Integrated Satellite-Terrestrial Networks: Architectures, Key Techniques, and Experimental Progress

Yaohua Sun, Mugen Peng, Shijie Zhang, Guangrong Lin, and Peng Zhang

Abstract

As a promising paradigm toward the sixth generation mobile communication, integrated satellite-terrestrial networks (ISTNs) can greatly extend network coverage and reduce the dependence on terrestrial infrastructure. Despite the charming potentials of ISTN, many challenges are still unsolved in terms of architectures, air interface protocol enhancement, mobility management, experimental validation, and so on. Therefore, in this article, we first clarify the four stages of ISTN architecture development and then discuss protocol enhancements as well as key techniques for ISTN. In addition, one of our previous experiments is reported in detail, where low Earth orbit satellite communication is used as the backbone connecting two private 5G networks that are 400 km away from each other. During the experiment, a remote immersive robot control service is realized with average end-to-end latency and uplink peak data rate being 30 ms and 50 Mb/s, respectively, which shows the feasibility of ISTN in supporting emerging industrial Internet applications. Meanwhile, other experimental progress is also presented, focusing on air interface protocol enhancement, transmission control protocol transmission, and network management. Finally, we point out future trends in ISTN, including programmable satellites and artificial-intelligence-based networking.

Introduction

Despite the rapid development of terrestrial mobile communication networks, it is expected to further integrate satellites as a beneficial supplement [1]. For example, satellites can provide backhaul links between a gNodeB (gNB) and its core network, which is suitable for maritime, airborne, remote area, and emergency communications. In addition, when satellites possess sufficient onboard processing capabilities, they can even perform as gNBs or execute some core network and service functions.

In the 3rd Generation Partnership Project (3GPP), the network integrating 5G, satellite communication, and high-altitude platforms is referred to as the non-terrestrial network (NTN), and the impacts brought by NTN on 5G New Radio (NR) and higher-layer procedures are discussed under different architectures, including satellites with transparent payload and satellites with full gNB functions. Moreover, the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) has identified four use cases of enhancing terrestrial networks with satellites, such as multi-cast transmission for multiple gNBs and serving users on the move. Meanwhile, the China Communications Standards Association established a technical committee in 2019 that focuses on unifying satellite and terrestrial communication networks.

In academia, the integration of 5G and satellites is also a hot topic. In [2], the authors propose a virtualized and programmable integrated satellite-terrestrial network (ISTN) architecture that incorporates a physical infrastructure level, a logical level, and a multi-domain orchestrator. Furthermore, network coding technique is explored to utilize both terrestrial and satellite paths to enhance capacity for Transmission Control Protocol (TCP)-based applications. In [3], a case study for NTN is provided, which preliminarily evaluates the feasibility of serving terrestrial mobile terminals over millimeter-wave frequency band by aerial/space vehicles. Taking advantage of edge computing, the authors of [4] highlight three computation offloading modes, namely proximal terrestrial offloading, satellite-borne offloading, and remote terrestrial offloading, and a cooperative computation offloading scheme is designed to make full use of terrestrial and satellite edge computing servers to finish user tasks. Note that ISTN is commonly used in academia to refer to any network formed by converging satellite communication networks with terrestrial communication networks and has a wider range than those discussed in 3GPP. Hence, ISTN is used throughout the following article.

Although standardization and academic research have both made progress recently, the development of ISTN toward practical deployment should be step by step. The first stage of ISTN is to use satellite communication infrastructure as backhaul or mid-haul or backbone for terrestrial networks, which provides a convenient manner to connect geographically separate gNBs and core networks or two private 5G networks. In the second stage, satellite communication starts to have a big influence on air interface protocol, and a satellite can even

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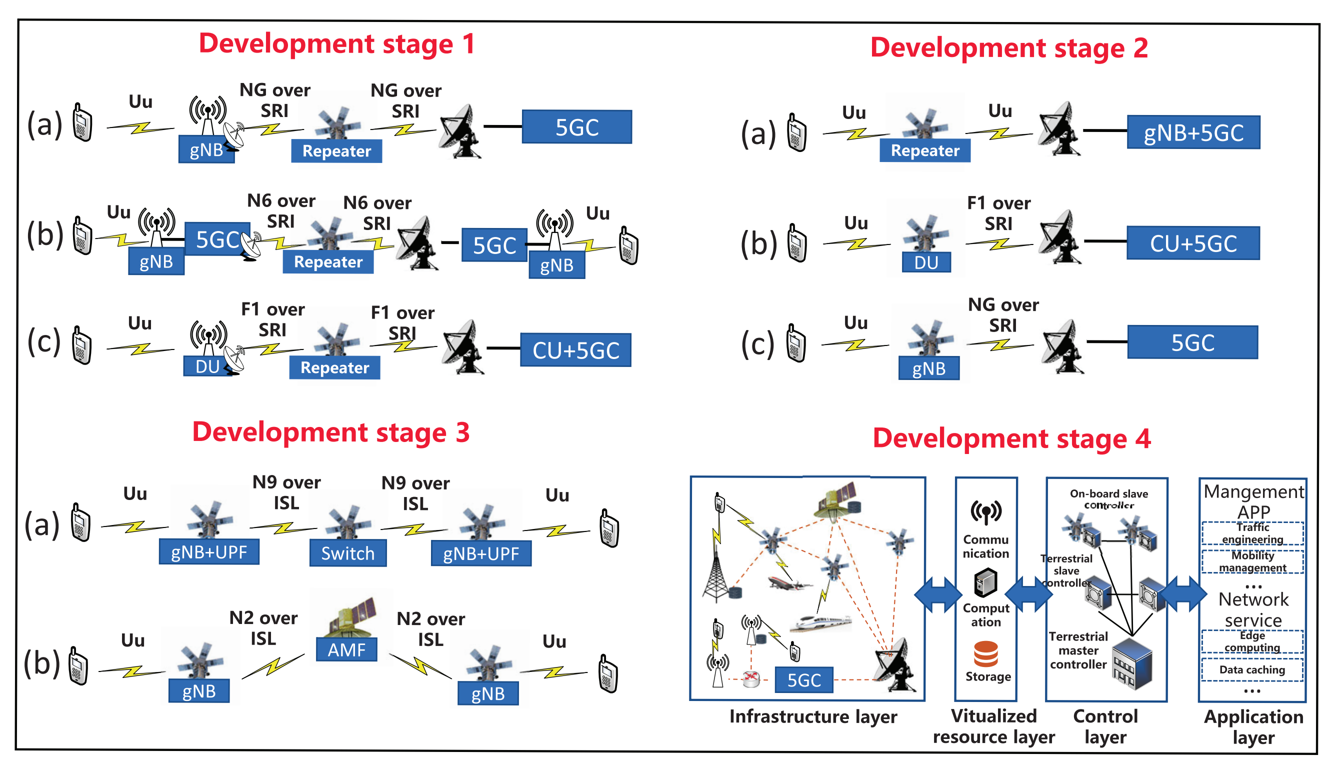

FIGURE 1. The four development stages of ISTN architecture.

perform as a gNB. In the third stage, to achieve low-latency user plane and control plane, some core network functions can be placed on satellites as well, and a complete satellite 5G network can be formed that does not rely on terrestrial infrastructure. For the fourth stage, satellite communication networks and terrestrial networks will be deeply converged, and communication resource, caching resource, as well as computing resource at both satellites and terrestrial nodes will be jointly managed to deliver seamless and continuous services.

The main contribution and novelty of this article can be summarized into two aspects.

Compared to state-of-the-art review papers, most of which only present theoretical discussion on ISTN, we additionally summarize several testbeds and experimental results that relate to radio interface, transport layer, network management, and the applicability of ISTN in supporting emerging services. Moreover, ISTN architecture development is classified into four stages, and some presented architectures, not covered in previous review papers, are very useful for vertical use.

To avoid heavy reliance on fiber connection in remote industrial Internet applications, a novel wide area communication system solution is proposed based on a basic ISTN architecture, which features high uplink data rate and low end-to-end latency. A practical experiment is conducted with our solution, *which is possibly the first to realize immersive remote robot control with 5G and low Earth orbit (LEO) satellites. In addition, the adopted 5G network equipments have a miniaturization design. Hence, the solution is also highly maneuverable and can be applied to emergency rescue.*

The remainder of this article is organized as follows. The four stages of ISTN architecture development are introduced in detail in the next section. Following that, protocol enhancements and key techniques for ISTN are elaborated. Then recent experimental progress is reported and future trends are outlined, followed by the conclusion.

ISTN Architecture Development

In this section, the architecture development of ISTN is divided into four stages, which are illustrated in Fig. 1.

Transparent Satellites for Backhaul/Backbone/Mid-Haul (Stage 1)

The most intuitive way of enhancing terrestrial networks by leveraging satellite communication is to use satellites to provide backhaul links between gNBs and core networks, backbone links between multiple remote private 5G networks for vertical use, or mid-haul links between distributed units (DUs) and centralized units (CUs). Since satellites only transparently transport packets on NG/N6/F1 interface as shown in Fig. 1, there is little impact on the radio access network (RAN) protocol stack and mobility management of 5G users except some timer extension. In addition, compared to geostationary Earth orbit (GEO) satellites, LEO satellites are promising in this stage due to short propagation latency. Considering this benefit, our team has finished an experiment that utilizes an LEO satellite to connect two private 5G networks that are 400 km apart from each other. Related details are reported later. As for the potential service discontinuity led by the frequent handover between satellite terminals and LEO satellites, it can be re-solved using the soft handover technique adopted by O3b [5], illustrated in Fig. 2.

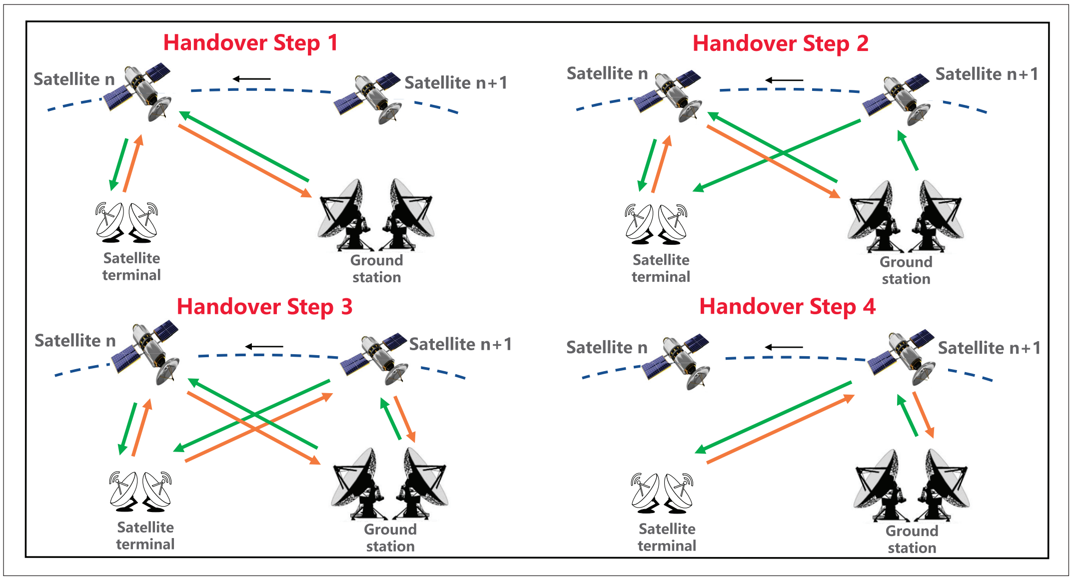

FIGURE 2. Soft handover procedure adopted by O3b.

Transparent Satellites for Uu-Interface and Satellites with gNB Functions (Stage 2)

Optional ISTN architectures in Stage 2 are illustrated in Fig. 1, and all the cases need to address the challenges incurred by long propagation latency and potentially large carrier frequency offset on Uu-interface. At this time, corresponding enhancements focus on time-frequency synchronization, hybrid automatic repeat request (HARQ), preamble design, and so on, whose details are discussed later. Moreover, it should be noted that user plane functions (UPFs) and access and mobility management functions (AMFs) are still placed on the ground, which can cause large latency for both control plane and user plane, especially when the satellite associated with user terminals has to reach a ground station via multiple inter-satellite links.

ISTN with Space Core Network Functions (Stage 3)

To shorten the latency of user and control planes, moving core network functions, such as UPFs and AMFs, to satellites is helpful. In case a) shown in Fig. 1, by placing UPFs together with gNBs, a 5G local area network (LAN) can be created in the space, allowing an authorized group of users to communicate directly with each other by leveraging N9 interface between UPFs. In case b) shown in Fig. 1, when an AMF is installed on a medium Earth orbit (MEO) satellite, the latency of inter-gNB handover via NG interface can be reduced. In both cases, satellite communication networks also become more robust due to less coupling with terrestrial infrastructure. However, considering the spatial and temporal dynamics of service requirements and the number of active users, it is critical to adaptively place proper core network functions at proper satellite nodes to fully utilize limited onboard processing capabilities, and this leads us to stage 4 of ISTN with full programmability and flexibility.

Software-Defined ISTN with Full Flexibility (Stage 4)

In stage 4, we envision that ISTN will finally be re-programmable in terms of single satellite functionalities and network capabilities. Due to soft payload that is built based on a common computation platform and re-configurable radio interface, a satellite can be either a radio access point, a space switch/router, an application server, or a remote sensing device. The computation platform leverages network function virtualization, running gNB, switch/router, and sensing functionalities as software, perhaps with the additional help of hardware acceleration techniques. On the network level, re-programmability means flexible network function deployment at satellite and terrestrial nodes in a collaborative fashion, flexible rules for traffic routing and mobility management, flexible spectrum resource partition, as well as flexible computing task distribution. Figure 1 shows a software-defined ISTN where network controllers are involved and organized hierarchically. Via south-bound interface, virtualized resource can be orchestrated by the control layer according to the commands issued by network management and service applications via north-bound interface. Meanwhile, controllers can also communicate with each other via east- or west-bound interface to achieve cross-domain coordination for higher spectrum utilization, end-to-end quality of service guarantee, and so on.

Protocol Enhancements and Key Techniques

In this section, RAN protocol stack enhancements and several key techniques for ISTN are discussed.

RAN Protocol Stack Enhancements

Frequency Synchronization: Due to the large relative velocity between satellite gNBs and terrestrial users, especially when LEO satellites are involved, carrier frequency offset (CFO) can be significant, which hinders downlink frequency synchronization. Facing this issue, the authors of [6] propose a low-complexity method to estimate CFO by leveraging primary synchronization signals, and the core idea is utilizing two key features of the time-domain Zadoff-Chu sequence, namely time-domain asymmetry and constant envelope. Moreover, satellite gNBs can make pre-compensation on frequency offset to narrow the offset range to help user equipments (UEs) estimate CFO more accurately.

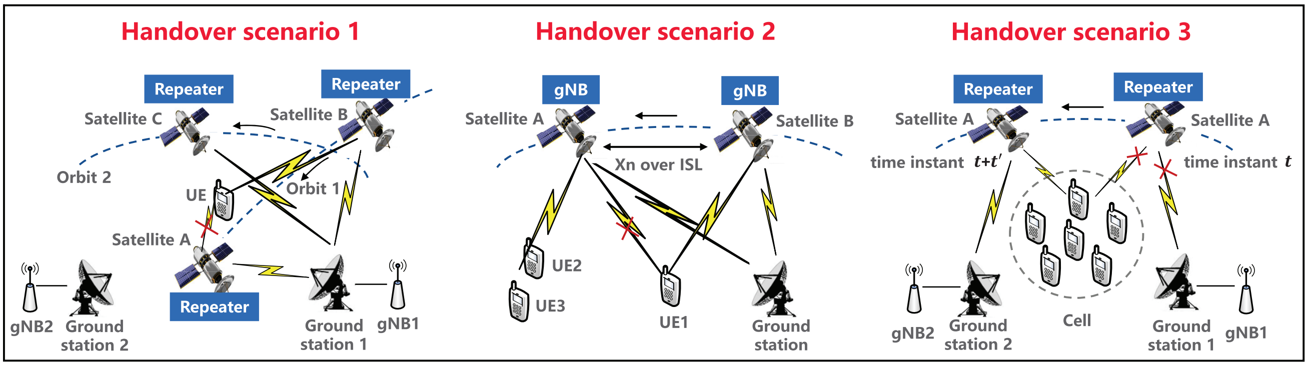

FIGURE 3. Complex handover scenarios in ISTN.

Random Access: Random access happens after cell search or inter-cell handover, and is a fundamental procedure before UEs ask for uplink scheduling to transmit data. However, since cell size is usually much larger in ISTN than that in the terrestrial case, satellite gNBs must hold a larger time window for UE preamble detection, which may lower uplink spectrum efficiency. Meanwhile, the current maximum timing advance (TA) value indicated in the 5G NR RAR message may be insufficient. To deal with these issues, one possible solution is to let each UE pre-compensate a TA value when sending preambles. Another enhancement for random access is simplifying the original four access steps considering the long propagation latency. For example, MSG1 and MSG3 can be sent together by UEs while the corresponding satellite gNB can respond with a combination of MSG2 and MSG4. In a more aggressive fashion, UEs can directly transmit their data without grant by leveraging non-orthogonal multiple access, and the four-step random access procedure is not needed anymore. Although this solution is particularly beneficial when supporting massive amounts of Internet of Things devices, pre-compensation on frequency and time is essential at the device side. Furthermore, some researchers also propose to use pruned discrete Fourier transform spread filter bank multicarrier waveform, resulting in a more robust preamble detection for random access under large CFO [7].

HARQ: HARQ is a procedure to guarantee reliable transmission by sending ACK or NACK at receiver side, upon which the transmitter side sends a new data packet or a repeated one. In ISTN, the traditional HARQ procedure may suffer low transmission efficiency incurred by long waiting time for ACK or NACK. Facing this problem, there are several enhancement options. The first one is to disable ACK/NACK feedback, while the transmitter side transmits the same data packet in several consecutive time slots to raise reliability. The second one is to pre-send ACK/NACK based on channel state evaluation to accelerate the data transmission process. In addition, 3GPP is discussing increasing the number of HARQ processes to fully utilize radio resource.

Mobility Management

Mobility management in ISTN is two-fold: link level and network level. In terms of link level, the main focuses are handover triggering conditions and how to make appropriate decisions on to which link to switch. In terrestrial networks, handover events like A3 are defined to trigger link handover decision making and are based on RSRP/RSRQ measurement reported by UEs. However, according to [8], RSRP at the edge of a satellite gNB cell can be nearly flat, which means accurate handover condition is hard to set. In this regard, handover triggering conditions in ISTN can be defined based on elevation angle and remaining satellite coverage time.

Handover decision making becomes more complicated. Considering the first handover scenario shown in Fig. 3, where satellites have transparent payload, a UE currently served by satellite A needs to be handed over to a new satellite due to, for example, a low elevation angle. Further, if the UE simply switches to satellite C with the largest elevation angle, the UE may subsequently encounter an inter-gNB handover because satellite C will move out of the coverage of ground station 1 by following its orbit and switch to ground station 2. On the contrary, if the UE switches to satellite B, which will be in the coverage of ground station 1 at a future period, inter-gNB handover can be avoided. From this scenario, it can be seen that orbit information should be fully utilized to improve handover efficiency. In the second scenario in Fig. 3, where satellites have gNB functions onboard, handover schemes should use inter-satellite links to create more opportunities for handover via Xn interface. In this way, compared to handover via NG interface, the interactions with AMF on the ground via feeder links are mitigated, and therefore lower handover latency can be achieved.

Another big issue faced by mobility management in ISTN is the group handover phenomenon illustrated in the third scenario in Fig. 3. In this scenario, when the satellite switches its feeder link from ground station 1 to 2, UEs have to perform inter-gNB handover, which causes significant signaling burden. To handle this situation, gNB A can pre-send a handover command to each subgroup of UEs via multicast transmission, which offers the corresponding UEs the time to access gNB B, hence realizing ordered handover.

Space Routing

Space routing strategy design in ISTN is differentiated from that in terrestrial networks. Specifically, the topology of terrestrial networks is often static on a large timescale, while satellite network topology frequently varies due to relative movement

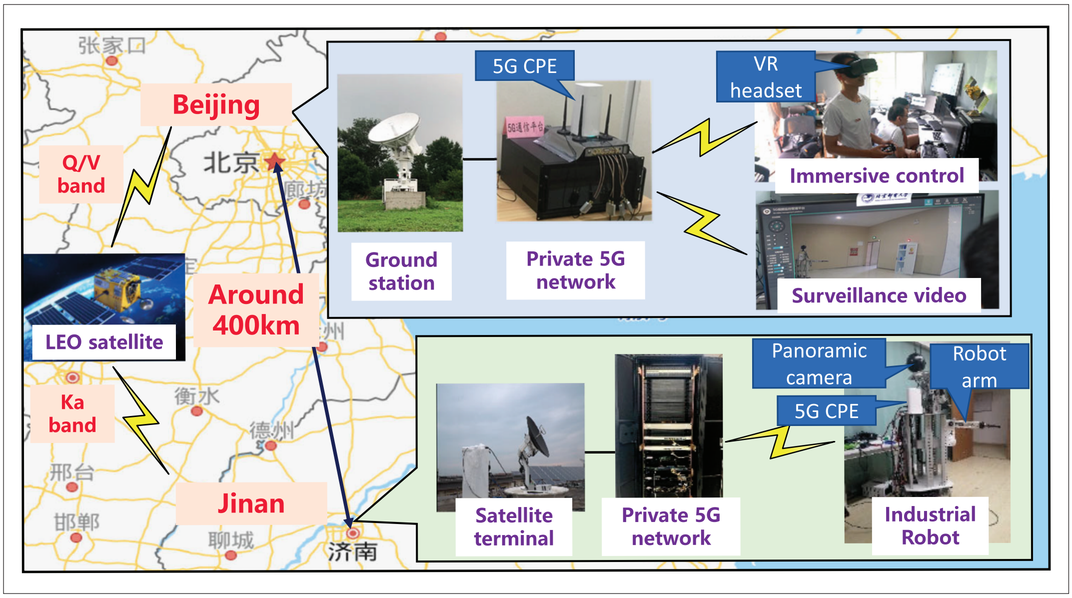

FIGURE 4. Experimental trial scenario combining 5G private networks with LEO satellite communication.

between satellites in different orbits and layers as well as relative movement between satellites and ground. Moreover, it is envisioned that the space segment has to support diverse traffic flows with different quality of service requirements, such as traffic flow with low-latency jitter and traffic flow with high throughput. Both of these aspects impose great challenges on routing strategy design for ISTN.

Facing network topology dynamics, a basic idea is to plan routes on each time slice of topology. Within each slice, the connection states of inter-satellite links and feeder links are unchanged. At the ground station, the shortest path first algorithm can be applied, and then routing tables are uploaded to each satellite. Obviously, given the large number of time slices, this approach is storage-consuming. Furthermore, to tackle the frequent change in inter-satellite links, a carry-and-forward strategy can be adopted, in which satellites store received data when the desired link is unavailable. At this time, the satellite segment is seen as a delay-tolerant network, and contact graph-based routing algorithms have been proposed [9].

Network Function Deployment

Network function deployment in ISTN directly affects user and control plane latency, which should be adjusted adaptively to meet different service demands. For example, when serving fast moving objects like airplanes, multiple DUs and a CU can be pre-deployed at proper LEO satellites and an MEO satellite according to ephemeris and flying path information. With inter-satellite links between LEO satellites and the MEO satellite, airplanes accessing LEO satellites just experience intra-CU handover, which greatly lowers handover latency. Moreover, when a UE has to experience a handover between two satellite gNBs via NG interface, placing AMF on satellites can also shorten handover latency by avoiding signaling transmission via feeder links. For the impacts of network function deployment on user plane, considering the 5G LAN scenario in Fig. 1, if UPFs are located on the ground instead of satellites, transmission latency between UEs in the same LAN group will be larger. Furthermore, deploying UPFs on satellites can also help realize satellite edge computing (S-EC), which is the key to support low-latency and computation-intensive services.

Space Computation

Due to the onboard computing and caching capability provided by S-EC, ground users can enjoy low-latency data analysis and data fetching services. Meanwhile, the transmission burden on feeder links is alleviated. However, considering the limited processing and storage capability of each single satellite, it is essential to utilize space computation resource collaboratively. To this end, we propose the concept of computing-force-aware collaborative space computation (CCSC). In the CCSC paradigm, LEO and MEO satellites are divided into multiple collaborative computation clusters, which takes into account the stability of inter-satellite links and satellite computing capability. Each cluster is governed by a central network controller deployed at a powerful MEO satellite or even a GEO satellite. By enhancing current routing protocols, each controller can gather computing capability information from each satellite within its cluster and further decide on the routing and computation task dissemination rules for each kind of service. In particular, CCSC is very beneficial to services containing multiple parallel computation tasks that can be executed at multiple satellites simultaneously.

Experimental Progress

In this section, recent experimental progress for ISTN is summarized, related to 5G plus LEO satellite communication for vertical use, RAN protocol stack enhancements, TCP transmission improvement, and so on.

5G and LEO Satellite Communication for Industrial Internet Application

To avoid heavy reliance on fiber connection in remote industrial control applications, Beijing University of Posts and Telecommunications (BUPT) and Yinhe Hangtian propose a novel wide-area

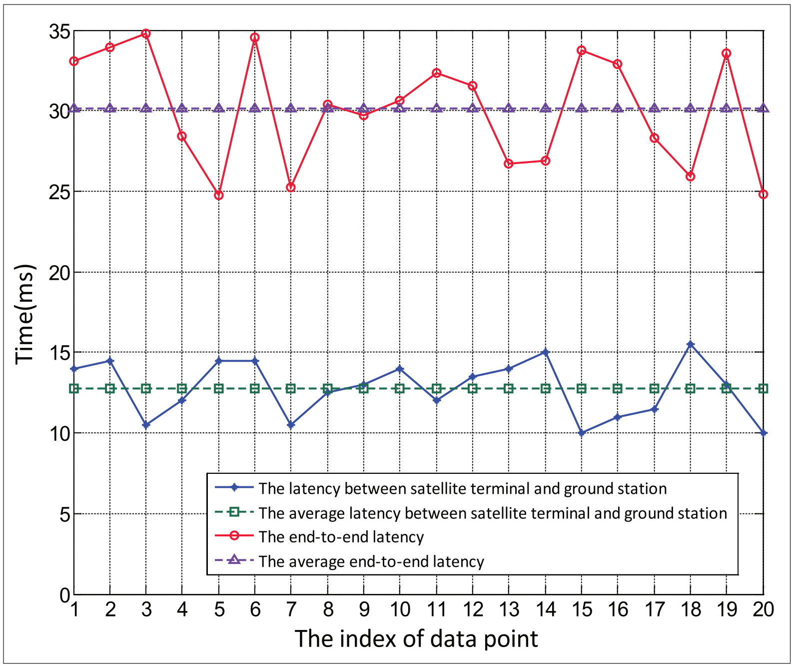

FIGURE 5. Latency test results during the experiment.

communication system solution based on architecture (b) in development stage 1 shown in Fig. 1. The solution implementation combines 5G private networks provided by BUPT with an LEO broadband satellite held by Yinhe Hangtian. Each private 5G network contains locally deployed base stations and core network. Our 5G base stations support uplink data rate of over 200 Mb/s by adjusting the time proportion of uplink transmission, and the broadband LEO satellite supports over 300 Mb/s transmission in uplink. Meanwhile, the transmission latency incurred by the 5G network is only several milliseconds, and the transmission latency from the ground station to a satellite terminal can be below 17 ms. Therefore, our solution can realize high uplink data rate and low end-to-end latency, which can support remote and immersive robot control.

In July 2021, BUPT and Yinhe Hangtian successfully conducted an experiment to verify the feasibility of the above solution. In the experiment demonstrated in Fig. 4, the staff at a control center in Beijing handle an emergency event happening in their company's factory located in Jinan, and both the control center and factory have deployed a private 5G network. Due to the LEO satellite communication infrastructure, the two private 5G networks are connected without terrestrial fiber. At the control center, staff can receive high-definition video streaming from a surveillance camera, 360° video streaming from a panoramic camera installed on an industrial robot, and video streaming from a camera located on top of the robot arm. The robot as well as all cameras are in Jinan and connect to the 5G network via CPEs. Once an emergency event is observed at the control center, two staff members start to manipulate the robot to move inflammable goods to a safe place. Specifically, one staff member wearing a virtual reality (VR) headset is responsible for controlling the robot movement based on the received 360° video, while another staff member controls the robot arm to fetch inflammable goods. As indicated by Fig. 5, the average end-to-end latency is around 30 ms, and the end-to-end uplink data rate from Jinan to Beijing is up to 50 Mb/s, which together contribute to smooth and precise control. Although this experiment only lasts 7 minutes due to the limited coverage time of a single LEO satellite, with more satellites on the orbit in the future and soft-handover capability of satellite terminals, it is expected to achieve long time and continuous services.

As for the challenges faced in the experiment, with 5G networks and the LEO satellite at hand, we have to further properly configure the communication interfaces of the satellite terminal and ground station to ensure they can receive data packets from 5G networks; meanwhile, routing rules should be added in the 5G core network to correctly forward data from 5G user devices to either Jinan or Beijing. On the other hand, we also need to develop various application software so that the robot arm moves accurately according to the command issued from Beijing. In addition, since our 5G network equipments are miniaturized, they are easy to carry and deploy. Hence, the wide area communication solution is highly maneuverable and can be widely adopted in emergency communication.

Other Progresses

5G Protocol Stack Enhancement: To adapt 5G NR protocol to the characteristics of terrestrial-satellite communication links, enhancements based on 5G OpenAirInterface software are reported in [10], where a GEO is responsible for relaying signals on Uu interface between a ground 5G UE and a ground gNB. Aimed at overcoming the negative effects brought by the long propagation latency, the parameter setting for time slot allocation is revised, and HARQ is also disabled. In China, CAICT has done a series of experiments on verifying the applicability of its proposed solutions for ISTN, including a new orthogonal frequency-division multiplexing (OFDM) waveform, time-frequency synchronization, and random access channel design.

Satellite Network as Backhaul: Funded by the European Space Agency (ESA), an ISTN testbed was demonstrated at MWC 2019, which was jointly developed by SES, iDirect, Fraunhofer FOKUS, and Software Radio Systems. The testbed features a 3GPP-compliant backhaul network and access-agnostic content delivery with edge computing. The backhaul network is further constituted by a satellite UE, SatRAN software, satellite core network functions, and a satellite network management system. Except satellite UEs, all the elements are virtualized using OpenStack. By aligning with 3GPP standards, satellite UEs and SatRAN can be managed like 5G UEs and 5G RAN. According to Fig. 4 in [11], N1, N2, and N3 interface have been implemented. In [12], an in-orbit GEO satellite belonging to SES is taken as backhaul between a WiFi access point and a 5G core network. With a live camera behind the core network, the user associated with the access point successfully receives a 360° monoscopic 4K video of 30 FPS.

Improved TCP Transmission: Compared to fully wired connection, data transmission in ISTN suffers from higher link errors and longer propagation latency, leading to low bandwidth utilization

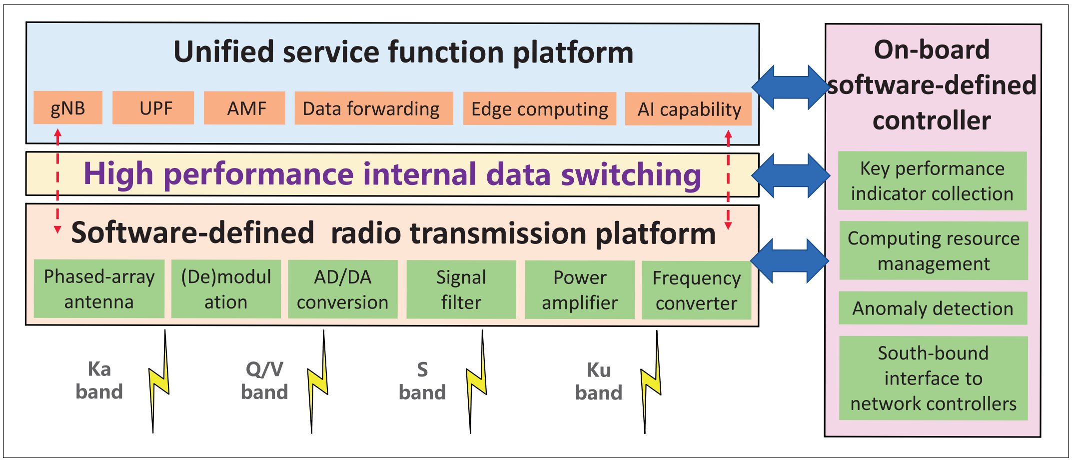

FIGURE 6. The envisioned architecture of programmable satellites.

with traditional TCP protocols. Specifically, the loss of TCP segments resulting from link error will trigger congestion avoidance, while long propagation latency will limit the growth rate of congestion window. To overcome these issues, improved TCP should be adopted to fit into the transmission conditions in ISTN. In [13], the authors evaluate the performance of TCP Hybla protocol based on real round-trip time data collected from a testbed involving a GEO satellite, and numerical results show that TCP Hybla outperforms standard TCP in terms of achievable throughput.

Future Trends and Research Directions

In this section, we discussn future trends in ISTN, which is related to programmable satellites and artificial intelligence (AI)-enabled networking.

Programmable Satellites

In July 2015, ESA and Eutelsat started the research on software-defined communication satellites, aimed at achieving software-defined payload design at Ku frequency band. With this paradigm, satellite operation frequency, bandwidth, signal strength, and coverage can be flexibly adjusted. However, this idea is mainly related to the programmability of satellite radio interface. Considering the cost of manufacturing and launching, it is expected to realize the multi-function satellites envisioned in Fig. 6. Specifically, with the help of programmable hardware and network function virtualization, a satellite can be re-programmed as a gNB, a space router, or a computation server for sensing image and Internet of Things data analysis. In addition, an onboard software-defined controller is involved for satellite monitoring and management, and it can be seen as the agent of network controllers shown in ISTN development stage 4 in Fig. 1. In this manner, it is convenient for network controllers to gather key performance indicators and configure satellite functions on demand. In the future, further study is needed on hardware implementation, satellite controller development, and modular software design under the constraints of onboard energy, payload size, and weight.

AI-Empowered Networking

With the increase of computing power force and the explosive growth of data, we have witnessed the rapid development of AI. In addition to its application in medicine, autonomous driving, face recognition, and so on, AI tools have also attracted a lot of interest of researchers in communication society. Actually, there are many studies on AI based resource management, mobility management and transmission design for terrestrial networks but the application of AI to ISTN is still to be fully explored. In this aspect, we envision that AI can particularly help UE handover and satellite routing. In [14], UE handover process is captured by a directed graph where each beam in each time slot is seen as a distinct node while the weight of each edge is affected by RSRP. Under the assumption that future RSRP and beam coverage can be predicted, the optimal handover strategy can be derived. On this basis, authors propose a convolutional neural network based handover decision model for each UE, which is trained using the data generated by the optimal strategy. After model training, each UE only needs to input its historical RSRP into the model to get a sub-optimal handover decision. As for satellite routing, authors in [15] transforms path selection into a multi-classification problem, in which each classifier decides whether a node is on the route between a source node and a destination node.

Conclusions

In this article, we have comprehensively summarized and discussed the development stages of integrated satellite-terrestrial network (ISTN) architectures, together with enhancements on air interface protocol stack and several key techniques, such as mobility management and space computation. Moreover, a practical experiment has been conducted to validate the feasibility of 5G plus low Earth orbit satellite communication in supporting remote, low-latency, and immersive robot control. Meanwhile, other experimental progress in protocol stack enhancement, network management, and TCP transmission has been introduced as well. Finally, future trends and research directions have been outlined with regard to programmable satellites and artificial-intelligence-driven networking.

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