Low-Complexity Beam Selection Technique for Multi-Beam LEO Satellite Communications

Hyeon Seung Ryu, Yong-Jin Song, Ki-Hun Lee, and Bang Chul Jung
Department of Electronics Engineering, *Chungnam National University*, Daejeon, South Korea
ryuhs.wicl@gmail.com, yjsong@o.cnu.ac.kr, kihun.h.lee@cnu.ac.kr, bcjung@cnu.ac.kr

***Abstract*—Multi-beam satellite communication systems have been studied to overcome the spectrum scarcity in 6G non-terrestrial networks (NTNs). The multi-beam allows a single satellite to configure multiple spot beams toward multiple ground areas over the same time-frequency radio resources. However, this may also lead to inter-beam interference, hindering spectral efficiency (SE) improvements. This paper proposes a low-complexity spot-beam selection technique for low-earth orbit (LEO) satellite communication systems that maximize the SE by activating some of the multiple spot beams based on each spot beam's signal-to-interference ratio (SIR). Simulation results reveal that the proposed algorithm effectively ameliorates the SE of multi-beam LEO satellite networks.**

***Index Terms*—Low-earth orbit (LEO) satellite networks, multi-beam satellite communications, spot-beam activation, inter-beam interference, throughput.**

I. INTRODUCTION

Sixth-generation (6G) cellular networks envision a non-terrestrial network (NTN) architecture, incorporating low-earth orbit (LEO) satellites, high-altitude platform stations (HAPSs), and unmanned aerial vehicles (UAVs) [1], [2]. In particular, LEO satellites are one of the indispensable components for realizing worldwide coverage and connectivity with high cost-efficiency and low latency [3], [4]. To overcome the spectrum scarcity in future NTNs, a multi-beam satellite communication system has been investigated, which allows a single satellite to serve multiple terrestrial areas with the same radio resources through multiple high-gain spot beams [5]. Unfortunately, this can also deteriorate the downlink sum-rate due to inter-beam interference, so various technologies, such as sophisticated beam design, interference cancellation, and frequency resource allocation, have been widely studied [6], [7]. From a different perspective, in this paper, we propose a spot beam activation technique to maximize the SE of multi-beam LEO satellite networks by alleviating inter-beam interference.

II. SYSTEM MODEL

We consider a downlink NTN consisting of an LEO satellite and multiple ground base stations (BSs) as in [6]. The satellite is located at a position $(0, 0, H)$ in three-dimensional Cartesian coordinates, and N_{B} BSs are placed with the same distance D between adjacent BSs based on the BS at the origin $(0, 0, 0)$. Moreover, the satellite is equipped with multiple parabolic antennas to configure N_{B} spot beams simultaneously, each serving one BS. Fig. 1 illustrates the system model considered in this paper with $N_{\mathsf{B}} = 19$. We assume that each spot beam is perfectly oriented towards its dedicated BS.

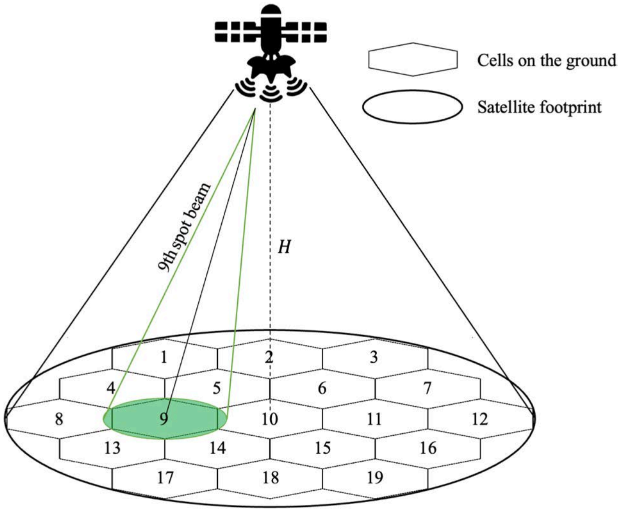

Fig. 1. System model of a multi-beam LEO satellite network with $N_{\mathsf{B}} = 19$.

Let $\mathbf{R} = [r_{j,i}] \in \mathbb{R}_{+}^{N_{\mathsf{B}} \times N_{\mathsf{B}}}$ be the received signal strength (RSS) matrix, where $r_{j,i}$ represents the RSS that the $j \in \{1, 2, \ldots, N_{\mathsf{B}}\}$th BS receives from the $i \in \{1, 2, \ldots, N_{\mathsf{B}}\}$th spot beam, which is expressed from [7, (11)] as follows:

$$r_{j,i} = \frac{P^{\mathsf{TX}}}{N_{\mathsf{A}}} \cdot \left(\frac{c}{4\pi f_c d_j}\right)^2 \cdot \frac{\sin\theta_j}{A_{\mathrm{zen}}(f_c)} \cdot G(\zeta_{j,i}) \cdot |h_j|^2, \tag{1}$$

where P^{TX} denotes the satellite's total transmission power and N_{A} represents the number of activated spot beams, i.e., the satellite is assumed to allocate the transmit power evenly for each activated beam; c, f_c, and d_j are the light speed (m/s), carrier frequency (Hz), and propagation distance (m) between the satellite and the jth BS, respectively. The third term on the right-hand side represents the atmospheric absorption, where $A_{\mathrm{zen}}(f_c)$ denotes the zenith attenuation depending on the carrier frequency, and θ_j is the satellite elevation angle from the jth BS. Next, $G(\zeta_{j,i})$ represents the beam gain from the ith spot beam to the jth BS, and $\zeta_{j,i}$ is the steering angle difference in degrees between spot beams i and j. This is modeled as follows [8]:

$$G(\zeta_{j,i}) = \begin{cases} 1, & \text{when } \zeta_{j,i} = 0, \text{i.e.}, j = i, \\ 4\left|\frac{J_1(ka\sin\zeta)}{ka\sin\zeta}\right|^2, & \text{when } 0 < |\zeta_{j,i}| \leq 90, \end{cases}$$

where $J_1(\cdot)$ is the first-order Bessel function of the first kind; a, $k = 2\pi/\lambda$, and λ are the parabolic antenna's radius, wave number, and carrier wavelength, respectively. Finally, $|h_j|^2$ represents small-scale fading modeled to follow a squared-shaded Rician (SSR) distribution. Note that if $j = i$ in (1), it

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Algorithm 1 Low-Complexity Spot-Beam Selection

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 1: Input: $\overline{\mathbf{R}} \in \mathbb{R}^{N_\mathsf{B}\times N_\mathsf{B}}$, $\mathcal{B}_\mathsf{all} = \{1, 2, \ldots, N_\mathsf{B}\}$.
 2: Output: $\mathcal{B}_\mathsf{act}$.
 3: Initialization: $\widehat{S} = 0$.
 4: for $n_\mathsf{A} = 1$ to $N_\mathsf{B}$ do
 5:     for $n_\mathsf{B} = 1$ to $N_\mathsf{B}$ do
 6:         Update $\mathcal{B}_\mathsf{A} = \varnothing$ and $\mathcal{B}_\mathsf{S} = \mathcal{B}_\mathsf{all}$.
 7:         for $n_\mathsf{C} = 1$ to $n_\mathsf{A}$ do
 8:             if $n_\mathsf{C} = 1$ then
 9:                 $\widehat{n} = n_\mathsf{B}$
10:             else
11:                 $\widehat{n} = \arg\max_{j\in\mathcal{B}_\mathsf{S}} \overline{r}_{j,j} \Big/ \sum_{i\in\mathcal{B}_\mathsf{A}\setminus j} \overline{r}_{j,i}$
12:             end if
13:             Update $\mathcal{B}_\mathsf{A} \leftarrow \mathcal{B}_\mathsf{A} \cup \{\widehat{n}\}$ and $\mathcal{B}_\mathsf{S} \leftarrow \mathcal{B}_\mathsf{S}\setminus\widehat{n}$
14:             Calculate the SE $S$ according to (2)
15:             if $S > \widehat{S}$ then
16:                 Update $\widehat{S} = S$ and $\mathcal{B}_\mathsf{act} = \mathcal{B}_\mathsf{A}$
17:             end if
18:         end for
19:     end for
20: end for
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is the desired signal strength; otherwise, it is the inter-beam interference.

III. PROPOSED SPOT BEAM SELECTION ALGORITHM

We design a low-complexity spot beam selection algorithm for the multi-beam LEO satellite communication system, which activates N_A of the N_B spot beams to maximize the spectral efficiency (SE). Algorithm 1 represents a pseudo-code of the proposed algorithm, where $\overline{\mathbf{R}} = [\overline{r}_{j,i}] \in \mathbb{R}_+^{N_\mathsf{B}\times N_\mathsf{B}}$. Due to the high mobility of LEO satellite constellations, it is infeasible for the satellite to estimate instantaneous channel state information (CSI) for all BSs; hence, the satellite only exploits the average RSS, $\overline{r}_{j,i} = \mathbb{E}[r_{j,i}], \forall j, i \in \{1, \ldots, N_\mathsf{B}\}$, based on the BSs' geographic information. In Algorithm 1, n_A and n_B indicate the number of activated spot beams and the index of the first activated beam for each iteration, respectively. In other words, the proposed algorithm determines a set that maximizes the SE, denoted by B_act, as the final activation beams, starting from each spot beam (line 9) and gradually increasing the number of beams activated according to the signal-to-interference ratio (line 11). Since the network operates on a single channel, the SE is given as

$$S = \sum_{j\in\mathcal{B}_\mathsf{A}} \log_2\left(1 + \frac{\overline{r}_{j,j}}{\sum\limits_{i\in\mathcal{B}_\mathsf{A}\setminus j} \overline{r}_{j,i} + N_0 W}\right), \tag{2}$$

where N_0 and W are the noise spectral density and channel bandwidth, respectively.

IV. SIMULATION RESULTS

We verify the proposed spot beam selection technique through computer simulations. The simulation parameters are the same as [7, Table II]. Furthermore, we consider heavy shadowing environments; hence, $|h_j|^2$ in (1) conforms to an independent and identically distributed SSR distribution, i.e., $|h_j|^2 \sim \mathsf{SSR}(0.063, 0.739, 8.97\times 10^{-4}), \forall j$. The simulations were performed according to satellite altitude $H \in \{500, 600, \ldots, 1000\}$, and the proposed algorithm was compared to two techniques: activating some beams based on maximum intensity (maxSNR) and exploiting all spot beams (Conv). Fig. 2 shows the SE performance of the proposed spot beam selection algorithm and benchmark schemes. In the proposed algorithm, the number of activated spot beams is $N_\mathsf{A} = \{7, 7, 3, 3, 3, 2\}$ for each altitude. As the satellite altitude increases, the desired signal strength gradually decreases, deteriorating overall SE. However, we can observe that the proposed algorithm significantly improves SE performance with a small number of spot beams. It demonstrates the effectiveness of the proposed beam selection mechanism.

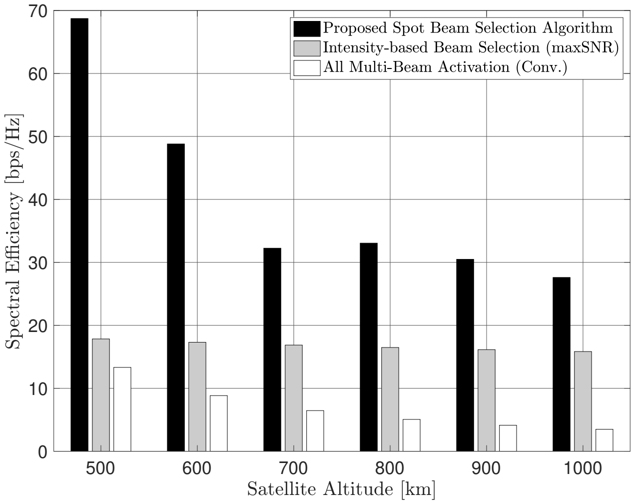

Fig. 2. Spectral efficiency of the proposed spot beam selection technique according to the satellite altitude.

V. CONCLUSION

This paper proposed a low-complexity spot-beam selection technique for multi-beam LEO satellite communication systems. The proposed algorithm activates multiple spot beams among all beam candidates to maximize SE by alleviating inter-beam interference. Simulation results showed that it outperforms using all available spot beams simultaneously. As further work, we will design a joint optimization technique of beam selection and frequency allocation for multi-beam LEO satellite networks.

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