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Flexible circle antenna for 5G system operating in 3.6 GHz band

Streszczenie. *Systemy radiokomunikacyjne zostały skierowane w stronę technologii piątej generacji (5G) ze względu na wymagania systemów zwartych, szybkich i szerokopasmowych. Tego typu systemy komunikacji radiowej wymagają nowych i bardziej wydajnych konstrukcji anten. W artykule przedstawiono proces projektowania anteny pracującej w systemie 5G. Proponowana antena ma środkową częstotliwość roboczą 4,085 GHz oraz dwie częstotliwości rezonansowe 3,6 GHz i 4,6 GHz. Wymiary anteny oraz jej parametry zostały obliczone, zasymulowane i zoptymalizowane za pomocą oprogramowania FEKO. Proponowana antena ma zwartą konstrukcję o wymiarach (50 mm x 56 mm x 1 mm). Jako podłoże do konstrukcji anteny użyto tkaniny dżinsowej o współczynniku dielektrycznym 1,76 i grubości h = 1,0 mm. W artykule przedstawiono analizę wyników symulacji i pomiarów parametrów elektrycznych i charakterystyk promieniowania proponowanej anteny płaskiej dla przypadku anteny umieszczonej w wolnej przestrzeni. Opisana w artykule antena planarna na podłożu typu jeans, pracująca w systemach 5G z częstotliwością środkową 4,085 GHz, niskim współczynnikiem odbicia -29,31 dB, zyskiem energetycznym 1,68 dBi oraz szerokim pasmem roboczym 2,23 GHz (54,58 %).* ***Elastyczna antena kołowa do systemu 5G pracującego w paśmie 3,6 GHz***

Abstract*. Radiocommunication systems have been directed towards the fifth generation (5G) technology due to the requirements of compact, fast and broadband systems. These types of radio communication systems require new and more efficient antenna designs. The paper presents the process of designing a wearable flexible antenna working in the 5G system. The proposed antenna has a center operating frequency of 4.085 GHz and two resonates frequency 3.6 GHz and 4.6 GHz. The dimensions of the antenna and its parameters were calculated, simulated and optimized using the FEKO software. The proposed antenna has a compact structure with dimensions (50 mm x 56 mm x 1 mm). A jeans fabric with a dielectric index of 1.76 and a thickness of h = 1.0 mm was used as a substrate for the antenna construction. The paper presents an analysis of the results of simulation and measurement of electrical parameters and radiation patterns of the proposed planar antenna for the case of an antenna placed in a free space. The planar antenna on jeans substrate described in the article, working in 5G systems with a center frequency of 4.085 GHz, a low reflectance of -29.31 dB, an energy gain of 1.68 dBi and a wide operating band of 2.23 GHz (54.58 %).*

Słowa kluczowe: antena, pasmo 3,6 GHz, system bezprzewodowy 5G, antena szerokopasmowa.
Keywords: antenna, 3.6 GHz band, 5G wireless system, broadband antenna.

Introduction

Nowadays, wireless networks play an increasingly important role in our lives. This is due to the fact that we are sending more and more information wirelessly. Therefore, such connections must be characterized by the highest data transfer speeds and the lowest possible delay. In order to meet these requirements, the latest technologies must be introduced. The important trend developed in engineering is the miniaturization of devices. It is very important because more and more often we want one device to be able to replace several other previously used devices. Miniaturization is visible in almost every field of technology: mechanics, optics and electronics. When analyzing miniaturization in the field of electronics, one should mention the antennas made with the microstrip technique or with the use of textiles, which are characterized by low weight and small size. The 5G systems will operate at frequencies other than those currently used - they will be increasingly higher frequencies. Combining this with the fact that the dimensions of the radiating elements in the antenna decrease with increasing frequency, it can be concluded that the miniaturization of antennas is inevitable [1], [2].

Antennas adapted to the 5G systems will allow us to develop many areas of our lives. So-called smart homes are becoming more and more popular, the purpose of which is to connect to the network as many devices used in our household as possible. Other areas of our life in which 5G systems will play a key role include industry, urban transport, medicine (controlling vital parameters) and agriculture .

In Poland the frequency ranges that will be used in 5G networks are: 600 - 700 MHz, 3 - 4 GHz, above 26 GHz (26 - 28 GHz and 38 - 42 GHz). Such a wide range of frequencies allows to obtain networks with high capacity, high data transmission speed, good coverage and high reliability.

The first frequency range is initially intended to serve users living in less built-up areas where there may be a problem with the appropriate infrastructure. The frequencies of 600 - 700 MHz are characterized by a large range and the fact that they are not absorbed by all kinds of obstacles. Accordingly, they can cover a territory with a large area. They can be used both in a highly urbanized area, in smaller towns and in the countryside [1], [2].

The second frequency range allows multiple connected devices to be operated at the same time. The frequencies in the 3 - 4 GHz range are characterized by good coverage of the area and at the same time have a large capacity allowing to connect many devices to it. In densely populated places with a large number of buildings and other obstacles in close proximity to each other, it will still be possible to transfer large amounts of data at a significant speed.

The last frequency band will be used by devices with priority low signal delay. Frequencies above 26 GHz, i.e. millimeter waves, are used where the fastest possible data transmission and the lowest possible delay is needed. However, their big disadvantage is a very short range, in open area it is 500 m, and in built-up areas it does not exceed 200 m [1], [2].

Textronics is a relatively young field of knowledge that combines electronics, computer science and textiles. Additionally, it uses the concepts of automation, cybernetics and metrology. Wearable products were created by the minimization of electronic circuits and the advanced development of textile technology, which resulted in the development of the so-called smart textiles. These are materials that can conduct electricity by using specialized treatments. This process is enabled by special metallic particles, nanomaterials or conductive polymers, which create conducting paths, diodes or all kinds of detectors to monitor the relevant states [3], [4].

The current challenge is to develop a technology that will allow all kinds of circuits, antennas and electronic components to be inserted into the fabric in such a way that garments with smart textiles do not differ from ordinary clothes. The most likely scenario is the one in which the everyday clothing we wear will monitor vital functions such as pulse, heart rate or respiratory rate without the user's interference or knowledge. Additionally, the discussed systems will allow the creation of wireless networks and locating the owner of smart textiles [3], [4].

In wearable systems there are many possibilities of using the antennas presented above. Due to the small dimensions and weight, these structures may be virtually im-perceptible to the user. They are most often used for wireless communication such as: Wi-Fi, Bluetooth or 5G networks.

This article presents the antenna design process, and then the results of simulated and measured electrical parameters of a wearable antenna operating in one of the frequency bands used in 5G systems (3.4 - 3.8 GHz). The model of antenna was simulated by FEKO software with using FDTD solver. In addition to the frequency band, other important requirements for the designed antenna are the dimensions that should not exceed 60 x 60 mm.

Analysis of current antenna solutions operating in 5G systems at 3.6 GHz

The available publications contain many proposed solutions for microstrip antennas working in 5G systems in the middle frequency band of 3.6 GHz [5]-[19]. These solutions are characterized by a compact solution, small geometrical dimensions and the antenna operating bandwidth of about 500 MHz. Many of these solutions are designed on the FR4 laminate or the popular RT Duroid laminates. In the analyzed antennas, the radiator in most cases has a rectangular shape or a shape similar to a rectangle with many indentations and is powered by a microstrip line. The differences that can be noticed in the proposed antennas concern the modification of the shape of the radiator. As a result, different bandwidths of the proposed antennas are obtained.

The antenna proposed in this article, working in systems intended for 5G communication, is designed for a resonant frequency of 3.6 GHz, initially with the use of FR4 laminate, and then with the use of jeans-type material with a circular radiator. The proposed planar antenna was assumed due to its location on the pocket of the front jeans jacket. This antenna location was chosen due to the fact that the jacket pocket is the least deformed from the flat surface during human movement. The proposed antenna is designed to obtain the largest possible bandwidth, a greater bandwidth than the analyzed antennas in the above-mentioned literature, and to obtain elliptical polarization and an omnidirectional characteristic in order to show the influence of human body parameters on its electrical parameters.

The developed final antenna on a jeans substrate, despite the use of a known power supply method, achieved a much wider bandwidth than similar designs of this type that can be found in the literature [5]-[19]. The basis for obtaining such an effect was to conduct optimization with a large number of variables, which was aimed at obtaining the lowest possible reflection coefficient and VSWR (Voltage Standing Wave Ratio) in the widest possible frequency range. The obtained results significantly exceed the previously published parameter values for antennas of this type in terms of the operating bandwidth, especially in the case of stringent matching conditions (VSWR ≤ 2, VSWR ≤ 1.5 and VSWR ≤ 1.25). Additionally, it should be remembered that the proposed antenna is a wearable antenna, for which obtaining a wide operating band is a relatively difficult task due to the limited materials used for the substrates in such antennas.

Analysis of materials used for dielectric substrates in wearable antennas

In order to implement the model of a textile antenna (wearable antenna), it is necessary to design an appropriate antenna structure and to select the electrical parameters of the base on which the antenna will be designed. The first step in designing a wearable antenna is to select a substrate to be the reference substrate. The designed antenna on such a substrate will be the reference antenna, the parameters of which will be related to the parameter values of the subsequent iterations of the antenna model. A 1.5 mm thick of FR4 dielectric material with a permittivity of 4.4 and a tan(δ) = 0.05 was chosen as the reference material. This material is commonly chosen by antenna constructors mainly due to its easy availability and low cost. Despite the disadvantages of this type of material, resulting from large losses and dispersion of electrical parameters, it is possible to use them in many types of HF solutions with practically no damage to the electrical and functional parameters of devices. The price of this material is several times lower than the price of the cheapest microwave laminates and its availability reduces the costs and time of producing models, prototypes and finished products [20]-[21].

In order to determine the impact of the selection of the substrate parameters on the parameters of textile antennas (thickness, electric permeability and loss angle tangent), an antenna model should be designed on various substrates with different radiator shapes, selected according to the resonant frequency of the 5G system, amounting to 3.6 GHz. Among the many antenna designs made in the textile technology, one was selected that requires the implementation of suitably shaped conducting paths (radiator and screen) located on both sides of the dielectric substrate. Antennas using conductive layers placed on both sides of the insulating substrate require the use of substrate materials with very precisely defined dielectric properties (dielectric constant, dielectric loss) and thickness. Such a choice forced the analysis of the relationship between the electrical parameters of the substrate used to design subsequent iterations of the antenna model [20]-[21].

Table 1. Electrical parameters of jeans material on the basis of literature review

	Public ation [22]	Public ation [13]	Public ation [14]	Public ation [25]	Public ation [15]	Public ation [26]	Public ation [28]
ε_r at 2.4 GHz	-	1.70	1.60	1.70	-	-	-
ε_r at 3.6 GHz	1.78	-	-	-	1.78	1.78	1.54
Tan(δ) at 2.4 GHz	-	0.025	-	0.025	-	-	-
Tan(δ) at 3.6 GHz	0.085	-	-	-	0.085	0.085	-
Material thickness [mm]	0.6	1.0	2.84	1.0	0.6	0.6	1.0

In the experiments described below, the basic structure of the wearable antenna is an antenna with a circular patch and a ground plane covering the other side of a textile substrate. In the case of a wearable antenna, which is most often sewn into clothing, a decision was made to choose the material for the antenna base in the form of jeans. It is a popular material used for sewing clothes (pants, jackets, sweatshirts, shirts), but its electrical parameters are not widely available. Therefore, the literature related to the publication of electrical parameters of the jeans material was analyzed [20]-[27]. On the basis of the available literature in Table 1 shown the parameters of the jeans type material for different frequencies.

Analyzing the values of the parameters of the material such as jeans available in the literature, it was found that these values have large differences. When designing antennas, it is very important to provide the exact values of the dielectric parameters of the substrate used, as it has a very large impact on obtaining the parameters of the designed antenna. For this reason, it was decided to measure the electrical parameters of the jeans-type material using the DAK measuring system by SPEAG and the vector analyzer ZVA67 by Rohde & Schwarz. To obtain accurate measurements of the dielectric properties of the material, the material should be homogeneous, isotropic and large enough so that the sample boundaries do not affect the reflected signal [24]. The relative electric permittivity εr should be in the range of 1 to 200, the tangent of the tan loss angle (δ) should be in the range of 10^{-5} to 10. The test probes are constructed from open sections of a 50 Ω coaxial transmission cable with contact with the dielectric material at one cut end. The probe is connected to the VNA to measure the complex reflectance (S_{11}) at the end of the probe. The measured reflectance is then converted into complex permittivity of the material under test. The DAK software is based on a very precise and fast method developed by Ellison and Moreau [24] The block diagram of the measuring system is shown in Figure 1.

Using the measuring system shown in Figure 1, the dielectric properties of the jeans material were measured in the frequency range of 5G systems from 3.4 GHz to 3.8 GHz to validate the measurement method. In the first step, the electric permittivity of a solid material in the form of a teflon disc was measured. The theoretical value of the electric permittivity of teflon in the frequency range from 3 GHz to 4 GHz is 2.07.

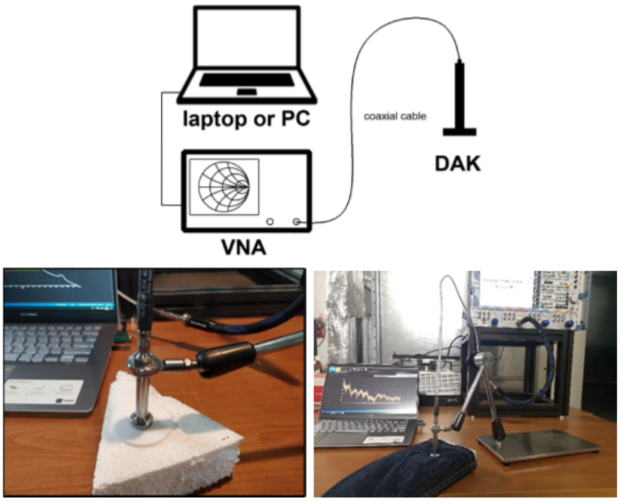


Fig. 1. The block diagram and photo of the measuring system using the DAK system

The measurement of the complex permittivity and tan (δ) was performed at an ambient temperature of 20 °C and 35 % humidity. The results of the measured value of electric permittivity for teflon are shown in Figure 2 with a purple line. The measured value of ε' at 3.6 GHz is 2.06 which shows the correct implementation of the measurement system with the use of DAKS-3.5 probe. The results of measurements of the electric complex permittivity (ε = ε' – iε'') value for the jeans type material are shown in Figure 2, while Figure 3 shows the measurement results of tan (δ) values for the jeans type material in the same frequency range. The standard deviation associated to the systematic uncertainty of the measurement is 3.3 % value for this measurement stand. Additionally, with the use of an electronic caliper, a precise measurement of the thickness of the measured jeans material was made, which is 1.0 mm [3].

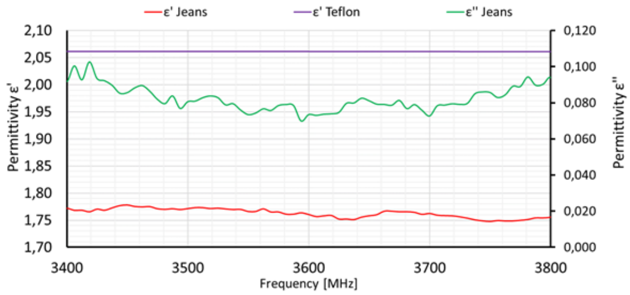


Fig. 2. Complex permittivity values for teflon and jeans material in the frequency range from 3.4 GHz to 3.8 GHz

On the basis of the analyzed literature [22]-[29] and the measurements made for the jeans type material, the following parameters were adopted for further analysis:

- permittivity ε_r = 1.76,
- loss angle tangent tan(δ) = 0.04,
- material thickness h = 1.0 mm.

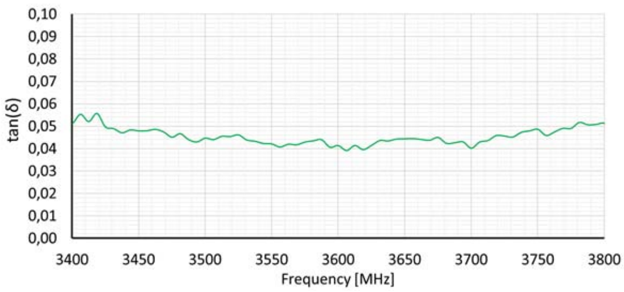


Fig. 3. Tan (δ) values for jeans material in the frequency range from 3400 MHz to 3800 MHz

Flexible circle antenna model

At first, it is necessary to perform preliminary calculations geometric dimensions of antenna based on the dielectric parameters and the resonant frequency of the antenna. These activities are aimed at obtaining a preliminary model of the antenna, which will ensure the compliance of the structure with the assumptions made for it and reduce the time to achieve the assumed target in the process of simulating and optimizing the antenna structure.

The main assumption of the designed antenna is to work on one of the frequency bands to be used in the fifth generation systems, i.e. 3.4 – 3.8 GHz. Another important requirement for the designed antenna are the dimensions of the antenna, which should not be larger than 60 x 60 mm, and the type of material from which the antenna is to be made to be located on one of the elements of human clothing. The main parameter on which the dimensions of the antenna will depend is its resonance frequency f_r and the relative electric permittivity ε_r of the dielectric layer of the laminate on which it will be made [1]. The proposed antenna is designed to obtain the largest possible bandwidth, a greater bandwidth than the analyzed antennas in the above-mentioned literature, and to obtain elliptical polarization and an omnidirectional characteristic.

The calculation of antenna dimensions was made according with equation in [1]. For the calculated parameters of a circular radiator, a model was developed in the Altair FEKO microstrip antenna design software. This software allows you to determine the electrical parameters and radiation patterns of the antenna [28]-[30]. The analysis of the electrical parameters of the design of the radiating element and the remaining antenna elements shows that it is possible to improve the electrical parameters of the antenna, such as reducing the VSWR, increasing the frequency bandwidth, miniaturization of the antenna dimensions or increasing the energy gain. For this purpose, the obtained antenna model was modified in the FEKO software by Altair in terms of impedance matching to the resonant frequency of the antenna and the bandwidth.

The calculation process was performed using a circular radiator with the parameters of the jeans type substrate and the basic assumptions for the resonant frequency and bandwidth. The process of determining the parameters of antenna with a circular radiator is analogous to that of an antenna with a rectangular radiator. In order to determine the radius of the radiator, the following relation should be used [1]:

(1) $$R = \frac{F}{\sqrt{\left\{1 + \frac{2h}{\pi \varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}}} = 18{,}38\ mm$$

where:

(2) $$F = \frac{1.8412 \cdot 10^9}{f_r \sqrt{\varepsilon_r}} = 18{,}40\ mm$$

Based on the above values, in the next step we determine the effective radius from the relationship:

(3) $$R_e = R \cdot \sqrt{\left\{1 + \frac{2h}{\pi \varepsilon_r R}\left[ln\left(\frac{\pi R}{2h}\right) + 1.7726\right]\right\}} = 18{,}43\ mm$$

On the basis of the performed calculations, a model was obtained, the dimensions of which are shown in Table 2 as 1st antenna iteration. This model is characterized by the fact that no resonance was obtained for the resonance frequency of 3.6 GHz, hence it was decided to correct the calculations using the optimization process available in the Altair FEKO software [28]-[30]. Thanks to this process, which mainly modified the size of the radiator feed line, another version of the antenna on a jeans substrate was obtained, the physical parameters of which are shown in Table 2 as 2nd antenna iteration.

Table 2. Dimensions of the preliminary and final antenna design

		1st Antenna Iteration	2nd Antenna Iteration	3rd Antena Iteration
Antenna Component	Symbol	(mm)	(mm)	(mm)
Substrate width	W_s	50.00	50.00	50.00
Substrate length	L_s	56.00	56.00	56.00
Ground plane width	W_e	50.00	50.00	1.14
Ground plane length	L_e	56.00	56.00	12.77
Patch radius	R	18.40	18.00	18.00
Copper thickness	Cu	0.05	0.05	0.05
Substrate thickness	h	1.0	1.0	1.0
Permittivity	ε_r	1.76	1.76	1,76
Feed line width	W_f	4.15	1.00	1.00
Feed line length	L_f	14.71	19.00	19.00

At this stage of the analysis, an antenna model was obtained (Antenna Iteration), which operates at a resonance frequency of 3.6 GHz. Unfortunately, the bandwidth is too narrow (the frequency range does not cover the frequency band for 5G systems operating at 3.6 GHz). For this reason, the process of optimizing the obtained model in terms of extending the antenna operating band was performed. FEKO software supports the process of optimization of electrical parameters of the designed antenna and a number of related options.

At the beginning of the optimization process, the parameters of the antenna model to be changed during the optimization in order to obtain the optimal solution were determined. Parameters define the variables that can be changed during the optimization process. Any variable defined in FEKO can be used as the optimization parameter [28]-[30].

In the next step, we define the range of parameters to be changed specifying the minimum, maximum and starting values that have been selected based on the calculated parameters of the circular staff and center frequency.

The last step of the optimization process is the selection of the optimization target. In our optimization process, we chose an impedance target (reflectance and VSWR) with a target minimization operator. The impedance target provides optimization related to the impedance and admittance of any voltage or current source, which is solved within the FEKO model. The reflectance ratio is calculated in relation to the indicated reference impedance [28]-[30].

In the case of an impedance target, the reflection factor is calculated directly from the observed input impedance. Therefore, this value is the active reflection factor, and may differ from the S_{11}, which was calculated during the calculation of the S parameter in the multiport model. The voltage standing waveform factor for the observed in-put impedance is considered in relation to the indicated reference impedance [28]-[30].

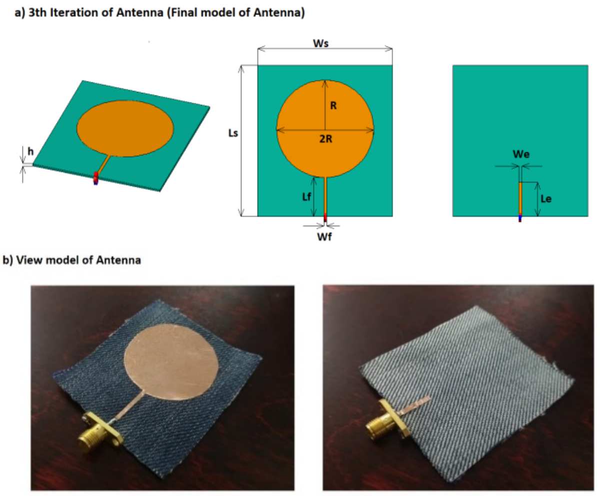


Fig. 4. Final wearable antenna designed: a) front view and rear view of planar antenna, b) front view and rear view of antenna physical model

In the optimization process, the length and width of the antenna substrate along with the ground (W_s, W_e, L_s, L_e), the length and width of the radiator (L_p, W_p) as well as the length and width of the feed line (L_f, W_f) were changed. Other structural elements, such as thickness and permittivity of the substrate, were not changed. As a result of the optimization process, the antenna model shown in Figure 4a) was finally obtained, the dimensions of which are presented in Table 2 as the 3th iteration (final model of antenna). Figure 4b) shows the front and rear view of antenna physical model.

The simulation and measurement results

The proposed antenna structure consists of three components: ground plane, patch and substrate. Due to the assumptions of the widest operating band and omnidirectional radiation pattern for the designed antenna, a planar antenna was selected for the further process of simulating electrical parameters (3th iteration). For this antenna, the results of simulation of electrical parameters and radiation pattern are presented in this section. Textile antennas are sewn into clothing, therefore the material selected as the substrate in the proposed antenna construction is jeans. It is popular and universal, and its dielectric constant, which was taken from Section above for the resonance frequency, is ε_r = 1.76. The antenna design it was created based on the determined electrical parameters specified in this article. The last element is the patch with the feed line. The round shape allows to obtain the appropriate bandwidth and the length and width of the supply part allowed for impedance matching of the antenna.

For the final model of the antenna designed in this way, a simulation process was carried out using the Altair FEKO software, as a result of which the results of electrical parameters were obtained, such as: reflection coefficient, voltage standing wave ratio, input impedance, energy gain, antenna efficiency, antenna current distribution and radiation patterns. Additionally, selected electrical parameters were measured for the physical model of the antenna. The appearance of the proposed antenna during the measurements is shown in Figure 5.

a) b)

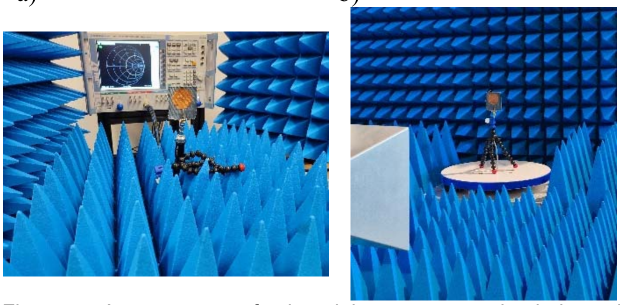


Fig. 5. Appearance of the laboratory stand during the measurements of: a) electrical parameters of the antenna, b) radiation patterns of the antenna

Reflection coefficient S_{11}

The first factor that allows to determine the operating band of the proposed antenna is the scattering matrix. It determines how much power the antenna has radiated and at what frequencies [16], [34].

Figure 6 shows the simulation and measurement results for the proposed antenna on a jeans type substrate. The proposed antenna has a center frequency at 4.035 GHz with a return loss of -16.24 dB from simulation results and a center frequency at 4.085 GHz with a return loss of -13.29 dB from measurement results. The proposed antenna has a working bandwidth of 2.07 GHz (2.23 GHz from measurements), which gives a relative working bandwidth of 51.30% (54,58 % from measurements) [15], [32].

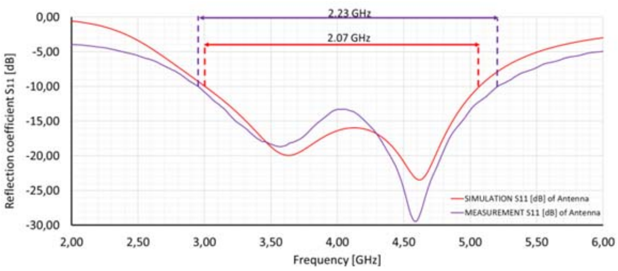


Fig. 6. The value of the reflection coefficient S_{11} as a function of frequency (simulation and measurement results) for proposed antenna

Voltage Standing Wave Ratio

Another parameter that determines the impedance properties of the antenna is the voltage standing wave ratio (VSWR) [16], [34]. Figure 7 shows the simulation and measurement results of VSWR as a function of frequency. As can be seen, the VSWR value obtained at the center frequency of 4.035 GHz is 1.37 from simulation results and for the center frequency of 4.085 GHz it is 1.49 from measurement results. The proposed antenna works in the entire assumed 5G frequency band, i.e. from 3.4 GHz to 3.6 GHz.

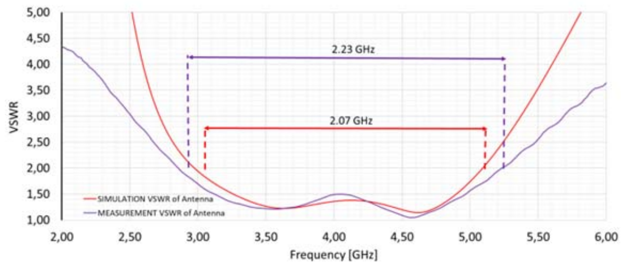


Fig. 7. The value of the VSWR as a function of frequency (simulation and measurement results) for proposed antenna

Input impedance

The input impedance of the antenna is an important parameter, because in the event of its mismatch with the impedance of the RF path standing wave will occur and no 100% power will be radiated out. As we can see, the input impedance consists of the real and the imaginary parts, the values of which change with frequency. The antenna design assumes that the impedance of the power line should be 50 Ω. Detailed values of the input impedance for the proposed antenna as a function of frequency are shown in Figure 8 [15], [32].

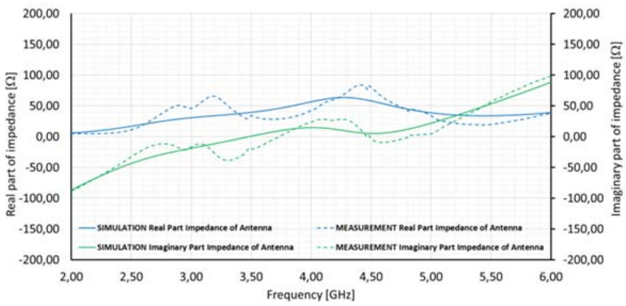


Fig. 8. The input impedance as a function of frequency (simulation and measurement results) of the proposed antenna

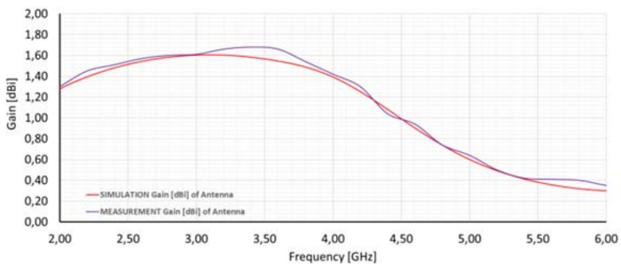


Fig. 9. Directional gain as a function of frequency (simulation and measurement results) of the proposed antenna

Gain

The antenna gain depends on its directivity and antenna energy losses resulting from the material from which it is made [32]. The proposed antenna has a gain of 1.54 dBi at a resonance frequency of 3.6 GHz, 1.59 dBi at a 3.31 GHz frequency from simulation results (1.68 dBi at a resonance frequency of 3.4 GHz, 1.66 dBi at a 3.6 GHz from measurements). The simulation and measurement results of antenna gain as a function of frequency is shown in Figure 9.

Current distribution

In the microstrip antenna at the end of the radiating element (edge of the staff), the current value should be minimal. The voltage at the edge of the staff is out of phase with the current. Consequently, the voltage will peak at the tip of the staff with currents close to zero [32]. Due to the operating frequency of the 5G system in the 3.6 GHz band, the current distribution is presented for three selected frequencies: 3.4 GHz, 3.6 GHz and 3.8 GHz. Figure 10 shows the current distribution of the developed antenna for the frequencies of 3.4 GHz, 3.6 GHz and 3.8 GHz.

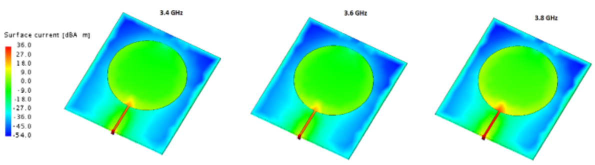


Fig. 10. The current distribution of the proposed antenna for the frequencies of 3.4 GHz, 3.6 GHz, 3.8 GHz

Radiation patterns

The radiation pattern shows how the antenna radiates energy depending on the direction. The radiation patterns are determined in two planes, horizontal (H vector plane) and vertical (E vector plane), and can also be presented in three-dimensional form [32].

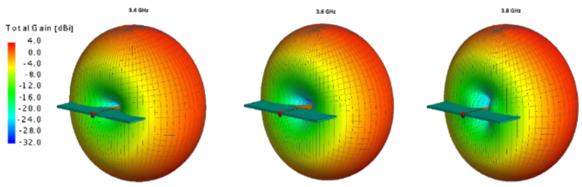


Fig. 11. 3D radiation patterns of the proposed antenna for the frequencies: 3.4 GHz, 3.6 GHz, 3.8 GHz

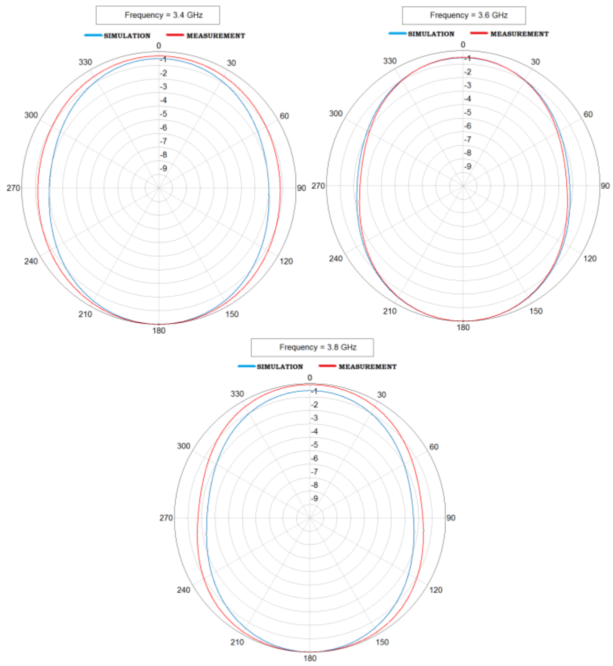


Fig. 12. Normalized radiation patterns (simulation and measurement results) of proposed antenna for the frequency: 3.4 GHz, 3.6 GHz, 3.8 GHz for vertical polarization

The proposed antenna should have an omnidirectional radiation pattern. Due to the operating frequency of the 5G system in the 3.6 GHz band, the radiation patterns are presented for three selected frequencies: 3.4 GHz, 3.6 GHz and 3.8 GHz. Figure 11 shows the three-dimensional radiation patterns of the proposed antenna for the frequencies of 3.4 GHz, 3.6 GHz and 3.8 GHz. Figure 12 shows the standardized radiation patterns of the proposed antenna for the frequencies of 3.4 GHz, 3.6 GHz and 3.8 GHz in the polar coordinate system for vertical polarization. Figure 13 shows the standardized radiation patterns of the proposed antenna for the frequencies of 3.4 GHz, 3.6 GHz and 3.8 GHz in the polar coordinate system for horizontal polarization.

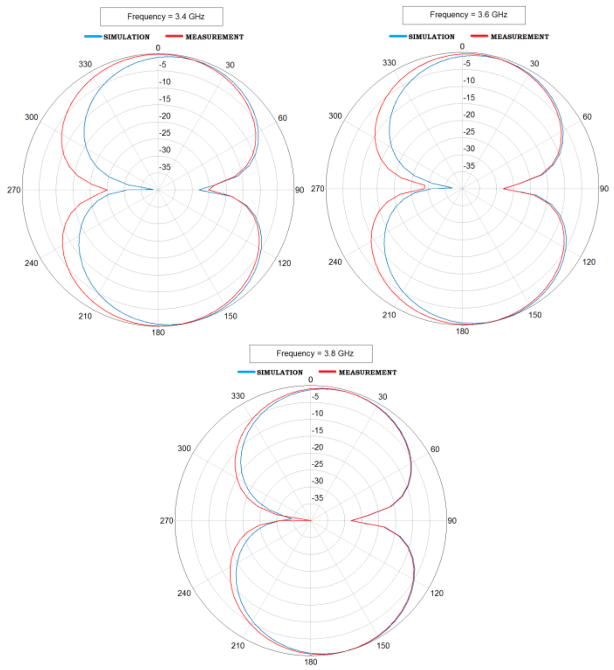


Fig. 13. Normalized radiation patterns (simulation and measurement results) of proposed antenna for the frequency: 3.4 GHz, 3.6 GHz, 3.8 GHz for horizontal polarization

Comparison of the proposed antenna with other antennas

The parameter values for the proposed wearable antenna in terms of impedance matching and bandwidth can be compared with other published results for a comparative assessment. The frequency response of the measured parameter S_{11} for the proposed antenna is not lower than the obtained value S_{11} of the antennas shown in [5], [16], [17], but it is relatively low. Figure 14 shows a comparison of the reflection coefficient as a function of frequency for the proposed antenna and antennas developed in other studies. Also, the frequency responses were compared with the use of the VSWR parameter, as shown in Figure 15.

The minimum S_{11} value obtained in this paper for the antenna is -29.31 dB (VSWR ≈ 1.05), while in [5] it was reached approximately -21.00 dB (VSWR ≈ 1.13), in [16] about -13.50 dB (VSWR ≈ 1.54) and in [17] about -24.50 dB (VSWR ≈ 1.12). Moreover, for the proposed antenna, the antenna operating band (BW) is wide and for $S_{11} \leq -10$ dB (VSWR ≤ 2) it is 2.23 GHz. The band's center frequency is 4.085 GHz, while in [5] the operating band is 0.52 GHz and the center frequency is 3.4 GHz, in [16] the operating band is 0.21 GHz and is also center around 3.5 GHz, and in [17] the operating band is 0.20 GHz and is also center at exactly 3.4 GHz.

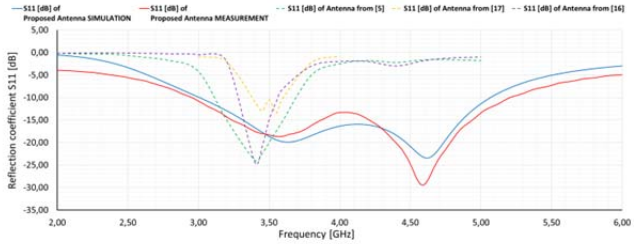


Fig. 14. The reflection coefficient as a function of frequency for the proposed antenna and antennas from other works

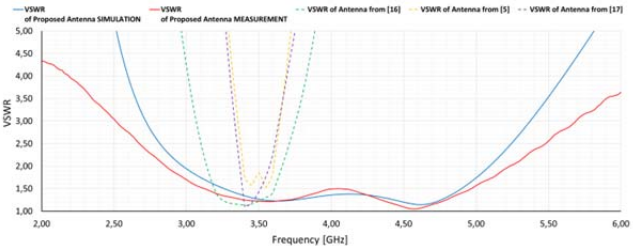
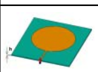
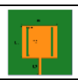


Fig. 15. The VSWR as a function of frequency for the proposed antenna, and antennas from other works

A comparative summary of the proposed antenna with the antennas described in [5], [16], [17] is presented in Table 3. It has been shown that the proposed wearable antenna in this study in two variants (simulation and measurement) has the best performance in terms of impedance matching bandwidth in all cases, and especially in cases of stringent matching conditions (VSWR ≤ 2 VSWR ≤ 1.5 and VSWR ≤ 1.25).

Table 3. Comparisons among the bandwidth achieved in the present work to those achieved in other published works

Performance Measure		**Proposed Antenna SIMULATION**	**Proposed Antenna MEASUREMENT**	**Work of [5]**	**Work of [16]**	**Work of [17]**
Antenna View						
Dimensions in [mm]		NA	50 x 56 x 1	36 x 36 x 3.4	44 x 44 x 1.6	25.3 x 26.8 x 1.6
Center frequency		4.035 GHz	4.085 GHz	3.40 GHz	3.50 GHz	3.40 GHz
BW	VSWR ≤ 1.25	0.46 GHz	0.40 GHz	0.29 GHz	NA	0.07 GHz
	VSWR ≤ 1.5	1.65 GHz	1.82 GHz	0.42 GHz	NA	0.12 GHz
	VSWR ≤ 2	2.07 GHz	2.23 GHz	0.52 GHz	0.21 GHz	0.20 GHz
Relative BW		51.30%	54.58%	15.29%	6.00%	5.88%
Max Gain		1.59 dBi	1.68 dBi	4.80 dBi	5.37 dBi	5.60 dBi

Conclusions

This article presents the process of designing a wearable flexible antenna operating in the 5G system. The presented antenna construction meets the requirements for operation in the 5G system for the frequency range from 3.4 GHz to 3.8 GHz. The proposed antenna can be used for communication in densely populated cities, where there are many terrain obstacles which, in the case of 4G networks, hinder the transmission of information. The material used for the antenna substrate is a jeans type textile material. Its universality, low price, versatility and relatively high durability contributed to the choice of this fabric as the main element of the antenna structure. Additionally, the low dielectric constant of denim makes it easier to obtain a structure that will work in the entire frequency range. The proposed flexible antenna was assumed due to its location on the pocket of the front jeans jacket.

The article also presents an analysis of the results of electrical parameters simulation for the proposed flexible antenna in free space.

The proposed antenna has a gain at a 3.6 GHz frequency of 1.66 dBi. The results also show that its bandwidth is 2.23 GHz (relative bandwidth 54.58 %), which is a very good result, much greater compared to results published in the world, e.g. antennas is on the order of 0.5 GHz [5], [16], [17]. The proposed antenna can be a good solution for 5G mobile communication that requires high bandwidth. The size of the antenna is very compact, its weight is very small, so it can be placed anywhere on your clothes.

The designed wearable flexible antenna can be used in everyday life by an ordinary user and by uniformed services during routine activities. It will ensure much faster information exchange than the current antennas, and sewn into clothes will not require human interference in its operation. The design of the antenna, due to its dimensions, should not adversely affect the range of movements and adversely affect human health and life.

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