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Two methods to analyze microstrip antennas for Wi-Fi bandwidth

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Abstract: The paper presents a series of designed microstrip antennas with different gain and width radiation characteristics and intended for use in Wi-Fi systems. These antennas in a multilayer system were analyzed with the use of computer programs, and then the parameters and characteristics of these antennas were measured. At the same time, to check the correctness of work, additional measurements of the temperature of the radiators were used with a thermal imaging camera. The obtained results were compared with the results of calculations and measurements. They show high compliance with both calculations and measurements. At the same time, thermovision measurements show the weaknesses of the designed power lines.

Key words: antenna gain, microstrip antenna, thermovision measurements

1. Introduction

The architecture of internal radiocommunication systems differs substantially from the architecture of open-air systems. In the outdoor systems the main goal is to cover fields, in order to ensure necessary access to point-to-point and point-to-multipoint networks, but at the same time designing the radio coverage in order to eliminate potential disruptions in designed systems and influence on other telecommunication systems. In-indoor environment coverage is precisely defined by the geometry of the building while borders directly influence the propagation. The technology used to ensure the indoor connection is Wi-Fi technology which ensures fast Internet connection to devices. Currently there are 5 main standards in wireless networks which work in 5 GHz or 2.4 GHz bandwidth. Due to the complex relation of coexisting factors, while designing a specific radio system, detailed knowledge on a specific place and determining requirements such as geometry, the selection of materials used to build the room, the amount of furniture, defined usage and projected changes in the usage of the room are needed. All the mentioned above factors need to be taken into consideration while designing the coverage of the selected area with the signal. Therefore, we must design an antenna which would ensure meeting all the requirements [16].

Currently, one of the most innovative fields of antenna technology is the field of microstrip antennas. Microstrip antennas have many interesting features, such as:

– accurate representation on the surface,
– low manufacturing cost,
– high repeatability of performance,
– insignificant volume,
– operating frequency masking,
– simplicity of production, provided that relatively advanced technologies are used,
– flat shape and low weight allow the use of antennas on a dielectric basis on fast-flying objects without fear of deteriorating their aerodynamic properties.

However, the dielectric substrate used favors the excitation of surface waves, which, propagating along the dielectric plane, interfere with the normal operation of the antenna. Other disadvantages of microstrip antennas are:

– narrow bandwidth,
– limited power load.

These antennas allow for the miniaturization of the antenna system, thus increasing its density. This causes the occurrence of mutual couplings changing the field distributions on aperture antennas and the current distributions in linear antennas. This state of affairs, in turn, changes the spatial characteristics of antenna radiation and their input impedance.

The article presents microstrip antennas made of one radiating element, two elements and four radiating elements. Then, the results of measurements of the characteristics of these antennas and the measurement of temperature distribution on the antennas are presented. High compliance has been achieved.

2. Antennas in radiocommunication system

Due to a variety of rooms where Wi-Fi is to be provided, antennas with different radiation characteristics and gains are needed depending on specific conditions. Therefore, we may use either a single radiation element or an antenna array. Currently, due to their characteristics in Wi-Fi networks, microstrip antennas are commonly used [8, 9]. An antenna is a very important element on the radiocommunication path. Its task is to transform directed electromagnetic waves into a wave approximately flat in the free space of the transmitting antenna or vice versa, the receiving antenna. Therefore, an antenna is a device matching waveguide to free space [2].

The description defines that not in every case energy emitted from an antenna shall be emitted only in the form of an electromagnetic wave. It's also obvious that some part of energy shall be emitted in the form of heat. Because we are not dealing with ideal elements we may state that heating of antenna elements is correlated with matching input impedance of the antenna with the impedance of the transmitter and matching of wave impedance of the antenna to the impedance of the transmitter, as well as matching the wave impedance of the antenna to the impedance of the free space in which the electromagnetic wave will propagate (Fig. 1).

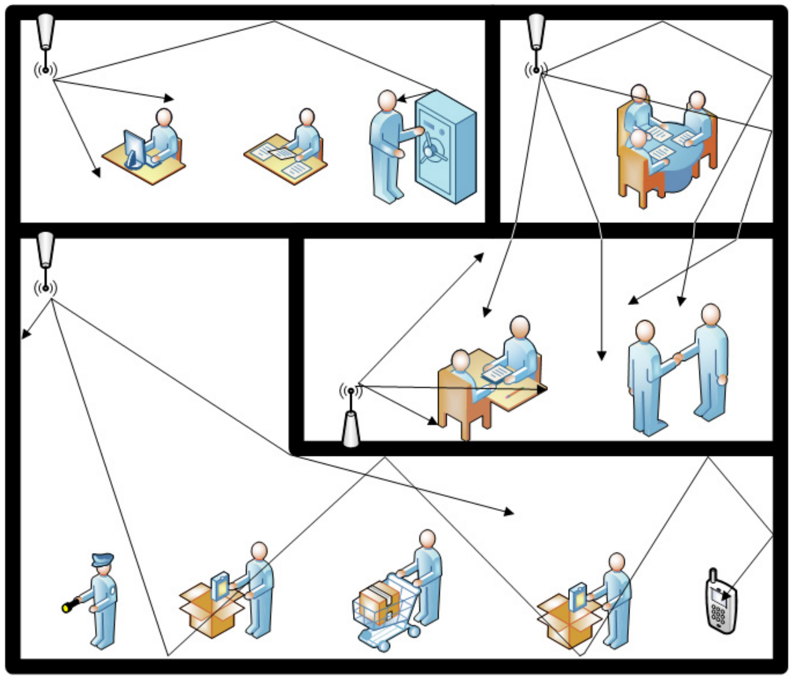


Fig. 1. Section of a building with marked indoor propagations of radio waves

One of the key parameters characterizing antennas is a standing wave coefficient, SWR (standing wave ratio), which defines the mutual fit of an antenna to a feeding line and surrounding environment [10].

3. Design of microstrip antenna to Wi-Fi system

Along with the development of theories and techniques of microstrip antennas we can use different ways of modeling the antennas [9], the most popular ones are:

– transmission model,
– cavity model,
– current net model,
– full wave model.

The selection of a proper analytic method depends on a model of the designed or analyzed antenna [7]. In microstrip antennas we need to pay attention to connections of field and circuit aspects which results in more complex methods used to analyze them. The selection of proper parameters of an antenna is the most important issue to be taken into account while designing of the antenna [5]. Nowadays, the designing of antennas is done in two steps. In the first phase basic geometrical dimensions: length (L) and width (W) are selected. A transmission line model is being used to determine those values. One of the most important parameters are geometrical length and width of radiators. Their values have been defined by the usage of the transmission line model based on the following relations:

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

where ε_{re} is the effective dielectric constant.

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{re}}} - 2\Delta L, \tag{2}$$

$$W = \frac{c}{2f_o\sqrt{\dfrac{(\varepsilon_r + 1)}{2}}}. \tag{3}$$

The width of radiators defines the width of working bandwidth and input impedance while increasing the width results in the increasing efficiency of radiation and an increase in radiated power. The resonant frequency of an antenna is dependent on the length of a radiator. The calculation of the relation of width to length has been defined as $W/L \approx 1.31$. This value is in line with the assumption that the relation should be within the range of $1 \leq W/L \leq 2$.

The next parameter of an antenna is the length of the radiation extension ΔL, it depends on the dielectric constant, height of laminate, length of a radiator and its width. The ΔL parameter and the radiating gaps are related to the scattering fields at the ends of the radiating element and are defined in the following transmission line model:

$$\Delta L = 0.412h\frac{(\varepsilon_{re} + 0.300)(W/h + 0.264)}{(\varepsilon_{re} - 0.258)(W/h + 0.813)}. \tag{4}$$

The input impedance has been calculated at a value of $Z = 50\ \Omega$. The value is dependent on the distance from the edge of the antenna to the edge of the radiator. The value increases with decreasing length. In the next step, the input resistance of the radiator has been calculated:

$$R_{in} = \frac{1}{G_{10}}, \tag{5}$$

where the G_{10} parameter is the conductance, representing radiation, losses in dielectric and losses in the patch and in the screen.

Following the values calculated from the above-mentioned relations, we can see that it has been possible to define the width of the gap, the length and width of the feeding line, which is connected to the radiator. The length of the cut has been defined as follows:

$$50 = R_{in}\cos^2\left(\frac{\pi}{L}y_0\right). \tag{6}$$

To determine the width of the feeding line W_f, relation (8) has been used, where the variable a has been defined as a supporting value, necessary to define the width. In the case when the parameter a is greater than 1.52, the width is calculated from Equations (7), (8).

$$a = \frac{50}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right), \tag{7}$$

$$W_f = \frac{8e^a}{e^{2a} - 2}h. \tag{8}$$

In order to improve the calculations performed for parameters of the microstrip antenna, a program in the MATLAB R2016b environment has been prepared.

Whereas, the environment of computer simulation technology (CST) and FEKO based on the finite-difference time-domain (FTDT) [4,11,15] have been used to optimize element dimensions of the antenna. It has been done manually or with the usage of the built-in optimizer function change of dimensions of exciting and radiating elements and recording of the SWR, S_{11}, distribution of currents and characteristics of radiation of the antenna built this way.

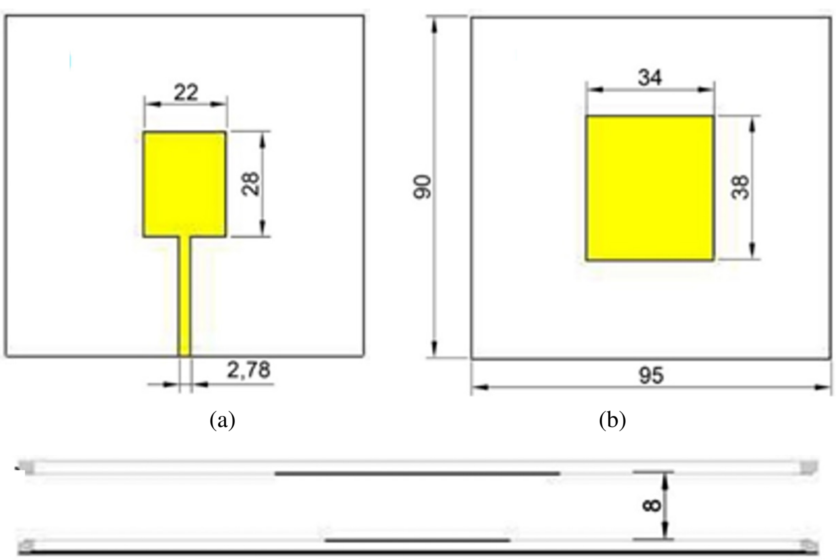
In the next step, in order to verify correlation of standing wave coefficients with the distribution of temperatures on the surface of the antenna, three models of microstrip antennas working at 2.4 GHz have been designed and built. The antennas are:

– one-element antenna,
– two-element antenna,
– four-element antenna.

The antennas models have been built in multilayer technology with electromagnetic coupling [1–3]. The following optimal dimensions of a single antenna's element have been obtained:

a) exciting element dimensions: $L_1 = 22$ mm, $W_1 = 28$ mm,
b) radiating element dimensions: $L_2 = 34$ mm, $W_2 = 38$ mm,
c) feeding line width: $w = 2.78$ mm,
d) distance between upper and lower dielectric: $h = 8.0$ mm.

Sizes of parameters of the designed antenna and the way of feeding have been presented in Fig. 2. Laminate FR-4 with the dielectric permeability $\varepsilon_r = 4.6$ and thickness $h_d = 1.5$ mm



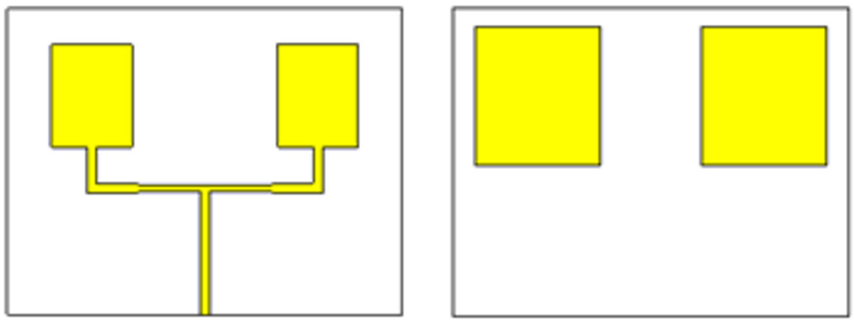
(a) (b)

(c)

Fig. 2. Project of antenna composed of single exciting element, radiating element and microstrip line: (a) lower patch; (b) upper patch; (c) side view

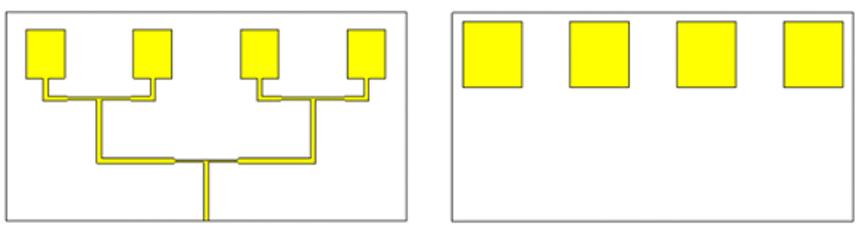
has been used. The laminate, where radiating and exciting elements are placed, is covered with copper 0.003 mm wide which has an emission rate of 0.07 at a temperature of $t = 0°C$.

The linear antenna array composed of two radiating elements placed centrally over feeding elements and the way of feeding by a Wilkinson divider [13, 14] are presented in Fig. 3 and Fig. 4. Another solution for supplying microstrip antenna arrays is the position presented in [12].



(a) (b)

Fig. 3. Design of linear antenna array composed of two exciting elements, two radiating elements and microstrip line: (a) lower patch; (b) upper patch



(a) (b)

Fig. 4. Design of linear antenna array composed of four exciting elements, four radiating elements and microstrip line: (a) lower patch; (b) upper patch

The selected models are presented in Fig. 5.

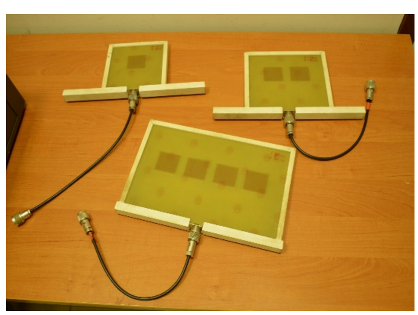


Fig. 5. Analyzed microstrip antennas

Following the working bandwidth of the antennas, the measurement has been made in the range from 2 GHz to 3 GHz. The results of the measurements of the standing wave ratio as a function of frequency have been presented in Fig. 6.

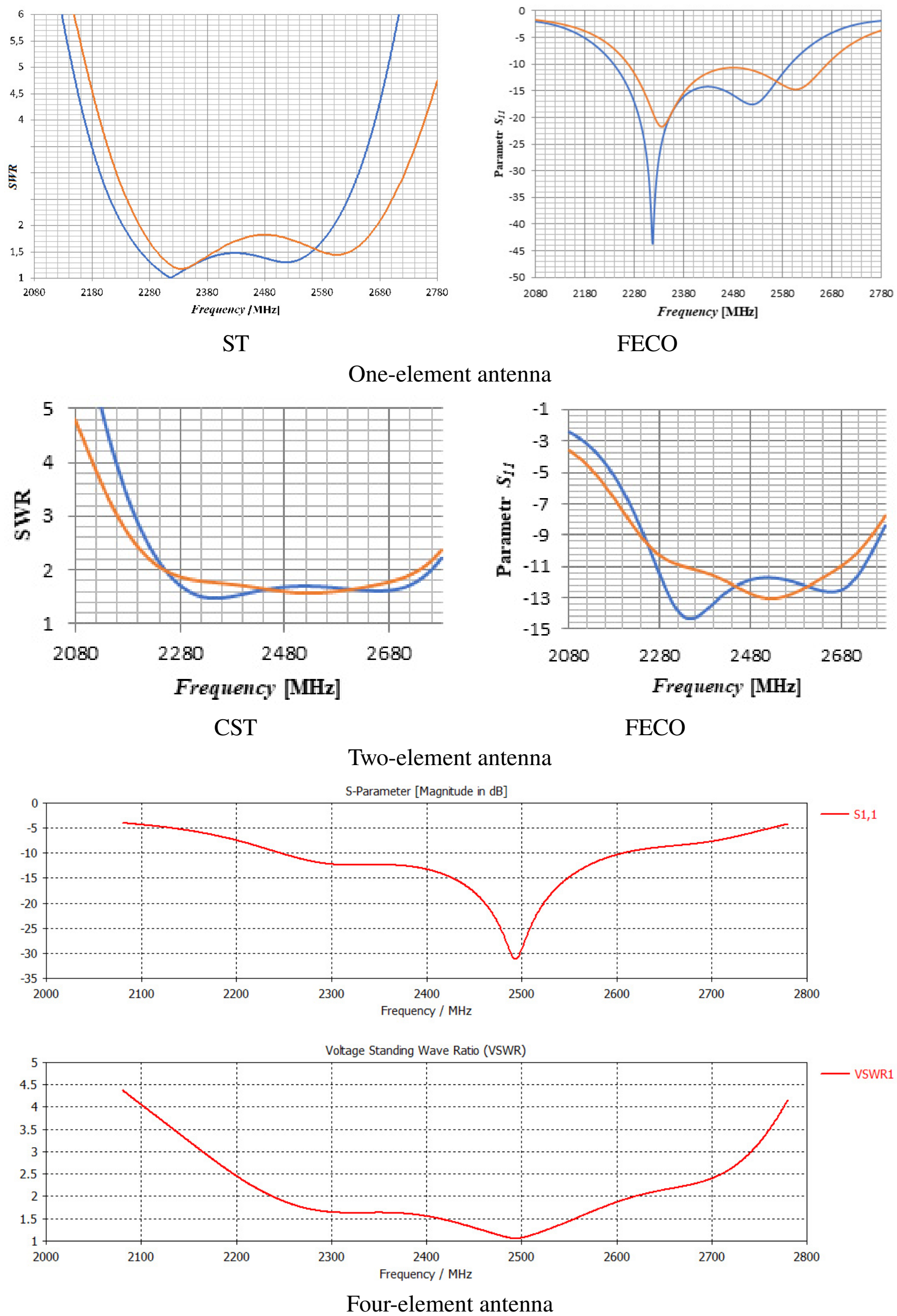
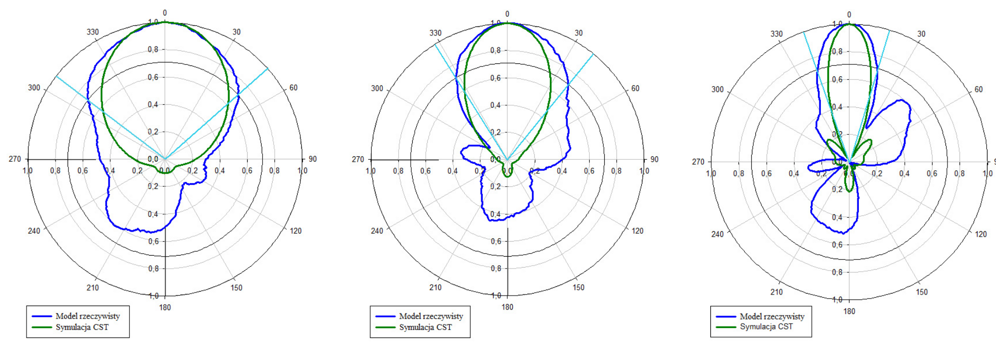


Fig. 6. SWR and S_{11} of antennas as a function of frequency

Analyzing the above characteristics presented in Fig. 6 it is worth noticing different working bandwidths dependent on the analyzed system. An increase in the number of radiating elements and the introduction of a Wilkinson divider as a feeding line had a significant influence on working bandwidth. It has been broadened. A bulge that can be observed in the middle part of the bandwidth is characteristic feature of the antenna consisting of one radiator and the antenna array built of two radiators. It can result in splitting the bandwidth into two and consequently negatively affect antenna operation. It's a common characteristic of microstrip antennas. The bulge can be decreased by accurately selecting the distance between microstrip antenna array layers [12]. In the analyzed case the distance has been selected in a way that the bulge does not affect the antennas operation. The SWR value varies in the expected range – below two.

In CST program radiation characteristics have been determined (Fig. 7) in polar coordinates and in 3D. We can observe many differences. The creation of an antenna array has an influence on radiation distribution, main beam direction and bandwidth characteristic at the level of 0.7 field strength. There are also differences in the levels of the side lobes in the radiation pattern.



(a) Single element (b) Two-element antenna array (c) Four-element antenna array

calculation measurement

Fig. 7. Normalised characteristics in polar coordinats for antennas in frequency 2430 MHz

Directions of main lobe are 2°, 0° and 16°, respectively, for setups with one, two and four radiating elements. The biggest bandwidth on the useful level (3 dB) – 110° has been recorded for a single antenna. The two-element array has reached 71.0°, and four-elements – 42.3°. It is clearly visible that this is a consequence of differences in signal phases resulting from inaccurate preparation of Wilkinson dividers.

Additionally, it is worth taking into consideration the radiation characteristics of 3D (Fig. 8) which well represents directions of signal emission. Designing antenna arrays has a great influence on increasing the energetic gain. It is in the range of 8.28 to 12.7 [dB], depending on the analyzed system.

The last analyzed element was to determine the distribution of currents for the analyzed systems. The CST program allows one to simulate the distribution of currents for a specific frequency. The results of the simulation are presented in Fig. 9

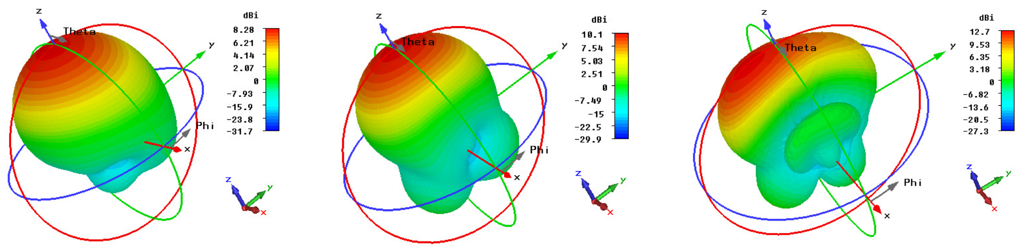
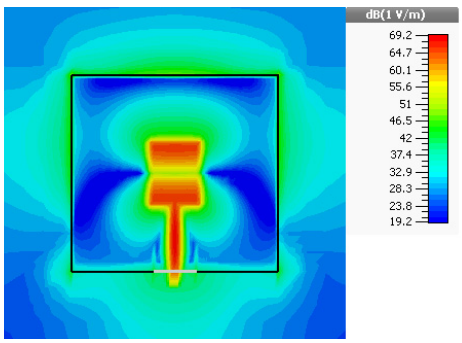
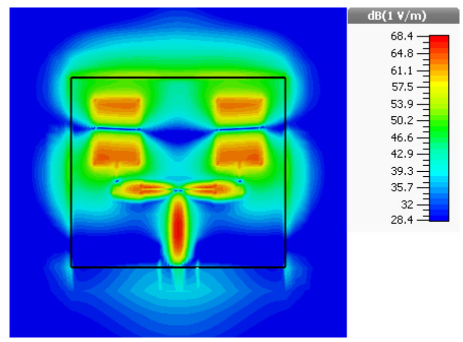


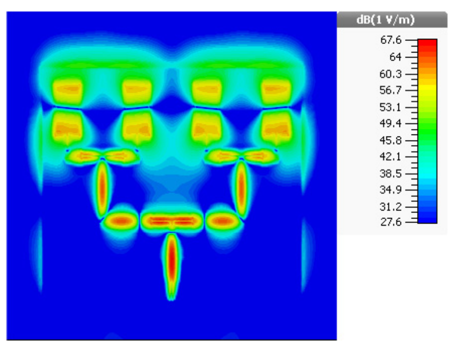
Fig. 8. 3D radiation characteristic for antennas radiating at frequency 2430 MHz



(a) Single element



(b) Two-element antenna array



(c) Four-element antenna array

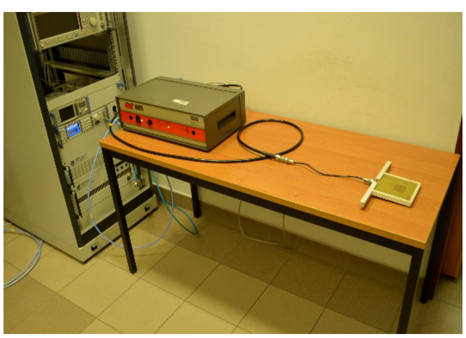
Fig. 9. Distribution of electromagnetic strength on a surface E for microstrip antenna arrays radiating in frequency 2430 MHz

4. Diagnostic possibilities for microstrip antennas via measurement of temperature distribution

An antenna is the final element of a transmission line, therefore the element which should receive all energy sent from the line. From the above description, we can draw the conclusion that not in every case the energy would be completely radiated from the antenna in the form of electromagnetic waves. It is also obvious that part of the energy will be distributed in the form of heat. The purpose of the task has been to verify which changes of heat distribution occur when antenna's working conditions change. We can assume that heating of the antenna elements is correlated with adjusting input impedance to the transmitter. As a result of the adjusted input impedance, the whole energy of the transmitting antenna should be radiated. A symptom of the phenomenon should be the substantial heating of the radiator versus other elements of the antenna, as this is the element that would disperse the energy. In the case of misalignment of antennas, the input impedance part of the energy will be reflected from the input clamp and reverted to the transmitter. At the moment when it reaches the transmitter, it should be reflected once again and returned to the antenna. In such a case we can expect higher temperature in the area of input clamps of the antenna. The line's impedance is defined by its geometrical dimensions therefore, it is constant. However, in the case of the antenna, the situation is different. Her impedance can change across a wide range. The impedance value changes along with changing frequency. To ensure the maximum range, the antennas of the Wi-Fi system are mounted at the highest possible heights. In the event of a system malfunction, we start with the antenna radiation. It requires technical means and considerable labor intensity. Therefore, the author proposed to use the first selection by remotely measuring the temperature of the antenna.

Frequency bandwidth has been carefully selected as antennas have been designed for a resonant frequency of 2.4 GHz. Measurements have been done starting from 2.0 GHz and later the frequency was gradually increased by 100 MHz. The research is used to observe the correlation of antenna's temperature distribution [6, 7] versus the change of the SWR for each frequency. A broadband amplifier with a maximal power of 5 W has been limited to 70% of the maximum power. It has been done following the results of the SWR measurement of the analyzed antennas.

In order to conduct the research a laboratory stand has been prepared, Fig. 10. It consists of:
– thermovision camera (VIGOcam V60),
– high frequency generator in the rage from 9 kHz to 6 GHz (Rohde & Schwarz SMB 100 A),
– 5 W power wide bandwidth amplifier (Amplifier Research),
– selected microstrip antennas made in electromagnetic coupling technology,
– connection cables.



(a) System to the measurement of SWR and return loss

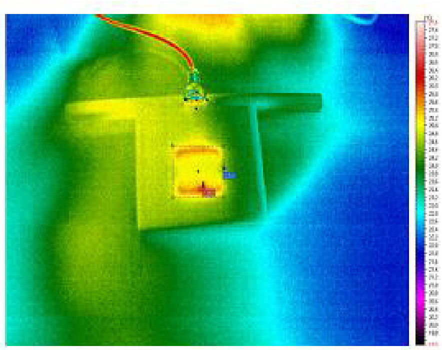
(b) Position to the measurement of radiation pattern

Fig. 10. Laboratory stand

A thermovision camera has been placed on a stand so each and every measurement has been done under the same angle and in the same distance. The measurements have been done in an environment temperature of 21°C and a distance of 50 cm. Based on the results of the measurement of the one-element antenna by the THERM program of Vigo System – used to analyze data – two areas with the highest temperature amplitude have been selected. First, in the shape of a rectangular, has been placed where the radiator is located.

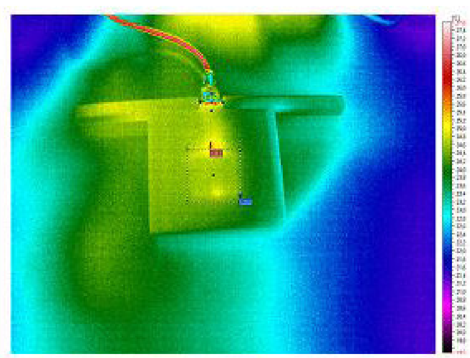
The second, in the shape of an ellipse, has been situated on antenna input clamps. Information on minimal, maximal and average temperatures has been collected in those two areas. The final result is the graph of characteristics of temperature changes as a function of frequency. Due to small differences in temperature distribution as a function of frequency in other antennas, only sample thermograms made in extreme measurement points and only for a working frequency of 2.4 GHz have been presented.

The presented thermographs allow one to state without any doubt that the designed feeding system can generate huge energetic losses, and in future can be a potential place where the antenna would break. Therefore, coincident transformers should be used, as they ensure a fluent impedance transformation and hence fit better. At the same time the electromagnetic strength presented in Fig. 9, as well as the results of the temperature measurements confirm that microstrip antennas can be modeled with the simplest model – the linear transmission line model shown in Figs. 11–13, the calculations obtained based on the model can be achieved faster with the results accurate enough for engineering purposes. The weakness of the method is the limitation of the antenna to have radiators in the shape of a rectangular or square.



N.o.	Description of the areas	t_{min} (°C)	t_{max} (°C)	t_{av} (°C)
1	256.130.43.26	24.3	26.1	25.1
2	302.124.34.24	22.6	25.9	24.5

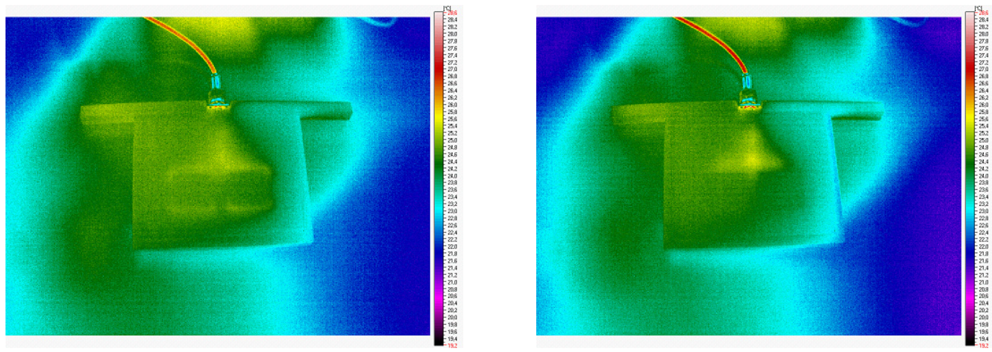
Antenna excited with frequency 2.4 GHz



N.o.	Description of the areas	t_{min} (°C)	t_{max} (°C)	t_{av} (°C)
1	256.130.43.26	24.1	25.3	24.6
2	302.124.34.24	22.36	25.3	24.5

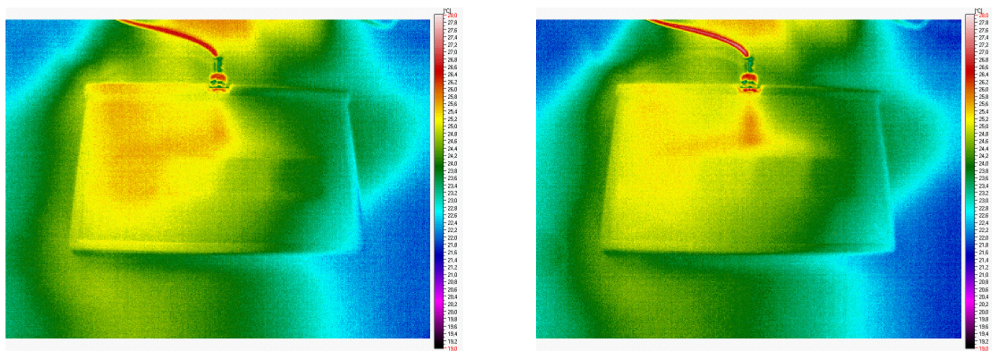
Antenna excited with frequency 2.8 GHz

Fig. 11. Thermograph of temperature distribution on a surface of one-element microstrip antenna



Antenna excited with frequency 2.4 GHz Antenna excited with frequency 2.8 GHz

Fig. 12. Thermograph of temperature distribution on a surface of two-element microstrip antenna



Antenna excited with frequency 2.4 GHz Antenna excited with frequency 2.8 GHz

Fig. 13. Thermograph of temperature distribution on a surface of four-element microstrip antenna

5. Conclusions

People, nowadays, require constant access to information. Wi-Fi networks are used for that purpose, both in the office and in the place of residence. One of the elements enabling correct and reliable transmission of information is an antenna. The microstrip antenna technique is one of the most innovative technologies of antenna production. Many tools for the design of this type of antenna have been developed. Computational technology has also been developed to simulate electromagnetic field problems. The result of the modelling of these techniques must be experimentally proven. The work presents antennas designed to work in the Wi-Fi system and in the 2.4 GHz band. Classic measurements of parameters and characteristics were made. Additionally, thermographic measurements of these antennas were made. Analysing the results of the research, it can be concluded that there is a large correlation between the temperature distribution on microstrip antennas and the standing wave ratio. This correlation is observed when comparing the SWR diagram and the temperature distribution of radiators as a function of frequency. The maximum temperature for the antennas was obtained exactly in the same places where the standing wave ratio was the lowest, i.e. for the 2.4 GHz frequency

The changes in the maximum temperature are within the range of 1.6 [°C], while the changes in the average antenna temperature in the marked area amount to a maximum of 0.9 [°C]. For this reason, the thermal imaging camera used for this type of application should have a resolution not lower than 0.1 [°C]. Failure to meet this condition could result in an incorrect reading of the changes in the antenna's temperature distribution.

The antennas consisting of two and four elements, due to their geometric dimensions, were not able to heat up to the same extent as the one-element antenna. This is due to insufficient energy supplied to the input terminals of these antennas. For antennas of this size, the input signal power should be at least twice as high.

A thorough theoretical analysis of the thermovision measurement and microstrip antennas allowed one to create a comprehensive description of the issue under consideration. The theoretical part has been supported by both calculations and tests of the temperature distribution of microstrip antennas during changes in their operating conditions. On the basis of the conducted research, we can unequivocally answer the question that the temperature distribution of microstrip antennas allows for the diagnosis of their parameters. Due to the wide use of microstrip antennas in cellular networks and their mass production, remote diagnostics of their parameters can be used to even faster development of this technology.

The development of antennas for all frequency sub-ranges used in Wi-Fi systems is now being carried out.

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