Abstract

to the thesis research. A subject of this thesis paper:

«Research and Development of Wearable Microstrip Antennas on Textile Substrate»,

submitted for the PhD degree in specialty 8D06201 – «Radioengineering, electronics and telecommunications»

by

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Relevance of the research topic

In Kazakhstan, digitalisation and the development of telecommunication technologies are among the principal priorities of state policy. The importance of this direction is reflected in the adoption by the Government of the Republic of Kazakhstan of the Concept for Digital Transformation, Development of the Information and Communication Technologies Sector and Cybersecurity for 2023–2029, as well as in the declaration of 2026 as the Year of Digitalisation and Artificial Intelligence. Under the conditions of digital transformation, particular importance is attached to Internet of Things (IoT) technology. At present, IoT is applied in the monitoring of industrial processes, the management of transport systems, healthcare, urban infrastructure and other fields.

One of the most rapidly developing areas of IoT technology is the development of wearable (body-centric) devices intended for the continuous monitoring of the parameters of a person and of the surrounding environment. In medicine, such devices are used for the remote monitoring of physiological indicators such as heart rate, blood pressure and body temperature. In sport, they make it possible to record parameters related to the physical activity of a person. In smart-city and safety systems, wearable devices may be used for emergency communication, location tracking and the provision of industrial and social safety.

One of the key components determining the quality and reliability of the wireless communication of a wearable IoT device is the antenna. It converts electrical signals into electromagnetic waves and performs the inverse conversion during reception. This ensures the wireless connection of the device with the external network. At present, the large-scale deployment of wearable IoT solutions is constrained by the problems of maintaining the stability of the antenna characteristics and of meeting the electromagnetic safety requirements when the antenna is placed close to or directly on the human body.

Several factors contribute to this problem. First of all, when the antenna is located close to the human body, part of the radiated energy is absorbed in biological tissues. Therefore, the specific absorption rate (SAR) must be controlled and compared with the limits set by international electromagnetic safety requirements: 1.6 W/kg averaged over 1 g of tissue according to the FCC and 2 W/kg averaged over 10 g of tissue according to ICNIRP. The second important issue is related to the

integration of the antenna into clothing or accessories. In this case, the use of flexible textile materials is required. Their permittivity and dielectric loss tangent differ from the parameters of the rigid dielectric substrates widely used in microstrip antennas: the relative permittivity of the fabrics used in wearable antennas typically lies within 1.1–1.9, whereas for rigid substrates it ranges from 2.2 to 12. A low permittivity may broaden the bandwidth, but soft fabric retains its shape poorly, which makes it difficult to keep the antenna geometry stable.

During operation, wearable antennas are also subjected to various mechanical influences, including bending, stretching and compression. Such deformations lead to changes in the antenna geometry. As a result, the resonant frequency is shifted and the main operating characteristics may deteriorate. Of these deformation types, bending was investigated in this work.

The analysis of the literature makes it possible to identify two unresolved issues. Firstly, textile microstrip antenna arrays have been studied fairly extensively; however, since different authors use different designs and measurement methodologies, a direct comparison of the influence of different fabrics on the antenna characteristics is not possible.

Secondly, directional Yagi–Uda antennas with a gain of 8–12.4 dBi have been implemented on rigid substrates or on metal bases with resonant cavities, which precludes their integration into clothing, whereas known textile directional antennas provide no more than 5.3–5.45 dBi. Existing solutions do not simultaneously combine a full-size Yagi–Uda topology, a high gain and a fully textile implementation.

A frequency of 2.45 GHz was selected as the operating frequency of the antennas under development. This frequency belongs to the ISM band intended for industrial, scientific and medical purposes. One of the main reasons for this choice is the compatibility of this band with the wireless communication technologies widely used in IoT devices, such as Wi-Fi, Bluetooth and Zigbee. In addition, the ISM band does not require licensing. The free-space wavelength is approximately 122 mm, while the resonant length of a patch on denim is about 48 mm, so the element fits easily into clothing. Increasing the frequency would reduce the antenna size but increase losses in body tissues. Therefore, this band is considered a suitable solution for the design of wearable antennas for various types of IoT applications.

The present dissertation research is aimed at solving the scientific and technical problems outlined above. A two-element linear antenna array of identical geometry is used as the initial structure for establishing the regularities of the influence of the electrophysical properties of textile substrates on the characteristics of wearable antennas, and on the basis of these regularities a fully textile microstrip Yagi–Uda antenna operating at 2.45 GHz has been developed. For both antennas, the influence of bending was studied (on a prototype for the array and by simulation for the Yagi–Uda antenna), and the SAR values under on-body placement were calculated and compared with the FCC and ICNIRP limits.

Aim of the research

The aim of the work is to establish, in the course of developing textile-based wearable microstrip antennas operating at 2.45 GHz, the regularities of the influence of the electrophysical properties of the substrates on the antenna parameters.

Objectives of the research

To achieve the stated aim, the following objectives have been defined:

1. To analyse and identify methods for the development of wearable microstrip antennas.
2. To establish the regularities of the influence of the electrophysical properties of textile substrates on the antenna parameters by developing a two-element antenna array.
3. To develop and optimise a Yagi–Uda antenna on textile substrates.
4. To investigate the resistance of the developed antennas to mechanical deformation and to assess their electromagnetic safety.
5. To investigate and comparatively assess the electrodynamic characteristics of the two topologies of the developed wearable antennas.

Object and subject of the research

The object of the research is wearable microstrip antennas on a textile substrate.

The subject of the research is the regularities of the influence of the geometric parameters of the antenna, the electrophysical properties of the substrate, bending and the effect of the human body on the electrodynamic characteristics of the antenna and on the specific absorption rate.

Research methods

The following methods were used to solve the stated objectives:

– analytical calculation of the geometry of the radiators, the feed network and impedance matching based on the theory of microstrip antennas and antenna arrays;

– full-wave numerical simulation with parametric optimisation in the CST Studio Suite 2024 software package;

– fabrication of prototypes on felt, denim, polyester and cotton substrates with conductive layers made of conductive fabric and copper tape;

– measurement of the reflection coefficient S_{11} of the prototypes with a NanoVNA 2024 vector network analyser; the radiation pattern, gain and radiation efficiency were determined by simulation only;

– simulation of the influence of bending on cylindrical surfaces with radii of 55–90 mm on the resonant frequency, impedance matching and radiation pattern, with experimental verification by S_{11};

– assessment of the electromagnetic safety of the antenna by numerical simulation of the specific absorption rate on a voxel model of the human body in CST and verification of its compliance with the ICNIRP and FCC limits.

Scientific novelty of the conducted research

The scientific novelty of the dissertation consists of the following results:

1. On the basis of a study of a two-element antenna array and a Yagi–Uda antenna on various textile materials, the regularities of the influence of the electrophysical properties of textile substrates on the characteristics of wearable microstrip antennas have been established.

2. For the first time, a topology of a wearable microstrip Yagi–Uda antenna has been proposed in which all elements are placed on the textile substrate layer, providing broad radiation and high gain.

Main statements submitted for defence

The following main statements are submitted for defence:

Statement 1. The gain and radiation efficiency of a two-element antenna array on a textile substrate depend on the substrate material rather than on the material of the conductive layer; therefore, the radiation characteristics of the antenna are preserved when the conductive materials are interchanged.

Statement 2. The proposed topology of the Yagi–Uda antenna, with all elements placed on the textile substrate layer and developed without multilayer structures or vias, provides a gain of 8.3–8.7 dBi in the 2.45 GHz ISM band while retaining flexibility.

Statement 3. The regularity of the influence of the relative permittivity of the textile substrate on the characteristics of wearable microstrip antennas is independent of the topology: as ε_r increases from 1.45 to 1.9, both the two-element array and the Yagi–Uda antenna show a decrease in directivity and gain and a broadening of the main lobe of the radiation pattern.

Practical significance of the work

The practical significance of the work lies in the fact that the established regularities of the influence of the electrophysical properties of textile materials on the antenna characteristics make it possible to select the substrate material and geometry of wearable antennas on a justified basis. The developed textile Yagi–Uda antenna with a gain of 8.3–8.7 dBi can be used in radio communication devices of safety and rescue services, as well as in wearable IoT devices for medical and sports monitoring and smart-city systems. The implementation of the results of this research is confirmed by the act of implementation of research results issued on 9 September 2025 by the Malaysian Institute of Marine Engineering Technology (UniKL MIMET, Lumut, Malaysia). According to this act, the scientific results and technical solutions concerning the increase of the gain of microstrip antennas have been introduced into the educational process of the institute and are used in lectures and laboratory work. The results of the dissertation may be further used within relevant research projects in the field of electronics.

Correspondence to the directions of science development and state programmes

The work corresponds to the priorities of the state policy of the Republic of Kazakhstan in the field of digitalisation defined by the Concept for Digital Transformation, Development of the Information and Communication Technologies Sector and Cybersecurity for 2023–2029, approved by Resolution of the Government of the Republic of Kazakhstan No. 269 of 28 March 2023.

Reliability of the obtained results

The reliability of the obtained results is ensured by the use of classical analytical relations of microstrip antenna theory, by simulation in the well-established CST Studio Suite package with control of mesh convergence, by the fabrication of physical prototypes and the measurement of their reflection coefficient with a calibrated vector network analyser, and by the publication of the results in peer-reviewed journals.

Personal contribution of the author to obtaining the scientific results

All original results presented in the dissertation, including the calculation of the geometric parameters of the antennas, electrodynamic simulation in the CST Studio Suite software package, the fabrication of the prototypes, the performance of the experimental measurements and the comparative analysis of the obtained results, were obtained by the author personally or with the direct participation of the author.

Approbation of the work

The report “A review of the multilayered microstrip antennas for IoT applications”, which covers the main results and methods of the research presented in the dissertation, was delivered at the XII International Scientific and Technical Conference “Power Engineering, Infocommunication Technologies and Higher Education” (Almaty, 20–21 October 2022), and the report “Comparative Study of Textile Based Wearable Antenna Designs for IoT Applications” was delivered at the IEEE SIST International Conference (Astana, 2026).

Publications

The main results of the dissertation have been published in the following scientific editions: the review article “Analytical review of a multilayer microstrip Yagi-Uda antenna for Internet of Things (IoT) applications” (in Russian) in the journal “Nauchnye trudy VIIREiS” (2022); the paper “A review of the multilayered microstrip antennas for IoT applications” in the proceedings of the XII International Scientific and Technical Conference (2022); the article “Characterization of high impedance of multilayer coplanar waveguide transmission line design for integration with nanodevices” in the Eastern-European Journal of Enterprise Technologies (2022); the article “Evaluation of high frequency behavior of the coplanar waveguide transmission line for integration with self-switching nanodevice” in the journal “Vestnik of the Almaty University of Power Engineering and Telecommunications” (2022); the article “Design of the Wearable Microstrip Yagi-Uda Antenna for IoT Applications” in the International Journal on Communications Antenna and

Propagation (IRECAP) (2024); the article “The Development and analysis of a wearable textile Yagi-Uda antenna design for security and rescue purposes” in the editions of the National Academy of Sciences of the Republic of Kazakhstan (2024); the paper “Comparative Study of Textile Based Wearable Antenna Designs for IoT Applications” in the proceedings of the IEEE SIST conference (2026); the collective monograph “Intelligent telecommunication solutions for 5G/6G networks and Smart City in ultra-dense urban environments” (in Russian) (Aldasheva L.S., Amirova A.S., Tussupov A.D., Nurzhaubayeva G.S., Abdiraman A.S., “Daryn” publishing house, Almaty, 2026); the article “Performance Evaluation of Wearable Antenna Arrays for IoT Applications in Smart City” in the International Journal of Antennas and Propagation (2026); the review article “Wearable Microstrip Antennas for IoT: A Comprehensive Review of Application Areas, Textile Materials, and Body-Centric Design Techniques” in the journal “Vestnik of the Almaty University of Power Engineering and Telecommunications” (2026). The publications include works in editions indexed in the Scopus database (percentiles 47–63%), as well as in editions recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan. In total, 10 scientific works have been published on the topic of the dissertation and on related issues, including 3 articles in editions indexed in the Scopus database, 4 articles in editions recommended by the Committee for Quality Assurance in Science and Higher Education, 2 papers in the proceedings of international conferences and 1 collective monograph.

Volume and structure of the dissertation

The dissertation consists of an introduction, five chapters, a conclusion, a list of scientific works, a list of references and an appendix. The total volume is 109 pages, including 42 figures and 13 tables; the list of references contains 123 items.

The introduction substantiates the relevance of the research topic and defines the aim and objectives of the work. The object and subject of the research are determined, the scientific novelty and the statements submitted for defence are formulated, and information is provided on the personal contribution of the author, the approbation of the work, its practical significance and the publications.

The first chapter describes the electrophysical properties of textile materials and the main application areas of wearable microstrip antennas for IoT technologies, and provides a review of the types of textile materials and of the technologies for their fabrication based on literature data. The electrophysical properties of the textile and conductive materials used in the research are analysed, and the regularities of their influence on the electrodynamic characteristics of the antenna are considered. In addition, a review of existing wearable antennas for IoT systems is carried out and the choice of the antenna topologies used in the research is substantiated.

The second chapter sets out the general methodology of antenna design. The choice of the feeding technique for the radiating elements is substantiated, and

analytical relations for calculating the geometric parameters of the radiator and of the feed line are given. Quantitative criteria for evaluating the antenna characteristics (the reflection coefficient, the voltage standing wave ratio and the radiation efficiency) are formulated. A generalised algorithm for the design and parametric optimisation of the antenna structure in the CST Studio Suite software package is also proposed.

The third chapter considers the design and optimisation of a two-element linear antenna array on a textile substrate. First, the main geometric parameters of the array are calculated. Then electrodynamic simulation and parametric optimisation are carried out in CST Studio Suite for six configurations formed by combinations of three textile substrates (felt, denim, polyester) and two conductive materials (conductive fabric, copper tape). The simulation results are compared with the S_{11} values measured with a NanoVNA vector network analyser. In addition, the characteristics of the array under bending with radii of 55–90 mm are studied, and the specific absorption rate is calculated on a voxel model of the human body. On the basis of the six configurations, the regularities of the influence of the properties of textile materials on the antenna characteristics are established.

The fourth chapter presents the results of the design and optimisation of a microstrip Yagi–Uda antenna on a fully textile substrate, developed with account of the established regularities. The dimensions of the driven element, the reflector and the directors are determined, and configurations on three substrates (polyester, denim, cotton) are simulated in CST Studio Suite. The calculated results are verified against S_{11} measurement data. The bending resistance of the antenna and the specific absorption rate on a voxel model of the human body are assessed using the methodology of the third chapter.

The fifth chapter presents a comparative analysis of the electrodynamic characteristics of the initial two-element linear antenna array and of the Yagi–Uda antenna developed with account of the established regularities. It is shown that, as the relative permittivity of the substrate increases from 1.45 to 1.9, the directivity and gain of both topologies decrease and the main lobe broadens, i.e. the regularity of the substrate influence is independent of the topology.

The conclusion summarises the main results of the dissertation and shows that the aim of the research has been achieved. The results of solving the stated objectives are summarised, and the main scientific and practical results of the work are formulated. Promising directions for further research and improvement of textile antennas for IoT applications are also outlined.

The appendix contains the act of implementation of research results issued by the Malaysian Institute of Marine Engineering Technology (UniKL MIMET).