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DEPARTMENT: INTERNET OF THINGS, PEOPLE, AND PROCESSES

The Sky is the Edge—Toward Mobile Coverage From the Sky

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Witnessing the recent rapid 5G commercialization with multiple advantages in terms of high throughput, low latency, great serviceability, and extreme density, people look forward to seeing a new innovation in the next-generation mobile networks–6G. As a demand response, 6G additionally integrates artificial intelligence into all operational perspectives of the network while incorporating new infrastructure to support service coverability to yet underserved areas. Since the artificial intelligence in 6G has been discussed significantly in the literature, this article, on the other hand, provides major insights of the 6G aerial radio access network (ARAN) as an expansion of mobile coverage from the sky. First, we highlight the distinct attributes of ARAN by constructing a comparative taxonomy among mobile access infrastructures. Consequently, comprehensive ARAN architecture, reference model, and potential technologies are analyzed. Next, current research trends are investigated followed by future challenge discussions.

The research maturity and rapid commercialization of the fifth generation (5G) have recently exposed multiple advantages for emerging application scenarios. Three major service categories such as enhanced mobile broadband, ultrareliable, and low-latency communications, and massive machine type communications have benefited from high throughput, low latency, great serviceability, and extreme density performance of the 5G networks. Although 5G has yielded an impressive success at improving service experience for a massive number of end-users, we have never stopped our efforts in further increasing and expanding its capabilities toward an innovative next-generation network: 6G. Based on inherited achievements from the predecessor, the 6G networks are expected to target three foundational directions including *i*) ultrareal service experience, *ii*) intelligent networking and service provisioning platform, and *iii*) global mobile Internet coverability.[1] While the first two directions can be seen as evolutionary strategies continuing current advanced features of the 5G networks as revealed from 6G literature review,[2] the last direction is proposed to handle recently emerging paradigms such as a new one–multialtitude airborne transportation and the missing one–underserved/isolated terrestrial areas.

As a demand response, 6G introduces the aerial radio access network (ARAN) to complement its access infrastructure for the aforementioned paradigms.[3] The ARAN involves airborne objects equipped with mobile transceiver antennas, a.k.a. aerial base stations (ABSs), to provide a radio access medium from the sky to end-users for Internet service connectivity. Typical ABS consists of the low-altitude platforms (LAPs) and the high-altitude platforms (HAPs) such as drones, unmanned aerial vehicles (UAVs),

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balloons, and flights. In ARAN, the fronthaul links between ABSs and end- users are designed to adopt common modulation schemes at the frequency spectrum assigned for mobile communications. Meanwhile, the backhaul links wirelessly interconnect the ABSs to the core networks via either satellite constellation and ground station or terrestrial macro base stations. The completely wireless infrastructure design provides ARAN with flexible deployment and quick adaptation abilities to serve diverse application paradigms such as search and rescue, aerial data harvesting, and remote/isolated areas that are difficult to be satisfactory by existing terrestrial infrastructure.

However, current proposals for aerial access have only focused on partially accommodating specific applications; there is no complete and systematical design. For instance, swarms of drones/UAVs are widely utilized to temporarily assist communication relay, traffic alleviation, and sensory data harvesting in terrestrial mobile networks such as postdisaster communication, aerial surveillance, and aerial crop monitoring systems. While satellite constellation has been exploited to provide users with expensive and limited Internet access in underserved areas over the past decades. Fortunately, OneWeb (https://www.oneweb.world) and Startlink (https://www.starlink.com), two ambitious airborne mobile broadband projects, have been recently launching thousands of miniaturized satellites forming dense constellations at low Earth orbit (LEO) altitude to deliver Internet across the globe cheaper and faster. Nevertheless, it is necessary to investigate these diverse and separate proposals and gather them into one comprehensive architecture, i.e., ARAN.

Inspired from the above observation, this article aims to clarify ARAN from multiple perspectives. First, we position ARAN in the 6G context through a comparative taxonomy among existing mobile access infrastructures within three categories: coverage area, assisted technology, and architectural design. Consequently, the multitier architecture and reference model are thoroughly analyzed for a comprehensive overview of ARAN with distinguished features. Then, potential technologies are deeply discussed to concretize the advanced features of ARAN. Finally, we provide statistical insights of recent ARAN research outcomes and draw future challenges.

AERIAL ACCESS INFRASTRUCTURE

To be ready for a broad range of emerging paradigms, one of the efficient strategies in 6G is to expand communication vertically and horizontally forming a ubiquitous 3-D mobile coverage.[4] Here, we investigate technical aspects of the additional aerial access infrastructure with the aim of efficiently accommodating emerging new aerial 6G communications.

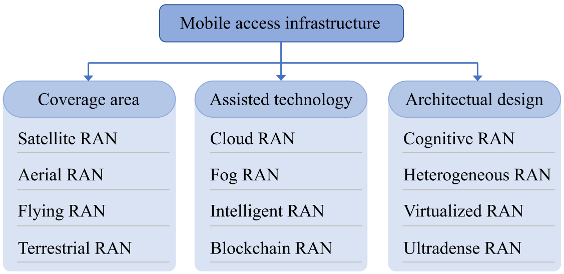


FIGURE 1. Radio access network taxonomy from multiple perspectives.

ARAN Positioning

As the frontier of the network to interact with end-users, radio access networks (RANs) play a critical role in all mobile generations. Involving in the whole system maturity, mobile access infrastructure flexibly integrates recent advanced technologies and design concepts into its organization. Accordingly, existing mobile access infrastructure can be classified into three categories: architectural design, assisted technology, and coverage area, as demonstrated in Figure 1.

- Architectural design: This category regards technical factors in the RAN design. In particular, the cognitive RAN improves frequency spectrum efficiency through vacant licensed/unlicensed spectrum sensing mechanisms, the heterogeneous RAN jointly utilizes various access technologies for diverse users and services. Meanwhile, the virtualized RAN softwarizes network functions and operations in a serverless manner, and the ultradense RAN exploits access point implementation density to serve a massive number of users concurrently.
- Assisted technology: This category represents a utilization of advanced technologies to facilitate user services with high performance. For instance, the cloud RAN introduces a high in-network computing capability at back-haul infrastructure for heavy offloading traffic, while the fog RAN provides low-latency response to user requests at the edge with localization. From other perspectives, the blockchain RAN ensures a secure environment for sensitive user activities and data go through, while the intelligent RAN

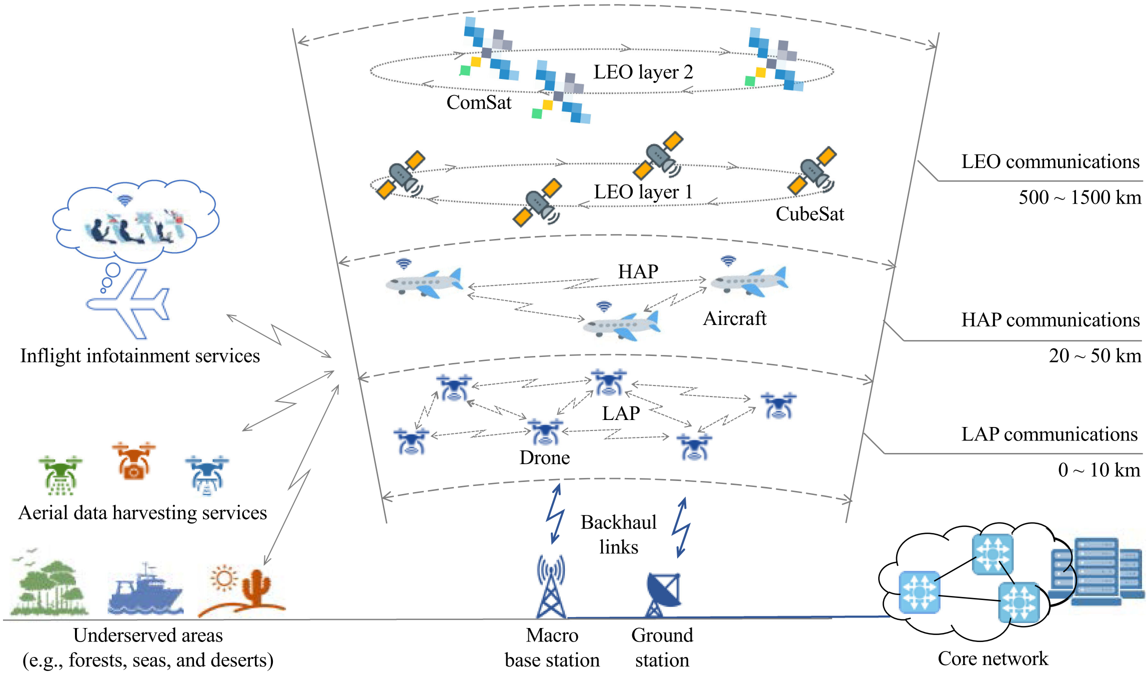


FIGURE 2. Overview of aerial radio access networks: Architecture and new emerging services.

can learn user behaviors for service response personality by integrating recent advanced artificial intelligent (AI) technology.

- Coverage area: This category considers RAN based on the coverage space. One of the most well-known systems in this category is the terrestrial RAN. The terrestrial RAN includes various mobile and wireless access infrastructures to provide user services on the ground such as cellular, radio, and WiFi systems. On the contrary, the satellite RAN incorporates satellite constellations into the access infrastructure to offer end-users Internet connection via satellite terminal stations on the global wide. In the middle, the flying RAN defines access medium encompassed by LAPs equipped with mobile transceiver antennas to expand service coverage of the terrestrial infrastructure. On the other hand, the aerial RAN (i.e., ARAN), as aforementioned, stands for a unified architecture harmonizing multitier aerial access infrastructures to support aerial users and users at underserved areas.

The ARANs are distinguished from existing RANs in four areas. First, ARAN supplements existing access infrastructure with additional physical components (e.g., LAPs, HAPs, CubeSats, and ComSats). This complement is indispensable in the 6G context, where new application scenarios are increasingly emerging but current infrastructures fail to support them with high performance and stable serviceability. Second, ARAN has a complete RAN architecture consisting of mobile access points (i.e., ABSs) at the fronthaul and traffic distribution components at the backhaul to interconnect with the core networks. The complete architecture allows ARAN to operate independently of other access infrastructures. Third, ARAN is definitely compatible with additional assisted technologies (e.g., cloudization, AI, and blockchain) and hybrid design concepts (e.g., cognitive radio, heterogeneous access, network virtualization, and access densification). Fourth, ARAN is a complete wireless architecture; in other words, the network components are dynamically interconnected via time-varying wireless links. This property helps ARAN with flexibility and quick adaptability to environmental changes and service requirements.

Multitier ARAN Architecture

As the aerial coverage is characterized by a 3-D mobile space wherein users are distributed discretely, ARAN architecture must adopt a multitier networking design to flexibly direct its communication resources for targeted narrow service areas. Figure 2 illustrates an overview of ARANs in the context of a complete user-core path. In detail, there are three tiers constituting

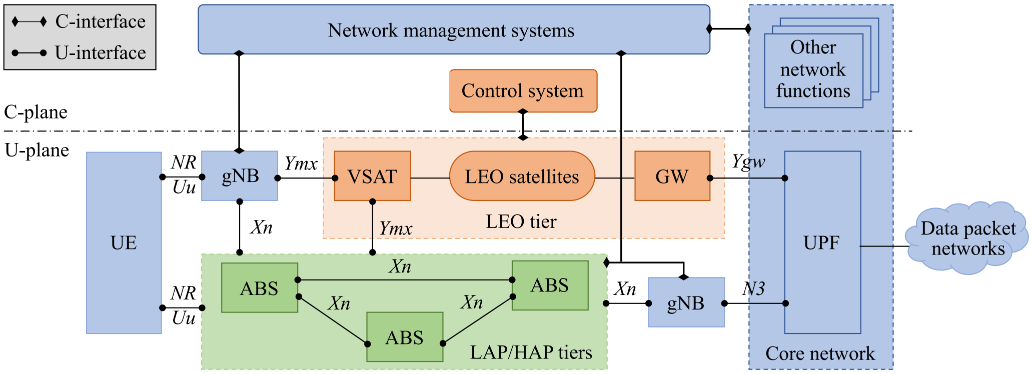


FIGURE 3. ARAN reference model adopting the 3GPP 5G Release 16 standards.

a typical ARAN; those are LAP communications at the altitude of 0–10 Km, HAP communications at the altitude of 20–50 Km, and LEO communications at the altitude of 500–1500 Km above the sea level.[3]

In charge of front-end interfacing directly to end-users, LAP communication tier establishes swarms of ABSs (e.g., drones and UAVs) providing Internet services through wireless transmission technologies such as 5G new radio and WiFi in the fronthaul. Depending on application scenarios, ABS swarms can be organized following different topologies including mesh, star, bus, chain, and hierarchical architectures. In all the collaboration topologies, ARAN defines several specific ABSs acting as gateways to maintain connection on the backhaul links to the core networks. There are two redundant backhaul links: one is via upper tiers of the ARAN (e.g., LEO satellites–ground station–core) and the other is via macro base stations of the terrestrial mobile networks (e.g., 5G gNB).

In the middle of the ARAN, HAP communication tier develops a stable mesh of HAPs (e.g., aircraft and balloon) for an ultrawide coverage area. In the fronthaul, the HAP mesh provides either direct access interface for end-users (here, HAPs are considered as ABSs) or relay connection for LAP tiers to the core networks. In the backhaul, HAP communication develops two redundant links to the core networks as the LAP tier does. As specified by the International Telecommunication Union (ITU) organization, 2 GHz, 6 GHz, 27/31 GHz, and 47/48 GHz bands are assigned for HAP communications.[5] Recently, some industries have successfully launched pilot projects to offer Internet connections to rural and remote areas at the HAP tier such as Loon (https://www.loon.com) and HAPSMobile (https://www.hapsmobile.com).

At the top of ARAN, LEO communication tier consists of multiple miniaturized satellite constellations (e.g., CubeSats and ComSats) orbiting at LEO altitude. In particular, CubeSat deployment is designed for low-latency broadband Internet satellite (tens-of-ms latency at Mbps data rate) while ComSats aim at wide coverage with high serviceability, compared to other satellite classes.[6] Different from two lower tiers, LEO communications typically provide Internet service to end-users as well as LAP/HAP gateways via satellite terminals (e.g., very small aperture terminals (VSATs)) instead of a direct access. On the opposite side, all LEO satellites can connect to the core networks through dedicated ground stations. Ku, Ka, and V bands are widely utilized on bidirectional satellite links as recommended by the ITU. Recent years have witnessed emerging LEO satellite projects such as Starlink, OneWeb, and Telesat with thousands-of-satellite constellation launches.

Reference Model

The reference model of ARAN is proposed by jointly considering the 5G Release 16[7] and the satellite terrestrial integrated network (STIN)[8] standardized by the third Generation Partnership Project (3GPP) organization and European Telecommunications Standards Institute (ETSI), respectively. Figure 3 shows the details of the ARAN reference model. Without loss of generality, the model is designed to be adapted for a complete integration into the recent 5G architecture.

From a functional perspective, it is observed that LAP and HAP tiers share the same set of networking operations; hence, LAPs and HAPs use the same representation–ABSs. Considered as a 5G point of attachment, the ABSs utilize the *Xn* interface for their peer-to-peer communications. While the fronthaul defines *NR Uu* interfaces between ABSs and end-users (UE–user equipment), the backhaul connects ABSs to the core through either 5G gNBs on the *Xn* interface or VSATs on the *Ymx* interface, respectively. In 5G core networks, the user plane function (UPF) acts as a contact point bridging between internal mobile infrastructure and the external networks (e.g., Internet and content providers). It is seen that the LAP/HAP tiers of ARAN are covered by the 3GPP 5G standard model as internal parts using native interfaces; therefore, management protocols and resource orchestration sharing with other 5G network functions are fully supported.[7]

Different from the LAP/HAP tiers, the 3GPP 5G standard model considers the LEO tier as an external system. For that, the ETSI TR 103.611 (V1.1.1) standard[8] defines a seamless integration of satellite systems into existing 5G infrastructure. In particular, the external interface *Ymx* is used for interconnection between VSATs and 5G gNBs at the fronthaul. For the backhaul link, a gateway (GW) of the LEO systems, i.e., the ground station, interacts with the UPF component of the core networks on the *Ygw* interface. Other links among VSATs, LEO satellites, and GWs use internal interfaces specified by satellite standards.

In the control plane, the operational control messages and data packets are delivered on the same interfaces but using different protocols. Meanwhile, in the resource management plane, ARAN reference model mainly follows the 5G management and orchestration (MANO) design, where the networking, computing, storage resources, and functional data are shared, exchanged, and collaborated among 5G network components.[9] The resource management messages are transferred on dedicated channels to/from the MANO systems.

POTENTIAL TECHNOLOGIES

To enable ARAN, several potential technologies are being applied to handle the distinct properties of ARAN architecture, especially the complete wireless infrastructure and various-altitude aerial communication. Potential technologies include energy refills, intelligent beamforming, mobile cloudization, and traffic engineering. The details are described below.

Energy Refills

The most important concern in ARAN is to replenish energy for airborne components efficiently while retaining the system stability. Although there are a variety of recharging solutions proposed in the literature, it is widely acknowledged that radio frequency (RF) wireless charging and solar energy harvesting (EH) techniques[10] are particularly appropriate owing to the ARAN features.

RF wireless charging is a far-field charging method that exploits electromagnetic radiation to transfer energy from the charging point to the receivers. As the RF wireless charging method can operate over a long distance, it exposes (*i*) the dynamicity allowing both charging points and receivers can move around during the charging time and (*ii*) the simultaneity implying multiple receivers can be powered at the same time by one charging point, even under a non-line-of-sight transmission. Furthermore, to improve the charging efficiency, directional antennas with intelligent beamforming technologies are implemented at the charging point to concentrate energy toward the targeted receivers. These advantages confirm the RF wireless charging method, an excellent candidate for energy refills in ARAN. Owing to the great potential in many-field applications, RF wireless charging method has recently attracted various companies to develop and launch trial products and services such as WiTricity(https://witricity.com), Ossia(https://www.ossia.com), and Energous Corporation (https://www.energous.com).

On the other hand, solar EH is a method that use energy-stored cells (e.g., photovoltaic) to capture solar energy radiated from the sun, then convert the heat to electrical energy. Comparing to other sources (e.g., thermal, wind, and kinetic), solar energy has been widely exploited to energize devices in various real-world applications because of the energy efficiency and reliability. Especially, the effectiveness of integrating solar energy harvester into power system of aerial devices have been proved in many success stories such asNASA'sPathfinder(https://mars.nasa.gov/MPF/index1.html), Indian MARAAL (https://www.iitk.ac.in/aero/maraal), and PHASA-35 (https://www.baesystems.com/en/product/phasa-35). Obviously, solar-powered capability provides airborne components with the potential to fly for days and even forever during their operational life cycles. Finally yet importantly, a hybrid solution between RF wireless charging and solar EH is definitely applicable for energy refills in ARAN.

Intelligent Beamforming

With a note that end-user locations disperse geographically in a wide 3-D space, efficiently configuring communication resources to focus on desired end-user(s) is critical for ARAN communication. In this circumstance, intelligent beamforming is a potential technology to resolve the requirement.[11] Here, the distribution of end-user locations in both time and space domains is learnt based on user behaviors and traffic changes. Consequently, communication requirements of end-user(s) are predicted to drive radio resource optimization. Beam parameters such as activation state, beam width, transmit power, azimuth, and down-tilt are configured automatically to obtain an optimal performance at certain narrow areas.

In addition, the utilization of dense distributed antenna array can significantly empower the intelligent beamforming capability with flexible transmit directions on the surface of airborne components.[12] Iteratively, the joint optimization model of antenna elements' parameters and beam configurations are updated to yield dynamic global adjustment for a maximal serviceability. As a result, long-range low-power wireless communication is natively featured on ARAN fronthaul.

Mobile Cloudization

In-network computing service is a must-have capability that was already specified as a native function in the recent 3GPP 5G standards[7]; therefore, ARAN cannot be an exception. Moreover, the in-network computing service is especially critical in ARAN to reduce the burdens of back-haul traffic over multihop wireless transmission. For that, mobile cloudization[9] is the key enabler, which aggregates computing resources from all networking components on a virtual pool to optimally allocate these resources on demand. Implemented on the MANO system, collaboration between virtual infrastructure managers and the central orchestrator tailors resources as requested by functional network operations as well as offloading services from users. The flexibility of mobile cloudization optimally exploits distributed computing resources of airborne components for advanced technologies such as reinforcement learning and network slicing within a prompt response. As user requirements prioritize whether performance or latency, appropriate computing tiers (e.g., edge, fog, and cloud) can offer in-network computing services with satisfaction, accordingly.

Traffic Engineering

As ARAN is constituted by mesh communication among airborne components and hierarchical communication among tiers, the complexity of such an architecture makes traffic engineering essential to be optimized globally. While network softwarization brings software-defined networking ability for ARAN to abstract the physical infrastructure, the gathered network knowledge at the central controller is a great source to be exploited for traffic patternization and prediction.[13] According to the traffic pattern, volume, and location, whether intratier (mesh connection) or intertier (hierarchical connection) traffic engineering mechanisms are implemented. To improve the system stability and serviceability in ARAN, load balancing and redundancy are typically setup as the objectives to optimize routing decision with latency commitments. A good traffic engineering mechanism facilitates user data delivery with not only reliability but also security and privacy against a wide variety of threats.

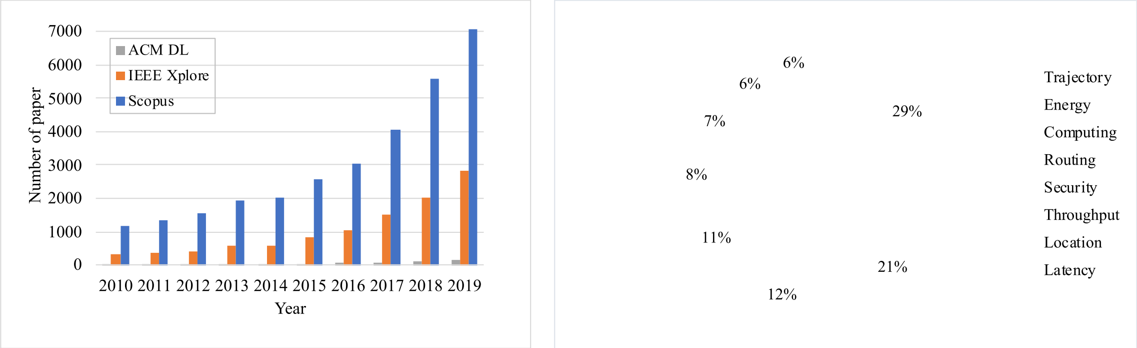
FUTURE RESEARCH

For ARAN maturity, a comprehensive knowledge of current trends and open challenges is necessary to direct the future research.

Current Trends

To have a historical view of ARAN attraction in the research community, we investigated related studies in three major publication databases: the Association for Computing Machinery Digital Library (ACM DL–https://dl.acm.org), the Institute of Electrical and Electronics Engineers Xplore (IEEE Xplore–https://ieeexplore.ieee.org), and the Elsevier Scopus (Scopus–https://www.scopus.com). The investigation was performed on September 30, 2020. To derive the statistical information from the databases, we configured the query syntax on *Document title* using keyword set of {*drone, unmanned aerial vehicle, UAV, low altitude platform, LAP, high altitude platform, HAP, LEO satellite, CubeSat*} during the publication date from 1/1/2010 to 9/30/2020. Results are demonstrated in Figure 4. Based on the given syntax configuration, the ACM DL, IEEE Xplore, and Scopus returned 521, 12153, and 34726 appropriate results, respectively. Since the year 2020 is not complete, Figure 4(a) plots the observation in recent 10 years (2010, 2019) with a note that there are 4401 publications from January to September in 2020. According to the ACM DL database, the number of publications increases 6.03 times after 10 years, from 1172 publications in 2010 to 7072 publications in 2019 within an exponential trending. The statistical insight shows an expectation that ARAN is retaining attractive megatrend to research community in the next years.

To discover recent research objectives in ARAN, individual keyword (and its variables) in the set {*trajectory, energy, computing, routing, security, throughput, location, latency*} is iteratively used to filter the observed results above. The distribution of research objectives is plotted in Figure 4(b). In particular, *Trajectory* topic dominates the publications with approximate 29% while the second place is for *Energy* topic with 21%. Here, *Trajectory* stands for mobility



(a) (b)

FIGURE 4. Research trends in ARAN-related publications from 2010 to September 30, 2020.

and topology designs and *Energy* regards energy consumption and recharging scheme solutions. Together, the *Trajectory* and *Energy* concerns attract the most attention from the research community wherein a half of the studies have been dedicated to resolve their issues. Next, *Computing* and *Routing* share approximately a quarter of publications with respectively 12% and 11%. These topics represent the mobile cloudization and traffic engineering concerns in ARAN. Finally, *Security*, *Throughput*, *Location*, and *Latency* complete the research attractiveness with 6–8% for each.

Open Challenges

Open challenges derived from the above research trend analyses are discussed to draw the future studies in ARAN. First, although the mobility and flexibility are auspicious capabilities of ARAN, they lead to challenging designs for the network to quickly adapt to the environmental and operational changes. As in an aerial wireless environment, the movement of individual airborne components directly affects communication states of adjacent components as well as the whole network topology. Therefore, optimizing the trajectory is a foundational factor for the ARAN system stability.

Second, energy efficiency must be in the focus because of the battery capacity limitation of airborne components. In particular, several aspects of energy refill techniques can be further improved such as charging distance, charging time, and energy transfer rate. On the other hand, energy consumption in ARAN operation, communication, and computation should be jointly minimized when optimizing the system performance.

Third, computing resource constraints of airborne components limit ARAN's capability to provide high-performance in-network computing services to heavy user applications. Although the mobile cloudization introduces a promising platform to optimize computing resource abstraction and orchestration, improving the global cloudization mechanism subject to various environmental factors and diverse user requirements still remains challenges to resolve.

Fourth, since ARAN operates in multiple altitudes to support different classes of user services, multiobjective communications should be satisfied to flexibly allow various requirements. To this end, reliable/low-latency and long-range/low-power properties are considered two critical metric pairs of an efficient traffic engineering mechanism for high serviceability in ARAN. The former is necessary to support mobile broadband users with high quality-of-service while the latter is vital for IoT sensory data harvesting applications. Nevertheless, long transmission distance in the fronthaul links is one of the most difficult obstacles toward user satisfaction in ARAN.

Fifth, as ARAN architecture is built from a grid of wireless link interconnections, this open infrastructure is vulnerable to a variety of common cyberattacks such as packet sniffing, signal jamming, man-in-the-middle, and denial-of- service. In addition, multitier communications lead to multiple protocols used in ARAN; hence, it is highly possible to be exploited by fault injection attacks. On the other hand, user data harvesting and offloading traffic are recommended to use in-network computing service in ARAN to process. In this circumstance, privacy and integrity are the most concerns to protect essential user information.

Sixth, owing to the distinct characteristics of ARAN, existing evaluation frameworks may not accurately configure multialtitude aerial wireless environment as in certain application scenarios. In particular, such a simulation-based evaluation typically simplifies environmental changes as well as mechanical constraints of airborne components resulting in reality reduction. Therefore, a dedicated ARAN emulation platform is essential for researchers to precisely validate their proposed solutions regarding performance metrics and applicability evaluation.

CONCLUSION

In this article, we provided a comprehensive overview of ARAN in the context of 6G development. Major aspects of the ARAN were discussed including the network identification, system architecture, reference model, potential technologies, emerging trends, and future research. As the ARAN is a vital complement in 6G access infrastructure, this article is considered to be a convenient facility for the readers to quickly touch on current states and future visions of ARAN. Furthermore, through the detailed technical investigation as well as pros and cons analyses, this article is expected to engage multidisciplinary research to integrate and exploit the ARAN in various fields.

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