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Seamless Handover in Software-Defined Satellite Networking

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Abstract—**Satellites have largely been designed as application-specific and isolated for the past decades. Though with certain benefits, it might lead to resource under utilization and limited satellite applications. As an emerging networking technology, software-defined networking (SDN) has recently been introduced into satellite networks. In this letter, we propose a software-defined satellite networking (SDSN) architecture, which simplifies networking among versatile satellites and enables new protocols to be easily tested and deployed. Particularly, we propose a seamless handover mechanism based on SDSN, and conduct physical layer simulation, which shows significant improvement over the existing hard handover and hybrid handover mechanisms in terms of handover latency, throughput and quality of experience of users.**

Index Terms—**Software-defined networking, satellite networks, handover, latency, throughput.**

I. INTRODUCTION

FOR the past few decades, most satellite companies have adopted proprietary, confidential and isolated protocols and algorithms in their networks [1], [2]. This has largely led to resource under utilization in contrast to the upsurge of satellite applications and advancement of satellite technologies nowadays. In the IRIDIUM system [2], a hard inter-satellite handover is triggered when a subscriber is approaching the boundary between two satellites. The gateway informs the trailing and leading satellites to prepare for the handover, and instructs the subscriber unit to resynchronize the signal. This is similar to the network-initiated and network-controlled hard handover in long-term evolution (LTE) systems [3], where the base stations make hard handover decisions in order to route data packets correctly. There have also been lots of academic research efforts studying resource management and handover schemes in satellite networks [4]–[6]. It has been shown that the centralized algorithm [4] and hybrid handover schemes [5] can improve the overall quality of service (QoS) during handover. Various handover mechanisms, including spotbeam handover, satellite handover and inter-satellite links handover are surveyed in [6].

Since proposed in 2008, the software defined networking (SDN) paradigm [7] and OpenFlow [8], where the data plane is separated from the control plane, have attracted a lot of attention from both the industry and research institutes. Recently, SDN technology has been recommended for satellite networks, to optimize QoS [9], improve security, standardize protocols for different vendors [10], and reduce the capital and operational expenses [11]. Particularly, SDN offers the flexibility to dynamically deploy different handover protocols (or a completely new protocol) in response to diverse QoS requirements and/or versatile satellites in satellite communications. However, to the best of our knowledge, there has not been any feasibility study or implementation of software defined satellite networks reported in the literature.

In this letter, we propose a software defined satellite networking (SDSN) architecture, which simplifies networking among versatile satellites and enables new protocols to be easily tested and deployed. We then present a seamless handover protocol that is tailored to and takes advantage of the SDSN, with a meaningful level of detail for implementation. Performance of the proposed SDSN handover protocol (in terms of handover latency, throughput, and user quality of experience (QoE)) is tested on a physical layer simulator and compared with those of existing hard [6] and hybrid [5] handover schemes for satellite networks. We also analyze the relationship between the height of satellites, the location of users and the communication quality for the considered satellite handover mechanisms, and reveal the relationship between communication metrics and the QoE of users.

The rest of this letter is organized as follows. In Section II, we propose the SDSN architecture and the handover procedure. In Section III, we present the physical layer simulation model and results. Conclusion is drawn in Section IV.

II. SDSN AND HANDOVER PROCEDURE

In SDSN, the data plane consists of satellite switches simply performing flow-based packet forwarding, and the control plane consists of controllers located in the earth stations, which centralize all the network intelligence and perform network control for routing, handover and resource allocation. The key idea is to let the control plane generate and send all the flow entries to the switch on each satellite via a satellite network OpenFlow (SNOF) channel, and to make the underlying data plane of satellites as simple as a flow table pipeline.

With the SDSN architecture, satellite networks will have the following characteristics: easy to deploy new applications, flexible to update and change services, and convenient to test new protocols. As a feasibility study of SDSN, we design a seamless handover protocol based on SDSN and demonstrate its performance in a broadband satellite network. Fig.1 illustrates a handover scenario in SDSN. The controller is logically connected to a location server (LS), which stores the international satellite equipment identities (ISEI) of all portable satellite terminals (PST) and their temporary addresses allocated by their gateway Low-Earth Orbit (LEO) satellites. In our proposed SDSN architecture, the controller sends the SNOF control packages to LEO satellites via Geostationary-Earth Orbit (GEO) satellites. This simplifies the topology of the control plane and reduces the control traffic, but requires extra hardware (i.e., the GEO satellites used). Every PST

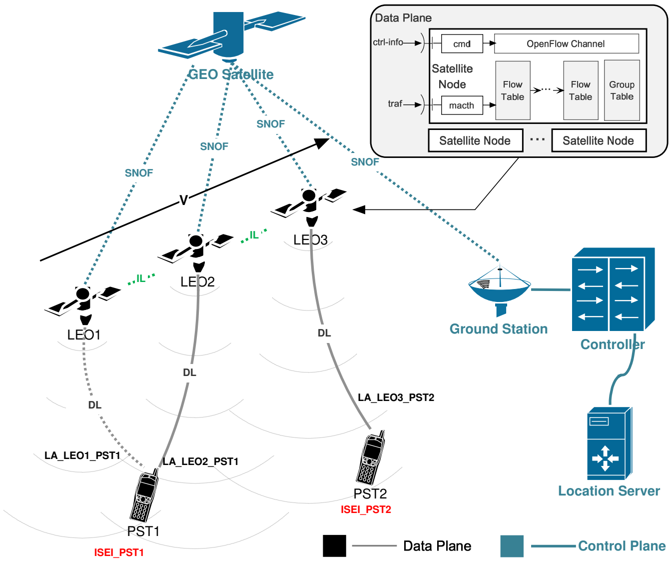
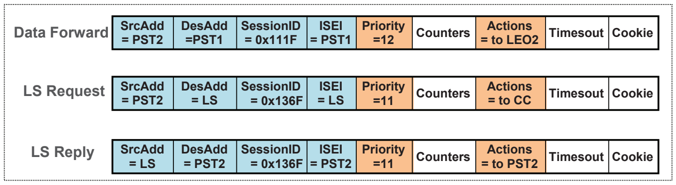


Fig. 1: Handover in SDSN

searches for transmissions from LEO satellites periodically. Once a PST receives the broadcast signal of a LEO satellite, it asks the LEO satellite for a local address (LA) and keeps the data link active. If a PST is covered by more than one satellites, it measures every received signal strength indicator (RSSI), selects the strongest data link as the main data link (MDL), and keeps the other data links as weak data links (WDLs). In Fig.1, PST1 has two data links and PST2 has only one data link. A solid line between a LEO satellite and a PST denotes a MDL and a dotted line denotes a WDL. A downlink data packet can be sent via either a MDL or a WDL, but an uplink data packet can only be sent via a MDL. Every unique packet is transmitted via exactly one link.

When PST2 wants to make a live call to PST1, it first sends a location query request (LQR) to the LS via the SNOF control channel. The LS will return the current main address (LA_LEO2_PST1) associated with the MDL of PST1 to PST2. Then, PST2 sends the live data to its gateway LEO satellite (LEO3 in Fig. 1), which acts as a SDN switch and forwards the data to LEO2 (according to LA_LEO2_PST1). After PST1 receives the data from LEO2, it replies to PST2 via its current MDL (LA_LEO2_PST1). Thus the call between PST2 and PST1 is established. In Fig.2, we present three flow table entries sampled in our SDSN simulator built on Mininet[1]. Every package includes a randomly generated session ID to identify the unique data flow and to trace it in the SDSN, and includes an ISEI to indicate the target of this data flow.



Data Forward	SrcAdd = PST2	DesAdd =PST1	SessionID = 0x111F	ISEI = PST1	Priority =12	Counters	Actions = to LEO2	Timesout	Cookie
LS Request	SrcAdd = PST2	DesAdd = LS	SessionID = 0x136F	ISEI = LS	Priority =11	Counters	Actions = to CC	Timesout	Cookie
LS Reply	SrcAdd = LS	DesAdd = PST2	SessionID = 0x136F	ISEI = PST2	Priority =11	Counters	Actions = to PST2	Timesout	Cookie

Fig. 2: Selected flow table entries in SDSN

As shown in Fig.1, the LEO satellites move from left to right on their orbit, and PST1 measures that the RSSI of LEO2 becomes weaker and the RSSI of LEO1 becomes stronger. When the RSSI of its current MDL (i.e., the LEO2 link) falls below a pre-defined threshold, PST1 sets it as a WDL and sets the link with LEO1 as its MDL. The handover procedure is described below and depicted in Fig.3.

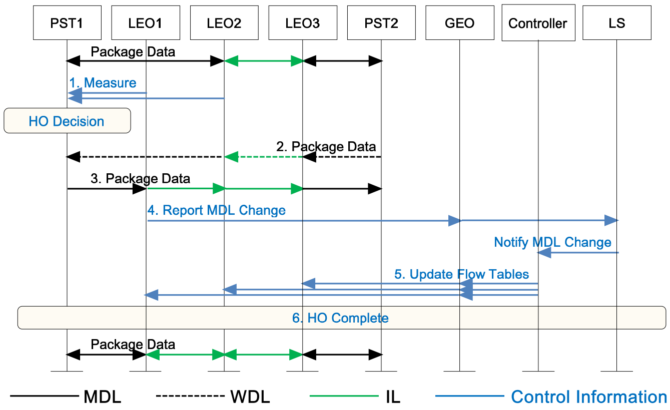


Fig. 3: The proposed handover procedure

1) PST1 periodically measures the RSSI of all received satellite signals. When the RSSI of LEO1 is measured to be higher than the RSSI of its current MDL (i.e., the LEO2 link), PST1 decides to hand over to LEO1, i.e., to set the link from LEO1 as its MDL and set the previous MDL as a WDL.
2) Since the LS has not been informed of the handover of PST1, the data sent by PST2 (targeting PST1) will still be forwarded by LEO3 to LEO2 and then from LEO2 (now a WDL) to PST1.
3) PST1 sends all data and acknowledgment via LEO1.
4) LEO1 receives data packages from PST1 and detects that PST1 has changed its MDL to the LEO1-PST1 link. LEO1 sends an MDL change report to the LS through the SNOF control channel via a GEO satellite.
5) The LS notifies the controller of the MDL change at PST1. The controller updates all flow-table entries associated with PST1 and sends the updated entries to the switch on each satellite via the SNOF channel.
6) After all flow tables are updated, the handover is completed. All downlink data will be sent to PST1 via the current MDL, i.e., from LEO1.

III. HANDOVER PERFORMANCE ANALYSIS

We perform physical layer simulation to compare the performance of the proposed SDSN handover protocol with those of hard handover [6] and the hybrid channel adaptive satellite diversity (HCASD) mechanism [5]. A satellite network consisting of 12 LEO satellites, 3 GEO satellites and 3 earth stations is simulated based on Mininet. For simplicity, we assume that both LEO and GEO constellations are in a same orbit plane, and the spotbeam handover [6] is not considered. A typical handover scenario is shown in Fig.4, where the orbit height of LEO satellites and the distance between a user and the projection of the LEO orbit on the ground are illustrated.

In the simulations, the LEO orbit height changes from 160km to 2000km. To avoid significant Doppler shift, each LEO satellite can only set up a communication link with its

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[1] http://www.mininet.org/

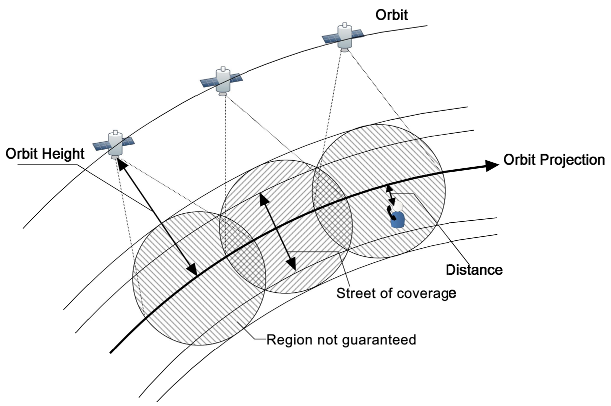

Fig. 4: Handover simulation scenario

nearest GEO satellite and its two neighboring LEO satellites. We assume that all LEO and GEO satellites and earth stations are equipped with parabolic antennas and the antenna gain G_P is calculated as [12]:

$$G_P = \begin{cases} \left(\frac{\pi d}{\lambda}\right)^2 e_A, & \text{LEO, GEO and earth station} \\ 0, & \text{PST receiver} \end{cases} \quad (1)$$

where e_A is the efficiency parameter of the antenna, d(m) is the diameter of the antenna, and λ is the wave length.

We utilize the free space path loss model [12]:

$$\frac{P_R}{P_T}(\text{dB}) = G_T + G_R - L_P - (20\log_{10} D + 20\log_{10} f - 147.55), \quad (2)$$

where P_T and P_R are the transmit power and the receive power respectively, G_T and G_R are the antenna gain (as defined in (1)) of the transmitter and the receiver respectively, D (m) is the distance between the transmitter and the receiver, f (Hz) is the signal frequency, and L_P is the power loss due to misalignment of antenna dishes [12]:

$$L_P(dB) = 0.00245\left(\frac{\alpha_T d}{\lambda}\right)^2, \quad (3)$$

where α_T is the angle between the antenna main reception direction and the main beam direction of the incoming signal.

Log-normal shadowing and Rician fading are also considered for each link between a satellite and a earth station (or a PST) [13]. Table I shows the key parameters used in the system level simulation [12], [13].

TABLE I: Simulation Parameters

Parameter	Value
Frequency band	6 GHz (C band)
GEO orbit height	35786km
Diameter of the antenna	3m
e_A	0.6
System bandwidth	1MHz
Noise power density at satellite antenna	-164dBm
Noise power density at earth station/PST antenna	-144dBm
Satellite transmit power	20dBW
Earth station transmit power	30dBW
PST transmit power	-10dBW
Rician fading	$K = 10$, $\sigma = 1$
Log-normal shadowing	Standard deviation of 4dB
SDSN packet size	1500 Bytes
Dynamic Host Configuration Protocol (DHCP) packet size	590 Bytes

A. Handover latency

We firstly consider the average handover latency, which can be calculated as [14]

$$T_{\text{latency}} = (1 - P_H)(T_{\text{retry}} + T_{\text{reconnect}}) + P_H T_H, \quad (4)$$

where T_{retry} and T_H are the time required to re-setup the handover process if a handover fails and the handover time, respectively [14], $T_{\text{reconnect}}$ is the waiting time between the occurrence of a handover failure and the start of re-connection, and P_H is the handover success probability, which is assumed to be constant.

For hard handover, T_H is the time required for satellite scan, negotiation and IP address auto-reconfiguration, etc. [6], [14]; and P_H contains both the successful signaling probability P_S [14] and the non-blocking probability $(1 - P_b)$ [6], i.e., $P_H = P_S(1 - P_b)$. For our proposed SDSN handover scheme, P_H in (4) is replaced by $P_H^* = 1 - (1 - P_S(1 - P_b^*))(1 - P_O)$, where P_O is the outage probability of the current MDL. In the HCASD mechanism, the switch threshold is $|S_{\text{th}} - 3\text{dB}|$ [5], where S_{th} is the lowest acceptable signal power level for communications. If the received signal power is higher than the switch threshold, then hard handover is performed; otherwise, soft handover scheme is performed [6]. In the simulation, we set $P_b = 0.127$ and $P_b^* = 0.08$ [15]. The average handover latencies of the three handover schemes are depicted in Fig. 5, where two user locations are considered: 0km or 90km away from the projection of the LEO satellite orbit on the ground. We can see that the average latency caused by our proposed SDSN handover mechanism is less than one third of that caused by hard handover or the HCASD mechanism. The reduction in latency is more significant when the height of the LEO system increases. For the SDSN handover and hard handover, the average latency increases with the user distance from the projection of the LEO satellite orbit on the ground; while the average latency of HCASD is much less sensitive to different user locations.

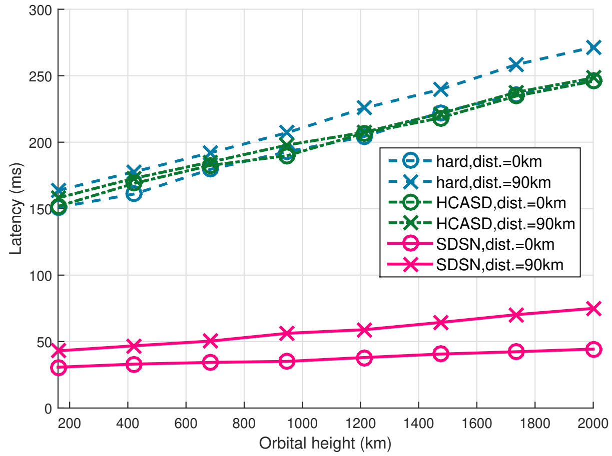

Fig. 5: Handover latency of the satellite system

B. Quality of experience

For a satellite user going through a handover process, two factors may affect the QoE of the user: latency and the handover failure rate. Accordingly, we define the user satisfaction score following [14] as

$$S_u = r * P_H - \exp\left(-\frac{1}{T_{\text{latency}}}\right) - p * (1 - P_H), \quad (5)$$

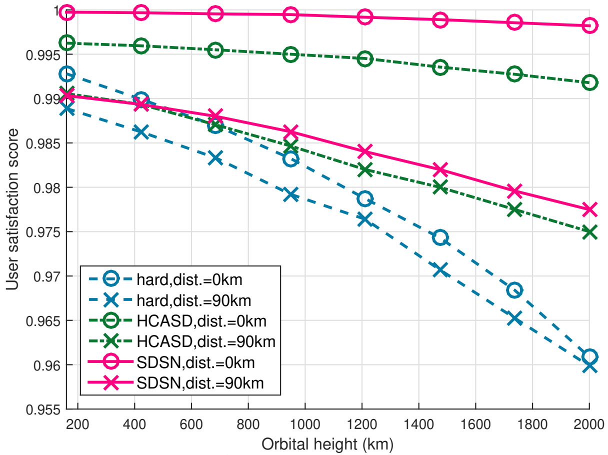

Fig. 6: User satisfaction score

where r and p are the handover success reward score and the handover failure penalty score, respectively, and T_{latency} is given by (4). In our simulation, we set $r = 1$ and $p = 0.1$ [14].

Fig. 6 plots the simulated user satisfaction scores for the three considered handover schemes under the same condition as Fig. 5. We can see that our proposed SDSN handover provides the best user QoE, followed by the HCASD. The QoE improvement achieved by SDSN increases with the height of the LEO satellite orbit. As compared with the other two handover schemes, the user satisfaction score of SDSN handover drops much slower when the height of the orbit increases. This is mainly due to the fact that the handover failure rate on a single link increases fast with the orbit height, while the MDL and WDL(s) used in SDSN handover can reduce the handover failure rate. For each handover scheme, the QoE becomes lower when the user is farther away from the center of spot beam.

C. Throughput

Finally we compare the average throughput of the three handover mechanisms in Fig. 7. The simulation result includes the approximate overhead caused by the control traffic (as a percentage of the total traffic): 0.065% for hard handover, 0.065% for HCASD, and 0.165% for SDSN handover. We can see that with our proposed SDSN handover mechanism, the average throughput is improved by nearly 40% at all orbit heights considered as compared with the other two schemes. For each handover scheme, the average throughput increases when the user is closer to the center of spot beam. Such increase is most significant with SDSN handover.

IV. CONCLUSION

SDN presents operators and researchers with an unprecedented opportunity to provide flexible broadband satellite services to users. In this letter, we propose a seamless handover mechanism based on SDSN, which achieves much better performance than the hard handover and HCASD in terms of handover latency, throughput and QoE of users. In particular, the relationship between the height of satellites, the locations of end users and the communication quality is analyzed. It is shown that these parameters may affect the performance of a satellite network differently: the handover latency is mainly affected by the satellite orbit height, the average throughput is mainly determined by the locations of end users, while the QoE of users is affected by both. Our results show that SDSN supports flexible low layer protocols to satisfy diverse QoS requirements in satellite networks and to make efficient use of the scarce satellite communication resources.

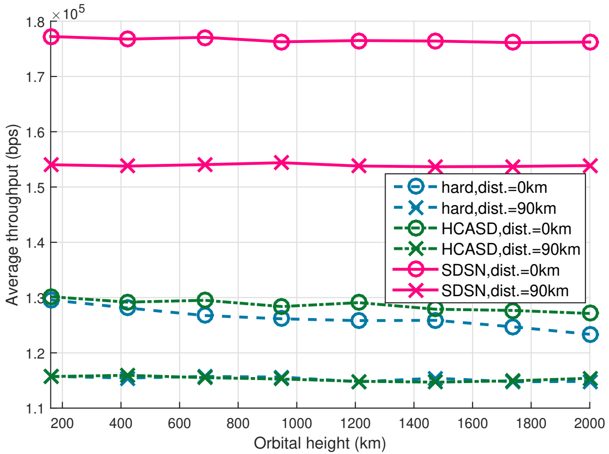

Fig. 7: Throughput of the satellite system

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