Study of the characteristics of broadband matching antennas for fifth-generation mobile communications based on new composite materials

Balausa Nakisbekova[1], Assel Yerzhan[1], Pavel Boykachev[2], Zhanat Manbetova[3], Manat Imankul[4], Anar Shener[1], Muratbek Yermekbaev[1], Pavel Dunayev[3]

[1]Department of Telecommunication Engineering, Institute of Communications and Space Engineering, Non-profit Joint Stock Company Almaty University of Power Engineering and Telecommunication named Gumarbek Daukeev, Almaty, Republic of Kazakhstan
[2]Department of Tactics and Weapons of Radio Engineering Troops, Faculty of Air Defense, Military Academy of the Republic of Belarus, Minsk, Republic of Belarus
[3]Department of Radio Engineering, Electronics and Telecommunications, Faculty of Energy, Saken Seifullin Kazakh Agrotechnical Research University, Astana, Republic of Kazakhstan
[4]Department of Radio Engineering, Electronics and Telecommunications, L.N. Gumilev Eurasian National University, Astana, Republic of Kazakhstan

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ABSTRACT

The presented research aims to analyze in detail the characteristics of broadband matching antennas specifically designed for 5G mobile communications applications, with an emphasis on innovative composite materials. The study focuses on a compact planar loop antenna designed for use on smartphones, covering the LTE/WWAN frequency bands 824 to 960 MHz, 1,710 to 2,690 MHz, and 3,300 to 3,600 MHz for full coverage of modern 5G networks. Experimental and numerical methods are used to broadly analyze the frequency range associated with 5G networks. The features of the use of composite materials in the implementation of antenna devices in 5G technologies are noted. A broadband matching circuit (BMC) with elements with lumped parameters and a reduced sensitivity invariant has been synthesized. A 3D model of the adaptive selective surface controller (SSC) was developed using CST Studio. The study results highlight the benefits of new composite materials in improving the performance of 5G antennas. This research makes a significant contribution to the development of 5G technologies by optimizing antenna design for efficient data transmission in modern mobile networks and can be a valuable resource for engineers and designers working in this field.

Corresponding Author:

Assel Yerzhan
Department of Telecommunication Engineering, Institute of Communications and Space Engineering, Non-profit Joint Stock Company Almaty University of Power Engineering and Telecommunication named Gumarbek Daukeev
Almaty, Republic of Kazakhstan
Email: asel.yerzhan@inbox.ru

1. INTRODUCTION

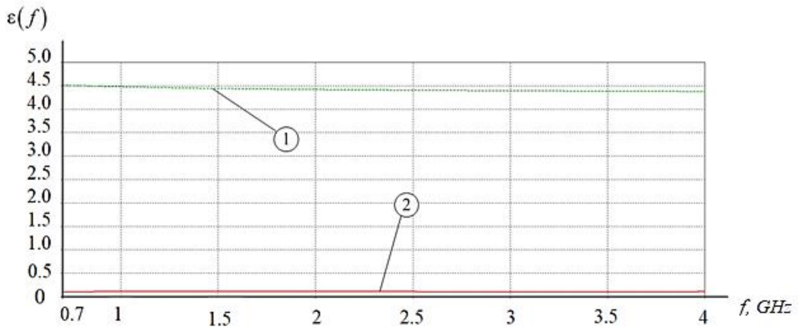
In today's era of rapid development of fifth-generation (5G) mobile technologies, broadband matching antennas play a key role in ensuring efficient data transmission. With the ever-increasing requirements for bandwidth and data rates in mobile communications, the need for innovative approaches to antenna design has become more urgent. This study provides a comprehensive analysis of the performance of broadband matching antennas intended for use in 5G networks, with a particular focus on the use of new composite materials. These materials represent innovative solutions aimed at optimizing the efficiency and performance of antenna systems. The study examines not only the technical aspects of antennas but also their applicability in the context of dynamically developing 5G technologies. The analysis of new composite materials in the context of broadband matching antennas provides unique opportunities to improve the performance of modern mobile communications, thereby creating new prospects for the development of related technologies and sustainable growth in the field of mobile networks. Compared with 4G communication, 5G communication has notable improvements in throughput, channel capacity, latency, and other aspects [1], [2]. 5G radio systems require new and more efficient antenna designs. Antenna selection is critical in 5G technology, which uses more frequency bands than 4G. Limited internal space and placement limitations of universal smartphone antenna systems affect the number of antenna elements. To solve this problem, each antenna element must be minimized [3], [4] and operate in wideband mode [5], [6]. A broadband antenna is required for 5G applications to access high-speed, low-latency Internet services and ultra-high-definition video streaming. However, the bandwidth of antenna systems can be limited by the harsh electromagnetic environment created by metal frame construction. Consequently, designing the required antenna configurations in confined spaces to avoid excessive interference while achieving high efficiency and channel independence has become an increasingly pressing and challenging problem. It is also required to use methods for synthesizing a wideband matching circuit that ensures maximum power transfer from the signal source (radio device (RTU)) to the antenna with varying load (antenna) resistance of the remote terminal unit (RTU). A change in the value of the complex resistance (impedance) of the antenna causes a mismatch between the RTU path and the antenna. This mismatch leads to the appearance of a reflected wave in the RTU path, which leads to the loss of power of the transmitted (or received) signal. One of the possible solutions to this problem is to use composite materials with controlled microwave properties (dielectric (ε) and magnetic permeability (μ)), which changes the characteristic impedance and geometric dimensions of the microstrip line, expanding the ability to provide the required electromagnetic characteristics of a mobile device. Thus, Huawei and Ericsson prefer to use microwave dielectric ceramic materials, while Zhongxing Telecom Equipment (ZTE) and Nokia still prefer miniature metal hollow filters. This publication will study the effect of changing the composite substrate material on the characteristics of the power transfer ratio (PTR) level (power transfer coefficient) of a mobile antenna in the operating frequency range, which, for clarity, will be characterized by the dependence of standing wave ratio (SWR) on frequency. Methods for solving broadband matching problems will also be investigated, leading to a maximum reduction in power losses of the transmitted (or received) signal in the antenna under consideration.

2. METHOD

Mechanisms for achieving low mutual coupling effects have been proposed in [7]–[9], but the designs of these studies require a distance between antenna pairs to maintain good isolation. In [10], a simple small-sized planar loop antenna with dimensions of 15×27 mm^2 is considered, which we will use as the antenna under study. This antenna includes tuning lines to achieve good impedance matching for the wireless wide area network/long-term evolution (WWAN/LTE) bands. Many antenna systems are designed to be placed on the edge or corner of a printed circuit board. To optimize circuit efficiency, impedance matching, and RF transmission lines must be considered. Impedance matching is always performed at 50 Ohms. Proper matching ensures that most of the power from the source (RTU) is transferred to the antenna and vice versa to receive data. The printed circuit board (PCB) traces (the transmission lines that carry RF power from the source to the antenna) must also match the impedance of the antenna and the rest of the circuitry. The antenna in question is connected to the transceiver module using a micro coaxial line with a resistance of 50 Ohms at point A, and at the end a short-circuited bending strip of the coupling is connected to the ground plate through a through hole in the substrate. The base material Flame Retardant-4 (FR-4) is used as a dielectric substrate in this antenna with dielectric constant characteristics, which are presented in Figure 1. The substrate based on the FR-4 material has a relative dielectric constant of 4.4 and a dielectric loss tangent of 0.02 (does not exceed hundredths of one). FR-4 is a fire-resistant material, which is a polymer system based on epoxy resin, which uses fiberglass as a reinforcing component. Having almost zero water absorption, FR-4 is most often used as an electrical insulator with significant mechanical strength [11]–[13].

The antenna for estimating the standing wave ratio (SWR) was recreated in the microwave simulation software environment CST Studio 2020 [14]. The structural model of the antenna is shown in 3D in Figure 2. Using this modeling environment provides an accurate study of antenna performance, including its efficiency and compliance with standards. By connecting this antenna to a signal port with a nominal impedance of 50 Ohms, we obtain the SWR function shown in Figure 3. This SWR function reflects the efficiency of signal transmission between the antenna and the signal port, and its analysis allows us to evaluate the antenna's compliance with the matching requirements. impedance. The results obtained have important implications for optimizing antenna efficiency in the context of intended applications in communication networks.

From Figure 4 it follows that this antenna, when connected to a signal port with a resistance of 50 Ohms, provides an SWR value of 3 to 5 in the range of 830 to 960 MHz and from 1.8 to 5.5 in the range of 1,710 to 2,690 MHz. This corresponds to coupling and power matching (CPM) losses in the range of 25% to 50% of the maximum value and is an unfavorable result. To solve this problem, a composite material consisting of fluorinated ethylene-propylene in combination with strontium hexaferrite SrFe12O19 in the ratio of 50% to 50%. The characteristics of this material, in the form of the dependence of dielectric (dashed line) and magnetic permeability (solid line) on frequency. 1 – real component; 2 – imaginary component.



1 – real component; 2 – imaginary component

Figure 1. Dependence of the dielectric constant of FR-4 on frequency

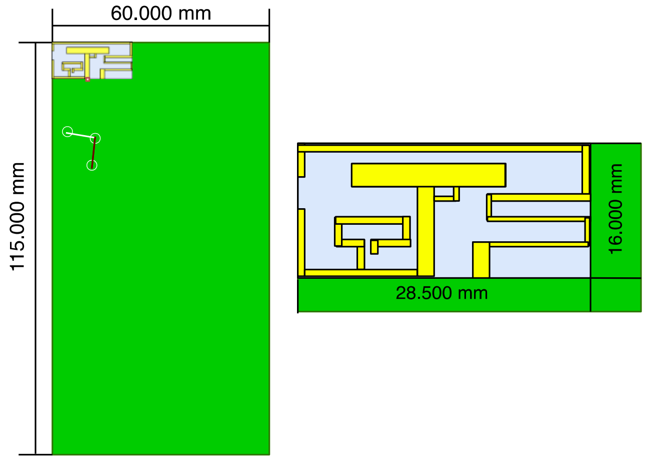


Figure 2. 3D model of a small planar loop antenna for WWAN/LTE frequency range

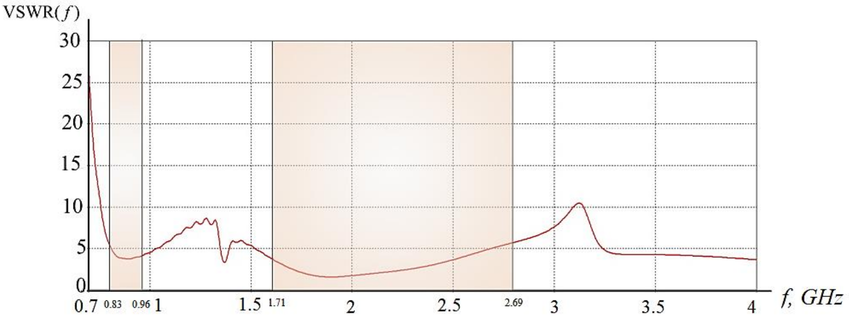
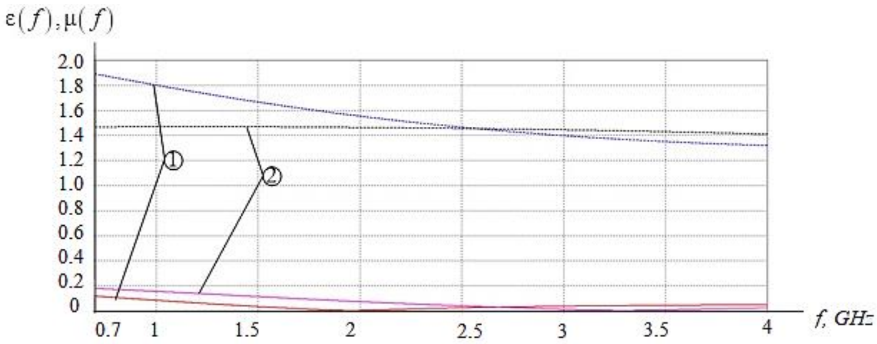


Figure 3. Dependence of SWR of a small planar loop antenna on frequency



1 – real component; 2 – imaginary component

Figure 4. Dependence of the dielectric and magnetic permeability of composite material on frequency, developed at the State Scientific and Practical Center of the National Academy of Sciences of Belarus for Materials Science

When replacing the substrate material in a planar loop antenna with a traditional FR-4 with a developed composite material (consisting of a mixture of fluorinated ethylene propylene resin and strontium hexaferrite SrFe12O19 in a ratio of 50% to 50%), a change in the dependence of the SWR on frequency is observed, as shown in Figure 5. These changes reflect the effect of the new composite material on the antenna's performance, which is of interest for optimizing its performance under specific application conditions. The data obtained can serve as a basis for further research and improvement of antenna performance in various use scenarios.

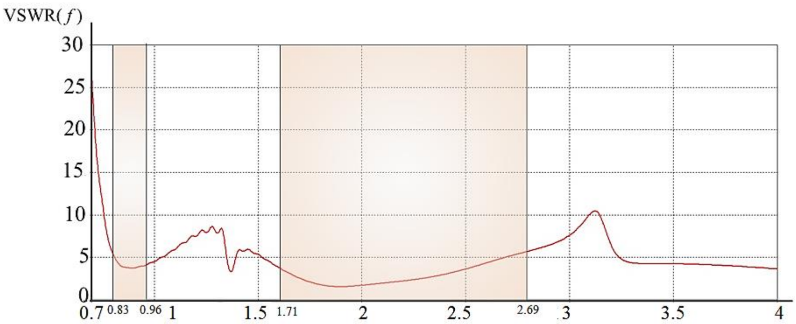


Figure 5. Dependence of SWR of a small-sized planar loop antenna deposited on a composite material on frequency

Analyzing the results presented in Figure 6, we can conclude that replacing the traditional FR-4 material with a composite material leads to a decrease in SWR values in the considered frequency ranges. This is achieved without the need to add additional radio devices (RTD), which makes the use of a composite material more effective in terms of reducing power transfer factor (PTF) losses compared to the use of FR-4 material. These findings are of practical significance for further optimization of antenna systems in 5G mobile communications.

Special attention should be paid to the fact that the microwave properties of most materials are strongly correlated with external influences (in particular, temperature), changes which will affect the complex resistance of the RTU. Thus, the influence of changes in the complex resistance of the antenna deposited on a substrate made of composite material on the dependence of the SWR function on frequency, caused by disturbing influences and leading to a deviation of the load impedance by ±25% from the nominal value, was considered. Figure 7 shows the results of a study of the effect of load impedance deviation on the SWR level, obtained during simulation in the design and simulation environment for RF/microwave components, printed circuit boards, and monolithic integrated circuits AWR Microwave Office [15]–[17]. The solid line in Figure 7 shows the results without deviation of the antenna impedance, and the dashed lines with deviations of the load impedance by ±25% of the nominal value.

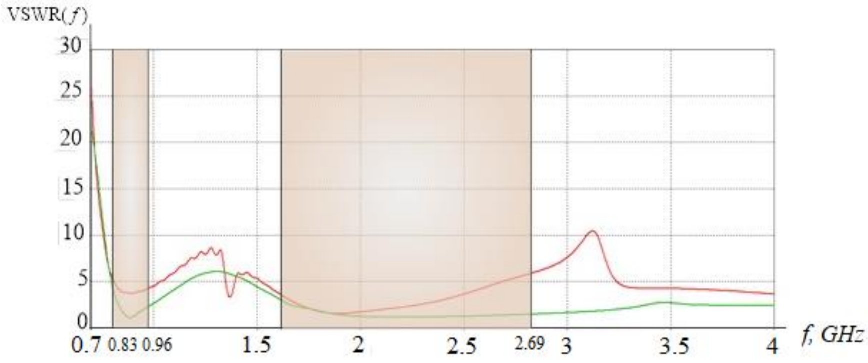


Figure 6. The final dependence of SWR on frequency

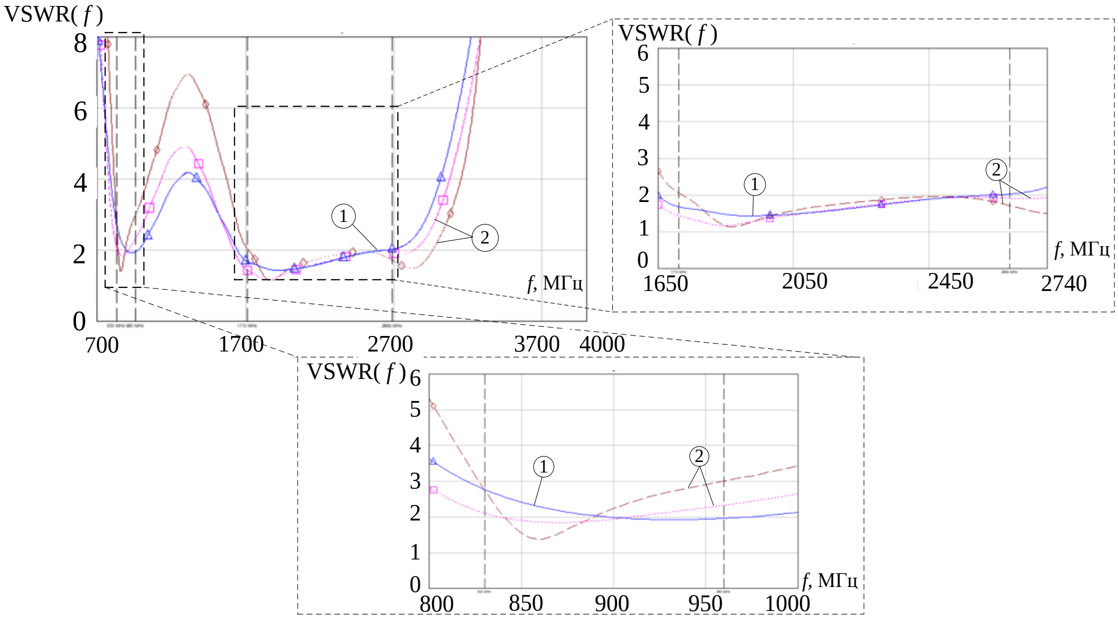


Figure 7. Dependence of SWR of a small-sized planar antenna on frequency when the load impedance deviates by ±25% from the nominal value

From the results presented in Figure 8, it follows that a load impedance deviation of ±25% from the nominal value leads to an increase in the SWR level from three to four in the range of 830 to 960 MHz and from 2.2 to 3.1 in the range of 1,710 to 2,690 MHz. In this connection, the potential functioning of the antenna in question is reduced. As a result, a broadband matching circuit (WMC) with ndc=2 and np=3 was synthesized, providing a reduction in the sensitivity invariant from 0.047 to 0.037 for the range of 830 to 960 MHz and from 0.038 to 0.034 for the range of 1,710 to 2,690 MHz. Sensitivity (absolute sensitivity) is understood as a measure of change in some characteristic of the SSC (circuit function), which occurred as a result of some change in one or more elements of the SSC [18], [19]. The resistance function of the synthesized SSC looks like this:

$$Z_{\text{mc}}(s) = \frac{1.28+1.95s+1.73s^2+0.5s^3+0.04s^4}{s+1.52s^2+0.42s^3+0.09s^4} \quad (1)$$

Based on expression (1) for the resistance function, the corresponding electrical circuit of the broadband matching circuit (BMC) was derived. The values of the elements of this circuit were selected from the standard range of E24 resistor values, providing optimal values for the given resistance function. This representation of the electrical circuit of the SSC in the form of a series of ratings facilitates the practical implementation and configuration of the antenna system by the required characteristics.

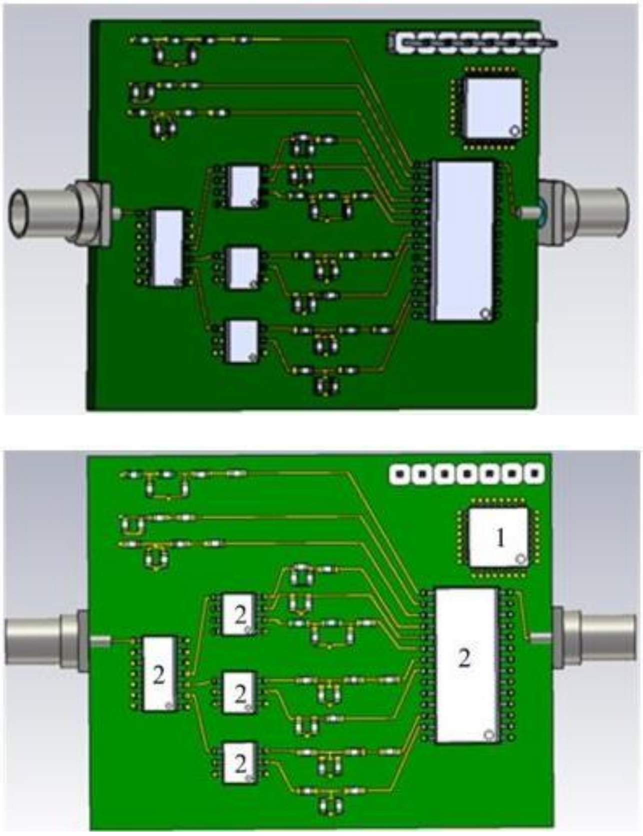


Figure 8. 3D model of the developed adaptive matching device

3. RESULTS AND DISCUSSION

In our research, based on the data you provided, we conducted a detailed comparison of two leading generative This antenna has a dielectric substrate based on a composite material consisting of fluorinated ethylene propylene in combination with strontium hexaferrite SrFe12O19 in a ratio of 50% to 50% and providing high insulation. It is shown that power transfer coefficient losses in the operating frequency range are significantly reduced relative to losses using a dielectric substrate based on FR-4. This SSC regulates the impedance and allows you to expand the bandwidth. The results show good impedance matching, which will provide reliable interference protection for the antenna system and improve its efficiency. The study of the effects of antenna impedance deviation on the level of standing wave ratio was obtained during simulation in the design and simulation environment for RF/microwave components, printed circuit boards, and monolithic integrated circuits AWR Microwave Office. The antenna exhibits good performance over a wide frequency range, making it suitable for 5G mobile communications devices. The main advantage of the antenna under study is that it covers various wireless service ranges in a very compact size and meets the requirements for wide bandwidth, light weight, and ease of manufacture. Acts of implementation of the synthesized/developed adaptive SSC into production were noted. The proposed 5G multi-band antenna with adaptive SSC reduces the number of antennas, system complexity, cost, and size of the mobile device. Currently, most mobile communications devices require a small planar antenna operating in multiple frequency bands to cover a large number of modern communications services. The planar structure without any ohmic loss makes it an ideal candidate for 5G portable devices. However, limited space in smartphones poses significant challenges in implementing 5G antenna technology while ensuring high isolation between antennas and wide operating frequency bands. Contributions to broadband access can be made in a variety of ways, such as through effective methods of increasing isolation. The insulation can be adjusted, for example, by changing the value of the capacitor, but this method is limited by reducing the size of the insulating element. In addition, the isolation level is limited by two aspects (the size of the T-slot and the capacitor capacity of the chip), which increases the complexity of the antenna. As a substrate for the antenna structure, we use, as noted above, a new composite material obtained from a combination of fluorinated ethylene-propylene resin, which has a maximum operating temperature of 205 °C (melting point 265 °C) [20], and strontium hexaferrite, having the necessary thermomechanical stability. The main task of synthesizing the SSC is to ensure the required level of PMC [21], and the correct choice of the method for synthesizing a broadband matching circuit ensures maximum power transfer from the signal source (RTU) to the load (antenna) with a changing impedance (complex resistance) of the radio device load.

To improve the potential functionality of the antenna, some works have explored the possibilities of applying existing synthesis methods (analytical, numerical, graphic-analytical synthesis methods) to the synthesis of BMC in the problems of adapting RTUs to disturbing influences on them and have developed broadband matching circuits for various types of loads (antennas). As shown in [22], the use of analytical theory for the synthesis of SSC, taking into account the changing impedance of the load (in our case, the antenna), is impractical. For the SSC to provide minimal sensitivity to solve the problem of synthesizing the SSC taking into account the influence of changes in load parameters, it is preferable to use the parametric synthesis method. In [23], to solve the problem of mismatch between the RTU path and the antenna, the method of synthesizing an adaptive matching device (MC) was used, which is a method of real (real) frequencies with a parametric representation of the denominator of the real part of the resistance function of the matching circuit (real frequency parametric approach) (as a method of synthesis of SSC (based on [24]). The main advantage of this method is that it does not require an approximation of the load impedance, and the CPM function is represented as an analytical expression. So, when designing microwave radio-electronic devices (including antenna devices), solving problems of broadband matching is important. When setting the dispersion parameters of matched microwave devices in the form of numerical discrete dependences of the module and argument on frequency, the matching problem can be solved exclusively by numerical methods. When the matching circuit is found using analytical methods, success in solving matching problems is directly related to the determination of adequate mathematical models (fractional rational functions) of matched loads of the form:

$$f(s) = \frac{a_0+a_1 s+a_2 (s)^2+\cdots+a_n (s)^n}{b_0+b_1 s+b_2 (s)^2+\cdots+b_m (s)^m} \quad (2)$$

where s is the complex frequency.

The obtained results of synthesizing the structure of a BMC are presented in Figure 9 in the form of a dependence of the SWR on frequency. In the graph, the solid line shows the SWR dependences for an antenna with a synthesized SSC without deviations, while the dashed lines represent variations when the complex impedance of the antenna deviates by ±25%. Analysis of these results allows us to evaluate the stability and effectiveness of the SSC in providing the desired characteristics of the antenna system under various conditions.

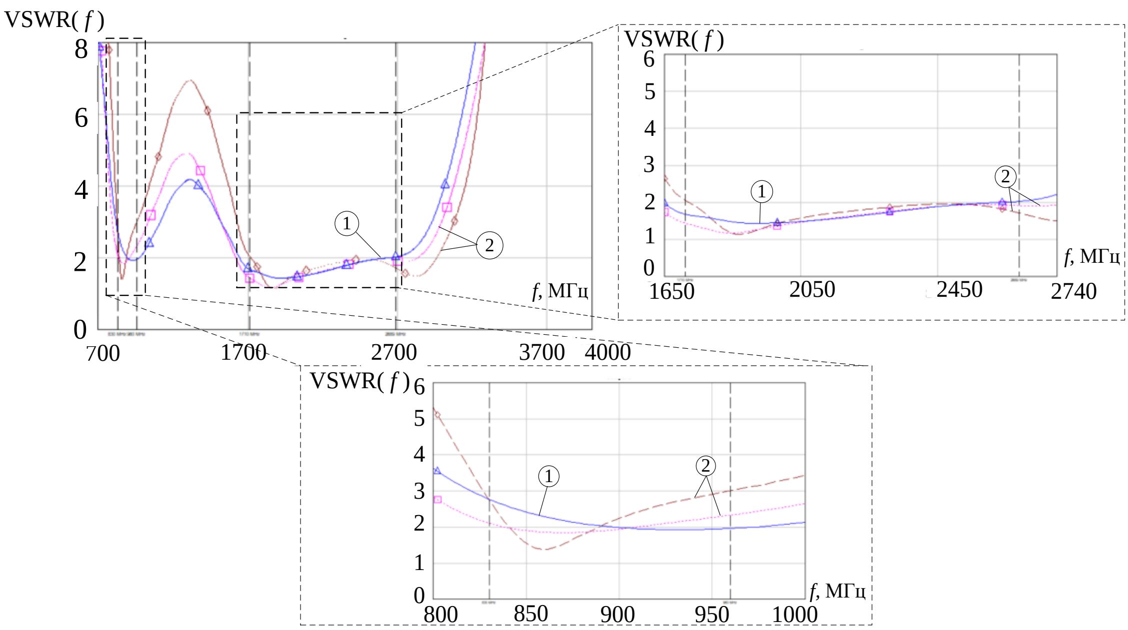


Figure 9. Dependence of SWR of a small-sized planar antenna on the frequency with a connected SSC when the load impedance deviates by ±25% from the nominal value

Having analyzed the curves in, it was concluded that when connecting the synthesized SSC to the antenna, a SWR level of ≤3 is provided in the frequency range of 830 to 960 MHz and a SWR of ≤2 in the range of 1,710 to 2,690 MHz. It should be noted that in addition to ensuring a stable level of SWR (SWR) in the required frequency ranges, the synthesized SSC also provides selectivity better than without it. Thus, the synthesized SSC made it possible to reduce the influence of load impedance deviation and maintain a high level of SWR about the antenna without a synthesized SSC (SWR≤3 in the frequency range 830 to 960 MHz and SWR≤2 in the range 1,710 to 2,690 MHz), which made it possible to obtain the act of implementation into production during the development of an experimental sample of the ShSC for a small-sized planar loop antenna of the WWAN/LTE range, implemented on a composite material consisting of fluorinated ethylene-propylene in combination with strontium hexaferrite in a ratio of 50% to 50% and a transceiver module (mobile prototype module of the Huawei company) within the framework of the implementation of the agreement PPA3071BLR190926004136890462791 dated 10/02/2019 between the State Organization “NPC NAS of Belarus for Materials Science” and LLC “Bel Huawei Technologies” on the topic “Development of magnetic-dielectric materials”. The solution to the problem of synthesizing a matching circuit (MC) to a changing load impedance of a radio-technical device (RTU) with tunable parameters was considered about the synthesis of a tunable CC for AD-25/CW-3512 in [25]. To verify (check the adequacy) of the mathematical model of this adaptive control system, based on the results obtained, a 3D model of the adaptive control system was developed, which is presented in Figure 10.

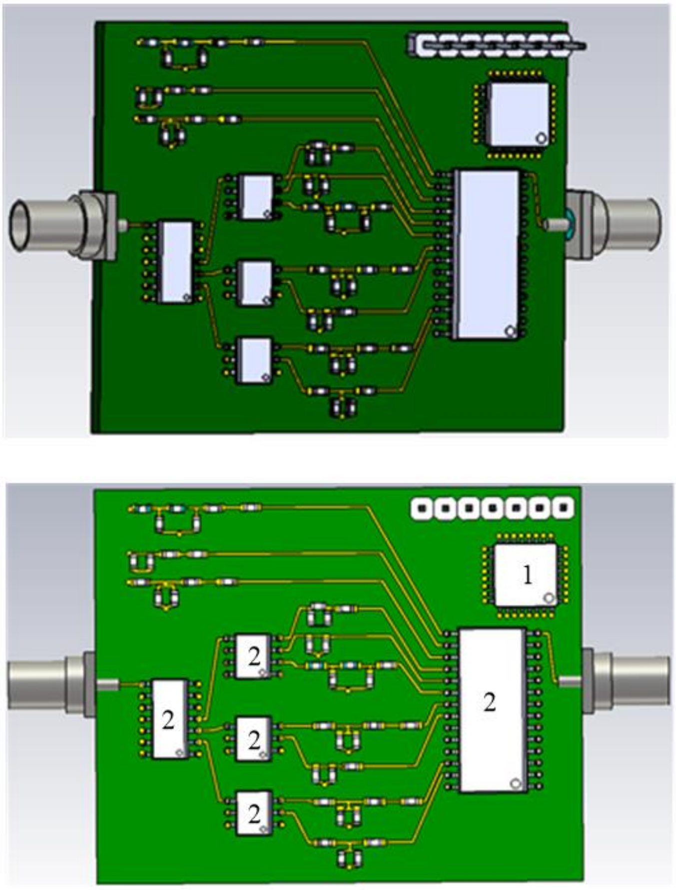


Figure 10. 3D model of the developed adaptive matching device

The geometric dimensions of the 3D model of the developed adaptive matching device are (52.5×42.5×2 mm). The 3D model is implemented in the CST Studio radio device modeling environment. SMD elements of the 0805 series are used as reactive elements, a microprocessor (1) in a QFP package is used as a measuring device and a control device, and analog multiplexers (2) in a PDIP package are used as switching devices. To bring the obtained results closer to the real characteristics of the SMD elements of the adaptive broadband matching device (AWM), the quality factors of the elements will be taken into account.

4. CONCLUSION

In conclusion, by comparing Pix2Pix and generative adversarial networks (GANs), both of this proposed antenna has the advantages of small volume with adjustable/expandable antenna bandwidth when using SSC. To verify the results obtained related to the synthesis of the SSC for the antenna device (AU) AD-44/CW-TA-30-512 (R-180) and the J-antenna (the rapidly deployable signaling complex "Spider"), mock-ups of the SSC were made, operability which was tested during experimental studies (SWR measurements under various operating conditions. The verification results showed that: when connecting a synthesized SC to the AD-44/CW-TA-30-512 AC, the loss of the CPM level relative to the maximum value is 4.0% (without a synthesized SC–9.1%) when the AC is located in indoors, 8.3% (without synthesized SC–17.2%) near equipment and 6.1% (without synthesized SC–12.2%) when located in a forest. As a result, it was concluded that the synthesized SSC ensures a reduction in losses of the AD-44/CW-TA-30-512 CPM level of the AD-44/CW-TA-30-512 when located in various operating conditions by at least 50% relative to the losses of the AC without it; when connected, the synthesized SSC to the J-antenna (of the quickly deployed “Spider” signaling complex) ensures a reduction in the degree of influence of load impedance variations on the level of power transmission (SWR) caused by the ingress of foreign objects between the emitter and the body kit. This is evidenced by the value of SWR≤2.5 in the operating frequency range with a load impedance deviation of up to 40 Ohms [10–A]. The results obtained were confirmed using the hardware and software complex for searching, receiving, and processing HF signals ARB-RM-APPR-U “Condor-U”, as well as during “research tests to assess the possibility of detecting unmanned aerial vehicles”, which took place in the period from 05/26/2021 to 05/28/2021 at the 174th training site of the Air Force and Air Defense Forces. Based on which the implementation certificate was obtained. Using the developed methodology, the SSC was synthesized for the radio modem STS ADAM SD "Buk-MB2 (MB3)" NPO "OKB TSP", providing an SWR level of ≤ 2 ($K(f) \leq 0.89$) in the entire operating frequency range. The effectiveness of the results obtained is confirmed by the value of the sensitivity invariant which decreased from five to three. This indicates a decrease in the influence of load impedance deviation on the level of SWR (SWR) in the operating frequency range. On the basis of this a certificate of implementation into production was received at the NPOOO OKB TSP enterprise.

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BIOGRAPHIES OF AUTHORS

Balausa Nakisbekova in 2006 she graduated from the Almaty Institute of Energy and Communications with a degree in radiocommunications, radio broadcasting and television. Graduated in 2013. Humanitarian University of Transport and Law named after D.A Konaev with a degree in "6M071900 – Radio engineering, electronics and telecommunications" and received a master's degree in technical sciences. Currently she is a 2nd year doctoral student at the Almaty University of Energy and Communications named after. G. Daukeeva. She is the author of 5 articles in the KOKSON database. Scientific interests: 5G, mobile antennas, antenna systems, mathematical models of antenna pattern formation. She can be contacted at email: balausa84-84@mail.ru.

Assel Yerzhan in 2003, she graduated from the Almaty Institute of Power and Communications with a degree in industrial electronics. In 2004, he received a master's degree in radio electronics and telecommunications. In 2013, she graduated from the doctoral program "Kazakh National Technical University named after K.I. Satbayev", specialty 6D071900, "Radio engineering, electronics and telecommunications". From 2014 to the present, he has been a Doctor of Philosophy PhD in the specialty 6D071900, "Radio Engineering, Electronics and Telecommunications" of the Gumarbek Daukeev Almaty University of Power and Communications. She is the author of more than 40 works. Her research interests include circuit engineering in telecommunications, wireless communications, mobile communication systems, GSM and mobile systems management, sensor networks, 5G and mobile communication technologies. She can be contacted at email: asel.yerzhan@inbox.ru.

Pavel Boykachev graduated from "Military Academy of the Republic of Belarus" in 2006 in the specialty "Engineer of radio technical systems". In 2014, he defended his dissertation in the specialty "Radio engineering, including television systems and devices". Currently, he is the head of the Department of Tactics and Radio Technical Troops of "Military Academy of the Republic of Belarus". He is the author of more than 150 scientific papers. His scientific interests are the theory of adapting radio systems to a wide range of natural operating conditions. He can be contacted at email: pashapasha.boi@mail.ru.

Zhanat Manbetova In 1999, she graduated from the Korkyt-Ata Kyzylorda State University with a degree in physics and additional mathematics. In 2014, she graduated with a master's degree in "Radio engineering, electronics and telecommunications" from Kazakh Agrotechnical University named after S. Seifullin. In 2022, she defended her doctoral dissertation in the specialty "Radio engineering, electronics and telecommunications". From 2021 to the present, he is a Doctor of Philosophy PhD of the Department of "Radio engineering, electronics and telecommunications" of the Kazakh Agrotechnical Research University named after S. Seifullin. She is the author of more than 40 works. His research interests include wireless communications, mobile communication systems, GSM, and mobile systems management, as well as mobile communication technologies. She can be contacted at email: zmanbetova@inbox.ru.

Manat Imankul in 1979, she graduated from the Tashkent Electrotechnical Institute of Communications with a degree in radio communication and broadcasting. In 1997, she defended her dissertation on the specialty "05.12.13 – Radio and television systems and devices" and received the degree of Candidate of Technical Sciences. Currently, she is an associate professor of the Department of Radio Engineering, Electronics and Telecommunications of the L.N. Gumilev Eurasian National University. She is the author of more than 200 scientific papers, including 1 monograph, 2 articles in the Scopus database. Her research interests include wireless communication technologies. She can be contacted at email: mimankul57@gmail.com.

Anar Shener in 2008, she graduated from Karaganda State University named after Academician E.A. Buketov with a degree in "541530 Information systems in business". In 2018, she defended her master's thesis in the specialty "Information systems" and received a master's degree in technical sciences. Currently she is a senior lecturer of the Department of Telecommunication Engineering of Almaty University of Energy and Communication named after Gumarbek Daukeev. I have more than 10 scientific articles. She can be contacted at email: a.shener@aues.kz.

Muratbek Yermekbaev in 1994 she graduated from the Kharkov Higher Military Aviation Engineering School and in 2004 graduated from the Military University of Communications in St. Petersburg. PhD, associate professor at the Almaty University of Power and Telecommunications named after. Gumarbek Daukeev. He is the author of 20 articles in the KOKNVO database. Scientific interests: 5G, mobile antennas, antenna systems, mathematical models of antenna pattern formation. He can be contacted at email: m.yermekbayev@aues.kz.

Pavel Dunayev in 2000, he graduated from the Kazakh State Agrotechnical University named after S. Seifullin with a degree in Automatic Telecommunication. In 2018, he defended his dissertation on the specialty “051213 - Telecommunications systems, networks and devices” and received the degree of Candidate of Technical Sciences. In 2021, he received a PhD degree in the specialty “6D071900-Radio engineering, electronics and telecommunications”. Currently, he is an acting Associate Professor, Head of the Department of Radio Engineering, Electronics and Telecommunications at the Kazakh Agrotechnical Research University named after S. Seifullin. He is the author of more than 50 scientific papers, including 1 monograph, 7 articles in the Scopus database. Research interests - digital television, telecommunication network bandwidth, fiber-optic communication lines. He can be contacted at email: dunayev.kz@mail.ru.