Space Information Networks: Technological Challenges, Design Issues, and Solutions


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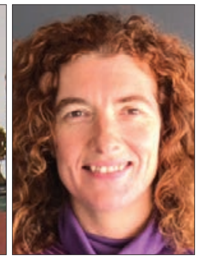
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It has been expected that space information networks (SINs), as an extension of terrestrial networks, would provide high-speed, high-capacity, global continuous communication, and data transmission services anywhere for anyone at any time. With the rapid advances in relevant technologies (e.g., satellite miniaturization technology, reusable rocket launch technology, and semiconductor technology), low-orbit satellites, drones, and airships can be integrated into the SIN to supply more comprehensive network connectivity. The standards development organizations including 3GPP, ITU, and ETSI already started corresponding standardization activities to support non-terrestrial networks in SINs. One can foresee that SINs will be expanded to provide not only telephone services but also various kinds of Internet services, and they will thus be able to serve many more users with different demands.

Though some progress has been made in related technologies, SINs still face a variety of technological challenges and design issues in the aspects of communication, networking, security and so on, which has delayed their practical implementation. First, since resources such as orbit, spectrum, and bandwidth are limited, how to allocate them efficiently and reasonably is a vital issue that needs to be addressed in SINs. In addition, with the increase of computing and storage resources in SINs, how to carry out the integrated design of computing, storage, and transmission capacity so as to optimize the overall network capacity is a new challenge that SINs researchers need to face. Second, the huge increase in the number of low-orbit satellites and various spacecraft, as well as the heterogeneous hybrid network formed by low-, medium-, and high-orbit satellites, bring a great challenge to networking. The high dynamics, long delay, and large variance of the connections make access and transmission hard to maintain effectively. Moreover, as an important step for B5G/6G networks, how to extend SINs with traditional terrestrial networks also triggers many concerns in practical systems. Third, security aspects still have not yet received sufficient attention, though they are a key issue in SINs. The features of spectrum openness and the fact that satellites are far away from physical control pose a desperate need of a certain degree of security protection in SINs. In addition, some emerging technologies in communication, networking, and security, such as Mobile Edge Computing (MEC), Software Defined Networking (SDN), Information-Centric Networking (ICN), and Blockchain, play great roles in promoting the development of SINs, but also bring about a series of new theoretical and technical problems that must be studied and solved. Moreover, the construction of SINs requires the joint efforts of multiple countries and a large number of enterprises and research institutions around the world, and it will last for decades, which makes its standardization increasingly important.

This special issue is intended to present and highlight the advantages, latest technologies, and implementations and applications related to the issues of communication, networking and security in SINs. We received 44 submissions, and after a rigorous review process, only 13 articles were accepted for the special issue. We hope these articles will show their value over time, while being helpful for our current readership. A brief view of each of the articles follows.

In the article "Satellite-Based Radio Spectrum Monitoring: Architecture, Applications, and Challenges", the authors present a space spectrum monitoring framework by using small satellites in low Earth orbit. This framework can greatly expand the monitoring coverage to a global scale and flexibly determine the locations of interference sources. Moreover, it can significantly promote international frequency coordination and spectrum sharing in future wireless networks. The authors also present key applications and identify the main challenges and future directions.

In the article "Spectrum Sharing for 6G Integrated Satellite-Terrestrial Communication Networks Based on NOMA and CR", the authors propose to improve satellite-terrestrial spectrum sharing performance by introducing non-orthogonal multiple access (NOMA) and cognitive radio (CR) in the spectrum access of integrated satellite-terrestrial communication networks (ISTCNs). By integrating NOMA and CR, the proposed scheme allows multiple satellite terminals to access both the idle and busy spectrum simultaneously, which will achieve high-efficiency full spectrum access. Furthermore, some open research and challenges for the spectrum sharing of the ISTCN are discussed in the article.

In the article "Scalable Traffic Control Using Programmable Data Planes in a Space Information Network", the authors design an in-network traffic control powered by SIN architecture to enhance network performance. They further present two use cases, i.e., in-network load balance and in-network congestion control, to demonstrate the feasibility of the designed architecture. For both of these two use cases, they conduct preliminary evaluations to prove the performance potential of the architecture design.

In the article "Converged Reconfigurable Intelligent Surface and Mobile Edge Computing for Space Information Networks", the authors propose a reconfigurable intelligent surface (RIS) assisted collaborative mobile edge computing (MEC) architecture for SINs, in which RISs and MEC platforms are integrated in SINs to improve the capability of communications and computations. They further design different offloading schemes for the different MEC platforms, and present an implementation strategy for the proposed RIS-assisted collaborative MEC. They also discuss the benefits, challenges, applications, and services of the proposed RIS-assisted collaborative MEC, and subsequently investigate three cases to evaluate the performance of the proposed architecture.

In the article "Blockchain-Based Secure Communication for Space Information Networks'', the authors investigate several challenges faced by SINs and give the possible roles of blockchain for secure communications. They design a blockchain architecture suitable for SINs and present two secure communication protocols, i.e., Fulgor and Rayo, designed for different application scenarios in SINs: 1) Fulgor is a secure communication protocol between users and the ground station based on the proposed efficient authentication and key agreement protocol; 2) Rayo is a user-to-user privacy-preserving communication protocol to protect users' privacy and avoid DoS attacks. Experiments are conducted and performed on a widely known blockchain platform, i.e., Hyperledger Fabric, and the findings demonstrate the feasibility of the proposal.

In the article "QoS Provisioning in Space Information Networks: Applications, Challenges, Architectures, and Solutions'', the authors first introduce the applications in three emerging scenarios in terms of traffic characteristics and Quality of Service (QoS) requirements, and then identify the accompanying technical challenges for SINs. Then, a QoS provisioning architecture with two differentiated transmission modes is proposed: 1) the mirror source mode for bandwidth-tolerant flows improves the network efficiency by centralized traffic scheduling; 2) the preemptive mode for bandwidth-sensitive flows reduces the end-to-end delay by edge node control. Furthermore, the authors analyze the enabling technologies and potential solutions for control logic and forwarding mechanism, and future research directions are also discussed.

In the article "Deep-Reinforcement-Learning-Based Intrusion Detection in Aerial Computing Networks'', the authors first discuss the intrusion threats in unmanned aerial vehicle (UAV) aerial computing networks. To detect malicious attacks effectively, they further present a case study based on a deep reinforcement learning approach to protect the security services.

In the article "Flexible and Distributed Mobility Management for Integrated Terrestrial-Satellite Networks: Challenges, Architectures, and Approaches'', the authors propose flexible and distributed mobility management architectures for integrated terrestrial-satellite networks (ITSNs) to improve mobility management performance by flexible reconfiguration of space-distributed mobility management functions (MMFs). Toward link-layer handover decisions, a lightweight and intelligent handover decision framework is devised to realize efficient and unified radio access point (RAP) selections for massive handovers and different decision making conditions. The simulation results validate the high performance of the proposed architectures and approaches in terms of handover delays, signaling overheads, and convergence property.

In the article "SpaceDML: Enabling Distributed Machine Learning in Space Information Networks'', the authors propose a distributed machine learning system, named SpaceDML, for SIN platforms that applies dynamic model compression techniques to adapt distributed machine learning training to SINs' limited bandwidth and unstable connectivity. SpaceDML has two key algorithms: adaptive loss-aware quantization, which compresses models without sacrificing their quality, and partial weight averaging, which selectively averages active clients' partial model updates. These algorithms jointly improve communication efficiency and enhance the scalability of distributed machine learning with SIN devices. By training a LeNet-5 model on the MNIST dataset, the experimental results show that SpaceDML can increase model accuracy by 2 to 3 percent and reduce communication bandwidth consumption by up to 60 percent compared to the baseline algorithm.

In the article "A Secure Architecture of Relay-Aided Space Information Networks'', the authors propose a relay-aided secure architecture to enable efficient connections for different IoT devices in a SIN with security, where relays are deployed together with hopped beams to relieve the jamming attack of the uplink and combat the eavesdropping attack of the downlink. In the proposed architecture, inter-satellite beam hopping is developed to build jamming-free uplink channels by using spatial diversity, while relay selection is carried out to generate eavesdropping-free downlink channels within the coverage of a beam. Meanwhile, relay deployment optimization is studied to maximize the system efficiency, and data aggregation is adopted to encrypt the data packets of IoT devices at relays.

In the article "QoE-Aware Video Streaming over Integrated Space and Terrestrial 5G Networks'', the authors propose a novel scalable video coding (SVC)-based content delivery framework for a satellite and terrestrial integrated 5G network, which aims at delivering an enhanced quality of video viewing experience to end users by efficiently utilizing both of the available backhaul links. The proposed framework is deployed at the MEC server, and utilizes a prefetching and processing mechanism during the content distribution process. The framework is validated using a real over-the-air satellite and terrestrial integrated 5G network. Experimental results reveal that the proposed content delivery framework is able to deliver a high-quality stalling-free video viewing experience to all active users by achieving a high degree of content offloading from the terrestrial link to the satellite backhaul link, thus saving limited terrestrial network resources.

In the article "Optimizing Computation Offloading in Satellite-UAV-Served 6G IoT: A Deep Learning Approach'', the authors formulate a computation offloading problem for the considered satellite-UAV-served 6G IoT system and propose a deep-learning based computation offloading approach. The proposed approach can improve the system computation performance considering the energy dynamics and different communication conditions. They further introduce some problems and challenges to provide inspirations for future researchers.

In the article "Centralized and Decentralized Routing Solutions for Present and Future Space Information Networks'', the authors propose two practical centralized routing approaches, i.e., centralized first ended (CFE) and exhaustive breath-first search (BFS), for SINs able to cover both IF and SCF traffic flows, which can ensure the discovery of all routes on the ground. Evaluation results provide compelling evidence that centralized routing schemes can safely, successfully, and efficiently connect SINs with up to 10,000 daily contacts, while contact graph routing (CGR) can be better entrusted with larger-scale SIN deployments.

Finally, the Guest Editor team would like to thank all the authors of the 44 papers that were submitted to this special issue, and thank all the reviewers who provided thorough and timely reviews. We would also like to thank Dr. Chonggang Wang, Editor-in-Chief (EiC), for his continuous support and constructive suggestions to improve this special issue, as well as the *IEEE Network* staff for their support in the preparation of this special issue. More importantly, we sincerely hope that the readers will find the articles published in this special issue interesting and helpful with further research in space information networks.

Biographies

Kaiping Xue (Senior Member, IEEE) received his bachelor's degree from the Department of Information Security, University of Science and Technology of China (USTC), in 2003 and received his Ph.D. degree from the Department of Electronic Engineering and Information Science (EEIS), USTC, in 2007. From May 2012 to May 2013, he was a postdoctoral researcher with the Department of Electrical and Computer Engineering, University of Florida. Currently, he is a Professor in the School of Cyber Security and the Department of EEIS, USTC. His research interests include next-generation Internet, transmission optimization, distributed networks and network security. He serves on the editorial board of several respected journals, including *IEEE Transactions on Dependable and Secure Computing* (TDSC), *IEEE Transactions on Wireless Communications* (TWC), and *IEEE Transactions on Network*

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TOMASO DE COLA (Member, IEEE) received the Master degree (with honors) in telecommunication engineering in 2001, the Qualification degree as a Professional Engineer in 2002, and the Ph.D. Degree in Electronic and Computer Engineering, Robotics and Telecommunications from the University of Genoa, Italy, in 2010. From 2002 until 2007, he worked with the Italian Consortium of Telecommunications (CNIT), University of Genoa Research Unit, as a scientist researcher. Since 2008, he has been with the German Aerospace Center (DLR), where he has been involved in several projects funded by EU and ESA programs, focusing on different aspects of DVB standards, CCSDS protocols, emergency communications, and testbed design. He has been taking part in different standardization activities within ETSI, IETF, DVB, and CCSDS, where he serves as deputy area director of the Space Internetworking Services (SIS). He is a co-author of more than 100 papers, including international conferences and journals. He has been an Editor for many IEEE journals such as *IEEE Transactions on Vehicular Technology*, *IEEE System Journal*, *IEEE Communications Letters*, and *IEEE Wireless Communications Letters*. He was also a Guest Editor for IEEE JSAC, *IEEE Wireless Communications*, and *IEEE Network*. Finally, he served as the chair of the Satellite and Space Communications (SSC) technical Committee (TC) within IEEE ComSoc from 2017 to 2020.

DAVID S. L. WEI (Senior Member, IEEE) received his Ph.D. degree in Computer and Information Science from the University of Pennsylvania in 1991. He is currently a Full Professor in the Computer and Information Science Department at Fordham University. From May 1993 to August 1997 he was on the Faculty of Computer Science and Engineering at the University of Aizu, Japan (as an Associate Professor and then a Full Professor). He has authored and co-authored more than 140 technical papers in the areas of parallel and distributed processing, wireless networks and mobile computing, optical networks, P2P communications, cloud and edge computing, and information security in various archival journals and conference proceedings. He served on the program committee and was a session chair for several reputed international conferences. He also served as an associate editor and lead guest editor for some leading journals, such as IEEE J-SAC, IEEE TCC, IEEE TBD, etc. Currently, he focuses his research efforts on cybersecurity and quantum computing and communications.

ANA PÉREZ-NEIRA (Fellow, IEEE) is a full professor at the Universitat Politècnica de Catalunya in the Signal Theory and Communication Department since 2006 and was a Vice Rector for Research (2010-14). She is a Fellow Researcher at the Centre Tecnològic de Telecomunicacions de Catalunya, where she is the Coordinator of the SatCom and Space activities. Her research is in signal processing for communications, focused on satellite communications. She has published more than 60 journal papers and 300 conference papers. She is a co-author of seven books. She has led more than 20 projects and holds eight patents. She is the coordinator of the Network of Excellence on Satellite Communications, financed by the European Space Agency: SatnexIV-V. She has been an associate editor of the IEEE TSP and EURASIP SP and ASP. Currently she is a senior area editor of OJSP. She is a member of the BoG of the IEEE SPS. She is an IEEE Fellow and member of the Real Academy of Science and Arts of Barcelona (RACAB). She is the recipient for the 2018 EURASIP Society Award and she has been the general chair of IEEE ICASSP'20.

HOSSAM S. HASSANEIN (Fellow, IEEE) is a professor in the School of Computing, Queen's University, Canada. He received the Ph.D. degree in computing science from the University of Alberta, Edmonton, AB, Canada, in 1990. He is a leading authority in the areas of broadband, wireless and mobile networks architecture, protocols, control and performance evaluation. His record spans more than 500 publications in journals, conferences and book chapters, in addition to numerous keynotes and plenary talks in flagship venues. He has received several recognitions and best paper awards at top international conferences. He is also the founder and director of the Telecommunications Research Lab (TRL) at Queen's University School of Computing, with extensive international academic and industrial collaborations. He is a former chair of the IEEE Communication Society Technical Committee on Ad Hoc and Sensor Networks (TC AHSN). He is an IEEE Communications Society Distinguished Speaker and is a fellow of the IEEE.

LINLING KUANG (Member, IEEE) received the B.S. and M.S. degrees from the National University of Defense Technology, Changsha, China, in 1995 and 1998, respectively, and the Ph.D. degree in electronic engineering from Tsinghua University, Beijing, China, in 2004, where she has been with the Tsinghua Space Center since 2007. Her research interests include wireless broadband communications, signal processing, and satellite communications.

SYMEON CHATZINOTAS (Senior Member, IEEE) is currently a full professor/chief scientist I and the Head of the SIGCOM Research Group at SnT, University of Luxembourg. He is coordinating the research activities on communications and networking, acting as a PI for more than 20 projects and the main representative for 3GPP, ETSI, DVB. In the past, he has been a visiting professor at the University of Parma, Italy, lecturing on "5G Wireless Networks''. He was involved in numerous R&D projects for NCSR Demokritos, CERTH Hellas and CCSR, University of Surrey. He was the co-recipient of the 2014 IEEE Distinguished Contributions to Satellite Communications Award and Best Paper Awards at EURASIP JWCN, CROWNCOM, ICSSC. He has (co-)authored more than 500 technical papers in refereed international journals, conferences and scientific books. He is currently on the editorial board of the *IEEE Transactions on Communications*, *IEEE Open Journal of Vehicular Technology* and the *International Journal of Satellite Communications and Networking*.