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Analyzing Capacitor-Based Reconfigurable Antennas Using Graph Models

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***Abstract*- This paper discusses reconfigurable antennas using variable capacitors or varactors to achieve reconfiguration. We propose graph models as tools to understand reconfigurable antenna topologies and their configurations. Guidelines are set to model this type of reconfigurable antennas using graphs and examples are studied to investigate their optimal performance.**

I. INTRODUCTION

Reconfigurable antenna designers have resorted to variable capacitors and varactors to reconfigure antenna structures. Reconfiguration is achieved through intentional change in the capacitance values of the capacitors connecting two parts or bridging over slots in an antenna structure.

In [1] variable capacitors were used to connect 11 wire segments of a reconfigurable planar wire grid antenna. The capacitors were then adjusted using a robust Genetic Algorithm (GA) optimization technique in order to achieve the desired performance.

In [2] the authors used varactors to bridge over slots in the antenna structure. The capacitance values were controlled with the biasing voltages of the varactors.

The antenna in [3] resorted to varactors as well to reconfigure a printed 10 element OPOMEX antenna array.

In [4] a variable capacitor and an inductor were installed at the input of a U-shaped slot microstrip antenna to achieve reconfigurability.

In this paper graph modeling of reconfigurable antennas is revisited and three previously published reconfigurable antennas are analyzed using graph models. The analyses consist of investigating the antennas topologies and determining the optimality of their structures.

II. GRAPH MODELING OF RECONFIGURABLE ANTENNAS

Graphs are mathematical tools used to model real life situations, in order to organize them aiming at improving their status. Graphs can help designers understand reconfigurable antennas structures and their different configurations. Previously developed graph algorithms can be used to improve the designs performance and optimize them. Graphs represent an easy tool that can replace more complicated optimization processes and design techniques [5].

A graph can be defined as a collection of vertices that are connected together by lines called edges. Several examples of graphs can be found in [5]. A graph can be either directed or undirected. The edges in a directed graph have a determined direction while this is not the case in an undirected graph.

Vertices may represent physical entities and the edges between them represent the existence of a function connecting these entities.

Edges may have associated weights to represent costs or benefits that are to be minimized or maximized. The corresponding weights in a graph are grouped into a matrix called the adjacency matrix [6]. The weight of a path is defined as the sum of the weights of its constituent edges [6].

There are several ways to graph model reconfigurable antennas that make use of variable capacitors. The graph modeling of a certain antenna is governed by its structure and the reconfigurability techniques used in that particular structure.

In this section, some guidelines are set for the graph modeling of capacitor-based reconfigurable antennas. These guidelines lead to a better understanding of the reconfigurable antenna structure using capacitors.

In this paper, an antenna is called a multi-part antenna if it is composed of an array of identical or different elements (triangular, rectangular…etc), otherwise it is called a single-part antenna.

Guideline 1: The graph modeling of a multi-part antenna with parts connected via capacitors or varactors is undirected with weighted edges connecting vertices that represent the different parts connected.

Constraints:

The edges' weights in this case are determined according to Eq. 1 where the normalized capacitances values are added to P_{ij} representing the connection angle of the corresponding edge.

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All the capacitances of the different capacitors connecting the parts should be normalized with respect to the largest capacitance. Also the connection between each two parts has a distinctive angular direction. The designer must define a reference axis that represents the direction that the majority of parts have connection with each other or with a main part. The connections between the parts are represented by the edges. $P_{ij}=1$ is assigned to an edge representing a connection that has an angle 0° or 180° with the reference axis; otherwise $P_{ij}=2$ is assigned to the edge. Fig.1 illustrates the application of Eq.1.

$$W_{ij} = P_{ij} + C_{ij\,normalized} \qquad (1)$$

$$Where\ P_{ij} = \begin{cases} 1 & A_{ij} = 0^{\circ} or 180^{\circ} \\ 2 & Otherwise \end{cases}$$

A_{ij} represents the angle that the connection i,j form with the reference axis. C_{ij} represents the normalized capacitance of the capacitor connecting parts i and j.

In Fig.1 a graph with 3 edges connecting 4 vertices is presented. The weights of the edges are calculated according to Eq. 1 as detailed below and assuming that the capacitors have the same unit:

$$W_1 = \frac{C1}{Max(C1,C2,C3)} + P_{AB} = \frac{C1}{Max(C1,C2,C3)} + 1$$

$$W_2 = \frac{C2}{Max(C1,C2,C3)} + P_{BC} = \frac{C2}{Max(C1,C2,C3)} + 1$$

$$W_3 = \frac{C3}{Max(C1,C2,C3)} + P_{BD} = \frac{C3}{Max(C1,C2,C3)} + 2$$

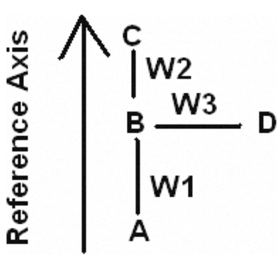
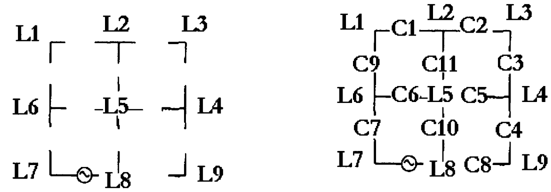


Fig.1 Illustration of Guideline 1

Example 1 on Guideline 1:

In this case the antenna shown in Fig. 2 [1] is taken. It is a 2x2 reconfigurable planar wire grid antenna designed to operate in free space. Variable capacitors were placed in the centers of 11 of the 12 wire segments that comprise the grid. The center of the 12th segment, located on the edge of the grid, was reserved for the antenna feeding. The values of the variable capacitors were constrained to the range 0.1pF to 1 pF. These capacitors were then adjusted using a robust Genetic Algorithm (GA) optimization technique in order to achieve the desired performance for the antenna. The graph modeling of this antenna follows Guideline 1 and is shown in Fig. 3. The vertices in this graph model represent the different parts of the lines that are connected together via a capacitor.



a) Wire grid antenna parts before connections **b) Wire grid antenna parts connected with capacitors**

Fig.2. Antenna structure in [1]

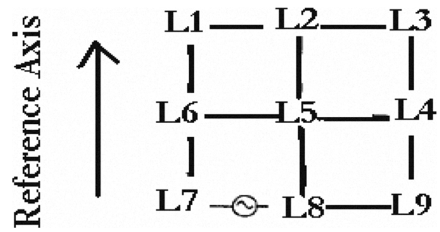


Fig.3. Graph model of the antenna in [1]

The values of the capacitors after the optimization were not specified by the authors. The weights governing the edges are defined according to Eq. 1 and are shown in the adjacency matrix A below:

$$A = \begin{bmatrix} 0 & W12 & 0 & 0 & 0 & W16 & 0 & 0 & 0 \\ W21 & 0 & W23 & 0 & W25 & 0 & 0 & 0 & 0 \\ 0 & W32 & 0 & W34 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & W43 & 0 & W45 & 0 & 0 & 0 & W49 \\ 0 & W52 & 0 & W54 & 0 & W56 & 0 & W58 & 0 \\ W61 & 0 & 0 & 0 & W65 & 0 & W67 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & W76 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & W85 & 0 & 0 & 0 & W89 \\ 0 & 0 & 0 & W94 & 0 & 0 & 0 & W98 & 0 \end{bmatrix}$$

$$W_{12} = \frac{C1}{Max(C1,...,C11)} + 2 \qquad W_{23} = \frac{C2}{Max(C1,...,C11)} + 2$$

$$W_{34} = \frac{C2}{Max(C1,...,C11)} + 1 \qquad W_{49} = \frac{C4}{Max(C1,...,C11)} + 1$$

$$W_{45} = \frac{C5}{Max(C1,...,C11)} + 2 \qquad W_{56} = \frac{C6}{Max(C1,...,C11)} + 2$$

$$W_{98} = \frac{C8}{Max(C1,...C11)} + 2 \qquad W_{85} = \frac{C10}{Max(C1,...,C11)} + 1$$

$$W_{52} = \frac{C11}{Max(C1,...,C11)} + 1 \qquad W_{76} = \frac{C7}{Max(C1,...,C11)} + 1$$

$$W_{61} = \frac{C9}{Max(C1,...,C11)} + 1$$

Example 2 on Guideline 1:

In this case the antenna shown in Fig.4 [4] is taken. The antenna is a microstrip antenna with a U-shaped slot. The reconfiguration of the antenna structure is achieved using a variable capacitor at the antenna input. The feeding network is shown in Fig.5 where a variable capacitor in shunt with an inductor was added to the feeding microstrip line. The graph modeling of this antenna follows Guideline 1 since the capacitor is connecting the microstrip line to the antenna structure. The graph model is shown in Fig.5 where the microstrip line is represented by P0 and the antenna is represented by P1.

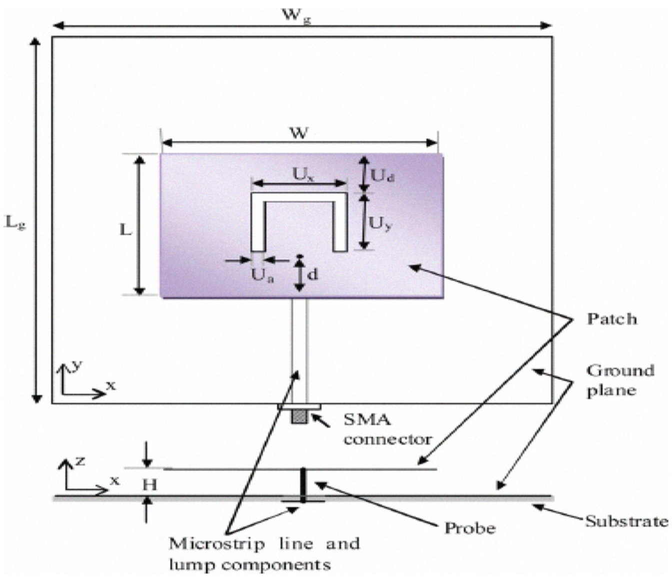


Fig.4. Structure of the antenna in [4]

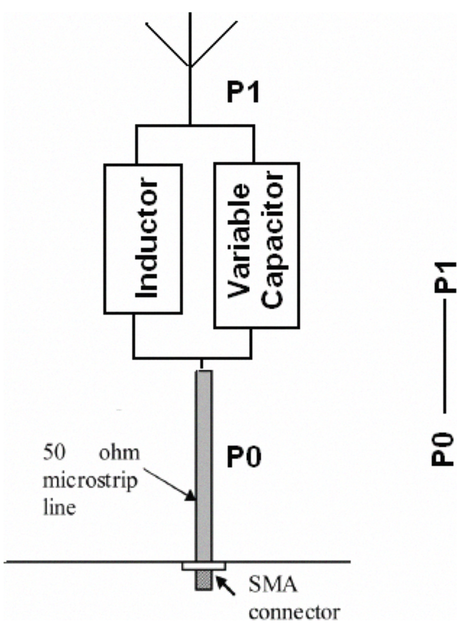


Fig.5 Graph model of the antenna system in [4]

Guideline 2: The graph modeling of a single part antenna where capacitors or varactors are bridging over slots is undirected with weighted edges connecting vertices that represent the end points of each capacitor.

Constraints:

The graph should be undirected and weighted where the weights are defined in Eq. 2.

$$W_{ij} = C_{ijnormalized} \qquad (2)$$

where C_{ij} represents the normalized capacitance of the capacitor connecting the end-points i and j. The capacitances values are calculated as discussed in guideline II.1.

Example on Guideline 2:

As an example, the antenna shown in Fig. 6 [2] is taken. The antenna is fed with an off-centered open circuited microstrip line with 50 Ω impedance.

Different capacitances are obtained by changing the bias voltage on the varactors. The graph modeling of this antenna follows Guideline 2. where the vertices represent the terminals of the different varactors. The undirected edges are weighted with the different capacitances values. The graph model is shown in Fig. 7.

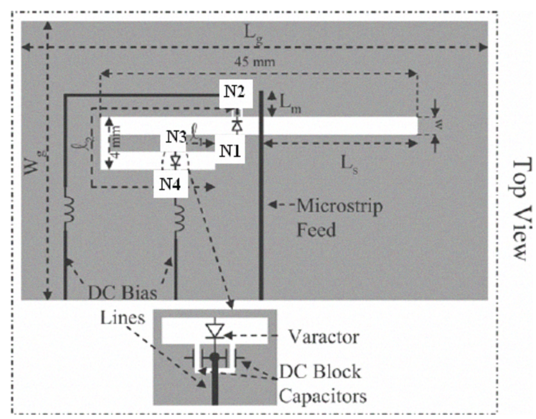


Fig.6. Antenna structure in [2]

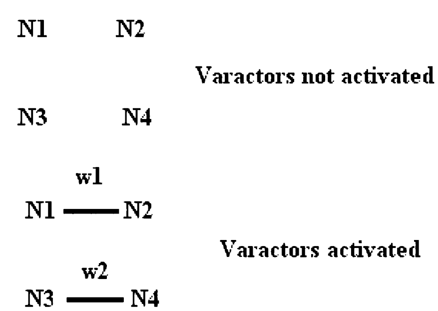


Fig.7. Graph modeling for the antenna in [2]

III. Reconfigurable Antennas Topology Investigation

The graph modeling of a reconfigurable antenna helps understanding the topology of that antenna and how it functions. It also expresses the number of possible configurations that the antenna can achieve. Reconfigurable antennas can be classified in two types: a) multi-part antennas [1,4] and b) single part antennas [2] . The guidelines set for each type of reconfigurable antennas allow us to determine if each connection made between two vertices in a graph model lead to a new antenna configuration. Each unique path in the graph model represents a unique antenna configuration.

The antenna in [1], shown in Fig.1, was graph modeled as presented in Fig.2. This antenna has 11 variable capacitors connecting 9 pieces of wires to form a reconfigurable planar wire grid. This antenna is able of achieving 38 possible configurations for each capacitance value. The authors in [1] have extended the planar geometry to a volumetric geometry as shown in Fig.8. The designers proved that this antenna can achieve a 360 degree beam steering.

To determine if this antenna has more functions than required, one has to compare the required number of configurations with the number of achievable configurations. If the number of achievable configurations (38 for a planar grid) is larger than required, then redundant parts might exist in the structure; their removal is recommended to reduce losses and cost.

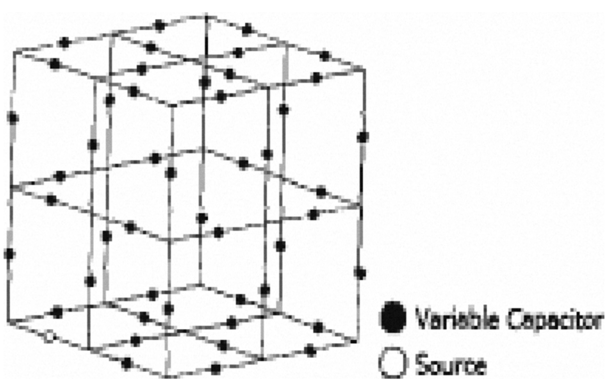


Fig.8. Volumetric grid of the antenna in [1]

Furthermore, the antenna discussed in [4] and shown in Figs.3 and 4 was graph modeled in Fig.5. This antenna uses only one capacitor to control the feeding structure of a U-shaped slot microstrip antenna. The graph model of this antenna has only 2 vertices and 1 edge. The weight of this edge changes with the capacitance value. This antenna's topology is optimal since one cannot minimize the only single component used for controlling. The number of achievable configurations depends on the number of capacitance values. The resonance tuning of this antenna is clear in [4] for each capacitance value.

Finally, the antenna detailed in [2] and shown in Fig.6 was graph modeled in Fig.7. The graph model consists of 4 vertices leading to 8 possible configurations for each capacitance value. The designers in [2] used 2 varactors to achieve a wide tuning range. The optimality of this choice depends on the functions required from this antenna. If the requirements are met solely then this antenna structure is optimal, if not redundant components can exist.

Redundant components should be removed from a reconfigurable antenna to save losses and costs. The removal of such components is possible as long as their absence will not affect the properties of the corresponding antenna.

IV. Conclusion

In this paper we presented reconfigurable antennas that use variable capacitors or varactors. We proposed guidelines for the modeling of these antennas into graphs. The graph modeling of such antennas helped understanding their topologies and studying their optimality.

Determining the optimal number of capacitors or varactors required in a reconfigurable antenna structure can reduce the complexity of the overall design, cost and possible losses.

V. References

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