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ANALYSIS OF THE MAIN REQUIREMENTS FOR 5G/6G NETWORKS

Abstract. Not long ago, the fifth-generation (5G) telecommunications standard was introduced, and active development is already underway for the sixth-generation (6G) standard. **The subject of the study** is the key characteristics and requirements of 5G/6G networks. **The purpose of the research** is to conduct a comparative analysis of the main features of communication networks built using 5G and 6G technologies. **The following results have been obtained.** Several key aspects of research directions and new technologies for designing 6G radio access networks, which meet the requirements of future wireless communication systems, have been examined. The main characteristics of terrestrial communication networks that must meet the declared requirements for 6G applications are analyzed in detail. Requirements for fifth-generation communication networks are identified, including distributed processing and analysis of large data volumes combined with content caching and delivery to mobile devices, support for ultra-low latency, scalability of arrays, and mobile communication management. These are compared with the projected features of sixth-generation communication networks. **Conclusions.** The transition to 6G will inevitably intensify the requirements for fifth-generation communication networks and introduce new ones to ensure the operation of systems demanding ultra-high reliability, high availability, and ultra-low response times.

Keywords: telecommunication network, communication network, terrestrial network, aerial network, radio access network, 5G standard, 6G standard, SDN network.

Introduction

This study examines the architecture of a terrestrial network capable of handling traffic from all levels, including dynamic terrestrial and flying networks. The terrestrial network, which serves as the core of the system, is designed with the requirements of 6G applications in mind [1]. The key features of 6G Radio Access Networks (RAN) focus on creating ultra-dense, heterogeneous, intelligent, and adaptive networks while improving overall network energy efficiency [2]. Integrating terrestrial and flying networks is one of the most complex challenges [3]. The network core is considered using the Software-Defined Networking (SDN) paradigm [4]. The core incorporates SDN multi-controller structures and OpenFlow switches [5]. The system must ensure interaction between terrestrial and flying networks, meeting 6G requirements. Integrated flying networks are key components of 6G networks [6]. These networks are expected to play a significant role in fulfilling the 6G wireless communication requirements. Moreover, their integration with terrestrial networks is highly demanded. However, such infrastructure faces numerous challenges, including the interaction of heterogeneous channels, processing vast amounts of traffic, and meeting security requirements [7]. This paper outlines the essential specifications supported by inter-layer communication technologies, primary use cases, and key performance indicators (KPIs) for various network levels. The architecture of the terrestrial network processes all types of traffic [8]. Numerical modeling and simulation using high-level software continuously support hardware prototyping within such a network model, helping to predict performance and interpret results [9]. Additionally, the development of the model includes determining precise technical specifications, such as power, bandwidth, and interfaces required by devices and equipment. These include radio access modules, high-performance edge computing nodes, SDN controllers, OpenFlow switches, and network interfaces [10]. The characteristics of all key network devices and elements are also defined.

Objective of the Study: To conduct a comparative analysis of the main characteristics of communication networks built using 5G and 6G technologies.

1. Radio Access Networks

The design of 6G Radio Access Networks (RAN) encompasses several key aspects and technologies that align with the requirements of future wireless communication systems. While 6G standards are not yet fully defined, several research directions and emerging technologies for designing 6G RAN have already been identified. Below are some of the key aspects:

Spectrum Utilization: 6G RAN is expected to utilize a broad range of frequency bands, including higher-frequency ranges such as terahertz (THz) and sub-terahertz (sub-THz) frequencies. These bands provide extensive resources for high-speed data transmission and massive device connectivity. Developing efficient spectrum utilization methods, such as advanced beamforming, carrier aggregation, and dynamic spectrum sharing, will be critical to maximizing 6G RAN capacity and efficiency.

Massive MIMO and Beamforming: Massive Multiple-Input Multiple-Output (MIMO) technology, combined with advanced beamforming techniques, will be a core component of 6G RAN. Massive MIMO involves deploying a large number of antennas on both base stations and user devices, enabling spatial multiplexing and enhanced spectral efficiency. Beamforming focuses radio signals toward specific users, improving coverage, capacity, and signal quality. These technologies will be further advanced in 6G to support even larger antenna arrays and more complex beamforming algorithms.

Ultra-Dense Networks: 6G RAN will incorporate ultra-dense networks, where base stations and access points are densely and systematically deployed. This network densification will increase capacity, coverage, and overall system performance. Advanced technologies such as network densification, small cell deployment, and dynamic base station coordination will be employed to mitigate interference and optimize resource utilization.

Heterogeneous Networks: 6G RAN will integrate various wireless access technologies, including traditional cellular networks, satellite communications, and new wireless technologies. This integration will enable seamless connectivity, continuous coverage, and efficient resource allocation. 6G RAN design will focus on developing protocols and algorithms to support seamless handovers, network selection, and efficient traffic routing between diverse transmission devices. This will facilitate the full integration of terrestrial and aerial communication layers. Deploying new technologies, including artificial intelligence (AI), distributed edge computing, and SDN, will help achieve these goals.

Intelligent and Adaptive Networks: 6G RAN will leverage artificial intelligence (AI) and machine learning (ML) techniques to create more intelligent and adaptive networks. AI/ML algorithms can be used for proactive network optimization, predictive resource allocation, dynamic spectrum management, interference minimization, and self-healing. These intelligent and adaptive features will allow the network to adjust to changing conditions, optimize performance, and provide personalized services based on user demands and network status.

Energy Efficiency: With energy consumption becoming a critical concern, 6G RAN will place significant emphasis on improving energy efficiency. Design approaches such as energy-efficient hardware, power management mechanisms, and the development of intelligent algorithms for transitioning to sleep modes will be adopted to minimize energy consumption while maintaining performance.

2. Terrestrial Network

The terrestrial network is a ground-based communication network that must meet the requirements set for 6G applications. The terrestrial layer of 6G acts as the heart of the system. All traffic from all levels is transmitted through the terrestrial network, which imposes significant limitations on its design. The overall structure of the terrestrial layer of such a system consists of two main parts: the Radio Access Network (RAN) and the Network Core.

RAN (Radio Access Network): This consists of the radio communication technologies and solutions deployed to provide ground-based communication services and support ground users.

Network Core: It manages the traffic of radio access networks and other levels to meet the requirements of 6G systems. The core network will be built using the Software-Defined Networking (SDN) paradigm. SDN with multiple controllers will be used to manage the vast amounts of network traffic. A special algorithm will need to be implemented on SDN controllers to address the placement and distribution of these controllers. The SDN network core should have the following characteristics.

Network Programmability: The SDN network core for 6G networks is expected to offer a high level of network programmability. This will allow network operators to dynamically configure and manage network resources, services, and protocols through SDN APIs. Such programmability will enable flexible and efficient resource distribution according to the constantly changing demands and traffic characteristics, supporting heterogeneous traffic from various applications and communication channels.

Virtualization and Orchestration: The SDN network for 6G systems will use Network Function Virtualization (NFV) and orchestration methods. An NFV MANO platform will be implemented to realize multiple virtualized network functions. Virtualization allows network functions to be decoupled from hardware and run in a virtual environment. Orchestration refers to the automated coordination and management of virtualized network functions for deployment, scaling, and managing network services. Virtualization and orchestration provide efficient resource utilization, scalability, and flexibility for the network core.

Service-Oriented Architecture (SOA): The 6G systems will use a service-oriented architecture (SOA) for the SDN network core. SOA enables the decomposition of network functions into smaller reusable components (network services). These services can be dynamically combined to create custom network fragments tailored to specific applications or service requirements. SOA promotes flexibility, scalability, and efficient service delivery in the network core.

Network Slicing: Network slicing will be a key feature of the SDN network core for 6G. It will allow the creation of multiple logical networks (slices) on a shared physical infrastructure, each optimized for specific use cases, applications, or service requirements. Network slices ensure individualized resource allocation, guaranteed Quality of Service (QoS), and isolation between different network services, allowing the network core to efficiently support diverse 6G use cases with varying network performance requirements.

Intelligent Resource Management: The SDN network core will include mechanisms for intelligent resource management. These mechanisms will use artificial intelligence (AI) and machine learning (ML) algorithms to optimize resource allocation, traffic routing, and load balancing based on real-time network conditions, user demands, and performance requirements. Intelligent resource management will enhance network efficiency, scalability, and QoS in 6G networks.

Functional Interoperability and Open Interfaces: The SDN network core will use open interfaces and standardized protocols to ensure compatibility between network components, domains, and providers. This will promote seamless interaction between different network elements, support an environment with multiple operators, and foster innovation, allowing third-party applications and services to leverage the capabilities of the network core.

3. Comparison of Requirements for 5G and 6G Communication Networks

In the ITU-R M.2083-0 recommendation, the key design principles for fifth-generation (5G) communication networks are flexibility and diversity to support a wide range of use cases [11]. These requirements vary in importance depending on the specific use case. The general list of existing requirements for 5G networks is shown in Table 1.

Table 1 outlines the following scenarios:

eMBB (enhanced Mobile Broadband): Distributed processing and analysis of large data, along with content caching and delivery to mobile devices.

uRLLC (ultra-Reliable Low Latency Communications): Support for ultra-low latency and scalable arrays.

mMTC (massive Machine-Type Communications): Management of mobile communications.

Table 1 – **Requirements for Fifth-Generation Communication Networks**

Possibility	Requirements	Scenario
Peak data rate over terrestrial channels	20 Gbit/s	eMBB
Peak data rate over radio channels	10 Gbit/s	eMBB
User data rate over terrestrial channels	100 Mbit/s	eMBB
User data rate over radio channels	50 Mbit/s	eMBB
Latency	4 ms 1 ms	eMBB uRLLC
Mobility	500 km/h	eMBB, uRLLC
Density of connections	10^6/ km^2	mMTC
Throughput	10 Mbit/cm^2	eMBB

In Table 1, the requirements for uRLLC networks include latency and mobility. Additionally, the round-trip latency must be imperceptible to humans, with a maximum of 1 ms for applications within the uRLLC group. Furthermore, mobility support must be maintained even at maximum object speeds of 500 km/h. Moreover, communication networks with ultra-low latency require data transmission reliability greater than 99.9999% [11]. Implementing these requirements ensures high reliability and accuracy of real-time data transmission, which is essential for applications in autonomous technology, telemedicine, industrial automation, and more. To build the corresponding level of network infrastructure, advanced technologies such as multi-user MIMO, broader frequency spectra, high-frequency bands, and intelligent optimization of network and device operations must be used. Additionally, new data analytics and processing technologies, as well as artificial intelligence, are needed to handle large volumes of information and make decisions based on the data obtained.

The architecture must be flexible and scalable, consisting of layers that interact with each other through separate network interfaces [11]. There should be control and efficient distribution of network resources. Overall, the implementation of uRLLC services requires a comprehensive approach to the development of network infrastructure and the use of advanced technologies. The transition to 6G strengthens the discussed requirements and introduces new ones (Table 2).

Let's break down the key differences between 5G and 6G technologies:

Table 2 – **Comparison of 5G and 6G**

Parameters	5G	6G
Start of operation	2020	Approximately 2030
Information transfer speed	20 Gb/s	1 Tb/s
Frequency ranges	3 – 300 GHz	1 – 10 THz
Accuracy / error	m - level	cm - level
Coating	2D	3D
Connection density (km^2)	10^3 devices	10^6 devices
Delay (ms)	4 – 5	0.1
Jitter	1 ms	1 μs
Security	Low	High, using block-chain technology
Battery life	Limited by battery size	Unlimited battery life*
Spectral efficiency (Hz)	30	100
Mobility support (vehicle speed)	More than 500 km/h	More than 1000 km/h
Satellite communication	No	Yes

* – zero-power devices and chips with external power supply function are used

Mobility: The maximum allowable speed will increase from 500 km/h to 1000 km/h.

Network latency: End-to-end latency will decrease by a factor of 10.

Throughput: The maximum throughput for 6G will be 1 Tbps, which is 1000 times faster than in 5G.

Energy efficiency and spectrum utilization: Energy efficiency will increase by a factor of 100.

Next, let's focus on reliability, security, and availability in more detail.

Reliability. Reliability refers to the probability that the system will operate without failure over a specific period. As 6G networks will be highly distributed, the main task for ensuring reliability will be organizing effective coordination of computing nodes. To achieve this, appropriate data transmission protocols between network nodes are necessary, as well as a reliable backbone network capable of handling large amounts of traffic generated during data storage and retrieval.

Availability. Availability refers to the probability that the system will be functioning correctly at any given moment. Distributed AI solutions for 6G networks are a promising option to reduce learning time while simultaneously lowering resource consumption, thus enhancing the availability of AI-based systems and services.

Security. Security is the system's ability to protect itself by detecting threats in a timely manner and taking the necessary actions to safeguard services deployed within the system, as well as data exchanged between devices and users. For 6G network services, distributed AI/MN algorithms are necessary for local model training to detect and eliminate threats, ensuring the confidentiality of end-user data. Furthermore, security also refers to the system's ability not to cause harm to human life, the environment, or private property. Since 6G networks will feature use cases where human life may be at risk, such as with autonomous vehicles, the role of AI/MN becomes particularly crucial.

Availability and Reliability. Availability can only be achieved after reliability is ensured. Reliability is the probability that the system is operational overall, while availability refers to the probability that it is operational at a specific moment in time. Availability guarantees that authorized access to the system will not be denied. A major advantage of distributed systems is that the presence of many nodes and communication channels helps prevent failures. Current trends in edge computing research aim to enhance system availability through careful planning of task and data transfers from end devices to edge servers, using mechanisms that make decisions based on network statistics and the computational capabilities of edge servers. Additionally, availability can be increased by reallocating tasks from failed nodes to functioning ones. Since availability and reliability are interrelated, it is important to note that both characteristics need to be balanced against each other, as different systems may require different values for these characteristics.

Conclusions

The article examines key aspects of research directions and new technologies for designing 6G radio access networks that meet the requirements of future wireless communication systems. It provides a detailed analysis of the main characteristics of terrestrial networks that must meet the requirements for 6G applications. The requirements for fifth-generation communication networks have been outlined for the following scenarios: distributed processing and analysis of large data, along with content caching and delivery to mobile devices; support for ultra-low latency and scalable arrays; management of mobile communications. The transition to 6G will inevitably strengthen the requirements for fifth-generation networks and introduce new ones that will ensure the operation of systems requiring ultra-high reliability, high availability, and ultra-low latency.

REFERENCES

1. Allam Z. Future (post-COVID) digital, smart and sustainable cities in the wake of 6G: Digital twins, immersive realities and new urban economies. / Z. Allam, D.S. Jones // Land use policy – 2021. 101, – P. 105201.
2. Ismail, S.F., Kadhim, D.J. Towards 6G Technology: Insights into Resource Management for Cloud RAN Deployment. IoT. 2024. Vol. 6, is. 2. Pp. 409–448. DOI: 10.3390/iot5020020
3. Ye, F., Li, J., Zhu, P., Wang, D., You, X. Intelligent Hierarchical NOMA-Based Network Slicing in Cell-Free RAN for 6G Systems. IEEE Transactions on Wireless Communications. 2024. Vol. 23, is. 5. Pp. 4724–4737. Doi: 10.1109/TWC.2023.3321717
4. Chowdhury, M. Campaign: A Personalized Offloading, Semantic Communication, Latency-aware Resource Slicing and SFC Orchestration for SDN and NFV Empowered 6G Serverless Computing Network. IAENG International Journal of Computer Science. 2024. Vol. 51, is. 10. Pp. 1480–1515. URL: https://www.iaeng.org/journals.html
5. Liotou, E., Alexiou, A., Passas, N., Merakos, L. QoE-centric implementation of SDN platform for Open-Flow-based network path selection. 2021 IEEE International Mediterranean Conference on Communications and Networking, MeditCom 2021. Pp. 234–239. Doi: 10.1109/MeditCom49071.2021.9647453
6. Ahmad, R., Ayyash, M., Salameh, H.B., El-Khazali, R., Eigala, H. Indoor Flying Networks for 6G: Concepts, Challenges, Enabling Technologies, and Opportunities. IEEE Communications Magazine. 2023. Vol. 61, is. 10. Pp. 156–162. Doi: 10.1109/MCOM.009.2200559
7. Ooomar, S.S., El-Haleem, A.M.A., Ibrahim, I.I., Saleh, A.M. Capacity Enhancement of Flying-IRS Assisted 6G THz Network Using Deep Reinforcement Learning. IEEE Access. 2023. Vol.11. Pp. 101616–101629. Doi: 10.1109/ACCESS.2023.3315660
8. Wang, J., Zhou, Y., Wang, B. Design of 6G Space-Ground Integrated Network Architecture Based on Ground Core Network. 2023 International Wireless Communications and Mobile Computing, IWCMC 2023. Pp. 1250–1255. Doi: 10.1109/IWCMC58020.2023.10182977.
9. Ahmadi H. Networked twins and twins of networks: An overview on the relationship between digital twins and 6G / H. Ahmadi, A. Nag, Z. Khar, K. Sayrafian, S. Rahardja // IEEE Communications Standards Magazine, – 2021. № 5(4). – P. 154 – 160.
10. Lu Y., Maharjan, S., Zhang Y. Adaptive edge association for wireless digital twin networks in 6G. IEEE Internet of Things Journal. 2021. Vol. 8, is. 22. Pp. 16219 – 16230. Doi: 10.1109/JIOT.2021.3098508
11. ITU-T Recommendation Y.3104. Architecture of the IMT-2020 network. ITU-T. Geneva. December, 2018.

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Аналіз основних вимог до мереж зв’язку 5G/6G

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Анотація. Предметом дослідження є основні характеристики та вимоги до них у мережах 5G/6G. **Метою** дослідження є проведення порівняльного аналізу основних характеристик мереж зв’язку, побудованих за технологіями та 6G. **Отримані наступні результати**. Розглянуті деякі ключові аспекти напрямів досліджень і нових технологій для проектування мереж радіодоступу 6G, що відповідають вимогам майбутніх систем бездротового зв'язку. Детально розглянуті основні характеристики мережі наземного зв'язку, яка повинна забезпечити для застосунків 6G заявлені вимоги. Виділені вимоги до мереж зв'язку п'ятого покоління для розподіленої обробки та аналізу великих даних разом з кешуванням контенту та доставкою на мобільні пристрої; підтримки наднизької затримки, а також масивів, що масштабуються; управління мобільними комунікаціями. Проведено їх порівняння із плануємими характеристиками мереж зв'язку шостого покоління. **Висновки**. Перехід до 6G у будь-якому разі посилить вимоги до мереж зв'язку п'ятого покоління та додасть нові, що забезпечать функціонування систем, які вимагають надвисокої надійності, високою доступності і наднизького часу відгуку.

Ключові слова: телекомунікаційна мережа, мережа зв’язку, наземна мережа, літаюча мережа, мережа радіодоступу, стандарт 5G, стандарт 5G, мережа SDN.