A User-Centric Handover Scheme for Ultra-Dense LEO Satellite Networks

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***Abstract*—In recent years, low earth orbit (LEO) satellite networks (LSNs) have attracted increasing attention due to economic prospect and advantages in high bandwidth and low latency. In order to provide higher quality of service (QoS) and address the frequent handover problem among LEO satellites, we propose a user-centric handover scheme for ultra-dense LSNs in this letter. Our basic idea is to exploit satellite's storage capability to improve user's communication quality. By buffering user's downlink data in multiple satellites simultaneously, the terrestrial user can realize seamless handover and always access the satellite with the best link quality. Simulation results show that our user-centric handover scheme outperforms the traditional handover scheme in terms of throughput, handover delay and end-to-end latency.**

***Index Terms*—LEO satellite networks, Internet access service, user-centric handover.**

I. INTRODUCTION

COMPARED with medium earth orbit (MEO) and geostationary earth orbit (GEO) satellites, low earth orbit (LEO) satellites have ability to achieve lower propagation latency and higher throughput, which provide a promising composition for future satellite networks. Unfortunately, due to the high mobility of LEO satellites, it is inevitable that frequent handover occurs between a terrestrial user and LEO satellites. Such frequent handovers have severe impact on the quality of service (QoS) provided by LEO satellite networks (LSNs). In traditional LSNs, only voice call service is considered and the handover schemes mainly targeted at seamless call service for terrestrial users [1]–[3]. However, in recent years, high-speed data service over Internet provided by LSNs has become a trend, such as the large-scale LSNs constructed by SpaceX (starlink project) and OneWeb (WorldVu constellation), which aim to launch thousands of LEO satellites and deploy ultra-dense constellation [4]–[8]. Given such applications, there is no doubt that high QoS requirements on low delay, large bandwidth and high robustness are preferred. Unfortunately, most traditional handover schemes, which were mainly designed for call services, can hardly satisfy these requirements.

In 1990s, a number of related works on the satellite handover have been done with the practical application of LEO system like Iridium. Del Re *et al.* [9] proposed a handover prioritization scheme, which utilizes the queuing of handover requests or reserves resources before handover occurrence in case there is no channel available in the destination cell. In [10], Maral *et al.* proposed a guaranteed handover scheme, which dynamically reserves the channel resource to maintain user's communication. After the millennium, Gkizeli *et al.* [1] considered satellite diversity and candidate set to ensure efficient handover according to real-time channel status for voice call services. Tsunoda *et al.* [11] proposed a mobility management scheme to make IP address independent of logical location but associate it with geographical location. Yang *et al.* [3] proposed a seamless handover scheme based on a software defined network (SDN) satellite architecture, which utilizes SDN controllers to make proactive data transfer through inter-satellite links when a user handovers its service from one satellite to another. Considering the predictable satellite trajectory, Wu *et al.* [12] proposed a novel method to model satellite handover design as a path-finding problem in the directed graph, which achieved flexible satellite handover.

The above work only consider handover schemes for Iridium-like constellation and call service with the objective of reducing call dropping rate and handover delay. These simple QoS criteria can hardly satisfy the performance requirements for numerous Internet-based data services. Inspired by rapid switching scheme in [13], in this letter, we propose a user-centric handover scheme for ultra-dense LSNs to better cope with this problem. The basic idea is to simultaneously buffer user's downlink data in multiple satellites to make sure that a terrestrial user can realize seamless and low-latency handover during communications. Specifically, we introduce the real-time signal measurement during handover window and discuss the criteria of updating candidate access satellites. Then, we evaluate the performance of our proposed scheme in an open-source simulator, and validate its advantages in terms of throughput, handover delay and end-to-end latency.

II. SEAMLESS SATELLITE HANDOVER SCHEME

A. Basic Idea & Handover Procedure

In this letter, we consider a LSN which provides Internet access service for terrestrial users. Each terrestrial user is covered by multiple LEO satellites simultaneously and he/she uses portable satellite terminal (PST) to establish communication link with a LEO satellite. Once a terrestrial user accesses the

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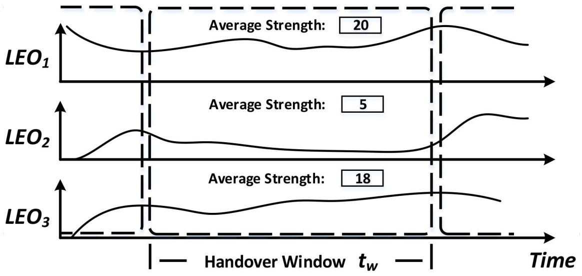

Fig. 1. Example of recorded RSSI information in each handover window.

LSN, he/she will be allocated with multiple candidate access satellites (CASs). During the communications with the LSN, the user can choose any satellite among CASs as the main access satellite (MAS) for current data transmissions according to the quality of the satellite-to-terrestrial link. For each satellite in CASs, it reserves a certain buffer space for the user and stores the user's downlink frames forwarded by ground station[1] through multicast. In this case, whenever the user decides to handover among CASs, he/she can get requested data immediately.

The procedure of satellite-to-terrestrial communication is divided into two steps, namely, communication setup and seamless handover. The detailed description is given as follows.

1) Communication Setup: Before a terrestrial user can access the LSN, his/her PST should search for periodic broadcast signal from LEO satellites. Once PST receives the broadcast signal from LEO satellites (at least one satellite's signal), it will measure every received signal strength indicator (RSSI) and choose the LEO satellite with the strongest signal as the MAS. To setup a connection, PST should send a request containing authentication information to the MAS. Once the access request is granted, PST will be allocated communication resources (containing access spectrum, onboard buffer space and IP address) and CASs.

2) Seamless Handover: During communications between PST and the MAS, channel conditions could vary significantly due to channel fading from LEO satellite mobility, thermal noises and blockage. To guarantee QoS, PST measures and records RSSI information of CASs periodically, a.k.a., every handover window, as shown in Fig. 1. The average strength of each link in a handover window can be calculated by

$$P_{avg} = \frac{1}{N_w} \sum_{t=t_0}^{t_w} P_t, \tag{1}$$

where t_w is the time duration of handover window and N_w is the number of measured RSSI records during a handover window. After each handover window, PST will make handover decision to choose the satellite with the strongest signal strength according to recorded RSSI information. For example, in Fig. 1, LEO_1 should be chosen as the MAS in the next handover window.

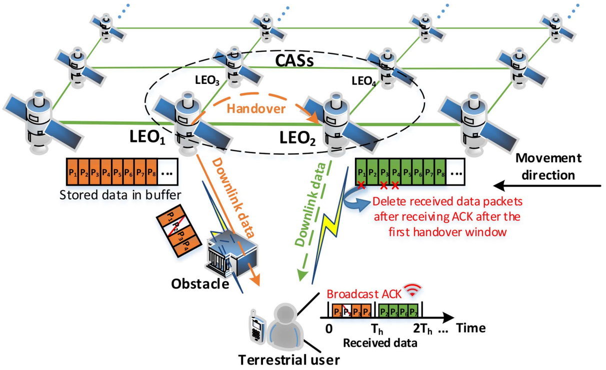

Fig. 2. The illustration of user-centric handover scheme in LSN.

Here we illustrate our user-centric handover process in Fig. 2. In the first handover window $[0, T_h)$, CASs have buffered the user's downlink frames $P_1 - P_8$ forwarded by ground station through multicast, and LEO_1, which is one of CASs, is the current MAS of user u. During time $[0, T_h)$, LEO_1 successfully transmits frames P_1, P_3, P_4 while the transmission of frame P_2 is failed. For the user's PST, it sends an acknowledgement for each received frame through broadcast. Thus, all CASs can receive ACK_1, ACK_3, ACK_4 as acknowledgement of frames P_1, P_3, P_4 and remove these frames from their buffer. In the second handover window $[T_h, 2T_h)$, according to the RSSI, PST decides to handover from LEO_1 to LEO_2 due to the better communication quality. This handover process consists of the following three steps:

1) PST broadcasts a handover request to inform LEO_1 and LEO_2, and also a replicated acknowledgement of ACK_1, ACK_3, ACK_4 sent in the last handover window in form of bitmap.
2) After receiving handover request, LEO_1 stops sending data frames to PST immediately, and sends an acknowledgement to PST and a handover confirmation signal to LEO_2 through inter-satellite link.
3) After receiving handover request from PST and confirmation signal from LEO_1, LEO_2 starts to transmit requested frames P_2, P_5, P_6, P_7 in the buffer to PST.

After the handover, similarly, PST broadcasts $ACK_2, ACK_5, ACK_6, ACK_7$ after receiving these frames and all CASs removes them from the onboard buffer. So doing, the efficiency of reliability of transmissions during the handover process can be enhanced.

To achieve aforementioned seamless handover process, another essential process is multicast transmission from ground station to CASs. An example is shown in Fig. 3. After receiving a data request, data server sends the requested IP packets to the user, these packets should be multicasted from ground station to CASs and then forwarded by current MAS. Since the destination IP address in layer-3 is used to identify different user, an extra multicast address destined to CASs is added into IP extension header at ground station. Once satellites in CASs receive user's packets from ground station through backhaul link, they will check multicast address in extension header and then decides to keep it or not through the interface of queue management in layer-2.

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[1] In this letter, "ground station" indicates the earth station that provides Internet access for the LSN.

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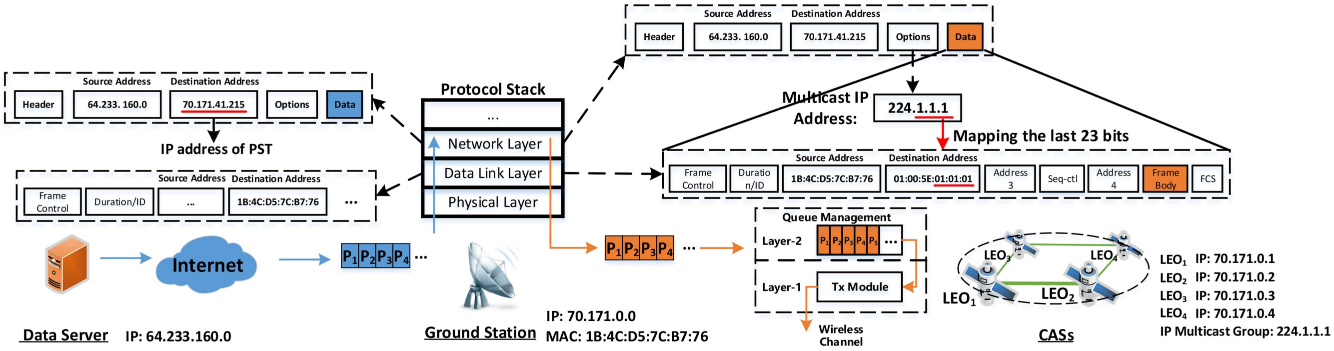

Fig. 3. Multicast example for the proposed scheme.

B. Candidate Satellite Update

During communications between the terrestrial user and the satellite, CASs should be selected at the beginning of the user-access step and also be updated after each handover window because of the movement of CASs. There are two options to achieve the update process of CASs, i.e., the central scheme and the distributed scheme:

- For the central scheme, ground station is responsible for CASs update process. When user tries to setup communication with the satellite network, the MAS should report this new access request to ground station and wait for the decision about CASs. Once CASs for the user have been decided, ground station should inform these satellites through satellite-ground link. During the communication, ground station should also monitor the real-time status of each satellite and dynamically allocate onboard resource for the user. This scheme is simply and effective, and also friendly for resource-limited environment since there is no extra cost onboard. However, due to the existence of signal propagation delay between ground station and satellite, which is related to the altitude of the orbit (3.4ms when altitude is 550km), the decision made by ground station may be delayed.
- For the distributed scheme, LEO satellites should select and update CASs by themselves. When the connection between user's PST and LEO satellite has been setup, this satellite should collect onboard information from neighbor satellites and execute selection algorithm. After that, it decides the CASs for the user and negotiate with these satellites through inter-satellite links. To ensure the efficiency of this "selection" and "update" process, the satellite which is responsible for the algorithm, should also changed dynamically. As one possible criterion, the satellite with the longest coverage duration can be selected as the decision maker.

To properly select and update CASs for each user, the selection should follow certain criteria. According to [2], [12], what follows are usually adopted for the satellite selection:

- *Maximal Service Time:* The service time of each satellite for a terrestrial user can be calculated according to the predictable trajectory. In order to maintain the candidate as long as possible, the LEO satellite with the maximum service time should be selected as the CAS.
- *Highest Elevation Angle:* The elevation angle can be obtained based on the relative location between the user and the satellite. In general, the communication link to the satellite with higher elevation angle has better communication quality. The reason is that the elevation angle is related to the distance between the user and the satellite, and the distance also has a clear relation to the signal to noise ratio/signal strength.
- *Least Satellite Load:* The satellite load is directly determined by the number of access users. Considering the limited resource on LEO satellites, such as finite channels and buffer size, the number of access users has upper bound for each LEO satellite. Besides, accessing satellite with less load can suffer shorter queueing delay and also benefit load balance in the LSN.

According to different QoS requirements, one or several of these criteria can be adopted to select CASs.

III. SIMULATION STUDY

A. Simulation Setup

In this section, we perform a series of simulations to evaluate the performance of the proposed access scheme. A modified simulator based on opportunistic network environment (ONE), called LSNS, is developed as an open-source project [4]. In this simulation, Starlink alike constellation [7] is adopted to construct satellite networks. The simulation platform runs on a PC that has Core i7-7700 CPU, 3.60GHz, 16G RAM, O.S. Windows 10 Professional 64bits. The two-body model[2] is adopted as the orbit calculation [14]. The specific simulation parameters are shown in TABLE I. Comparison schemes are given as follows.

- *User-Centric Handover (UCH):* The proposed user-centric handover scheme with a certain number of CASs. All CASs are selected according to the maximum elevation angle criterion.
- *Elevation Angle-Based Handover (EAH):* A terrestrial user can only access one satellite at a time, and the handover criterion is elevation angle as described in [12].

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[2] Two-body model assumes that the two objects interact only with one another. In our simulation, we only consider the interaction between earth and the satellite.

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TABLE I
SIMULATION PARAMETERS

Parameter	**Value**
LEO orbit height	550km-1050km
Number of LEO satellites	192
Number of orbital planes	24
Number of LEO satellites in each orbital plane	8
Inclination	53°
Maximum elevation angle	50.4°
Buffer size	16Mb
Duration of handover window	200ms
Channel model	Rice
Frequency center	20GHz
Frequency band for typical user	1MHz
Noise power density	-164dBm
Satellite transmit power	40dBm
Rician fading	$K = 10, \sigma = 1$
Simulation duration	$20min$
Frame size	18kb

- *Service Time-Based Handover (STH):* A terrestrial user can access one satellite at a time, and the handover criterion is connection duration as described in [12].
- *Signal Strength-Based Handover (SH):* The seamless handover scheme proposed in [3] is used, the user's PST makes handover decision according to the current channel status. The handover threshold is $|P_{avg} - 6dB|$, where P_{avg} is the average value of the received signal strength from the satellite.

In the simulations, we focus on one terrestrial user to evaluate the performance of the aforementioned schemes. The handover delay is calculated by $T_{handover} = T_{trans} + T_p$, where T_{trans} denotes the waiting time from the time the handover happens to the time that the current MAS retrieves the requested data frames from the ground station. T_p is the propagation time for necessary signaling interactions. Note that we independently repeat the simulation 15 times with 120000 generated packets for each point and plot Figs. 5-7 with 95% confidence interval.

B. Handover Window Size

Since the proposed scheme adopts a handover window to compare channel quality from different satellites, the size of handover window is a critical parameter to the handover performance. Considering the potential handover cost such as signaling process, especially in communication environment with long propagation delay, the unnecessary handover should be avoided. In order to improve handover efficiency, compared with the performance of STH scheme, the throughput improvement of unit handover in different window sizes are shown in Fig. 4. Suggested by the simulation result, we choose t_w as 200ms in this simulation scenario. In a practical satellite system, based on realistic requirements and handover cost, the handover window size can be adjusted by experiment results.

C. Performance Analysis

At first, we compare the performance of the aforementioned schemes in different orbital altitudes as shown in Fig. 5. Results show that the proposed handover schemes, i.e., UCH with 2 CASs and 4 CASs, are better than other handover schemes in terms of throughput and handover delay. From comparison, UCH with 4 CASs incurs shorter handover delay. Due to the difference of the number of CASs, UCH with 4 CASs has fewer CASs replacements than UCH with 2 CASs after each handover window. Since a new CAS needs to request data frames from the ground station and the user has to wait for data frames if this new CAS is selected as the MAS, longer handover delay is incurred. For EAH scheme, although it selects the access satellite based on the evaluation angle rather than real-time signal strength, the selected satellite with the maximum evaluation angle has the shortest communication distance so it leads to better performance than SH scheme.

For satellite communications, the wireless channel can be affected by bad weather and obstacles like buildings and trees. To evaluate system performance in the situation of fading, we use the log-normal shadowing for two links which have the best channel condition and adopt shadowing parameters of city environments as in [15]–[17]. Results are shown in Fig. 6. Not to our suprise, the proposed handover schemes are better

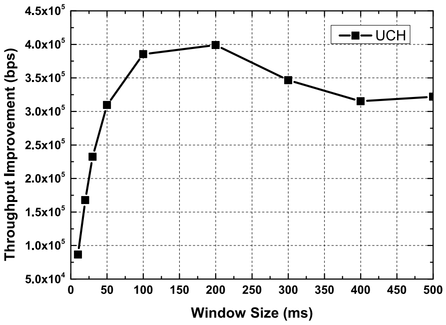
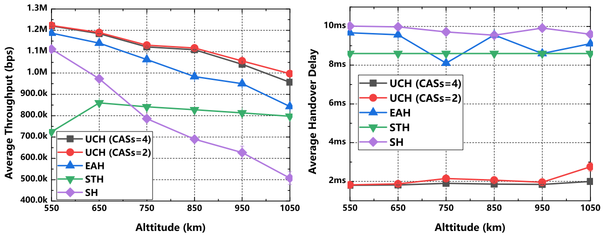
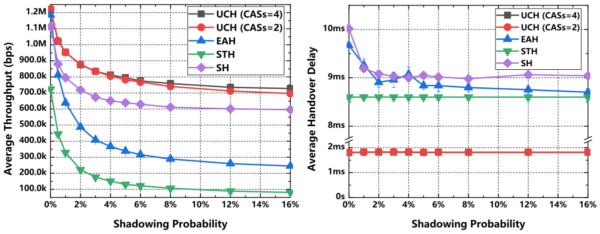


Fig. 4. Throughput improvement of unit handover vs handover window size.



(a) throughput vs altitude (b) handover delay vs altitude

Fig. 5. Performance comparison vs orbital altitude (shadowing probability = 0%).



(a) throughput vs shadowing (b) handover delay vs shadowing

Fig. 6. Performance comparison vs shadowing probability (orbital altitude = 550km).

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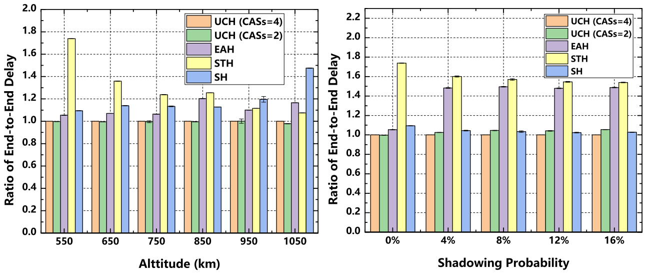

(a) end-to-end latency vs altitude (b) end-to-end latency vs shadowing

Fig. 7. Performance comparison in terms of ratio of end-to-end delay.

than other handover schemes. Nevertheless, the performance of UCH scheme with 2 CASs becomes worse with the increase in shadowing probability compared to UCH scheme with 4 CASs. The reason is that UCH scheme with 2 CASs can only select 2 candidate satellites. With the increase in shadowing probability, the link quality becomes worse, so whatever the selection is, the handover performance of the UCH with 2 CASs can only have limited improvements.

Another interesting fact is that the performance of EAH scheme becomes worse than SH scheme with the increase in shadowing probability. This observation can be explained as follows. The SH scheme can handover to the satellite which is not affected by the shadowing effect while EAH scheme cannot. In this case, EAH scheme can only maintain the communications with the satellite which is affected by the shadowing. For STH scheme, it selects the satellite with the longest connection time and there is always one handover for STH scheme during the whole simulation time, so STH always has stable handover delay under different altitudes.

At last, we depict the performance comparison in terms of ratio of the end-to-end latency in Fig. 7. UCH scheme with 4 CASs is treated as the baseline. The performance of UCH scheme with 2 CASs is very close to the baseline (i.e., UCH scheme with 4 CASs) in Fig. 7(a), and 7(b) shows the same trend that the performance of UCH scheme with 2 CASs becomes worse with the increase in shadowing probability, which is caused by limited choices of CASs. For SH scheme, its performance is also better than EAH in Fig. 7(b) with the increase in shadowing probability, which specifically outperforms EAH as much as 42% to 44.5% from 4% to 16% shadowing probability.

IV. CONCLUSION

In this letter, we proposed a user-centric handover scheme which exploits satellites' storage capability to improve the performance of the user's access service. We also described our handover scheme and several criteria for access satellite selection during the handover process in details. To evaluate the performance of our scheme, we made several comparisons with the traditional handover schemes which make handover decision according to single criterion and cannot remain good performance under temporal shadowing situations. Results show that the proposed scheme outperforms the traditional handover schemes in terms of throughput, handover delay and end-to-end latency. In the future, we will further improve the utilization efficiency of limited storage capacity onboard satellite. Meanwhile, we will further leverage storage and computing capacities to reduces transmission performance degradation due to frequent handover and try to quantify the performance improvement through simulation and theoretical analysis.

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