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Analyzing the Complexity and Reliability of Switch-Frequency-Reconfigurable Antennas Using Graph Models

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***Abstract* - This paper addresses the functional reliability and the complexity of reconfigurable antennas using graph models. The correlation between complexity and reliability for any given reconfigurable antenna is defined. Two methods are proposed to reduce failures and improve the reliability of reconfigurable antennas. The failures are caused by the reconfiguration technique or by the surrounding environment. These failure reduction methods proposed are tested and examples are given which verify these methods.**

I. INTRODUCTION

The incorporation of switches into reconfigurable antenna structures increases their complexity which in turn diminishes the reliability of the antennas. In particular, the reliability of reconfigurable antennas is of upmost importance in unknown and unpredictable environments. The design of switching elements is highly dependent on environmental conditions. For instance, if the reconfigurable antennas were deployed in space, the environment is unpredictable and the antenna structure is difficult to access.

Various publications discuss certain environmental effects on different types of switches which are used in antennas to achieve reconfiguration. In [1], RF MEMS capacitive switches are built on microwave-laminate printed circuit boards (PCBs). The proposed technology promises further monolithic integration of switches and antennas on PCBs to form reconfigurable antennas without the mismatch problems associated with the use of discrete switching elements.

In [2] the authors explain that the one-switch membrane topology of RF MEMS switches used in most designs is limiting for highly dynamic applications. Such applications require a great deal of reconfigurability. Three sets of electrostatic actuated RF MEMS switches with different actuation voltages are used to sequentially activate and deactivate parts of a Sierpinski fractal antenna. This allows direct actuation of the MEMS switches through the RF single feed without the need for individual DC bias lines. The antenna is fabricated on liquid crystal polymer substrate and constitutes the first integrated RF MEMS reconfigurable antenna on a flexible organic polymer substrate.

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Air-bridged RF-MEMS switches in single pole single-through transmission (SPST) configuration are proposed in [3] for antenna applications. In [4], tunable RF MEMS are proposed for the development of reconfigurable antennas fabricated on sapphire substrate with a barium strontium titanate dielectric.

The problem of integrating commercially packaged RF MEMS into a reconfigurable antenna is discussed in [5-6], not only the insertion loss and isolation behavior of the switches are addressed, but also their impact on the radiation characteristics of the antenna.

In [7] the effect of carbon contamination on the reliability of RF MEMS is considered. It is shown that the use of RF MEMS in many commercial and military applications is limited by poor reliability [7]. Most publications in this area do not reflect the reliability of systems relying on switches, and few designers investigate the environmental effects, as in [7], on the good operation of the system.

The fundamentals of improving systems reliability is first addressed by *Shannon* and *Moore***,** they propose using redundancy to increase reliability [8]. Another publication [9] discusses reliability, where the fundamental mathematics of fault-tolerant circuit-switching networks is illustrated. These publications [8-9] emphasize and recommend redundancy to improve the reliability of any switching circuit. This work [8-9] is done on electronic circuits without considering any electromagnetic aspects. Finally in [10-11] a complexity reduction approach for switch-reconfigurable antennas is developed. This approach reduces the number of unnecessary switches.

In this paper we base our discussion on finding a trade-off between the reduction in redundancy and the improvement in reliability. The analysis in [8] is used to study the effect of the complexity reduction approach [11] on the reliability of a particular antenna. Even though the number of switches decreases after the implementation of the approach in [11], the number of equivalent configurations is proven to be sufficient. The electromagnetic behavior is sufficient for reliability while the number of switches is decreased. We also show that the frequency dependent reliability is inversely proportional to the complexity. We propose two methods to increase the robustness of reconfigurable antennas and present a methodology that ensures the reliability of a reconfigurable antenna system. In the next section graphs are presented as a modeling tool for reconfigurable antennas and equivalent configurations are discussed.

II. Graph Modeling Of Reconfigurable Antennas and Equivalent Antenna Configurations

Graph modeling is a useful tool for analyzing reconfigurable antennas as discussed in [10-13]. A graph is defined as a collection of vertices connected by lines called edges [10-13]. 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 examples of a directed and an undirected graph.

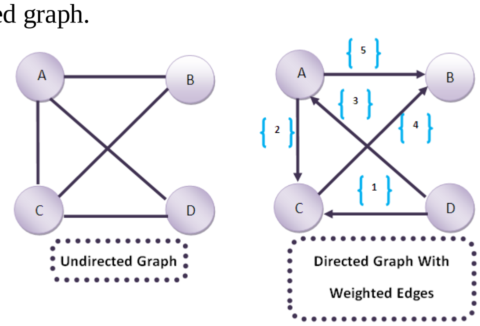

Fig. 1. Example of an undirected graph, and a directed graph with weighted edges

The vertices represent physical entities and the edges indicate the existence of functions relating these entities. In a graph model of antennas, an edge is created between two vertices whenever their physical connection represents a meaningful antenna function [13].Edges can have weights associated with them in order to represent costs or benefits that are to be minimized or maximized. The directed graph in Fig. 1 is an example of a weighted graph. 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 connects two parts of an antenna, then a weight represents the connection's distinctive direction.

There are several ways to graph model reconfigurable antennas. Rules for graph modeling switch-reconfigurable antennas are discussed in [10]. Graph modeling a reconfigurable antenna translates this antenna from a bulky device into a software accessible device. The use of graph models allows designers to use their algorithms for control and automation [14]. Graphs also allow a swifter and better implementation of cognitive radio applications [15] and a reduction in redundant configurations. Thus Graphs improve the antenna efficiency and reduce cost and losses.

Graph Models are also used to represent equivalent antenna configurations. In a switch frequency reconfigurable antenna, many switching configurations yield the same antenna frequency behavior without affecting the other radiation properties. Equivalent configurations are obtained from simulations. These equivalent configurations constitute back-up configurations for maintaining the same antenna performance at a certain frequency.

For example, the antenna shown in Fig. 2 [16], and its graph model, resonates at 5 GHz for eight different switch configurations. These eight configurations are shown in Table 1 and a comparative S11 plot is shown in Fig. 3. These eight configurations allow us options for achieving the desired resonance frequency at 5 GHz while each configuration has different multiband characteristics.

It is true that reducing the number of switches decreases the number of equivalent antenna configurations at each resonant frequency [10-11]. However the number of remaining configurations is sufficient for reliable antenna operation and decreases the total "cost" of the antenna.

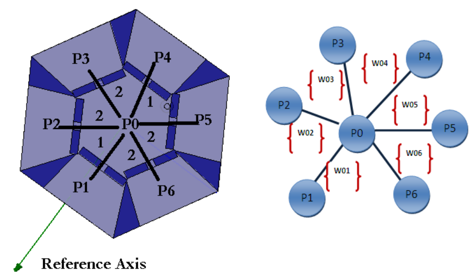

Fig. 2. The antenna in [16] with its graph model

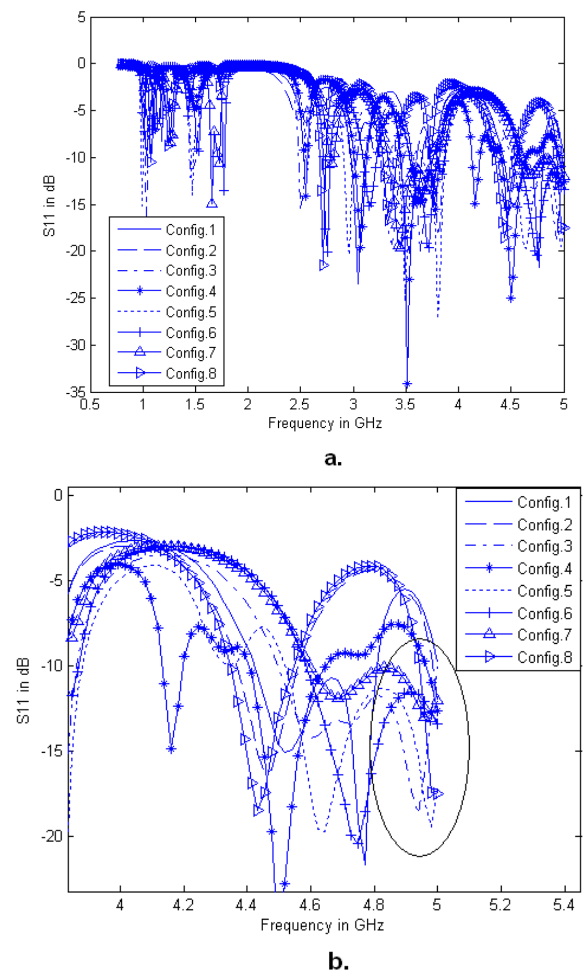

Fig. 3. S11 plot for the antenna in [16] for the configurations presented in Table 1. A) zoomed out, B) zoomed in at 5 GHz

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To demonstrate reduced redundancy without loss of reliability, a previously optimized antenna (in [12-13]) is studied below. The optimized antenna is shown in Fig. 4. Some of the antenna configurations for different antenna resonances are shown in Table 2.

Fig. 4. The Optimized Antenna [12-13]

Even after optimization, this antenna has several equivalent configurations for each resonant frequency. The optimization technique reduced the number of switches and hence cost without reducing the reliability of the system at operating frequencies.

It is also important to point out that certain resonant frequencies are only achievable with a single configuration. There is a need to develop some methods to improve the efficiency and insure continuous antenna operation. In the next section the complexity and reliability of reconfigurable antennas are formulated and methods for improving the antenna reliability are proposed.

III. Reliability Formulations for Frequency Reconfigurable Antennas

According to Shanon and Moore [8] a switch failure occurs when:

1- A switch is originally OFF and fails to switch ON upon request
2- A switch is originally ON and fails to switch OFF upon request

A switching failure heavily affects the reliability of a switch reconfigurable antenna. These failures are due to the environment of operation, the aging and corrosion process, and the frequency of operation. Thus, the reliability of reconfigurable antennas depends on all the previously mentioned factors.

With graphs, we can calculate the reliability using models which represent the different antenna configurations. The reliability is dependent on the number of antenna configurations at a certain frequency and the probability to achieve these configurations. However it is inversely proportional to the number of edges needed to create these configurations. The solution is to design reconfigurable antennas with several alternative configurations but only a small number of connections. This relationship is shown by Eq. 1:

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

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=1-P(a switch failing)

<u>Example 1:</u>

Let us consider the antenna shown in Fig. 4. Assume we want to calculate the antenna's reliability at 2.9 GHz. According to Table 2, at 2.9 GHz the antenna has three equivalent configurations which resonate at this particular frequency. Assuming the probability that each edge exists in a given configuration is equal to 0.98, this is the probability of success, then according to Eq. 1:

$$R(2.9GHz)=\frac{\sum_{i=1}^{3}\sum_{j=1}^{NE_i(2.9)}P(E_{ij})}{\sum_{i=1}^{3}NE_i(2.9)}\times 100$$

$$=\frac{\sum_{j=1}^{NE_1(2.9)}P(E_{1j})+\sum_{j=1}^{NE_2(2.9)}P(E_{2j})+\sum_{j=1}^{NE_3(2.9)}P(E_{3j})}{NE_1(2.9)+NE_2(2.9)+NE_3(2.9)}\times 100$$

$$=\frac{P(E_{11})+P(E_{12})+P(E_{21})+P(E_{22})+P(E_{23})+P(E_{31})+P(E_{32})+P(E_{33})+P(E_{34})}{2+3+4}\times 100$$

$$=\frac{9\times 0.98}{9}\times 100=98\%$$

<u>Example 2:</u>

Let us now consider the same antenna shown in Fig. 4 but at 1.7 GHz. Let's assume that the probability of switching success with switch 1 is 0.999, the probability of success with switch 2 is 0.998, and the probability of success with switch 3 is 0.900. According to Eq.1, the reliability at 1.7 GHz is:

$$R(1.7GHz)=\frac{\sum_{i=1}^{1}\sum_{j=1}^{NE_i(1.7)}P(E_{ij})}{\sum_{i=1}^{3}NE_i(1.7)}\times 100=\frac{\sum_{j=1}^{NE_1(1.7)}P(E_{1j})}{NE_1(1.7)}\times 100$$

$$=\frac{P(E_{11})+P(E_{12})+P(E_{13})}{3}\times 100$$

$$=\frac{0.999+0.998+0.900}{3}\times 100=96\%$$

The variation of the reliability for different probability values at a particular frequency is linear and Fig.5 shows this variation at f=1.7 GHz. Here, if no switches are used for achieving a certain reconfiguration, then the reliability is 100%. An example of such a 100% reliable antenna is the antenna in Fig. 4 at 5.2 GHz. One of The configurations which resonate at this frequency does not use any switches.

IV. General Complexity of Reconfigurable Antennas

Increasing the number of edges in a reconfigurable antenna graph model adds to the complexity of the system. The complexity is based on the size of the graph; i.e. the number of edges for all possible connections in that graph.

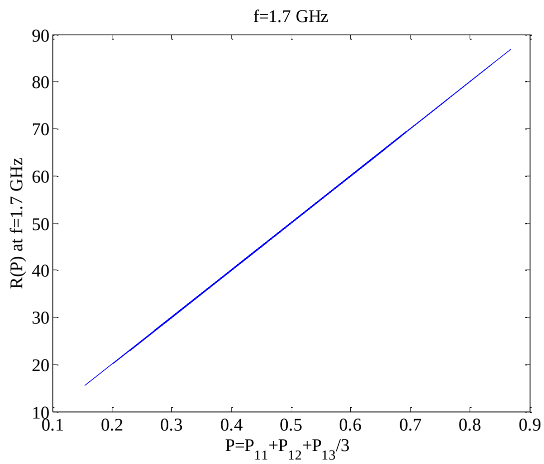

Fig.5 The variation of the reliability for different values of the probabilities at f=1.7 GHz

$$C = NE \qquad (Eq.2)$$

where NE represents the number of edges for all possible connections.

This definition of complexity is different from other definitions of complexity, such as computational complexity. Removal of redundant elements results in reduction of the general complexity of the hardware used as well as simplification of software analysis employed to control the reconfiguration technique. We show below some examples where complexity is decreased using the optimization technique [10-11].

<u>Example 3:</u>

In [17], a reconfigurable pixeled antenna is proposed and is shown in Fig. 6. A discussion of the reliability issues and redundancy minimization is presented in [10]. This antenna exhibits 5 different modes of operation for any frequency between 6 and 7 GHz [17]. Graph models showing the different antenna configurations based on different switch activation status are shown in Fig. 7. The different sections of the optimized antenna are shown in Fig. 8.

The antenna is optimized while preserving its core function and its topology[11]. One notes that some of the switches are not needed to achieve the required functions. This reduction in switches reduces the complexity of the antenna. The general complexity of this antenna before optimization is C= NE= 312, and after optimization C is reduced to C=166.

<u>Example 4:</u>

The general complexity of the unoptimized structure of Fig. 4 is C=8 according to Eq.2 whereas the general complexity of the optimized topology discussed in [13] is C=4.

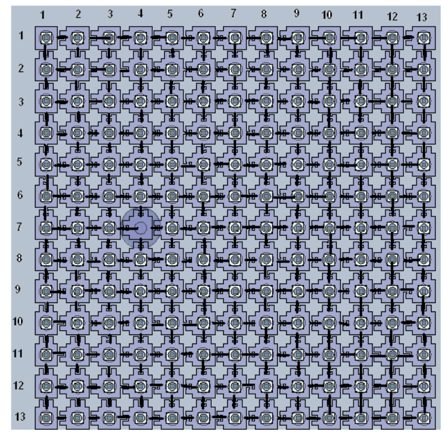

Fig. 6. The antenna in [17].

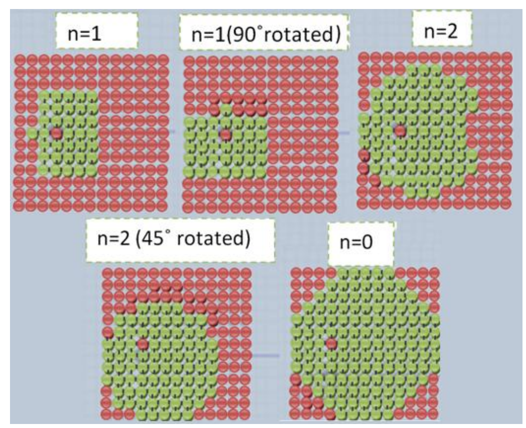

Fig. 7 Graph models for the required antenna configurations (5 different modes) – parts in green indicate parts where switches are ON, parts in red indicate switches are OFF

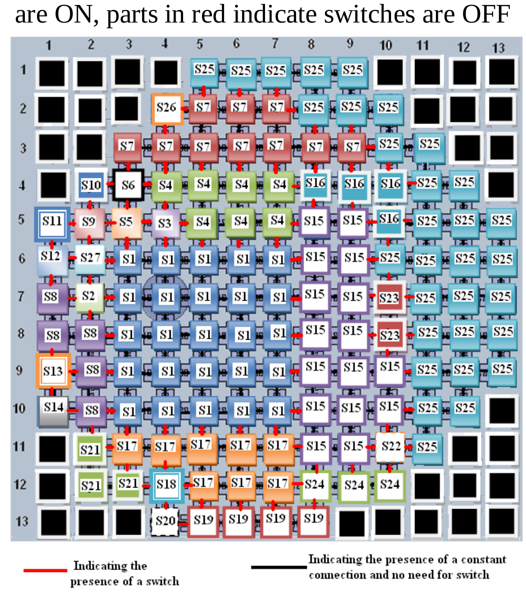

Fig. 8 Different antenna sections as discussed in [10]

V. Correlation of Complexity and Reliability of Reconfigurable Antennas

The redundancy reduction technique presented in [10-11] can reduce the general complexity of reconfigurable antenna systems. However, since an antenna can have several configurations at different frequencies of operation, we must define complexity at each particular frequency. Eq. 3 defines this frequency-dependent complexity.

$$C(f) = \max_{i=1,NC(f)} (NE_i(f)) \qquad (Eq.3)$$

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. 2. The different configurations of this antenna at 5 GHz are shown in Table 1. The complexity of this antenna at 5 GHz is calculated by Eq. 3 as:

$$C(5GHz) = \max_{i=1,8}(NE_i(5)) = Max(2,2,2,3,3,4,4,5) = 5$$

The complexity of the optimized antenna shown in Fig. 4. at 5.2 GHz is calculated by Eq.3 as:

$$C(5.2GHz) = \max_{i=1,7}(NE_i(5.2)) = Max(1,1,1,2,2,2,0) = 2$$

The correlation of the complexity of an antenna at a frequency f and its reliability at that same frequency can be derived using Eq. 2, as shown below in Eq. 4:

$$R(f) = \frac{\sum_{i=1}^{Nc(f)} \sum_{j=1}^{NE_i(f)} P(E_{ij})}{C(f) + \sum_{k=1}^{N'C(f)} NE_k(f)} \times 100 \qquad (Eq.4)$$

Where:

C(f) is calculated in Eq. 3

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

From Eq. 4 we can deduce that the reliability of a reconfigurable antenna at a frequency f is inversely proportional to the complexity of that antenna's structure at the same frequency f.

Example 5:

Taking the same antenna from example 1 and recalculating the reliability according to Eq. 4 reveals:

$$C(2.9GHz) = \max_{i=1,3}(NE_i(2.9)) = Max(2,3,4) = 4$$

$$R(2.9GHz) = \frac{\sum_{i=1}^{3} \sum_{j=1}^{NE_i(2.9)} P(E_{ij})}{C(2.9) + \sum_{k=1}^{2} NE_k(2.9)} \times 100 =$$

$$\frac{\sum_{j=1}^{NE_1(2.9)} P(E_{1j}) + \sum_{j=1}^{NE_2(2.9)} P(E_{2j}) + \sum_{j=1}^{NE_3(2.9)} P(E_{3j})}{4 + NE_1(2.9) + NE_2(2.9)} \times 100$$

$$= \frac{P(E_{11}) + P(E_{12}) + P(E_{21}) + P(E_{22}) + P(E_{23}) + P(E_{31}) + P(E_{32}) + P(E_{33}) + P(E_{34})}{4+2+3} \times 100$$

$$= \frac{9 \times 0.98}{9} \times 100 = 98\%$$

VI. Increasing The Reliability of Reconfigurable Antennas

In this section we propose two methods to improve the reliability of a reconfigurable antenna system. These methods are based on the presence of antenna redundant configurations even after the implementation of the redundancy reduction approach [10-11]. These redundant configurations are a manifestation of the antenna electromagnetic behavior under the remaining switch states. These methods utilize redundant configurations to improve the reliability of the reconfigurable antenna.

The first method suggests that one should organize the desired frequencies starting from high priority to low priority. If the first method is not sufficient to increase the reliability of an antenna at a certain desired frequency then the second method is applied. This method, based on adding a back-up switch, utilizes the analysis in [8] to improve the reliability of such antenna as explained below:

.***<u>Method 1: The no-switch configuration</u>***

The first method advises the designer to first prioritize the frequencies needed. The frequency with the highest priority should have more than one equivalent configuration. If we look at Table 2, we can deduce that the frequency with the largest number of equivalent configurations is f=5.2 GHz. It has seven equivalent configurations, including the no-switch configuration (all switches off). A good design approach is to design the antenna to operate at the most important frequency or frequencies with all switches off. In that case, under the worst possible scenario of all switches breaking down at the same time, the most important frequency is always achievable.

<u>Method 2: The back-up switch</u>

This method proposes installing a back-up switch. The back-up switch can be installed at any place in the antenna system as long as its presence achieves the desired frequency. This method is used when a certain frequency is needed at all times;

and the design does not include enough back-up configurations.

Many factors come in play when installing a back-up switch. We assume that the probability of failure of a switch remains constant in time and does not change. Thus, the back-up switch method can be used if and only if, it satisfies the following constraints:

1- Its probability of failure is lower than or equal to the lowest probability of failure among all switches.

2- The sum of probabilities of success in the back-up configuration is higher than the sum of probabilities of success in the original configuration.

Example 6:

The optimized antenna in Fig. 4 operates at 2.05 GHz for only one configuration (S1 ON) as shown in Table 2. Installing a back-up switch as shown in Fig. 9 and activating switches S2 and S3 constitutes a back-up configuration. . The graph model of this system is represented in Fig. 10 where P0 is replaced by P'0 since by adding the back-up switch new vertices appear and the topology of the antenna section represented by P0 has changed. As stated, the placement of the switch is up to the designer as long as the presence of that switch achieves the desired function.

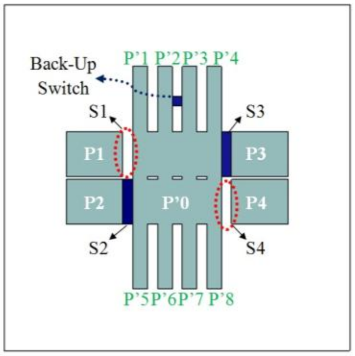

Fig. 9 Antenna using backup switch for 2.05 GHz equivalent configurations

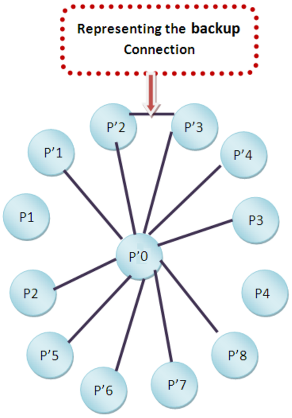

Fig. 10 Graph model of the equivalent configuration in Fig. 9

The reflection coefficient plot is shown in Fig. 11. The reliability of this antenna can be increased by applying either or both of the two methods proposed in this section.

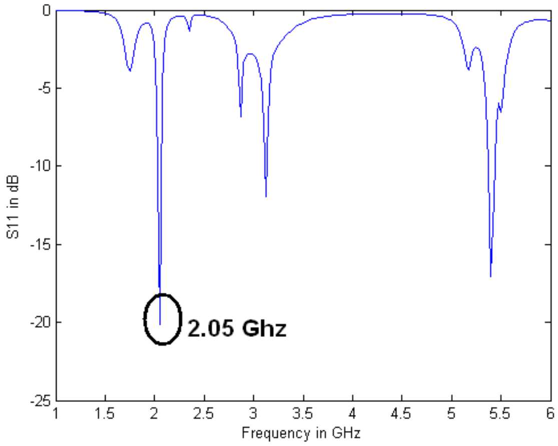

Fig. 11 The antenna's reflection coefficient with backup switch S2 and S3 activated showing clear operation at 2.05 GHz

This antenna originally has only one configuration that achieves 2.05 GHz, that configuration requires only the activation of S1. Assuming the probability of switch activation success is 0.98 for switch 1, 0.985 for switch 2 and 0.999 for switch 3, then according to Eq.1:

$$R(2.05GHz) = \frac{\sum_{i=1}^{1}\sum_{j=1}^{NE_i(2.05)} P(E_{ij})}{\sum_{i=1}^{3} NE_i(2.05)} \times 100 = \frac{P(E_{11})}{1} \times 100$$

$$= \frac{0.98}{1} \times 100 = 98\%$$

The back-up switch configuration adds a new configuration possibility to achieve 2.05 GHz by switching ON S2, S3 and BUS (back-up switch), so calculating the reliability with the back-up switch ON according to Eq. 1 gives us:

$$R(2.05GHz) = \frac{\sum_{i=1}^{2}\sum_{j=1}^{NE_i(2.05)} P(E_{ij})}{\sum_{i=1}^{3} NE_i(2.05)} \times 100$$

$$= \frac{\sum_{j=1}^{NE_1(2.05)} P(E_{1j}) + \sum_{j=1}^{NE_2(2.05)} P(E_{2j})}{NE_1(2.05) + NE_2(2.05)} \times 100$$

$$= \frac{P(E_{11}) + P(E_{21}) + P(E_{22}) + P(E_{23})}{1+3} \times 100$$

$$= \frac{0.98 + 0.985 + 0.999 + 0.999}{4} \times 100 = 99.075\%$$

Thus proving that adding the back-up switch not only assures the continuous functionality of this antenna but also improves its reliability at that particular frequency.

To overcome a switch failure and thus restore a lost resonance, the following methodology is proposed. This methodology identifies the defected switch, specifies the desired frequency and changes the antenna topology to restore the desired resonance based on the equivalent configuration.

Before applying this approach, the designer creates a library similar to Table 2 in which all possible configurations for all desired frequencies are identified. The designer installs switches or RF components on the antenna structure for the specific purpose of tuning it to a certain frequency or achieving a certain antenna reconfiguration function. Neural Networks "NN" can also be used as in [6] to determine the library of equivalent configurations. The use of NN speeds up the library assembly process for large structures.

The designer should include in the library the backup switch configuration if such configuration exists for specific frequencies. The algorithm is described below:

Step 1: Identify defected switch.
Step 2: Identify desired frequency, where the desired frequency is the resonance at which the antenna operation is required.
Step 3: In the library table, create a pointer at row i corresponding to the desired frequency.
Step 4: In the library table, create a pointer at column j corresponding to the defected configuration.
Step 5: Move the pointer j to the placement j+1.
Step 6: Search for a possible edge representing a connection from the defected switch.
Step 7: If no connection is found, use configuration in the column j+1.
Step 8: If a connection is found repeat step 5 and 6.
Step 9: If no solution is found, declare frequency unachievable.

VII. CONCLUSION

In this paper we use graph models to study the reliability and complexity of reconfigurable antenna systems. We analyze the different reliability and complexity aspects and present methods for improving the reliability of switch-reconfigurable antennas. We correlate the complexity and reliability parameters of reconfigurable antennas that are proven to be inversely proportional. Examples are presented and discussed to demonstrate the validity of the proposed concept. Finally, the continuous functioning of reconfigurable antennas is studied and a methodology is presented to ensure the reliability of such systems under different conditions.

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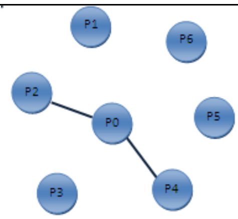
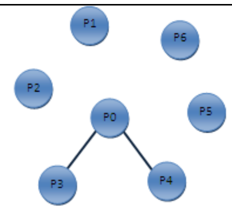
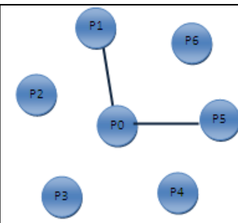
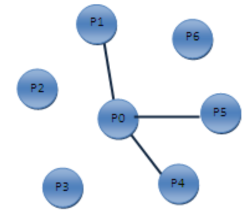
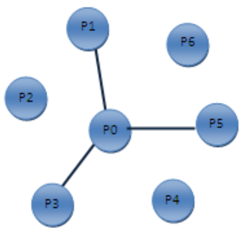
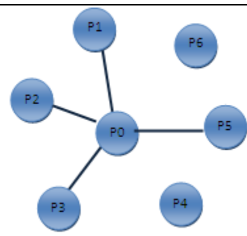
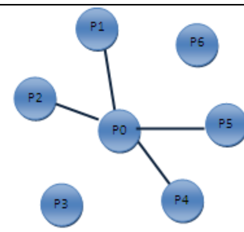
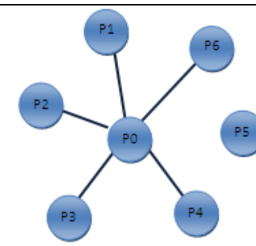
 **Configuration 1: S2S4 ON**	 **Configuration 2: S3S4 ON**	 **Configuration 3: S1S5 ON**	 **Configuration 4: S1S4S5 ON**
 **Configuration 5: S1S3S5 ON**	 **Configuration 6: S1S2S3S5 ON**	 **Configuration 7: S1S2S4S5 ON**	 **Configuration 8: S1S2S3S4S5 ON**

Table 1. The different configurations of the antenna in [15] that lead to operation at 5 GHz

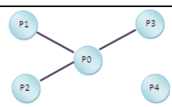
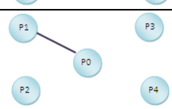
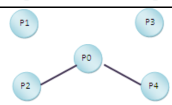
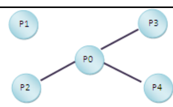
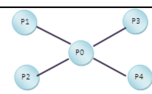
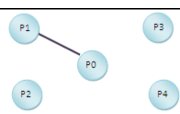
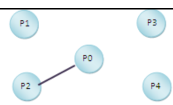
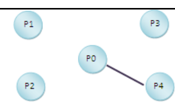
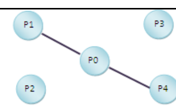
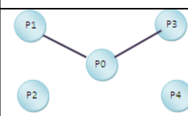
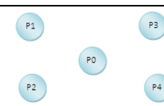
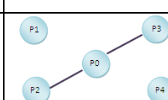
F=1.7							
F=2.05							
F=2.9							
F=5.2							

Table 2. Some antenna configurations for different resonances (all frequencies are in GHz)