Delay Advantage of Optical Satellite Networks (OSN) in Long-Distance Transoceanic Communication

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Abstract: We study the impacts of traffic source/destination location, routing strategy and load on the end-to-end delay benefit of OSN. Simulation and emulation results show that OSN has great delay advantage over terrestrial/undersea optical networks. © 2022 The Author(s)

1. Introduction

The Optical Satellite Networks (OSN) consisting of inter-satellite laser links and Low Earth Orbit (LEO) mega-constellation is a key component of the future six-generation wireless communication networks [1]. Compared with Terrestrial/Undersea Optical Networks (TUON), the higher speed of light in vacuum and possible shorter propagation distance in OSN can greatly reduce the end-to-end delay of long-distance transoceanic communication. This advantage is crucial for applications such as real-time gaming and high-frequency trading [2-4]. However, the end-to-end delay in OSN is a complex problem. It depends on many factors including satellite network topology, optical antenna characteristics, capacity, load, routing strategy, traffic source/destination location and the distribution of satellite ground stations. Relative researches have first studied the impact of traffic source/destination distance and satellite network topology, but there is a lack of studies on the impact of routing strategy and load [3-5]. In this paper, we study the three factors affecting end-to-end delay in OSN: 1) traffic source/destination location, 2) routing strategy, 3) load, and analyze how these factors enhance/reduce the delay advantages of OSN based on simulation results. Emulation regarding time-varying end-to-end delay and path reconfiguration in OSN is also implemented on the Open Optical Satellite Network Emulation Platform (OOSN-EP) [6].

2. End-to-End Delay in OSN and TUON

Fig. 1 depicts a long-distance transoceanic communication scenario with OSN and TUON. Three terrestrial optical networks on different continents are connected by undersea optical cables via coastal cable landing stations and are covered by OSN. Transoceanic traffic can be transmitted via either terrestrial/undersea optical paths or optical satellite paths. For terrestrial/undersea optical paths, since the capacity of optical fiber cables is ultra-high, the end-to-end delay of the paths is mainly determined by the propagation distance and light speed in the optical fiber (about 200,000km/s). While for optical satellite paths, the length of inter-satellite laser links is time-varying, and the capacity of the links and satellite routers is limited. Therefore, the end-to-end delay of the path is subjected to time-varying optical propagation distance, light velocity in vacuum (about 300,000km/s) and load. Besides, an optical satellite connection may require frequent switching between multiple paths due to accessibility constraints between satellites, which may bring extra variation in the end-to-end delay.

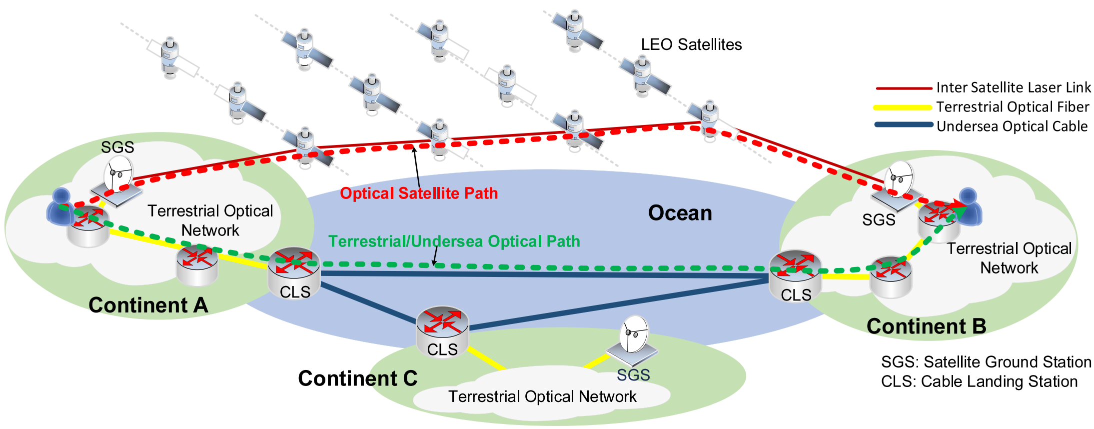

Fig. 1. Long-distance transoceanic communication scenario.

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3. Performance Simulation and Comparative Analysis

Long-distance transoceanic communication scenarios are constructed to evaluate the performance of OSN and TUON. Regional terrestrial optical networks in China, the United States and Australia are connected by undersea optical cables and also covered by a LEO walker constellation (Delta, 100/100/2). The Altitude of the satellites is 550km and the inclination is 52°. Each satellite has a satellite router with four 2Gbps ports [7]. The terrestrial optical network topology is CHINANET in China and NSFNET in the United States. The undersea optical cables connecting China to the United States is HKA (between Hong Kong and Los Angles). While the undersea optical cables connecting China to Australia is SEA-ME-SW 3 (between Hong Kong and Perth) [8]. In the above simulation scenario, we calculate the end-to-end delays of transoceanic communication from Beijing (40°N, 116°E) to New York (40°N, 74°W) and to Perth (32°S, 116°E).

In the simulation, the routing strategy is determined by access threshold (AT) and switching threshold (ST). AT restricts the link length in path computations, while ST restricts the maximum possible link length throughout the entire period of communication. In order to reduce the intolerable computing time on the 10,000-node topology, we propose an ephemeris-based filtering method to select only the sets of Satellites of Interest (SOI) for path computation. The working path can also be seamlessly switched to a pre-calculated rerouting path to avoid the link length exceeding the ST.

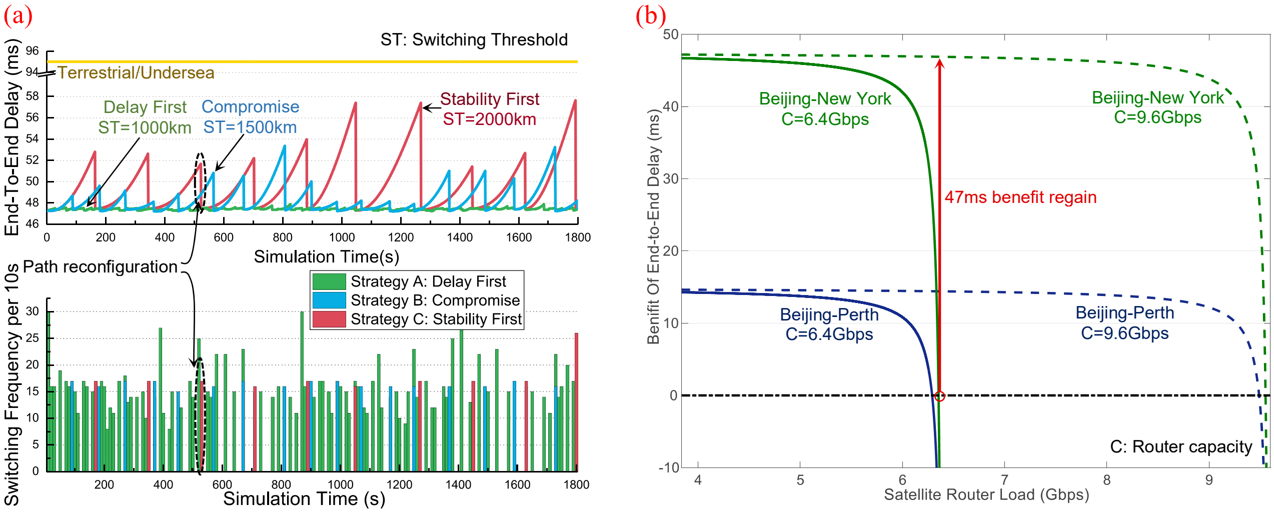

Fig. 2. Factors affecting end-to-end delay: (a) Routing strategy; (b) Traffic source/destination location and traffic load.

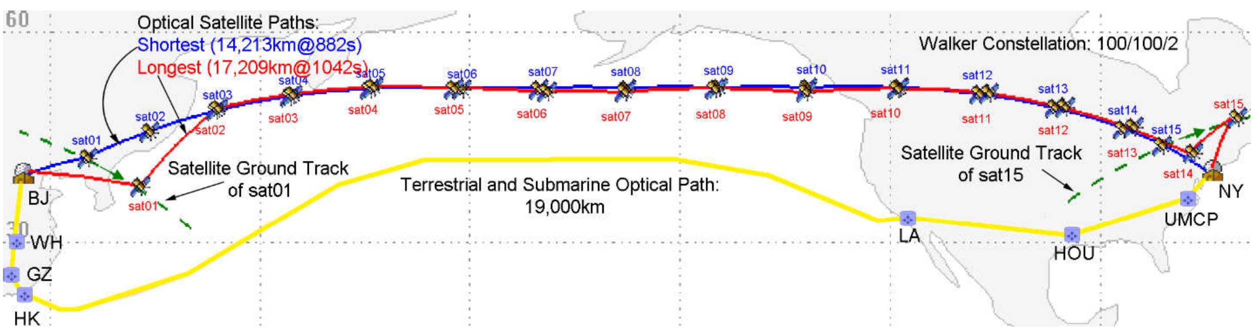

Fig. 3. Paths from BJ to NY in OSN and TUON.

The top half of Fig. 2(a) shows the end-to-end delay between Beijing and New York under light load, where the access threshold of the three routing strategies is set to 1000km. Inter-satellite link switching time is eliminated by using the Preset-Satellite-Chain-Based seamless handover technology proposed in [9]. The bottom half of Fig. 2(a) compares the switching frequencies of the three routing strategies. It can be seen from Fig. 2(a) that OSN has significant delay advantages over TUON. Lower end-to-end delay can be further obtained by reducing the switching threshold. The expense, however, is higher path switching frequency, which may lead to worse QoS and higher signaling overhead

Fig. 2(b) shows the delay advantage of OSN under different loads and traffic source/destination locations. It can be seen that the advantage is weakened from Beijing to Perth (9,000km) than from Beijing to New York (15,000km), indicating that the benefit is negatively correlated with geographical distance between traffic source and destination. When traffic load increases to approach the capacity limit of the satellite routers, the delay benefit will decline rapidly. Take the Beijing-New York connection for example, after increasing the satellite router capacity by 50%, the delay benefit will increase to 47ms, alleviating the decline of the delay benefit in OSN.

An example of length variation of optical satellite paths is presented in Fig. 3. The optical satellite path in the figure is corresponding to the path at 882s with the Stability First strategy in Fig. 2(a). Within 160s, the length of the optical satellite path increases from 14,213km to 17,209km, but still significantly shorter than the path length in TUON.

4. Experimental Emulation

We emulate time-varying end-to-end delay and path reconfiguration on the OOSN-EP emulation platform as shown in Fig. 4(a) to further verify the feasibility of the key technologies proposed in this paper. Architecture of the OOSN-EP is described in Fig. 4(b). By using ephemeris-based dynamic satellite grouping and realtime mapping technologies, we map 10,000 satellites into less than 150 groups, achieving time-varying topology within 150 practical nodes. Fig. 4(c) shows the emulated end-to-end path delay with the Stability First strategy under the same scenario of Fig. 2(a) (0-600s). The emulation result is in strict accordance with the simulation result with an average error of 3.4ms (or 0.2ms per hop, generated by nodal processing delay of the OOSN-EP).

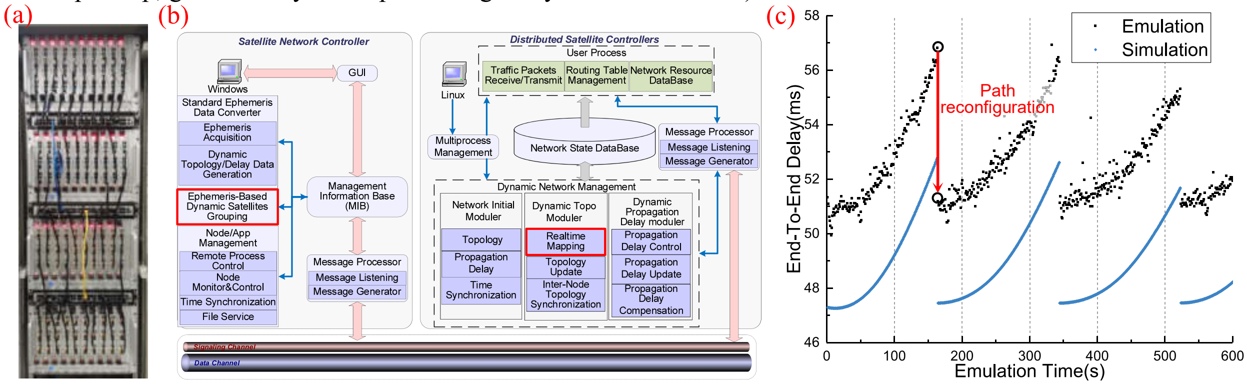

Fig. 4. Experimental emulation on OOSN-EP: (a) Practical platform; (b) Architecture of OOSN-EP; (c) Emulation result.

5. Conclusion

We present a comprehensive study of the advantage and impact factors of end-to-end delay of OSN in long-distance transoceanic communication. Simulation result shows that in most long-distance communication scenarios, end-to-end delay of OSN can be significantly lower than that of TUON. The delay advantage of OSN can be further enhanced by increasing route reconfiguration frequency and satellite router capacity, which may be limited by actual ability of optical antenna and onboard processing on the satellite. Emulation of route path reconfiguration and precise time-varying end-to-end delay is also implemented to verify the feasibility of key technologies.

6. References

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