# A Review on Satellite-Terrestrial Integrated Wireless Networks: Challenges and Open Research Issues

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***Abstract*—Satellite-Terrestrial Integrated Network (STIN), which integrates terrestrial network systems, aerial platforms, and satellites, is recently recognized as an indispensable solution to address the new network requirements including ultra-reliable communication, massive machine type communication, seamless Internet connectivity for global ubiquitous network access and son on. Despite these benefits, the road to integrate satellite and aerial platforms in future wireless networks is not without challenges. Network architecture design, radio resource management, and edge resource management are among the main challenges in STIN networks because of a number of factors than need to be taken into account and has been attracting a lot research attention. In this paper, we provide a review on the state-of-the-art researches on STIN networks. In addition, we point out the existing research challenges and present future research issues that deserve further research investigations in STIN.**

***Index Terms*—LEO satellite, integrated networks, satellite networks, edge computing, aerial networks, wireless network.**

## I. Introduction

THE number of connected Internet of Things (IoT) devices and average monthly mobile data traffic have been forecasted to reach 29.4 billions and 281 exabyte in 2030, respectively [1]. These unprecedented growth of IoT devices and massive mobile data traffic has provoked surging appeals for diverse applications with various quality-of-service (QoS) requirements. To entertain such appeals, the traditional terrestrial networks have constitute rigorous demands on high capacity communications, ultra low latency, ubiquitous communication, and high reliability. However, it is difficult to achieve those demands using the traditional terrestrial networks, especially in emergency circumstances and remote areas, where about 50% of the world population have no regular Internet connections [2]–[4]. For instance, the traditional terrestrial networks have limited network coverage in remote and rural areas, such as oceans, islands, and isolated mountainous areas. In addition, traditional terrestrial networks are exposed to natural disasters, including earthquakes and flood, which can interrupt user communication and end-to-end communication networks. Thus, looking for ways to support lower latency and reliable communications, huge machine type communications, and global anytime anywhere network access have been the main wireless network development directions [5], [6]. Towards this end, satellite-terrestrial integrated network (STIN) has been considered as the potential solution to guarantee the above mentioned objectives and attracts a lot of attention. The main idea of STIN is to integrate the satellite, aerial, and terrestrial networks and uses the advantage of these communication technologies to address the limitation of traditional terrestrial networks so as to guarantee large network coverage and high performance communications.

Considering the distance between the Earth surface and the satellite, satellite systems can be three types, such as low Earth orbit (LEO), medium Earth orbit (MEO), and geostationary Earth orbit (GEO) [7], [8]. A GEO satellite is mostly installed at around $36 \times 10^6$ m above equator. Although GEO satellite has advantages in terms of large area coverage and fixed position relative to the Earth, it has also many issues including high latency and channel attenuation resulting in low user experience, and very expensive to launch and use. Compared to GEO satellite, MEO satellite can be positioned more closer to the Earth, which is from $2\times10^6$ m to $2\times10^7$m. MEO satellite has lower latency than GEO satellite due to its lower distance from terrestrial user compared to GEo satellite. However, MEO satellite has limited coverage than GEO and requires many MEO satellites to continuous cover the globe. In contrast to GEO and MEO satellites, LEO satellites can be situated from $5 \times 10^5$m to $2 \times 10^6$m and have the benefits of lower latency and lower cost of deployment and launch. However, it has a limitation in terms of connectivity duration with a specific user due to their high mobility and has limited coverage areas. In addition, aerial platforms such as high altitude platform (HAP) and low altitude platforms (LAP) are also considered essential networking components in STIN and can extend coverage of the network to IoT devices in emergency, hotspot, and remote areas which are not served by existing ground base stations [9]–[12]. Thus, in STIN, densely deployed terrestrial networks can provide high data rate access for users, the aerial networks consisting of HAPs and LAPs can boost the capacity in hotspot areas, emergency areas, and areas with less covered or uncovered by terrestrial base stations, while the satellite networks can provide seamless Internet connectivity for global ubiquitous network access including in mountain areas, oceans, and rural areas. Thus, STIN, which integrates satellite, aerial, and terrestrial network segments would bring numerous advantages to future wireless networks. However, Integration of these networking components in STIN is not without challenges. Considering the various characteristics of the networking segments and their corresponding resource constraints, it is highly required to design an efficient and optimal networking architecture and resource management to achieve optimal performance in end-to-end data transmission. Towards this end, a number of researches have been conducted with various objectives including network architecture design, radio resource management, mobile edge computing (MEC) resource managements, and so on.

In this paper, we provide a review on the stat-of-the-art researches on STIN. Moreover, we point out the existing challenges and provide future research directions that need further investigations. The remained parts of the paper are structured as: An extensive review on state-of-the-art researches in STIN by classifying into network architecture design, communication resource management, and MEC resource managements is presented in Section II. Section III provides challenges and future research directions. We provide the conclusion of the paper in Section IV.

## II. State-Of-The-Art Researches on STIN

In this section, we provide the review on state-of-the-art researches on STIN focusing on the network architecture design, communication resource allocation, and satellite-assisted edge computing.

### A. STIN Architecture Design

As a new networking paradigm, various studies have proposed network architecture for STINs. For instance, in [5], following the technological advancements of satellite networks, mobile networks and IoT, a potential heterogeneous STIN architecture that consists of a wireless network employing licensed and unlicensed bands, a backbone network, and a satellite is proposed. The terrestrial wireless network employs different communication technologies to interconnect terminal devices, such as Bluetooth, WiFi, 5G, and so on and uses the satellite terrestrial integrated gateway to connect with the satellite network. While the backbone network is supposed to support the entire network in terms of computation and stable routing transmission, the satellite network is employed to extend the network coverage. In addition, to enhance the network management, a self organizing STIN system that consists of perception, cognition, and intelligence layers is proposed. In [7], focusing on LEO system with inter-satellite links, the authors first introduced the network architecture for broadband LEO satellite communications. Based on the designed network architecture, a comprehensive overview on the main issues including resource management, interference coordination, coverage models, and various satellite constellation modalities are presented. In [13], the authors proposed a network architecture that integrates LEO satellites into the 5G network to provide seamless and ubiquitous global wireless connectivity. Through various physical layer techniques including diversity techniques (e.g., access and spatial diversity), cognitive radio schemes, and interference management, the authors showed the introduced architecture can furnish seamless and high data rate wireless links for IoT devices with various QoS requirements.

On the other hand, to enhance the network flexibility and effective network resource management, advanced technologies such as network function virtualization (NFV) and software defined networking (SDN) have been considered in STIN architecture design. For instance, in [14], the authors proposed a cross-domain SDN architecture for multi-layer STIN that consists of terrestrial, aerial, and satellite domains and discussed its design and implementation. In [15], utilizing SDN and MEC paradigms, the authors proposed a unified network architecture that integrates terrestrial and space networks to provide anywhere anytime communications. Moreover, the authors identified the main issues of the introduced STIN architecture including security, traffic steering, routing, resource management, and mobility management and discussed some potential solutions. In [16], considering a SDN-based STIN, the joint computing, caching, and networking resource allocation is formulated, deep Q-learning-based scheme is proposed as solution.

### B. Communication Resource Management

As mentioned in the previous subsection, designing efficient radio resource management is identified as one of the main issues in STIN for optimal performance as the network architecture consists of various components with different wireless communication technologies. To this end, various studies have been introduced for efficient communication resource management with various objectives including energy efficiency, sum-rate maximization, delay-minimization, and so on. For instance, in [17], to achieve efficient data offloading, the terrestrial network is integrated with ultra-dense LEO networks, where each terrestrial user can connect to the network via a traditional small-cell, a macro-cell or a a satellite-backhauled small-cell over C-band, and the ka-band is considered for each satellited-backhauled small-cell to upload their data via multiple satellites. In addition, a matching algorithm is proposed to optimize the number of connected users and sum data rate under the backhaul capacity constraint. In [18], the problem of power allocation for communication, computing, and caching is formulated as a Nash bargaining game aiming to maximize throughput while guaranteeing fairness among users in STIN. A dual decomposition method is employed to solve the formulated problem, and the blockchain technology is considered to achieve data security. In [19], energy efficient power allocation for delay constrained cognitive STIN is investigated to optimize the energy efficiency of satellite communications under interference constraints caused by the primary terrestrial networks. The results revealed that integrating cognitive radio into STIN can improve the network capacity. In [20], the authors formulated the problem of energy efficiency for downlink data offloading in multi-cell STIN by jointly optimizing the resource allocation of satellite backhaulling and satellite-terrestrial terminal downlink. A binary search-assisted algorithm is proposed to solve the formulated problem. Considering a cache-enabled LEO in STINs, the authors in [21] investigated a cooperative transmission scheme to facilitate an energy efficient radio access network by offloading traffic from terrestrial base stations via LEO broadcast transmission. The energy efficiency maximization problem is formulated as a nonlinear fractional programming problem under LEO energy constraint by jointly optimizing cache sharing variable, power allocation, and block placement, and an iterative algorithm is proposed to solve the problem. In [22], the authors pinpoint three technical issues such as cross-layer power management, beam resource management, and spectrum resource management in STIN and discussed the possible solutions. In [23], a dynamic channel resource allocation problem in satellite IoT network is investigated, where the problem is formulated as a Markov decision problem, and a deep reinforcement leaning-based algorithm is proposed to solve the problem. In [3], the problem of data collection for users in remote areas by the cooperation of HAP-based massive access and LEO-based backhaul network framework with the objective of maximizing the revenue in terms of total number of users connected is investigated, and a matching-based algorithm is introduced to solve the problem.

### *C. Satellite-Assisted Edge Computing*

STINs not only required to extend network coverage for seamless and ubiquitous network access across the globe but also required to furnish user devices with different computing service requirements. Thus, considering edge computing-enabled satellite networks, various studies have been proposed for computation offloading and resource allocation problems in STINs with various objectives. For instance, in [24], considering edge computing-enabled LEO satellites, the energy consumption optimization problem for IoT devices in STIN is investigated, where the task data bits of IoT devices are offloaded to the LEO satellites via terrestrial satellite terminal. Taking into account the constraints of limited computation capability and coverage duration of LEO satellites, the authors in [25] investigated the computation offloading strategy with the aim of minimizing the sum energy dissipation of terrestrial users in a hybrid cloud and LEO edge computing network architecture, where terrestrial users can offload either to the LEO edge or central cloud server. A low computational complexity scheme using on alternating direction methods of multipliers is introduced to resolve the problem. In [26], the response time and energy consumption minimization problem in satellite edge computing is formulated using game theory taking into account the intermittent connectivity of LEO satellites due to their high speed mobility's. An iterative algorithm is proposed to obtain the Nash equilibrium. The authors in [27] considered a combined HAPs and a LEO satellite integrated network to furnish edge computing services for terrestrial users and formulated a problem in terms of minimizing energy consumption via the joint optimization of resource allocation, computation task assignment, multi-user MIMO transmit precoding, and user association.

On the other hand, to handle the network dynamicity and environment uncertainty, learning based approaches, especially deep reinforcement learning with deep neural network approximation techniques have been used to solve various networking and resource allocation problems recently. In [28], energy and latency minimization problem in edge-enabled satellite IoT network with the joint optimization of offloading decision, user association, and computation and communication resource allocation variables is formulated as a dynamic mixed-integer programming problem. To circumvent the difficulty of solving the original formulated problem, the authors decomposed it into resource allocation sub-problem and user association and offloading decision sub problem, where Lagrange multiplier and deep reinforcement learning methods are proposed to solve the sub-problems, respectively. In [29], an edge-enabled space-air-ground integrated framework for supporting different services of Internet of Vehicles with the objective of minimizing satellite resource usage and task completion time is proposed. A deep imitation learning-based with action pre-classification algorithm is proposed for efficient task offloading and caching services. In [30], a collaborative offloading in LEO satellite IoT network is investigated, where LEO satellites are employed to forward user tasks to ground MEC server. A weighted latency and energy consumption minimization problem is designed as a partially observable MDP and proposed a multi-agent deep reinforcement learning-based algorithm to solve the problem.

## III. Challenges and Open Research Issues

In the near future, it is expected that space and terrestrial networks will complement each other and eventually realize network convergence for seamless and ubiquitous connectivity across the world. Towards this end, although a number of studies are conducted for various objective, there are still various challenges to fully leverage the potential of STINs. For instance, as STIN consists of various networking components with different features and communication technologies, an unified, efficient, and flexible network architecture is required. Due to the high mobility of aerial platforms such as UAVs and LEO satellites, STIN link is usually intermittent and the connectivity duration with user devices or with other network components is limited. In addition, UAVs and LEO satellites have limited onboard computation and battery resources. Thus, resource efficient and intermittent connectivity resilient algorithms are required. Moreover, exploiting high spectrum such as visible light and THz to achieve fast and huge data access are envisioned as promising candidates in STIN [31]. However, high spectrum communications are highly delicate to attenuation due to changes in environmental conditions. Thus, designing an adaptive channel estimation and propagation model is a potential open research issue. As aforementioned, STIN integrates various types of networks designed for civil and military applications such that huge amount of resources and data must be secure and reliable. However, due to the high mobility of networking nodes (e.g., UAVs and LEO satellites), dynamic network typologies, limited available resources, and open links, it is highly challenging to provide highly secured communications to efficiently withstand malicious attacking, message tampering, jamming, etc. Thus, designing mobility- and resource-aware security protocol is essential and requires further investigation. Furthermore, interference management and resource coordination among different networking components need further investigations.

## IV. Conclusions

In this paper, we provided a review on studies related to satellite-terrestrial integrated networks (STINs). In particular, we first presented an extensive review on the state-of-the-art researches on STIN focusing on STIN architecture design, communication resource management, and satellite-assisted edge computing. Then, we pointed out the existing research challenges and provided open research issues which are considered to deserve further research investigations.

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## REFERENCES

[1] Statista:, "Number of internet of things (iot) connected devices worldwide from 2019 to 2021, with forecasts from 2022 to 2030, May 2022." *[Online]. Available: https://www.statista.com/statistics/1183457/iot-connected-devices-worldwide/.*

[2] J. Qiu, D. Grace, G. Ding, M. D. Zakaria, and Q. Wu, "Air-ground heterogeneous networks for 5g and beyond via integrating high and low altitude platforms," *IEEE Wireless Communications*, vol. 26, no. 6, pp. 140–148, 2019.

[3] Z. Jia, M. Sheng, J. Li, D. Zhou, and Z. Han, "Joint HAP access and LEO satellite backhaul in 6G: Matching game-based approaches," *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 4, pp. 1147–1159, 2020.

[4] D. S. Lakew, W. Na, N.-N. Dao, and S. Cho, "Aerial energy orchestration for heterogeneous uav-assisted wireless communications," *IEEE Systems Journal*, vol. 16, no. 2, pp. 2483–2494, 2022.

[5] W.-C. Chien, C.-F. Lai, M. S. Hossain, and G. Muhammad, "Heterogeneous space and terrestrial integrated networks for iot: Architecture and challenges," *IEEE network*, vol. 33, no. 1, pp. 15–21, 2019.

[6] D. S. Lakew, V. D. Tuong, N.-N. Dao, and S. Cho, "Adaptive partial offloading and resource harmonization in wireless edge computing-assisted ioe networks," *IEEE Transactions on Network Science and Engineering*, vol. 9, no. 5, pp. 3028–3044, 2022.

[7] Y. Su, Y. Liu, Y. Zhou, J. Yuan, H. Cao, and J. Shi, "Broadband leo satellite communications: Architectures and key technologies," *IEEE Wireless Communications*, vol. 26, no. 2, pp. 55–61, 2019.

[8] S. Min, "Engineering design and application of satellite communication system," *Publishing House of Electronics Industry*, 2015.

[9] D. S. Lakew, A.-T. Tran, N.-N. Dao, and S. Cho, "Intelligent offloading and resource allocation in heterogeneous aerial access iot networks," *IEEE Internet of Things Journal*, 2022.

[10] N.-N. Dao, Q.-V. Pham, N. H. Tu, T. T. Thanh, V. N. Q. Bao, D. S. Lakew, and S. Cho, "Survey on aerial radio access networks: Toward a comprehensive 6g access infrastructure," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 2, pp. 1193–1225, 2021.

[11] D. S. Lakew, A.-T. Tran, N.-N. Dao, and S. Cho, "Intelligent offloading and resource allocation in hap-assisted mec networks," in *2021 International Conference on Information and Communication Technology Convergence (ICTC)*. IEEE, 2021, pp. 1582–1587.

[12] D. S. Lakew, U. Sa'ad, N.-N. Dao, W. Na, and S. Cho, "Routing in flying ad hoc networks: A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 2, pp. 1071–1120, 2020.

[13] B. Di, L. Song, Y. Li, and H. V. Poor, "Ultra-dense leo: Integration of satellite access networks into 5g and beyond," *IEEE Wireless Communications*, vol. 26, no. 2, pp. 62–69, 2019.

[14] Y. Shi, Y. Cao, J. Liu, and N. Kato, "A cross-domain sdn architecture for multi-layered space-terrestrial integrated networks," *IEEE Network*, vol. 33, no. 1, pp. 29–35, 2019.

[15] Y. Bi, G. Han, S. Xu, X. Wang, C. Lin, Z. Yu, and P. Sun, "Software defined space-terrestrial integrated networks: architecture, challenges, and solutions," *IEEE Network*, vol. 33, no. 1, pp. 22–28, 2019.

[16] C. Qiu, H. Yao, F. R. Yu, F. Xu, and C. Zhao, "Deep Q-learning aided networking, caching, and computing resources allocation in software-defined satellite-terrestrial networks," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 6, pp. 5871–5883, 2019.

[17] B. Di, H. Zhang, L. Song, Y. Li, and G. Y. Li, "Ultra-dense leo: Integrating terrestrial-satellite networks into 5g and beyond for data offloading," *IEEE Transactions on Wireless Communications*, vol. 18, no. 1, pp. 47–62, 2018.

[18] S. Fu, J. Gao, and L. Zhao, "Integrated resource management for terrestrial-satellite systems," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 3, pp. 3256–3266, 2020.

[19] Y. Ruan, Y. Li, C.-X. Wang, R. Zhang, and H. Zhang, "Energy efficient power allocation for delay constrained cognitive satellite terrestrial networks under interference constraints," *IEEE Transactions on Wireless Communications*, vol. 18, no. 10, pp. 4957–4969, 2019.

[20] Z. Ji, S. Wu, C. Jiang, D. Hu, and W. Wang, "Energy-efficient data offloading for multi-cell satellite-terrestrial networks," *IEEE Communications Letters*, vol. 24, no. 10, pp. 2265–2269, 2020.

[21] J. Li, K. Xue, D. S. Wei, J. Liu, and Y. Zhang, "Energy efficiency and traffic offloading optimization in integrated satellite/terrestrial radio access networks," *IEEE Transactions on Wireless Communications*, vol. 19, no. 4, pp. 2367–2381, 2020.

[22] L. Kuang, X. Chen, C. Jiang, H. Zhang, and S. Wu, "Radio resource management in future terrestrial-satellite communication networks," *IEEE Wireless Communications*, vol. 24, no. 5, pp. 81–87, 2017.

[23] B. Zhao, J. Liu, Z. Wei, and I. You, "A deep reinforcement learning based approach for energy-efficient channel allocation in satellite internet of things," *IEEE Access*, vol. 8, pp. 62 197–62 206, 2020.

[24] Z. Song, Y. Hao, Y. Liu, and X. Sun, "Energy-efficient multiaccess edge computing for terrestrial-satellite internet of things," *IEEE Internet of Things Journal*, vol. 8, no. 18, pp. 14 202–14 218, 2021.

[25] Q. Tang, Z. Fei, B. Li, and Z. Han, "Computation offloading in leo satellite networks with hybrid cloud and edge computing," *IEEE Internet of Things Journal*, vol. 8, no. 11, pp. 9164–9176, 2021.

[26] Y. Wang, J. Yang, X. Guo, and Z. Qu, "A game-theoretic approach to computation offloading in satellite edge computing," *IEEE Access*, vol. 8, pp. 12 510–12 520, 2019.

[27] C. Ding, J.-B. Wang, H. Zhang, M. Lin, and G. Y. Li, "Joint optimization of transmission and computation resources for satellite and high altitude platform assisted edge computing," *IEEE Transactions on Wireless Communications*, vol. 21, no. 2, pp. 1362–1377, 2021.

[28] G. Cui, X. Li, L. Xu, and W. Wang, "Latency and energy optimization for mec enhanced sat-iot networks," *IEEE Access*, vol. 8, pp. 55 915–55 926, 2020.

[29] S. Yu, X. Gong, Q. Shi, X. Wang, and X. Chen, "Ec-sagins: Edge-computing-enhanced space–air–ground-integrated networks for internet of vehicles," *IEEE Internet of Things Journal*, vol. 9, no. 8, pp. 5742–5754, 2021.

[30] Y. Lyu, Z. Liu, R. Fan, C. Zhan, H. Hu, and J. An, "Optimal computation offloading in collaborative leo-iot enabled mec: A multi-agent deep reinforcement learning approach," *IEEE Transactions on Green Communications and Networking*, 2022.

[31] P. Yang, Y. Xiao, M. Xiao, and S. Li, "6G wireless communications: Vision and potential techniques," *IEEE network*, vol. 33, no. 4, pp. 70–75, 2019.