A Novel Dual-Size Interleaved Spot-Beam Architecture for Mobile Satellite Communications

Wei Zheng*, Bin Li*, Jiang Chen*, Jianjun Wu*

*Institute of Advanced Communications, EECS, Peking University, 100871, China

selina@pku.edu.cn, sueno@pku.edu.cn, chenjiang@pku.edu.cn, just@pku.edu.cn

***Abstract*— In wireless communication systems, system capacity is mainly restricted to limited spectrum. In satellite systems, frequency reuse can be accomplished by using multiple beams. Spot beam technique is widely adopted in satellite systems, with similar frequency reuse factor as in terrestrial cellular systems, leading to a relatively low spectral efficiency. In this paper, a novel dual-size interleaved spot-beam architecture for mobile satellite communications is proposed. The system performance is analysed by calculating frequency reuse factor, uplink inter-beam interference and system throughput. The results suggest that the proposed spot-beam architecture has almost the same Signal to Interference plus Noise Ratio (SINR) performance as the traditional spot-beam architecture, and that the proposed architecture outperforms the traditional one in frequency reuse and system throughput, making better utilization of frequency spectrum.**

***Keywords*— Dual-size, frequency reuse, multi-beam, spot-beam architecture, satellite communication**

I. INTRODUCTION

In modern wireless communications, satellite systems have raised great interest for the past years, since they provide large coverage area, long communication distance, flexible networking and stable radio link conditions. Current mobile satellite communication systems include geostationary orbit (GEO) systems such as Inmarsat, and low earth orbit (LEO) systems like Globalstar and Iridium.

Spot beam technique is widely used in mobile satellite communication systems. Compared with single-beam architecture, multiple beams can achieve the optimal coverage by adjusting the number of beams, the spot-beam architecture and the transmitting power of each spot beam. With similar architecture and frequency reuse factor as in terrestrial cellular systems, the spectral efficiency of satellite systems is relatively low, thus the limited spectrum restricts the maximum available throughput.

Many studies have worked on this problem. Some of them focus on new resource allocation methods, under traditional spot-beam architecture [1]-[3]. Some of them adapt fractional frequency reuse scheme and soft frequency reuse scheme of terrestrial cellular system into satellite systems, divide each spot beam into central region and edge region, and allocate different frequency resources to those two regions [4], [5]. A new design of spot-beam architecture may have better performance and inspire new ideas. In this paper, a novel dual-size interleaved spot-beam architecture is proposed and its performance is analysed and simulated.

The rest of this paper is organized as follows: Section II introduces a dual-size interleaved spot-beam architecture. In Section III, the system performance is analysed by frequency reuse factor, uplink inter-beam interference and system throughput. Section IV shows the simulation results of uplink mean SINR and system throughput. At last, Section V concludes the paper.

II. DUAL-SIZE INTERLEAVED SPOT-BEAM ARCHITECTURE

In multi-beam satellite communication systems, the satellite coverage area is divided into several regions, each of which is served by a different satellite spot beam. On the surface covered by a satellite spot beam, the boundary is a level contour. Usually, when planning network, the level of beam boundary is set by a 3dB decrease of antenna gain [6]. Existing mobile satellite communication systems have adopted spot beam architecture similar as that in terrestrial cellular systems, and the frequency reuse factor can be i^2+ij+j^2 (i and j are nonnegative integers), such as 1, 3, 4 and 7. Multi-beam satellite cellular coverage is shown in Figure 1.

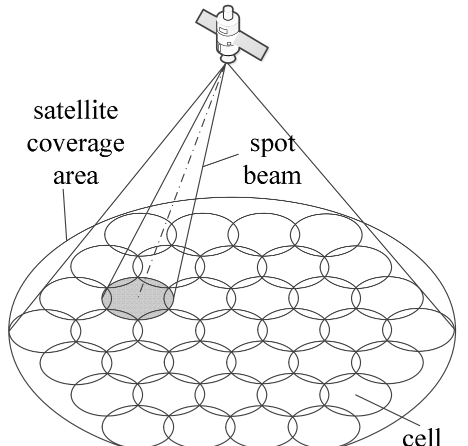

Figure 1. Multi-beam satellite cellular coverage

Traditional spot-beam architecture is formed by spot beams of the same size (the radius of spot beams is registered as r_0) and cells are approximately considered as compact regular hexagons. With the frequency reuse factor FR, the system spectrum is divided to *FR* equal parts and each cell can employ *1/FR* of the system spectrum. For example, when *FR*=3, the traditional spot-beam architecture is shown in Figure 2.

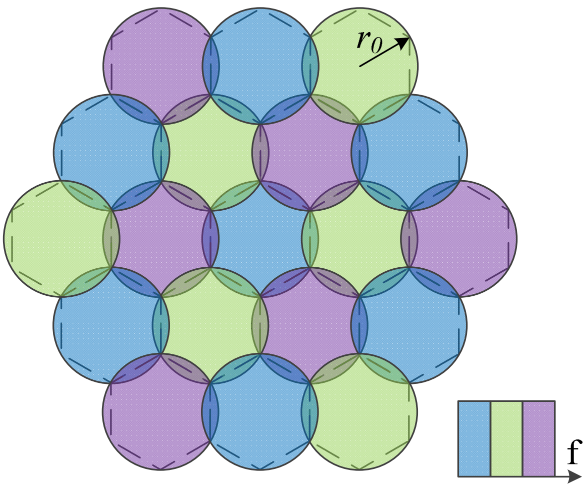

Figure 2. Traditional spot-beam architecture (*FR*=3)

If the *FR* is small, the system will get high spectral efficiency, but the inter-beam interference will be severe and limit the system capacity. If the system adopts a big *FR*, the inter-beam interference will be low but the system capacity is limited to the low spectral efficiency.

Instead of using the spot beams of the same size, the spot beams of dual-size interleaved spot-beam architecture are interleaved by beams of two different sizes, which can be implemented by a multiple aperture design [7], as shown in Figure 3.

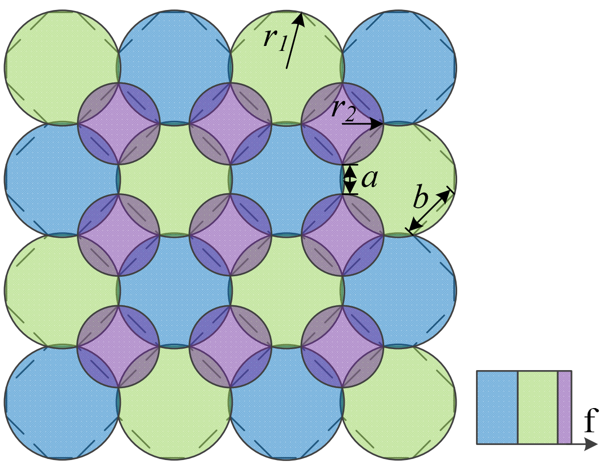

Figure 3. Dual-size interleaved spot-beam architecture

The spot beams are classified into big beams and small beams, which are interleaved to provide seamless coverage. The system spectrum is divided into 3 parts, including 2 equal big parts and 1 small part, according to the area proportion of 2 big beams and 1 small beam. The radius of big beams is registered as r_1 and big beams can be approximately considered as octagons, with side length a and b shown in Figure 3. Let r_2 represent the radius of small beams, which can be approximately considered as squares. It can be easily derived that

$$b = \sqrt{2} r_2 \quad (1)$$

Let k represent the a to b ratio, then

$$a = k \cdot b \quad (2)$$

With different values of k, the area proportion of beams and the frequency allocation scheme changes, leading to different system performance.

III. Performance Analysis

In order to make a comparison between tradition spot-beam architecture and proposed dual-size interleaved spot-beam architecture, a beam unit is defined as the smallest set of spot beams which utilizes the whole system spectrum and can be tiled to achieve complete coverage. The performance analysis is based on that those two designs of spot-beam architecture have the same beam unit area.

As shown in Figure 4, the beam unit of traditional spot-beam architecture is the same as a cluster, consists of 3 hexagons, while the beam unit of proposed spot-beam architecture is composed of 2 octagons and 2 squares, and the small part of system spectrum is used twice in one beam unit.

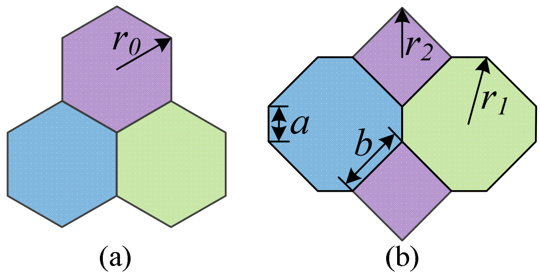

Figure 4. Beam unit (a) traditional spot-beam architecture (b) proposed spot-beam architecture

A. Frequency Reuse Factor

In dual-size interleaved spot-beam architecture, frequency resources are allocated to each beam according to their area proportion. The area of an octagon cell (big cell) S_b is calculated as

$$S_b = 2r_2^2 \cdot \left(k^2 + 2\sqrt{2}k + 1\right) \quad (3)$$

The area of a square cell (small cell) S_s is calculated as

$$S_s = 2r_2^2 \quad (4)$$

Assume the system has a total bandwidth W. The frequency allocated to a big beam W_b and the frequency allocated to a small beam W_s are given by, respectively,

$$W_b = \frac{S_b}{2S_b + S_s} W \quad (5)$$

$$W_s = \frac{S_s}{2S_b + S_s} W \quad (6)$$

So the frequency reuse factor *FR* is calculated as

$$FR = \left(\frac{S_b}{2S_b + 2S_s} \cdot \frac{W_b}{W} \cdot 2 + \frac{S_s}{2S_b + 2S_s} \cdot \frac{W_s}{W} \cdot 2 \right)^{-1} = \frac{\left(k^2 + 2\sqrt{2}k + 2\right)\left(2k^2 + 4\sqrt{2}k + 3\right)}{\left(k^2 + 2\sqrt{2}k + 1\right)^2 + 1} \quad (7)$$

For example, when k=0.5, FR=2.86, which is smaller than 3, indicating a better utilization of frequency spectrum.

B. Uplink Interference

Orthogonal Frequency Division Multiple Access (OFDMA) scheme is a prospective candidate for satellite communications, so OFDMA system is considered in this paper. For OFDMA system, it can be considered that no intra-beam interference exists and that all interference comes from other beams.

In mobile satellite communication systems, on-board antenna acts as a spatial filter and the angular selectivity of beams is not very ideal, so the level of interference depends on the user angular separation, referred to the satellite position, as shown in Figure 5.

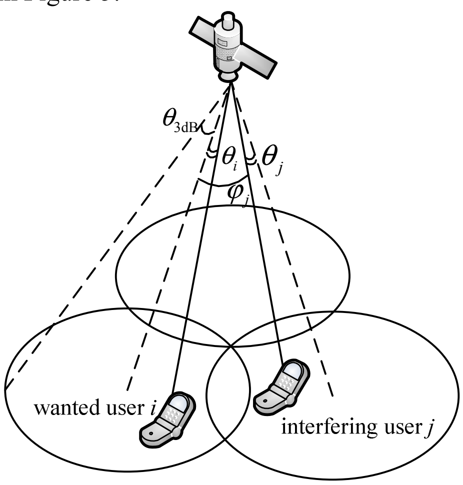

Figure 5. Angular parameters for interference analysis

Let $G_j(\theta)$ represent the antenna gain of the jth spot beam, then

$$G_j(\theta) = G_{Mj} F_j^2(\theta) \quad (8)$$

where θ is the angular separation shown in Figure 5, G_{Mj} is the maximum gain of the jth spot, and $F_j(\theta)$ is the normalized far-field radiation pattern. An approximate expression of radiation pattern is given in [8], [9]

$$F_j(\theta) = \hat{F}(u_j) \quad (9)$$

$$F(u_j) = \frac{(p+1)(1-T)}{(p+1)(1-T)+T} \cdot \left[\frac{2J_1(u_j)}{u_j} + 2^{p+1} p! \frac{T}{1-T} \frac{J_{p+1}(u_j)}{u_j^{p+1}} \right] \quad (10)$$

where: $\hat{F}(u_j)$ is the envelope of $F(u_j)$; $u_j = \pi d_{aj} \sin\theta / \lambda$; d_{aj} is the effective aperture diameter of the jth spot; λ is the wavelength; $J_p(u)$ is the Bessel function of the first kind and order p; T is the aperture edge taper.

Assume that uplink power control is ideal and that every signal received by each spot beam can reach the uniformed receiving threshold $(E_b/N_0)_{Th}$, after deploying power control technology and without considering the interference brought by other beams. According to [4], for user i, the SINR at the satellite is

$$SINR_i = \frac{1}{\sum_k^K \frac{G(\varphi_k)}{G(\theta_k)} + \left[\frac{R}{W_i} \left(\frac{E_b}{N_0} \right)_{Th} \right]^{-1}} \quad (11)$$

where R is the symbol rate, W_i is the bandwidth allocated to user i, and set K includes all interfering users of user i.

C. Beam Unit Throughput

After SINR is obtained, the modulation and coding scheme (MCS) can be determined under the given block error ratio (BLER) value when adopting the adaptive modulation and coding (AMC) technology, thus the maximum rate can be calculated. Take LTE system which adopts OFDMA technology for example. According to the protocol standards [10], under the condition of $BLER \leqslant 10^{-1}$, the required SINR and corresponding MCS, as well as the maximum bit rate per resource block (RB), are shown in Table 1.

TABLE 1. REQUIRED SINR AND MAXIMUM BIT RATE PER RB IN LTE SYSTEM WHEN $BLER \leqslant 10^{-1}$

Required SINR (dB)	Modulation	Coding Speed	Max Rate (Mbps/RB)
-1.3	QPSK	1/3	0.096
1	QPSK	1/2	0.144
2.1	QPSK	2/3	0.192
6.3	16QAM	1/2	0.288
7.5	16QAM	2/3	0.384
9	16QAM	3/4	0.432
14.2	64QAM	2/3	0.576
15.5	64QAM	3/4	0.648

The bit rate of user i, registered as R_i, is calculated as

$$R_i = \frac{W_i}{W_{RB}} \cdot R_{RB} \quad (12)$$

where W_i is the bandwidth allocated to user i, W_{RB} is the bandwidth of each RB, which in 180kHz in LTE, and R_{RB} is the maximum bit rate per RB. Then the total throughput in one spot beam T_b is given by

$$T_b = \sum_{i=1}^{N} R_i \quad (13)$$

where N is the number of users in the spot beam.

Considering the spot beams of dual-size interleaved spot-beam architecture have two kinds of size and the throughput of each kind of beams may be different, so the throughput of one beam unit T_u is calculated.

For traditional spot-beam architecture,

$$T_u = 3 \cdot T_b \quad (14)$$

For proposed spot-beam architecture,

$$T_u = 2 \cdot T_{bb} + 2 \cdot T_{sb} \quad (15)$$

where T_{bb} represents the throughput in one big beam and T_{sb} represents the throughput in one small beam.

IV. Simulation Results

In this paper, simulations are made to compare the uplink mean SINR and beam unit throughput of two designs of spot-beam architecture. The simulation conditions are: the system is full-loaded (each frequency in each beam is used); the uplink power control is ideal; G_{Mj} and d_{aj} for each kind of beam are the same; and the isolation between beams is 3dB. Other parameters used in the simulation are listed in Table 2.

TABLE 2. Simulation Parameters

Parameter	Value
Carrier frequency	1990MHz
RB bandwidth	180kHz
System bandwidth	20MHz [108 RBs + 3RBs for signaling]
Number of RBs per user	1
Satellite elevation	70°
Aperture edge taper	0.7dB
Users distribution	Uniform random distribution

A. Uplink Mean SINR

The first simulation investigates the impact of inter-beam interference in different designs of spot-beam architecture, by measuring the uplink mean SINR at different E_b/N_0 level. The value of k influences the size relationship between big beams and small beams, and then influences the SINR performance. When k=1, the uplink mean SINR is shown in Figure 6.

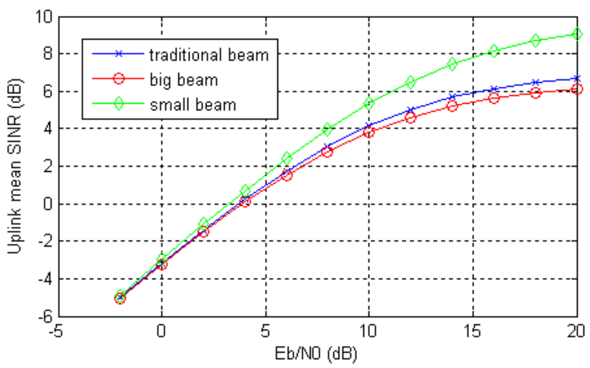

Figure 6. Uplink mean SINR when k=1

It can be seen from Figure 6 that when k=1, small beams of proposed architecture has the best SINR performance, while the SINR of traditional beams is slightly higher than that of big beams of proposed architecture. By decreasing k, the small beams will be bigger and spaced more closely while the big beams will be smaller and spaced more loosely. When k=0.5, the SINR of small beams decreases and the SINR of big beams increases, compared to the condition that k=1, and the uplink mean SINR values of two kinds of spot-beam architecture are almost the same, as shown in Figure 7. Keep decreasing k, the SINR of small beams will keep decreasing and the SINR of big beams will keep increasing. As shown in Figure 8, when k=0.1, big beams of proposed architecture has better SINR performance than traditional beams, while the SINR performance of small beams of proposed architecture is much worse.

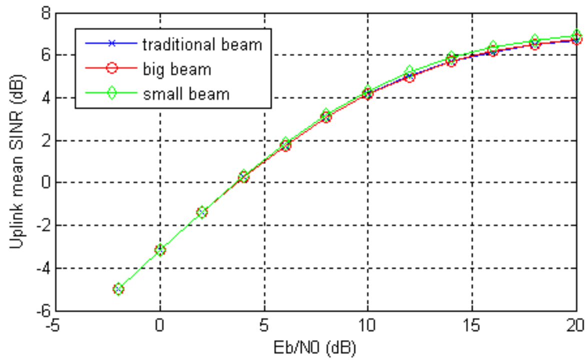

Figure 7. Uplink mean SINR when k=0.5

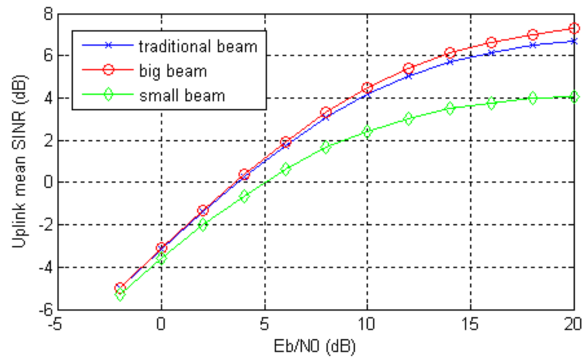

Figure 8. Uplink mean SINR when k=0.1

Considering both the SINR performance and the fairness between big beams and small beams of the proposed architecture, 0.5 is chosen as the optimal value of k.

B. Beam Unit Throughput

System throughput depends on both spectral efficiency and inter-beam interference. With a higher spectral efficiency and the SINR not worse than traditional spot-beam architecture, the proposed architecture will get a higher beam unit throughput.

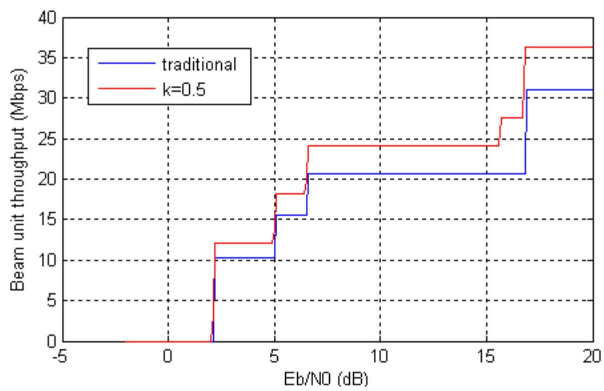

Figure 9. Beam unit throughput of traditional spot-beam architecture and proposed architecture with k=0.5

Figure 9 shows the beam unit throughput of traditional spot-beam architecture and proposed architecture with k=0.5. It can be seen that the proposed spot-beam architecture has a higher beam unit throughput than the traditional architecture.

V. Conclusions

In this paper, a novel dual-size interleaved spot-beam architecture for mobile satellite communications is proposed. The system performance is analysed by calculating frequency reuse factor, uplink mean SINR and beam unit throughput. Although the complexity of antenna system and handover procedure is increased, the simulation results suggest that the proposed spot-beam architecture outperforms the traditional spot-beam architecture, making better utilization of frequency spectrum.

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Corresponding author: Jianjun Wu; Phone: +86-10-62752848; E-mail: just@pku.edu.cn.

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Wei Zheng was born in Shandong Province, China. She received her bachelor degree in electronic information science and technology from Peking University, China, in 2010. Since 2010, she has been a postgraduate student in Institution of Advanced Communications, Peking University, China. Her research interests are in the area of networking scheme and interference management of satellite mobile communications.

Jianjun Wu received his B.S., M.S. and Ph.D. degree from Peking University, Beijing, P.R.China, in 1989, 1992 and 2006, respectively. Since 1992, he has joined the School of Electronics Engineering and Computer Science, Peking University, and has been appointed as an associate professor since 2002. His research interests are in the areas of satellite communications, wireless communications, and communications signal processing.