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To cite this article: D N Tumakov et al 2019 J. Phys.: Conf. Ser. 1158 042029

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Fast method for designing a well-matched symmetrical four-tooth-shaped microstrip antenna for Wi-Fi applications

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Abstract. The problem of fast designing of a well-matched symmetrical four-tooth-shaped microstrip antenna at frequency of 2.44 GHz is considered. To solve the problem, we use regression models for wavelength, resistance and bandwidth. The optimization problem for finding the geometrical parameters of the antenna radiator is formulated by using these models. In the first step of approximation, the antenna is obtained as a solution to the optimization problem. In the next step, the geometry of the radiator is refined so as the base frequency of the antenna is closer to 2.44 GHz.

1. Introduction

Today, in practice, many types of antennas are used for Wi-Fi applications [1]. Microstrip antennas are most widespread of them [2, 3]. This is due to a number of their advantages, such as compact size, light weight and ease of manufacture.

Microstrip antennas play an important role in communication systems [4]. There are many ways to design such antennas [5-7]. They use various feeding methods [8] and various substrate materials [9], adding slots in the radiator [10], or sequentially correcting the sizes of the slots until the antenna is well-matched in a given frequency range. Most often, the geometry of the radiator [11-13] or the ground plane [14] are varied.

For example, two dual-band antennas were designed in [15]. The first antenna had a radiating patch of the complex T-shape. The tuning and optimization of the antenna were performed by consequentially changing the lengths of the elements of the patch. The second antenna had a rectangular radiator with stepped slots on both sides. The antenna was tuned by adding slots on the patch and changing the geometry of the stepped slots. The design of a compact broadband microstrip patch antenna for wireless communication systems was presented in [16]. The form of the radiator antenna was made in a cruciform form.

However, the designing of a Wi-Fi antenna is a rather long and time-consuming process. The authors of the present paper propose the following approach: to study the family of antennas and to establish a relation between the electrodynamic characteristics of the antenna and the radiator geometry [17]. In the present work, a microstrip antenna with a tooth-shaped radiator is chosen [11]. For example, for microstrip antennas with such a radiator, the dependences of the electrodynamic characteristics on the geometry of the radiator were revealed in [18, 19], and mathematical models were constructed in [20] by using the correlation and regression analysis.

In the present paper, we develop a fast algorithm for designing a microstrip Wi-Fi antenna with a radiator of a symmetrical four-tooth shaped form. The process of designing such an antenna consists in
obtaining regression models for base frequency and identifying the optimal geometry of the radiator. The radiator parameters obtained in this way are adjusted in the next step.

2. Problem statement
We consider the configuration of the following monopole printed antenna. Its radiator has a symmetrical four-tooth-shaped form (Fig. 1). The radiator dimensions are determined by the width \( a_R \) and the length \( b_R \). Two rectangular cutouts are placed on the sides of the radiator. The depth of cutouts is set by the parameter \( d_R \); the spike length \( c_R \) is determined from the formula \( c_R = b_R / 3 \). The radiator is located on the front side of the substrate and is fed by a coaxial cable through the feedline with the resistance of 50 \( \Omega \). The length and width of the feedline are given by the parameters \( l_F = 15 \) mm and \( w_F = 1 \) mm, respectively. The ground plane is placed on the back side of the substrate (in Fig. 1, the shaded area). The width of the ground plane coincides with the width of the substrate, and the length coincides with the length of the feedline \( b_G = l_F \). The dimensions of the substrate are given by the parameters \( a_S = 30 \) mm and \( b_S = 75 \) mm, the dielectric constant \( \varepsilon_r \) is 4.5; and the density of the material \( \rho \) is 1000 kg/m\(^3\). The thickness of the substrate is equal to 1 mm.

![Figure 1. The design of a monopole printed antenna with a symmetrical four-tooth-shaped radiator](image)

We simulate a well-matched microstrip antenna operating on a Wi-Fi band with the frequency of 2.44 GHz. To design such an antenna, we use a regression model for the wavelength at the base frequency, a model for the bandwidth and a regression model for the resistance. We calculate the values of the geometrical parameters of the radiator \( a_R, b_R \) and \( d_R \) using these regression models. Since the regression models have certain errors, the constructed antenna is not being precisely tuned to the 2.44 GHz frequency. Therefore, we further improve certain characteristics of the designed antenna; for example, we correct the base frequency, improve the matching, etc.

3. Definition of "almost optimal" geometric parameters of the radiator using regression models
We start designing the antenna by determining the appropriate radiator length \( b_R \) for given \( a_R \) and \( d_R \). We use the regression formula for the wavelength \( \lambda(a_R, b_R, d_R) \) at the base frequency from the work [18] of the following form

\[
\lambda(a_R, b_R, d_R) = 10.1558 \sqrt{b_R} + 0.916588 \sqrt{a_R b_R} + 2.74456d_R \exp(7.19012d_R / (a_R - d_R)^2).
\]

The model (1) gives the good relative error \( \varepsilon = 3.613 \) mm and the absolute error \( \delta = 1.69 \% \). The value of the wavelength \( \lambda \) at 2.44 GHz is calculated by the formula \( \lambda = c / f' \) where \( c \) is the velocity of light; \( f' \) is the frequency. We obtain \( \lambda = 122.95 \) mm. We substitute the value of \( \lambda \) in (1) and solve the equation for the parameter \( b_R \). As a result, we obtain two roots in the following form
We exclude from consideration the second root (with a plus sign), since it gives the radiator length \( b_R \) beyond the permissible length of the substrate \( b_S \). We note that the parameters \( a_R \) and \( d_R \) in (2) are still undefined.

We continue the process of the designing a well-matched antenna using the regression model for resistance \( \hat{R}(a_R, b_R, d_R) \) of a symmetrical four-tooth-shaped antenna from [21]

\[
\hat{R}(a_R, b_R, d_R) = 86.426 - 3.819a_R + 0.0806a_R^2 + (8.0568 - 0.131)d_R + (10 - 0.723a_R + 0.0166a_R^2)d_R^2 + (-1.6478 + 0.0921a_R)d_R^3 + (-0.1823 + 0.0241a_R - 0.000806a_R^2)d_R^4
\]

(3)

where \( d_R = 0.5a_R/2 \) + \( 0.1a_R(b_R - 24) + d_R \)/\( (6.576 - 0.4228b_R + 0.00415b_R^2) \). This formula gives the errors \( \varepsilon = 10.25\Omega \) and \( \delta = 5.12\% \). We note that the regression model for reactance could not be constructed.

We consider in Fig. 2 the dependence of \( S_{11} \) on the resistance \( R \) for a family of antennas with a four-tooth-shaped radiator. We take into account that a well-matched antenna with the best \( S_{11} \) is achieved in the case of \( R = 50\Omega \) and \( X_C = 0\Omega \).

In Fig. 2, the band (colored area) indicates the interval for the values of \( R \in (40\Omega, 60\Omega) \). It is obvious that antennas located in the interval have minimum values of \( S_{11} \). However, such antennas well-matched in the interval \( (40\Omega, 60\Omega) \) can be present in a large quantity and not all of these antennas can have a wide bandwidth. Therefore, we use the regression model to determine the bandwidth \( BW(a_R, b_R, d_R) = BW(b_R, a_R, d_R) \) from [19]:

\[
BW(a_R, b_R, d_R) = -0.1265a_R + 0.00236a_R^2 + 1.784\ln(a_R - d_R)/b_R - 0.16161.784\ln(a_R - d_R)^2/b_R + 0.8073\ln(a_R - d_R),
\]

(4)

which gives errors \( \varepsilon = 0.03 \) GHz and and \( \delta = 7.44\% \).

![Figure 2. The dependence of \( S_{11} \) on active resistance \( R \)](image)

We proceed to the calculation of suitable (“close to optimal”) parameters of width \( a_R \) and length \( b_R \) of the radiator, the depth of rectangular cutouts \( d_R \) such that the bandwidth is maximum; the resistance is \( R \in (40\Omega, 60\Omega) \); the dimensions of the radiator’s geometric parameters are not beyond the antenna substrate.

Thus, we obtain the following optimization problem using regression models (3) and (4):
\[ BW^f (a_R, d_R) \rightarrow \text{max} \]
\[ 40\Omega < R(a_R, d_R) < 60\Omega, \]
\[ 10\text{mm} \leq a_R \leq 24\text{mm}, 0.5\text{mm} \leq d_R \leq 11.5\text{mm}. \]

Where
\[
BW^f (a_R, d_R) = \begin{cases} 
    BW(a_R, b_R^f (a_R, d_R)), & \text{if } d_R < a_R / 2 - 0.1, \\
    0, & \text{otherwise}
\end{cases}
\]
and
\[
R(a_R, d_R) = \begin{cases} 
    \hat{R}(a_R, b_R^f (a_R, d_R)), & \text{if } d_R < a_R / 2 - 0.1, \\
    0, & \text{otherwise}
\end{cases}
\]

As a result of the numerical solution of the problem (5), we obtain the symmetrical four-tooth-shaped antenna with \( BW^f (a_R, d_R) = 0.5690\text{GHz} \) at \( a_R = 10.2903\text{mm} \) and \( d_R = 4.57069\text{mm} \) at the frequency \( f = 2.44\text{GHz} \). We define the radiator length using formula (2) and obtain \( b_R^f = 21.4342\text{mm} \).

### 4. Improving the antenna performance

We calculate in the FEKO program a microstrip four-tooth-shaped antenna with geometrical parameters obtained in the previous section. The antenna with radiator parameters \( a_R = 10.2903\text{mm}, \)
\( b_R^f = 21.4342\text{mm} \) and \( d_R = 4.57069\text{mm} \) is shown in Fig. 3 (the front side of the antenna is on the left and the back side of the antenna is on the right). The green color is for the dielectric; the brown color is for the metal.

The calculation results in FEKO are shown in Fig. 4. As we see from Fig. 4, the bandwidth \( BW = 0.6348\text{GHz} \) turned out to be slightly larger than that obtained when calculating the problem in the previous section (\( BW^f (a_R, d_R) = 0.5690\text{GHz} \)). The value of the base frequency \( f \) is 2.586 GHz. However, initially we calculated the antenna parameters at the frequency of 2.44 GHz. Such deviations in the values of the base frequency and the bandwidth are primarily due to the error in the regression models, as well as possible errors of numerical simulation in FEKO. We note that the reflection coefficient is equal to \(-18.3583\text{dB} \), and the resistance is \( 59.557\Omega \).

![Figure 3. The design of the four-tooth-shaped microstrip antenna](image)
computational grid to improve the accuracy of numerical simulation in FEKO. As a result, for an antenna with the new length $b_R$, we obtain the following characteristics: $S_{11} = -19.9533\text{dB}$, $f = 2.53061\text{GHz}$, $BW = 0.6315\text{GHz}$ and $R = 55.347\Omega$.

We again increase the radiator length by 1 mm and obtain $b_R = 23.4342\text{mm}$. We perform numerical calculations in FEKO and obtain the antenna with the reflection coefficient $S_{11} = -20.4885\text{dB}$ at $f = 2.46939\text{GHz}$ and the bandwidth of 0.6318 GHz. Herewith, the resistance of the antenna $R$ is $56.073\Omega$.

We construct a linear model that relates the radiator length to the base frequency. For this, we use the results obtained for the last two designed antennas: at $b_R = 22.4342\text{mm}$, the working frequency of the antenna $f$ is $2.53061\text{GHz}$ and at $b_R = 22.4342\text{mm}$, the working frequency of the antenna $f$ is $2.46939\text{GHz}$. We obtain the following dependency

$$b_R(f) = 63.7705 - 16.3345f. \quad (6)$$

![Figure 4. Characteristics for symmetrical four-tooth-shaped antenna](image)

We apply the model (6) to designing a four-tooth-shaped antenna at $2.44\text{ GHz}$. We substitute the required value of the frequency in (6) and obtain $b_R = 23.9143\text{mm}$. We perform a numerical calculation of the antenna in FEKO with the corrected radiator length and obtain the antenna with the following characteristics: $S_{11} = -20.9748\text{dB}$ at $f = 2.44898\text{GHz}$, $BW = 0.6265\text{GHz}$ and $R = 53.313\Omega$. (see Fig. 5).

![Figure 5. Characteristics for symmetrical four-tooth-shaped antenna in FEKO](image)
We also present in Fig. 6 the radiation pattern of the designed antenna at the base frequency of 2.45 GHz. It can be seen that the antenna is the omnidirectional antenna with the gain of 1.75.

Figure 6. The radiation pattern of the designed antenna at the frequency of 2.45 GHz

5. Conclusions
The algorithm for designing a well-matched microstrip four-tooth-shaped Wi-Fi antenna using regression models is proposed. This algorithm allows to select from the family of four-tooth-shaped antennas the most well-matched antenna.

This approach is characterized, first of all, by a high speed of finding the “optimal antenna”, since it does not require large calculation cycles with sequential changes in the dimensions of the geometric parameters. Based on the proposed algorithm, the microstrip Wi-Fi antenna is designed, which has the bandwidth $BW = 0.63\text{GHz}$ and the reflection coefficient $S_{11} = -21\text{dB}$. For the designed antenna, the radiation pattern is presented.

Acknowledgments
The work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University.

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