ELEKTROTEHNIŠKI VESTNIK 83(4): 177-182, 2016
ORIGINAL SCIENTIFIC PAPER

Segmented Wire Antennas

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Abstract. The properties of many wire antennas can be improved by breaking the antenna conductors into many segments, interconnected by capacitances and/or inductances. A fast design procedure is described for determining the values of individual reactances that will simultaneously optimize the input match and the directivity. The procedure requires a multiport impedance matrix generated by an electromagnetic simulation software. Practical examples illustrate how to fabricate the segmented antennas for a low microwave range in a printed-circuit technique.

Keywords: Antenna directivity, design optimization, input match, omnidirectional antenna

Segmentne žične antene

Lastnosti mnogih žičnih anten se dajo izboljšati tako, da se prevodniki razsekajo v več odsekov medsebojno povezanih s kondenzatorji ali s tuljavami. Vrednosti posameznih reaktanc je možno določiti s hitrim postopkom, ki hkrati optimizira vhodno prilagojenost in usmerjenost antene. Postopek potrebuje impedančno matriko, izračunano s pomočjo programa za elektromagnetno simulacijo. Praktični primeri prikazujejo postopek izdelave segmentne antene za nizko mikrovalovno področje v tehnologiji tiskanih vezij.

1 INTRODUCTION

A segmented antenna is obtained from an ordinary wire antenna by partitioning it into a number of short segments. An example of a segmented monopole antenna, consisting of 6 segments and 6 ports, is shown in Fig. 1. The length of individual segments should be shorter than one-quarter of the free-space wavelength. To operate this segmented monopole as a transmitting antenna, one connects a source at port 1 and one attaches five lumped capacitors or inductors to the remaining ports. By doing this, an antenna system has been created with five reactances which can be individually adjusted to modify the performance of the antenna. An antenna designer is therefore provided with five additional degrees of freedom. If the monopole was made of a solid piece of conductor, the designer would have been left with only two degrees of freedom: the monopole thickness and its length.

Section II describes three different examples of what can be achieved by segmentation. Section III describes a simple approach to analysis of a segmented antenna. The optimization procedure for determining the values of reactances at individual ports is described in Section IV.

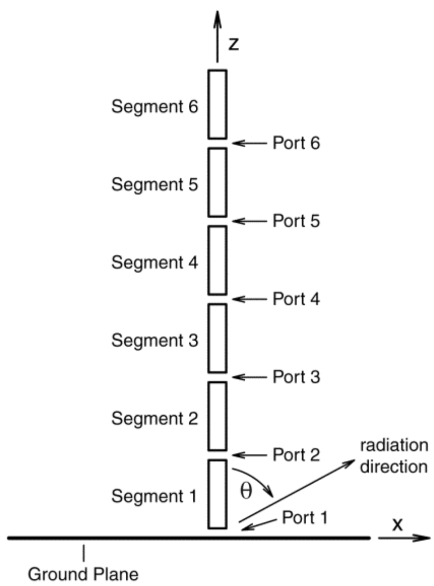

Figure 1. A segmented monopole antenna.

2 PRACTICAL REALIZATIONS

2.1 Omnidirectional Square Loop Segmented Antenna

It is a well-known fact that a small loop antenna creates an omnidirectional radiation pattern. Unfortunately, as long as the loop is small in comparison with the wavelength, its radiation resistance is so small that it is not suitable for an efficient transmitting antenna. Increasing the size of the loop makes the radiation resistance larger, but eventually the current distribution along the loop begins to create some standing waves so

Received 13 June 2016
Accepted 22 July 2016

that the radiation pattern no longer remains omnidirectional. One way of preserving the omnidirectional pattern and at the same time matching the input impedance to the value of 50Ω is to increase the circumference of a square loop to about one wavelength, and partition it into straight segments interconnected by four capacitances [1, 2]. The antenna is made on a two-sided printed circuit as shown in Fig. 2. Because of its flat shape this antenna was intended to be used in a wing of a model airplane at 956 MHz. To make it possible to drive the antenna from a 50Ω coaxial cable, a miniature balun was inserted at the input port.

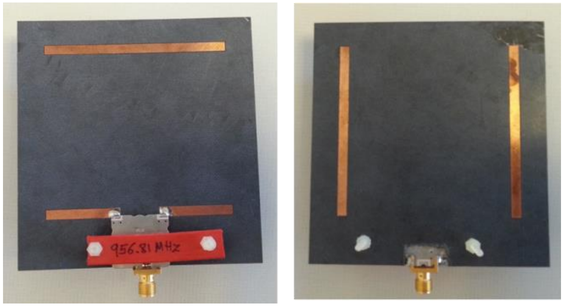

Figure 2. Omnidirectional square loop segmented antenna.

The segmentation details are shown in Fig. 3. The length of each side of the square-shaped antenna is equal to about one-quarter of the free-space wavelength. The antenna can be thought to consist of eight segments. There are four capacitances interconnecting the segments, one in each of the corners. The remaining segments are interconnected by short circuits. Capacitance values were determined by an optimization procedure, the principles of which will be described later in Section IV.

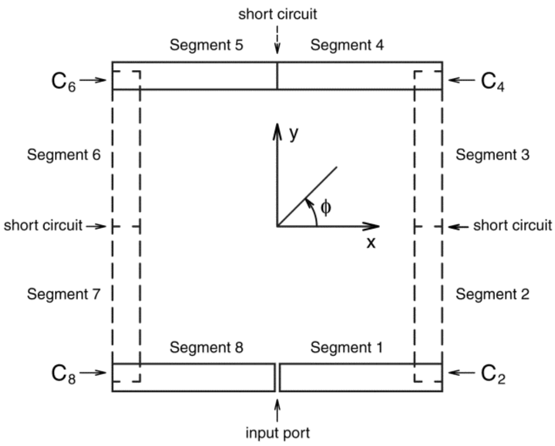

Figure 3. Segmentation details of a square-loop segmented antenna.

A convenient fact is that the capacitances are of the order of one picofarad, so that they are fabricated by simply overlapping the ends of the neighboring segments on the opposite sides of the dielectric substrate. The maximum gain of 2 dB occurs in the negative y direction. Antenna efficiency in the direction of maximum is measured to be 94%. The cross-polarized field is 27 dB smaller from the maximum field. The plots of measured radiation patterns can be found in [2].

2.2 Segmented Monopole Antenna

Figure 4 shows a segmented monopole antenna described in [3]. It consists of 6 segments, interconnected by 3 inductances, one capacitance (at port 5), and one short circuit (at port 3). The return loss is better than 10 dB within relative bandwidth of 8%, and the directivity in the horizontal direction is 7.3 dB.

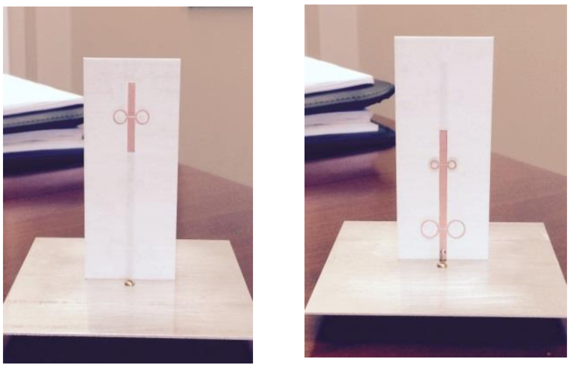

Figure 4. Front and back views of the segmented half-wavelength monopole antenna.

Any monopole antenna that is perpendicular to the ground plane of infinite size produces a perfectly omnidirectional radiation pattern. The length of a typical solid conductor monopole antenna is about equal to one-quarter of the free-space wavelength. The theoretical directivity in the horizontal direction is 5.1 dBi. One expects that by doubling the length of the monopole to one-half wavelength, the directivity could be increased by 3 dB more. Therefore, 8.1 dBi is a theoretical limit one would like to achieve using segmentation. Unfortunately, the input impedance of a solid half-wavelength monopole is prohibitively high, so a complicated impedance matching circuit would be required. The segmented half-wavelength monopole in Fig. 4 matches the input impedance without problem, and its simulated directivity comes close to the ideal limit. More details can be found in [3].

2.3 Segmented Half-Loop Antenna

An antenna suitable for communication with non-stationary satellites should have a radiation pattern omnidirectional in the xz plane, similar to the pattern produced by a horizontal magnetic dipole. Such a pattern can be realized by a segmented half-loop antenna [4, 5], sketched in Fig. 5.

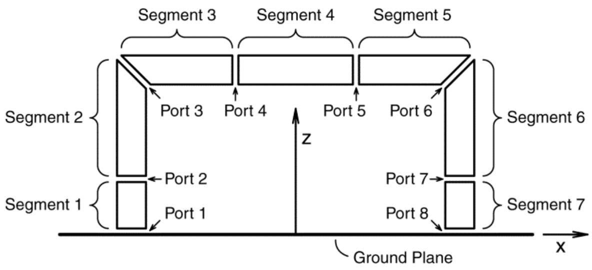

Figure 5. Segmentation details of a half-loop segmented antenna.

The excitation should be produced by two sources in a phase opposition, located at ports 1 and 8. The reactances at ports 3 and 6 should be inductive, while the remaining ones should be capacitive. As shown in Fig. 6, the inductances are realized by small loops, while the capacitances are made by overlapping the opposite segments.

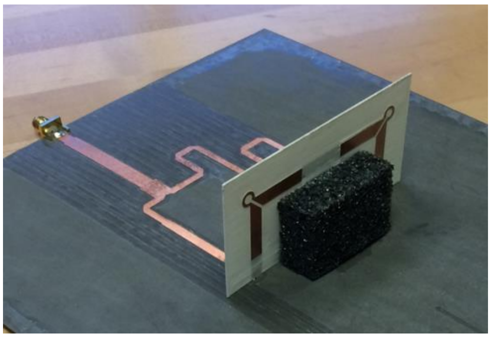

Figure 6. The segmented half-loop antenna

The prototype antenna was designed for a frequency of 1.2276 GHz, which is one of the frequencies used for GPS (Global Positioning System). With the use of a ground plane of 1 meter diameter, the measured radiation pattern shows the gain of 3.8 dBi down to an angle of θ=70° away from the z axis. The measured radiation efficiency is 93%. The measured relative bandwidth for 10 dB return loss is 7%.

3 SIMPLIFIED ANTENNA ANALYSIS

The segmented monopole from Fig. 1 is a linear, reciprocal 6-port network. With the use of electromagnetic simulation software, it is possible to determine a 6×6 impedance matrix $\boldsymbol{Z_a}$, which describes this particular antenna. The equivalent circuit of a transmitting segmented monopole is shown in Fig. 7.

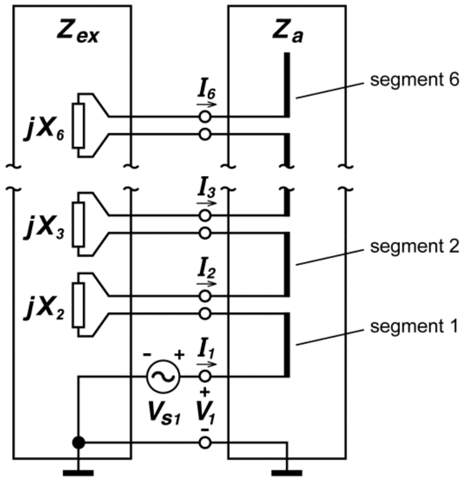

Figure 7. Equivalent circuit of a segmented monopole antenna.

The values of the individual reactances are grouped in a 6×6 diagonal matrix $\boldsymbol{Z_{ex}}$:

$$\mathbf{Z}_{\mathbf{ex}} = diag\left(0,\, jX_2,\, jX_3,\dots jX_6\right). \qquad (1)$$

For simplicity of fabrication, the series reactance at port 1 is set to be zero. The circuit in Fig. 7 is thus described by

$$\left|I\right\rangle = \left(\mathbf{Z}_{\mathbf{ex}} + \mathbf{Z}_{\mathbf{a}}\right)^{-1}\left|V_g\right\rangle, \qquad (2)$$

where $\left|I\right\rangle$ is the 6-vector of individual port currents, and $\left|V_g\right\rangle$ is a 6-vector of impressed voltages (having only the first component different from zero). The voltages at individual ports are:

$$\left|V\right\rangle = \mathbf{Z}_{\mathbf{a}}\left|I\right\rangle. \qquad (3)$$

and the input power delivered to the antenna becomes:

$$P_{in} = \frac{1}{2}\left|I_1\right|^2 \mathrm{Re}\left(Z_{in}\right). \qquad (4)$$

The input impedance of the antenna is given by the ratio of voltage and current at the first port:

$$Z_{in} = \frac{V_1}{I_1}, \qquad (5)$$

so that the reflection coefficient magnitude at the input is:

$$\rho = \left|\frac{Z_{in} - R_c}{Z_{in} + R_c}\right|. \qquad (6)$$

R_c is the value of the characteristic impedance of the coaxial cable which is feeding the antenna.

Equations (1) to (6) enable one to compute the accurate value of ρ for any arbitrary combination of individual reactances. The best combination of reactances which minimizes the value of ρ, can be found by an optimization procedure. As the computation of ρ is based only on circuit-theory equations, without the need to use the electromagnetic simulation software again, the execution times will be very fast. However, an arbitrary combination of lumped reactances might degrade the directivity of the antenna. To prevent that from happening, the optimization must also attempt to maximize the directivity. Unfortunately, an accurate computation of directivity would require the use of electromagnetic simulation software, which would significantly slow down the optimization procedure.

An approximate way to determine the directivity without involving the use of EM simulation software is the following. It can be seen from the equivalent circuit in Fig. 7 that the current on the segment *p* (where *p*=1 to 6) starts with the value of I_p and ends with the value of I_{p+1}. As the segment length d_p is shorter than one-quarter wavelength, the current distribution on the segment cannot form distinct standing waves, but displays only a gradual variation of its phase and/or amplitude. One can assume that the effective current causing the radiation from the segment *p* can be approximated by simply taking the average of the two end values:

$$I_{sp} = \frac{1}{2}\left(I_p + I_{p+1}\right). \tag{7}$$

The current at the top of the monopole (p+1 = 7) is assumed to be zero.

In a free-space environment, the current element I_{sp} will produce the far field $E_{\theta p}$ at the distance *r* in the horizontal direction (θ = 90°) [6]:

$$E_{\theta p} = \eta \frac{jI_{sp} d_p}{2\lambda r} e^{-jkr}, \tag{8}$$

where $\eta = 120\pi$ is the free-space intrinsic impedance and λ is the operating wavelength. When a perfectly conducting infinite ground plane is present, the image of the current element doubles the value of $E_{\theta p}$. The *current moment* of the segment *p* is defined to be:

$$I_{mp} = \frac{2\pi d_p I_p}{\lambda} = kd_p I_p. \tag{9}$$

The power density of the radiated field at the (far) distance *r* produced by all the current elements is then:

$$S = \frac{\left|\sum_{p=1}^{6} E_{\theta p}\right|^2}{2\eta} = \frac{1}{\eta}\left|\frac{60}{r}\sum_{p=1}^{6} I_{mp}\right|^2. \tag{10}$$

For comparison, the power density of an isotropic source at distance *r* that is driven by an input power P_{in} is:

$$S_{iso} = \frac{P_{in}}{4\pi r^2}. \tag{11}$$

The desired approximate formula for the directivity *D* in the horizontal direction is obtained from the ratio

$$D = \frac{S}{S_{iso}} = \frac{60}{P_{in}}\left|\sum_{p=1}^{6} I_{mp}\right|^2. \tag{12}$$

The beauty of (12) lies in the fact that it requires only the circuit-theory algorithms, and it therefore executes the computation many times faster than any electromagnetic simulation software is able to do. The speed of execution is very important in an optimization procedure, because it enables the designer to investigate various possibilities within a reasonable amount of time. Once the acceptable values of individual reactances are determined by such an approximate method, the antenna design can be finalized with a full-wave simulation software, as was done in [4].

The above derivation was selected for its simplicity: all segments are aligned in the same direction, and the directivity is computed only for the case θ =90°. A more general formula for the approximate computation of directivity as a function of θ, when segments are forming a polygon, can be found in [5].

4 OPTIMIZING THE IMPEDANCE MATCH AND DIRECTIVITY

The objective function is selected to consist of two parts:

$$U = \frac{w_1}{D} + w_2 U_m \tag{13}$$

In order to maximize the directivity, the first part of (13) is simply proportional to the inverse of the directivity. The second part of (13) is defined as follows:

$$if\, \rho > \rho_{\min} \Rightarrow U_m = \left(10\frac{\rho - \rho_{\min}}{\rho_{\min}}\right)^2, \quad else\, U_m = 0. \tag{14}$$

The weights w_1 and w_2 are initially set to unity, but later they may be used to emphasize or to ignore any part of the objective function.

Therefore, if ρ is smaller than the minimum required value, the second part of the objective function is set to zero, so that the optimization routine will concentrate on maximizing the directivity. Otherwise, the second part starts growing from zero so that when ρ is 10% larger than ρ_{min}, U_m becomes unity. Beyond that, its value grows fast, so that the optimization routine becomes preoccupied only with the impedance matching.

Suppose one wants to design a monopole with an increased gain for frequency 2.44 GHz. The total monopole length is selected to be 69 mm (thus slightly longer than one-half wavelength) which will be partitioned into 6 equally long segments. The printed-circuit antenna will be made of 3 mm wide strips. The impedance matrix is generated by the Awas software [7]. This software assumes the wire conductors to be of a circular cross section. A wire radius of 0.75 mm corresponds to a strip of the width 3 mm. Using these dimensions, a 6×6 impedance matrix $\boldsymbol{Z_a}$ is generated. A program is then written in Matlab® language [8] to compute the objective function U defined by (13) and (14). The minimum of U will be found by the function “fminimax” which is a part of Matlab®.

In order to start searching, the optimization function requires some initial guess for the values of reactances X_2 to X_6. Certain starting points may lead to a useful results, others may lead to useless results. It was found that repeatable results can be obtained by starting the search from several randomly selected reactances, located between - 50Ω and +50Ω. With the approximate directivity evaluation, it takes less than 30 seconds to perform 50 such searches on a laptop computer.

In the following paragraphs, two different design strategies will be described, the so-called *single-tuned* and *double-tuned* ones. The first one refers to an operation which is optimized to perform at a single frequency, and the second one is optimized at two different frequencies.

The target value of the reflection coefficient can be selected at the beginning of the optimization procedure. For a single-tuned operation it was possible to select quite a small value, namely ρ_{min}=0.01. Expressed in decibels, the return loss is RL=40 dB. Using this value, the optimized (approximate) directivity, expressed in decibels, comes out to be D=7.46 dBi.

To check the performance of this single-tuned antenna as a function of frequency, the optimized reactance values are substituted in the Awas software, and the resulting return loss is plotted in Fig. 8. The return loss is very good at the center frequency, but the 10 dB relative bandwidth is very narrow, namely only 2.3%. The directivity evaluated by Awas was 7.9 dBi, which is approaching the ideal value of 8.1 dBi (see Fig. 10).

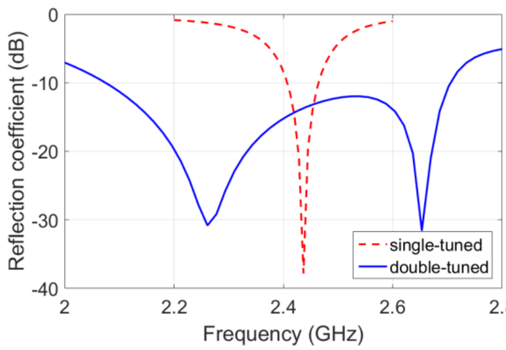

Figure 8 Simulated reflection coefficient of the optimized single-tuned and double-tuned monopoles.

When the input impedance of single-tuned monopole is plotted on a Smith chart, one can see that it forms a perfect circle, which is characteristic of any resonant circuit. Figure 9 is plotted with software “Q0REFL” from [9]. As the circle passes close to the origin of a Smith chart, the coupling coefficient is almost unity (κ=0.95). The software estimates the unloaded Q of this antenna to be Q_0 =30.

The narrow bandwidth achieved in the single-tuned design can be significantly increased by double-tuned optimization. In that case, the objective function is simply a sum of the two objective functions of the type described by (13) and (14), one for each of the two frequencies. The optimization data for double-tuned response, and the values verified by Awas are summarized in Table I. The two frequencies cannot be arbitrarily selected, but they should be separated only so much, that the intermediate return loss does not exceed the prescribed value. As seen in Fig. 8, the relative 10 dB bandwidth obtained with double-tuned operation has been increased from 2.3% to a value of 26%. The directivity at 2.44 GHz evaluated by Awas is 6.52 dBi. This is still 1.4 dB better than what can be expected from a solid-conductor quarter-wavelength monopole.

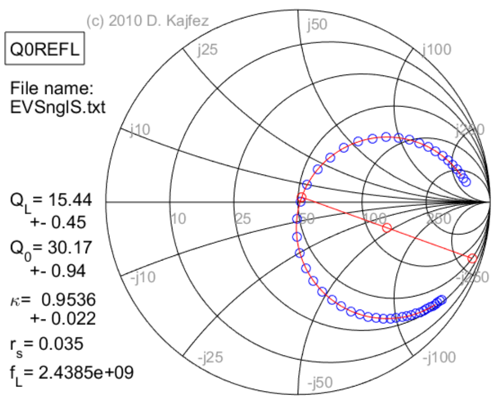

Figure 9. Estimating the Q factor of the single-tuned monopole.

Table I. The details of the double-tuned optimization

General conditions	f_1 MHz	f_2 MHz	f_c MHz	*RL dB*	n_o
	2340	2640	2440	20	50
Optimized reactances	X_2 Ω	X_3 Ω	X_4 Ω	X_5 Ω	X_6 Ω
	40.8	-500	-500	-153	191
Cap. (pF)		0.130	0.130	0.427	
Ind. (nH)	2.66				12.4
Optimized	RL_1 dB	RL_2 dB	D_1 dBi	D_2 dBi	D_c dBi
	20.0	20.0	5.67	5.42	
Simulated	19.1	20.3	6.22	5.88	6.52

The value n_o signifies the number of random optimization starts. It is reassuring to observe in the last two rows of the table that the difference between the approximate directivity evaluated by (12), and the more accurate one simulated by Awas, is less than one dBi. Furthermore, the simulated directivities are higher than the approximate ones obtained by optimization.

The directivities as functions of frequency, simulated by Awas are shown in Fig. 10. Although the directivities appear to cover a very wide range of frequencies, one should keep in mind that the useful gain of the antenna will be similar to directivity only within the well matched bandwidth (recall Fig. 8).

5 CONCLUSIONS

It has been demonstrated that by partitioning a wire antenna into a number of short segments, it becomes possible to manipulate both the input match and the radiation properties of the antenna. This is achieved by interconnecting the segments with lumped capacitances and inductances. An approximate method of determining the values of individual interconnecting reactances by a fast optimization procedure is described in detail. None of the printed-circuit segmented antennas described in the paper requires a separate impedance matching circuit, because the input impedance is inherently matched by a proper combination of reactances.

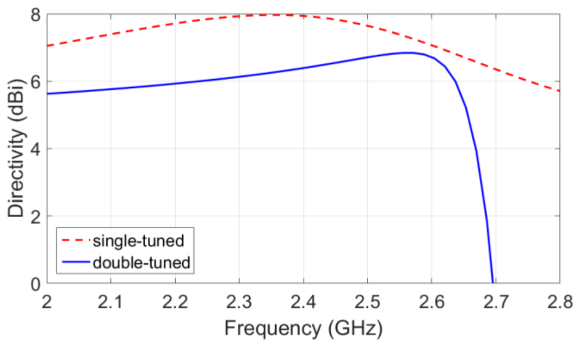

Figure 10. Simulated directivities as functions of frequency

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