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WHEN TO CROSSOVER FROM EARTH TO SPACE FOR LOWER LATENCY DATA COMMUNICATIONS?

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ABSTRACT

For data communications over long distances, op- tical wireless satellite networks (OWSNs) can offer lower latency than optical fiber terrestrial networks (OFTNs). However, when is it beneficial to switch or crossover from an OFTN to an OWSN for lower latency data communications? In this work, we introduce a crossover function that enables to find the crossover distance, i.e., a distance between two points on the surface of the Earth beyond which switching or crossing over from an OFTN to an OWSN for data communications between these points is useful in terms of latency. Numerical results revealthat a higher refractive index of optical fiber (or ί) in an OFTN and a lower altitude of satellites (or h) in an OWSN result ina shorter crossover distance. To account for the variation in the end-to-end propagation distance that occurs over the OWSN,we examine the crossover function in four different scenarios. Numerical results indicate that the crossover distance varies with the end- to-end propagation distance over an OWSN andis different for different scenarios. We calculate the average crossover distance over all scenarios for different h and ί and use it to evaluate the simulation results. Furthermore, for a comparative analysis of OFTNs and OWSNs in terms of latency, we study three different OFTNs having different refractive indices and three different OWSNs having different satellite altitudes in three different scenarios for long-distance inter- continental data communications, including connections between New York and Dublin, Sao Paulo and London, and Toronto and Sydney. All three OWSNs offer better latency than OFTN2 (with ί2 = 1.3) and OFTN3 (with ί3 = 1.4675) in all scenarios. For example, for Toronto–Sydney connection, OWSN1 (with $h1$ = 300 km), OWSN2 (with $h2$ = 550 km) and OWSN3 (with $h3$= 1,100 km) perform better than OFTN2 by 18.11%, 16.08%, and 10.30%, respectively, while they provide an improvement in latency of 27.46%, 25.67%, and 20.54%, respectively, compared to OFTN3. The OWSN1 performs better than OFTN1 (with ί1= 1.1) for Sao Paulo–London and Toronto–Sydney connections by 2.23% and 3.22%, respectively, while

OWSN2 outperforms OFTN1 for Toronto–Sydney connection by 0.82%. For New York–Dublin connection, all OWSNs while for Sao Paulo–London connection, OWSN2 and OWSN3 exhibit higher latency than OFTN1 as the corresponding average crossover distances are greater than the shortest terrestrial distances between cities in these scenarios. Multiple satellites (or laser inter-satellite links) on its shortest paths drive up the propagation distance to the extent that OWSN3 ends up with a higher latency than OFTN1 for the Toronto–Sydney inter-continental connection scenario although the related average crossover distance is less than the shortest terrestrial distance between Toronto and Sydney. The challenges related to OWSNs and OFTNs that may arise from this work in future are also highlighted.

Keywords- Crossover distance, crossover function, LEO, network latency, optical fiber terrestrial networks, optical wire- less satellite networks, satellite constellations.

[1] INTRODUCTION

Optical be created in space by employing laser inter-satellite links (LISLs) between satellites in upcoming low Earth orbit (LEO)or very low Earth orbit (VLEO) satellite constellations, like SpaceX's Starlink [1] and Telesat's Lightspeed [2]. The LISLs[3], also known as optical inter-satellite links, will be essentialin ensuring low-latency paths (or routes) within the OWSN [4], [5]. Without LISLs, a long-distance inter- continental data communications connection between two cities, such as New York and Dublin, will have to bounce up and down between ground stations and satellites, and this will negatively affect latency of the satellite network.

The provision of long-distance low-latency data communi- cations could be the primary use case of an OWSN that is created by using LISLs in an upcoming LEO/VLEO satellite constellation like Phase I of Starlink [6]. An OWSN can offer such type of communications as a premium service to the financial hubs around the globe, and such a use-case can be beneficial in recovering the cost of deploying and sustaining such satellite networks. In high-frequency trading (HFT) of stocks at the stock exchange, a one millisecond advantage can translate into $100 million a year in revenues for a major brokerage firm [7]. An advantage of a few milliseconds in HFT could mean billions of dollars of revenues for thesefirms. Technological solutions in the form of communications networks that can provide lower latency data communications are being highly coveted by such firms, and a low-latency OWSN could be the ideal solution.

Unlike optical fiber terrestrial networks (OFTNs) wheredata is sent using a laser beam over a guided medium, i.e., optical fiber, data communications in OWSNs takes places over LISLs by using laser beams between satellites over an unguided medium, i.e.,vacuum of space. The refractive index of a medium indicates the speed of light through that medium,and a higher refractive index means a slower transmissionof light [8]. Optical fibers typically have a refractive indexof approximately 1.5. This means that the speed of light in an optical fiber is approximately ▯/1.5, where ▯ is the speed of light in vacuum [9]. This translates into speed of light in vacuum being approximately 50% higher than the speed of light in optical fiber. This has significant implications, and thehigher speed of light in OWSNs operating in the vacuum of space composed of transmission delay, processing delay, queueing delay, and propagation delay [10]. For optical communications in OFTNs or OWSNs over optical fiber or vacuum of space, propagation delay is the delay arising from the transmission of the optical signal along the medium. It is directly proportional to the distance between the source and the destination and becomes very significant in long-distance data communications [11]. In this work, we study the latency of OWSNs and OFTNs, and we define latency (or end-to-end network latency) as the propagation delay from the source to the destination.

Firstly, we propose a crossover function for data communi- cations between two points on the surface of the Earth over an OFTN and an OWSN. The crossover function is then used to calculate the crossover distance that indicates when switching or crossing over from an OFTN to an OWSN can be beneficial for data communications in terms of latency. The crossover function and thereby the crossover distance depend upon the refractive index of the optical fiber in an OFTN and the altitude of satellites in an OWSN. From numerical results, we observe that a higher optical fiber refractive index and a lower altitude of satellites result in a shorter crossover distance.For each scenario, we find minimum-latency paths between cities over these six different networks. From the results, we observe that all three OWSNs outperform the OFTN with a realistic refractive index of 1.4675 as well as the OFTN with a refractive index of 1.3 in terms of latency in all scenarios. The OWSN operating at 300 km altitude performs closely to the OFTN with a refractive index of 1.1 for the New York–Dublin connection and outperforms it for the Sao Paulo–London and Toronto–Sydney connections while the OWSN at 550 km altitude offers lower latency than this OFTN for the Toronto–Sydney connection. Within all scenarios, it is observed that the lower the refractive index of an OFTN or the lower the altitude of satellites in an OWSN, the lower the latency of a network. For data communications in different scenarios over a network, it is seen that the greater the inter- continental distance between cities, the higher the latency of a network. Preliminary work in this regard has appeared in [13].

[2] MOTIVATION

In addition to providing an ideal solution for low-latency long-distance inter-continental data communications for HFT between stock exchanges around the globe, OWSNs can also be beneficial in other scenarios. In one such use case, anOWSN can help in extending broadband Internet to rural remote areas when integrated as a backbone with the existing 4G/5G networks. The OWSN can provide a backhaul network to connect the 4G/5G access networks in rural and remote areas to their core network. By providing the ability to connect any two points on Earth over the OWSN arising from employing LISLs between satellites in their upcoming satellite constellation Lightspeed, Telesat plans to enable the provision of broadband Internet to unserved and underserved communities and individuals in rural and remote areas. Telesat has already successfully demonstrated this use case for Internet backhauling with TIM Brasil – an Internet Service Provider – in their 4G network where a Lightspeed's Phase I satellite was used to connect remote communities in Brazil to the Internet by linking TIM Brasil's access network to its core [17].

In another use case for OWSNs, the European Space Agency's High thRoughput Optical

Network (HydRON) project is targeting a “Fiber in the Sky” network in space [18]. The goal of this project is to enable an all-optical transport network in space. It will utilize all-optical pay- loads interconnected via Tbps optical inter-satellite links to realize a true “Fiber in the Sky” network. The HydRON system is expected to have the following main functionali- ties: bidirectional very high-capacity laser inter-satellite links and reliable very high-capacity optical feeder links; interface compatibility with RF/optical customer payloads for traffic distribution/collection to/from these payloads; on-board fast transparent optical switching and on-board fast regenerative electrical switching; and network optimization using artificial intelligence [19].

Developing a better understanding of latency in satellite networks arising from upcoming LEO/VLEO satellite constel- lations has been the focus of the research community [4], [5], [13], [20]–[27]. A study has investigated the use of ground- based relays as a substitute of inter-satellite links to provide low-latency communications over satellite networks [4]. It is concluded that lower latency is achieved when inter-satellite links are used between satellites in a satellite constellation at 550 km altitude than using ground stations as relays. It is reported in a study that inter-satellite links substantially reduce latency variations in the satellite network [5]. A sim- ulator for studying different parameters, including latency, of satellite networks arising from upcoming LEO/VLEO satellite constellations has been developed [20]. It is stated in [21] that a satellite network using inter- satellite links within a satellite constellation can provide lower latency than an OFTN for data communications over long distances greater than 3,000 km.

It is mentioned that a dense small satellite network (i.e., a satellite network arising from a satellite constellation consist- ing of hundreds of satellites, such as Starlink and Lightspeed) has the potential to provide lower latency than any terrestrial network of comparable length due to the higher speed of light in free space than in optical fiber [22]. It is further stated that although the target latency of 1 ms for 5G cellular systems cannot be directly attained with the help of a dense small satellite network, it may indirectly support 5G networks in decreasing latency by offering alternate backhaul.

A. Scenario 2

This scenario is illustrated in Fig. 5, where points ⍰ ′ and ⍰ ′ indicate the positions of the satellites in Scenario 1, and yellow circles represent the positions of the satellites ⍰ and ⍰ in this scenario. When assuming an anti-clockwise orbital movement of satellites, note that the LEO satellites ⍰ and ⍰ are located before ⍰′ and after ⍰′, respectively, in this scenario.

The end-to-end propagation distance over the OWSN in thi

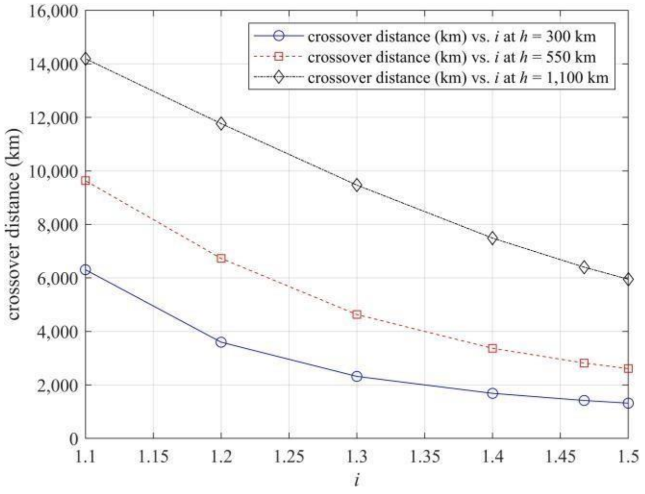

Fig. 3. Plot of crossover distance (km) for Scenario 1 vs. at different valuesof *h* (km). As the value of optical fiber refractive index decreases for some value of satellite altitude *h*, the value of the crossover distance increases. This trend is similar for all values of *h*.

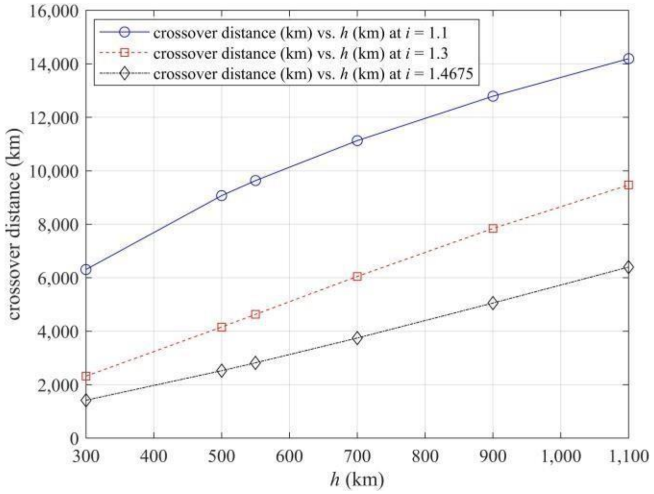

Fig. 4. Plot of crossover distance (km) for Scenario 1 vs. *h* (km) at different values of . As *h* increases for some , the crossover distance increases. A similar trend is seen for all values of .

[3] METHODOLOGY FOR CALCULATING LATENCY OF AN OFTN AND AN OWSN

In this section, we describe in detail the different steps of our methodology for calculating the latency in an OFTN and an OWSN. The values used in this study of the different parameters for the three different OFTNs and the three different OWSNsare listed in Table 4.

A. Optical Fiber Terrestrial Network

For the three OFTNs, we use three different refractive indices, 1 for the first OFTN (or OFTN1), 2 for the second OFTN (or OFTN2), and 3 for the third OFTN (or OFTN3). We consider different refractive indices for OFTN1, OFTN2, and OFTN3 to study the impact of optical fiber refractive index on latency in OFTNs as well as for comparative analysisof latency between OFTNs and OWSNs. For example, weuse 1.4675 as the value for 3, which is the refractive index of a single-mode optical fiber (manufactured by Corning®)that is suitable for long-distance communications at 1,310 nm operating wavelength [12].

Technological developments may lead to a reduction of optical fiber refractive index in future and we assume lower values for 2 and 1 accordingly. The speed of light in optical fiber with a refractive index can be calculated using /, where the value of the speed of light in vacuum or is 299,792,458 m/s [30]. For example, we consider the speed of light in OFTN3 to be /1.4675 or 204,287,876

[4] LATENCY COMPARISON – OFTNS VS. OWSNS

To study the impact on latency of optical fiber refractive index in OFTNs and altitude of satellites in OWSNs, we consider three different OFTNs and three different OWSNs as specified in Table 4. To compare these OFTNs and OWSNs in terms of latency, we examine them in three different inter- continental connection scenarios, including New York–Dublin, Sao Paulo–London, and Toronto–Sydney. We simulate the three different OWSNs using the well-known satellite constel- lation simulator STK Version 12.1 [32], the satellite constellation for Phase I of Starlink, and the parameters given in Table 4 and described in Section IV-B. For example, to simulate the OWSN1, we generate Starlink's Phase I constellation using $h1$

[5] CONCLUSIONS

A crossover function is proposed to enable the determination of the crossover distance for switching from an OFTN on Earth to an OWSN in space for lower latency data communications. The crossover distance depends upon the optical fiber refrac- tive index in an OFTN and the altitude of satellites h in an OWSN. The numerical results indicate that a higher and a lower h result in a shorter crossover distance. The crossover function is examined in four different scenarios to account for the different end-to-end propagation distances that occur over the OWSN due to the orbital movement of satellites with time. It is observed from the numerical results that the crossover distance varies with the end-to-end propagation distance over an OWSN. It is minimum for Scenario 3 and maximum for Scenario 2 since the end-to-end propagation distance overan OWSN is smallest in Scenario 3 and largest in Scenario.

The average crossover distance, which is the average of the crossover distances of all four scenarios, is calculated for different h and □, and is used to evaluate the simulation results. Furthermore, three different OFTNs having different □s and three different OWSNs with different hs are compared in terms of latency under three different scenarios for long-distance inter-continental data communications. The simulation results indicate that OWSN1 (i.e., the first OWSN with $h_1 = 300$ km), OWSN2 (i.e., the second OWSN with $h_2 = 550$ km) and OWSN3 (i.e., the third OWSN with $h_3 = 1{,}100$ km) outperform OFTN2 (i.e., the second OFTN with $\square_2 = 1.3$) and OFTN3 (i.e., the third OFTN with $\square_3 = 1.4675$) in all scenarios. For New York–Dublin connection, OWSN1, OWSN2, and OWSN3 perform better than OFTN2 by 15.17%, 11.84%, and 2.66%, respectively, while they provide an improvement in latency of 24.85%, 21.90%, and 13.76%, respectively, compared to OFTN3.

[6] FUTURE CHALLENGES

In the following, we highlight some future challenges re- lated to OWSNs and OFTNs that can arise from this work.

Incorporating Processing Delay in the End-to-End Latency of OFTNs and OWSNs:

For congestion-free OFTNs and OWSNs with very high data rate links, the queueing and transmission delays can be considered as negligible, and the end-to-end latency consists of processing and propagation delays. Therefore, in addition to the propagation delay, processing delay is an important part of the end-to-end latency that needs to be considered in both OWSN and OFTN. It is the delay that is incurred by a hop/node (i.e., an optical fiber relay station or a satellite) to process a packet, such as the time used to read the packet header to make appropriate routing and switching decisions, before sending the packet to the appropriate next hop. It depends upon the number of hops between the source and destination points (i.e., optical fiber relay stations or satellite ground stations) on the Earth's surface and becomes significant when the data communications has to go through several intermediate hops. The crossover function could be extended to incorporate this delay. It would also be interesting to study the effect of this delay on the end-to-end latency in OWSN and OFTN and to compare these two networks after incorporating this delay in the simulations.

A. *Making the Crossover Decision at Each Time Slot Based on Current Ingress and Egress Elevation Angles in the OWSN:*

Instead of comparing the average crossover distance and the shortest terrestrial distance, another approach to switch from the OFTN to the OWSN for long-distance lower latency data communications can be based on checking the elevation angles of the ingress and egress satellites at every time slot, calculating the corresponding crossover distance at a time slot, and comparing it with the shortest terrestrial distance between cities to make the crossover decision at that time slot. For instance, the crossover function for Scenario 2 in this case can be written as in (29). It would be interesting to evaluate such an approach in future.

B. *Incorporating Extra Distance to Account for the Zig-Zag Path of OFTNs:*

In this work, we consider the shortest distance between two cities over the OFTN along the Earth’s surface. In reality, long- haul submarine optical fiber cables do not adhere to the shortest path to connect two points on Earth’s surface and are installed along paths that avoid earthquake prone areas and difficult seabed terrains with high slopes. Another approachto model the shortest distance between cities over the OFTN can be to add an extra distance to account for the extra length of the long- haul submarine optical fiber cables due to the zig-zag nature of their path. This extra distance can be added tothe shortest distance as a percentage of the shortest distance. For example, the crossover function for Scenario 2 in (29) canbe calculated in this case as in (30). Such an approach couldbe investigated in future.

[7] ACKNOWLEDGMENT

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REFERENCES

[1] SpaceX FCC update, Nov. 2016, "SpaceX Non-Geostationary Satellite System, Attachment A, Technical Information to Supplement Schedule S," [Online]. Available: https://licensing.fcc.gov/myibfs/download.do?att achment_key=1158350, Accessed: February 17, 2022.

[2] Telesat Canada FCC update, May 2020, "Application for Modification of Market Access Authorization," [Online]. Available: https://fcc.report/I BFS/SAT-MPL-20200526-00053/2378318.pdf, Accessed: February 17, 2022.

[3] A.U. Chaudhry and H. Yanikomeroglu, "Laser Intersatellite Links in a Starlink Constellation: A Classification and Analysis,"

[4] *IEEE Vehicular Technology Magazine*, vol. 16(2), pp. 48–56, Jun. 2021.

[5] M. Handley, "Using Ground Relays for Low-Latency Wide-Area Routing in Megaconstellations," in *Proc. 18th ACM Workshop on Hot Topics in Networks*, New York, NY, USA, 2019, pp. 125–132.

[6] Y. Hauri, D. Bhattacherjee, M. Grossmann, and A. Singla, ""Internet from Space" Without Inter-Satellite Links?," in *Proc. 19th ACM Workshop on Hot Topics in Networks*, New York, NY, USA, 2020, pp. 205–211.

[7] SpaceX FCC update, Nov. 2018, "SpaceX Non-Geostationary Satellite System, Attachment A, Technical Information to Supplement Schedule S," [Online]. Available: https://licensing.fcc.gov/myibfs/download.do?att achment_key=1569860, Accessed: February 17, 2022.

[8] R. Martin, "Wall Street's Quest to Process Data at the Speed of Light," *Information Week*, Apr. 2007, [Online]. Available: https://rubinow.com/ 2007/04/21/wall- streets- quest- to-process- data- at- the- speed- of- light/, Accessed: February 17, 2022. S.C. Gupta, *Textbook on Optical Fiber Communication and Its Applica- tions*, PHI Learning Private Limited, New Delhi, 2018.

[9] J. Hecht, *Understanding Lasers: An Entry-Level Guide*, Wiley, Hoboken, NJ, 2018.

[10] J.F. Kurose and K.W. Ross, *Computer Networking – A Top Down Approach Featuring the Internet*, Addison-Wesley, Boston, MA, 2009.

[11] Corning Inc., "The Super Connected World: Optical Fiber Advances and Next Gen Backbone, Mobile Backhaul, and Access Networks [White Paper]," Jun. 2012, [Online]. Available: https://www.corning.com/medi a/worldwide/coc/documents/Fiber/white-paper/WP6024_06- 121.pdf, Accessed: February 17, 2022.

[12] Corning Inc., "Corning® Hermetic Single-mode and Multimode Spe- cialty Optical Fibers," Mar. 2010, [Online]. Available: https://www.corn ing.com/media/worldwide/csm/documents/Hermetic%20Single-mode%2 0&%20Multimode.pdf, Accessed: February 17, 2022.

[13] A.U. Chaudhry and H. Yanikomeroglu, "Optical Wireless Satellite Net- works versus Optical Fiber Terrestrial Networks: The Latency Perspective – Invited Paper," in *Proc. 30th Biennial Symposium on Communications*, Saskatoon, Canada, 2021, pp. 1–6.

[14] M.S. Awan, Marzuki, E. Leitgeb, B. Hillbrand, F. Nadeem, and M.S. Khan, "Cloud Attenuations for Free-Space Optical Links," in *Proc. 2009 International Workshop on*

Satellite and Space Communications, Siena, Italy, 2009, pp. 274–278.

[15] E. Erdogan, I. Altunbas, G.K. Kurt, M. Bellemare, G. Lamontagne, and H. Yanikomeroglu, “Site Diversity in Downlink Optical Satellite Networks Through Ground Station Selection,” *IEEE Access*, vol. 9, pp. 31179–31190, Feb. 2021.