EAI Endorsed Transactions
on Tourism, Technology and Intelligence
Research Article EAI.EU

Impact of 6G Space-Air-Ground Integrated Networks on Hard-to-Reach Areas: Tourism, Agriculture, Education, and Indigenous Communities

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Abstract

Due to low population density, difficult terrain, and insufficient infrastructure, the deployment of wireless communication in hard-to-reach areas has long been a challenge from the perspective of companies and governments, despite the high demand from many local communities. The birth of space-air-ground integrated networks (SAGINs) which are designed to provide ubiquitous, seamless, and high-throughput connectivity is a promising solution to this challenge. In this paper, we investigate the unique difficulties in rural and remote areas that lack connectivity in the information era. To address these problems, a general architecture of SAGINs is described with the aim of applying it in these regions, following the benefits to tourism, agriculture, education, and indigenous communities. Although SAGINs have gained researchers' attention lately, there is a need to look at their applications to remote and hard-to-reach areas. Important open research topics are crucial to be investigated at the beginning of the design process to ensure that their full potential is leveraged to improve the well-being of local populations and support sustainable development.

Received on 06 Apr 2024; accepted on 02 Aug 2024; published on 23 Sep 2024

Keywords: Space-air-ground integrated networks, hard-to-reach areas, tourism, agriculture, education, and indigenous communities

doi:10.4108/eettti.6812

1. Introduction

Billions of people, nearly half of the world's population in many rural and remote areas are out of the information era due to the lack of connectivity or poor wireless communication [1]. As a result, tourism in these regions is limited in its access to advertising and its ability to provide safety and satisfactory services to tourists, making it less competitive compared with other locations [2]. In agriculture, it is hard to apply new technologies, replace inefficient old farming methods and create abundant yield and bountiful harvest in both amount and quality [3]. Unreliable internet connections also restrict students from accessing the latest lectures, online learning, and advanced teaching methods, causing an imbalance in education quality between different regions [4]. Besides, the lack of a reliable mobile network adversely affects locals' well-being by preventing access to smart healthcare systems and entertainment. Without digital records or experts' restoration, local communities also face heritage loss [3]. Overall, seamless, ubiquitous, and reliable connectivity is extremely essential in hard-to-reach areas to build a multi-discipline system for sustainable development.

Although the current terrestrial networks provide wireless connections with high throughput and low latency, they can only be applied in cities, metropolises, and areas where the infrastructure is well developed. Their coverage only accounts for around 25% of the Earth's surface [5]. A vast area of oceans, mountains, villages, and islands is still out of service while the internet can be a highly important factor in boosting the various sectors of the economy and social development,

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enhancing the quality of life. The deployment of terrestrial networks in hard-to-reach areas is cost-inefficient and even impossible due to rugged terrains. Therefore, satellite communication is one of the most promising solutions to provide wireless connectivity to these regions. Although satellites can serve users distributed in a vast area, multiple obstacles such as high attenuation, extreme weather, i.e. cloud, fog, rain, snow, and low-gain transceiver antennas at the users, cause the loss of connection [6]. Thus, two more layers including unmanned aerial vehicles (UAVs)-supported aerial networks and terrestrial networks aided by local ground base stations are deployed together with satellite-aided space networks. The amalgamation of these three-layer networks called space-air-ground integrated networks (SAGINs) is expected to provide high-throughput and low-latency two-way connections to many remote areas simultaneously.

SAGINs have high potential to be applied in the sixth generation of networks (6G) to enable global connectivity anytime and anywhere [7]. Thanks to the ultra-large coverage of satellites and the flexibility of UAVs, wireless communication in SAGINs can allow people in rural and hard-to-reach areas, where the infrastructure is under-developed, to access the internet as well as exchange their data to the rest of the world. As such, the quality of life, residents' well-being and the economy can be improved significantly by the enhancement of key sectors including tourism, agriculture, and education that fully leverage the advanced technologies.

In this paper, we first provide a general discussion on the demands and challenges related to wireless communication in rural and remote areas in four key fields. Then, the paper dives into a technical description for designing a potential architecture of SAGINs combining space, aerial, and ground networks. This architecture does not require well-developed infrastructure like base stations, high-gain antennas, and a powerful power grid, resulting in the ability to be efficiently deployed in hard-to-reach areas. Subsequently, disruptive technologies are enabled to provide an economic boost in tourism, effective productivity and sustainability in agriculture, quality enhancement in education, and life-quality improvement in indigenous communities. However, to leverage the full potential of SAGINs, open research topics including infrastructure and deployment, privacy and security, and real-time solutions for large-scale problems need to be conducted at the same time of the design process.

2. Challenges in Hard-to-Reach Areas

To promote the development of under-developed areas, a series of operations in multi-disciplinaries is required along with the cooperation between governments and locals. The maturity of infrastructure plays a vital role in enabling modern and sustainable development. In this section, we delve into the specific challenges faced by various sectors in the hard-to-reach areas from the technical perspective.

2.1. Tourism

Unstable or non-internet connectivity issues can cause extreme communication barriers to tourism in isolated areas. Indeed, tourists to remote destinations often suffer from poor connectivity, which can significantly hinder their experience. For example, the lack of reliable internet and mobile connection makes tourists unable to access real-time information and book services online all in the context of limited guided tours and information kiosks. In the event of accidents, natural disasters, or other emergencies, tourists in remote areas may face a long delay in essential support and first aid. On the other hand, many tourist service providers may see their marketing and advertising campaigns become restricted in reaching the target audience.

2.2. Agriculture

Traditional agriculture in isolated areas can face many challenges that make the production inefficient such as environmental changes (i.e. weather, soil salinity, disasters, and other natural factors), pests, farming decisions and methods, and many others. The implementation of modern technologies including Internet-of-Things (IoT), artificial intelligence (AI), robotics, precision agriculture, and biotechnology as a transformative method can improve significantly productivity and sustainability, save natural and human resources. However, these technologies require exchanging, storing, and analysing the high volume of data for training AI models for example. Meanwhile, current terrestrial networks cannot adapt to meet this requirement due to the limitation in coverage, or the scattered construction of multiple wireless communication infrastructures in vast agricultural lands, cultivation, livestock, and aquaculture. This leads to resources wasted, inefficient costs, or even infeasiblilty to realise. Furthermore, the lack of real-time information access can cause long delays in the optimal responses to urgent cases, for example, disasters, floods and pandemics which can be predicted by applying AI for data collected from sensors, signs, and then avoid or limit a part of the possible damages.

2.3. Education

Advanced technologies are essential to improve the quality of both learning and teaching in remote areas, yet the use of smart devices i.e. smartphones, computers, laptops, and tablets and the applications of digital technologies namely virtual reality (VR), augmented reality (AR), and digitisation is significantly restricted by unstable and insufficient connectivity. In terms of quality, the lack of high-speed internet and smart devices using in education creates inequality between remote and urban areas. Students in hard-to-reach regions probably suffer from inadequate infrastructure and resources, causing challenges in fulfilling their potential. Since the COVID-19 pandemic, online learning and online libraries have an irreplaceable role in education with many benefits such as flexibility, cost efficiency, time-saving, and carbon footprint reduction. However, these methods are challenging to implement in remote areas due to poor connectivity which can restrict the teachers' access to advanced resources and students' access to new knowledge.

2.4. Indigenous Communities

Indigenous communities in hard-to-reach areas face the challenges of gradually fading away their cultures and heritages as well as social and economic disparities. Due to changes in lives and external influences, the unique traditional cultures and heritages have a risk of being permanently lost while storing and restoring are hard to deploy. For example, thousands of known endangered languages are predicted to disappear in the near future because of the lack of advanced tools and support for community knowledge holders and experts who have many years of experience in these languages. Additionally, ancient architectures have suffered damages from environmental factors that require foreign multi-disciplinary expertise and skilled craftsmen to repair and restore. These issues rely on information exchanges about the status, progress, and accidents that would be impossible without connectivity. Limited connectivity can restrict indigenous people's access to essential opportunities ranging from advanced healthcare, and education to the economy. Stable, ubiquitous, and high-throughput wireless connectivity plays a vital role in addressing these challenges thanks to the suitable architecture that are generally described in the following section.

3. Space-Air-Ground Integrated Networks for Hard-to-Reach Areas

For a few past years, SAGINs have been attracted intensive attention of both academic and industry due to significant benefits for providing seamless and ubiquitous wireless services [7]. To efficiently adapt these services, three network layers consisting of space, aerial, and terrestrial networks are proposed to be cooperatively integrated [8, 9]. In this section, we describe the general architecture of SAGINs tailored for remote areas shown in Fig. 1.

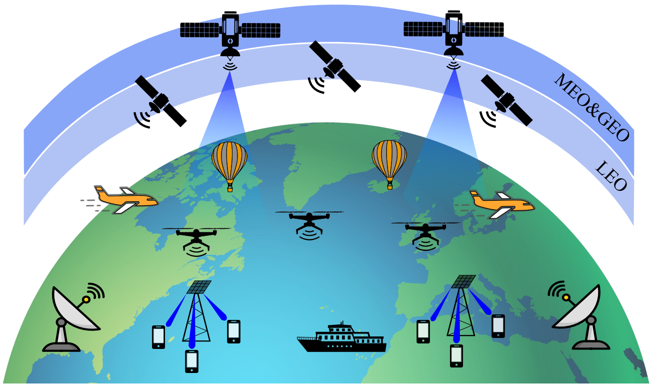

Figure 1. Space-air-ground integrated networks

3.1. Space Networks

The first layer of SAGINs consists of a constellation of many satellites connected together. Although the latency in low earth orbit (LEO) satellite communication is much lower than their other counterparts (medium earth orbit (MEO) and geostationary (GEO) satellites), it is still significant compared to the traditional terrestrial networks due to the existing physical latency in long-distance transmission. Therefore, satellites are responsible for providing long-term and reliable connectivity for applications without strict time constraints. Additionally, since LEO satellites move with ultra-high speed of around 7.65 km/s relative to the Earth's surface, to provide high-throughput wireless communication to remote areas, many LEO satellites are required [10]. Additionally, satellites can use multibeam design to generate narrow beams toward UAVs, ground base stations, and the clusters of users in hard-to-reach areas [11]. In inter-satellite communication, free-space optical satellite networks can be created using laser links with high-throughput connections [12]. As such, we can design automated space networks consisting of satellites with different missions such as computing and storing GEO, MEO satellites and communicating MEO, LEO satellites.

3.2. Aerial Networks

Aerial networks with high flexibility by leveraging various platforms such as high-altitude platforms (HAPs) and drones can provide line-of-sight and low-latency links to ground base stations and user devices [13]. In remote areas, charging batteries and energy for continuous operation of UAVs is challenging. Therefore, HAPs situated from 17 to 22 km above the Earth's surface with extended period operation can be used as stable intermediate relays to enhance the signals from satellites for downlink or base stations for uplink. They can cover specific regions and provide persistent, cost-effective connections with lower latency than satellites. Meanwhile, highly flexible drones can be used in urgent situations such as network recovery in disasters [14], searching and rescuing at remote rugged terrains, real-time data collection in agriculture, and environment monitoring. Overall, aerial networks are the complement of space networks to improve the quality of signals in both uplink and downlink communication, and the network flexibility.

3.3. Terrestrial Networks

Terrestrial networks are classified into two types according to their roles. The first ones are core networks deployed at well-developed areas to provide backhaul links and operation commands for SAGINs. These core networks consist of hardware with high computing and storing capacity, and synchronous optical networking between elements and to other networks. The processing of cutting-edge technologies can be integrated to leverage their capability. To communicate with satellites or UAVs in the coverage, many ground gateways and macro base stations can be distributed in multiple different locations. The second terrestrial networks are deployed in remote regions. Regarding uplink communication, user devices are usually designed with strict limitation in both computing and power capacity, while downlink communication can be interrupted by different factors caused by long-distance transmission. To tackle this issue, one or a few ground base stations are required at each desired hard-to-reach area to ensure the quality of two-way communication and enhance reliability. Additionally, the architectures of large-cellular networks and wireless ad-hoc networks are promising to be applied in these regions. With cellular networks, each transceiving tower can not only serve a cluster of users with high data transmission and low latency but also be easy to deploy and extend in difficult terrains [15]. Meanwhile, ad-hoc networks, which leverage device-to-device (D2D) connections to create decentralised networks, reduce outage probability and enhance network coverage.

4. The Benefits and Cutting-Edge Technologies of Space-Air-Ground Integrated Networks

The deployment of 6G SAGINs brings key benefits to various sectors in hard-to-reach regions. The potential advantages of ubiquitous wireless communication are explored to leverage cutting-edge technologies to improve tourism, agriculture, education, and address many challenges to indigenous communities. In this section, we present these benefits, technologies in SAGINs as well as the general methods to integrate them in reality as shown in Fig. 2.

4.1. Tourism

Together with the development of wireless communication supported by SAGINs, new technologies are leveraged to level up local tourism in remote areas in many different aspects such as advertising, tourist experience and safety. To attract more attention of visitors, AI and machine learning (ML) methods can be used to learn featuring data transmitted from many remote areas. Subsequently, depending on the objectives of visitors, suitable locations are advertised to promote local tourism. Additionally, virtual tours have become common as well as been a spectacular tool that enable people to preview their trips from different angles to choose the most suitable ones [16]. Aerial and terrestrial networks connect cameras placed in remote areas and UAVs, following by sending real-time visual data to the central processing. Then, VR is used to create a virtual environment and synchronise to online websites in real-time to allow worldwide people access using smart devices without the requirement of any installation [2]. In terms of safety, satellite networks can provide a wide positioning system to track tourists and wild animals to warn these tourists of dangerous animals nearby, and rescue them quickly in emergency cases. Besides, the accuracy of weather forecast can be improved significantly by incorporating traditional weather forecasts and AI for the combination of historical and real-time data from sensors monitoring radiosonde, wind, river stream, imagery and sensing data collected by satellites. The process of synthesising data of a huge area can be aided by uploading from ground base stations and UAVs to central processors placed at satellites.

4.2. Agriculture

Wireless communication allows modern technologies to be applied to offer significant increases in the avenues for productivity and sustainability in agriculture in hard-to-reach areas. Regarding precision farming, optimisation-enabled IoT systems are employed to revolutionise farming methods in saving resources such as human labour, water, soil, and fertilisers [3]. However, in remote areas, the majority of farmers opt to farm on single small scales, resulting in high costs in the deployment of IoT systems, local transceivers for data collection, and computers. Therefore, SAGINs with wide coverage can be an optimal approach to build centralised controlled systems to simultaneously collect the data from sensors, analyse it, and then transmit control signals to automatic systems. There are multiple benefits in this type of system including cost efficiency, synchronisation in optimally farming, scalability, and the ability to receive support from overseas experts.

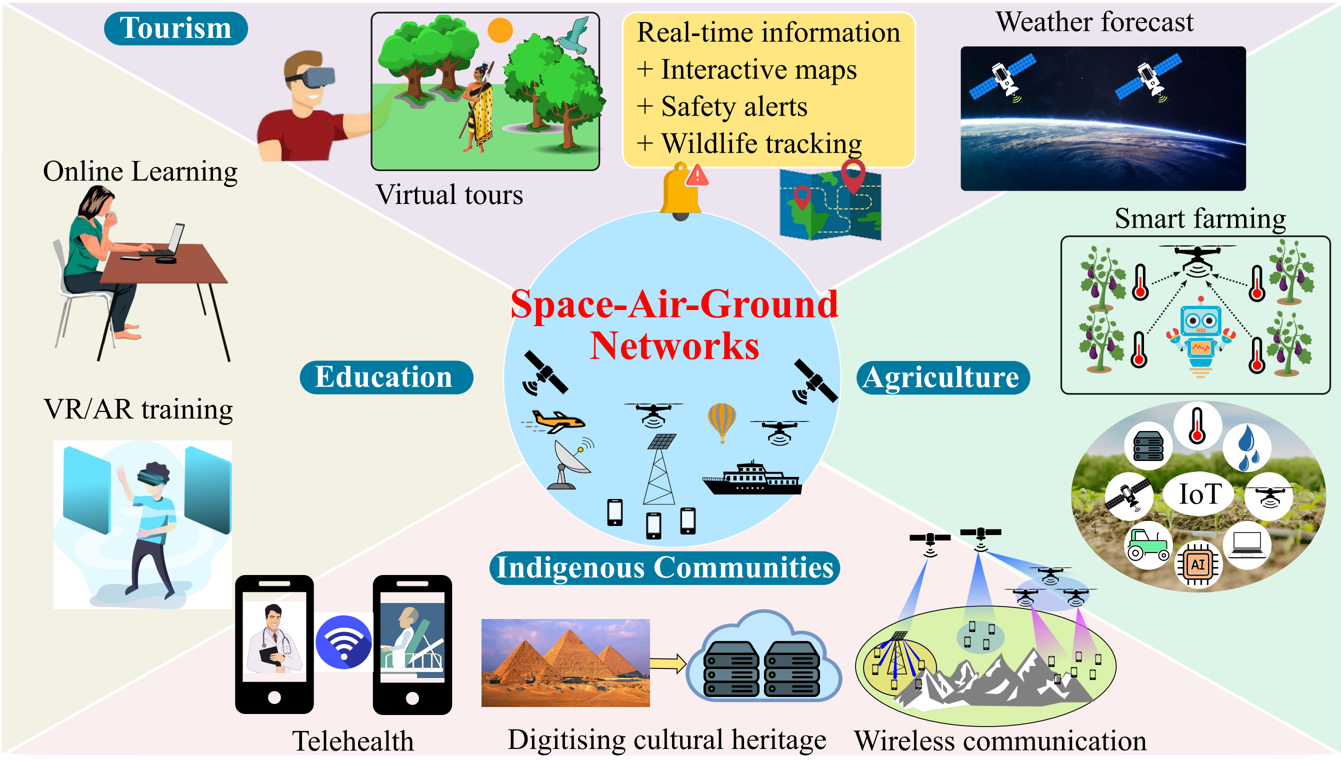

Figure 2. SAGIN-supported key applications in tourism, agriculture, education, and indigenous communities.

For example, in [17], an online application programme which is designed using optimisation to solve practical agriculture problems allows users to connect and input real-time data and then provides the optimal decision from the web app. Additionally, to create sustainability in agriculture progression, smart farming with the support of automated machines and vehicles optimises resources used and obtains higher yields. Additionally, data from IoT sensors can be wirelessly transmitted to local centres and forwarded to cloud computing systems at satellites for analysing and evaluating by AI and ML algorithms. These help to forecast weather, detect early diseases as well as prevent them through actionable insights and automated decision-making support for farmers.

4.3. Education

Through high-speed internet, SAGINs allows people in remote areas to access advanced education which can be one of the key factors to create a solid foundation for sustainable development. On the one hand, web-aided education, for example, online learning, online resources, and online libraries, not only provides a flexible environment for learners regardless of their locations but also does not require intensive computing and storing capacity in user devices, other than seamless and reliable internet connections. To meet this requirement, LEO satellites and HAPs in SAGINs can act as primary relays to access the cloud data at ground gateways or storing satellites and deliver high-speed internet to schools in remote areas, enabling the use of online learning platforms and digital resources. On the other hand, e-learning platforms and digital libraries can be easily adjusted, customised and scaled to meet the different needs in many local remote areas and address the problem of the lack of teachers in hard-to-reach areas. Together with e-learning, digitisation in the processes and management of schools can reduce delays, optimise the operation, and be easily managed by governments. Additionally, with the support of SAGINs, advanced digital technologies (e.g. VR and AR) can be applied to create immersive virtual classrooms and varying educational opportunities. The learning experiences of students are improved through interactions and a real-time sense of physical appearance in a shared virtual environment generated by computers [18].

4.4. Indigenous Communities

By leveraging the advancements of 6G SAGINs, the unique challenges regarding indigenous communities in isolated areas can be addressed efficiently. First, thanks to ubiquitous connectivity, featured indigenous cultures and traditions are shared and introduced to many people. They can be recorded using digital documents, text, photos, and videos, then be stored in cloud platforms for preservation. Subsequently, the VR- and AR-supported services such as digital archives and virtual museums can be exploited to share traditional heritage globally. Secondly, health of locals can also be improved thanks to healthcare and social services using telehealth and telemedicine. Through reliable internet connectivity, skilled doctors can support local ones to diagnose and treat patients remotely. Furthermore, mobile health devices which are attached on body parts of patients can collect real-time data for monitoring and health consulting. Also, financial support and food packages can be offered to help indigenous communities overcome difficulties such as disasters, disease, and crop failure.

5. Open Research Directions of Applying SAGINs to Hard-to-Reach Areas

6G SAGINs can not only address the challenges faced by remote areas but also unlock key benefits for tourism, agriculture, education, and indigenous communities to foster sustainable development. However, the integration of space, aerial, and terrestrial networks in these regions requires comprehensive studies in infrastructure and deployment, privacy and security, and large-scale problems which are more strictly compared to the construction in cities.

5.1. Infrastructure and Deployment

The requirements of infrastructure for providing wireless communication in remote areas are reduced by leveraging the large coverage of satellites and aerial vehicles. However, as mentioned in Section 3.3, at each remote area, a number of ground base stations with two-way communication is required to guarantee the quality of communication. Meanwhile, the space and aerial networks are responsible for providing high-throughput backhaul links to these base stations and directly connected with users in the case of good-condition channels. Besides, control centres at core networks placed in well-developed areas are required for SAGIN management, backup, and process of computing-intensive tasks. Regarding satellite networks, although fully reusable launch vehicles for satellites are used to reduce launching costs significantly by reusing rocket engines and boosters, the cost of launching satellites is still prohibitive. Therefore, research on the integration of multi-discipline applications along with communications on satellites is essential to be conducted to leverage the most their capability.

In terms of deployment, the consideration of every single remote area is not efficient and wasteful since multiple satellites and many UAVs are required to provide reliable and high-speed connectivity, while their coverage can cover other areas while travelling in their orbits. For example, LEO satellites move around the Earth in their given orbits, resulting in their ability to wirelessly connect with ground devices in many different areas. Therefore, the research into designing optimal orbits for satellites and trajectories for UAVs to efficiently cover multiple varying hard-to-reach areas simultaneously is essential. Additionally, in reality, the locations of ground users cannot be fixed. Therefore, the proposed networks are required to guarantee the minimum quality of service in the varying densities of ground users. To achieve multiple objectives of throughput maximisation for ground users and energy efficiency for satellites and UAVs, some directions need to be comprehensively investigated as follows

- Multi-beam design is applied in satellites, while massive antenna beamforming techniques are used at UAVs and ground base stations to simultaneously enhance the signals and mitigate interference between beams [11, 19].
- Beam hopping in areas with a heterogeneous density of users can be essential to be employed in satellite communication in order to allocate more resources to the dense deployment of users and reduce fewer resources to the others by switching beams [20, 21].
- Rate-splitting multiple access which is a novel multiple access technique splitting users' messages into common and private ones for transmission. This technique improves significantly spectral and energy efficiency, fairness of users, and quality of service compared to the traditional methods such as orthogonal multiple access, space division multiple access, and non-orthogonal multiple access [22].

5.2. Privacy and Security

Physical layer security (PLS) is crucial for SAGINs due to inherent vulnerabilities such as large coverage and limited security options. Unlike terrestrial networks, signals from satellites can emitted to multiple ground users in a vast area where eavesdroppers can be located. This makes the sensitive data susceptible to wiretapping by illegal devices which are equipped with the precise equipment of legitimate users [23]. Additionally, in terms of upper-layer security approaches, complex encryption algorithms are inappropriate to operate in satellites and UAVs due to the limitation in processing capacity and power. Also, additional data for encryption and decryption can lead to data overhead for the networks. PLS exploits the inherent randomness of the wireless channel to improve security performance for communication. Although there are many related studies investigating PLS in terrestrial networks, the implication to non-terrestrial networks is still challenging.

In more detail, creating extremely narrow spot beams to transmit green interference to eavesdroppers can be impossible in the case of long-distance transmission of satellite communication, especially when the difference in the channels of legitimate users and eavesdroppers is negligible. Therefore, the cooperation between UAVs and satellites for PLS is a promising open topic.

5.3. Real-time optimisation

Achieving real-time optimisation for large-scale problems is one of the near-future challenges in SAGINs. To provide continuous communication services for many different hard-to-reach areas, there is a requirement for mega-constellations of thousands of LEO satellites operating simultaneously and cooperatively. Thus, controlling and optimising the system are large-scale problems which are not only highly complex due to multi-layer networks but also consist of many stringent constraints. In addition, LEO satellites move in their orbits around the Earth with a speed of up to 7.65 km/s while the locations of UAVs are not fixed because of fast movements and jitters caused by winds or other environmental effects. Differing from terrestrial networks, the movement of flying base stations in non-terrestrial networks makes wireless channels change quickly and unpredictably. Therefore, designing real-time optimisation algorithms which can adapt efficiently to changes in the networks is an essential and attractive research topic in SAGINs. Additionally, quantum computing with its unprecedented computing capacity is expected to outweigh classical computers in solving large-scale problems [24]. However, quantum computing is still in its fancy, requiring more comprehensive research to exploit its capabilities to the fullest.

6. Conclusion

The deployment of 6G SAGINs can revolutionise connectivity in hard-to-reach areas by the operative cooperation of space, aerial, and terrestrial networks. This architecture shows great potential to be applied in these regions in order to provide low-cost broadband connections without necessitating extensive development infrastructure. Due to their fancy stage, SAGINs requires further research on network deployment, security, and large-scale problems tailoring rugged terrains and isolated areas. Prioritising research and investment in SAGINs can not only offer benefits of the information era to remote communities but also allow the enlargement of fields in other regions, creating circular development.

Acknowledgement

This work was supported in part through the Canada First Research Excellence Fund for two projects Qanittaq Clean Arctic Shipping and Transforming Climate Action.

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