Demand-aware Flexible Handover Strategy for LEO Constellation

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***Abstract*—Low-earth orbit (LEO) satellites will play a significant role in 6G and beyond systems to provide global connectivity. For this, multiple satellites should work together to provide the required services to ground users. Each satellite only views a user for a few minutes, thus a user needs to apply a handover strategy to switch to another satellite. However, the handover strategy needs to be optimal to avoid frequent and unnecessary handovers. While the existing handover strategy is purely based on system geometry, it may not be efficient when user demand changes dynamically. This paper considers a demand-aware flexible handover strategy to obtain a minimum number of handovers while continuously satisfying user demand. The simulation results show that using the proposed handover strategy, the system requires fewer handovers than using the benchmark schemes.**

***Index Terms*—Demand-aware handover, LEO satellite, handover strategy, satellite constellations.**

I. Introduction

Satellite communication has been a crucial technology in providing internet access to areas where terrestrial networks cannot provide service. In 6G and beyond systems, satellite communication is expected to play an even more critical role in delivering broadband internet services across the globe. Due to its broad coverage capabilities, satellite communication can provide connectivity to remote areas that terrestrial networks cannot cover and underserved areas with limited terrestrial networks [1]. To achieve this level of coverage, multiple satellites are often required to form a constellation. A satellite constellation is a group of satellites that work together to provide continuous coverage over a specific region or the entire globe. These satellites are carefully designed to maintain their relative positions and coordinate with each other to ensure seamless coverage without any gaps or overlaps [2].

The Low Earth Orbit (LEO) constellations have lower latency and a better link budget than Medium Earth Orbit (MEO) [2] and Geostationary Earth Orbit (GEO) [3] satellites. However, the LEO satellite's speed is extremely fast compared to a user terminal position on the ground, thus each satellite can only serve a user for a few minutes. Hence, the user must initiate handover strategies to another visible satellite to remain connected. In this case, a poor handover strategy can lead to frequent and unnecessary handovers of users' terminals. This increases signaling overhead, resulting in high power consumption and interruptions due to signaling latency. Hence, an optimal design of handover strategies is required to minimize frequent handovers.

Several handover techniques have been proposed in the literature for LEO constellation. In [4], a graph-based approach has been proposed for handling satellite handovers in low earth orbits. The satellite handover process, in this case, is viewed as finding a path in a directed graph, where the node of the graph is assumed to be the covering period of the satellite, and the link of the graph is assumed to be the possible handover between two overlapping periods. In [5], a network-flow graph has been developed for the satellite handover problem, where the handover is determined by the minimum cost and maximum flow of the graph. Similarly, in [6], a graph-based handover framework has been proposed to overcome frequency handovers between aircraft and LEO satellites while optimizing the system's overall throughput. Furthermore, performance analysis of different handover methods through extensive system-level simulations has been studied in [7]. Our recent works in [8], [9] have focused on determining the optimal association between LEO satellites, BSs, and users (UEs) in an integrated satellite-terrestrial network, where Low-Earth-Orbit (LEO) satellites are used to provide the backhaul link between base stations (BSs) and the core network. The works also aim to ensure load balance and optimize the capacity of the serving link between the BS and the LEO satellite. However, the design of the above-mentioned techniques does not consider the time-varying demand of the users, which may not be optimal when user demand changes dynamically [10].

Demand-based optimization for allocating satellite resources such as power and bandwidth has been extensively studied in the literature [11]–[15]. This method is shown to be effective since it allocates fewer resources to users with low demand while more to users with high demand. However, the impact of user demand on handover optimization has not been explored yet. In this paper, we design a demand-aware flexible handover strategy to obtain a minimum number of handovers required to satisfy continuously each user demand over the orbital period. Consequently, we can decrease the signaling overhead caused by frequent handovers. The contribution of the paper is described as follows.

- Firstly, we propose a satellite constellation design for the Walker-star configuration. For this, we first determine the radius coverage of the satellite for a given elevation angle. Accordingly, we obtain the required number of satellites and geometric plans that satisfies the Walker-star constellation design.
- Secondly, we propose a demand-aware flexible handover strategy for 6G and beyond non-terrestrial networks. In this case, we determine the minimum handover required by the user terminal by formulating and solving an optimization problem while considering user demand, service time, and elevation angle.
- Finally, we compare the performance of the proposed method with benchmark schemes through extensive numerical results. It is shown that the demand-aware handover strategy provides less number of handovers than the benchmark schemes.

The paper is organized as follows. Section II provides the system model. Section III contains the problem formulation and the proposed solution. The simulation result is presented in Section IV. Finally, the contribution of the paper is concluded in Section V.

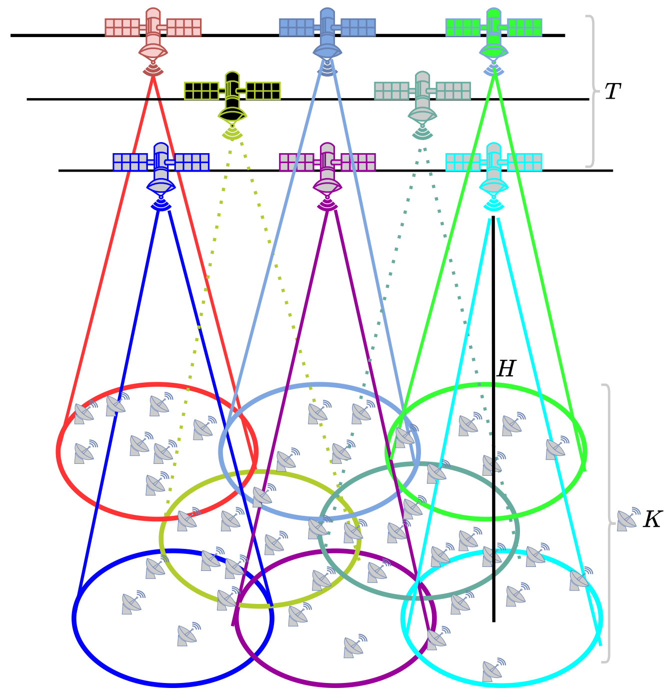

Fig. 1. LEO constellation.

II. System Model

Consider a downlink LEO constellation with T satellites at altitude H serving K users, as shown in Fig. 1. Each satellite covers a certain geographical area which is indicated by a circle in Fig. 1. Furthermore, a user can be seen by multiple satellites depending on its elevation angle.

The time visibility of a satellite j to a user k is denoted as $\mathcal{T}_{k,j}^{t}$. Furthermore, we define a satellite handover indicator[1] as $x_{k,j}^{t} \in \{0,1\}$ and $x_{k,j}^{t} = 1$ means the user k at time t is connected to satellite j. Additionally, at time t, a user k must be connected to only one satellite, thus $\sum_{j=1}^{T} x_{k,j}^{t} \leq 1$.

A. Satellite constellation design

We consider a Walker-star constellation I: T/P/F, where I is the orbital inclination, T is the total number of satellites, F is the phasing between satellites in adjacent planes, P is the number of equally spaced geometric planes which are distributed over a span of 180 degrees.

To determine T and P, first, we calculate the radius coverage of a satellite at a given elevation angle δ which is provided as follows[2] [16].

$$R_s = R_E \left(\frac{\pi}{2} - \delta - \arcsin \left(\frac{R_E}{R_E + H} \cos \delta \right) \right), \quad (1)$$

where R_E is the radius of the earth. The coverage of satellite is shown in Fig. 2. Then, assuming an overlapped circular coverage area, T and P are obtained as

$$T = \left\lceil \frac{180}{\mathcal{D}\frac{\sqrt{3}}{2}} \right\rceil \left\lceil \frac{360}{\mathcal{D}\frac{\sqrt{3}}{2}} \right\rceil, \quad (2)$$

$$P = \left\lceil \frac{180}{\mathcal{D}\frac{\sqrt{3}}{2}} \right\rceil, \quad (3)$$

where $\mathcal{D} = \frac{360 R_s}{\pi R_E}$ is the diameter of the coverage area in degree and $\mathcal{D}\frac{\sqrt{3}}{2}$ is the distance in degree between adjacent satellites from the center of the coverage area[3] [17]. Additionally, we chose the value of F to be between 0 and $P-1$ that

[1]This work focuses on satellite-to-satellite handover; beam-to-beam handover within satellites is not considered.

[2]For this calculation the unit of δ is in rad.

[3]We can simplify (2) and (3) as follows.

$$T = \left\lceil \frac{\pi}{\sqrt{3}\theta} \right\rceil \left\lceil \frac{2\pi}{\sqrt{3}\theta} \right\rceil, \quad (4)$$

$$P = \left\lceil \frac{\pi}{\sqrt{3}\theta} \right\rceil, \quad (5)$$

where θ is in rad given by

$$\theta = \left(\frac{\pi}{2} - \delta - \arcsin \left(\frac{R_E}{R_E + H} \cos \delta \right) \right), \quad (6)$$

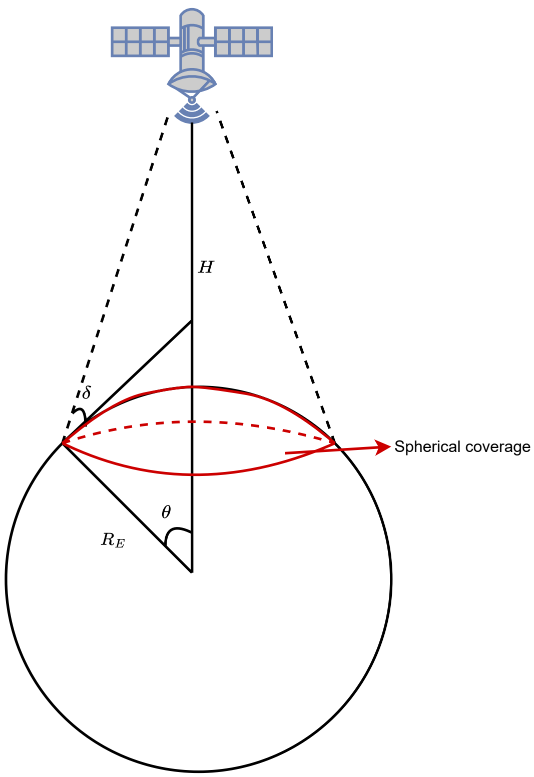

Fig. 2. Coverage geometry [16].

minimizes the maximum distance between adjacent satellites, as follows:

$$\begin{aligned} \underset{F}{\text{minimize}} \quad & \sum_{j=1}^{T} \max_{j} \{\Phi_{j,i}^{F}\} \\ \text{s.t.} \quad & F \in \{0, P-1\}, \end{aligned} \tag{7}$$

where $\Phi_{j,i}^{F}$ is the distance between the jth satellite and the ith adjacent satellite when the constellation uses the phasing F. Hence, the solution to (7) is the value of F that gives the minimum value of its objective function.

Finlay, the orbital period [18] ($\mathcal{T}$) is given by

$$\mathcal{T} = \sqrt{\frac{4\pi^2}{\mu}(R_E + H)^3}, \tag{8}$$

where μ is Kepler's Constant. The design of the satellite constellation at $H = 1200$ km and $\delta = 0.6109$ rad is shown in Fig. 3. In this case, T = 190, P = 10, F = 9 and $\mathcal{T}$=1.8237 hours.

B. Channel Capacity

The channel coefficient at time t from satellite j towards user k is given by

$$h_{k,j}^{t} = \frac{\sqrt{G_R G_{k,j}^{t}}}{4\pi \frac{d_{k,j}^{t}}{\lambda}}, \tag{9}$$

where λ is the is the wavelength, G_R is the user antenna gain, $G_{k,j}^{t}$ denotes the received gain from the jth satellite by the kth user and $d_{k,j}^{t}$ is the slant range between the satellite j and the kth user.

The signal-to-noise ratio (SNR) received by the kth user from satellite j is given by

$$\gamma_{k,j}^{t} = x_{k,j}^{t} \frac{S|h_{k,j}^{t}|^2}{N_0}. \tag{10}$$

where S is the power spectral density and N_0 is the noise spectral density. Note that we do not consider interference among users since we assume that the system uses interference management techniques (e.g. four-color frequency reuse). Then, the Shannon capacity for the kth user from the jth satellite is

$$C_{k,j}^{t} = B \log_2(1 + \gamma_{k,j}^{t}). \tag{11}$$

Hence, the overall capacity obtained by the kth user is provided as

$$C_{k}^{t} = \sum_{j=1}^{T} C_{k,j}^{t}. \tag{12}$$

III. Problem Formulation and Proposed Solution

In this work, we want at time t the jth satellite to remain connected with a user k as far as 1) the satellite offered capacity meets the user demand, i.e., $C_k^t \geq D_k$, 2) the time visibility of the satellite to a user k at least have the minimum time visibility (τ), i.e. $\mathcal{T}_{k,j}^{t} \geq \tau$ and 3) the user k elevation angle ($\mathcal{E}_{k,j}^{t}$) satisfies the minimum elevation angle (ϵ), i.e. $\mathcal{E}_{k,j}^{t} \geq \epsilon$. Otherwise, the user requests a handover to another satellite that meets the above requirements. Accordingly, we can determine the optimal number of handovers required by the system to satisfy user demand over a given orbital period $\mathcal{T}$. In this context, let $x_{k,j}^{t-1}$ be the previous connectivity status between the kth user and the jth satellite. Then we define a handover indicator function for user k at time t as follows.

$$\mathcal{HI}_{k,j}^{t} = |x_{k,j}^{t} - x_{k,j}^{t-1}|, \tag{13}$$

and $\mathcal{HI}_{k,j}^{t} = 0$ means no handover is required. Accordingly, we formulate an optimization problem to minimize the handover indicator function at time t as follows.

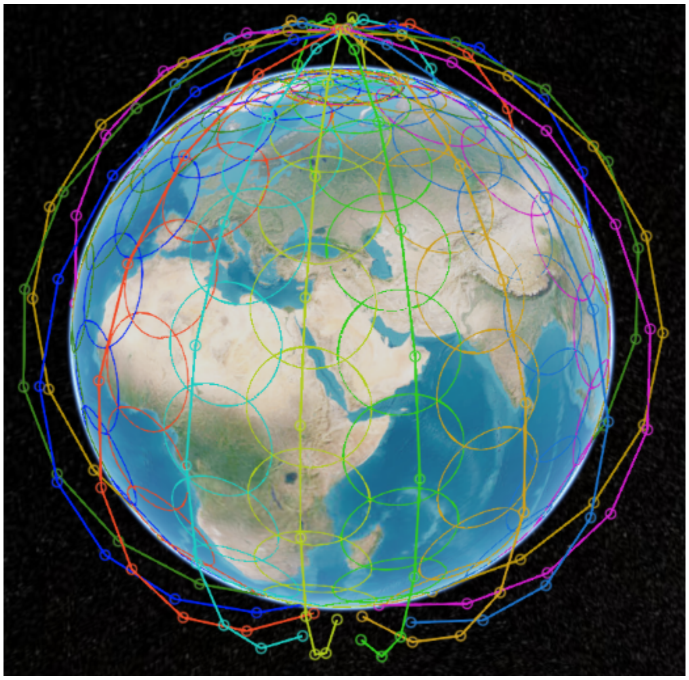

Fig. 3. Walker-star constellation.

$$\begin{aligned}
&\underset{x_{k,j}^t \forall_{k,j}}{\texttt{minimize}} \quad \sum_{j=1}^{\mathrm{T}} \sum_{k=1}^{\mathrm{K}} \frac{\mathcal{H}\mathcal{I}_{k,j}^t}{\mathcal{T}_{k,j}^t} \\
&\texttt{s.t.} \\
&\quad L1: \sum_{j=1}^{T} x_{k,j}^t = 1, \forall_k, \\
&\quad L2: \sum_{k=1}^{K} x_{k,j}^t \leq N, \forall_j, \\
&\quad L3: x_{k,j}^t \leq \min\left\{1, \left\lfloor \frac{\mathcal{T}_{k,j}^t}{\tau} \right\rfloor \right\}, \forall_k, j, \\
&\quad L4: x_{k,j}^t \leq \min\left\{1, \left\lfloor \frac{\mathcal{E}_{k,j}^t}{\epsilon} \right\rfloor \right\}, \forall_k, j, \\
&\quad L5: x_{k,j}^t \in \{0,1\}, \forall_{k,j}. \\
&\quad L6: C_k^t \geq D_k, \forall_k.
\end{aligned} \tag{14}$$

The objective function is weighted by $\mathcal{T}_{k,j}^t$ to ensure that most users are connected to satellites with high time visibility. In constraint $L1$, a user should only be assigned to one satellite. On the other hand, the $L2$ constraint indicates that a satellite can serve up to N users. Furthermore, the constraint $L3$ states that a user must not be connected to a satellite that does not meet the minimum time visibility τ. Additionally, $L4$ ensures that the satellite-to-user elevation angle must satisfy the minimum elevation angle ϵ. The $L5$ constraint refers to a binary handover indicator. Finlay, $L6$ guarantees that the offered capacity by the satellite must meet user demand.

Problem (14) is an integer program that can be solved by the MOSEK solver using the CVX tool [19]. In particular, the MOSEK solver uses the Branch & Bound technique to handle integer optimization. In principle, the Branch & Bound technique reduces the search space by solving the problem in every iteration. Since, in successive iterations, the search space size of the optimization decreases, the solution obtained from it converges to a stationary point. Furthermore, iteration ends when the algorithm's optimality gap is sufficient. For more detail on the Branch & Bound algorithm and its termination criteria, see [20].

TABLE I
SYSTEM PARAMETERS

Parameter	**Value**
Satellite Altitude (H)	1200 km
Orbital Inclination (I)	90°
Number of Satellites (T)	190
Phasing (F)	9
Planes (P)	10
Orbital period ($\mathcal{T}$)	1.8237 hours
Elevation angle (δ)	0.6109 rad
Minimum user Elevation angle (ϵ)	5°
Minimum time visibility (τ)	50 ms
User Bandwidth (B)	250 MHz
Noise power density (N_0)	-204 dBW/Hz
Satellite gain ($G_{k,j}^t$)	38.5 dBi
User antenna gain (G_R)	38.5 dBi
Power spectral density (S_{spd})	-88.5 dBW/Hz

IV. SIMULATION RESULTS

In this section, the performance of a demand-aware flexible handover strategy (HO_{DA}) is evaluated through simulation. The system parameters used for this simulation are shown in Table I. We consider $T = 190$ satellites with $P = 10$. Furthermore, a satellite is assumed to serve a single user, thus $N = 1$. Additionally, the requested demand is assumed to be equal for all users at any time t, i.e., $D_k^t = D, \forall_k$. The other parameters in TABLE I are obtained from 3GPP TR 38.821 [21].

We compare the performance of the proposed method with the benchmark of non-demand aware handover optimization provided in (15).

$$\begin{aligned}
&\underset{x_{k,j}^t \forall_{k,j}}{\texttt{maximize}} \quad \sum_{j=1}^{\mathrm{T}} \sum_{k=1}^{\mathrm{K}} \mathcal{W}_{k,j}^t x_{k,j}^t \\
&\texttt{s.t.} \\
&\qquad L1 - L5.
\end{aligned} \tag{15}$$

The following are the benchmark schemes deduced from (15).

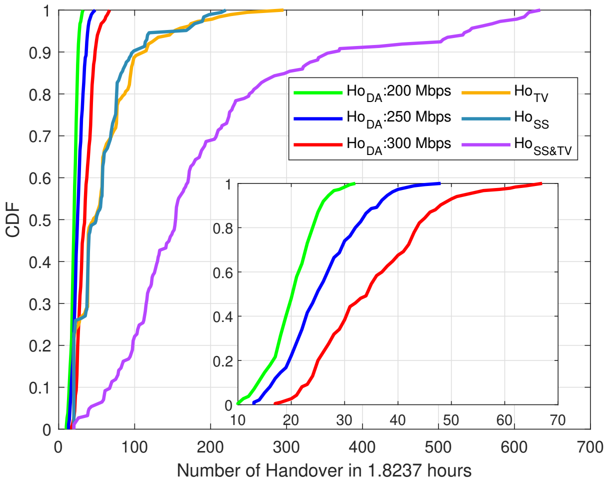

Fig. 4. Handover comparison of the proposed method vs. benchmark schemes.

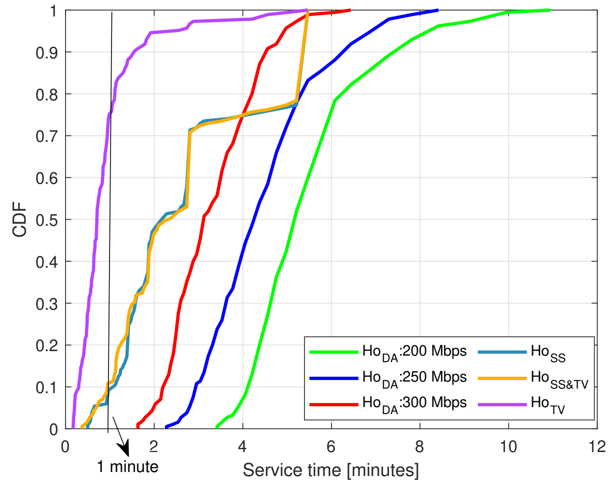

Fig. 5. Service time comparison of the proposed method vs. benchmark schemes.

1) Handover based on user received Single Strength ($\mathrm{HO_{SS}}$): We obtain this method from (15) for $\mathcal{W}_{k,j}^t = \gamma_{k,j}^t$.
2) Handover based on satellite Time-Visibility ($\mathrm{HO_{TV}}$): This method is obtained from (15) when $\mathcal{W}_{k,j}^t = \mathcal{T}_{k,j}^t$.
3) Handover based on both user single Strength and Satellite Time Visibility ($\mathrm{HO_{SS\&TV}}$): In this case, $\mathcal{W}_{k,j}^t = \mathcal{T}_{k,j}^t \gamma_{k,j}^t$.

Fig. 4 shows the CDF of the handovers initiated by the satellites/users for the proposed and benchmark schemes in 1.8237 hours of the orbital period. In this case, the proposed method uses less number of handovers than the benchmark schemes. For example, for $\mathrm{HO_{DA}}$, to serve 90% of the users, 25, 36, and 48 handovers are required per user when the demand is 200 Mbps, 250 Mbps, and 300 Mbps, respectively. In contrast, in the case of $\mathrm{HO_{SS}}$, $\mathrm{HO_{SS\&TV}}$, and $\mathrm{HO_{TV}}$, 99, 113, and 370 handovers are required per user, respectively, over the orbital period to serve 90 % the users continuously.

Generally, using the proposed method, the whole network has fewer handovers than the benchmark schemes. This is shown in TABLE II, which describes the average handover required by a user in 1.8237 hours of the orbital period. In this case, the $\mathrm{HO_{DA}}$ for 200 Mbps, 250 Mbps, and 300 Mbps, uses 21, 27, and 36 handovers, respectively, while $\mathrm{HO_{SS}}$, $\mathrm{HO_{TV}}$, and $\mathrm{HO_{SS\&TV}}$ requires 60, 192, 61, respectively. Consequently, the proposed method reduces the number of handovers by 40%, 41% and 81% compared to the $\mathrm{HO_{SS}}$, $\mathrm{HO_{SS\&TV}}$, and $\mathrm{HO_{TV}}$ methods, respectively.

Fig. 5 shows the CDF of satellite average service time for a user in the case of the proposed method and the benchmark schemes. The service time is obtained as the orbital period divided by the number of handovers. We observe that the service time of the proposed method is longer than the benchmark schemes. For example, at 1 minute service time, the proposed method can serve all users. In contrast, the $\mathrm{HO_{SS}}$, $\mathrm{HO_{SS\&TV}}$, and $\mathrm{HO_{TV}}$ can serve only 20%, 95%, and 95% of users, respectively. Additionally, the service time of 5 % of the users by the satellite is less than 1 minute in the case of the benchmark schemes. As a result, service interruptions may increase during the handover process. However, $\mathrm{HO_{DA}}$ service time is longer; thus, the service interruptions are less during the handover process.

The $\mathrm{HO_{DA}}$ provides flexible handover management depending on the demand of users. As can be seen in Fig. 1 and TABLE I, for low demand, the user needs a few handovers to be continuously served by multiple satellites. This is because the proposed method allows most users to remain connected with their respective satellite even at a small elevation angle as long as the received SNR satisfies the user demand. Hence, it may not be necessary to have a high SNR for low demand, as shown in Fig. 6. For instance, at 200 Mbps, the average SNR received by the user is between 5 and 7. However, in high demand, users need to switch to a satellite that provides a higher SNR, resulting in more handovers than when there are low demands. Accordingly, at 300 Mbps, the average SNR is between 8 and 10. In benchmark schemes, the received SNR is always independent of user demand. For instance, the SNR for $\mathrm{HO_{SS}}$ and $\mathrm{HO_{ss\&TV}}$ is between 13 and 14. However, the number of handovers required by $\mathrm{HO_{SS}}$ and $\mathrm{HO_{ss\&TV}}$ to select satellites with such SNR is very high and may not be practical. In the case of $\mathrm{HO_{TV}}$, we observe that it is inefficient in terms of handover management.

V. Conclusions

In this paper, we study a demand-aware flexible handover strategy for LEO constellations. The proposed method requires

TABLE II

THE AVERAGE NUMBER OF HANDOVER OVER 1.8237 HOURS

Method	HO_{DA} 200 Mbps	HO_{DA} 250 Mbps	HO_{DA} 300 Mbps	HO_{SS}	HO_{TV}	$HO_{SS\&TV}$
Handover	21	27	36	60	192	61

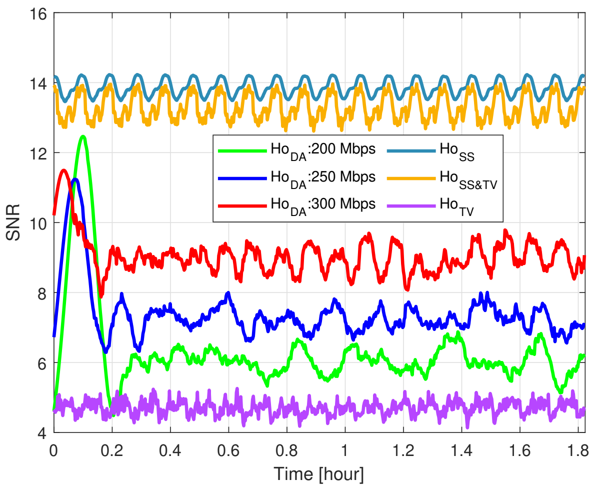

Fig. 6. The average SNR received by a user over the orbital period.

fewer handovers to serve a user throughout the orbital period continuously than the benchmark schemes. In the future, we will examine the performance of the proposed method when a satellite serves multiple users while including the effect of rain and cloud attenuation in the channel model.

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