UDC 621.391 DOI: 10.20535/2411-2976.22025.4-18

PROSPECTIVE RESEARCH DIRECTIONS IN THE ELECTRONIC COMMUNICATIONS INDUSTRY

Serhii O. Kravchuk, Iryna M. Kravchuk

Educational and Research Institute of Telecommunication Systems
Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine

Background. At the present stage, electronic communications must provide: ultra-fast data exchange between production systems, which increases productivity and safety; the use of robotic systems and artificial intelligence to support people in production processes. Reliable electronic communications ensure the security of industrial networks and personal data; intelligent factories with network sensors and automated data processing systems. In this context, new challenges are facing electronic communications and, accordingly, new problems are identified, the solution of which requires conducting promising scientific research.

Objective. The purpose of this work is to generalise and highlight the key areas of development of electronic communications, which determine the current and future state of the industry. It is aimed at outlining scientific challenges and prospects associated with the digitalisation of society, the growth of demand for fast, reliable and secure data transmission.

Methods. Analysis of factors and technologies that influence the growth of needs for the further development of electronic communications, the quality of telecommunications services in fifth and next generation networks, the introduction of new types of electronic communications and their integration with advanced information technologies.

Results. The presented research directions determine the future of electronic communications. Research in these areas will ensure the sustainable development of the industry, taking into account the growing needs of modern society in fast, secure and reliable data transmission technologies.

Conclusions. The main goal of the 6G direction and future generations of networks is to create ultra-fast, ultra-reliable and intelligent networks capable of supporting new types of services and applications, from autonomous control and remote medicine to full-scale multimedia communications. The direction of quantum communications is a revolutionary direction that promises to ensure absolute security of information transmission and open up new opportunities for communication. The direction of IoT scaling is a key direction that determines the future of many communication technologies. The research area that includes artificial intelligence (AI) and machine learning (ML) calls for further integration of AI and ML into all aspects of electronic communications, leading to smarter, more efficient and secure networks. Security and privacy in electronic communications is a dynamic area that is constantly evolving due to the growth of cyber threats and technological advancements. Edge and Fog Computing are key technologies for the future of electronic communications, and their development requires an interdisciplinary approach that combines computer science, telecommunications, AI and IoT. Research in the field of NFV and SDN is necessary to improve the performance, automation and security of networks. They play a key role in the future of 5G/6G, cloud computing, IoT and industrial networks. Green communications is an important research area that aims to improve the energy efficiency and sustainability of telecommunications networks. Networks for critical applications are a key element of modern infrastructures, and their development requires an interdisciplinary approach that combines telecommunications, cybersecurity, artificial intelligence and other fields. Holographic and tactile communication interaction technologies will become the basis of future digital communications, changing the way people and machines interact.

Keywords: *6G; Quantum communications; Green Communications; Security and privacy; Internet of Things; Artificial Intelligence; Deep Space; network functions virtualisation; Mission-Critical Networks; Holographic and tactile communications.*

I. INTRODUCTION

The field of electronic communications continues to develop rapidly, driven by the ever-increasing demand for speed, reliability, and security of data transmission, as well as the integration of new technologies [1]-[7]. It is particularly relevant to identify key areas for further research that will contribute to the development of electronic communications in the context of society's digitalisation.

It should be noted that informatisation was the first step that created the basis for the development of society through the introduction of information technologies, and digitalisation is the next step that uses this basis for fundamental changes in all areas of life [8].

The key differences between informatisation and digitalisation are as follows:

- depth of change: informatisation usually refers to computerisation and the introduction of basic information technologies, while digitalisation involves a fundamental transformation of processes, business models, and structures of society.
- the goal itself: informatisation aims to provide access to information and its efficient processing, and digitalisation - to rethink and optimise processes through the use of advanced digital technologies.
- the approach: informatisation is more focused on technical support (infrastructure), and digitalisation - on the integration of digital technologies into everyday life and the transformation of economic and social models.

Electronic communications play a key role in the digitalisation of society and the development of Industry 5.0, as they ensure fast, efficient and secure data transfer between people, devices and systems.

Electronic communications should provide: ultra-fast data exchange between production systems, which increases productivity and safety; the use of robotic systems and artificial intelligence to support people in production processes. Reliable electronic communications ensure the security of industrial networks and personal data; smart factories with networked sensors and automated data processing systems.

In this context, new challenges are facing electronic communications and new problems are identified accordingly, the solution of which requires conducting promising scientific research [9].

This work aims to summarise and highlight the key areas of development of electronic communications, which determine the current and future state of the industry. It is aimed at outlining scientific challenges and prospects associated with the digitalisation of society, the growth of demand for fast, reliable and secure data transmission. The material also serves as a reference for scientists, researchers and specialists in the field of telecommunications, helping to identify relevant topics for further research and development.

II. Relevant Areas for New Research

The general list of the most relevant areas for new research in electronic communications, which can determine the future of this industry, is given in Fig. 1.

The list includes the following research directions:

- 6G and the next generations of networks;
- Quantum communications;
- Internet of Things (IoT) and its scaling;
- Artificial Intelligence (AI) and Machine Learning (ML) in Networks;
- Security and privacy in electronic communications;
- Edge and Fog Computing;
- network functions virtualisation (NFV) and software-defined networks (SDN);
- Green Communications;
- Holographic and tactile communications;
- Mission-Critical Networks (MCN);
- Deep Space and Interplanetary Connection.

Let us consider the listed areas in more detail.

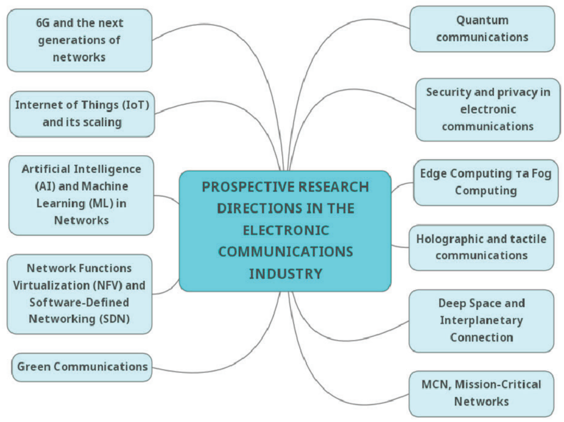

Fig. 1. Directions for new scientific research that can determine the future of electronic communications

III. 6G and Future Generation Networks

The “6G and Future Generation Networks” area covers not only the development of sixth generation (6G) networks, but also research into technologies that can become the basis for further network development (7G and beyond). 6G is the successor to 5G and promises to revolutionise the communications industry. 6G is expected to be implemented by 2030 [10]-[14].

The main areas of 6G research and innovation include:

1. Ultra-high data rates: speeds of up to 1 Tb/s (100 times faster than 5G), which will allow the transmission of huge amounts of data, such as holographic images or data for quantum computing.

2. Ultra-low latency and high-performance networks: Ultra-low latency - providing latency less than 1 ms for mission-critical applications such as autonomous vehicles, remote control of robots, virtual and augmented reality; Edge computing and MEC - developing architectures that allow data processing closer to end users, reducing latency and increasing network efficiency.

3. Supporting new use cases: holographic communications, tactile Internet, precise control of robots in real time; integration with quantum technologies and artificial intelligence; integration of

IoT and mass networks: ensuring efficient management and communication between millions of IoT devices with various data transmission requirements.

4. Expansion of the frequency spectrum and new radio frequency technologies: THz band - research into the use of terahertz (THz) waves for data transmission, which will allow for incredibly high transmission speeds and minimise latency; new generation of antennas and antenna arrays - development of innovative solutions in the field of massive MIMO and active antenna systems for the effective use of the high-frequency spectrum.

5. Energy efficiency and environmental friendliness: optimisation of network energy consumption - development of new methods of resource management to reduce energy consumption, which is critical for the sustainable development of technologies; environmentally friendly technologies: research into the impact of future networks on the environment and development of environmental standards for 6G.

6. Security and privacy: new methods of encryption and data protection - development of algorithms and protocols that ensure a high level of security of data transmission in networks of future generations; blockchain and decentralised authentication systems - implementation of blockchain technologies to increase trust and ensure data integrity in distributed networks.

Although 6G is still in the research phase, scientists are already considering the possibilities for future generations of networks (7G, 8G, etc.). These networks can be based on fundamentally new technologies that are still hypothetical, but have great potential [15], [16].

The main research areas of "Future Generations of Networks (7G and beyond)" are as follows.

1. New protocols and architectural solutions: dynamic traffic management protocols - development of new standards and protocols that provide more flexible and adaptive routing under variable load conditions; distributed control systems - innovative approaches to building network architectures with decentralised control that reduce the risks of points of failure and improve scalability.

2. Integration with quantum technologies: quantum networks - use of quantum entanglement to transmit information with absolute security; quantum repeaters will allow data to be transmitted over long distances without loss of quality; quantum computing in networks - networks can use quantum computers to optimise routing and traffic management.

3. Biological and neural networks: biocomputers - use of biological systems for data processing, which can lead to the creation of networks that operate on principles similar to the human brain; neuromorphic computing - networks can mimic neural connections for efficient resource allocation.

4. Artificial intelligence-based networks: AI optimization - using AI to predict traffic, prevent attacks, and efficiently allocate resources; AI and machine learning for network management - using artificial intelligence algorithms to automate network resource management, optimise routing, and predict load; autonomous network management and orchestration - researching solutions for self-organising networks that can adapt to environmental changes in real time.

5. Networks for interplanetary communication: Internet for space - developing networks that provide communication between Earth, spacecraft, and colonies on other planets. This requires new data transmission protocols that can operate over long distances and delays; laser communications - using lasers to transmit data in space at high speeds.

6. Energy-autonomous networks: the use of renewable energy sources: networks powered by solar, wind or other environmentally friendly energy; energy networks - the integration of communication networks with energy systems for efficient energy distribution.

7. Privacy-enhanced networks: decentralised networks - the use of blockchain and other decentralised technologies to ensure security and privacy; personalised security - networks that adapt the level of protection according to the needs of each user.

8. Extended reality (XR) networks: augmented reality (AR), virtual reality (VR) and mixed reality (MR) - networks that provide seamless data transmission for XR applications, including holographic images and tactile internet; interactive environments - the creation of networks that support full immersion in virtual environments.

IV. Quantum Communications

Quantum communications is a promising area of research in the field of electronic communications, based on the principles of quantum mechanics. This technology promises to revolutionise information transmission, providing absolute security and new possibilities for communication [17], [18].

Quantum communications are based on the following key phenomena of quantum mechanics:

1. Quantum entanglement: two or more quantum particles (e.g. photons) become entangled, meaning their states remain correlated regardless of distance. A change in the state of one particle instantly affects the state of the other.

2. Quantum superposition: a quantum particle can be in several states at the same time, which allows the

transmission of more information compared to classical systems.

3. Quantum teleportation: the transmission of the quantum state of a particle over a distance without physically moving the particle itself.

4. Heisenberg's Uncertainty Principle: It is impossible to simultaneously accurately measure certain pairs of characteristics of a quantum particle (for example, position and momentum). This makes quantum systems resistant to hacking attempts.

Current challenges for implementing quantum communications are as follows: signal loss - quantum states are easily destroyed by external factors, such as noise or losses in optical fibers; technical complexity - creating stable quantum devices requires high precision and controlled conditions; distance - quantum entanglement is preserved only over limited distances, which requires the use of quantum repeaters; cost - the development and implementation of quantum technologies remain expensive; integration with existing systems - quantum communications require new infrastructure that may be incompatible with classical systems.

Promising research for quantum communications is as follows.

1. Quantum Internet: creating a global network that provides absolutely secure communication between quantum computers and devices.

2. Protection against quantum attacks: Quantum computers can break traditional encryption methods, so quantum cryptography will become the main means of protection.

3. Medicine and finance: Quantum communications will ensure the security of sensitive data transmission in these industries.

4. Space communications: Quantum satellites will allow for highly secure communication between Earth and spacecraft.

5. Internet of Things (IoT): Quantum technologies will ensure the security of millions of connected devices.

Well-known examples of modern quantum communications projects: Chinese satellite Micius: the world's first quantum communications satellite that successfully performed quantum teleportation and key transfer; European project Quantum Internet Alliance: the goal is to create a quantum internet in Europe; NASA Quantum Communication project: research into the possibilities of using quantum communications for space missions; Google and IBM: development of quantum networks to connect quantum computers.

V. Internet of Things (IoT) and its Scaling

The Internet of Things (IoT) and its scaling is one of the most dynamic areas in modern technology, transforming and expanding the ways in which people, devices and systems interact. IoT involves connecting billions of devices to the Internet to collect, exchange and analyse data. IoT scaling is about ensuring the stable operation of such systems as the number of devices, data volumes, and performance requirements grow [19], [20].

The following challenges can be identified for IoT scaling:

- number of devices: by 2030, the number of connected devices is expected to exceed 25 billion. This requires new approaches to network management;
- data volumes: IoT devices generate huge amounts of data, which requires powerful storage and processing systems;
- energy efficiency: many IoT devices are battery-powered, so energy efficiency is critical;
- security: the large number of devices makes IoT networks vulnerable to cyberattacks;
- interoperability: different manufacturers use different standards, which makes it difficult to integrate devices;
- latency: real-time applications (e.g. autonomous cars) require networks with minimal latency.

Promising research for IoT scaling could be:

1. Global coverage: IoT will become available in remote regions thanks to satellite networks and LPWAN.

2. Integration with AI and quantum technologies: AI will allow for the creation of intelligent IoT systems, and quantum technologies will ensure absolute security.

3. Environmental sustainability: development of energy-efficient IoT devices and the use of renewable energy sources.

4. New business models: IoT opens up new opportunities for monetization of data and services.

5. Development of 6G: future generations of networks will provide even higher performance for IoT.

VI. Artificial Intelligence and Machine Learning in Networks

The research direction in the field of electronic communications, which includes artificial intelligence (AI) and machine learning (ML), is one of the most promising in modern science and technology. These technologies open up new opportunities for optimising, managing and improving network systems [21], [22]. Here is more about the main aspects of this direction.

1. Optimisation of network resources: dynamic traffic management - using ML to analyse traffic in real time and predict network load. This allows you to efficiently allocate resources, avoid congestion and ensure stable network operation; energy efficiency - AI can help reduce the power consumption of network devices by optimising their operation depending on the current load.

2. Network Security: Anomaly Detection - ML algorithms can analyse network traffic to detect unusual patterns that may indicate cyberattacks, such as DDoS attacks or unauthorised access attempts; Threat Prediction - AI can use historical data to predict and prevent potential threats; Incident Response Automation - AI-powered systems can automatically block suspicious activity or redirect traffic to minimise risks.

3. Self-Organising Networks (SON): Automatic Network Configuration - AI enables networks to automatically adapt to changes in the environment, such as changes in the number of users or geographical location; Quality of Service (QoS) Improvement - ML algorithms can optimise network parameters to ensure high-quality data, voice, and video transmission.

4. 5G and 6G networks: managing a huge number of devices - in 5G/6G networks, where the number of connected devices can reach millions per square kilometer, AI helps to efficiently manage resources and ensure stable connectivity; latency reduction - using AI to minimise delays in critical applications such as autonomous vehicles or remote surgeries; network virtualization (Network Slicing) - AI helps to create virtual subnetworks for different types of services (e.g. IoT, streaming, critical communications), optimising them for specific needs.

5. Internet of Things: big data management - AI helps to process and analyse the huge amounts of data generated by IoT devices to improve efficiency and make real-time decisions; power optimisation - ML algorithms can manage the operation of IoT devices, reducing their power consumption and extending battery life.

6. Quantum networks: Quantum machine learning - research in quantum computing can lead to the creation of new algorithms for optimising network processes that cannot be implemented on classical computers; quantum communications security - AI can help develop methods for protecting quantum networks that are invulnerable to classical cyberattacks.

7. Personalised services: adapting the network to user needs - AI can analyse user behaviour and offer personalised solutions, for example, optimising internet speed for streaming video or online games; improving user experience - using ML to analyse feedback and improve the quality of services.

8. Ethics and regulation: ethical use of AI in networks - research aims to ensure transparency and fairness in the operation of AI algorithms to avoid discrimination or privacy violations; regulation of AI in telecommunications - developing standards and norms for the use of AI in networks to ensure security and reliability.

9. Research into new network architectures: neuromorphic networks - using the principles of the human brain to create more efficient and adaptive network systems; Edge Computing - AI helps process data at the edge of the network, which reduces latency and load on central servers.

10. Modeling and simulation: virtual test environments - using AI to create virtual network models that allow testing new solutions without risk to the real infrastructure; network development forecasting - ML models can predict future trends in electronic communications, which helps plan infrastructure development.

VII. Security and Privacy in Electronic Communications

Security and privacy in electronic communications is a critically important area of research that is gaining increasing importance due to the increasing number of cyberattacks, data leaks, and spyware. In a world where information is exchanged via the Internet, mobile networks, IoT devices, and cloud services, ensuring security and privacy is becoming a key task [23]-[26].

The research and technology areas are as follows.

1. Cryptography, which is the basis of data protection in electronic communications: post-quantum cryptography - the development of encryption algorithms that are resistant to attacks by quantum computers; homomorphic encryption - allows processing encrypted data without decrypting it; quantum cryptography - the use of quantum entanglement to ensure absolute security.

2. Authentication and authorization (ensuring access to systems only by authorised users): biometric authentication - using fingerprints, face scanning, voice; multi-factor authentication (MFA) - a combination of passwords, SMS codes, biometric data; Zero Trust Architecture - an approach that requires constant verification of users and devices.

3. Network protection, because they are the main channel for attacks: software-defined networks (SDN) - allow you to dynamically manage network security;

protection against DDoS attacks - using AI to detect and block attacks; VPN and Tor networks - ensuring anonymity and confidentiality of users.

4. Security of IoT devices. IoT devices often have weak protection and become targets for attacks: firmware updates - regular software updates to eliminate vulnerabilities; data encryption - protecting data transmitted between IoT devices; network segmentation - isolating IoT devices from critical systems.

5. Protecting cloud services that store large amounts of sensitive data: Data encryption in the cloud - ensuring data confidentiality during storage and transmission; Access control - restricting access to data based on user roles; Threat analysis - using AI to detect suspicious activity in cloud environments.

6. Data privacy. The collection and analysis of user data raises privacy concerns: Privacy by Design - integrating privacy protection measures at the design stage of systems; Data anonymisation - removing personal information from data sets; Regulation (GDPR, CCPA) - complying with regulatory requirements for data protection.

7. Artificial intelligence (AI) for cybersecurity. AI allows you to quickly detect and respond to threats: Anomaly detection - using machine learning to detect suspicious activity; Attack prediction - analysing data to predict possible attacks; Defense automation - creating systems that block threats on their own.

8. Decentralised systems (blockchain). Blockchain provides a high degree of security and transparency: transaction protection - using blockchain for secure data exchange; decentralised identification - creating identification systems that do not depend on centralised authorities; smart contracts - automating the execution of transactions with a high level of security.

VIII. Edge Computing and Fog Computing

Edge Computing and Fog Computing are two related approaches to data processing in the field of electronic communications, which are developing against the background of the growth of the Internet of Things (IoT), 5G/6G networks, artificial intelligence (AI), and real-time data processing. These technologies allow computing resources to be transferred closer to the data source, which significantly increases efficiency, reduces latency, and reduces the load on centralised cloud systems [27]-[28].

Edge Computing involves processing data closer to its source — directly on IoT devices, microcontrollers, gateways, or other network nodes. The main idea is to reduce latency when transmitting data to cloud servers, reduce the load on the main communication channels, and increase security. The calculations are performed on devices or at the "edge" of the network. This allows data to be processed in real time without the need to transfer it to centralised servers.

Fog Computing extends the concept of Edge Computing by adding an intermediate layer between Edge and Cloud infrastructure. Fog provides data preprocessing closer to end devices, but not on the devices themselves, but on servers or special nodes located within local networks (for example, in data centers, campus networks, telecommunications nodes) closer to users.

The main challenges and future research in these areas are: complexity of managing distributed systems; limited resources of Edge devices; ensuring compatibility between different platforms and devices.

The main promising research in this area is as follows.

1. Edge and Fog Computing architecture: optimising the architecture for different use cases (for example, industrial IoT, smart cities, autonomous vehicles); developing standards for interaction between Edge, Fog and cloud systems; research on hybrid models that combine Edge, Fog and cloud computing; use of containerization (Docker, Kubernetes) for scalability of Fog infrastructures.

2. Energy efficiency and resource management: development of energy-efficient algorithms for data processing; use of machine learning technologies for dynamic resource allocation; optimisation of device operation in real time; research on wireless technologies (Wi-Fi 6, 5G, LPWAN) for effective load distribution between Edge nodes.

3. Security and privacy: development of data encryption mechanisms on Edge devices; ensuring data integrity during transmission between nodes; use of blockchain technologies to improve security; decentralised authentication and encryption mechanisms for Edge devices; use of Zero Trust approach for authentication of Fog nodes; research on anomaly detection mechanisms in distributed networks.

4. Real-time data processing: development of algorithms for fast processing of streaming data; using AI/ML for data analysis on Edge devices; minimising latency in 5G/6G networks.

5. Integration with IoT and 5G/6G networks: optimising interaction between IoT devices and Edge/Fog nodes; using network slicing in 5G/6G to support Edge Computing; developing protocols for efficient data transmission in distributed systems.

6. Machine learning and artificial intelligence: developing lightweight machine learning models for

Edge devices; optimising AI algorithms for working in resource-constrained environments; implementing small neural networks for analysing video, images, and audio data at the edge; adapting large machine learning models to work on devices with limited resources; automating resource management of Fog environments based on AI/ML; using reinforcement learning for dynamic routing of computational tasks..

IX. Network Function Virtualization and Software-Defined Networking

Network Function Virtualisation (NFV) and Software-Defined Networking (SDN) are some of the key areas of modern research in the field of electronic communications. They allow you to create flexible, scalable and efficient networks, which is especially important in the context of increasing requirements for speed, reliability and data processing [29]-[30].

NFV consists in replacing traditional physical network devices (e.g. routers, firewalls, load balancers) with software solutions that run on a virtualised infrastructure. This allows you to reduce costs, increase flexibility and accelerate the deployment of new services. The main goal of NFV is to reduce dependence on specialised hardware and increase flexibility in network resource management.

Software-defined networks SDN separates the control plane from the data plane, allowing for centralised network management through software. This provides flexibility, automation, and rapid response to network changes.

It should be noted that both technologies (NFV and SDN) complement each other, creating a flexible, programmable, and scalable network infrastructure. They are used together to create fully software-defined and virtualised networks.

Main research areas in NFV.

1. NFV performance optimisation: acceleration of virtualised functions using hardware accelerators (SmartNIC, DPDK, SR-IOV); use of containerization (Docker, Kubernetes) instead of classic virtual machines to improve performance; optimisation of real-time operation for mission-critical applications (autonomous cars, industrial networks); development of efficient algorithms for resource allocation between NFV.

2. Integration with 5G and MEC (Multi-access Edge Computing): development of virtualised network functions (NFV) for 5G networks (vRAN, vEPC); research on effective deployment of NFV on MEC edge servers to reduce latency in mobile networks; use of NFV to support network slicing in 5G/6G networks.

3. NFV orchestration and scaling: use of AI/ML for automated management of network resources; intelligent orchestration of virtual network functions (e.g. MANO – Management and Orchestration); development of Open Source platforms for NFV (OpenStack, ONAP, OSM); use of containerization (Docker, Kubernetes) to improve the efficiency of NFV deployment.

4. Security in virtualised networks: research on methods for secure isolation of NFV; use of Zero Trust approach for authentication of virtual network functions; development of attack detection mechanisms in virtualised environments.

5. Energy efficiency: research into methods for reducing energy consumption of virtualised infrastructure.

Main research areas in SDN.

1. SDN in 5G and 6G networks: study of the use of SDN in distributed 5G architectures (vRAN, Network Slicing); optimisation of traffic and routing in networks using millimeter waves; integration of SDN in 6G networks for dynamic adaptation to changes in load; use of SDN for network slicing management and dynamic resource allocation in 5G/6G networks.

2. SDN security: use of blockchain to increase trust between SDN nodes; protection of SDN controllers from DDoS attacks; automation of security policies for IoT and distributed cloud environments; use of SDN to implement security mechanisms such as dynamic attack blocking.

3. SDN architecture: study of new architectural approaches to improve the performance of SDN controllers; development of distributed SDN controllers for large-scale networks; optimisation of protocols such as OpenFlow for efficient network flow management; research into new protocols to support dynamic network environments; application of quantum computing to improve the performance of SDN controllers.

4. AI-Driven SDN: use of machine learning to automatically detect anomalies and cyber threats; optimisation of traffic management based on demand forecasting; dynamic adjustment of QoS (Quality of Service) policies in real time.

5. SDN in the cloud and data centers: development of automated SDN clusters for traffic management in large cloud environments (AWS, Google Cloud, Azure); optimisation of containerized applications (Kubernetes + SDN); research into the integration of SDN with virtual private networks (VPN) for secure data center connectivity; research into methods for

combining SDN and NFV to create flexible and scalable networks.

Key research interests in the interaction of NFV and SDN include: integrating SDN for dynamic management of NFV functions; using AI for automated orchestration of SDN+NFV; deploying secure, adaptive networks with NFV in cloud and edge environments; developing integrated architectures that combine the benefits of NFV and SDN; developing algorithms for dynamic scaling of network resources; environmental aspects to investigate the impact of NFV/SDN on energy consumption and environmental footprint.

X. GREEN COMMUNICATIONS

Green Communications is a concept for developing energy-efficient, environmentally friendly and sustainable telecommunications technologies. It aims to reduce energy consumption, carbon dioxide (CO_2) emissions and the use of environmentally friendly materials in communication networks [31], [32].

Given the increasing number of devices (IoT, 5G, future 6G), the need to optimise energy consumption is becoming critical. It is estimated that the ICT industry already consumes more than 2% of the world's electricity, and this figure continues to grow.

The main research areas in Green Communications are as follows.

Energy-efficient data centers, cloud and edge computing. Data centers, cloud and edge computing consume significant amounts of energy, so their optimisation is an important research area.

Research areas:

- Optimisation of cloud data centers: using virtualisation and containerization to reduce energy consumption; research on methods for dynamic load distribution between servers.
- Energy-efficient edge computing: development of algorithms for optimising the power consumption of Edge devices; use of renewable energy sources to power peripheral nodes.
- Green machine learning algorithms: development of lightweight AI/ML models to work on devices with limited resources.
- Reducing server energy consumption: distributed computing to optimise the load on data centers; use of "cold zones" (Free Cooling) for natural cooling of server rooms; optimisation of server processor operation and reduction of energy consumption at low load.
- Carbon-neutral cloud computing: use of renewable energy sources for data center operation; research on "Green AI" – machine learning algorithms that consume less energy; optimisation of CDN (Content Delivery Networks) operation to reduce the data transmission distance. Note that carbon neutrality represents a measure of achieving net zero carbon dioxide emissions.

Use of renewable energy sources. The integration of renewable energy sources (solar, wind, geothermal) into the network infrastructure is a key direction of green communications.

Research areas:

- Hybrid power systems: development of systems that combine traditional and renewable energy sources; research into methods of efficient energy storage (e.g., energy-efficient battery systems).
- Energy-neutral networks: creation of networks that are fully powered by renewable energy sources; optimisation of network operation in conditions of unstable energy supply.
- Harvesting Energy - energy harvesting from the environment: use of radio signal energy (RF energy harvesting) to power IoT devices; use of piezoelectric and thermoelectric materials for energy harvesting.

Environmental Impact of ICT. Research aims to assess and reduce the environmental impact of information and communication technologies (ICT).

Research areas:

- Carbon footprint assessment: development of methods for measuring the carbon footprint of network infrastructure; research into the impact of electronic communications on climate change.
- Green devices and components: use of biodegradable materials for the production of network equipment; development of a new generation battery without toxic materials.
- Server equipment recycling and recycling programs: research into methods for recycling e-waste; use of secondary materials in the production of new communication devices.

Green IoT networks and smart cities. The Internet of Things (IoT) includes billions of devices that consume energy, so their optimisation is an important area of research.

Research areas:

- Low-power IoT devices: development of energy-efficient sensors and communication modules; use of technologies such as "Energy Harvesting" to power devices.
- Network protocol optimisation: research into protocols that minimise energy consumption during data transmission (e.g. MQTT, CoAP).
- Energy-efficient sensor networks: optimisation of LoRaWAN, Zigbee and NB-IoT communication

protocols to minimise energy consumption; use of low-power processors (ARM Cortex-M, RISC-V).

- Smart Grid and energy-efficient communication networks: integration of communication networks with smart power systems; optimisation of power distribution between communication nodes.

Energy-efficient wireless networks. Research areas:

- Dynamic power management algorithms: use of AI/ML for adaptive reduction of transmitter power; intelligent algorithms for regulating base station operation depending on load; shutdown of inactive towers during low load (Sleep Mode); research on methods for reducing delays and power consumption in wireless networks.

- Green solutions for 5G and 6G: use of energy-efficient antenna technologies (Massive MIMO, Beamforming); research on self-organising networks (SON – Self-Organising Networks) to minimise power consumption; optimisation of MEC (Multi-access Edge Computing) to shorten the data transmission route and reduce energy consumption; optimisation of power consumption for different types of network slices Network Slicing.

- Efficient spectrum use: dynamic use of frequency spectrum to minimise energy losses; innovative cognitive radio methods for energy-efficient management of radio resources; research on methods for increasing spectrum efficiency (e.g. NOMA – Non-Orthogonal Multiple Access).

- Low-power transmitters and receivers: development of energy-efficient radio interfaces for IoT devices; use of technologies such as Low-Power Wide-Area Networks (LPWAN) to support long-term operation of devices.

Use of AI and Big Data in Green Communications:

- energy forecasting - analysis of big data to dynamically adjust the power consumption of network devices;

- traffic routing optimisation - selection of the least energy-consuming paths for data transmission;

- automatic load balancing - redistribution of computing tasks between servers depending on their level of load.

XI. Holographic and Tactile Communications

Holographic and tactile communications are innovative areas in the field of electronic communications that promise to revolutionize the way people interact at a distance. These technologies allow the transmission of not only audio and video, but also three-dimensional holographic images and tactile sensations, which makes communication more immersive and realistic [33].

The key areas of promising research in the field of holographic and tactile communications in electronic communications are as follows.

1. Holographic communications

Holographic communications involve the creation of three-dimensional images in real time for video communication, telemedicine, education and entertainment. This allows you to create the effect of presence when subscribers see each other in full 3D format.

The main characteristics of holographic communications: three-dimensionality: holograms create the illusion of a three-dimensional image, which allows you to view an object from different angles; real-time: holograms are transmitted without delay, making communication natural; high detail: holograms can reproduce even the smallest details, such as facial expressions or the texture of objects.

The following technologies are used:

- Holographic displays: use lasers, projectors or special panels to create 3D images. Examples: Microsoft HoloLens, Looking Glass.

- Hologram capture cameras: multi-camera systems that capture an object from different angles to create a 3D model. Example: Intel RealSense.

- Artificial intelligence (AI): used to process data, compress holograms and improve image quality.

- High-bandwidth networks: hologram transmission requires networks with very high data rates (e.g. 5G, 6G).

Research in the field of holographic communications must address the following challenges: large data volumes: holograms require significantly higher bandwidth compared to traditional video; latency: real-time holographic communications require networks with minimal latency; cost of equipment: holographic displays and cameras remain expensive for mass use.

Key research:

- Holographic 6G: transmission of holographic video over ultra-wideband channels (THz frequencies).

- Holographic data compression and transmission algorithms: development of processing and compression methods, such as neural network compressors.

- Cloud and MEC infrastructure optimisation: use of Multi-Access Edge Computing (MEC) to reduce latency in holographic calls.

- AI for holographic rendering: machine learning to generate realistic holograms.

- Quantum communications for holography: research into quantum technologies for ultrafast and secure transmission of holographic data.

2. Tactile communications (Internet of Senses, Tactile Internet)

Tactile communications allow the transmission of the sense of touch over networks, which opens up new possibilities for human interaction with the digital world. This opens up new possibilities for interaction, especially in industries where physical contact is important.

The main characteristics of tactile communications are as follows: tactile feedback: users can "feel" objects or actions at a distance; real-time: sensations are transmitted without delay, which makes interaction natural; high accuracy: technologies allow even the smallest tactile sensations to be reproduced.

The following technologies are used: tactile devices: gloves, suits or other devices that transmit tactile sensations. Examples: HaptX Gloves, Teslasuit; sensors: devices that capture tactile data (for example, pressure or vibration); artificial intelligence (AI): used to process tactile data and transmit it; low-latency networks: networks with minimal latency are needed to transmit tactile sensations in real time.

The following challenges in this direction should be considered: technical complexity: creating accurate tactile devices requires high precision and miniaturisation; energy consumption: tactile devices require energy to create sensations; cost: tactile technologies remain expensive for mass use.

Key research:

- Tactile Internet in 6G: using ultra-low latency (<1 ms) to transmit sensory information.
- Tactile interfaces: developing sensory devices that simulate tactile sensations over a network.
- Neural interfaces and brain communications: researching brain-computer interfaces for direct transmission of sensory signals.
- Energy-efficient technologies: minimising energy consumption for mass adoption of haptic technologies.
- Haptic communications security: protecting against cyberattacks at the level of sensory feedback.

Interaction of holographic and haptic communications.

The greatest potential lies in the combination of holographic and haptic technologies, which requires research:

- Development of Haptic Holography (tactile holograms): research into technologies that allow interaction with virtual 3D objects through haptic feedback.
- Integration with 6G: development of new network protocols for simultaneous transmission of holographic video and haptic sensations, creation of virtual meetings.
- Artificial intelligence for prediction and optimisation: using AI to compensate for delays in the haptic Internet and improve the interactive experience.

XII. Mission-Critical Networks

Mission-Critical Networks (MCNs) are specialised networks that provide reliable, secure, and uninterrupted connectivity for applications where any failure could result in serious consequences, such as life-threatening situations, significant financial losses, or disruption of critical infrastructure. Therefore, they provide high reliability, minimal latency, security, and continuity of service even under challenging conditions [34], [35].

MCNs are used in areas such as healthcare (remote surgery, real-time patient monitoring), energy (power system management, critical infrastructure monitoring), transportation (autonomous vehicles, traffic management and V2X (Vehicle-to-Everything)), defense industry, financial networks (stock exchange systems, banking, cyber security), operational services (emergency services, police, firefighters, medical care), emergency services (rescue coordination, critical information transmission) and smart city infrastructure.

The following are promising research areas in this area.

1. Network reliability and fault tolerance.

- Intelligent failure management: using AI to predict network failures; automatic traffic switching in the event of a failure (Failover Mechanisms); optimisation of data backup algorithms; use of backup communication channels and duplication of critical nodes.
- Self-Healing Networks: use of machine learning to detect anomalies; autonomous algorithms for restarting critical nodes without operator intervention; creation of virtual isolated environments for localisation of failures.
- Distributed architectures: research of architectures that ensure network operation even with partial failures (e.g. mesh networks).

2. Integration with 5G/6G for critical applications.

- Network Slicing: guaranteed communication channels for medical and emergency services; dedicated segments for industrial networks (Industry 4.0); development of methods for creating isolated network slices for critical applications; optimisation of resources to ensure quality of service (QoS).

- Ultrareliable Low Latency Communication (URLLC): minimisation of delays <1 ms for V2X, drones, surgical robots; using MEC for fast data processing at the network edge; research on methods for ensuring reliable communication with ultra-low latency.

- Energy-efficient networks: research on methods for reducing energy consumption under high loads; use of adaptive transmitter operating modes.

3. Cybersecurity of critical networks.

- AI-Driven Security: use of machine learning to detect attacks in real time; analysis of behavioural anomalies in network traffic.

- Zero Trust Architecture (ZTA) in critical networks: multi-level authentication for connected devices; trust-based data access control (Microsegmentation).

- Quantum cryptography for communication security: use of quantum key distribution (QKD) for resistance to hacker attacks; integration of quantum networks with classical IP networks.

4. Internet of Things (IoT) and critical infrastructures.

- Industrial IoT (IIoT) and secure networks: using Low-Power Wide-Area Networks (LPWAN) for remote monitoring; developing wireless sensor networks for SCADA systems.

- Drones and autonomous robots in critical networks: optimising V2X communications for secure fleet management; using drones to provide communications in MCNs; using MEC for fast processing of data from drones.

5. Cloud and edge computing in critical networks.

- Multi-access Edge Computing (MEC) in critical applications: using MEC for real-time data processing (Smart Grid, V2X); optimising resource allocation between cloud and local nodes; real-time data processing: developing algorithms for fast data processing and transmission; using Edge Computing to reduce latency.

- Hybrid Cloud & Private Cloud: using closed cloud platforms for government and military communications; orchestrating resources between public and private clouds.

XIII. Deep Space and Interplanetary Communication

Research in the direction of “Deep Space and Interplanetary Communication” is one of the most promising and complex areas in the field of electronic communications. This area is becoming increasingly relevant due to the active development of space programs, plans for the colonisation of the Moon and Mars, as well as due to the increase in the number of satellites and spacecraft in Earth orbit [36], [37].

The main challenges of space and interplanetary communication: large distances, for example, the distance between Earth and Mars ranges from 55 to 400 million kilometers, which leads to significant signal delay (from 4 to 24 minutes one way); interference - cosmic radiation, solar flares, dust and other factors can affect the quality of data transmission; energy constraints - spacecraft have limited energy sources, so energy efficiency is critically important; technical limitations - the need to create compact, lightweight and reliable devices that can operate in extreme conditions.

The areas of promising research in space and interplanetary communications are as follows.

1. Laser communications. Laser data transmission systems provide much higher speeds compared to radio waves, as well as lower latency. Research: development of laser transmitters and receivers for spacecraft; ensuring stable communication through atmospheric interference; using lasers for communication between planets.

Example: NASA's LCRD (Laser Communications Relay Demonstration) project demonstrates the capabilities of laser communication for transmitting data from orbit to Earth.

2. Satellite networks. Satellite networks such as Starlink, OneWeb and others provide global Internet coverage. Research: creation of low-latency networks to support real-time; development of autonomous satellites that can navigate and communicate independently; use of satellites for communication between planets.

3. Interplanetary Internet. To support future missions to Mars and beyond, a robust communications infrastructure is needed. Research: Developing data transmission protocols that take into account long delays (e.g., Delay-Tolerant Networking, DTN); Building a network of relays in planetary orbits to ensure uninterrupted communications; Integrating with existing Internet technologies.

Example: NASA is already using DTN to communicate with spacecraft such as the International Space Station (ISS).

4. Quantum communications in space. Quantum technologies provide absolute security for data transmission, which is critical for space missions. Research: Using quantum entanglement to transmit information over long distances; Developing quantum satellites such as China's Micius; Building quantum networks for interplanetary communications.

5. Energy-efficient communications systems. Spacecraft have limited energy sources, so efficiency is

key. Research: Developing energy-efficient antennas and transmitters; using solar energy to power communication systems; optimising data transmission protocols to reduce energy consumption.

6. Real-time communication. To support manned missions and autonomous robots on other planets, communication with minimal delays is required. Research: using laser technologies to reduce delays; creating networks of repeaters in planetary orbits; developing algorithms to compensate for delays.

7. Protection from space interference. The space environment is full of interference, such as solar flares, cosmic rays, and dust. Research: developing radiation-resistant components; using reliable error correction methods; protecting signals from interference using new modulation/coding methods.

8. Integration with AI and autonomous systems. Autonomous spacecraft require intelligent systems to manage communications. Research: using artificial intelligence to optimise data transmission; developing autonomous systems that can independently select optimal communication channels; AI integration for real-time data analysis.

XIV. Conclusion

Summing up the material presented in the article, the following conclusions can be drawn. Research in the direction of 6G and future generations of networks is interdisciplinary and covers both hardware and software aspects of technological development. The main goal is to create ultra-fast, ultra-reliable and intelligent networks capable of supporting new types of services and applications, from autonomous driving and remote medicine to full-scale multimedia communications. The successful integration of these solutions will have a significant impact on the economy, society and global communications infrastructure.

The direction of quantum communications is a revolutionary direction that promises to ensure absolute security of information transmission and open up new opportunities for communication. Despite the technical challenges, research in this area is actively progressing, and we are already seeing the first successful implementations, such as quantum satellites and networks. In the future, quantum communications may become the basis for a global quantum internet that will change the way we interact with information.

The IoT scaling direction is a key direction that is defining the future of many communication technologies. Despite challenges such as security, energy efficiency and interoperability, IoT continues to develop rapidly thanks to innovations in edge computing, 5G, AI and blockchain. In the future, IoT will become the basis for smart cities, industry, medicine and other industries, changing the way we interact with technology.

The research direction in the field of electronic communications, which includes artificial intelligence (AI) and machine learning (ML), continues to develop actively, and its results are already finding applications in modern networks. In the future, it is expected that AI and ML will be even more integrated into all aspects of electronic communications, leading to the creation of smarter, more efficient and secure networks.

Security and privacy in electronic communications is a dynamic direction that is constantly evolving due to the growth of cyber threats and technological advances. Research in this area aims to create innovative data protection methods that will ensure the security and privacy of users in the digital world. This direction has a huge potential to influence the future of electronic communications, making them safer and more reliable.

Edge and Fog Computing are key technologies for the future of electronic communications, and their development requires an interdisciplinary approach that combines computer science, telecommunications, AI and IoT. They allow reducing data transmission delays, increase network security and efficiency. New research in this area is aimed at optimising resource usage, improving security, integrating with 5G and AI, as well as developing new architectures that will make digital communications even faster and more reliable.

Research in the field of NFV and SDN is necessary to improve network performance, automation and security. They play a key role in the future of 5G/6G, cloud computing, IoT and industrial networks. The integration of NFV and SDN allows for the creation of flexible, dynamic and self-adjusting telecommunications systems. NFV and SDN are key technologies for the future of networks, and their development requires an interdisciplinary approach that combines computer science, telecommunications, artificial intelligence and cybersecurity.

Green communications is an important research area aimed at improving the energy efficiency and sustainability of telecommunications networks. Key aspects include reducing energy consumption in wireless networks, using renewable energy sources, optimising data centers, energy-efficient IoT solutions and introducing environmentally friendly materials in the production of telecommunications equipment. The expected effect is to reduce the carbon footprint of the ICT industry, increase the environmental responsibility of telecommunications companies and create more sustainable communication networks of the future.

Networks for critical applications are a key element of modern infrastructures, and their development requires an interdisciplinary approach that combines telecommunications, cybersecurity, artificial intelligence and other fields. Research in this area focuses on ensuring high reliability, minimal delays and cybersecurity.

Holographic and tactile communication interaction technologies will become the basis of future digital communications, changing the ways in which people and machines interact.

Thus, the presented research areas determine the future of electronic communications. Research in these areas will ensure sustainable development of the industry, taking into account the growing needs of modern society for fast, secure and reliable data transmission technologies.

References

1. N. Engheta, H.N. Krishnaswamy, "Shroff Future Directions Workshop on Wireless Communications: XG and Beyond", Workshop sponsored by the Basic Research Office, Office of the Under Secretary of Defense for Research & Engineering June 8-9 (2022). Retrieved from: https://basicresearch.defense.gov/Portals/61/Documents/future-directions/ Future%20Directions%20-%20Wireless%20Communications%20-%20for %20public%20release.pdf? ver=LL4z9Lfey_VSpFp6Nnmwmw%3D%3D.
2. 10 telecommunications trends for 2025, IOT Insider News, 19 November 2024. Retrieved from: https://www.iotinsider.com/news/10-telecommunications-trends-for-2025/.
3. T. Magri, "2025 Digital Communications Outlook: Top 5 Predictions", Industry Insight, January (2025). Retrieved from: https://www.smarsh.com/blog/thought-leadership/2025-digital-communications-outlook-top-5-predictions.
4. ICT Innovations Set to Dominate in 2025, Telecom Review Europe, December 2024. Retrieved from: https://www.telecomreview.com/articles/ reports-and-coverage/8735-ict-innovations-set-to-dominate-in-2025.
5. Results of the exploratory consultation on the future of the electronic communications sector and its infrastructure, Directorate-General for Communications Networks, Content and Technology (European Commission), October 2023. Retrieved from: https://digital-strategy.ec.europa.eu/en/library/results-exploratory-consultation-future-electronic-communications-sector-and-its-infrastructure.
6. S. Kravchuk, L. Uryvsky, "Prospects for the spread of information technologies and artificial intelligence in the context of Academician Glushkov V.M. predictions", 2023 IEEE International Conference on Information and Telecommunication Technologies and Radio Electronics (UkrMiCo), ISBN: 979-8-3503-4848-4, 13-18 November 2023, Kyiv, Ukraine. – pp. 21-24. Retrieved from: https://doi.org/10.1109/ UkrMiCo61577.2023.10380386.
7. M. Ilchenko, S. Kravchuk, L. Uryvsky, "Continuation of academician V.M. Glushkov work on the development of modern information & communication technologies", Information and Telecommunication Sciences, No. 1, pp. 4-8 (2023) https://doi.org/10.20535/2411-2976.12023.4-8; http://infotelesc.kpi.ua/article/view/281956/276244.
8. Strategy for the digital development of innovative activity of Ukraine for the period until 2030: Order of the Cabinet of Ministers of Ukraine dated 31.12.24 No. 1351-p. Retrieved from: https://zakon.rada.gov. ua/laws/show/1351-2024-%D1%80#Text
9. S.O. Kravchuk, I.M. Kravchuk, "Prospective directions of new research in the field of electronic communications", XIX International Scientific Conference "Modern Challenges in Telecommunications" MCT-2025. Conference proceedings. April 14-18, 2025, Kyiv. - Igor Sikorsky Kyiv Polytechnic Institute, 2025 – pp. 49-51. Retrieved from: https://conferenc-journal.its.kpi.ua/issue/archive (ISSNonline 2664-305)
10. M. Ilchenko, S. Kravchuk, "Mobile Infocommunication Systems", Information and Telecommunication Sciences, Vol. 11, Number 1, pp. 11-19 (2020), (Retrieved from:: https://doi.org/10.20535/2411-2976.12020.11-19)
11. S. Kravchuk, T. Narytnyk, "Telecommunication systems of the terahertz range". – Zhytomyr: FOP "Evenok O.O.", 2015. – 208 p.
12. S. Kravchuk, L. Afanasieva, I. Kravchuk, "Investigation of a millimeter-wave radio link characterstics of IEEE 802.11 AD standard in urban areas", Information and Telecommunication Sciences, N. 1, pp. 5-11 (2021). Retrieved from: https://doi.org/10.20535/2411-2976.12021.5-11 (Published: 2021-06-29).
13. I.P. Vetoshko, S.O. Kravchuk, "Possibilities of improving the voice services quality in 5G networks", Information and Telecommunication Sciences, Vol.14, No 2, pp. 9-16 (2023). Retrieved from: https://doi.org/10.20535/2411-2976.22023.9-16.
14. S.O. Kravchuk, "Theory of mobile information communication systems. System architecture" [Electronic resource]: study guide for bachelor's degree holders, Kyiv: Igor Sikorsky KPI, 2023. – 683p. Retrieved from: https://ela.kpi.ua/handle/123456789/53198.
15. C. D. Alwis, Q.-V. Pham, M. Liyanage, "6G Frontiers: Towards Future Wireless Systems", Wiley-IEEE Press, 2022, 336 p. ISBN: 978-1-119-86234-5
16. A. S. Rao, S. Mole, R. Raju, Beyond 5G and 6G: A Comprehensive Overview of 7G Wireless Communication Technologies, Eur. Chem. Bull, 12 (Special Issue 4), pp. 9725-9739 (2023). Retrieved from: https://www.researchgate.net/publication/373548998_Beyond_5G_and_6G_A_Comprehensive_Overview_of_7G_Wireless_Communication_Technologies_Section_A_-Research_paper_Beyond_5G_and_6G_A_Comprehensive_Overview_of_7G_Wireless_Communication_Technologies
17. G. Cariolaro, "Quantum Communications", Springer, 2015, 680 p. ISBN 978-3-319-15599-9, ISBN 978-3-319-15600-2 (eBook), doi 10.1007/978-3-319-15600-2.
18. D. Minoli, B. Occhiogrosso, "Quantum Communication and Quantum Internet Applications", 2025, 394 p., ISBN 9781032779669.
19. B. Haughian, Design, "Launch, and Scale IoT Services: A Practical Business Approach", First Edition, 2018, 292 p., ISBN-10: 1484237110. Retrieved from: https://www.amazon.com/Design-Launch-Scale-IoT-Services/dp/1484237110.
20. E. Koç, "Internet of Things (IoT) Applications for Enterprise Productivity", 2020, 357 p., doi: 10.4018/978-1-7998-3175-4
21. O. Turovsky, M. Ryzhakov, "Methodological approach to comprehensive identification and analysis of cyberthreats in traffic in 5G/IMT-2020 telecommunication networks based on artificial intelligence technologies", International Scientific-technical journal «Measuring and computing devices in technological processes», Issue 1, pp. 267-277 (2025). Retrieved from: https://doi.org/10.31891/2219-9365-2025-81-33
22. Concept of the State Targeted Scientific and Technical Program for the Use of Artificial Intelligence Technologies in Priority Sectors of the Economy for the Period Until 2026: Order of the Cabinet of Ministers of Ukraine No. 320-p. Retrieved from: https://zakon.rada.gov.ua/laws/ show/320-2024-%D1%80#Text
23. S. O. Kravchuk, "Countering hacker attacks in mobile infocommunications", Kyiv: Igor Sikorsky Kyiv Polytechnic Institute, 2025. – 813 p. Retrieved from: https://ela.kpi.ua/handle/123456789/72330
24. M. Kaidenko, S. Kravchuk, "Protection against the effect of different classes of attacks on UAV control channels", Information and Telecommunication Sciences, No. 1 (2022), pp. 35-43. Retrieved from:: https://doi.org/10.20535/2411-2976.12022.35-43.
25. Security and Privacy in Communication Networks: 19th EAI International Conference, SecureComm 2023, Hong Kong, China, October 19-21, 2023, Proceedings, Part II, Editors: H. Duan, M. Debbabi, X. de C. de Carnavalet, X. Luo, X. Du, M. H. A. Au, Springer Cham, 2025. Retrieved from: https://doi.org/10.1007/978-3-031-64954-7.
26. Network Security and Data Privacy in 6G Communication Trends, Challenges, and Applications, Edited by R. Kumar, V. Jain, D. Ather, V. Kukreja, M. Singhal, CRC Press, 2025. -336 p., ISBN 9781032758176
27. Fog and Edge Computing: Principles and Paradigms (Wiley Series on Parallel and Distributed Computing), by Editor R. Buyya and S.N. Srirama, Part of: Wiley Series on Parallel and Distributed Computing, Wiley, 2019,

512 p., ISBN-10: 1119524989. Retrieved from: https://www.amazon.com/Fog-Edge-Computing-Principles-Distributed/dp/1119524989

28. A. Singh, "Fog and edge computing", 2nd Edition, 2022, 114 p., ISBN-13: 979-8849409917. Retrieved from: https://www.amazon.com/FOG-EDGE-COMPUTING-Ajit-Singh/dp/B0BCCZ9RVC

29. J. Doherty, "SDN and NFV Simplified: A Visual Guide to Understanding Software Defined Networks and Network Function Virtualization", Addison-Wesley Professional, 2016, 320 p., ISBN-10: 0134306406. Retrieved from: https://www.amazon.com/SDN-NFV-Simplified-Understanding-Virtualization/dp/0134306406

30. I.V. Mariyappan, V. Kavitha, R. Aravindaraj, S.C. Chockalingam, and J.M. Guerrero, "Prospects of Network Function Virtualization (NFV) and Software-Defined Networking (SDN): Techniques for Smart Grid Cyber Defense", 2024, 306 p., ISSN:1948-9730-332

31. 31. Green Communications: Principles, Concepts and Practice, Edited By K. Samdanis, P. Rost, A. Maeder, M. Meo, C. Verikoukis, Wiley, 2015, 456 p., ISBN: 978-1-118-75923-3

32. Green Communication Technologies for Future Networks: An Energy-Efficient Perspective, Edited By G. Kaur, A. Srivastava, 2024, 300 p., ISBN 9781032206318

33. A. Kaushik, "Integrated Sensing and Communications for Future Wireless Network: Principles, Advances and Key Enabling Technologies", Elsevier Science & Technology, 2024, 375 p. ISBN 9780443221439

34. L. Afanasieva, D. Minochkin, S. Kravchuk, "Providing telecommunication services to antarctic stations", Proceedings of the 2017 International Conference on Information and Telecommunication Technologies and Radio Electronics (UkrMiCo) 11-15 Sept. 2017 Year, Odessa, Ukraine. IEEE Conference Publications (IEEE Xplore Digital Library, DOI: 10.1109/UkrMiCo.2017.8095419), 2017. – pp. 1-4.

35. M. Ilchenko, S. Kravchuk, M. Kaydenko, "Combined Over-the-Horizon Communication Systems", Advances in Information and Communication Technologies. Processing and Control in Information and Communication Systems. UKRMICO 2018. Lecture Notes in Electrical Engineering, vol 560. Springer, Cham, 2019 - pp. 121-145. Retrieved from: doi: 10.1007/978-3-030-16770-7 (https://doi.org/10.1007/978-3-030-16770-7_6).

36. D. Doody, "Deep Space Craft: An Overview of Interplanetary Flight" (Astronautical Engineering), Springer, 2009, 464 p., ISBN-10: 3642100465.

37. Deep Space Telecommunications Systems Engineering, Edited By J.H. Yuen, National Aeronautics Administration, 2014, 622 p., ISBN 9781495250767.

Кравчук С.О., Кравчук І.М.

Напрямки перспективних досліджень в галузі електронних комунікацій

Навчально-науковий інститут телекомунікаційних систем КПІ ім. Ігоря Сікорського, м. Київ, Україна

Проблематика. На сучасному етапі електронні комунікації повинні забезпечити: надшвидкий обмін даними між виробничими системами, що підвищує продуктивність та безпеку; використання роботизованих систем та штучного інтелекту для підтримки людей у виробничих процесах. Надійні електронні комунікації забезпечують безпеку промислових мереж і персональних даних; інтелектуальні фабрики з мережними сенсорами та автоматизованими системами обробки даних. В цьому контексті перед електронними комунікаціями постають нові виклики й відповідно їм визначаються нові проблеми, вирішення яких потребує проведення перспективних наукових досліджень.

Мета досліджень. Метою даної роботи є узагальнення та висвітлення ключових напрямків розвитку електронних комунікацій, які визначають сучасний та майбутній стан галузі. Вона спрямована на окреслення наукових викликів і перспектив, що пов'язані з цифровізацією суспільства, зростанням попиту на швидку, надійну та безпечну передачу даних.

Методика реалізації. Аналіз факторів та технологій, що впливають на зростання потреб в подальшому розвитку електронних комунікацій, якості надання телекомунікаційних послуг у мережах п'ятого і наступного покоління, впровадження нових видів електронних комунікацій та їх інтеграція з передовими інформаційними технологіями.

Результати досліджень. Представлені напрями досліджень визначають майбутнє електронних комунікацій. Дослідження у цих сферах дозволять забезпечити стійкий розвиток галузі, враховуючи зростаючі потреби сучасного суспільства у швидких, безпечних та надійних технологіях передачі даних.

Висновки. Основна мета напрямку 6G та майбутніх поколінь мереж є створення надшвидких, наднадійних та інтелектуальних мереж, здатних підтримувати нові види сервісів і додатків, від автономного керування та дистанційної медицини до повномасштабних мультимедійних комунікацій.

Напрямок квантових комунікацій — це революційний напрямок, який обіцяє забезпечити абсолютну безпеку передачі інформації та відкрити нові можливості для зв'язку. Напрямок масштабування IoT — це ключовий напрямок, який визначає майбутнє багатьох комунікаційних технологій.

Напрямок досліджень, що включає штучний інтелект (AI) та машинне навчання (ML), вимагає ще більше інтеграції AI та ML у всі аспекти електронних комунікацій, що призведе до створення більш розумних, ефективних і безпечних мереж. Безпека та конфіденційність у електронних комунікаціях — це динамічний напрямок, який постійно розвивається через зростання кіберзагроз та технологічний прогрес.

Edge та Fog Computing є ключовими технологіями для майбутнього електронних комунікацій, і їх розвиток вимагає міждисциплінарного підходу, що поєднує комп'ютерні науки, телекомунікації, AI та IoT. Дослідження у сфері NFV та SDN необхідні для покращення продуктивності, автоматизації та безпеки мереж. Вони відіграють ключову роль у майбутньому 5G/6G, хмарних обчислень, IoT та промислових мережах.

Зелені комунікації є важливим напрямом досліджень, що спрямований на підвищення енергоефективності та сталості телекомунікаційних мереж. Мережі для критично важливих застосувань є ключовим елементом сучасних інфраструктур, і їх розвиток вимагає міждисциплінарного підходу, що поєднує телекомунікації, кібербезпеку, штучний інтелект та інші галузі. Технології взаємодії голографічних і тактильних комунікацій станут основою майбутніх цифрових комунікацій, змінюючи способи взаємодії людей та машин.

Ключові слова: *6G; квантові комунікації; зелені комунікації; безпека та конфіденційність; інтернет речей; штучний інтелект; глибокий космос; віртуалізація мережевих функцій; критично важливі мережі; голографічні та тактильні комунікації.*

Received by the Editorial Office
June 3, 2025

Accepted for publication
September 25, 2025