1. Marian WNUK, 2. Konrad SZCZEPANKIEWICZ

ORCID: 0000-0003-4576-4023; 0000-0003-3292-8113

DOI: 10.15199/48.2025.04.04

Broadband microstrip antenna for the 2G to 5G system

Szerokopasmowa antena mikropaskowa do systemu od 2G do 5G

***Abstract**. The paper presents a model of a wideband microstrip antenna, for which the main assumption is the operating frequencies in the system from 2G to 5G. The dimensions and parameters of the antenna were calculated, simulated and optimized using CST Microwave Studio software. The developed antenna has a compact structure with dimensions of (52.5x29.41x-0.57) mm. RT Duroid 5880 with a dielectric constant of εr= 4.3 and thickness h = 0.57 mm was used as the dielectric material, which served as the substrate for the construction of the antenna.*

***Streszczenie.** W artykule przedstawiono model szerokopasmowej anteny mikropaskowej, dla której głównym założeniem są częstotliwości pracy w systemie od 2G do5G. Wymiary i parametry anteny obliczono, zasymulowano i zoptymalizowano przy użyciu oprogramowania CST Microwave Studio. Opracowana antena ma zwartą konstrukcję o wymiarach (52,5x29,41x-0,57) mm. Jako materiał dielektryczny wykorzystano RT Duroid 5880 o stałej dielektrycznej εr= 4,3 i grubości h = 0,57 mm, który posłużył jako podłoże do budowy anteny. Szerokopasmowa antena mikropaskowa do systemu 2G do 5G*

Keywords: antenna; microstrip antenna; 5G antenna; broadband antenna
Słowa kluczowe: antena; antena mikropaskowa; antena 5G; antena szerokopasmowa

Introduction

Radio communication and wireless technologies are an integral part of the functioning of modern societies. Everyday communication, from calling home with a mobile phone to advanced medical applications such as monitoring and diagnostic solutions are commonly used in wireless systems and are used to communicate with each other. In the field of wireless cellular network technologies, there has been a significant development in the recent years, which has allowed the emergence of many new applications in addition to traditional telephone calls. 3G and 4G data transmission standards have changed mobile phone technology and available wireless services. We are currently in the stage of implementing the 5G system, which is replacing previous technologies on the market. At the same time, the development of cellular technologies and wireless local area networks (WLAN), operating based on IEEE 802.11 (Wi-Fi) standards, are spreading rapidly. With the rapid development of communication technology, the demand for mobile terminals with cellular communication capabilities and wireless local area network (WLAN) communication capabilities is growing. Currently, these systems offer much higher throughput than cellular telephony systems. At the same time, the number of access points (hotspots) that enable connection to the network is constantly growing. The desire to use the advantages of both cellular telephony and wireless local area networks gave rise to the idea of integrating the currently used communication systems in one device. The future of telecommunications will belong to solutions that can do this and flexibly adapt to changing technical and geographical conditions [1,2].

Wireless communication has developed greatly over the past few decades. At present, it would be hard to imagine life in which only wired transmission existed. Research into new technological solutions is constantly being conducted by manufacturers of electronic equipment. The number of people using wireless data transmission is still growing. The growth of the world's population has caused the need to increase the transmission speed. The transmission speed that was 20 years ago would not meet the requirements set today.

5G technology is a response to the requirements that wireless transmission users place on manufacturers of electronic equipment. It is a fifth-generation network. It was created to increase the efficiency of the wireless transmission in cellular network systems, as well as communication between vehicles and infrastructure. 5G is a fifth-generation cellular network that enables a new type of network and was designed to create new radio communication systems. In these systems, it is possible to connect everything and everyone together. From now on, 5G is identified with both cellular network systems and wireless sensor networks, local networks and communication between infrastructure and vehicles. This also includes communication between devices (machine-to-machine) and satellite communication systems. One of the goals of the next generation is, among others, to increase its efficiency compared to previous systems. We can list many benefits by introducing the fifth-generation network: [1, 2]

The 5G network brings to life many essential techniques and solutions that guarantee crossing previously inaccessible barriers in existing cellular and mobile networks. Several basic requirements must be met to implement the assumptions related to 5G. One of them is the use of optical fibers in rural, suburban and city center areas. Pico-cells with a range of several dozen meters will be used as local points available in public space. 5G technology is still in the development stage, and when the number of transmitters operating at higher frequencies increases, the data transfer speed will increase significantly. The launch of the 5G network has set engineers new requirements for antennas in mobile devices. Countries such as Austria, Denmark, Finland, France and many others have launched networks in the 3-4 GHz range. The 26-28 GHz and 38-42 GHz ranges are planned. Future 5G implementations will be able to use millimeter waves in bands up to 86 GHz. The general availability of 5G services is planned for 2025. ETSI TS 138 101-2 [3]. In this system, the antenna has become one of the most difficult challenges in the design of wireless communication systems in portable devices [4]. Mobile phones must be able to support many different frequencies to provide full functionality to which users have been accustomed by phone manufacturers. Table 1 shows the frequencies used in telecommunications systems used in individual generations of GSM.

Until now, the implementation of subsequent generations of mobile networks involved, among other things, the use of new radio techniques or the addition of new network elements. However, the implementation of the 3G generation was not dependent on whether the operator had already made the provision of services in the 2G system available or not. These technologies work well together but are functionally independent of each other. The situation is slightly different with 5G systems. The signal range can be achieved using higher frequencies intended for 5G, such as the so-called C-Band, i.e. the range of 3400-3800 MHz, or mmWave (millimeter wave), i.e. 26÷28 GHz [5-8].

Table 1. Bands in telecommunications technology.

Technology	Bands	Purpose
2G	B3 (1800), B8 (900)	Phone + data
3G	B1 (2100), B8 (900)	Phone + data
4G	B1 (2100), B3 (1800), B7 (2600), B8 (900), B20 (800), B38 (TDD 2600)	Phone + data WiMAX™
5G	N1 (2100), n38 (2600), n41 (2500), n78 (3500)	Phone + data WiMAX Network WLAN ™

The 3.6 GHz band allows the use of MIMO (multi-input multi-output). Due to its large capacity and the possibility of allocating large spectrum resources, this band can also be used to provide access to the Internet as part of the so-called fixed wireless access service. An important conclusion resulting from the assumptions for the 5G system is that the reduction of propagation losses occurs mainly at the 3.6 GHz and 28 GHz frequencies in the base station due to the higher antenna gain and other techniques. Consequently, for the 3.6 GHz frequency (compared to 1.8 GHz), the downlink will have a better range than the uplink, conversely. The phone has limited dimensions and limited power, so it cannot be used by optimization procedures like in the base station [9,10].

The implementation of the fifth-generation network requires close cooperation between 4G and 5G technologies. An important element of cooperation is the fact that 4G makes better use of the propagation properties of the lower frequency band [4,5,11].

Analysis of 5G dual band broadband antenna solutions

There is a small number of proposed solutions of wideband microstrip antennas operating in 5G systems in the literature [12-18]. The published solutions are characterized by compactness of the solution, small geometrical dimensions and a relatively wide transfer band. Many of these solutions were designed on the RT Duroid 5880 laminate or FR 4 laminate with a dielectric constant ε_r equal to 2.2 or with a dielectric constant ε_r equal to 4.2, respectively. In the analyzed antennas, the radiating area is in most cases rectangular and is fed with a microstrip line. The differences in the antenna solutions presented in the literature mainly concern the modification of the radiator shape based on the solutions used in fractal antennas. As a result, different transfer bands of the proposed antennas are obtained, but with relatively large dimensions. The antenna proposed in the article, intended for operation in the 5G system, is designed to cover the frequency band of 1.72 GHz to 4.05 GHz, using a FR 4 laminate in the form of a rectangular patch with a specially shaped lower edge of the radiating plane. The designed antenna covers the frequency range in systems from 2G to 5G (from 1.72 GHz to 3.95 GHz) including the ranges of the B3-4G, B7- LTE-4G, B38-4G,5G bands of the 5G n1, n3, n47, n78 bands.

Wideband microstrip antenna designed for 2G to 5G systems

Before developing an appropriate numerical model of the designed antenna in a simulation environment, it is necessary to perform preliminary calculations of its geometric dimensions based on the parameters of the dielectric substrate and the antenna resonance frequencies. These activities are aimed at obtaining a preliminary antenna model that will ensure compliance of the structure with the assumptions adopted for it and will streamline and shorten the achievement of the assumed goal in the process of simulation and optimization of the antenna structure. The assumption for the designed microstrip antenna operating in the 5G system is the frequency range, which should include frequency bands from 2.1 GHz to 3.5 GHz (5G system operating frequencies).Tab.1. In addition to the frequency band, another important requirement for the designed antenna is its antenna dimensions, which should not be larger than 52.41 mm x 29.41 mm and have an omnidirectional radiation pattern. The main parameter on which the dimensions of the antenna will depend is its resonant frequency f_r and the relative electrical permittivity ε_r of the dielectric layer of the substrate on which it will be made. The thickness of the substrate directly affects the efficiency and bandwidth of the microstrip antenna. As the thickness of the dielectric substrate increases, the width of the antenna's working bandwidth increases, while its efficiency decreases. To determine the dimensions of the radiating element, the transmission line model should be used, and the following relations should be applied to determine the length (L) and width of the radiator (W) from the following [19]:

(1) $$L = \frac{c}{2f_r\sqrt{\varepsilon_{re}}} - 2\Delta L$$

(2) $$W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_r+1)}{2}}}$$

where:

ε_{re} - effective dielectric constant.

Determined from the relationship:

(3) $$\varepsilon_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-1/2}$$

The width of the radiator determines the operating bandwidth and input impedance, increasing the width increases the radiation efficiency and thus the radiated power. The antenna resonance frequency depends on the length of the radiator. After making calculations, it was assumed that the width to length ratio is W/L ≈ 1.31. This ratio should be consistent with the relationship 1≤W/L≤2. This value is within the assumptions.

Another antenna parameter is the value of the radiator extension ΔL, which depends on the effective value of the dielectric constant ε_{re}, the laminate thickness, the radiator length and its width. The parameter ΔL is related to the scattering fields occurring at the ends of the radiator. It was determined from the relationship [19]:

(4) $$\Delta L = 0{,}412h\frac{(\varepsilon_{re}+0{,}300)(W/h+0{,}264)}{(\varepsilon_{re}-0{,}258)(W/h+0{,}813)}$$

distance from the antenna edge to the radiator edge. This value increases with decreasing this distance. Then the input resistance of the radiator was determined:

(5) $$R_{in} = \frac{1}{G_{10}}$$

The G_{10} parameter is the conductance, representing the radiation phenomenon, losses in the dielectric and losses in the radiating element and the screen.

In addition to the frequency band, another important requirement for the designed antenna is the antenna dimensions, which should not exceed 60 mm x 30 mm, and the omnidirectional radiation pattern. The main parameter that will determine the antenna dimensions is its resonant frequency f_r and the relative permittivity ε_r of the dielectric layer of the substrate on which it will be made. The last element of the antenna design is to determine the dimensions of the feed line. Calculation of the dimensions of the microstrip feed line with characteristic impedance Z_C = 50 Ω begins with determining the dependence of auxiliary variables a and b [19]:

(6) $$a = \frac{50}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}(0{,}23 + \frac{0{,}11}{\varepsilon_r})$$

(7) $$b = \frac{60\pi^2}{Z_c\sqrt{\epsilon_r}}$$

Since the parameter a is less than 1.52, the width and length of the feeder line are determined from the following equation [19]:

(8) $$W_f = A = \frac{2}{\pi}\left\{b - 1 - ln(2b-1) + \frac{\epsilon_r}{2\epsilon_r}\left[ln(2b-1) + 0{,}39 - \frac{0{,}61}{\epsilon_r}\right]\right\} * h$$

(9) $$L_f = 3 \cdot h$$

Determining the length of the supply line completes the step of determining the input data to the preliminary simulation model.

To improve the calculations for microstrip antenna parameters, a program was developed in the Matlab R2016b environment.

The obtained values were entered into the CST Microwave Studio software. Based on the calculations performed, assuming the basic data for the center frequency of 3.0 GHz, a model was obtained in which, unfortunately, full coverage of the frequency band was not achieved, therefore it was decided to correct the calculations using the optimization process available in this software. In short, the optimization process consists in increasing the number of basic functions and thereby increasing the number of iterations in order to meet the set requirements [20,21]. Thanks to this process, the final version of the antenna was obtained after introducing modifications in the scope of the shape of the radiating rectangle with a special shape of the lower edge of the antenna, the dimensions of the feed line; and the size of the reference plane (screen). The appearance of the final version of the antenna model is shown in Figure 1, while Figure 2 shows the appearance of the physical model of the antenna. The antenna was designed to operate in the frequency range from 1.8 GHz to 3.8 GHz. This covers the 5G frequency range (from 3.4 GHz to 3.8 GHz) and one range of the ISM band (from 2400 MHz to 2483 MHz). The dielectric used in the project is FR 4. The radiator is made of 280 μm thick copper. This material is characterized by electrical permittivity ε_r = 4.3. The antenna is powered by a microstrip line. The input impedance is 47.5 Ω. Figure 1 shows the shape of the designed antenna and the exact dimensions of the antenna.

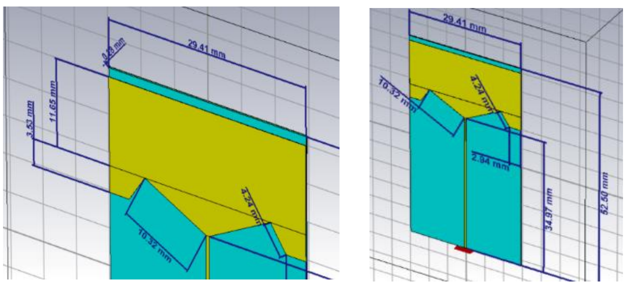

Fig. 1 Radiator dimensions

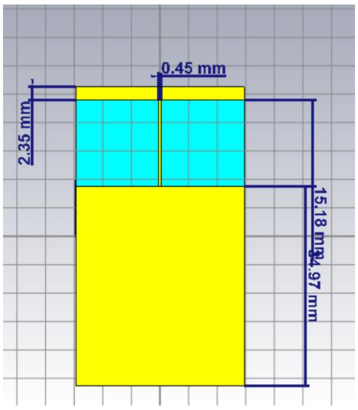

Fig. 2 Screen dimensions

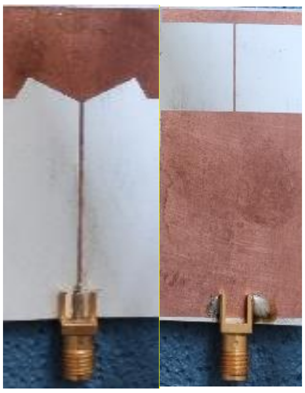

Fig. 3. Optimized view of the physical antenna model - front and back.

Simulations and Measurements results

The designed antenna structure consists of three components: ground plane, radiating element and substrate. For the calculated parameters of the radiating element, a preliminary simulation of the electrical parameters of the developed antenna model was performed and the structure optimization process was carried out, assuming that the main assumptions for the antenna remained unchanged. The analysis of the electrical parameters of the radiating element and other elements of the preliminary antenna model showed that it is possible to improve the electrical parameters of the antenna, such as reducing the VSWR coefficient, increasing the bandwidth, miniaturizing the antenna dimensions or increasing the energy gain. [22,23]. Additionally, selected electrical parameters were measured for the physical model of the antenna. The appearance of the proposed antenna during the measurements of radiation patterns is shown in Figure 4.

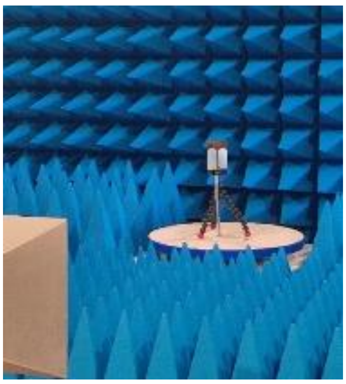

Fig. 4. Appearance of the laboratory stand during the measurements of radiation patterns of the antenna.

Reflection coefficient S11

The value of the basic reflection coefficient is assumed to be −10 dB, which means that 10% of the incident power is reflected, while 90% of the power is received by the antenna, which is considered good for mobile communication. Figure 5 shows the results of the reflection coefficient as a function of frequency for the proposed antenna. The dark blue line shows the simulation results obtained in CST Microwave Studio, while the orange line shows the measurement results for the physical model of the antenna. The proposed antenna has two resonances, one at 2.75 GHz with a return loss of -29.70 dB and the other at 3.17 GHz with a return loss of -23.28 dB for the results obtained from measurements and at 2.76 GHz with a reflection coefficient of -27.34 dB and 3.17 GHz with a reflection coefficient of -25.81 dB for the results obtained from calculations. The antenna has an operating bandwidth of 2.08 GHz, which gives a relative bandwidth of 75.36%.

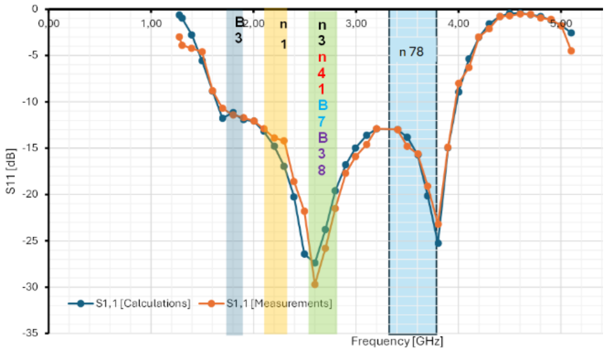

Fig. 5. Reflection coefficient as a function of frequency for the proposed antenna operating in 2G to 5G systems.

Voltage Standing Wave Ratio

For any antenna, including microstrip antennas, the voltage standing wave ratio (VSWR) should not be greater than 2 over the entire frequency band. Ideally, this value should be 1. Figure 8 shows the voltage standing wave ratio as a function of frequency for the proposed antenna. The dark blue line shows the simulation results obtained in CST Microwave Studio, while the orange line shows the measurement results for the physical antenna model. The VSWR value obtained for the simulation results at the first resonant frequency of 2.75 GHz was 1.43, and at 3.17 GHz it was 1.41. The VSWR value obtained for the measurement results at the resonant frequency of 2.75 GHz was 1.15, and at 3.17 GHz it was 1.52. The values presented in Figure 6 show that the proposed antenna operates in the entire assumed frequency band (for systems from 2G to 5G), i.e. from 1.72 GHz to 4.05 GHz.

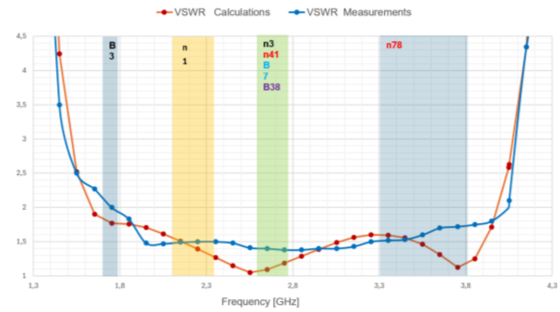

Fig. 6. Voltage standing wave ratio as a function of frequency for the proposed antenna operating in 2G to 5G systems

Input impedance

The antenna design assumes that the feedline impedance should be 50Ω. In the case of large discrepancies, it is possible to use a matching circuit, but this is another circuit that introduces additional losses and, in financial terms, generates additional costs. The input impedance as a function of frequency for the proposed antenna is shown in Figure 7. The blue line shows the results of simulations obtained in CST Microwave Studio, while the orange lines show the results of measurements made for the physical model of the antenna.

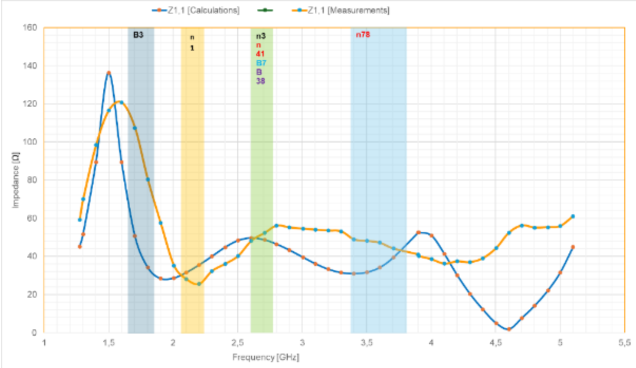

Fig. 7. Input impedance as a function of frequency for the proposed antenna operating in 2G to 5G systems.

Antenna gain

The antenna gain is most often given in relation to an isotropic antenna and is expressed in dBi units. Sometimes it is also given in relation to a dipole antenna and is expressed in dBd units. The antenna gain depends on its directivity, and the antenna energy losses depend on the material from which it is made. The value of the antenna gain as a function of frequency is shown in Figure 8. The blue line shows the results of simulations obtained in CST Microwave Studio, while the orange line shows the results of measurements performed for the physical antenna model. The proposed antenna has a maximum energy gain of 4.51 dBi at a frequency of 3.92 GHz for the simulation results and 4.38 dBi at the same frequency for the measurement results.

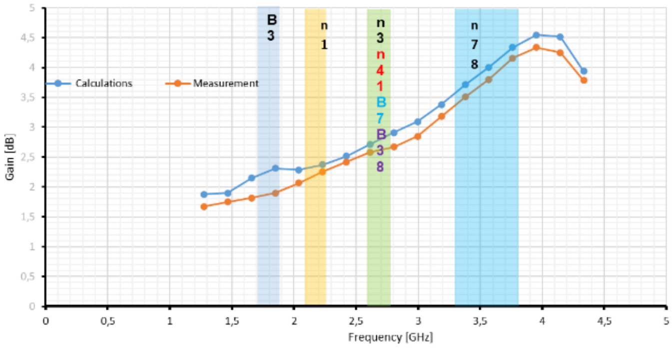

Fig. 8. Antenna gain as a function of frequency for the proposed antenna operating in 2G to 5G systems.

Efficiency

Antenna efficiency is a term used to describe the relationship between the amount of radiated power and the power delivered to the antenna. Antenna efficiency often helps identify any problems with the antenna design itself, and helps identify other factors that may interfere with the antenna's ability to transmit signals efficiently. For the proposed antenna, only a simulation process was performed to determine the antenna efficiency as a function of frequency. The efficiency value of the proposed antenna as a function of frequency is shown in Figure 9. The proposed antenna has a high-power efficiency ranging from 80% to 96.68%.

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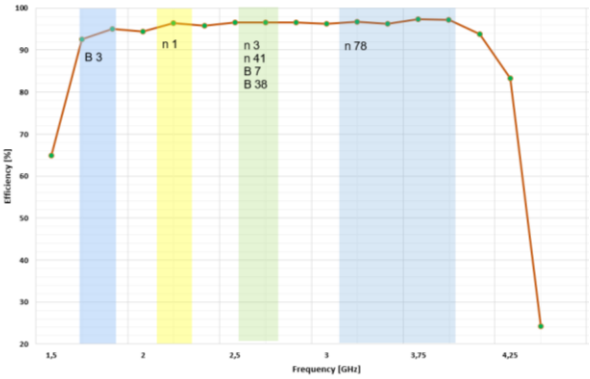

Fig. 9. Antenna efficiency as a function of frequency for the proposed antenna operating in 2G to 5G systems.

Current distribution in the antenna

In a microstrip antenna, the current value at the end of the radiating element (patch edge) should be minimal. The voltage at the edge of the patch is phase shifted with the current. Consequently, the voltage will peak at the end of the patch at currents close to zero. The voltage phase shifted with the current phase creates fields at the edges of the microstrip antenna. Figure 10 shows the current distribution of the proposed antenna for the selected frequencies from 1.8 GHz to 3.5 GHz.

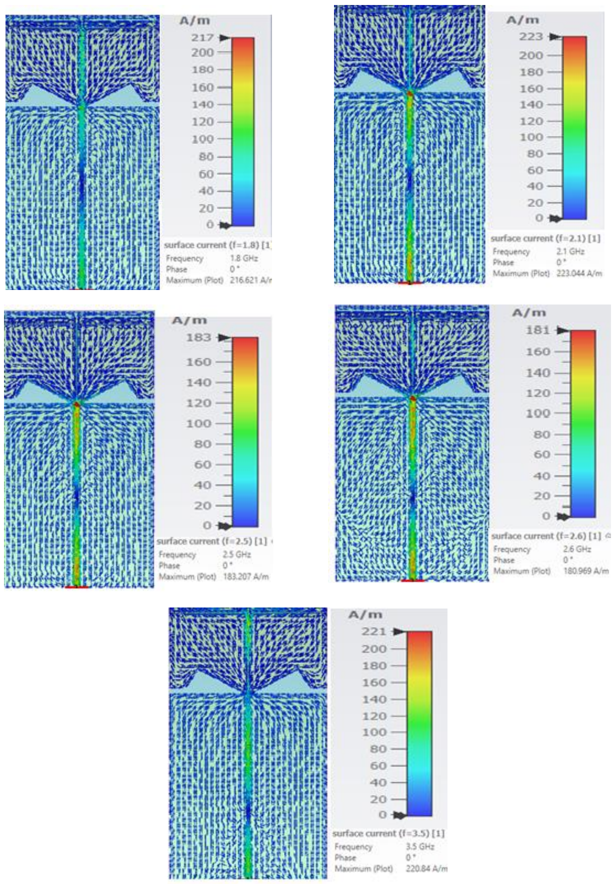

Fig. 10. Surface current distribution for the proposed antenna for selected frequencies of 2G to 5G systems.

Spatial radiation characteristics

Radiation characteristics show how the antenna radiates energy depending on the direction. It represents the normalized electric field distribution or relative power density distribution. Radiation characteristics are determined in two planes, horizontal and vertical, but can also be presented in three-dimensional form. The designed antenna should have an omnidirectional radiation pattern. The ones shown in Figure 11 show the three-dimensional appearance of the radiation pattern of the proposed antenna for selected frequencies of 2G to 5G systems, Figure 12 shows the normalized radiation characteristics of the proposed antenna for the frequency of 5.5 GHz (simulation with a green line, measurement with a red dashed line) in the polar coordinate system for vertical polarization planes. In this case, only two characteristics are presented, because when analyzing the characteristics presented in Figure 11, the first four characteristics have very similar shapes.

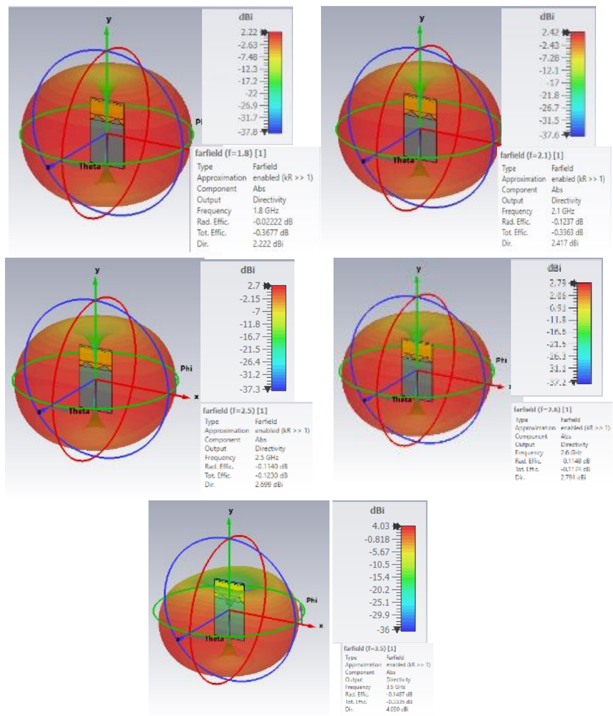

Fig. 11. 3D view of the radiation pattern for the proposed antenna model for the selected frequencies

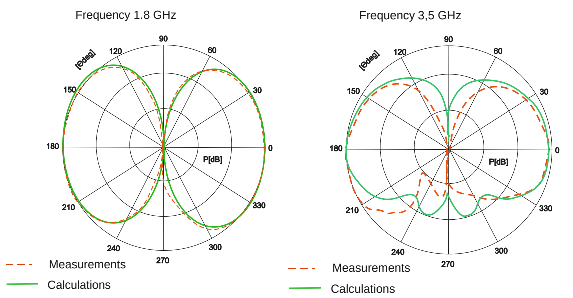

Fig. 12. Normalized radiation patterns for the proposed antenna model operating in 2G to 5G systems (green line — simulation results, red line — measurement results) in polar coordinates for the vertical plane.

Comparison of the proposed antenna with other antennas

The values of the proposed antenna parameters in terms of impedance matching and bandwidth can be compared with other published results to obtain a comparative evaluation. The frequency response of the measured S11 parameter for the proposed antenna is not the lowest (especially when comparing simulation values) compared to the obtained S11 value of the antennas presented in [24–29], but it is relatively low. Table 2 shows the comparison of the electrical parameters of the proposed antenna with other selected antennas available in the literature. The table shows the comparison of the reflection coefficient, frequency bandwidth and gain of the antennas.

Table 2. Comparison of the electrical parameters of the proposed antenna with other antennas, considering the bandwidth.

Ref.	Footprint area (λ_0^2)	Profile (λ_0)	Bandwidth
[24]	1.1×1.1	0.06	25%
[25]	0.75×0,75	0.045	21.3%
[26]	0.88×0.78	0.11	24,8%
[27]	1.17×0.5	0.039	10%
[28]	0.58×0.39	0.048	14%
[29]	0.59×041	0.052	18%
Proposed	0.525×0.294	0.057	75.36%

Based on the comparison of the electrical parameters of the proposed antenna with other antennas, it is shown that the proposed wideband antenna has comparable performance in terms of impedance matching in all cases, especially for stringent matching conditions and antenna gain values.

Conclusions

Due to the increasing demand for mobile data and mobile devices, for 5G applications and applications using broadband WiFi internet access, a wideband microstrip antenna “rectangular” is proposed in this paper. The proposed antenna has two resonances: one at 2.75 GHz with a return loss of -29.70 dB and the other at 3.17 GHz with a return loss of -23.28 dB for the results obtained from the measurements. The proposed antenna covers the frequency ranges from 1.72 GHz to 4.05 GHz, (working frequencies of systems from 2G to 5G) The proposed antenna shows efficiency in the range of 80.00-96.68% and the maximum antenna gain for the resonance frequency of 3.6 GHz is 4.03 dBi. The results also show that its bandwidth is 2.33 GHz (relative bandwidth: 75.36%) which is a very good result, much larger (but not the best) than the results of other works published in the world, e.g. [22–29], where the working band of the proposed antennas is in the order of 0.6 GHz (11.00%). The proposed antenna can serve as a good option for mobile communication from 2G to 5G and wireless access to local networks requiring high bandwidth. The size of the antenna is very compact, and its weight is very low, making it suitable for devices where space is the main limitation.

The work was financed by UGB MUT No. 750.

Authors: *prof. dr hab. inż. Marian Wnuk,*
Military University of Technology, Faculty of Electronics, Institute of Communication Systems, str., Gen. Sylwestra Kaliskiego 2, 00-908, Warszawa,
E-mail: marian.wnuk@wat.edu.pl; mgr inż. Rafał Szczepankiewicz
E-mail: rafał.szczepankiewicz@wat.edu.pl; address as above,

REFERENCES

[1]. Andrews, J.G.; Buzzi, S.; Choi, W.; Hanly, S.; Lozano, A.; Soong, A.C.K.; Zhang, J.C. “*What Will 5G Be?*” IEEE JSAC Spec. Issue 5G Wirel. Commun. Syst. 2014, 1, 1–17.
[2]. Pirinen, P. “*A Brief Overview of 5G Research Activities*”. In Proceedings of the 1st International Conference on 5G for Ubiquitous Connectivity, Levi, Finland, 26–27 November 2014; pp. 17–22.
[3]. Arya, A.K.; Kim, S.J.; Kim, S. *“A dual-band antenna for LTE-R and 5G lower frequency operations*”. Prog. Electromagn. Res. Lett. 2020, 88, 113–119.
[4]. Park, J.; Kim, J.; Choi, J.; Choi, D.; Hong, W. “*Concept of Integrating 4G LTE and Millimeter-wave 5G Antennas within Zero-Bezel Cellular Devices*”. In Proceedings of the 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, Montreal, QC, Canada, 5–10 July 2020; pp. 1675–1676.
[5]. Roh, W.; Seol, J.-Y.; Park, J.; Lee, B.; Lee, J.; Kim, Y.; Cho, J.; Cheun, K.; Aryanfar, F. “*Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results*”. IEEE Commun. Mag. 2014, 52, 106–113.
[6]. Imai, T.; Imai, T.; Kitao, K.; Tran, N.; Omaki, N.; Okumura, Y.; Sasaki, M.; Yamada, W. “*Development of high frequency band over 6 GHzfor5Gmobilecommunication systems*”. In Proceedings of the 2015 9th European Conference on Antennas and Propagation (EuCAP), Lisbon, Portugal, 13–17 April 2015; pp. 1–4.
[7]. Benisha, M.; Prabu, R.; Bai, V. “*Requirements and challenges of 5G cellular systems*”. In Proceedings of the 2016 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), Chennai, India, 26–28 February 2016; pp. 251–254.
[8]. Rodriguez, I.; Mogensen, R.; Fink, A.; Raunholt, T.; Markussen, S.; Christensen, P.; Berardinelli, G.; Mogensen, P.; Schou, C.; Madsen, O. “*An Experimental Framework for 5G Wireless System Integration into Industry 4.0 Applications. Energies*” 2021, 14, 4444.
[9]. Gohar, A.; Nencioni, G. “*The Role of 5G Technologies in a Smart City: The Case for Intelligent Transportation System*”. Sustainability 2021, 13, 5188.
[10]. Zou, Y.; Pan, J. “*Broadband and High-gain Antenna based on Novel Frequency Selective Surfaces for 5G Application*”. In Proceedings of the 2019 IEEE 4th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), Chengdu, China, 20–22 December 2019; pp. 2488–2491.
[11]. Kakkar, A.; Nirdosh; Sah, S. A “*Multiband Circular Patch Microstrip Antenna for K and Ka Applications. In Intelligent Communication, Control and Devices*”. Advances in Intelligent Systems and Computing; Singh, R., Choudhury, S., Gehlot, A., Eds.; Springer: Singapore, 2018; Volume 624.
[12]. Ali, H.; Ren, X.-C.; Hashmi, A.M.; Anjum, M.R.; Bari, I.; Majid, S.I.; Jan, N.; Tareen, W.U.K.; Iqbal, A.; Khan, M.A. “*An Eight Element Dual Band Antenna for Future 5G Smartphones*. “Electronics” 2021, 10, 3022.
[13]. Li, J.; Zhang, X.; Wang, Z.; Chen, X.; Chen, J.; Li, Y.; Zhang, A. “*Dual-Band Eight-Antenna Array Design for MIMO Applications in 5GMobile Terminals*”. IEEE Access 2019, 7, 71636–71644.
[14]. Li, Y.; Sim, C.-Y.; Luo, Y.; Yang, G. “*12-Port 5G Massive MIMO Antenna Array in Sub-6GHz Mobile Handset for LTE Bands 42/43/46*” Applications. IEEE Access 2017, 6, 344–354.
[15]. Yuan X.-T., He W., Hong K.-D., Han C.-Z., Chen Z., and Yuan T., “*Ultra-Wideband MIMO Antenna System With High Element-422 Isolation for 5G Smartphone Application*,” IEEE Access, vol. 8, pp. 56281–56289, 2020, doi: 10.1109/ACCESS.2020.2982036. 423
[16]. Marian Wnuk Konrad Szczepankiewicz „*Wielozakresowe anteny mikropaskowe dla systemu 5G*” Przegląd Elektrotechniczny, NR 9/2024 str.223-227
[17]. Jiang J.-Y. and Su H.-L., “*A Wideband Eight-Element MIMO Antenna Array in 5G NR n77/78/79 and WLAN-5GHz Bands for 433 5G Smartphone Applications*,” Int. J. Antennas Propag., vol. 2022, pp. 1–11, Nov. 2022, doi: 10.1155/2022/8456936.
[18]. Kiani S. H., Savci H. S., Abubakar H. S., Parchin N. O.,. Rimli H and Hakim B., "*Eight Element MIMO Antenna Array With Tri-444 Band Response for Modern Smartphones*," in IEEE Access, vol. 11, pp. 44244-44253, 2023.

[19]. Bajracharya, R.; Shrestha, R.; Bin Zikria, Y.; Kim, S.W. “*LTE in the Unlicensed Spectrum: A Survey”*. IETE Tech. Rev. 2016, 35, 78–90.
[20]. Rutschlin, M.;Wittig, T.; Iluz, Z. *Phased antenna array design with CST STUDIO SUITE*. In Proceedings of the 2016 10th European Conference on Antennas and Propagation (EuCAP), Davos, Switzerland, 10–15 April 2016; pp. 1–5.
[21]. Hirtenfelder, F. *“Effective Antenna Simulations using CST MICROWAVE STUDIO®*”. In Proceedings of the 2007 2nd International ITG Conference on Antennas, Munich, Germany, 28–30 March 2007; p. 239.
[22]. Radavaram S., Pour M. , “*Wideband Radiation Reconfigurable Microstrip Patch Antenna Loaded With Two Inverted*” IEEE Transactions on Antennas and Propagation, Vol. 67, No. 3, 2019 1501-1505
[23]. Park, J.; Kim, J.; Choi, J.; Choi, D.; Hong, W. “*Concept of Integrating 4G LTE and Millimeter-wave 5G Antennas within Zero-Bezel Cellular Devices*”. In Proceedings of the 2020 IEEE International Symposium on Antennas and Propagation and North American
[24]. Liu, G. A,: Chen, Z.; Quig X “*Metamaterial-based low-profile broadband mushroom antenna*” IEEE Transactions on Antennas and Propagation, Vol. 62, No. 3, 2014 1165-1172
[25]. Liu, G. A,: Chen, Z.; Quig X,: ”*Broadband low profile L-probe fed metasurface wave resonances*” IEEE Transactions on Antennas and Propagation, Vol. 68, No. 3, 2020 1348-1355
[26]. Sun W. Y. and Li Y.. "*Gain stabilization method for wideband slot-coupled microstrip antenna*." IEEE Transactions. on Antennas and Propagation, vol. 69. no. 12. pp. 8932-8936,2021.Liu W., Zhu L., W. Choi. W. et al.. "*A low-profile differential-fed patch antenna with bandwidth enhancement and sidelobe reduction under operation of TM„ and TM,, modes*." IEEE Transactions on Antennas and Propagation, vol. 66. no. 9. pp. 4854-4859. 2018-
[27]. Chen C. L., "*A wideband coplanar L-probe-fed slot-loaded rectangular filtering microstrip patch antenna with high selectivity.*" IEEE Atarorail,s and Wireless Propagation Letters, vol. 21, no. 6, pp. 1134-1138.2022.
[28]. Wang. D., Ng K. B., Chan C. H., et al.. "*A novel wideband differentially-fed higher-order mode millimeter-wave patch antenna."* IEEE 7ranscuon Antennas and Propagation. vol. 63. no. 2. pp.