

Enhancing Inter-Satellite Data Relay in Dynamic Space Communication

Refik Caglar Kizilirmak, Israel Ehile Ehile, Bekzat Kabdrashev, Sergey Khvan

Dept. of Electrical and Computer Engineering, Nazarbayev University, Astana, Kazakhstan

Abstract—In this paper, we explore the design and operations of an inter-satellite data relay network, which includes Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit (GEO) satellites. Due to the different orbiting speeds and dynamic behaviors of these satellite constellations, we consider Delay-Tolerant Networking (DTN) between them and implement contact graph routing (CGR) at the layer-3 and Licklider Transmission Protocol (LTP) at layer-4. We base our analysis on a realistic space scenario where satellite locations and movements over time are extracted from a real-time satellite database. We demonstrate end-to-end latency and goodput of a file transfer through the satellite network under consideration.

Index Terms—Delay Tolerant Networks (DTN), Contact Graph Routing (CGR), Licklider Transmission Protocol (LTP)

I. INTRODUCTION

Traditional transport and network layer technologies are not suitable for dynamic space networks, especially for interplanetary networks (IPN) [1], prompting the search for novel architectures and protocols. These novel approaches must address various space network challenges, such as intermittent connectivity among nodes, vast distances, and significant delays. In 2007, an Internet Research Task Force (IRTF) working group proposed a delay-tolerant networking (DTN) architecture as the backbone of space networks, restructuring the layered architecture of traditional networks. They introduced the Bundle Protocol (BP) with store-and-forward features to manage intermittent connectivity and, at layer-4, replaced TCP with the Licklider Transmission Protocol (LTP) to reduce acknowledgment traffic overhead between nodes. Subsequently, the Consultative Committee for Space Data Systems (CCSDS) introduced IPN Contact Graph Routing (CGR) at layer-3 to handle dynamic topology and find the shortest path in space [2]. Recently, the standardization efforts for IPN shifted from IRTF to the Internet Engineering Task Force (IETF).

The fundamental components of DTN architecture in space (CGR, LTP, BP) have been the focus of extensive research. They have also received continuous support through the implementation of ION (Interplanetary overlay network) [3], developed by NASA-JPL. Many studies have explored these technologies individually rather than examining the DTN system as a cohesive whole. In studies conducted in [4] [5], the focus was on investigating BP and LTP for modeling and performance analysis of space networks, with limited attention to their interactions with CGR. Similarly, [6] [7] [8] delved into the study of CGR in isolation, with minimal

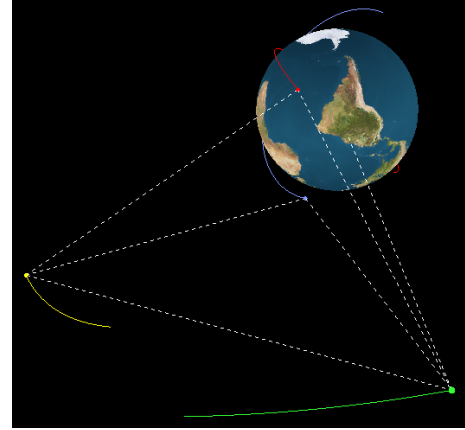


Fig. 1. Satellite constellation under consideration. Intermittent connectivity and dynamic topology can be seen at https://youtu.be/c7G9_8GdAX4

consideration of its interactions with upper layers. There have also been sporadic efforts that comprehensively analyzed the interplay between the various multilayer technologies within DTN in space [9]. In this paper, we study and demonstrate end-to-end latency and goodput of a file transfer through a satellite network while considering multilayer interactions of DTNs.

Fig. 1 illustrates the satellite constellation that we consider, consisting of two Low Earth Orbit (LEO) satellites, one Medium Earth Orbit (MEO) satellite, and one Geostationary Orbit (GEO) satellite. We obtained real satellite locations from <http://celestrak.org/> and visualized them using a software tool that we developed. Please note that these satellites serve distinct operational objectives; however, we configured a DTN utilizing them for our research study. LEO satellites orbit the Earth, traversing various Earth regions to capture sensor data. MEO satellites play a vital role in data relay, receiving data from LEO satellites and forwarding it to GEO satellites. Positioned over specific Earth regions, GEO satellites gather data from LEO satellites and transmit it to ground stations. This configuration is beneficial in cases where data collection in a particular Earth region is distant from the ground station, and data needs to be relayed.

In this scenario, we employ DTN protocols to ensure reliable data transfer between the satellites which is a challenging task with traditional protocols due to the intermittent connectivity. As LEO satellites pass through the coverage

region of MEO satellite, they establish connections and transmit the stored sensor data. MEO satellite implements store-and-forward relaying, buffering the received data until they come within the coverage area of GEO satellite. Finally, the GEO satellite forwards the data received from the MEO satellite to the ground station through its continuous communication link.

This paper is organized as follows. In Section II, we briefly provide discussion of use of DTNs in space communication. In Section III, we revisit LTP. In Section IV, we present our performance analysis results, namely for latency and goodput, for the scenario under consideration. In Section V, we conclude our paper.

II. DELAY TOLERANT NETWORKING FOR DEEP SPACE COMMUNICATION

The delay tolerant network research group (DTNRG) suggested a structure and framework design in response to the demand for interoperable communication in harsh and efficiency-defying conditions where constant point-to-point connectivity is not possible [10]. According to [11] DTN architecture is a viable technique for Interplanetary Internet (IPN) networks. To overcome the difficulty of constantly delivering messages in intermittent connections, the DTN architecture employs a store-and-forward strategy that comprises storing messages in the buffer of DTN routers for long periods of time. This architecture employs a new layer known as the "bundle layer" to provide communications [12]. According to [9] the end-to-end path is divided into many DTN hops by adding the bundle protocol (BP) to endpoints and certain intermediate nodes on the route. The term "bundles" refers to data packets transmitted at the bundle layer. Since bundles are devoid of any size restrictions, they have the potential to be substantially bigger than standard IP packets, mainly when they include vast amounts of data, such as an image. The bundle layer offers store-and-forward relay for end-to-end bundle transfer.

Instead of IP, which links heterogeneous networks by assigning an IP address to each node at the network layer, a DTN employs "naming, layering, encapsulation, and permanent storage" [13]. The same concepts and mechanisms developed to address the delays and disruptions of interplanetary communications can be easily applied in certain connectivity regions with long signal propagation times, regular node obstruction, throughput flexibility, or constrained transmission range and information. Every communication network must be capable of effectively transmitting data from point to point. In the context of DTNs, conventional routing strategies should be able to manage network latency without significantly reducing information transfer efficiency. Many of these protocols may be classified based on the prospective contacts' level of global awareness [14]. Furthermore, in [14], the main idea of DTN networking is to solve the design and routing ideas in order to provide effective interoperability with/among severe and performance-challenged devices. The fundamental DTN core concept allows network routers to

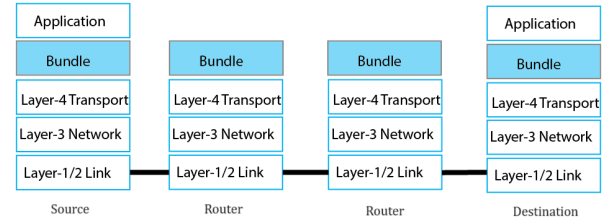


Fig. 2. DTN architecture.

send and store data to be forwarded later when the connection is restored.

III. LICKLIDER TRANSMISSION PROTOCOL (LTP)

LTP is suitable for DTNs' transport layer operations. While it shares some similarities with TCP (Transmission Control Protocol), LTP differs from TCP in several key ways. Firstly, unlike TCP, which operates exclusively between the two endpoints, LTP runs on every node, including both routers and endpoints (see Fig. 2). The primary rationale behind this approach is to address the considerable distances and associated delays between the end nodes. In cases where a packet is lost during transit, implementing Automatic Repeat reQuest (ARQ) solely between the end nodes would result in prohibitively long recovery times. Therefore, LTP incorporates ARQ at every hop within the network. Secondly, LTP optimizes the number of acknowledgment packets. In contrast to TCP, where each individual segment is acknowledged separately, LTP groups bundles into LTP blocks. This aggregation reduces the acknowledgment overhead within the network.

In LTP, file transfer is accomplished by first fragmenting the file into a number of bundles, which are later divided into several LTP data blocks. Each data block is further divided into segments and transmitted to the receiver node. LTP allows for the option of reliable transmission, for example, by requiring acknowledgments. LTP segment size is set to ensure it fits into Ethernet MTU (1500 bytes) for later processing. Red blocks indicate reliable transmission, while green blocks indicate unreliable transmission. In this study, we assume that all the blocks are set as 100% red. At the end of the block transmission, the sender sends a checkpoint (CP) segment. When the receiver receives the CP segment, it checks for any loss of segments within the block. Upon receiving the CP, the receiver sends a report segment (RS) to the sender to indicate whether any segments were lost or not. When there is no loss, the receiver cumulatively acknowledges the sender with RS. On the other hand, when there is any loss, RS informs the sender about the lost data, and the sender retransmits any lost segments, followed by another CP at the end of its transmission. In LTP, both CP and RS segments are transmitted with a timer to ensure delivery to the other side. In case of a timeout, they are retransmitted.

IV. PERFORMANCE ANALYSIS

For the satellite network considered in Fig. 1 (also given in Fig. 3 for illustration), due to the different orbiting speeds

and dynamic behaviors of these satellite constellations, we consider DTN protocols between them and implement CGR at the layer-3 and LTP at layer-4. We demonstrate end-to-end latency and goodput of a file transfer through this satellite network.

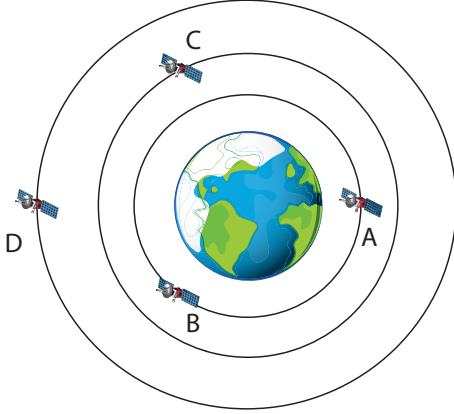


Fig. 3. 2D illustration of nodes A,B,C and D orbiting Earth. Nodes A and B are the LEO satellites, C is the MEO satellite, and D is the GEO satellite (not to the scale).

A. Contact Graph Routing (CGR)

Table I shows the contact plan we obtained for a duration of 2 hours, where nodes A and B are the LEO satellites, C is the MEO satellite, and D is the GEO satellite. In Table I, for example, the first row shows the first contact between nodes A and B; contact starts at 23.33 min and lasts for 20 mins. The average distance between A and B during this contact is 5500 km, which corresponds to the propagation delay of 0.018 sec.

The CGR relies on adapted Dijkstra's shortest path algorithm [15]. This algorithm computes a route from a source to a target node using a contact graph that is based on a contact plan. Each vertex in the contact graph represents connectivity period between two nodes. Two vertices are connected by a directed edge if the end of the earlier contact matches the start of the next contact. The computed route is a sequence of contacts from the source to the destination.

TABLE I. Contact Plan

Cont.	From	To	Start (min)	End (min)	avg. distance (km)
1	A	B	+23.33	+43.33	5500
2	A	B	+76.66	+93.33	3400
3	A	D	+0	+8.33	42000
4	A	D	+53.33	+105	39000
5	A	C	+0	+13	28000
6	A	C	+36.66	+90	26000
7	B	D	+0	+4	46500
8	B	C	+15	+98.33	25500
9	C	D	+0	+120	46000

For the contact plan in Table 1, we run CGR to find the shortest path from source node A to destination node D by implementing the algorithm described in [15]. The shortest path is found as through contacts #1,#8 and #9, A→B, B→C and C→D. In this route, the longest path in terms of propagation delay is contact #9 with 0.15 sec.

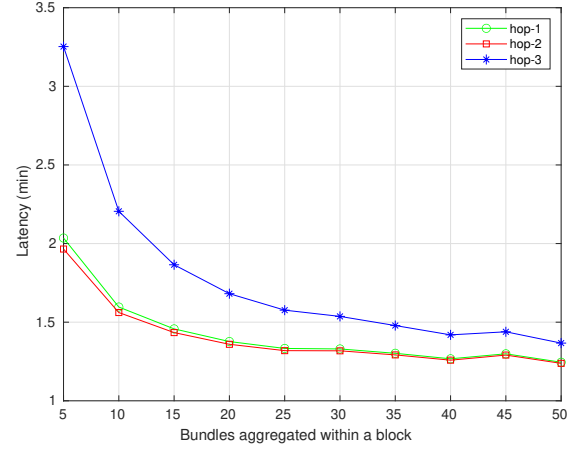


Fig. 4. End-to-end latency for each hop.

B. LTP goodput and delay performance

After finding the shortest path, we employ LTP and demonstrate a file transfer of 1 MB size through this path. In the analysis, we investigate the goodput and latency performance of LTP. We assume that each link has symmetrical data rates of 115200 bps. In the context of LTP, if the bundles are configured as 'red,' a series of checkpoint (CP), report segment (RS), and report acknowledgment (RA) exchanges occur after each block transfer between any two nodes along the communication path. The segment size is considered to be equal to the bundle size, which is set at 1000 bytes, as are the sizes of the CP, RA, and RS segments. To maintain generality, we assume that there occurs no errors in the links.

Fig. 4 shows the end-to-end delay for the file transfer for each hop individually. To simplify the discussion, no forwarding is demonstrated in Fig. 4. For the hop-1 (A→B) when 5 bundles are aggregated within an LTP block, the complete file transfer takes 2.04 min. For the same bundle configuration, hop-2 (B→C) and hop-3 (C→D) require 1.97 and 3.26 min, respectively. When the number of bundles aggregated within a block is increased, the acknowledgment overhead, including the number of CR, RS, and RA exchanges, is reduced, and the file transfer duration also decreases. Fig. 5 shows the goodput achieved by each hop individually. Hop-1 (A→B) achieves the highest goodput at around 13.5 KBps when 50 bundles are aggregated within a block. For the same configuration, hop-2 (B→C) and hop-3 (C→D) achieve 13.5 KBps and 12.2 KBps, respectively.

Next, we investigate the end-to-end file transfer latency, including forwarding. In LTP, forwarding typically occurs at the block level; in other words, the intermediate node can start forwarding after receiving a block and completing RS and RA exchanges. In Fig. 6, this strategy is indicated as incremental forwarding. The contact plan in Table 1 shows that the second and third hops (B→C and C→D) are already available when source node A starts its transmission. Therefore, incremental forwarding is feasible for this route, where nodes B and C forward the blocks as they receive without waiting for

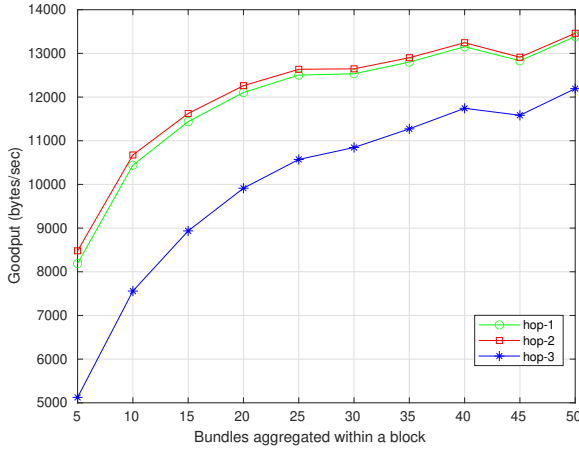


Fig. 5. Goodput (bytes/sec) for each hop.

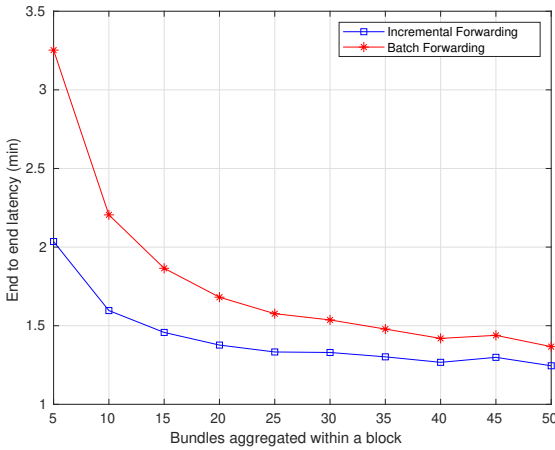


Fig. 6. End-to-end latency.

the entire file. In Fig. 6, we further compare incremental forwarding with batch forwarding, where a complete file is stored before forwarding it to the next hop. As more bundles are aggregated within a block, end-to-end delay converges to 1.2 and 1.4 mins. respectively for incremental and batch forwarding.

V. CONCLUSION

In this work, we investigated the expanding landscape of space networking by providing a comprehensive analysis of DTN technologies and their multi-layer interconnections. Our research exemplifies the practical significance of DTN protocols, focusing on their potential to provide efficient and reliable communication within the demanding space environment. In our work, we first generated a satellite network using real satellite locations and then built a contact plan based on their movements. We ran the CGR algorithm to find the shortest path for the given scenario and demonstrated a file transfer using LTP over this path. The results of this research have important significance for the development and improvement of space communication systems in the future,

establishing possibilities for networks based on satellites and interplanetary space that are more effective. Our future work includes incorporating the impact of segment losses, using instantaneous distances between nodes, and building a visual simulator that shows all these interactions.

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Refik Caglar Kizilirmak (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees in electrical and electronics engineering from Bilkent University, Ankara, Turkey, in 2004 and 2006, respectively, and the Ph.D. degree from Keio University, Yokohama, Japan, in 2010. He was with the Communications and Spectrum Management Research Center, Turkey, on several telecommunication and defense industry projects. He is currently with the Department of Electrical and Computer Engineering, Nazarbayev University, Astana, Kazakhstan.

He has contributed to the technical requirements document of IEEE 802.15.7r1 standardization, which will enable visible light communication. He has authored several articles in the field of wireless communications and has filed three patent applications with the patent offices of USA and Japan.



Israel Ehile Ehile received the B.Eng. in electrical and electronics engineering from the University of Agriculture, Makurdi, Nigeria in 2018. He was a Research Assistant with the Department of Electrical and Computer Engineering, Nazarbayev University, Astana, Kazakhstan in 2023. He is currently a Master student in Electrical and Computer Engineering at Nazarbayev University, Astana, Kazakhstan. His research interests include Communication in Inter-Satellite, Routing in Deep Space Network, Computer Networks and Cloud

Security.



Bekzat Kabdrashev was born in Akmola region, Kazakhstan in 2001. Kabdrashev graduated from National School of Physics and Mathematics in Astana, Kazakhstan in 2019. He is a senior computer science student at Nazarbayev University in Astana, Kazakhstan. Alongside with his studies at Nazarbayev University, he is researching interplanetary networks as a Research Assistant of Professor Refik Kizilirmak. His research interests include computer networks and programming language design.



Sergey Khvan is a graduate student in Computer Engineering at the University of Padova, Italy. The author completed his bachelor's studies in Electrical and Computer Engineering at Nazarbayev University, Astana in 2023. Previously worked as a Research Engineer at "Robotics and Artificial Intelligence" LLP and Research Assistant at Nazarbayev University. Previous projects include the spheres of the Internet of Things(IoT), Blockchain, and Robotics. Current research interests include Machine/Deep Learning Applications,

Computer Vision, and Natural Language Processing.