$-th cells are the edge cells which are visible from the reference satellite.

Assume that all users are distributed uniformly and that the number of users in each cell is M. Then, the total interference power to the user in the k-th cell can be expressed as

$$\begin{aligned} I_{C_k} &= (M-1)S + \\ &\frac{M}{2\Phi} \left[\sum_{j \in (j \neq k, |j| \leq K)} \int_{(2j-1)\Phi}^{(2j+1)\Phi} i_{k,j}(\phi) d\phi \right] + \\ &\frac{M}{2\Phi} \left[\sum_{j \in (K+1 \leq |j| \leq J-1)} \int_{(2j-1)\Phi}^{(2j+1)\Phi} i_{k,j}(\phi) d\phi \right. \\ &\left. + \int_{-\phi_{\max}}^{(-2J+1)\Phi} i_{k,-J}(\phi) d\phi + \int_{(2J-1)\Phi}^{\phi_{\max}} i_{k,J}(\phi) d\phi \right]. \end{aligned} \tag{8}$$

In the equation, $\phi_{\max}$ (>0) denotes the position where the elevation angle toward the reference satellite is 0.

Let Γ be the required "bit energy to interference-and-noise power density spectrum ratio, $E_b/(I_0+N_0)$," to maintain quality of service. Then the maximum acceptable number of users of the k-th cell, M_k, is defined as the largest M which satisfies

$$\Gamma \leq \frac{S/R}{I_{C_k}/W + N_0} \quad , \tag{9}$$

where N_0 is the noise power density spectrum, W is the spread-spectrum bandwidth and R is data symbol rate. The maximum acceptable number of users of the k-th cell, M_k, varies according to the locations of cells. Then we define the minimum M_k in all cells as the maximum acceptable number of users per cell of the system, $M_{\max}$.

B. FDMA, TDMA

In FDMA system, the spectrum bandwidth is divided into disjoint frequency channels. In TDMA system, users are distinguished by disjoint time periods called time slots or channels. In both systems, different sets of channels are assigned to adjacent cells and the same set of channels is reused in distant cells at which the co-channel interference is acceptably small. The maximum acceptable number of users depends on how often a set of channels can be reused.

In this manuscript, the minimum distance where the same channels can be reused is called the "reuse distance". To find the maximum acceptable number of users of the system, we have to derive the minimum reuse distance, $\eta_{\min}$, which can ensure that $E_b/(I_0+N_0)$ is larger than the required value, Γ.

Under the assumption that the same set of channels are reused every η cells, the co-channel interference to the k-th cell is caused by the users in the $k+L_{(-)}\eta$, $k+(L_{(-)}+1)\eta$, ..., $k-\eta$, $k+\eta$, ..., $k+(L_{(+)}-1)\eta$, $k+L_{(+)}$-th cells, where the $(k+L_{(-)}\eta)$-th cell is leftmost cell visible from the reference satellite and $(k+L_{(+)}\eta)$ denotes the rightmost one. Their interference power is also expressed by (6) or (7). In oder to ensure the quality of service, the worst case has to be considered, i.e., each co-channel user is located at the position causing the largest interference in its corresponding cell. Then maximum total interference power to a user in the k-th cell, I_{F/T_k}, is expressed as

$$I_{F/T_k} = \sum_{l=L_{(-)}, l \neq 0}^{L_{(+)}} \max_{\phi} \left[I_{k,k+l\eta}(\phi) \right]. \tag{10}$$

In actual satellite cellular systems, a cell is surrounded by more than two cells. Thus, the interfering signals come in more than two directions. For example, in the hexagonal cellular model shown in Fig. 3, the number of

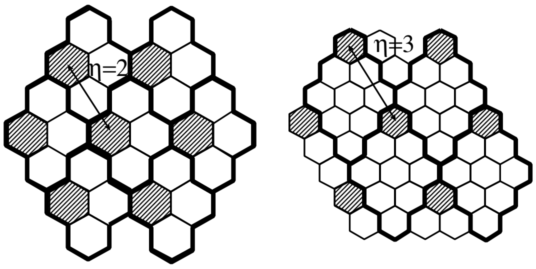

Fig. 3. The hexagonal cellular model.

TABLE I
RELATION BETWEEN REUSE DISTANCE η AND REUSE FACTOR σ

η	2	3	4	...
σ	4	9	16	...

TABLE II
PARAMETERS

Name	Notation	Value
minimum elevation angle	α	$15 \cdot \frac{\pi}{180}$ [rad]
size of a cell	$R_e \cdot 2\Phi$	500 [km]
processing gain (CDMA) available channels (FDMA/TDMA)	W/R	100
required $E_b/(I_0 + N_0)$	Γ	7 [dB]

the nearest interfering cells are six which is three times as large as that of the two-dimensional model. Thus for the evaluation of $E_b/(I_0+N_0)$, total power of the co-channel interfering signals is assumed to be three times as large as that of the two-dimensional model, and $E_b/(I_0+N_0)$ of a user in the k-th cell, $E_b/(I_0+N_0)_k$, is

$$E_b/(I_0+N_0)_k = \frac{S/R}{3I_{F/T_k}/R + N_0}, \tag{11}$$

where binary PSK is assumed as a modulation method and R is the bit rate or the bandwidth of each channel. Then, the minimum reuse distance, η_{min}, which makes $E_b/(I_0+N_0)_k$ larger than the required value Γ for all cells can be found.

Let σ denote the reuse factor which shows how often the same channel is reused with the reuse distance η in the hexagonal cellular model as shown in Table I. Then, the maximum acceptable number of users per cell of the system, $M_{\max}$, can be represented as

$$M_{\max} = \frac{W}{R}\frac{1}{\sigma(\eta_{\min})}, \tag{12}$$

where W is the total frequency bandwidth assigned to the uplinks of the system.

IV. NUMERICAL RESULTS

All numerical results are obtained for the parameters given in Table II. Since the minimum elevation angle and the size of a cell are fixed, service area of a satellite and the number of cells per satellite depend on the altitude of satellites. The bit energy-to-noise power density spectrum ratio, $E_b/N_0 = (S/R)/N_0$, is employed as the parameter of the state of a channel.

Figure 4 shows the maximum acceptable number of users of the k-th cell as the functions of the satellite altitude (or the number of cells) in CDMA system. We focus on three typical cells. One of them is the cell including the subsatellite point ($k = 0$). The second is the cell located at the edge of the service area of a satellite ($k = K$). The last is the cell located at the middle of these two cells (for $K \geq 2$, $k = K/2$ when K is even and $k = (K-1)/2$ when K is odd). The plotted points correspond to $K = 0, 1, \ldots, 14$ from the low altitude to the high altitude.

From Fig. 4, we find that all cells have almost the same maximum acceptable number of users for all altitudes. In other words, the location of a cell and the altitude of the satellite do not dominate the number of users per cell of the system $M_{\max}$. And we can find that the number of users is strongly affected by E_b/N_0.

Figures 5 and 6 show that $E_b/(I_0+N_0)$ of the FDMA (or TDMA) system as the functions of the altitude of the satellite for different combinations of E_b/N_0 and η (or σ). In both figures, it is shown that FDMA (or TDMA) system is sensitive to the altitude of the satellite and the location of a cell. For example, in Fig. 5, the $E_b/(I_0+N_0)$ increases along with the altitude and reaches its maximum at the altitude of about 1000 [km], then it decreases along with the altitude. This is caused by the trade-off of the effects of main lobe and side lobes. If the altitude is low, the visual angle of a cell at the satellite is large and the beam width is wide. Thus the main lobe of the beams illuminates the cells using the same channels with its main lobe causing strong interference. This co-channel interference can be mitigated when the altitude of satellites is higher; however, if the altitude is higher than a certain level, the co-channel interference arises in the direction of the side lobe. And co-channel interference power by the side lobe becomes larger along with the altitude.

Figure 5 and 6 also show the $E_b/(I_0+N_0)$ performance depends on the cell location, and the edge cell is the worst and the most sensitive to altitude characteristic.

From Fig. 5, it is confirmed that the required $E_b/(I_0+N_0)$, Γ=7 [dB], is satisfied by η=2 (and σ=4) if the altitude is higher than 700 [km] and lower than 5000 [km]. Then, the maximum acceptable number of users per cell, $M_{\max}$, becomes 100/4=25 by (12). This value is about 25/15=1.7 times as large as the number of users in CDMA systems. If the altitude is higher than 5000 [km], however, the required value Γ is not satisfied in the subsatellite cell and the middle cell. Then the minimum reuse distance $\eta_{\min}$ have to be larger than 2, and if

$\eta_{\min}$=3 (and $\sigma_{\min}$=9), $M_{\max}$ becomes 100/9=11.1 which is 11.1/15=0.74 of CDMA systems.

Figure 6 shows the $E_b/(I_0+N_0)$ performance for larger reuse distance (η=3 and σ=9), but with smaller E_b/N_0. In this figure, we can find that the required $E_b/(I_0+N_0)$, Γ=7 [dB], is satisfied in all cells under the condition that the altitude is higher than 500 [km] and lower than 2000 [km] or under the condition that the altitude is higher than 20000 [km]. Under these conditions, the minimum reuse factor $\sigma_{\min}$ is 9 and the maximum acceptable number of users per cell, $M_{\max}$, is 100/9=11.1, which is 11.1/8=1.4 times as large as the number of user in CDMA systems. Otherwise the required value Γ is not satisfied in the edge cell: the minimum reuse distance $\eta_{\min}$ have to be larger than 3. If $\eta_{\min}$=4 (and σ=16), $M_{\max}$ is 100/16=6.25 which is 6.25/8=0.78 times as large as that of CDMA.

V. Conclusions

In this paper, the maximum acceptable number of users of CDMA and FDMA (or TDMA) are compared for the uplink of satellite communication systems.

As the result, it is found that the altitude of the satellites does not dominate the maximum acceptable number of users with CDMA, while that with FDMA or TDMA greatly depends on the altitude of the satellites.

The numerical examples show that FDMA or TDMA has better performance than CDMA in low earth orbital (LEO) satellite systems. On the other hand in medium earth orbital (MEO) satellite systems and geostationary (GEO) satellite systems, CDMA is often superior to FDMA or TDMA.

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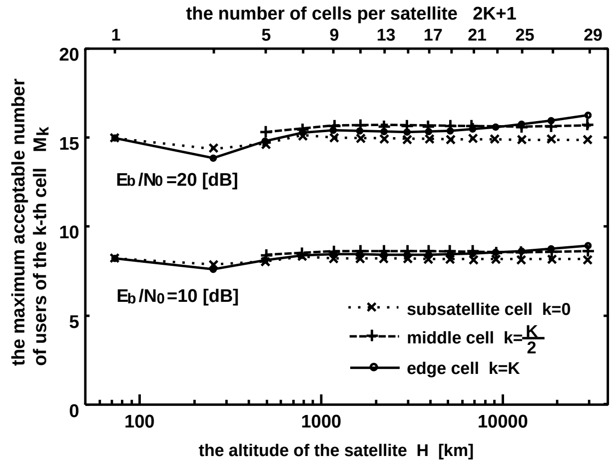

Fig. 4. The maximum acceptable number of users of the k-th cell in CDMA system.

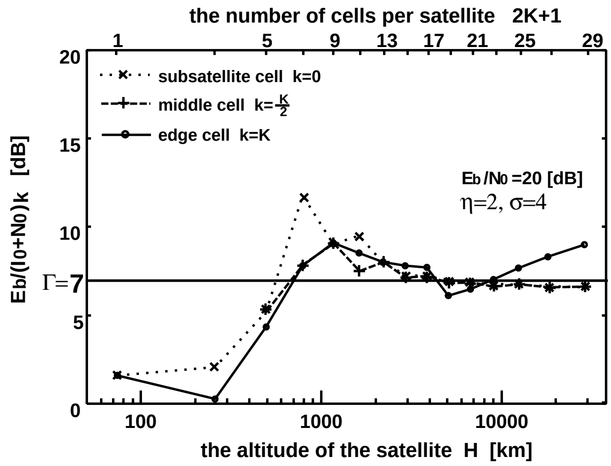

Fig. 5. The $E_b/(I_0+N_0)$ of the user signal of the k-th cell in FDMA system, E_b/N_0=20 [dB].

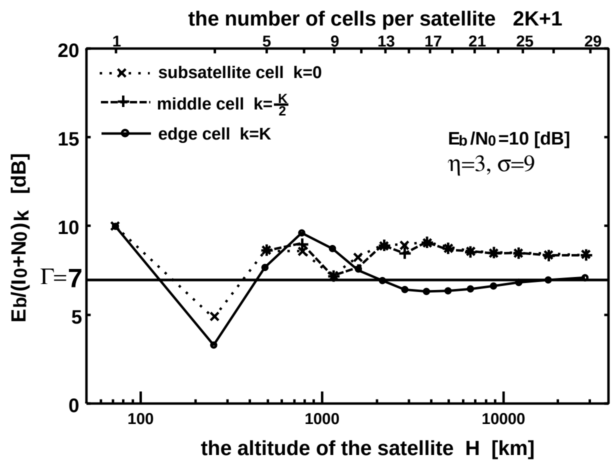

Fig. 6. The $E_b/(I_0+N_0)$ of the user signal of the k-th cell in FDMA system, E_b/N_0=10 [dB].