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A FUZZY MODEL FOR COMPUTING INPUT IMPEDANCE OF TWO COUPLED DIPOLE ANTENNAS IN THE ECHELON FORM

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Abstract—In this paper, the previously introduced fuzzy modeling method is used to model the input impedance of two coupled dipole antennas in the echelon form. The initial data of two coupled dipole antennas in the parallel and collinear form, which are required for the model, are obtained using the MoM (Method of Moments). Then, the knowledge of two coupled dipole antennas in the echelon form is easily predicted based on the knowledge of two coupled dipole antennas in the parallel and collinear form and the concept of spatial membership functions. Comparing the results of the proposed model with MoM shows an excellent agreement with a vanishingly short execution time comparing with MoM.

1. INTRODUCTION

Wire antennas are widely used in communication systems from low to ultra-high frequencies, either in the form of individual elements or arranged together to form an array [1]. They are also frequently used as probes to sense unknown environments or as bases for modeling more complex systems and structures [2–5]. As we know, there are several analytical and numerical methods to analyze dipole antennas, either in individual or in coupled form, e.g., the method of moments (MoM) [6]. When encountering with large scale arrays, these methods are suffering from the complex and time-consuming calculations. This will increase when good accuracy is required. Hence, recently, much research work has been devoted to rapid numerical techniques for reducing the computation effort in full-wave analysis [7–13]. In contrast with these methods, qualitative inferences and soft calculating methods can be taken into consideration. A new modeling approach by using fuzzy inferences for computing the input impedance of an isolated monopole antenna has been introduced by Tayarani et al. [14]. In this paper, the introduced method in [14] is used to model input impedance of an isolated dipole antenna to extract its behavior. Then we apply the same method for modeling input impedance of two coupled parallel and collinear dipole antennas individually and extract their knowledge. After then using spatial membership functions and the extracted knowledge of two above mentioned structures, knowledge of two coupled staggered dipole antennas is extracted. Behavior of two coupled antennas is then approximated using the same fuzzy inference method and finally, we show that our modeling results are in a very excellent agreement with MoM, and the execution time is vanishingly reduced.

2. A FUZZY MODEL FOR INPUT IMPEDANCE OF AN ISOLATED DIPOLE ANTENNA

In this section, a dipole with an arbitrary radius (for instance, $a = 2.7\,\mathrm{mm}$) is considered as shown in Figure 1. Its input impedance is computed versus normalized length, (L/λ) using MoM and shown in Figure 2 in polar plane.

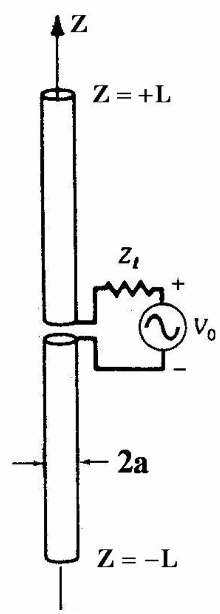

Figure 1. A dipole of an array.

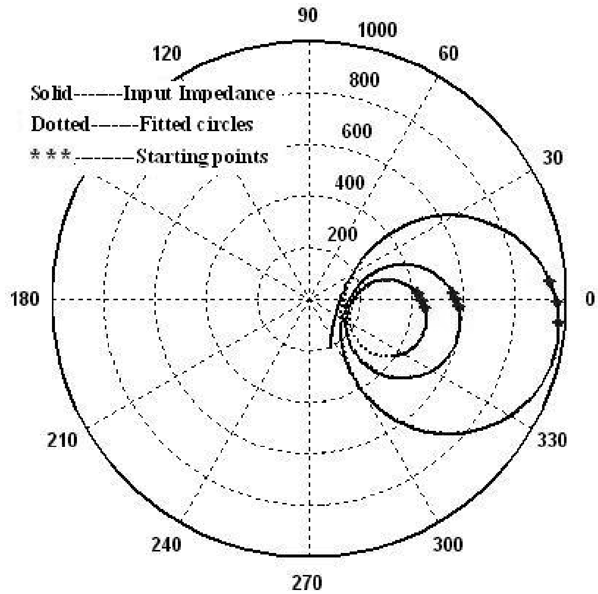

Figure 2. Input impedance of isolated dipole in polar plane as well as fitted circles (dotted circles).

This kind of curve is introduced and modeled previously in [14]. Here, we use the same method to create our fuzzy model for input impedance of the dipole antenna of Figure 1. At first, we choose three-points sets around the even resonances,$L/\lambda = 0.42, 0.9,\ 1.4$ (* marks) to define the first, second and third circles as introduced in [14]. These circles are changing around odd resonances smoothly and this smooth movement can be modeled easily using fuzzy membership functions. Three fuzzy sets are defined in the range and could be extended for longer antennas. The membership functions, which are used here, were defined by Shouraki [15] and are selected because of their flexibility and smoothness as shown in Figure 3. The general form of membership functions, which are used in Figure 3, can be expressed as Equation (1):

$$\alpha(x) = \begin{cases} \dfrac{1}{2}\left(1 + \cos\pi\left(\dfrac{x-a}{b-a}\right)^{\beta_1}\right) & \text{for } \ x : a \to b \\ \\ \dfrac{1}{2}\left(1 - \cos\pi\left(\dfrac{x-a}{b-a}\right)^{\beta_2}\right) & \text{for } \ x : b \to a \end{cases} \tag{1}$$

where $\beta_{1,2}$ *are optimizing parameters*, and a, b are defined in [14].

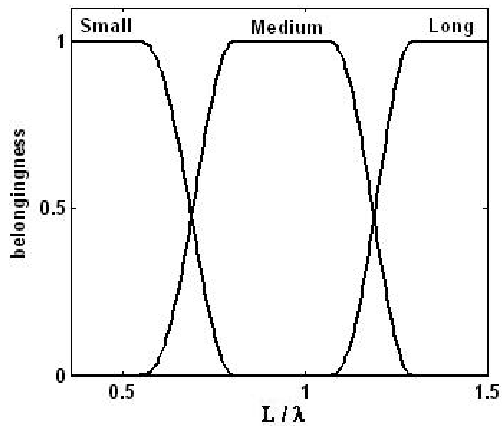

Figure 3. Membership functions for modeling the moving circles.

If we put a name on each of fuzzy sets, like Short, Medium and Long from the left to right in Figure 3, then the implications below can be written as:

$$\begin{cases} \text{If L}/\lambda \text{ belongs to short set then first circle} \\ \text{If L}/\lambda \text{ belongs to medium set then second circle} \\ \text{If L}/\lambda \text{ belongs to Long set then third circle} \end{cases} \quad (2)$$

where the first, second and third circles are those defined in Figure 2 (fitted circles or dotted circles), a new circle can be inferred for each L/λ using simple inferences of Equation (3).

$$\begin{cases} x\left(\dfrac{L}{\lambda}\right) = \displaystyle\sum_{i=1}^{3} x_i \alpha_i \left(\dfrac{L}{\lambda}\right) \\ y\left(\dfrac{L}{\lambda}\right) = \displaystyle\sum_{i=1}^{3} y_i \alpha_i \left(\dfrac{L}{\lambda}\right) \\ r\left(\dfrac{L}{\lambda}\right) = \displaystyle\sum_{i=1}^{3} r_i \alpha_i \left(\dfrac{L}{\lambda}\right) \end{cases} \quad (3)$$

where x_i, y_i and r_i are coordinates of center and radius of the basic circles (fitted circles in Figure 2) respectively, and α_i is the belongingness of desired L/λ derived from Figure 3 and finally the new circles are specified by x, y and r as center coordinates and radius for each L/λ respectively. To choose the proper point on the resulted circle, we need to define the partial phase as defined in [14]. The Partial Phase is shown in Figure 4(a).

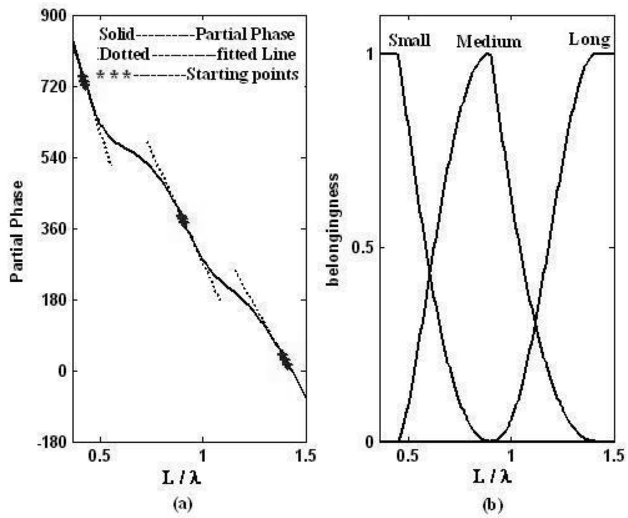

Figure 4. (a) partial phase (b) belongingness for Partial Phase.

As it is seen, at least there are three linear parts in Figure 4(a). The marked phases in the linear parts belong to the three-point sets, which were used in the pervious section to define circles.

Using Takagi/Sugeno's method in [16], this phase curve could be modeled by using the above-mentioned three lines. In this case also, three fuzzy sets with suitable membership functions are used as shown in Figure 4(b) and the rules are the same as Equation (2), but circles modify to lines and Equation (3) reduces as following:

$$\begin{cases} m\left(\dfrac{L}{\lambda}\right) = \dfrac{\displaystyle\sum_{i=0}^{i=3} m_i \alpha_i'\left(\dfrac{L}{\lambda}\right)}{\displaystyle\sum_{i=1}^{3} \alpha_i'\left(\dfrac{L}{\lambda}\right)} \\ n\left(\dfrac{L}{\lambda}\right) = \dfrac{\displaystyle\sum_{i=0}^{i=3} n_i \alpha_i'\left(\dfrac{L}{\lambda}\right)}{\displaystyle\sum_{i=1}^{3} \alpha_i'\left(\dfrac{L}{\lambda}\right)} \end{cases} \tag{4}$$

where m_i and n_i are slopes and biases of three lines and α_i is the belongingness of desired L/λ deriving from Figure 4(b) and finally the new lines are specified by m, n as slope and bias for each L/λ respectively. Finally, with only three three-point sets in the vicinity of $L/\lambda = 0.42$, 0.9, 1.4, and membership functions from modeling moving circles and partial phase, Input impedance can be regenerated as shown in Figure 5.

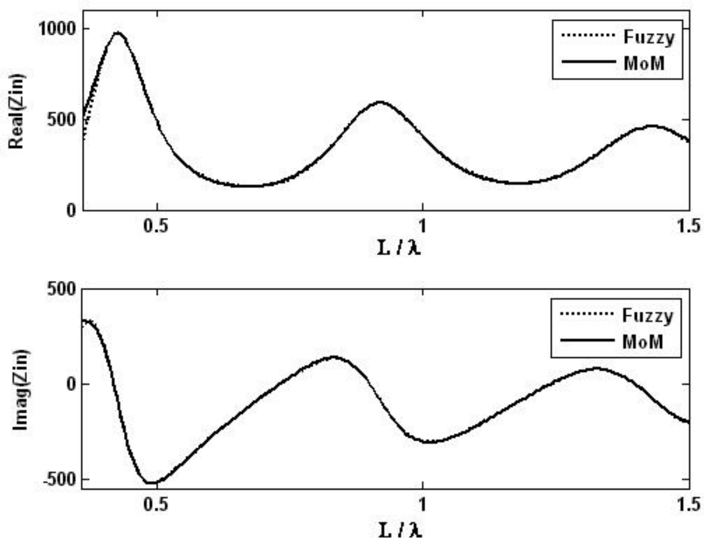

Figure 5. Modeled input impedance of the isolated dipole antenna.

3. A FUZZY MODEL FOR COMPUTING INPUT IMPEDANCE OF TWO COUPLED DIPOLE ANTENNAS IN THE PARALLEL FORM

In this section, an array of two coupled dipole antennas in parallel is considered as shown in Figure 6.

Input impedance for a number of samples with different spacing, D_h is calculated and shown in Figure 7 in polar plane.

As it is seen, these curves are similar to the introduced curve in the previous section. Therefore, the introduced method in previous section can be applied to model these curves as well. The membership functions, which model moving circles and partial phase for each sample, are shown in Figure 8.

As it is seen in Figure 8, the membership functions of moving

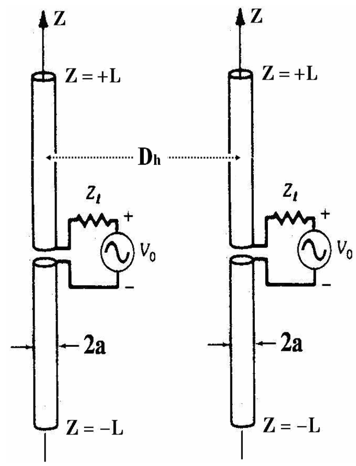

Figure 6. Array of two coupled parallel dipole antenna.

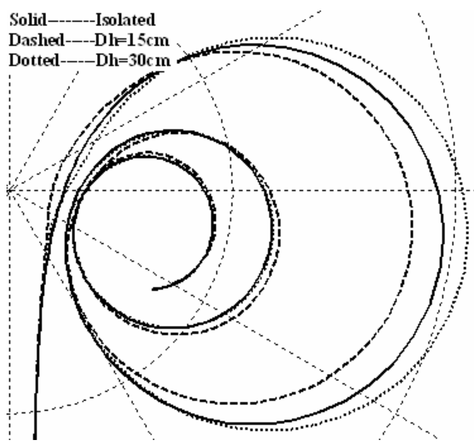

Figure 7. Input impedance for several samples of two coupled parallel dipole antennas in polar plane.

circles have not been changed for different spacings, and only slight changes for the partial phase can be seen. Therefore, we approximate them to membership functions of the isolated dipole antenna as a first order approximation. Therefore, the only parameters which change for different spacings are the initial point values that can be supposed as a knowledge base and can be extracted simply through applying the proposed algorithm. The knowledge base for the first circle and line is shown in Figure 9.

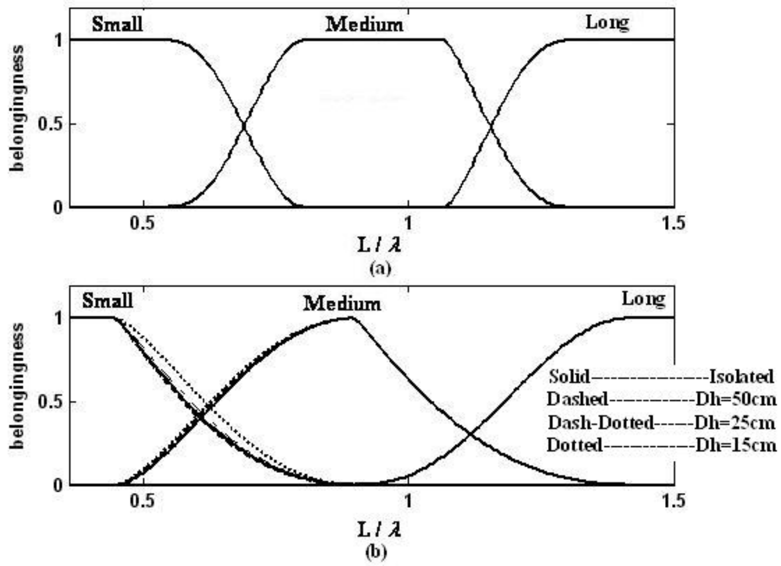

Figure 8. Membership functions of two coupled parallel dipole antennas as well as membership functions of the isolated dipole antenna for (a) moving circles (b) partial phase.

Now, we can read the inputs of our fuzzy system, circles and lines through the Figure 9 and then using the membership functions of the isolated dipole antenna, the input impedance for each dipole antenna is generated. For instance, a sample with $D_h = 27\,\text{cm}$ is run. The predicted input impedance has been shown in Figure 10. As shown in Figure 10, an excellent agreement with a vanishingly short computing time is achieved.

Another sample is $D_h = 15\,\text{cm}$ (strong coupling region). The predicted input impedance of this sample is shown in Figure 11.

As it is seen in Figure 11, the fuzzy predicted input impedance is good enough even in strong coupling region, but we may make even more accurate model by adding a new fuzzy set between the short and medium fuzzy set where we encounter higher errors. Since there is no new data for this new fuzzy set, the technique below, is used.

1- Suppose the last point of the short set and the first point of the medium set as margins.
2- Let the short and medium sets go to zero at these margins.
3- Allocate a new set between two margins with a membership function as shown in Figure 12(b).

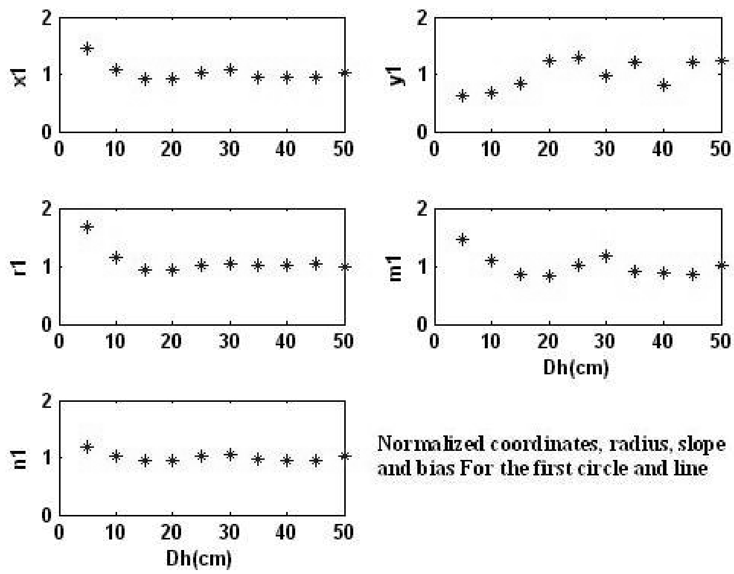

Figure 9. Extracted knowledge of two coupled Dipole antennas in the parallel form for the first circle and line.

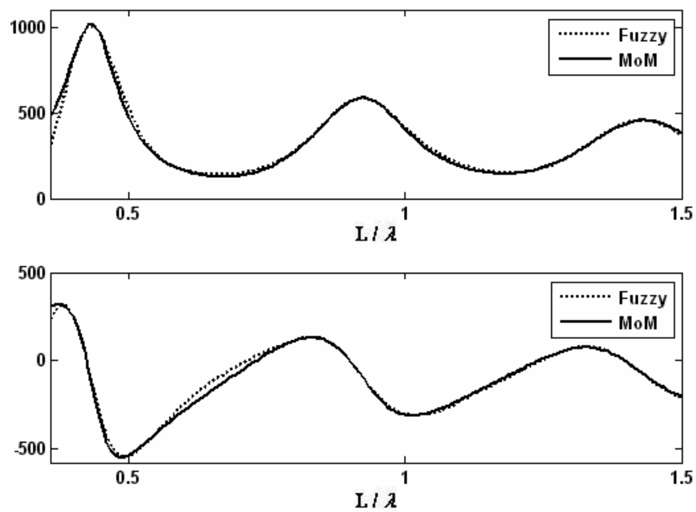

Figure 10. Predicted input impedance of two coupled dipole antennas with $D_h = 27\,\mathrm{cm}$.

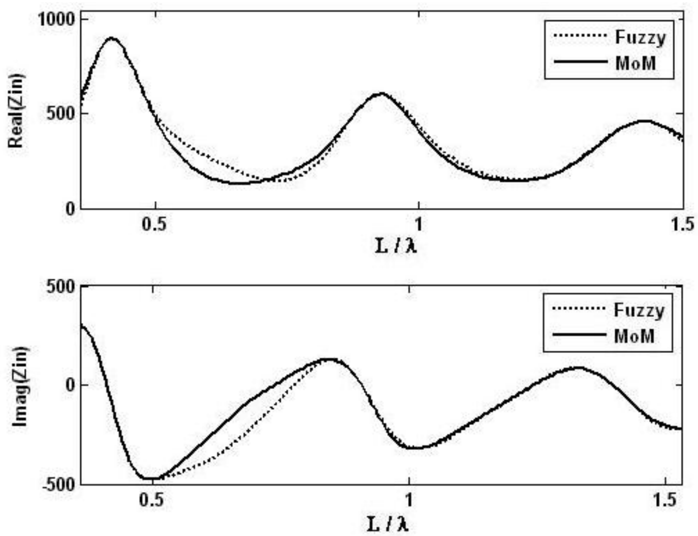

Figure 11. Predicted input impedance of two coupled parallel dipole antennas with $D_h = 15\,\mathrm{cm}$.

4- Draw a line between two margin points and use it in the new implications below:

$$\begin{aligned}
&\text{If } \frac{\mathrm{L}}{\lambda} \text{ belongs to short set then first line}\\
&\text{If } \frac{\mathrm{L}}{\lambda} \text{ belongs to new set then new line}\\
&\text{If } \frac{\mathrm{L}}{\lambda} \text{ belongs to medium set then second line}\\
&\text{If } \frac{\mathrm{L}}{\lambda} \text{ belongs to long set then third line}
\end{aligned} \tag{5}$$

Note that, we create a new fuzzy set such that the new resulted membership functions are valid both in strong and in week coupling regions.

We can see the improvement in our fuzzy model using the membership functions of Figure 12 as shown in Figure 13.

Now, using the resulted membership functions, strong coupling region is again tested.

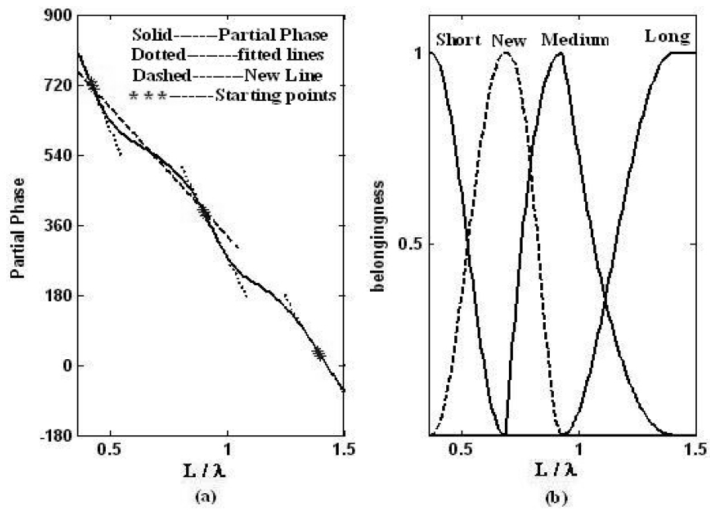

Figure 12. (a) Creating a new line in the partial phase of isolated dipole antenna (dashed line) and (b) creating a new fuzzy set in membership functions (dashed set).

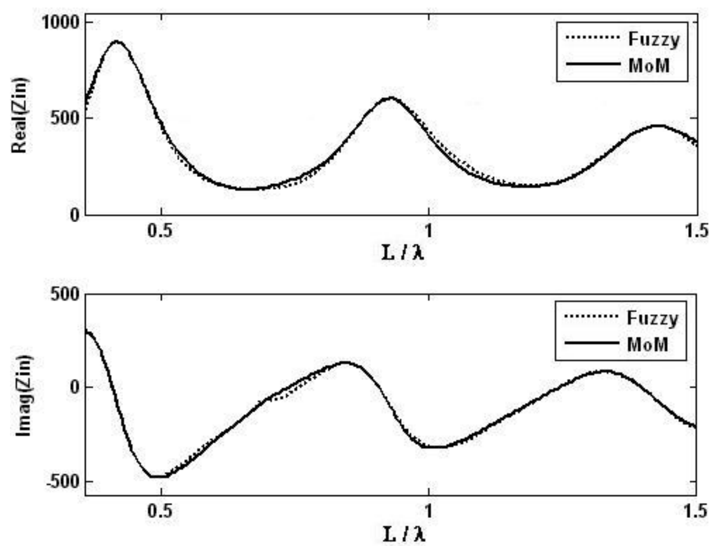

Figure 13. Predicted input impedance of two coupled parallel dipole antennas with $D_h = 15\,\text{cm}$.

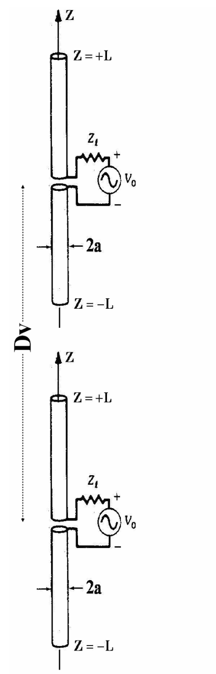

Figure 14. Array of two coupled collinear dipole antenna.

4. A FUZZY MODEL FOR COMPUTING INPUT IMPEDANCE OF TWO COUPLED DIPOLE ANTENNAS IN COLLINEAR FORM

In this section we model an array of two coupled dipole antennas, the same as the previous section but in collinear as shown in Figure 14.

The resulted membership functions of two coupled dipole antennas in the collinear form are shown in Figure 15.

As it is seen, these membership functions can also be approximated by the membership functions of the isolated dipole antenna. Now, we can extract the related knowledge through the proposed method for each sample. The extracted knowledge for the first circle and line is shown in Figure 16.

Again, we can read inputs of our fuzzy system (circles and lines through the Figure 16), and then using the membership functions of the isolated dipole antenna, the input impedance is easily extracted. For instance, a sample with $Dv = 45\,\mathrm{cm}$ is run. As shown in Figure 17, a very good agreement is achieved and the execution time is vanishingly short.

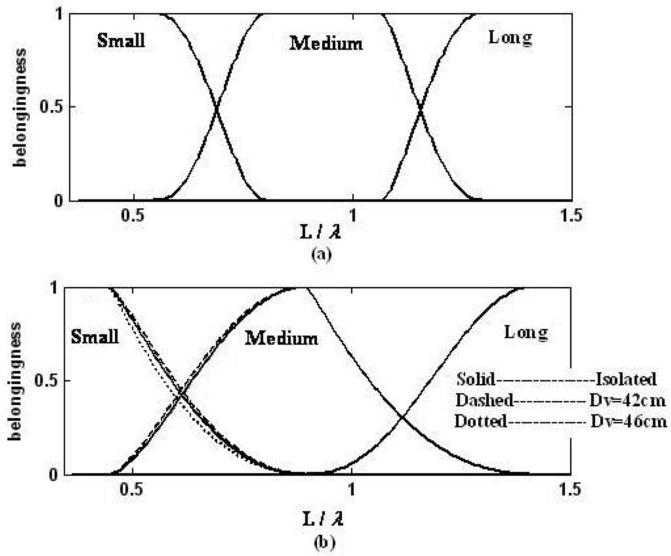

Figure 15. Membership functions of two coupled collinear dipole antennas as well as membership functions of the isolated dipole antenna for a: moving circles b: partial phase.

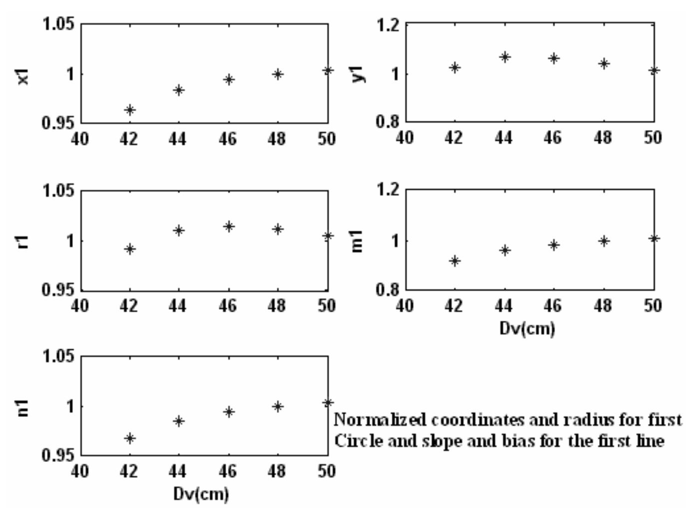

Figure 16. Extracted knowledge for two coupled collinear dipole antennas for the first circle and line.

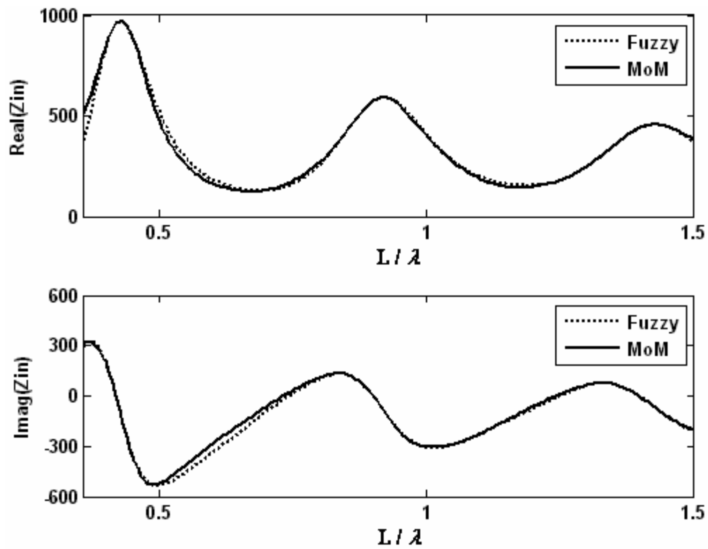

Figure 17. Predicted input impedance of two coupled collinear dipole antennas with $Dv = 45\,\mathrm{cm}$.

5. EXTRACTING KNOWLEDGE OF TWO COUPLED DIPOLE ANTENNAS IN ECHELON FORM USING SPATIAL MEMBERSHIP FUNCTIONS

In two previous sections, we modeled two coupled dipole antennas both in parallel and in collinear form. After then, we have shown that the behavior of two coupled dipole antennas could be approximated using the membership functions of the isolated dipole antenna. Then we obtained their knowledge bases separately. In this section, we consider two coupled dipole antennas in echelon as shown in Figure 18.

In the previous sections, two sets of membership functions for moving circles and partial phase were obtained. The behavior of two structures as two SIMO (Single-Input-Multi-Output) systems (two coupled dipole antennas in parallel and collinear form) were also extracted and saved as the simple curves. Here we combine these two SIMO systems using the definition of appropriate spatial membership functions introduced for the first time by S. B. Shouraki in [17] to achieve the knowledge base for two coupled dipole antennas in echelon form and predict its input impedance using the same fuzzy modeling method. The functions used here are the same as those defined before

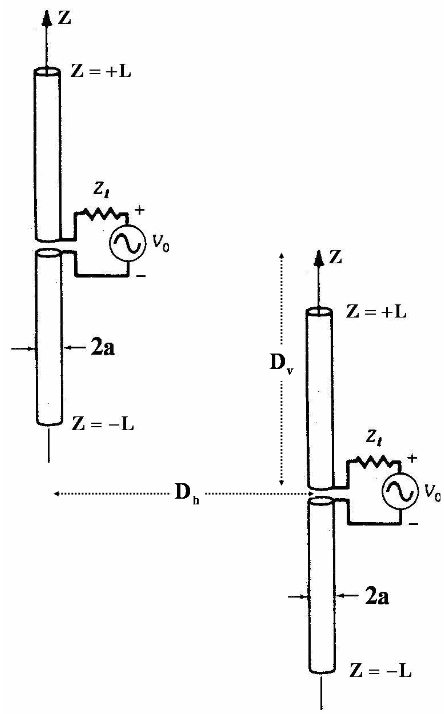

Figure 18. Two coupled staggered dipole antennas.

in [15], but in the spatial form as following:

$$\alpha_i(D_h, D_v) = \begin{cases} \frac{1}{2}\left(1 - \cos\pi\left(\frac{\psi - \varphi_2}{\varphi_2 - \varphi_1}\right)^{\beta_1}\right) & \text{for } \varphi_1 \to \varphi_2 \\ \\ \frac{1}{2}\left(1 + \cos\pi\left(\frac{\psi - \varphi_2}{\varphi_2 - \varphi_1}\right)^{\beta_2}\right) & \text{for } \varphi_2 \to \varphi_1 \end{cases} \tag{6}$$

where $\psi = \tan^{-1}\left(\frac{D_h}{D_v}\right)$, β_1, β_2 = optimizing parameters.

The spatial membership functions, which we used here, are shown in Figure 19. Now, using the following equations, we can infer the knowledge base of two coupled dipole antennas in echelon form as

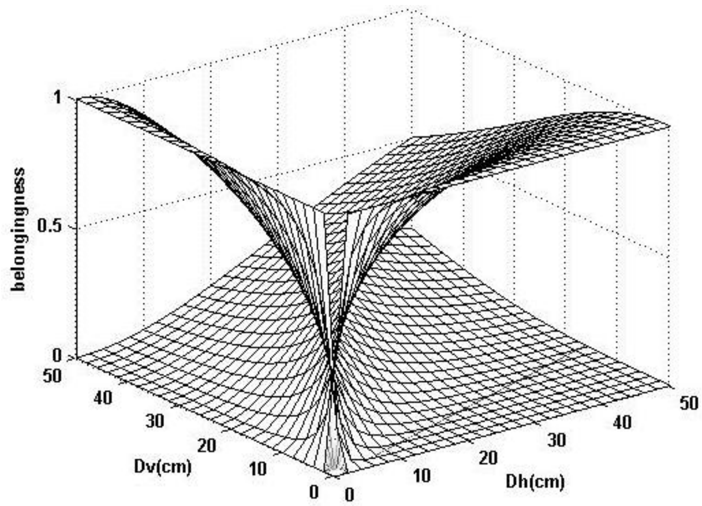

Figure 19. Spatial membership functions for combining two SIMO systems.

Equations (7):

$$
\begin{aligned}
x_i(D_h, D_v) &= \frac{x_i(D_h)\alpha_1(D_h, D_v) + x_i(D_v)\alpha_2(D_h, D_v)}{\alpha_1(D_h, D_v) + \alpha_2(D_h, D_v)} \\
x_i(D_h, D_v) &= \frac{x_i(D_h)\alpha_1(D_h, D_v) + x_i(D_v)\alpha_2(D_h, D_v)}{\alpha_1(D_h, D_v) + \alpha_2(D_h, D_v)} \\
r_i(D_h, D_v) &= \frac{r_i(D_h)\alpha_1(D_h, D_v) + r_i(D_v)\alpha_2(D_h, D_v)}{\alpha_1(D_h, D_v) + \alpha_2(D_h, D_v)} \\
m_i(D_h, D_v) &= \frac{m_i(D_h)\alpha_1(D_h, D_v) + m_i(D_v)\alpha_2(D_h, D_v)}{\alpha_1(D_h, D_v) + \alpha_2(D_h, D_v)} \\
n_i(D_h, D_v) &= \frac{n_i(D_h)\alpha_1(D_h, D_v) + n_i(D_v)\alpha_2(D_h, D_v)}{\alpha_1(D_h, D_v) + \alpha_2(D_h, D_v)}
\end{aligned}
\tag{7}
$$

where $\alpha_i(D_h, D_v)$, $i = 1, 2$ are spatial membership functions and $x_j(D_i)$, $y_j(D_i)$, $r_j(D_i)$, $m_j(D_i)$, $n_{ji}(D_i)$ $i = h, v$, $j = 1, 2, 3$, is knowledge of two SIMO systems, and $\varphi_1 = \frac{\pi}{2}$, $\varphi_2 = 0$. Now, using the inferred knowledge and the membership functions of the isolated dipole antenna, the input impedance for each dipole antenna in the echelon form is generated. Our fuzzy system is run for a sample with $D_h = 30\,\text{cm}$, $D_v = 44\,\text{cm}$ and $D_h = 15\,\text{cm}$, $D_v = 46\,\text{cm}$. As shown in Figure 20 and 21, an excellent agreement is achieved. The execution time is considerably reduced again.

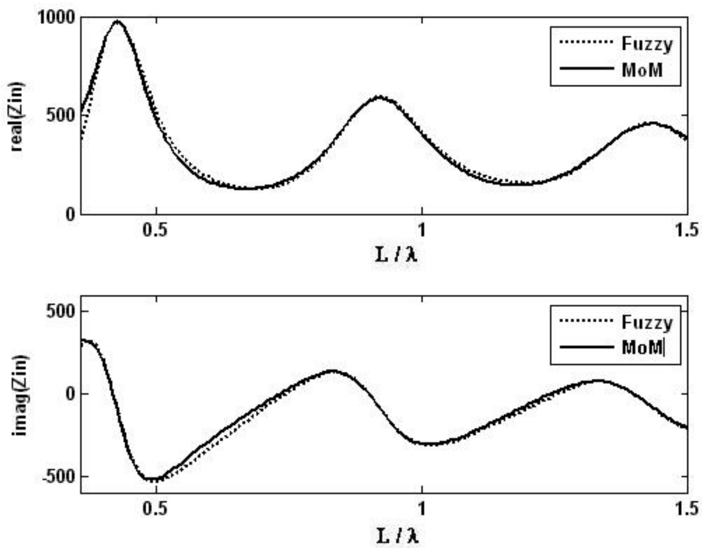

Figure 20. Predicted input impedance for two coupled dipole antennas with $D_h = 30\,\mathrm{cm}$, $D_v = 44\,\mathrm{cm}$.

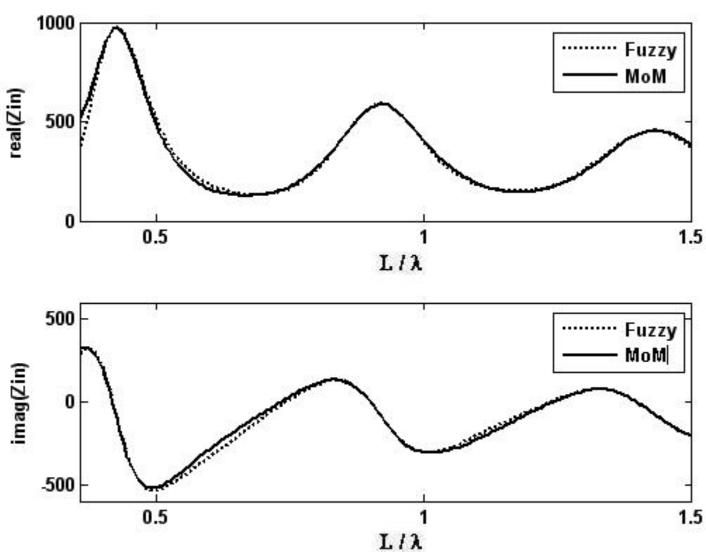

Figure 21. Predicted input impedance for two coupled staggered dipole antennas with $D_h = 15\,\mathrm{cm}$, $D_v = 46\,\mathrm{cm}$.

6. CONCLUSION

In this paper, we have introduced a method based on fuzzy inferences to predict the input impedance of two coupled dipole antennas in echelon form. The knowledge base for two coupled dipole antennas in echelon was extracted using the knowledge of two coupled dipole antennas in parallel and collinear form and a new concept, which is called spatial membership functions. The array behavior (membership functions) was approximated by the behavior of the isolated dipole antenna. Therefore, using the obtained spatial knowledge, and membership functions of the isolated dipole antenna, the input impedance for the new structure is generated. Comparing our modeling results with the accurate results (MoM) shows an excellent agreement with vanishingly short execution time. This paper could be considered as a key for fast and accurate calculations of large scale antenna arrays.

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