Design of 6G Space-Ground Integrated Network Architecture Based on Ground Core Network

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***Abstract*— Space-ground integration is a key component of 6G with diverse topologies, time-varying topologies, broad geographical and temporal scales, and limited spatial node resources, bringing new development opportunities and scope for mobile communications. Before designing the 3D 6G space-ground integrated network architecture, we first examine the main difficulties of space-ground integrated networks, and then examine the common use cases and requirements of 6G-oriented space-ground integrated networks. Finally, we propose a space-ground integrated network architecture based on a decentralized core network and a ground-centralized core network. For the former, the core network is placed on the ground while the airborne platform performs certain access network activities. To meet the needs of various application scenarios, the latter airborne platform performs access network operations and loads a portion of the core network components. Dynamic deployment of key network functions becomes possible as the network functions are reconfigured to meet the changing application scenario needs and network operation requirements.**

Keywords—6G, space-ground, network architecture, centralized core network, distributed core network

I. INTRODUCTION

The need for access to large terminals, the rapid expansion of Internet traffic, and the stringent requirements for latency and reliability in telemedicine and industrial control have all led to the development of 5G communication technology, which also offers a qualitative improvement in communication capabilities in seven areas: mobility, latency, user-perceived rate, peak rate, connection number density, traffic density, and energy efficiency [1, 2]. Future networks are facing new difficulties as a result of the recent fast expansion of sectors like 5G, cloud computing, and the Internet of Things. In order to achieve seamless global coverage, an air interface with a latency of no more than 275 ms, and seamless switching between terrestrial and satellite networks, it is necessary to further advance current ground-based network technologies, according to 3GPP TR 22.891 [3], which presents a scenario of using satellites for 5G network connectivity.

Future network orientation is represented by key technologies as DetNet (deterministic network) [4], intelligent network [5], and SAGIN (space-air-ground integrated network) [6]. SAGIN [7] seeks to achieve network collaboration and integrated development. SAGIN serves people on Earth as well as satellites, which utilize it to carry out computational or communication activities including image processing and remote sensing [8]. The space-air-ground integrated network may be employed in a variety of practical sectors, including as earth observation and mapping, intelligent transportation systems (ITS), military operations, disaster assistance, and more because to its broad coverage, high throughput, and robust resilience [9].

The space-ground integrated network integrates satellite network (including high/medium/ground orbiting satellites), air-based network (high-altitude platforms, UAVs, hot air balloons, etc.), and ground network to create a network architecture with full-scene coverage, multi-network synergy, convergence and complementarity, intelligence, and efficiency. Utilizing convergent networking strategies to the fullest extent possible is the Ultra Dense Network (UDN) [10] technology for 5G networks. However, when the demands of converged networking for 6G networks [11] [12] are confronted, numerous additional needs and problems need to be resolved. Converged networking is a practical answer to the needs of future 6G networks for full-scene coverage, vast interconnection, and high traffic transfer. The 6G-oriented converged networking [13] [14] seeks to achieve the convergence and complementarity of cross-domain multi-layer networks, such as terrestrial networks, satellite networks, and high-altitude platform networks, which are not simply multi-layer network overlays but require the collaborative coverage of multi-layer networks. This is in contrast to the traditional cellular networks' converged networking. In order to achieve cooperative coverage among multi-layer networks, improve network coverage, and boost network service capability, it is required to first build the space-ground integrated convergent network, followed by designing the cooperative interaction mechanism under this network.

II. Challenges

Space-ground integrated networks have intriguing applications, but designing such networks is difficult. The following significant difficulties might now be encountered by space-ground integrated networks [15].

A. Network Design

High levels of agility and resilience, as well as the capacity to provide coverage everywhere, are requirements for 5G and B5G. The majority of the research to date has, however, concentrated on the performance study of UAV networks, and there is a disconnect between the usage of UAVs and the objective of ubiquitous coverage. The proactive deployment of drones should be used to close this gap, and a key component of this strategy is the prediction of traffic patterns (such as traffic fluctuations and user movement). In order to increase the effectiveness of network resource use, software-defined networking (SDN) and network function virtualization (NFV) have also been intensively researched in terrestrial cellular networks. Future study will continue to focus on their use in airborne networks, which is still in its early stages. NFV solutions may be looked for to restore applications in the event of UAV failure and consequent application disruptions. NFV enables the use of generic drones rather than customized drones to carry out certain network operations, such as network gateways. This is accomplished by scripting the hardware. Sharing available network resources enables more effective use of resources while also lowering network expenses. On the other hand, the aerial network should be self-healing/self-organizing owing to the frequent changes in network configuration, since this would increase fault tolerance. Software-defined networking (SDN) may be used to adaptably control and alter network configuration (e.g., add/remove pathways, update protocols). This adaptable control improves the network's ability to tolerate faults [16, 17].

B. Heterogeneous Resource Allocation

The space-ground integrated network is a heterogeneous multidimensional network, and the convergence of multiple networks results in an extremely complex network structure and diverse network resources. In addition, the distinct dynamic properties of air-based and ground-based networks result in more complex mobile properties of the network as a whole compared to those of ground-based networks, making it challenging to accurately describe and model the network. The space-ground integrated network simultaneously offers network services for a variety of air-based, ground-based, and marine information services, and the varied service characteristics and quality of service (QoS) requirements make network resource allocation and service scheduling incredibly challenging, which results in the traditional optimization methods being ineffective and slow to react, unable to adapt to the complex and dynamic network environment of the air-gro Methods based on artificial intelligence are seen to have a lot of promise for solving complicated, dynamic issues that are difficult to model. Large volumes of data may be extracted and analyzed to create an appropriate mapping model of the network environment and network control, allowing for the effective and intelligent design, control, management, and optimization of the network. Given the complex and dynamic nature of the space-ground integrated network and the high cost of network data collection, reinforcement learning is a crucial class of machine learning techniques that can learn the best action strategy through feedback of the interaction between intelligence and environment. It can also deal with learning decisions in an unknown network environment.

C. Air Communication Platform Deployment Control

Several restrictions, including energy consumption, collision avoidance, trajectory cost, communication cost, flyable cost, and mission cost, are applied to the issue of route planning for air communication platforms. Due to the sharp increase in the number of variable dimensions, there may be a combinatorial explosion issue when mathematical optimization theory is employed to address the air communication platform route planning problem. Emerging intelligent algorithms may be the focus of future study as they can prevent the combinatorial explosion issue. The proactive deployment of drones should be used to close this gap, and a key component of this strategy is the prediction of traffic patterns (such as traffic fluctuations and user movement).

D. Practical Considerations

When building and implementing space-ground integrated networks, there are a lot of practical factors to take into mind, such as cost and platform security. Because of the possibility for physical and electronic assaults, maintaining and sustaining air platforms may be costly. For security reasons, air platforms should be protected [18]. In addition, by offering dependable and efficient area coverage services (such as surveillance and monitoring) or communication coverage services (such as airborne trunking/base stations), the space-ground integrated network must respond to changes in the dynamic environment. In order to facilitate information exchange, the space-ground integrated network must be connected with existing infrastructure and should not be planned as an isolated network.

III. Network Architecture

Air platform, gateway station, and user terminal make up most space-ground integrated communication systems. In order to provide signal coverage to the ground and air, air platforms, which may be both high-altitude and low-altitude, often create several beams across a particular service area within their field of vision. The gateway station, which is on the ground, links the public data network to the air platform network.

The space-ground integrated communication system consists of the following links.

- *Operational link:* The communication link between the terminal and the air platform.
- *Feeder link:* The communication link between the gateway station and the air platform.
- *Air-to-air platform link:* The air platform may implement signal forwarding over the inter-air platform connection when the gateway station cannot be deployed (for example, at sea). The radio band or the optical band are two options for the air-to-air platform connectivity.

Different types of air platforms may carry a variety of communication duties due to their varied performance. Various application scenarios also provide various needs for 6G space-ground integrated network designs at the same time. Therefore, by examining the roles of the network components loaded on the air platform, we suggest two space-ground integrated network architectures in this paper: one based on a dispersed core network and the other on a centralized core network on the ground. The core network is installed on the ground and is carried by the earlier air platform in order to meet the demands of various application scenarios. The later air platform also carries access network functions and loads a portion of the core network parts as needed.

A. Space-Ground Integrated Network Architecture Based on Ground Centralized Core Network

The air platform may be split into two groups based on its various signal processing capabilities (i.e., communication payload): transparent payload and regenerative payload. Transparent payloads perform fundamental tasks including RF filtering, frequency conversion, and amplification while maintaining the original conveyed waveform, which is comparable to an RF repeater [19]. In addition to demodulation/decoding, switching and routing, coding/modulation, and other operations that are equal to all or some of the 6G base station functions on the air platform, regenerative payloads also perform these fundamental activities.

1) Space-Ground Integrated Network Architecture Based on Transparent Payloads

a) Reference architecture A-1: Single-connected space-ground integrated network architecture based on transparent air platform.

The air platform merely serves as a node for signal amplification and forwarding, as seen in Figure 1. Prior to being sent to the ground users via the air platform, the data from the core network is first transferred to the gNB, then sent to the air platform through the gateway. The transparent payload on the air platform performs communication processing duties similarly to an RF repeater. The NR-Uu interface does not end on the air platform; rather, it does so between the terminal (UE) and the ground-based 5G base station (gNB). As a result, the payload's communication processing function is rather straightforward and does not need a highly sophisticated payload implementation. To handle the significant delay induced by transmission through the air platform, several timers on the NR-Uu interface need to be taken into consideration for expansion for the 5G standard. All functionalities required for conveying the signals from the NR Uu interface are supported by the air-port station. The same gNB on the ground may be linked to a variety of transparent air platforms [20].

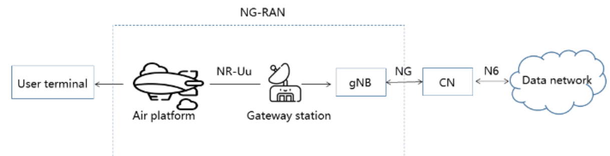

Fig. 1. Single connection space-ground integrated network architecture based on transparent air platform

b) Reference architecture A-2: Multi-connected space-ground integrated network architecture based on transparent air platform and terrestrial cellular.

User devices are linked to CN via both cellular NG-RAN and transparent air platform-based NG-RAN in the multi-connected space-ground integrated network architecture based on terrestrial cellular and Fig. 2 shows.

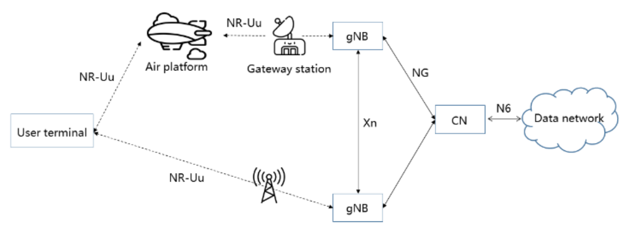

Fig. 2. Multi-connected space-ground integrated network architecture based on transparent air platform and terrestrial cellular

c) Reference architecture A-3: Multi-connected space-ground integrated network architecture based on transparent air platform.

A multi-connected space-ground network architecture may be created using two transparent air-based platforms (transparent HAP, transparent LAP, or both), which makes sense for serving UEs outside of service regions. While high-altitude platform-based NG-RAN will provide more bandwidth to satisfy targeted throughput needs, low-altitude platform-based NG-RAN with reasonably low latency may be employed to accommodate latency-sensitive traffic.

be supported by the current 5G radio network architecture, although essential upgrades for the NR-Uu interface, NG interface, or F1 interface protocol timings are required.

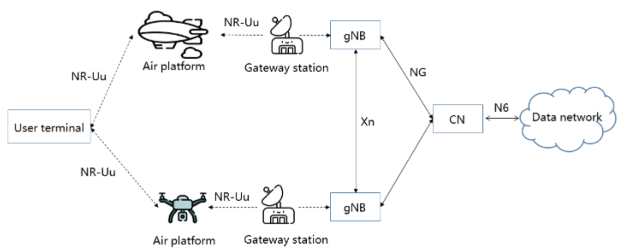

Fig. 3. Multi-connected space-ground integrated network architecture based on transparent air platform

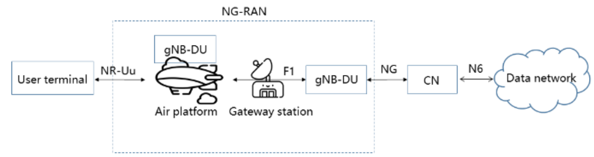

Fig. 5. Single-connected space-ground integrated network architecture based on regenerative air platform supporting gNB-DU processing capabilities

2) Space-Ground Integrated Network Architecture Based on Regenerative Payloads

The space-ground integrated network architecture based on regenerative payloads may take several forms, such as payloads implementing complete gNB functions or gNB distributed unit (gNB-DU) functions, depending on how the payloads implement communication functions. The single-connected space-ground integrated network topologies based on the aforementioned two types of regenerative payloads are provided by the reference designs B-1 and B-2.

a) Reference architecture B-1: Single-connected space-ground integrated network architecture based on regenerative air platform supporting gNB processing capabilities.

In this design, the air platform is loaded with the full capability of the gNB, and messages on the NG interface at the gNB and CN are transparently conveyed on the interface of the air platform.

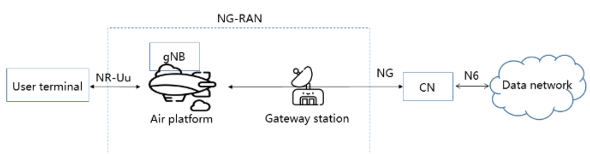

Fig. 4. Single-connected space-ground integrated network architecture based on regenerative air platform supporting gNB processing capabilities

b) Reference architecture B-2: Single-connected space-ground integrated network architecture based on regenerative air platform supporting gNB-DU processing capabilities.

The gNB centralized unit (gNB-CU) is situated on the ground and transmits the F1 interface signal on the feeder connection between the payload and the gateway station for regenerative payloads supporting the gNB-DU processing function. It is necessary to take into account the expansion of a few timers for the F1 interface with this design. This design can

c) Reference architecture B-3: Multi-connected space-ground integrated network architecture based on regenerative air platform supporting gNB processing capabilities.

User terminals in non-service zones may get services by combining two regenerative air platforms (a mix of both HAP or LAP) that enable gNB processing functionalities and creating an inter-air platform connection between them. In Fig. 6, the precise architecture is shown.

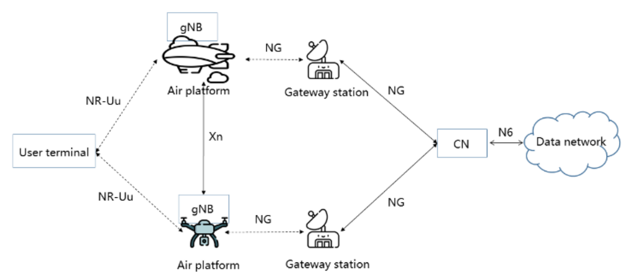

Fig. 6. Multi-connected space-ground integrated network architecture based on regenerative air platform supporting gNB processing capabilities

d) Reference architecture B-4: Multi-connected space-ground integrated network architecture based on regenerative air platform and terrestrial cellular supporting gNB-DU processing capabilities.

Fig. 7 depicts a multi-connectivity combination based on a regenerative air platform that supports cellular NG-RAN and gNB-DU processing capabilities. The architecture is important for giving UEs in underserved regions services.

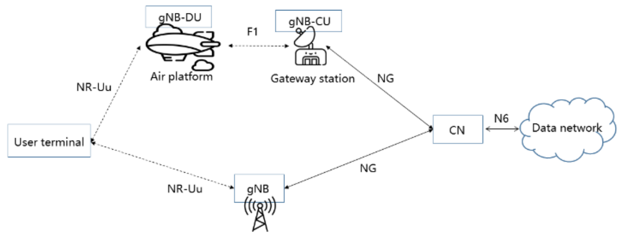

Fig. 7. Multi-connected space-ground integrated network architecture based on regenerative air platform and terrestrial cellular supporting gNB-DU processing capabilities

e) Reference architecture B-5: Multi-connected space-ground integrated network architecture based on regenerative air platform supporting gNB-DU processing capabilities.

An space-ground integrated network architecture with many connections may also be created by combining two regenerative air platforms based on supporting gNB-DU processing capabilities, as illustrated in Fig. 8.

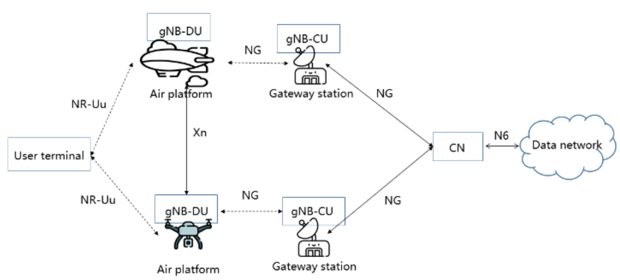

Fig. 8. Multi-connected space-ground integrated network architecture based on regenerative air platform supporting gNB-DU processing capabilities

B. Space-Ground Integrated Network Architecture Based on Distributed Core Network

In order to achieve the objectives of streamlining the signaling interaction process and lowering data transmission latency, we split the RAN functions in this section in a fine-grained manner based on the service-oriented principle, combine them with some core network functions, and simplify the interfaces between network elements [21]. By combining the core access and mobility management functions (AMF) with the mobility management and access control-related functions in CU-CP to form a new AMF network element and creating the functions related to radio resource management and radio bearer control in CU-CP into a new network element named radio resource and bearer management control (RRBMCF), we improve on the original 5G architecture. Packet data unit and Sessions (PDUSF) are used to handle this (SDUs).

1) Core Network Deployment Solutions for Super Wireless Broadband Communication Scenarios

Ultra-high-resolution video, virtual reality, voice communications, and augmented reality are a few typical uses for super wireless broadband communications. Broadband and low latency are needed in these settings. AMF, SMF, UPF, RRBMCF, and PDUSF may all be placed on the air platform to accommodate this. Access and mobility management is handled by AMF, session management is handled by SMF, user plane forwarding is handled by UPF, wireless resource management and bearer control is handled by RRBMCF, and packet data units and sessions are handled by PDUSF. It is necessary to adapt the fundamental algorithms of the aforementioned network components to the specifics of the air platform. The control signals only has to be delivered to the air platform during the switching process rather than to the ground, which shortens the switching time and preserves service continuity. Additionally, choices on routing may be taken by the SMF deployed on the air platform or sent directly to the UPF situated on the same air platform. Delays in forwarding and processing may be minimized in this fashion.

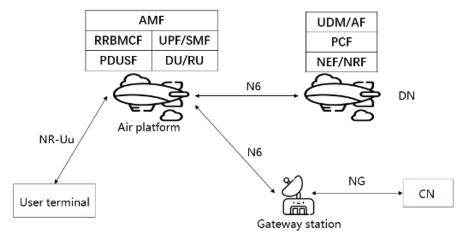

Fig. 9. Core network deployment solutions for super wireless broadband communication scenarios

2) Core Network Deployment Solutions for Large-Scale IoT Scenarios

Smart cities, smart homes, distant area coverage, ecological remote sensing and navigation are a few examples of typical large-scale IoT applications. High connection density, huge data processing and transmission capabilities, and the capacity to handle a variety of unique applications are all necessary in these cases. In this case, high-altitude platforms may be used to install MEC, AMF, UPF, SMF, RRBMCF, and PDUSF, while low-altitude platforms can be used to deploy DU and RU's access network functions for flexible access to IoT terminals. Since MEC is installed on a high-altitude platform, large amounts of data produced by large IoT terminals can be processed there instead of being transmitted to the ground, lowering bandwidth and backhaul costs while enhancing the capacity for processing and transmitting massive amounts of data, increasing the number of connections, and improving the quality of service [22, 23]. Additionally, the functionalities of the network pieces may be altered in our suggested design in accordance with the specifics of various application cases. In order to prevent signaling storms and minimize switching costs in large-scale IoT, unique mobility management techniques may be created for AMF.

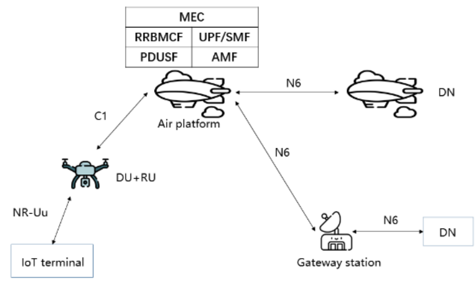

Fig. 10. Core network deployment solutions for large-scale IoT scenarios

IV. Conclusion

The investigation of the space-ground integrated network architecture is the main topic of this research. We examine the usual application scenarios and specifications for 6G space-ground integrated network features and suggest space-ground integrated network architectures based on dispersed core networks and ground-centralized core networks. For the former, all core network operations are located on the ground and the over-the-air platform is just supplied with access network services. Data forwarding delay and control message transmission delay are both quite significant since all user traffic data and control messages must be routed back to the ground for processing. When it comes to the latter, some of the core network functions are installed in the air nodes, the edge core network is built closer to the RAN, and the cloud core network is built on the ground. This can significantly decrease the service transmission delay and increase the robustness of the system. The cloud core network installed at the ground node is primarily in charge of resource scheduling, policy orchestration, complex signaling processing, and deep message processing. The edge core network installed at the space node is a functional entity with minimal cohesion and no obvious network element boundary. With the network function reconfiguration to satisfy changing application scenario needs and network operation requirements, the dynamic deployment of key network functions is made possible.

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