A New User-Centric Opportunistic Handover for LEO Satellite Communication Systems

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***Abstract*—With the rapid increase in the number of users, user-centric handover research has attracted extensive attention for low Earth orbit (LEO) satellite communication (SatCom) systems. However, in densely populated areas, a large number of users may access a certain satellite, leading to severe bottlenecks as the users independently select a target satellite for handover. To address this issue, we propose a new user-centric opportunistic handover (OHO) scheme that leverages randomness to enable efficient channel resource utilization and mitigate bottlenecks. Specifically, each user calculates the probabilities derived from the transmission rate and the number of available channels of visible satellites and then selects a target satellite for handover based on these probabilities. The proposed OHO scheme effectively addresses bottleneck issues by allowing the users to connect to various satellites rather than a certain one. Simulation results demonstrate that the proposed OHO scheme outperforms the conventional user-centric handover schemes in terms of the average number of handovers, the average blocking rate, and the average throughput as the number of users increases.**

***Index Terms*—Non-terrestrial networks (NTNs), low Earth orbit (LEO) satellite communication (SatCom), user-centric handover, bottleneck**

I. INTRODUCTION

The telecommunications industry is evolving toward expanding services and widely leveraging the anywhere-anytime communication paradigm, resulting in unprecedented demand for high-data rate connectivity and low latency requirements [1]. To meet such demand, satellite communication (SatCom) has recently garnered significant attention due to its wide coverage and reliable connectivity [2]. In particular, low Earth orbit (LEO) satellites, operating at altitudes of approximately 500-1,500 kilometers, have gained notable interest due to their lower operational costs, shorter propagation delay, and less path loss compared to geosynchronous Earth orbit satellites [3], [4]. However, due to the high mobility of LEO satellites, it yields frequent handovers among satellites, which cause heavy signaling overhead [5].

In the past few years, several handover techniques have been developed to address the frequent handover problem for LEO SatCom systems [6]. Handover techniques for LEO SatCom systems are largely divided into satellite-centric and user-centric handover. In the satellite-centric handover technique, each satellite makes handover decisions by considering a large number of users within its coverage area [7]. Especially as the number of users increases, each satellite needs to take into account more users, making the handover procedure more complex. However, in the user-centric handover technique, each user independently makes handover decisions by considering the limited visible satellites covering the user, which simplifies the handover procedure [8].

Many user-centric handover techniques have been proposed in LEO SatCom systems. E. Papapetrou *et al.* introduced a handover technique that selects a target satellite with the minimum distance to avoid link failures in [9]. In [10], the longest service time is considered as the basic criterion for satellite selection to reduce the number of handovers. To reduce the handover rate, A. Bottcher and R. Wemer proposed an approach based on the maximum elevation angle for selecting a target satellite in [11]. However, these techniques do not consider the number of available channels of the visible satellites, which may lead to bottlenecks in densely populated areas.

To address the bottleneck issues, a new strategy that integrates handover decision-making with reinforcement learning has emerged [12]. The Successive Deep Q-Learning (SDQL) scheme allows each user to select an appropriate satellite by jointly considering the transmission rate requirements and the number of available channels of the visible satellites. However, since the SDQL scheme is location-dependent, it may still lead to multiple users making handover decisions to a certain satellite in densely populated areas.

In this paper, we propose a new user-centric opportunistic handover (OHO) scheme for LEO SatCom systems to mitigate bottlenecks. Specifically, the proposed OHO scheme allows users to calculate normalized probabilities derived from the transmission rate and the number of available channels of the visible satellites. Note that the number of available channels is determined by the number of remaining serviceable users of each visible satellite. The user then selects one of the visible satellites based on the normalized probabilities. This approach reduces bottlenecks that occur in hotspot areas.

The rest of this paper is organized as follows: Section II describes the system model. Section III proposes a user-centric OHO scheme for LEO SatCom systems. Simulation results are analyzed in Section IV and conclusions are drawn in Section V.

II. System Model

A. Network Model

Let us consider a downlink communication from LEO satellites to users. The set of LEO satellites is denoted by $\mathbf{J} = \{1, 2, \ldots, J\}$. I users, the set of which is denoted by $\mathbf{I} = \{1, 2, \ldots, I\}$. Each satellite is assumed to have C_{max} channels, and each user served occupies only one channel. The time is divided into slots with the duration T_s. Then, if user i ($i \in \mathbf{I}$) locates in the coverage area of satellite j ($j \in \mathbf{J}$), i.e., satellite j is visible to user i, the overall channel power gain between user i and satellite j at slot t can be written as [13]

$$Q_{i,j}(t) = L_{i,j}(t) \cdot G_T(\varphi_{i,j}) \cdot G_R \cdot h_{i,j}(t), \tag{1}$$

where $L_{i,j}(t)$ is the free space loss, $G_T(\varphi_{i,j})$ is antenna gain of transmitter, G_R is antenna gain of receiver, and $h_{i,j}(t)$ is the small scale channel power gain between user i and satellite j in slot t, respectively. Moreover, $h_{i,j}(t)$ is assumed to follow the shadowed Rice fading model with the probability density function (PDF) given by [14]

$$\begin{aligned} f_{h_{i,j}|\theta_{i,j}(t)}(x) = \frac{1}{2b_{i,j}} \left(\frac{2b_{i,j}m_{i,j}}{2b_{i,j}m_{i,j} + \Omega_{i,j}} \right)^{m_{i,j}} \exp\left(\frac{-x}{2b_{i,j}} \right) \\ {}_1F_1\left(m_{i,j}, 1, \frac{\Omega_{i,j}x}{2b_{i,j}(2b_{i,j}m_{i,j} + \Omega_{i,j})} \right), \end{aligned} \tag{2}$$

where $2b_{i,j}$ being the average power of the multipath, $m_{i,j}$ denoting the Nakagami-m fading parameter, and $\Omega_{i,j}$ denoting the line-of-sight (LoS) components between user i and satellite j, respectively. Additionally, ${}_1F_1(\cdot,\cdot,\cdot)$ representing the confluent hypergeometric function. Moreover, the relations of parameters $b_{i,j}$, $m_{i,j}$, and $\Omega_{i,j}$ to elevation angle $\theta_{i,j}$, within the range $20^\circ < \theta_{i,j} < 80^\circ$, are given by [14]

$$\begin{aligned} b_{i,j} &= -4.7943 \times 10^{-8}\theta_{i,j}^3 + 5.5784 \times 10^{-6}\theta_{i,j}^2 \\ &\quad - 2.1344 \times 10^{-4}\theta_{i,j} + 3.271 \times 10^{-2}, \\ m_{i,j} &= 6.3739 \times 10^{-5}\theta_{i,j}^3 + 5.8533 \times 10^{-4}\theta_{i,j}^2 \\ &\quad - 1.5973 \times 10^{-1}\theta_{i,j} + 3.5156, \\ \Omega_{i,j} &= 1.4428 \times 10^{-5}\theta_{i,j}^3 - 2.3798 \times 10^{-3}\theta_{i,j}^2 \\ &\quad + 1.2702 \times 10^{-1}\theta_{i,j} - 1.4864. \end{aligned} \tag{3}$$

As the positions of users and satellites will not change significantly within one time slot, i.e., the elevation angle $\theta_{i,j}(t)$ can be viewed as static within one time slot, it is reasonable to assume that $Q_{i,j}(t)$ remains unchanged in each slot [12].

In slot t, a transmission rate between user i and satellite j is given by [12]

$$R_{i,j}(t) = B\log_2\left(1 + \frac{P_T L_{i,j}(t) G_T(\varphi_{i,j}) G_R h_{i,j}(t)}{\sigma^2} \right), \tag{4}$$

where B is the bandwidth of each channel, P_T is the transmit power, and σ^2 is the average power of additive white Gaussian noise (AWGN). Additionally, the transmission outage probability is determined by [12]

$$P_{i,j}^f = \Pr\{R_{i,j}(t) < R_{\min}\} = \int_0^{\phi_{i,j}(t)} f_{h_{i,j}|\theta_{i,j}(t)}(x)\,dx, \tag{5}$$

where $\phi_{i,j}(t) = \frac{\sigma^2\left(2^{R_{\min}/B}-1\right)}{P_T L_{i,j}(t) G_T(\varphi_{i,j}) G_R}$ and $R_{\min}$ denotes a minimum transmission rate.

B. User-Centric Soft Handover Mechanism

Due to the high mobility of LEO satellites, the available satellites for each user change dynamically. To enable users to track the highly dynamic LEO satellite network and avoid the transmission outage, we define the handover frame that includes T_H slots [12], as shown in Fig. 1. H. Liu *et al.* considered a hard handover procedure in the existing paper [12], such that if a user is blocked from the target satellite, the user does not receive service from any satellite. However, we consider a soft handover procedure in which, if a user is unable to successfully access the target satellite, the user continues to receive service from the serving satellite. In addition, we assumed that a user makes a handover decision when the average transmission rate between the user and the serving satellite in the previous handover frame is lower than the minimum transmission rate.

We consider the user-centric soft handover mechanism as follows:

- When an average transmission rate between the user and the serving satellite in the previous handover frame is lower than the minimum transmission rate, the user makes a handover decision at the beginning of the handover frame.

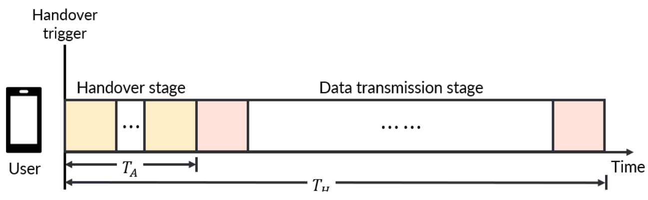

Fig. 1. A handover frame used in proposed OHO scheme.

- When the user does not make a handover decision in the current handover frame, then the entire T_H slots can be used for data transmissions from the serving satellite.
- When the user decides to perform the handover, then T_A slots, representing the handover stage duration, will be consumed.

III. The Proposed User-Centric OHO Scheme

Our main goal is to mitigate bottlenecks while efficiently utilizing the channel resources. The key idea is that a user randomly selects a target satellite based on the probabilities derived from the handover factors (i.e., the transmission rate and the number of available channels) of the visible satellites. The detailed procedure of the proposed OHO scheme is as follows:

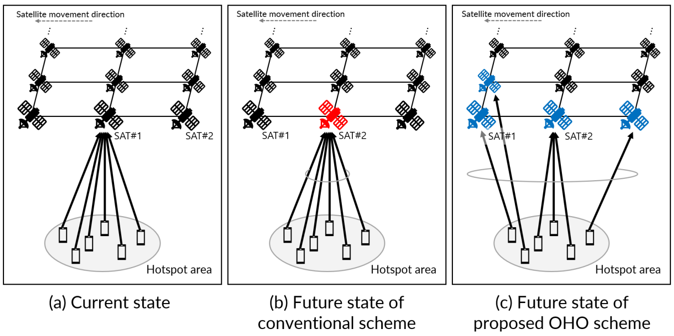

Fig. 2. Comparison of a target satellite selection method. (a) Current state (b) Future state of conventional scheme (c) Future state of proposed OHO scheme.

- **Step 1. Initialization:** The visible satellites of each user periodically send the handover factors to the user. The user measures the handover factors, including the distance between the user and the visible satellites, reference signals received power (RSRP) and the number of available channels of the visible satellites. Note that the transmission rate between the user and the visible satellites can be predicted through the measured distance and RSRP.
- **Step 2. Handover trigger:** When the average transmission rate between the user and the serving satellite in the previous handover frame is lower than the minimum transmission rate, the user makes a handover decision.
- **Step 3. Opportunistic handover decision:** The user calculates normalized probabilities derived from handover factors such as the transmission rate and the number of available channels of the visible satellites. Specifically, the formula for calculating the normalized probability derived from the transmission rate and the number of available channels of visible satellite j for user i in slot t is as follows:
$$\bar{p}_{i,j}(t) = \alpha \cdot \frac{R_{i,j}(t)}{\sum_{j=1}^{J} R_{i,j}(t)} + (1-\alpha) \cdot \frac{C_j(t)}{\sum_{j=1}^{J} C_j(t)}, \quad (6)$$
where $R_{i,j}(t)$ represents the transmission rate between the user i and the visible satellite j and $C_j(t)$ represents the number of available channels (i.e., the number of remaining serviceable users) of the visible satellite j. In (6), the relationship between the ratio $\alpha \in [0, 1]$ and the normalized probability $\bar{p}_{i,j}(t)$ is as follows:
  - If α approaches 1, more weight is given to the transmission rate between the user and each visible satellite.
  - If α approaches 0, more weight is given to the number of available channels of each visible satellite, which is advantageous in hotspot areas with extremely high user traffic. Since users at similar distances from a satellite experience comparable transmission rates, a transmission rate-based handover scheme leads most users to select the same target satellite, resulting in bottlenecks. Therefore, in highly dense areas, a handover scheme that places greater weight on the number of available channels of each visible satellite, rather than the transmission rate, as a handover factor is more advantageous.
  - If α is 1/2, the transmission rate and the number of available channels of each visible satellite are considered equally.

  The performance of the proposed OHO scheme in terms of the number of handovers, average blocking rate, and average throughput depends on what α value is. The user then randomly selects one of the visible satellites based on the normalized probabilities $\bar{p}_{i,j}$ calculated.
- **Step 4. Handover stage:** After the user makes a handover decision, the user then enters a handover stage. The user sends a *Handover Request* to the target satellite. The target satellite that received the *Handover Request* then performs admission control. If the target satellite has sufficient available channels, it sends a *Handover Request ACK* back to the user.
- **Step 5. Data transmission stage:** If the user receives the *Handover Request ACK*, the user successfully accesses the target satellite and then disconnects from the current serving satellite. On the other hand, if the target satellite blocks the user due to insufficient available channels, the user continues to receive service from the current serving satellite.

The proposed OHO scheme enables more efficient channel resource utilization compared to existing handover schemes in hotspot areas. In conventional user-centric handover schemes, users select an appropriate target satellite by considering handover factors such as service time, maximum elevation angle, the transmission rate, the number of available channels, and the movement direction of the visible satellites. Specifically, in the SDQL scheme [12], users select a satellite via reinforcement learning by considering the transmission rate, the number of available channels, and the movement direction of the visible satellites. However, users in similar locations have similar distances to the satellites, resulting in comparable transmission rates between the users and satellites. Additionally, since the set of the visible satellites is similar, handover factors such as the number of available channels and the movement directions of the visible satellites are similar. Therefore, as shown in Fig. 2(b), most users are likely to select the same target satellite, increasing bottlenecks.

On the other hand, when the proposed OHO scheme is applied in hotspot areas, it reduces bottlenecks by allowing users to select various satellites, as shown in Fig. 2(c). In the proposed OHO scheme, each user selects a target satellite based on normalized probabilities derived from the transmission rate and the number of available channels of the visible satellites. Therefore, unlike conventional schemes, users are unlikely to select the same target satellite in hotspot areas. Thus, even though the existing SDQL scheme applies complex reinforcement learning, the proposed OHO scheme, which simply leverages randomness, outperforms it in terms of average blocking rate and average throughput in hotspot areas.

TABLE I
SIMULATION PARAMETERS

Notation	Value
Maximum antenna gain of transmitter $G_{\max}$	30dBi
Antenna gain of receiver G_R	0dBi
Transmit power of spotbeam P_T	16dBW
Bandwidth of users B	2MHz
Minimum transmission rate $R_{\min}$	2Mbps
Carrier frequency f_T	20GHz
Noise power spectral density	-173dBm/Hz
Arrival rate λ	0.1s^{-1}
Duration of a slot t	10ms
Duration of an accessing process T_A	100ms
Duration of a handover frame T_H	1000ms
Size of a packet S_P	1000bits
Simulation time	10min

IV. Simulation Results

In this section, we evaluate the performance of the proposed OHO scheme and compare it with the following handover schemes:

- **Random scheme:** Users randomly select one of the visible satellites when a handover is triggered.
- **Maximum Elevation angle-based (ME) scheme:** Users select a satellite with the maximum elevation angle when a handover is triggered.
- **Successive Deep Q-Learning (SDQL) scheme [12]:** Users select a satellite with maximum Q-value, taking into account both the transmission rate and the number of available channels of the visible satellites via reinforcement learning when a handover is triggered.

The satellite constellation is constructed as described in the existing paper [12]. The constellation consists of 18 planes, each containing 40 deployed satellites. The altitude and inclination of each plane are 1200 km and 90°, respectively. The minimum elevation angle of visible satellites is 20°. Users are assumed to be uniformly distributed in a square area with a side length of 220km, centered on (40°N, 116°E). We assumed an equal antenna gain of transmitter in this paper [15]. Users' service arrivals are modeled as a Poisson process with an arrival rate λ. Since the speed of the satellites is much larger than the moving speed of the users, we assumed that the users are stationary with respect to the Earth's surface. The Earth's rotation is taken into consideration in the simulation. The rest of the parameters are provided in TABLE I.

Fig. 3 and Fig. 4 show the average blocking rate and the average number of handovers, respectively. The average blocking rate is the value obtained by dividing the block count for each user by the average number of handovers. The average number of handovers is the value obtained by dividing the average number of handover decisions per user by the simulation time. We can observe that the schemes based on randomness outperform the ME and SDQL schemes. In particular, the ME scheme has the worst performance since a target satellite with the maximum elevation angle for each user in similar locations is almost the same. Therefore, most users will be blocked from the target satellite with limited channel resources. Whenever a user is blocked from the target satellite, the user makes a new handover decision. Therefore, a higher blocking rate results in an increase in the average number of handovers, as shown in Fig. 4.

Similarly, the performance of the SDQL scheme is poor, since this scheme is location-dependent. Specifically, since users select a target satellite based on the transmission rate, the number of available channels, and the movement direction of the visible satellites, this leads to users in densely populated areas attempting handover access converging on a certain target satellite. Therefore, the SDQL scheme results in a high blocking rate. The high blocking rate also leads to an increase in the average number of handovers.

In addition, among the schemes based on randomness,

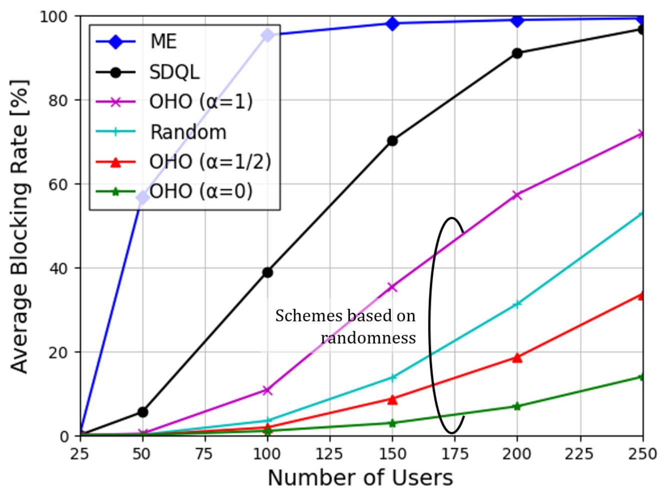

Fig. 3. The average blocking rate from a serving satellite over the number of users

the proposed OHO scheme (α = 0) performs the best. It is followed by the proposed OHO scheme (α = 1/2), the random scheme with no consideration of handover factors, and finally the proposed OHO scheme (α = 1). The proposed OHO scheme (α = 1) exhibits both a higher average blocking rate and a higher average number of handovers than other schemes based on randomness as the number of users increases, performing even worse than the random scheme with no consideration of handover factors of the visible satellites. Because this scheme considers the transmission rate when a handover is triggered, most users with similar transmission rates tend to select the same target satellite. This leads to a high blocking rate and a high average number of handovers. Nevertheless, the proposed OHO scheme significantly outperforms the ME and SDQL schemes in terms of the average blocking rate and the average number of handovers. Additionally, since the proposed OHO scheme (α = 1/2) considers not only the transmission rate but also the number of available channels,

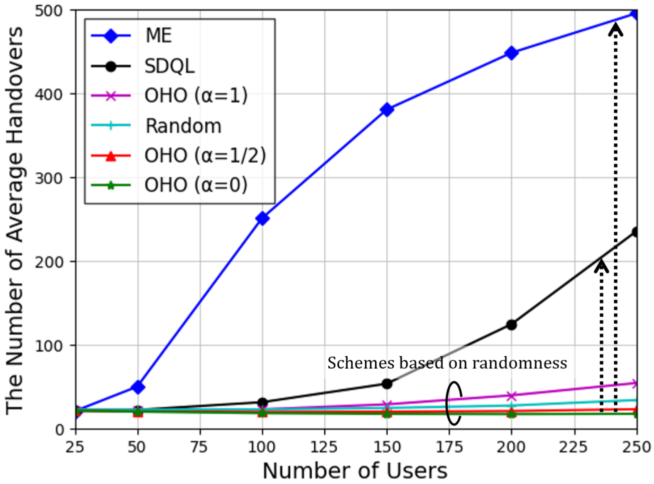

Fig. 4. The average number of handovers over the number of users

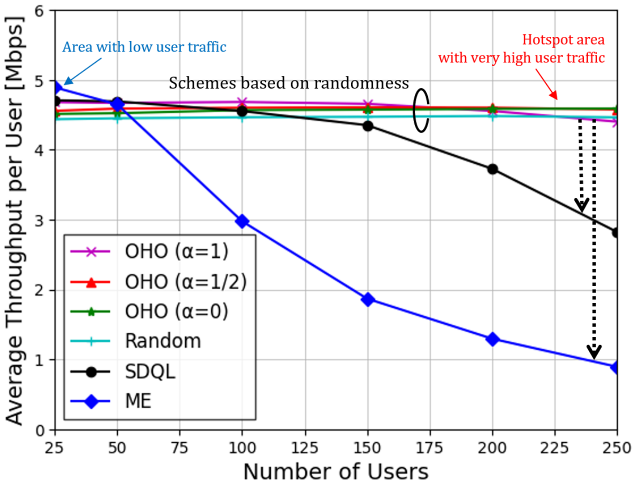

Fig. 5. The average throughput over the number of users

this scheme improves performance over the proposed OHO scheme (α = 1). In the proposed OHO scheme (α = 0), users randomly select a satellite based only on the number of available channels, which enables them to effectively alleviate bottlenecks and achieve the best performance in both the average blocking rate and the average number of handovers.

Fig. 5 shows the average throughput per user. The ME scheme has the best average throughput performance when the number of users is 25 (i.e., when the user traffic is low) since users always select the closest satellite with the maximum elevation angle without considering the number of available channels of the satellite. However, as the number of users increases, the average throughput performance of the ME scheme deteriorates rapidly. Compared to the ME scheme, the average throughput performance of the SDQL scheme considering the number of available channels of the satellite deteriorates slowly as the number of users increases. Compared to the conventional schemes without randomness, the performance of the schemes based on randomness almost does not deteriorate even as the number of users increases. In addition, the proposed OHO scheme outperforms the random scheme in most areas. However, when the number of users is larger than about 225 (i.e., when the user traffic is very high), the random scheme outperforms the proposed OHO scheme (α = 1). Because users located at similar distances receive service at similar transmission rates, applying a handover scheme based on transmission rates in highly dense areas causes most users to select the same target satellite. This increases bottlenecks and reduces the average throughput per user.

V. Conclusions

In this paper, we investigate the user-centric handover problem for LEO SatCom systems, especially in hotspot areas. Specifically, we propose a new user-centric handover scheme that enables users to efficiently select a target satellite when making a handover decision. The proposed OHO scheme that leverages randomness is designed to maintain reliable satellite connections while mitigating bottlenecks. Simulation results demonstrate that the proposed OHO scheme lowers the average blocking rate and the average number of handovers, and improves the average throughput compared to conventional techniques. Future research could explore a user-centric handover strategy that enables efficient channel resource utilization in various satellite constellation environments.

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