Towards Reliable Space-Ground Integrated Networks: From System-level Design to Implementation

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***Abstract*—The integration of space and terrestrial networks results in a promising future network architecture, which exploits the high data rate and low latency of terrestrial networks as well as the wide-range coverage of satellite networks. However, space-ground integrated networks (SGINs) face some unprecedented challenges, including the rapidly fluctuating network topology, limited resources, intermittent connections, lossy links, asymmetric bandwidth allocation, and so on. The traditional end-to-end (E2E) transport protocols designed for reliable terrestrial networks exhibit inherent limitations in the context of dynamic SGIN. A promising solution is to decouple the E2E perfect reception confirmation into hop-by-hop acknowledgments, which results in prompt packet loss recovery and high transmission resilience in the face of high-dynamic topologies. Hence, in this paper we propose a reliable cache-enabled transport system, which enhances the efficiency of reliable hop-by-hop transmission, and supports multi-orbit breakpoint transmission, while at the same time facilitates the reliability of intra-satellite communication with a novel transport protocol. In addition to unveiling a compelling system-level design, we demonstrate the benefits of the proposed reliable transport system (RTS) in a real SGIN prototype relying on satellites having onboard processing capability. Our experimental results validate the feasibility of the proposed RTS in the face of lossy links, intermittent connections and intra-satellite transmission failure. Moreover, one of the satellites has been launched in April 2021, while the other two will be launched to perform on-orbit test.**

I. INTRODUCTION

LIMITED by the cost of construction and operation, terrestrial networks are unable to cover remote areas (oceans, mountains, deserts, etc.). However, human activities cover the entire globe, which makes seamless global coverage a critical requirement. Therefore, space-ground integrated networks (SGINs) have been proposed as a promising infrastructure [1], which takes advantage of the high data rate and/or low latency of terrestrial networks as well as the global coverage of satellite networks. The SGIN is by definition composed of satellite and terrestrial networks, but the integration of satellite and terrestrial networks imposes numerous fundamental challenges. Firstly, the high mobility and limited onboard resources of satellites result in high-dynamic and time-varying network topology. Secondly, both the inter-satellite and the satellite-to-ground (S2G) links suffer from long propagation delay. Moreover, satellite networks tend to have different bandwidth in their uplink (UL) and downlink (DL). Furthermore, the mobility of satellites, the long propagation distance and the low transmit power are likely to cause burst errors in satellite networks [2]. For integrating multiple networks, high-efficiency network protocols are required. The most natural choice would be adopting network protocols designed for terrestrial networks, such as the transmission control protocol (TCP) and user datagram protocol (UDP). However, the design of conventional network protocols exploited the facts that terrestrial networks have fixed topology and low bit error rate (BER). The limited energy and short coverage time of the high-velocity mobile satellites make it impractical to adopt the unreliable UDP transport protocol for example, because the high packet loss rate (PLR) of unreliable transport protocols will waste precious onboard resources. By contrast, reliable transport protocols (e.g. TCP) may result in frequent retransmissions, since the time-varying topology and intermittent connections of SGIN will cause excessive PLR. Therefore, designing an efficient and reliable transport protocol for SGINs has been a critical issue, which has attracted many researchers' attention.

In the existing literature, transport protocols aiming for enhancing the transmission reliability of satellite networks can be divided into two classes, namely the E2E reliable transport methods (e.g. TCP and its variants) and the hop-by-hop reliable transport methods.

A. End-to-end reliable transport methods

The popular TCP has been shown to provide poor performance in SGINs [3], because the long Round-Trip Time (RTT), long Retransmission Time Out (RTO), dynamic topology and burst losses of SGIN decrease bandwidth use of TCP. Moreover, as an E2E transport mechanism, TCP relies on stable E2E paths to transmit data packets and feedback acknowledgments. Transmission failures will occur if the E2E path is invalid. The high mobility of low earth orbit satellites (LEOs) and MTs results in short path life-time, leading to frequent transmission failures. Furthermore, the TCP adjusts its transmission rate according to the PLR, hence the connection's intermittence results in a poor bandwidth-efficiency. For improving the TCP performance of satellite networks,

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many variants have been proposed. A typical variant is the TCP Performance Enhancing Proxy (TCP-PEP) [4], which enhances the network performance by employing proxies to separate the space segment. Then, satellite networks can adopt any modified protocol. Although TCP-PEP has been widely adopted for commercial systems, the commonly employed connection splitting results in poor mobility support. The main drawback of the TCP is that it cannot distinguish transmission errors, and its congestion control mechanism will reduce the transmission rate after errors occur. Moreover, the jitter in satellite networks imposes additional challenges to congestion control. As a remedy, Bottleneck Bandwidth and Round-trip propagation time version 2 (BBR, also referred to as BBRv2) based congestion control [5] was proposed for achieving model-based congestion control. BBR improves link utilization by controlling the transmission rate according to the measured available bottleneck bandwidth and the minimum RTT. It has been reported in [3] that BBR outperforms conventional loss-based algorithms in TCP-based satellite networks.

In addition to the TCP variants, Quick UDP Internet Connection (QUIC) protocol [6] has been proposed for providing low-latency and reliable transport. By exploiting 0-RTT connection and multiplexing, QUIC has been proved to speed up transmissions. Although QUIC operates on top of UDP, it adopts a packet loss detection mechanism to enable loss recovery. Performance gains have been demonstrated by deploying QUIC in satellite networks [7]. However, QUIC relies on E2E retransmission for loss recovery, which induces long delays and extra resource consumption in satellite networks.

Although the above TCP variants attained improved transport performance, it still remains limited, especially in SGINs having lossy links and dynamic network topology.

B. Hop-by-hop reliable transport methods

As an alternative to E2E feedback mechanisms, hop-by-hop transport protocols deal with lossy links individually. Typical hop-by-hop transport protocols include the mobility-first transport protocol (MFTP) [8] proposed for dealing with mobility. In MFTP, multiple packets are grouped into a chunk as the basic transmission unit, and chunk-level reliability is guaranteed in each hop, which eliminates long-delay E2E retransmission. Motivated by [8], a hop-by-hop resilient inter-satellite transmission mechanism has been proposed in our previous work [9] for enhancing the resilience against the inter-satellite link intermittence. However, the existing hop-by-hop reliable transmission solutions fail to address the following issues.

1) Reliable intra-satellite data transmission: To cope with the long delay of S2G transmission, onboard processing payloads (OPPs) have been deployed to perform in-orbit data processing, which significantly increases the data traffic among OPPs. However, the intra-satellite transmission [10] is challenged by Single Event Upsets (SEU), Electro-Magnetic Interference (EMI) and hardware defects [11]. The existing research of hop-by-hop reliable transmission [8], [9] is only focused on enhancing the transport reliability between two nodes, but not within them. An intra-satellite transmission failure should be recovered by application layer retransmission which may impose severe delay. Moreover, the wired intra-satellite connections have high bandwidth and low PLR, which makes the chunk-level feedback mechanisms inefficient. Therefore, reliable intra-satellite transmission protocols are required.

2) System-level design and implementation: The transmissions in SGINs can be divided into three segments, including the terrestrial segment (i.e. ground-to-ground (G2G) transmission), S2G segment and space segment (i.e. inter-satellite transmission), which have different characteristics. For example, the terrestrial segment is likely to have high bandwidth and stable connections, while the S2G segment is more intermittent than the space segment, since S2G links may be affected by obstacles, weather, etc. However, the existing solutions adopted a single transport protocol in SGINs and ignore the different characteristics of these three segments. Furthermore, the existing solutions (e.g. [9]) were only validated by simulations, rather than by practical implementation. But the system-level design and practical implementation of reliable transport solutions should also be studied in practice.

Against this background, we propose an efficient reliable transport system (RTS) for SGINs, which relies on distributed cache resources for enhancing the transmission reliability. Facilitated by these caching resources, three key technologies are proposed for supporting both high-integrity hop-by-hop transmissions, intra-satellite transmissions as well as multi-orbit breakpoint transmissions [12]. The main contributions of this paper can be summarized as follows.

- In contrast to [9] which is focused on inter-satellite transmission, we propose a reliable SGIN design, which guarantees the reliability of S2G, S2S as well as intra-satellite transmissions by exploiting the distributed caching resources provided both in the ground stations and satellites.
- We partition the E2E confirmation mechanism of traditional solutions into hop-by-hop acknowledgements. Instead of adopting a single transport protocol in [8], [9], we propose a hybrid hop-by-hop transmission mechanism for accurately matching the different characteristics of both the S2G and inter-satellite segments of SGINs.
- For mitigating the occasional intra-satellite transmission failure imposed by signal corruption [13] or SEU [14], a novel intra-satellite transport protocol is proposed, which adopts the packet-level transmission-failure-triggered feedback mechanism for achieving prompt low-cost retransmission.
- Moreover, we employ a multi-functional gateway module (MFGM) at each ground station to perform Internet protocol conversion, data caching and reliable S2G transmission. Based on the distributed cache resources, we propose a space-ground cooperation aided multi-orbit breakpoint transmission mechanism to cope with the dynamic network topology.
- In addition to the system-level design, we implement the reliable transport mechanism advocated in a SGIN prototype, which consists of real satellites and mobile stations. The experimental results show that our proposed solution substantially enhances the transport reliability.

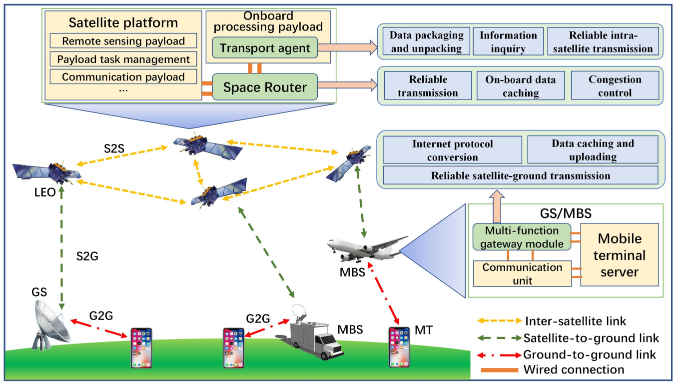


Fig. 1. The space-ground integrated network architecture.

In the remainder of this paper, we first present the SGIN architecture, followed by a suite of reliable transmission techniques. We will then elaborate on the implementation of the proposed RTS, highlighting its advantages. Finally, we conclude by summarizing our key contributions.

II. DESIGN OF A SGIN ARCHITECTURE

Let us consider the SGIN of Figure 1 constituted by LEOs, ground stations (GSs), mobile base stations (MBSs) and mobile terminals (MTs). The LEO satellites are connected by inter-satellite (S2S) links to form a space network, while the S2G links connect LEO satellites to GSs and MBSs, which provide services for MTs through G2G links. It is assumed that the mobile platforms of Figure 1 (e.g. vehicles and ships) are equipped with antennas to communicate with LEO satellites and act as MBSs to serve either their on-board users or ground-based MTs. To cope with the dynamic network topology, intermittent links and long-delay SGIN, we adopt a hop-by-hop transport mechanism for improving the transmission reliability. We assume that each LEO satellite is equipped with a space-router for in-orbit ad-hoc networking, data caching and routing. Furthermore, it is assumed that a transport agent is deployed at each OPP, which is designed to provide network call interfaces to enable data transmission and information sharing between the OPPs and the space-router. To make the space network compatible with the existing TCP-based terrestrial networks, we assume that a MFGM is deployed at each GS and each MBS. In our approach, we amalgamate the space-router and the transport agent of the satellite with the MFGM of the GS/MBS to form a RTS. The software-based transport agent and MFGM provide generic interfaces to the onboard application payloads and the terrestrial networks, making it feasible to deploy RTS in general scenarios.

A. Space-Router

The satellite network topology is determined by calculating the satellites' orbits, albeit this has limited accuracy. Firstly, the pre-calculated network topology may turn out to be invalid, since a LEO satellite may be turned off due to power outage. Moreover, without using so-called Topology-Learning Packets (TLPs), LEO satellites have no knowledge of the link conditions, which limits the overall transmission rate. Furthermore, when the satellite-density increases, the cost of calculating the network topology may become unacceptable. Therefore, in contrast to traditional routers, the space-router of Figure 1 is equipped with caching as well as processing capabilities, and it cooperates both with the network and transport layers in support of ad-hoc networking and reliable transmission. The main functions of the space-router of Figure 1 are as follows:

1) Reliable transmission: In contrast to E2E confirmations, the space-router adopts hop-by-hop acknowledgments for reliable S2G, S2S and intra-satellite data transmission. The space-router will retransmit the lost packets based on the feedback from the next hop.

2) Onboard data caching: Storage resources are used in the space-router for caching the transmitted data, which has not been confirmed by the next hop.

3) Congestion control: To cope with bandwidth asymmetry, the space-router limits the maximum number of parallel transmitted chunks to control network congestion.

B. Transport agent

A LEO satellite may have multiple OPPs for accomplishing different tasks, which significantly increases the intra-satellite data traffic. For the sake of facilitating reliable intra-satellite transmission as well as the compatibility of the space-router with existing payloads, we provide a transport agent for each payload managing the interactions of the application layer with the network layer. The main functions of the transport agent of Figure 1 are summarized as follows:

1) Data packaging and unpacking: The transport agent is responsible for bridging the space-router and OPPs. It will unpack the data received from the space-router and package the data generated by OPPs.

2) Information inquiry: The transport agent of Figure 1 provides programming interfaces for OPPs to query the satellite or network status information.

3) Reliable intra-satellite transmission: For the data transmission between the transport agent and the space-router of Figure 1, a reliable intra-satellite transport protocol is designed and implemented.

C. Multi-functional gateway module

Terrestrial networks routinely adopt the TCP/IP, which uses the IP address to represent both a node's identity (ID) and its network address (NA). The coupling of ID and NA limits the mobility support of TCP/IP. In SGINs, it has reached broad consensus that new evolving network protocols should completely split the ID and NA. Therefore, we assume that satellite networks adopt an evolving protocol different from terrestrial networks, and employ a MFGM in each GS and each MBS to perform Internet protocol conversion. In contrast to traditional gateways, we assume that each MFGM is equipped with cache resources and enhance the S2G transmission reliability.

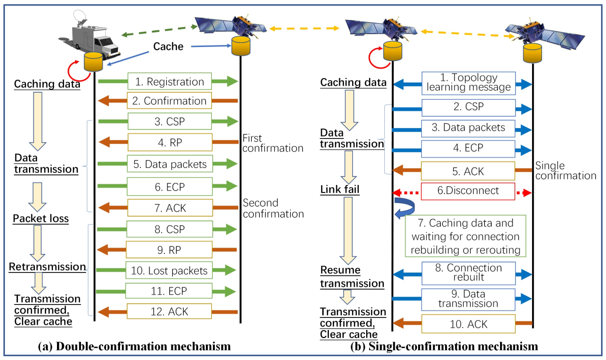
1) Internet protocol conversion: The MFGM is designed for supporting Internet protocol conversion and cross-protocol transmission.

2) Data caching: Given the limited power of MTs and the intermittent connections in SGINs, the data which should be uploaded to satellite networks would first be transmitted to a GS/MBS of Figure 1, while the MFGM will cache and upload the data whenever possible.

3) Reliable S2G transmission: Considering the intermittency of S2G links, the MFGM is responsible for supporting reliable hop-by-hop transmission between satellites and the GSs/MBSs of Figure 1.

In the next section, we propose a reliable cache-enabled transport system capable of accommodating the time-varying topology, lossy links and intermittent connections of SGINs. Despite using extra protocol packets, the proposed RTS can be deployed in mega LEO satellite networks with distributed cache resources for avoiding redundant E2E retransmission and for reducing the E2E transmission delay. Since the security and privacy of transmitted data can be protected by application layer encryption, we focus on three key techniques conceived for enhancing the data transmission reliability of SGINs.

III. KEY TECHNOLOGIES



(a) Double-confirmation mechanism (b) Single-confirmation mechanism

Fig. 2. Reliable hop-by-hop transmission.

A. Reliable hop-by-hop transmission

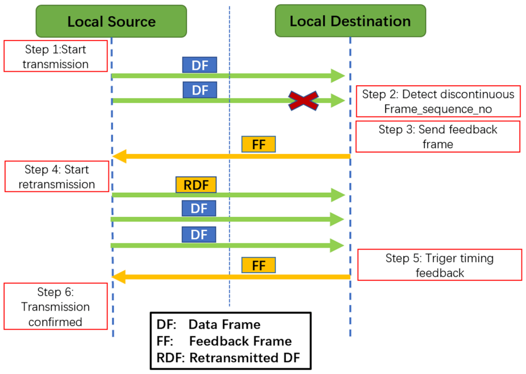
To achieve efficient and reliable transmission, we adopt a pair of transmission mechanisms to cope with the intermittent connections caused by the dynamically fluctuating SGIN links. Firstly, the store-and-forward mechanism is adopted, which exploits the cache resources of satellites or GSs/MBSs to temporarily cache the transmitted data. Once a transmission failure occurs, the transmitter can immediately retransmit the cached data, instead of starting retransmissions from the original source node. In addition to the store-and-forward mechanism, we use a hop-by-hop confirmation mechanism for ensuring the integrity of the transmitted data. To reduce the communication overhead imposed by frequent feedback and ensure the efficiency of hop-by-hop transmission, we first aggregate multiple data packets into a chunk, which is used as the basic transmission unit in hop-by-hop confirmation. Considering the low coherence time and high fluctuations of the channel quality, the maximum number of packets in a chunk can be changed according to the channel conditions. Each chunk consists of a chunk start packet (CSP), followed by multiple data packets and an end of chunk packet (ECP). To identify different chunks, a unique chunk ID is assigned to each chunk, which is recorded in the CSP and the ECP. The IDs of the transmitter and receiver, as well as the length of the chunk are recorded in CSP.

In contrast to the existing solutions, where the same transmission mechanism is adopted for the inter-satellite and S2G segments of SGINs, we propose a hybrid hop-by-hop transmission mechanism, which takes the different characteristics of the inter-satellite and S2G links into consideration. As shown in Figure 2, a single-confirmation based mechanism is adopted for inter-satellite transmission, while a double-confirmation mechanism is used for S2G transmission. This is because for reliable inter-satellite transmission, we assume that satellites periodically send TLPs for updating their routing tables. When a satellite has to transmit data to a neighbor satellite, it will first check whether the next-hop target satellite can be found in its routing table. If so, the satellite will send chunks to its next-hop neighbor and wait for an acknowledgment packet (ACK) for each chunk. An ACK contains a bit map, which represents the receipt status of each data packet, and the transmitter may start a retransmission according to the received ACK. In case the ACK was not received by the transmitter after a pre-defined time threshold, the corresponding chunk will be retransmitted and the receiver will feed back the same ACK once receiving the retransmitted chunk. By contrast, if the next-hop target satellite disconnects from the transmitter satellite, the data will be cached locally until the connection is rebuilt or a new routing path is found.

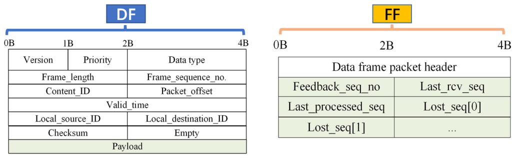
As for S2G transmission, when a MT connects to the satellite network through a GS/MBS, we assume it will first register at the connected satellite and the registration information will be broadcast to other satellites for updating the routing tables. However, due to the lack of periodic TLPs and the connection intermittency of the S2G links, the routing information for S2G links may be invalid. Therefore, we adopt a double-confirmation mechanism for S2G transmission. We assume that each GS/MBS is equipped with a MFGM to cache the data received from MTs and upload the data whenever possible. For each chunk, the MFGM will first send the CSP and wait for a response-packet (RP) from its serving satellite. Once the response-packet is received, the remaining packets of the chunk will be transmitted, otherwise the MFGM will periodically retransmit the CSP. It is worth mentioning that multiple data chunks can be transmitted at the same time, for improving the spectrum efficiency of S2G transmission. When a data chunk is received by the serving satellite, an ACK will be sent to the MFGM for confirming the successful receipt or guiding the retransmission of lost packets. In this way, the response-packet for CSP is used as the first confirmation to ensure the validity of the S2G connection, while the ACK for a data chunk is treated as the second confirmation to achieve reliable S2G hop-by-hop transmission, as detailed in Figure 2.

B. Reliable intra-satellite transmission

In the inter-satellite and S2G transmissions, data packets are aggregated into chunks, which includes extra protocol packets (i.e. the CSP and the ECP) for hop-by-hop confirmation. When a chunk-error occurs, the receiver can only feedback an ACK to the transmitter, if both the CSP and the ECP are successfully received. This will cause extra retransmission delay, especially when the CSP or ECP is lost. In contrast to inter-satellite wireless transmissions, wired intra-satellite transmissions have high bandwidth and impose low transmission delay. Moreover, intra-satellite transmissions have low packet error rate, hence



(a) Intra-satellite transmission process



Version	Priority	Data type
Frame_length		Frame_sequence_no.
Content_ID		Packet_offset
Valid_time		
Local_source_ID		Local_destination_ID
Checksum		Empty
Payload		

Data frame packet header	
Feedback_seq_no	Last_rcv_seq
Last_processed_seq	Lost_seq[0]
Lost_seq[1]	…

(b) Protocol header of intra-satellite data frame

(c) Payload of intra-satellite feedback frame

Fig. 3. Reliable intra-satellite transmission.

it is inefficient to adopt chunk-level acknowledgments, since the extra protocol packets will result in transmission capacity loss. Therefore, in this subsection we propose a new reliable packet-level intra-satellite transport protocol, which adopts a hybrid (i.e. event-driven and time-driven) feedback mechanism to support prompt retransmissions and enhance reliability.

To facilitate reliable intra-satellite transmission, we design the intra-satellite packet header shown in Figure 3(b), which includes the priority, data type, frame length, validity time and checksum of the data packet. When a checksum error is detected, the packet will be dropped and a transmission failure occurs. In Figure 3(b), $Local\_source\_ID$ and $Local\_destination\_ID$ are used to denote the IDs of the transmitter and the receiver in intra-satellite transmission. For each [$Local\_source\_ID$, $Local\_destination\_ID$] pair, $Frame\_sequence\_no.$ is a consecutive and incremental integer, which varies in $[0, Frame_{max}]$ periodically. We use the triplet [$Local\_source\_ID$, $Local\_destination\_ID$, $Frame\_sequence\_no.$] as a unique ID for each data frame, which facilitates packet-level acknowledgments.

The proposed reliable intra-satellite transmission mechanism is presented in Figure 3(a), in which the local source transmits its data frames (DF) to the local destination. To reduce the retransmission delay, when the local destination detects a discontinuous frame sequence number, it will immediately send a feedback frame (FF). The payload of FF is illustrated in Figure 3(c), which consists of the FF sequence number (i.e. $Feedback\_seq\_no$), the frame sequence number of the last received DF (i.e. $Last\_rcv\_seq$), the frame sequence number of the last-processed lost packet ($Last\_processed\_seq$), and the sequence numbers of the lost packets. When a FF triggered by packet loss is received, the local source will immediately retransmit the data packets specified in the FF. In addition to the transmission-failure-triggered feedback, we also adopt a timing feedback mechanism to enhance the intra-satellite transmission reliability. The local destination node will periodically send an FF to the local source node for feeding back the lost packets or for confirming the success of transmission. In this way, even if the transmission-failure-triggered DF is lost, the time-driven feedback will guarantee the reliability. Once the transmission is confirmed by an FF, the local source node will delete the cached data. By using this hybrid feedback mechanism relying on Figure 3, we realize efficient and reliable intra-satellite transmission.

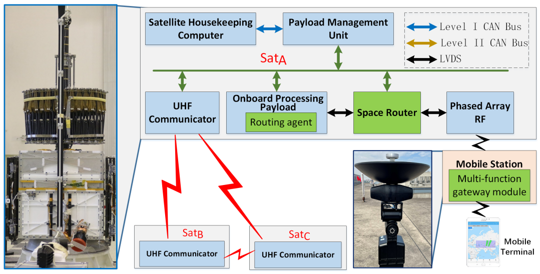
C. Multi-orbit breakpoint transmission

Limited by the intermittent nature and low capacity of S2G links, the transmission of large files (e.g. updating files of onboard software, the download of log files or bulk data from remote sensing satellites) should be delay-tolerant, since it may not be completed in a single orbit. In addition, the delay-tolerant bulk data is preferred to be transmitted via S2G links without inter-satellite transmission for saving the limited onboard resources. Moreover, the satellites orbiting outside their serving area may be powered off to save energy until the arrival at the next serving area. This significantly reduces the service capability of SGINs. To cope with the intermittent S2G connections and the frequent powering off of satellites, we propose a seamless space-ground cooperation aided continuous-time multi-orbit breakpoint transmission mechanism, which exploits the storage of the space-router and MFGM.

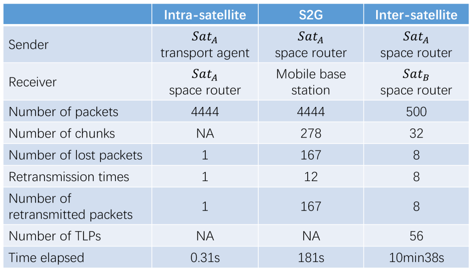
Upon considering the S2G UL transmission of a large file, instead of uploading the file to the satellite directly, we assume that a MT will first send the file to its serving MBS, where the MFGM will cache the file and be responsible for uploading it, as and when the destination satellite is connected. Since the link capacity between a MT and its serving MBS of Figure 1 is much higher than that of the S2G link, the MT only requires a short-duration connection and it may then disconnect from the network to save energy. When the connection between a GS/MBS and the destination satellite is established, the MFGM will map the cached file into multiple chunks and upload these chunks by applying the above reliable hop-by-hop transmission mechanism. The space-router of the destination satellite will repackage the received chunks and use the proposed intra-satellite transmission mechanism for forwarding the data packets to the transport agent, while the transport agent will cache the received data until all the data packets are received. When the destination satellite is out of service, both the MFGM and the transport agent will store the cached chunks and wait for the next orbit to continue their transmission. After the reconstruction of the S2G connection in a new orbit, the MFGM will continue the transmission of the remaining chunks. When all the data packets are successively received, the transport agent will push the recombined file to its hosting OPP of Figure 1.

Similarly, for S2G DL transmission, data packets arriving from OPPs will be cached in the space-router, which will be packaged into chunks and transmitted to a GS/MBS using the reliable hop-by-hop transmission mechanism. The MFGM of the MBS will cache the received data. When the satellite is out of coverage, both the space-router and the MFGM will store the cached data and continue their transmission during the next orbit. Compared to the E2E transmission mechanism, the proposed multi-orbit breakpoint transmission mechanism avoids redundant S2G transmissions, while maintaining the integrity of the transmitted data.

IV. IMPLEMENTATION AND PERFORMANCE EVALUATIONS

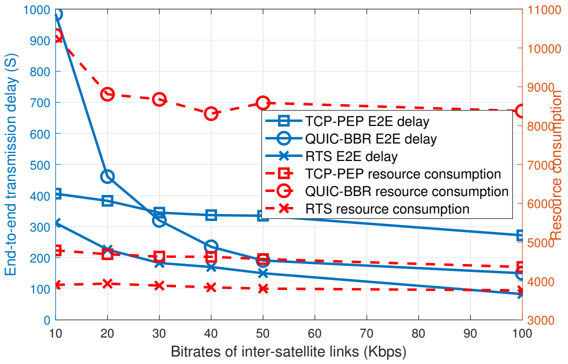


(a) Experimental settings of SGIN



	Intra-satellite	S2G	Inter-satellite
Sender	Sat_A transport agent	Sat_A space router	Sat_A space router
Receiver	Sat_A space router	Mobile base station	Sat_B space router
Number of packets	4444	4444	500
Number of chunks	NA	278	32
Number of lost packets	1	167	8
Retransmission times	1	12	8
Number of retransmitted packets	1	167	8
Number of TLPs	NA	NA	56
Time elapsed	0.31s	181s	10min38s

(b) Experimental results



(c) Performance comparisons

Fig. 4. Implementation and performance evaluation.

The transmission reliability is critical for networks with low bitrates and lossy links, since the long E2E retransmission delay may become unacceptable when a transmission failure occurs. Based on the above system-level design, we have implemented the proposed RTS in a prototype network having ultra-low bitrates and lossy links for validating the feasibility and robustness of the proposed techniques under extreme conditions. As shown in Figure 4(a), the prototype network consists of three LEO satellites, an MBS and multiple MTs. Each LEO is equipped with an OPP, which is responsible for the onboard processing of remote sensing images, mission planning and inter-satellite synchronization. In April 2021, one of the three satellites, namely ”Qilu-1”, was launched as a co-passenger on a CZ-6 rocket, while the other two satellites will be launched in near future to carry out multi-satellite on-orbit test of the proposed RTS. Due to the hardware limitations and the limited onboard resources, the LEO satellites communicate in the ultra-high frequency (UHF) band having 1 kilobits per second (Kbps) bitrate, while X-band phased array antennas are used for S2G transmission. For the same reasons, the S2G DL bitrate is 1 Megabits per second (Mbps), while the UL transmission has 1Kbps bitrate due to the adoption of spread spectrum communication for copying with the long transmission distances. Attenuators are deployed at each UHF communicator for modeling the real inter-satellite communication. As shown in Figure 4(a), the UHF communicator, the OPP, the space-router and the phased array RF of a satellite communicate with the payload management unit using the Level II CAN (controller area network) bus, while the LVDS (low-voltage differential signaling) interface is adopted to connect the space-router with the OPP and the phased array RF. The space-router is equipped with a central processing unit with 1 Gigahertz maximum operating frequency for data processing, and with a 2 Gigabits random-access memory for data caching. We grouped a maximum of 16 data packets into a chunk, and set the UHF transmit period to 1 second. To verify the reliability of intra-satellite transmission, we set a 10^{-4} random packet loss rate (PLR) at satellite A’s (also denoted as Sat_A) space-router to reflect SEU or EMI, while the inter-satellite transmission is tested using attenuated links. For achieving *ad hoc* networking, each space-router will broadcast TLPs to its neighbors along with the transmitting period of $T = 20s$, while each TLP records the source Satellite IDentifier (SID), the last-hop SID, the number of hops from the source, the time-to-live, and the packet ID which is a consecutive and incremental integer to identify a TLP and indicate the timeliness of the TLP received. Once receiving the TLP from a new source node, a satellite will create a new entry in its routing table, which includes the destination SID, the available next hops leading to the destination and the corresponding hop counts. Otherwise, the satellite will update its routing table according to the received TLP. After modifying the last-hop SID, the number of hops from the source and the time-to-live, the satellite will forward the received TLP to its neighbors, unless a TLP with the same source and packet ID had been received or the TLP is timeout. Both the resilience of the proposed RTS against connection intermittency and the feasibility of the multi-orbit breakpoint transmission mechanism are validated in S2G transmission, where we power off Sat_A during the transmission and continue the transmission after Sat_A rejoins the network. Our experimental results characterizing the intra-satellite, S2G and inter-satellite links are presented in Figure 4(b), which shows that all the lost packets can be successively retransmitted locally. Specifically, it can be observed that intra-satellite transmission failure is recovered immediately without application layer retry, which has long trigger-delay and may require the retransmission of the whole file. It is worth mentioning that the packet loss in S2G transmission is caused by powering off of Sat_A, since some chunks have not been confirmed by the MFGM. Figure 4(b) indicates that the proposed solution guarantees reliable transport in SGINs in the face of lossy links, intermittent connections and intra-satellite transmission failure.

Considering the strict hardware limitations, it is not trivial to change the transmission rates of real satellites. Thus, we constructed a virtual SGIN to provide comprehensive comparison between our RTS and the existing solutions. The virtual SGIN uses virtual machines to simulate network nodes and has the same network topology as Figure 4(a). The virtual nodes are connected through socket interfaces and it is assumed that all S2S links have the same bitrate and PLR. Since inter-satellite and S2G communication only have few multi-path links due to the lack of scatters, we adopt a simplified channel model with free-space path loss and additive white Gaussian noise. We consider the DL transmission of 1000 data packets from the OPP in Sat_B to the MT served by Sat_A. Specifically, the OPP in Sat_B is also simulated as a virtual machine to enable the simulation of intra-satellite transmission. By employing *ad hoc* networking, the transmission from Sat_B to the MT has two available paths including Sat_B-Sat_A-$Mobile\ station$ (referred to as path-1) and Sat_B-Sat_C-Sat_A-$Mobile\ station$ (path-2). Without loss of generality, the shortest path routing algorithm is adopted. Thus, path-1 is selected at the beginning. To model dynamic network topologies, Sat_A and Sat_B are suddenly disconnected at t_1. Since Sat_B cannot receive TLPs from Sat_A, it will delete the entry corresponding to Sat_A in its routing table and the routing path switches to path-2. The performance of the proposed RTS is compared to those of TCP-PEP [15] and QUIC with BBR (QUIC-BBR) [7] in Figure 4(c) in terms of both the E2E transmission delay and resource consumption. Here, the E2E delay of RTS is the sum of the delay in each intra-satellite, S2S and S2G hops, while the delay in each hop consists of the queuing delay, processing delay, transmission delay, propagation delay and possible retransmission delay imposed by packet loss events. For simplicity, we assume that the single-hop forwarding of either a data packet or a protocol packet consumes the same amount of resource. We show that the proposed solution significantly reduces both the E2E transmission delay as well as the resource consumption, especially in networks having low inter-satellite bitrates. Observe that the E2E delay of QUIC-BBR is more than tripled compared to that of the proposed solution, when a 10 Kbps bitrate is assumed for the S2S links. Moreover, both QUIC-BBR and TCP-PEP suffer from frequent E2E retransmissions resulting in high resource consumption, while the proposed RTS provides efficient and reliable hop-by-hop transmission in the presence of both lossy links and dynamic network topologies.

V. CONCLUSION

A cache-enabled space-ground cooperation aided RTS was conceived for SGINs to cope with dynamically time-varying network topology, lossy links and connection intermittence. Distributed cache resources have been used for reliable hope-by-hop transmission and multi-orbit breakpoint transmission. Furthermore, a reliable intra-satellite transport protocol was provided for handling intra-satellite transmission failures imposed by the space environment. The proposed solution has been implemented in an SGIN prototype with three satellites for characterizing its performance. One of the three satellites, which integrates the key technologies, has been launched on 27 April 2021, while the other two will be launched in the near future. In-orbit tests will constitute our future work for further evaluating the performance of the proposed RTS.

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