IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 15, 2019, accepted April 10, 2019, date of publication May 1, 2019, date of current version May 13, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2913441

Time-Sliced Flexible Resource Allocation for Optical Low Earth Orbit Satellite Networks

ZELIN ZHENG, NAN HUA, ZHIZHEN ZHONG, JIALONG LI, YANHE LI, AND XIAOPING ZHENG

Beijing National Research Center for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China

Corresponding author: Xiaoping Zheng (xpzheng@mail.tsinghua.edu.cn)

This work was supported in part by NSFC under Grant 61871448 and Grant 61621064.

ABSTRACT In future optical satellite networks with various service requirements, the bandwidth of a single traffic request occupies part of an inter-satellite link (ISL) channel capacity, thus leading to a greater demand for flexible resource allocation. The switching scheme is the most important determinant for flexible resource allocation in optical satellite networks, whereas the widely used optical switching techniques, including wavelength switching (WS) and electronic packet switching (EPS), have their own drawbacks such as bandwidth underutilization and high power consumption. In this paper, we utilize optical time slice switching (OTSS) to provide enormous transparent fine-grained connections for various traffic requests. To implement OTSS into low earth orbit (LEO) satellite networks, where the lengths of inter-orbit ISLs vary along time, we propose a distance-varying routing and time slice allocation (DV-RTSA) scheme. The simulation results demonstrate that the OTSS-based DV-RTSA scheme not only utilizes less active transponders when compared with the traditional schemes, but also achieves a significant throughput increase over the WS-based scheme and reaches the level of the EPS-based scheme exempting from its defects.

INDEX TERMS Distance-varying routing and time-slice resource allocation (DV-RTSA), electronic packet switching (EPS), low earth orbit (LEO) satellite networks, optical time slice switching (OTSS), wavelength switching (WS).

I. INTRODUCTION

Satellite networks have been gaining significant importance in many application areas where terrestrial networks fail to meet the requirement, such as remote sensing, military reconnaissance, and radio astronomy [1]–[3], leading to an ever-increasing demand for the capacity of satellite networks. Free space optical (FSO) communication has the advantages of large bandwidth and less power consumption when compared with traditional radio frequency communication, guaranteeing optical satellite networks based on FSO communication to be a promising infrastructure in the near future.

In scenarios where various kinds of service requirements are proposed [1], [2], multi-satellite relay transmission becomes a key technique in optical satellite networks, which greatly increases the complexity of the satellite networks. Moreover, as different services may demand unequal bandwidth and the bandwidth of a single traffic request may not fully occupy the inter-satellite link (ISL) capacity, the flexible allocation of bandwidth resource becomes a critical problem. As an important factor determining the fineness of bandwidth resource allocation in optical satellite networks where multi-satellite coordination is utilized in inter-satellite communication, the switching method becomes the main research content of this paper. An all-optical switching technique, optical time slice switching (OTSS) [4], is introduced into the resource allocation of optical satellite networks to deal with the problem. In OTSS, switching is processed in the time domain with the bandwidth resource divided into time slices. OTSS provides transparent connections and has been demonstrated to be effective to achieve fine-grained optical-layer resource allocation.

The rest of this paper is organized as follows. Related work is reviewed in Section II and challenges of OTSS on satellite are listed in Section III. In Section IV, we set up the OTSS-based satellite network system model. With the routing and resource allocation problem described, the OTSS-based distance-varying routing and time-slice resource allocation (DV-RTSA) scheme is also proposed.

The associate editor coordinating the review of this manuscript and approving it for publication was Shuai Han.

In Section V, the DV-RTSA algorithm is described and the numerical analysis is shown in Section VI. Conclusions are drawn in Section VII.

II. RELATED WORK

A. OPTICAL SATELLITE NETWORKS

Satellite networks based on FSO communication have been studied in several works [5]–[8]. An early review of several probable satellite network architectures is given in [5], and the promising prospect of optical satellite networks is also described. A satellite backbone network utilizing optical burst switching (OBS) and software defined network (SDN) is proposed in [6], which aims to solve the flexible resource allocation problem in GEO/LEO satellite networks. Very High Throughput Satellite Systems (VHTS) are proposed in [7] to provide Terabits per second transmission rates, whereas these systems utilize optical GEO feeder links and require a change in ground network topology to deal with cloud-blockage diversity. In [8] software-defined payloads based on microwave photonics have been discussed with the technical difficulties analyzed. The main drawback of these microwave photonics systems is that electrical-to-optical and optical-to-electrical conversions occur frequently from the receivers to the transmitters, which may severely degrade the performance of the whole system. The above researches have fully proved the significance and feasibility of optical satellite networks, while there is still room for development.

B. OPTICAL SWITCHING TECHNIQUES ON SATELLITES

As to alternative optical switching techniques on satellites, wavelength switching (WS) and electronic packet switching (EPS) have been well studied. In [9], [10], WS is proposed to be utilized in time-varying optical LEO satellite networks. WS with wavelength division multiplexing (WDM) ISLs have a coarse switching granularity, which can avoid frequent multiplexing and demultiplexing. However, it fails to achieve flexible bandwidth resource allocation with a fine granularity. In [11], [12], the power consumption models in optical networks are analyzed. As is shown in these works, EPS is performed in the electrical domain and has been a mature technology with a fine granularity, whereas its requirement for grooming matrices in the electrical domain and additional optical-electrical-optical (OEO) conversion leads to ultrahigh power consumption in future high-throughput optical satellite networks. This drawback makes it inappropriate for optical satellite networks where payload volume and power consumption should be limited.

III. CHALLENGES OF OTSS ON SATELLITE

Although OTSS has proved to be a feasible switching technique in terrestrial networks, there exist certain technical challenges to introduce OTSS into optical satellite networks. The most critical challenge is how to implement OTSS in satellite networks with high mobility, while there exist other challenges such as whether ultrafast time slice switching can be realized in space. To deal with these problems, a detailed discussion is carried out as below.

How to implement OTSS in satellite networks with high mobility is the main research content of this paper, for the reason that OTSS relies on route switching at the precise time and suffers gravely from the variation of the intersatellite propagation delays caused by high mobility. The propagation delay variation caused by the orbit error (which can be controlled to the centimeter level [13]), can be limited to the nanosecond level and neglected. As a more important aspect, the variation of the lengths of inter-orbit ISLs leads to the variation of the inter-satellite propagation delays.

In our proposed OTSS-based scheme, the time slices on different ISLs should be allocated with different but related start time due to the signal propagation delay [4], and the variation of the inter-satellite propagation delay results in the start time variation of time slices on these ISLs. This variation may lead to time slice conflict, which means the time slices of different traffic requests collide in the time domain. To address this problem, we propose a DV-RTSA scheme and more details are described in Section IV.

There exist other problems such as 1) the realization of ultrafast time slice switching in space and 2) OTSS's requirement for ultrahigh time synchronization precision, which can be solved by existing methods and are not mainly discussed in this paper. As to problem 1, ultrafast time slice switching can be realized by optical switches in space. Nowadays certain optical switches are already able to reach a switching time of several microseconds even nanoseconds [14], [15], while magneto-optical switches have already been utilized in space, guaranteeing optical switches to be a maturing technique in optical satellite networks. An all-optical FSO link with optical switches as been experimental validated in [16], which also proves the maturity of optical switches in FSO communication. As to problem 2, the requirement of OTSS for ultrahigh time synchronization precision can be met with the assistance of atomic clocks on satellites, which have an accuracy of several nanoseconds [17]. As the atomic clocks are essential parts on certain types of satellites, the cost caused by atomic clocks is not analyzed in the paper.

IV. OTSS-BASED SATELLITE NETWORK SYSTEM

A. OPTICAL LEO SATELLITE NETWORK ARCHITECTURE

The proposed optical LEO satellite network in this paper adopts a classic model of the Iridium satellite constellation, as is shown in Fig. 1. The seam area is a zone surrounding which the two orbits are counter-rotating, and the satellites in these orbits do not communicate directly with those on the other orbit. The illustration of the proposed network architecture is shown in Fig. 2, and these satellites form a bidirectional Manhattan Street Network (b-MSN) [18]. Each terrestrial user terminal station communicates with the nearest satellite as the network gateway, which is not the key point of this paper as only the ISLs in optical satellite networks and routes between satellites are taken into consideration.

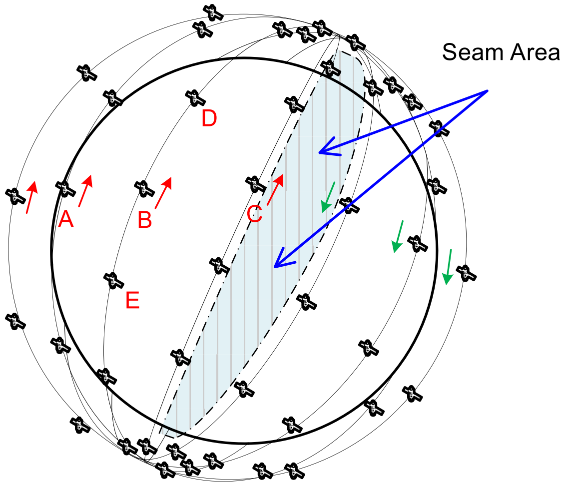


FIGURE 1. Iridium-like satellite constellation.

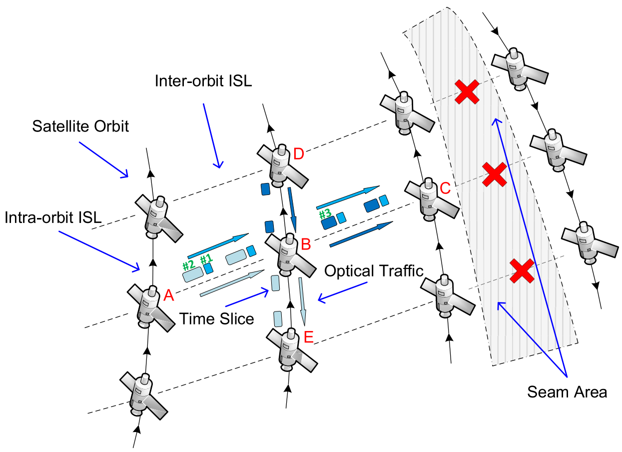


FIGURE 2. Illustration of the optical LEO satellite network architecture.

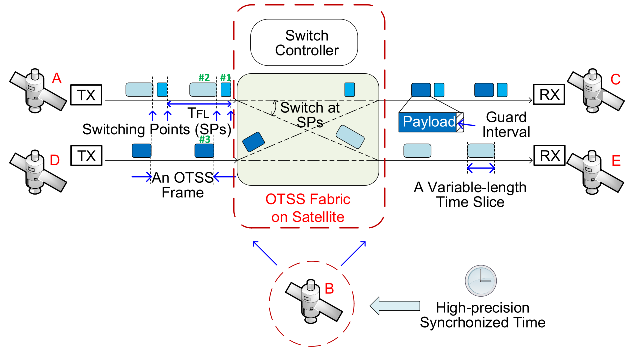


FIGURE 3. OTSS architecture on satellite.

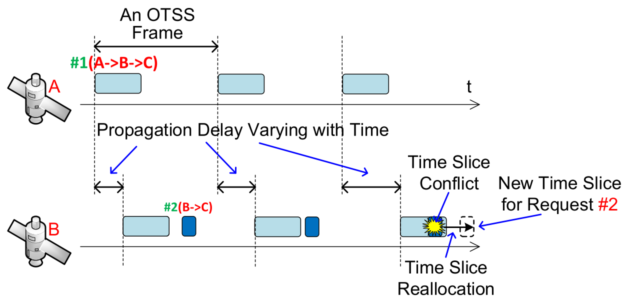


FIGURE 4. Time slice conflict and the time slice reallocation scheme.

B. OTSS ARCHITECTURE ON SATELLITES

To overcome the drawbacks of the current switching schemes, we introduce OTSS into optical satellite networks to achieve flexible bandwidth resource allocation, as is shown in Fig. 3. The implement details of OTSS are demonstrated in [19], [20].

In this OTSS architecture, the optical inter-satellite transmission channels are organized into repetitive OTSS frames in the time domain with a period of T_{FL}. These OTSS frames each contain one or several variable-length time slice(s). The allocation of time slices in a service should be bound to the time slice continuity constraint [4], which means a traffic flow traversing multiple intermediate satellites should not change the time slices in an OTSS frame.

The receivers in the OTSS architecture are burst-mode receivers to deal with the ultrahigh switching frequency of the optical switches [4]. The switch controllers on board the satellites send periodic control signals to the OTSS fabric at the precise time to direct the arriving time slice to the expected output port. A central controller placed on the ground is in charge of distributing switching configurations to the switch controllers on satellites, which is not shown in these figures.

C. SOLUTION TO TIME SLICE CONFLICT

As is shown in Fig. 4, the variation of the distance between satellite A and B leads to the change of the ISL propagation delay. Therefore, the time slice for traffic request 1 (from satellite A to C) changes its starting time in an OTSS frame on the ISL between satellite B and C, and the time slices of the two traffic requests collide at time 2, which means the occurrence of time slice conflict.

To address the time slice conflict problem, a relevant solution and its corresponding algorithm are proposed. When time slice conflict occurs, we reallocate the time slices of the affected traffic request with the lower bandwidth if there is adequate bandwidth resource in other relevant ISLs, as is shown in Fig. 4. If the time slice reallocation is not successfully performed, the latter one of the conflicted traffic requests will be abandoned. The details of the corresponding DV-RTSA algorithm are proposed in Section V.

V. DV-RTSA ALGORITHM

A. PROBLEM DESCRIPTION

In the DV-RTSA scheme, the bandwidth resource is assigned to different traffic requests by providing the required time slices in an OTSS frame. In this paper, the traffic requests are listed in a set V and each request is in the form of $\{N, S, D, T, B, F\}$. N is the traffic request index. S and D are the source and destination satellites. T is the start/end time of the service. B stands for the required bandwidth of the traffic request, which is presented by the number of minimum time slices. F stands for whether the traffic request arrives (0) or departs (1). Let R be the time slice resource matrix with a size of P by Q, where P is the number of unidirectional ISLs and Q is the maximum number of time slices in an OTSS frame. The number of tested routes is set to k, which means that k routes with the highest link weights will be tested when a traffic request arrives, and the traffic request will be rejected if all the k routes have failed.

The possible routes with the least ISLs in a b-MSN are determined by the source and destination satellites, and the number of ISLs in the routes is denoted by j. When a traffic request arrives, k routes with the highest weights are tested whether there is adequate bandwidth. The weight of the ith possible route $W(i)$ is given as:

$$W(i) = (N_s + 1) \Big/ \sum_{j=1}^{l} B_j \tag{1}$$

In the above formula, N_s is the number of ISLs assigned to the route in the orbit of the source satellite, and B_j is the occupied bandwidth in the jth ISL. To handle the situation when N_s is 0, an offset (which is set to 1 in this paper) is added to N_s.

B. PROPOSED SOLUTION

We propose a DV-RTSA algorithm to deal with the routing and resource allocation problem in optical LEO satellite networks, which is shown in Fig. 5 and Algorithm 1. In this scenario, the length of the ISLs in the orbit of the source satellite remains stable, which guarantees that the time slices on these ISLs do not change their start time. The increase in the number of these ISLs in the route path will reduce the probability of time slice conflict occurrence. Consequently, in the DV-RTSA algorithm, the ISLs in the orbit of the source satellite have the highest priority when routing. Each newly arrived traffic request will be served if adequate bandwidth resource exists, and involved bandwidth resource will be freed when a traffic request departs. The time slice resource matrix R will be updated when a traffic request arrives or departs, and time slice conflict is also checked. When time slice conflict happens, the time slice of the later request will be reallocated if adequate spare bandwidth exists, otherwise abandoned.

C. COMPLEXITY ANALYSIS

When a traffic request arrives, the resource matrix R is updated and the complexity of this part is $O(PQ)$. As the number of possible routes can be extremely large, we select k routes with the highest link weights from routes with the

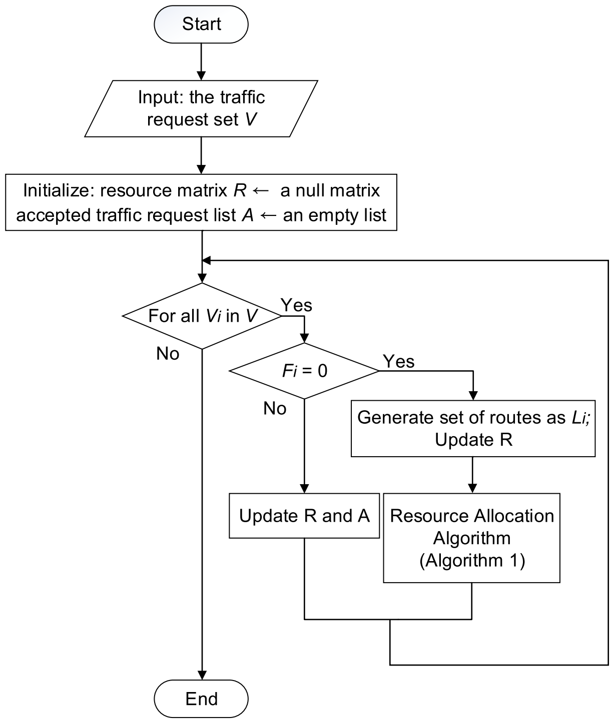


FIGURE 5. Flowchart for the DV-RTSA algorithm.

Algorithm 1 Resource Allocation Algorithm

Input: Set of possible routes L_i; a traffic request $V_i = \{N_i, S_i, D_i, T_i, B_i, F_i\}$; the number of tested routes k;
Output: Accepted traffic request list A;
1: Sort L_i in descending order of the link weight W;
2: Update R according to the variation of the link propagation delay;
3: Abandon the later arrived traffic request if time slice conflict occurs;
4: **for each** $L_{ij} \in L_i$ **do**
5:   **if** $j > k$ **then**
6:     Break;
7:   **end if**
8:   Record available time slices $Ts = \{slice_1, slice_2 ... slice_n\}$ on L_{ij};
9:   **for each** $slice_i \in Ts$ **do**
10:     **if** $B_i < slice_i$ **then**
11:       Append N_i to A;
12:       Update R;
13:       Continue loop in line 1;
14:     **end if**
15:   **end for**
16: **end for**

least and second least N_ss as candidates. The complexity of the step to find the available time slice on a possible route is $O(k\sqrt{PQ})$, where $O(\sqrt{P})$ is the approximate value of the average number of ISLs in a route. Adding the two parts together, we get $O(nPQ + nk\sqrt{PQ})$ as the complexity of the DV-RTSA algorithm, where n stands for the number of traffic requests that arrive in the observed time period. As our proposed algorithm requires the information of the whole network, the scheme has a slightly higher complexity than the benchmark schemes (WS-based and EPS-based schemes).

VI. NUMERICAL ANALYSIS

A. SIMULATION SETUP

The algorithm is implemented in Matlab and C++. A model of Iridium satellite system with 66 LEO satellites is utilized in this paper. In this paper, each traffic request is generated between a source satellite and a destination satellite randomly chosen from the 66 satellites. When a traffic request arrives, our proposed DV-RTSA algorithm is utilized to find the possible route and allocate the bandwidth resource. The number of tested routes k is set to 5. The OTSS frame is set to 20 ms and the guard interval is 10 μs. The ISL capacity of some special satellites can reach a rather high level of 100 Gbps [21], therefore the ISL capacity is also set to 100 Gbps in this paper. The required bandwidth of the traffic requests satisfies a uniform distribution from 100 Mbps to 1 Gbps.

Two types of traffic are considered: traffic requests characterized by Poisson arrivals with negative exponential holding times and traffic requests with constant service time. Poisson traffic on satellites is adopted in [22]–[24] while traffic with constant service time is employed in [25]. As to Poisson traffic requests, the arrival rate is set to λ and the mean service time is $1/\mu$, therefore the network traffic load is defined by $\rho = \lambda/\mu$. As the longest propagation delay in the satellite network is around 100 ms, any assumption with the arrival rate λ less than 10 s^{-1} is feasible. As to traffic requests with constant service time, the service time is determined by the time during which the corresponding satellite is accessible to terrestrial user terminal stations. As each Iridium satellite can be accessed by a terrestrial user terminal station for around 10 minutes in an orbit period, the service time can be set to a constant of 10 minutes when the orbit altitude is 780 km. In this case, the constant service time can only be altered by the change of the orbit altitude (which changes the time during which the satellite is accessible to a terrestrial user).

In Fig. 6, we compare the network bandwidth utilization of the OTSS-based scheme with the granularity of 50 Mbps when Poisson traffic and traffic with constant service time are adopted. In this case the traffic load is set to 700 ErLang. As to traffic with constant service time, the service time is mainly determined by the orbit altitude with the beam angle fixed, and the altitudes of the LEO satellites are set to a range of 200-2000 km [26]. As to Poisson traffic, the service time refers to the mean service time. As to both types of traffic, the bandwidth utilization decreases slightly with the increase of service time, for the reason that the increase of service time may raise the occurrence of time slice conflict. The result proves that the performance of our proposed OTSS-based scheme does not rely on the traffic characteristics, and the simulations below are all based on Poisson traffic.

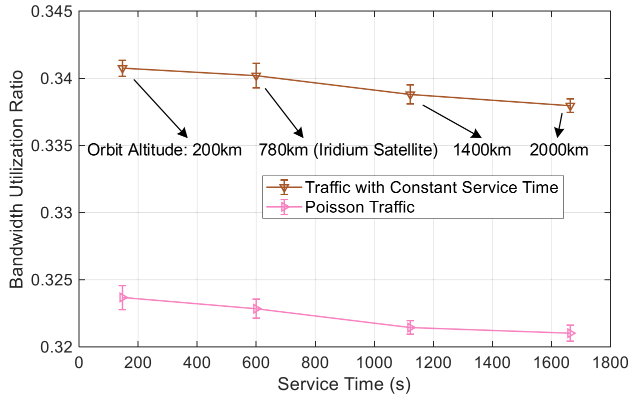


FIGURE 6. Bandwidth utilization of the OTSS-based scheme with the granularity of 50 Mbps with traffic load set to 700 ErLang when Poisson traffic and traffic with constant service time are adopted.

In the benchmark experiments for performance evaluation, resource allocation schemes based on WS and EPS are tested. WS refers to all-optical switching at wavelength granularity with optical bypass enabled, whereas in EPS all signals are converted into the electrical domain for packet switching at intermediate nodes without optical bypass. In these benchmarks, each port is divided into 10 wavelengths, and each wavelength can support a service of at most 10 Gbps. Each of the simulations has been repeated 20 times and the 95 percent confidence intervals of the simulation results are also shown in the figures below.

B. SIMULATION RESULTS

1) NUMBER OF ACTIVE TRANSPONDERS

In optical satellite networks with different schemes, the main difference of power consumption is caused by the number of transponders and the usage of optical switches or electrical matrix switches. In this paper, the number of active transponders is analyzed to evaluate the power consumption of different schemes.

As to the EPS-based scheme, the signal should be transformed into the electronic domain to be switched, while in the WS-based or OTSS-based scheme the signal can be switched in the optical domain directly. When a traffic request traversing multiple ISLs is accepted in the EPS-based scheme, an extra pair of transponders will be utilized for each intermediate satellite when compared with the WS-based and OTSS-based schemes, thus greatly increasing the power consumption. While in the WS-based scheme, each traffic request occupies a single bandwidth and utilizes an individual pair of transponders. Fig. 7 shows the cumulative distribution function (CDF) curve of the number of active transponders with different switching schemes utilized and the traffic load set to 700 ErLang.

It is demonstrated that our proposed OTSS-based scheme dramatically reduces the number of active transponders in the optical satellite network when compared with its EPS-based and WS-based counterparts, thus achieving better

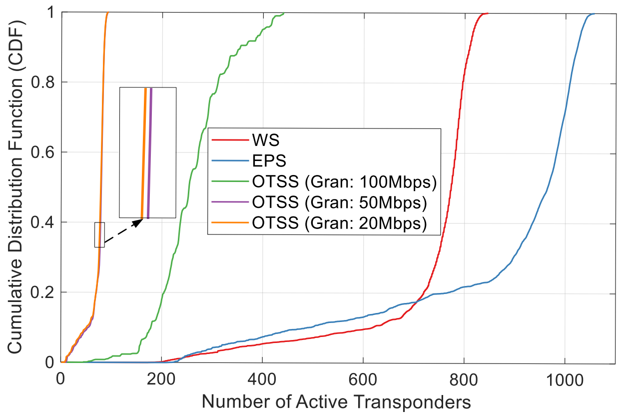


FIGURE 7. Number of active transponders with different switching schemes utilized and traffic load set to 700 ErLang. (Gran: Granularity)

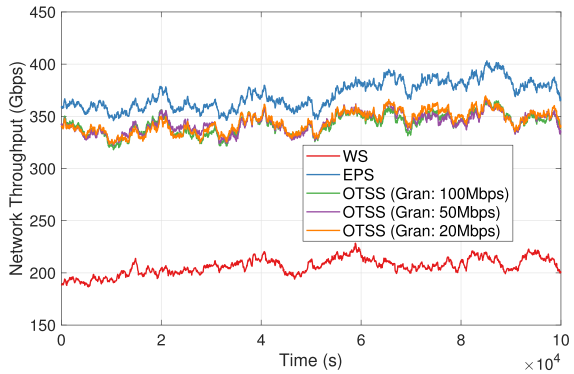


FIGURE 8. Network access bandwidth versus time when different switching schemes are utilized with traffic load set to 700 ErLang.

performance in term of power consumption. It is also shown that the OTSS-based scheme achieves almost exactly the same performance when the granularity is set to 50 Mbps and 20 Mbps, which correspond to the two leftmost curves that are almost completely coincident. Additionally, most of the time the WS-based scheme utilizes 700-850 transponders and the EPS-based scheme utilizes 900-1100 transponders, which respectively correspond to when a significant amount of traffic requests are accepted in the network and when most of the traffic requests traverse multiple ISLs.

2) NETWORK PERFORMANCE

Fig. 8 shows the network throughput when the traffic load is set to 700 ErLang with different switching schemes adopted. The network throughput of the OTSS-based scheme with the granularity of 50 Mbps is more than 50 percent higher than that of the WS scheme, demonstrating that the OTSS-based DV-RTSA scheme outperforms the WS-based scheme and performs almost the same as the EPS-based scheme in the aspect of network throughput.

In Fig. 9, the traffic acceptance ratios with different switching schemes utilized are compared. The OTSS-based scheme with the granularity of 50 Mbps maintains a traffic acceptance

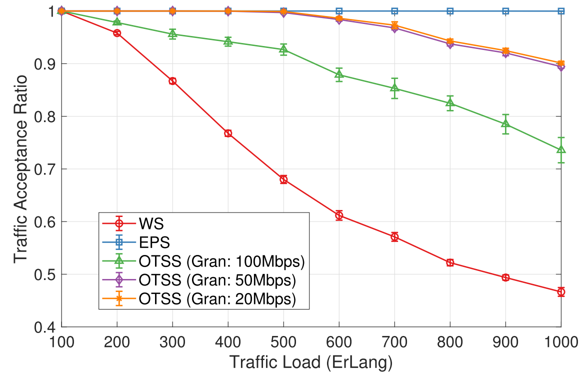


FIGURE 9. Traffic acceptance ratio with different switching schemes utilized.

ratio of higher than 95 percent when the traffic load is lower than 700 ErLang, which outperforms the WS-based scheme by nearly 50 percent. Fig. 9 also demonstrates that the traffic acceptance ratio grows higher when the granularity of OTSS gets finer.

VII. CONCLUSION

In this paper, a novel OTSS-based optical satellite network architecture with DV-RTSA algorithm is proposed for flexible resource allocation. In the numerical analysis with Poisson traffic, the OTSS-based scheme with a granularity of 50 Mbps is able to accept more than 95 percent of the traffic requests and has a similar traffic acceptance ratio with the EPS-based scheme when the traffic load is no more than 700 ErLang, verifying its feasibility. The simulation results also demonstrate that our OTSS-based scheme reduces the number of active transponders greatly when compared with its benchmarks and is available under circumstances of both Poisson traffic and traffic with constant service time. In summary, our proposed OTSS-based scheme with DV-RTSA algorithm allocate the network resource in a much finer granularity and increase the network resource utilization, and will gain better performance in future satellite networks with the increase of the switching frequency of optical switches.

REFERENCES

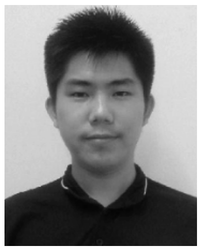
[1] L. Bai, L. Zhu, X. Zhang, W. Zhang, and Q. Yu, "Multi-satellite relay transmission in 5G: Concepts, techniques, and challenges," *IEEE Netw.*, vol. 32, no. 5, pp. 38–44, Sep./Oct. 2018.
[2] H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 57–96, 1st Quart., 2017.
[3] Y. Zheng, S. Zhao, Y. Liu, Y. Li, Q. Tan, and N. Xin, "Weighted algebraic connectivity maximization for optical satellite networks," *IEEE Access*, vol. 5, pp. 6885–6893, 2017.
[4] N. Hua and X. Zheng, "Optical time slice switching (OTSS): An all-optical sub-wavelength solution based on time synchronization," in *Proc. Asia Commun. Photon. Conf. Opt. Soc. Amer.*, 2013, p. AW3H.3.
[5] V. W. S. Chan, "Optical satellite networks," *J. Lightw. Technol.*, vol. 21, no. 11, p. 2811, 2003.
[6] T. Li, H. Guo, C. Wang, and J. Wu, "Optical burst switching based satellite backbone network," *Proc. SPIE*, vol. 10697, Mar. 2018, Art. no. 106975Q.
[7] D. Giggenbach, E. Lutz, J. Poliak, R. Mata-Calvo, and C. Fuchs, "A high-throughput satellite system for serving whole europe with fast Internet service, employing optical feeder links," in *Proc. 9th ITG Symp. Broadband Coverage Germany*, Apr. 2015, pp. 1–7.

[8] S. Pan *et al.*, "Satellite payloads pay off," *IEEE Microw. Mag.*, vol. 16, no. 8, pp. 61–73, Sep. 2015.
[9] L. Tan, Q. Yang, J. Ma, and S. Jiang, "Wavelength dimensioning of optical transport networks over nongeosychronous satellite constellations," *J. Opt. Commun. Netw.*, vol. 2, no. 4, pp. 166–174, 2010.
[10] Y. Dong, S. Zhao, H. dan Ran, Y. Li, and Z. Zhu, "Routing and wavelength assignment in a satellite optical network based on ant colony optimization with the small window strategy," *J. Opt. Commun. Netw.*, vol. 7, no. 10, pp. 995–1000, Oct. 2015.
[11] W. Van Heddeghem, F. Idzikowski, W. Vereecken, D. Colle, M. Pickavet, and P. Demeester, "Power consumption modeling in optical multilayer networks," *Photonic Netw. Commun.*, vol. 24, no. 2, pp. 86–102, 2012.
[12] M. Murakami and K. Oda, "Power consumption analysis of optical cross-connect equipment for future large capacity optical networks," in *Proc. 11th Int. Conf. Transparent Opt. Netw. (ICTON)*, Jun./Jul. 2009, pp. 1–4.
[13] R. Scharroo and P. Visser, "Precise orbit determination and gravity field improvement for the ERS satellites," *J. Geophys. Res.-Oceans*, vol. 103, no. C4, pp. 8113–8127, 1998.
[14] L. Lu *et al.*, "16 × 16 non-blocking silicon optical switch based on electro-optic Mach–Zehnder interferometers," *Opt. Express*, vol. 24, no. 9, pp. 9295–9307, 2016.
[15] Z. Li, L. Zhou, L. Lu, S. Zhao, D. Li, and J. Chen, "4 × 4 nonblocking optical switch fabric based on cascaded multimode interferometers," *Photon. Res.*, vol. 4, no. 1, pp. 21–26, 2016.
[16] J. Libich, M. Komanec, S. Zvanovec, P. Pesek, W. O. Popoola, and Z. Ghassemlooy, "Experimental verification of an all-optical dual-hop 10 Gbit/s free-space optics link under turbulence regimes," *Opt. Lett.*, vol. 40, no. 3, pp. 391–394, 2015.
[17] J. M. Dow, R. Neilan, and C. Rizos, "The international GNSS service in a changing landscape of global navigation satellite systems," *J. Geodesy*, vol. 83, nos. 3–4, pp. 191–198, Mar. 2009.
[18] T. Dong and G. Shen, "Traffic grooming for IP over WDM optical satellite networks," in *Proc. 13th Int. Conf. Opt. Commun. Netw. (ICOCN)*, Nov. 2014, pp. 1–6.
[19] Z. Zhong *et al.*, "Throughput scaling for MMF-enabled optical datacenter networks by time-slicing-based crosstalk mitigation," in *Proc. Opt. Fiber Commun. Conf. Opt. Soc. Amer.*, 2018, p. M2E.5.
[20] N. Hua and X. Zheng, "All-optical time slice switching method and system based on time synchronization," U.S. Patent 9 608 763 B2, Mar. 28, 2017.
[21] A. S. Karasuwa, I. Otung, and J. Rodriguez, "Joint precoding and spreading in the forward downlink of multi spot-beam satellite communication system," in *Proc. 35th AIAA Int. Commun. Satellite Syst. Conf.*, 2017, p. 5403.
[22] Z. Wang, P. T. Mathiopoulos, and R. Schober, "Performance analysis and improvement methods for channel resource management strategies of LEO–MSS with multiparty traffic," *IEEE Trans. Veh. Technol.*, vol. 57, no. 6, pp. 3832–3842, Nov. 2008.
[23] M. Mohorcic, A. Svigelj, G. Kandus, Y.-F. Hu, and R. E. Sheriff, "Demographically weighted traffic flow models for adaptive routing in packet-switched non-geostationary satellite meshed networks," *Comput. Netw.*, vol. 43, no. 2, pp. 113–131, 2003.
[24] L. Franck and G. Maral, "Routing in networks of intersatellite links," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 38, no. 3, pp. 902–917, Jul. 2002.
[25] H. Uzunalioğlu, I. F. Akyildiz, and M. D. Bender, "A routing algorithm for connection-oriented low earth orbit (LEO) satellite networks with dynamic connectivity," *Wireless Netw.*, vol. 6, no. 3, pp. 181–190, 2000.
[26] J.-C. Liou and N. L. Johnson, "Instability of the present LEO satellite populations," *Adv. Space Res.*, vol. 41, no. 7, pp. 1046–1053, 2008.

ZELIN ZHENG received the B.E. degree from Tsinghua University, in 2016, where he is currently pursuing the degree. His research interests include software-defined optical networks and optical satellite networks.

NAN HUA received the B.S. and Ph.D. degrees from Tsinghua University, Beijing, China, in 2003 and 2009, respectively, where he is currently an Associate Professor. He has published more than 100 papers and is the holder of more than 10 issued patents. He is a member of OSA.

ZHIZHEN ZHONG received the B.E. degree from Tsinghua University, in 2014, where he is currently pursuing the Ph.D. degree. He was a visiting Ph.D. student with the University of California at Davis, Davis, CA, USA, in 2018. He is a Student Member of OSA. He was a recipient of the IEEE Photonics Society First Place Best Poster Award on the IEEE CLEOPR/OECC/PGC 2017.



JIALONG LI received the B.E. degree from Tsinghua University, in 2016, where he is currently pursuing the Ph.D. degree. His research interests include software-defined optical networks and passive optical networks.

YANHE LI received the B.S. and M.S. degrees from Tsinghua University, in 1983 and 1987, respectively, where he is currently a Professor. He has published more than 100 papers. He is a Fellow of the Electronics Society of China, a Senior Member of the Optical Society of China, and a member of OSA.

XIAOPING ZHENG received the B.S. degree from Zhongshan University, in 1986, the M.S. from Southeast University, in 1994, and the Ph.D. degree from Tsinghua University, in 1998, where he is currently a Professor. He was a member of the Expert Group that was responsible for drafting the strategic program of the High Performance WideBand Communication Network during the tenth five-year plan of China. He is the Standing Director of the Beijing Society of Optics. He was awarded four prizes by the Chinese Governmental Ministries for his scientific contributions and invention achievements.