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Reducing complexity and improving the reliability of frequency reconfigurable antennas

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Reducing Complexity and Improving the Reliability of Frequency Reconfigurable Antennas

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Abstract— **In this paper the complexity and reliability of frequency reconfigurable antennas are presented. A new approach for decreasing the complexity of reconfigurable antennas while maintaining the reliability of such structures is discussed. An example is given to prove the validity of the proposed approaches.**

I. INTRODUCTION

Switches are widely used to reconfigure antennas [1-2]. Despite their advantages, the problem of integrating commercially packaged switches into a reconfigurable antenna arose in [3] where not only the simple open /closed behaviour of the switches has to be addressed but also their impact on the radiation characteristics. The authors in [4] questioned the reliability of RF MEMS installed on antennas subject to carbon contamination.

This paper discusses a new optimization technique for frequency reconfigurable antennas [5]. This technique based on graph models, decreases the antenna structure complexity, without compromising the desired performance. In this paper, we minimize the number of electronic components used to reconfigure antennas, discuss the general complexity of such antennas, their reliability and the correlation between the complexity and reliability of such systems.

II. THE GRAPH MODELLING OF RECONFIGURABLE ANTENNAS

A graph is a collection of vertices connected together by lines called edges or links [5].A graph may be either directed or undirected**.** In a directed graph, the edges have a determined direction while in an undirected graph edges may be traversed in either direction. Fig. 1 shows example of directed and undirected graphs.

The vertices represent physical entities and the edges indicate the existence of functions relating these entities. If one is graph modelling antennas, then a possible modelling rule may be to create an edge between two vertices whenever their physical connection results in a meaningful antenna function [5].

Edges may have weights associated with them in order to represent costs or benefits that are to be minimized or maximized. An example of a weighted graph is shown in Fig.1. A path is an ensemble of edges connecting two vertices and its weight is defined as the sum of the weights of its constituent edges. For example if a switch is connecting two parts of an antenna system then a weight might represent the connection distinctive direction.

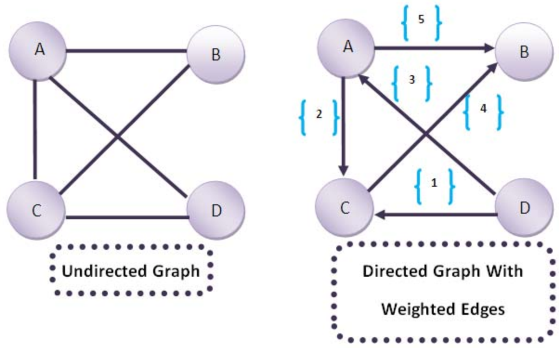

Fig.1 An example of an undirected as well as directed graph with weighted edges

There are several ways of graph modeling reconfigurable antennas. Rules for graph modelling Switch-reconfigured antennas are discussed in [5] in order to optimize antenna structure redundancy.

III. RECONFIGURABLE ANTENNAS GENERAL COMPLEXITY

Every edge in a graph modelling a reconfigurable antenna represents the activation of a switch or any other reconfiguration technique. The increase in the number of edges in a graph model adds to the complexity of the system. Therefore the complexity of a reconfigurable antenna is calculated from the size of the graph which is represented by the number of edges existing in that particular graph for all possible connections. This definition of complexity is different than other definitions of complexity such as computational complexity. This complexity expression is shown in Eq. 1:

$$C = NE \qquad (1)$$

Where NE represents the number of edges for all possible connections

The complexity of the antenna [5] shown in Fig.2 is calculated according to Eq. 1 and the graph model of Fig.2. This complexity is shown to be equal to C= 6.

IV. THE COMPLEXITY REDUCTION APPROACH

This approach aims at removing redundancies from the antenna structure in order to reduce costs, losses and complexity.

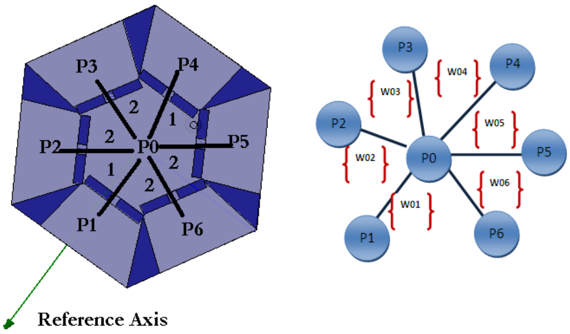

Fig.2 The Antenna in [6] and its graph model

A part is defined as redundant in a reconfigurable antenna if its presence gives the antenna more functions than required and its removal does not affect the antenna's desired performance. The removal of a part from the antenna structure may require a change in the dimensions of the remaining parts in order to preserve the antenna original characteristics. If the number of unique paths in the graph model is larger than the number of configurations, then redundancy might exist in the antenna structure. An example of counting the number of unique paths in a graph model is shown in Fig. 3.

Based on specific graph modelling rules [5], a set of equations are applied to reconfigurable antenna structures to optimize their topology and minimize their redundancies. As an example we will take the switch reconfigurable antenna shown in Fig. 2 [6]. This antenna is built out of a hexagonal main patch and six trapezoidal parts placed around it. The graph model of this antenna is also shown in Fig.2. This antenna is designed on an FR4 Epoxy substrate (ε_r=4.4) with height =0.32 cm. This antenna is required to have, in addition to its original frequencies of operation when all the switches are off, 3 more configurations as follows:
Configuration 1: 1 GHz, 3.5 GHz, 4.5 GHz
Configuration 2: 2.35 GHz, 3.5 GHz, 4.5 GHz
Configuration 3: 1 GHz, 2.5 GHz, 5 GHz
These frequencies represent a lot of practical applications such as WIMAX, WIFI, and GPS. When all the switches are off this antenna resonates at 3 GHz, 3.5 GHz and 4.5 GHz. The structure redundancy optimization equations [5] for a switch-reconfigured antenna composed of many parts are shown in Eq.2(a.b.c) , where NUP represents the minimum number of unique paths in the corresponding graph model, NAC represents the minimum necessary number of antenna configurations and N represents the number of vertices.

$$NUP = \frac{N(N-1)}{2} \qquad (2.a)$$

$$NAC = NUP + 1 \qquad (2.b)$$

$$N^2 - N - 2\times(NAC-1) = 0 \Rightarrow$$

$$N = \left\lceil \frac{1+\sqrt{1+8\times(NAC-1)}}{2} \right\rceil \qquad (2.c)$$

The application of Eqs.2 to the graph model of this antenna shows that this antenna has a minimum bound of 22 configurations, while the required configurations are 4.

$$NUP = \frac{N(N-1)}{2} = \frac{7(7-1)}{2} = 21$$

$$NAC = NUP + 1 = 22$$

The application of Eq.2.c, reveals that at most 3 vertices are needed in the graph model to achieve these 4 configurations required.

$NAC = 4$

$$N = \left\lceil \frac{1+\sqrt{1+8\times(NAC-1)}}{2} \right\rceil = \left\lceil \frac{1+\sqrt{1+8\times(4-1)}}{2} \right\rceil = 3$$

The number of switches used has to be reduced to 2 to remove redundant switches. The general shape of the antenna as a six armed hexagon can't be disturbed to preserve the radiation properties especially when all switches are OFF. The designer has to optimize by simulations the placement of the 2 switches to achieve the required frequencies and configurations. The placement of these switches as well as the graph model of the optimized antenna is shown in Fig.4. The S11 plot of this antenna for all possible configurations is shown in Fig.5. Switches are spared and the radiation characteristics are preserved since the antenna's topology is not altered. The radiation pattern at 2.8 GHz in the E plane is shown in Fig.6 when all switches are OFF.

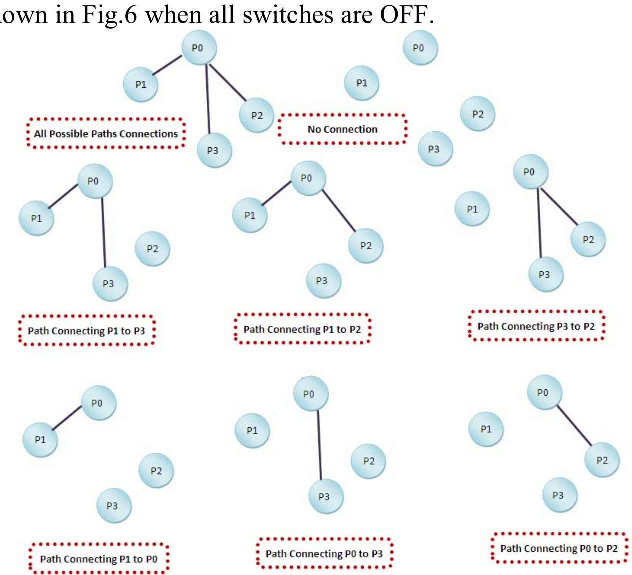

Fig.3. An example of all possible unique paths in a graph model

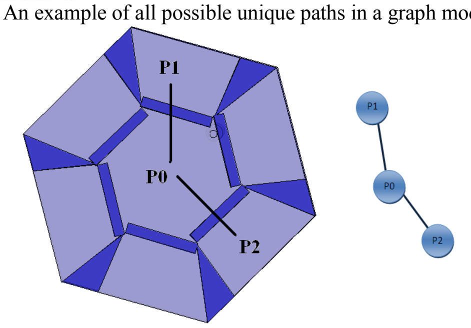

Fig.4 The Optimized structure with its graph model

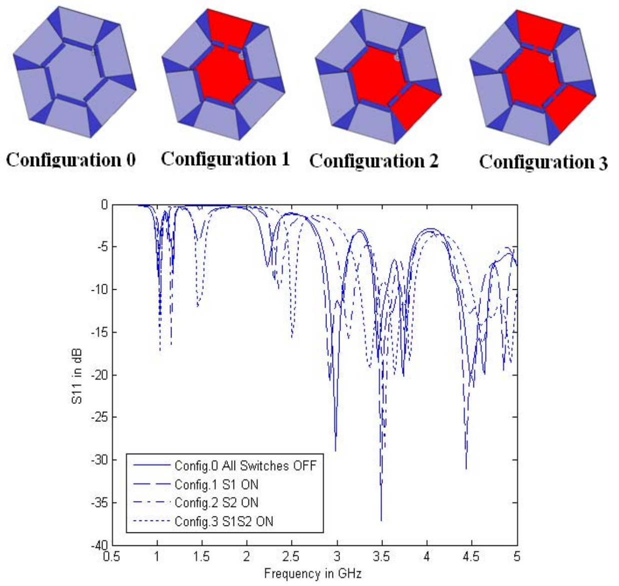

Fig.5. The required configurations as well as the S11 plots for the all the configurations

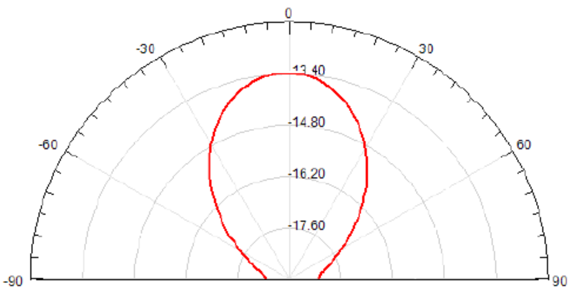

Fig.6. The E-Plane radiation pattern for the antenna at 2.8 GHz when all switches are OFF

The calculation of the complexity for this antenna after it was optimized reveals that according to Eq.1 and the graph model of Fig.4, the complexity dropped to C=2 .

V. The Reliability of Reconfigurable Antennas

Reconfigurable antenna reliability depends on the antenna's frequency of operation and its environment of operation. One way of calculating reliability is to relate that reliability to the number of alternative configurations that the antenna has at a certain frequency and the probability of achieving all these configurations. This correlation is also inversely proportional to the number of edges achieving these constellations. In other words the reliability is higher if the number of configurations is higher but it gets decreased by the number of edges or connections to achieve these configurations. The optimum solution will be to have many alternative configurations with a small number of connections. Eq.3 shows this relation:

$$R(f) = \frac{\sum_{i=1}^{Nc(f)} \sum_{j=1}^{NE_i(f)} P(E_{ij})}{\sum_{i=1}^{Nc(f)} NE_i(f)} \times 100 \qquad (3)$$

where:

R(f)= The reconfigurable antenna reliability at a particular frequency f

NC(f)= The number of configurations achieving the frequency f

NE(f)=The number of edges for different configurations at the frequency f

P(E)= Probability of achieving the edge E

As an example let's take the antenna shown in Fig.2 and calculate the antenna's reliability at 5 GHz. At 5GHz the original antenna has 8 equivalent configurations at this particular frequency [6]. After reducing the number of switches and considering the four required configurations, this antenna radiates at 5 GHz for the third configuration only. Assuming the probability of achieving each edge in each configuration equal to 0.95 then according to Eq. 3:

$$R(5GHz) = \frac{\sum_{i=1}^{1} \sum_{j=1}^{NE_i(5)} P(E_{ij})}{\sum_{i=1}^{1} NE_i(5)} \times 100$$

$$= \frac{P(E_{11}) + P(E_{12})}{2} \times 100$$

$$= \frac{2 \times 0.95}{2} \times 100 = 95\%$$

VI. The Correlation Between the Complexity and Reliability of Reconfigurable Antennas

It is true that the optimization technique has reduced the general complexity of reconfigurable antenna systems; however an antenna having many different configurations at different frequencies of operation reveals the question of the complexity at each particular frequency. Eq.4 defines such frequency dependent complexity.

$$C(f) = \underset{i=1,NC(f)}{Max} (NE_i(f)) \qquad (4)$$

where :

C(f) represents the complexity of the antenna system at a frequency f

NC(f) represents the number of equivalent configurations at a frequency f

NE_i (f) represents the number of edges at the configuration i for a frequency f

As an example let's take the antenna shown in Fig.4. This antenna has two configurations that achieve 1 GHz (configuration 1and configuration 3). The complexity of this antenna at 1 GHz is according to Eq.4:

$$C(1GHz) = \underset{i=1,2}{Max}(NE_i(1)) = Max(1,2) = 2$$

A correlation can be established between the complexity of an antenna at a frequency f and its reliability at that same frequency. That correlation can be derived from Eq. 3 and it is shown below in Eq.5:

$$R(f)=\frac{\sum_{i=1}^{Nc(f)}\sum_{j=1}^{NE_i(f)}P(E_{ij})}{C(f)+\sum_{k=1}^{N'C(f)}NE_k(f)}\times 100 \qquad (5)$$

where :

C(f) is calculated in Eq.4

N'C(f) is the number of equivalent configurations at a frequency f without one configuration of the configurations with maximum edges.

From Eq. 5 we can deduce that the reliability of a reconfigurable antenna at a frequency f is inversely proportional to the complexity of that antenna structure at the same frequency f.

Taking the same antenna from Fig.4 and recalculating reliability at 5 GHz according to Eq. 5 reveals:

$$C(5GHz)=\underset{i=1}{Max}(NE_i(5))=Max(2)=2$$

$$R(5GHz)=\frac{\sum_{i=1}^{1}\sum_{j=1}^{NE_i(5)}P(E_{ij})}{C(5)}\times 100$$

$$=\frac{P(E_{11})+P(E_{12})}{2}\times 100$$

$$=\frac{2\times 0.95}{2}\times 100=95\%$$

Taking the same antenna and assuming the probability of achieving a connection through switch 1 =0.9 and a connection through switch 2 =0.98. Recalculating the reliability of that antenna at 1 GHz according to Eq. 5 reveals:

$$C(1GHz)=2$$

$$R(1GHz)=\frac{\sum_{i=1}^{2}\sum_{j=1}^{NE_i(1)}P(E_{ij})}{C(1)+\sum_{k=1}^{1}NE_k(1)}\times 100$$

$$=\frac{\sum_{j=1}^{NE_1(1)}P(E_{1j})+\sum_{j=1}^{NE_2(1)}P(E_{2j})}{2+NE_1(1)}\times 100$$

$$=\frac{P(E_{11})+P(E_{21})+P(E_{22})}{2+1}\times 100$$

$$=\frac{1\times 0.9+2\times 0.95}{3}\times 100\approx 93.3\%$$

VII. CONCLUSION

In this paper we discuss a method for reducing the complexity of reconfigurable antennas based on graph models. The complexity reduction method is based on eliminating redundancies from antenna structures. The reliability of reconfigurable antennas is addressed, formulated and is shown to be inversely proportional to the complexity of frequency reconfigurable antennas, thus by reducing that complexity the reliability improves.

Since minimizing the trade-off between the complexity and performance of reconfigurable antennas is an objective; future work will present methods for increasing the robustness of frequency reconfigurable antennas with reduced complexity.

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