An Efficient Approach for Reducing the Complexity of Reconfigurable Antennas

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Abstract **─** This paper proposes a new method of characterizing reconfigurable antennas for reducing its complexity while still maintaining its reconfigurability. The proposed method is performed by removing the less important switches of a conventional reconfigurable antenna. Therefore, the proposed antenna only has the switches that play important roles in the reconfigurability. The importance of each switch is evaluated by the correlation coefficient of the two envelopes of frequency responses of the antenna. During the evaluating process, the switch to be determined is turned on and off, respectively; whereas, the other switches are in ON and OFF states randomly to provide sufficient number of antenna configurations. To verify the concept of this approach, a frequency configurable antenna is designed and simulated. After reducing the switch number of the antenna from 40 to 8, the final structure still has an evenly-distributed reconfigurable coverage of reflection coefficients which are less than -20 dB within the band of 1.7 GHz ~ 2.7 GHz.

Index Terms **─** Complexity reduction, correlation coefficient, multi-port network method, reconfigurable antenna.

I. INTRODUCTION

Reconfigurable antennas have received much attention in recent years, and they are playing important roles in smart and adaptive systems nowadays. Antenna properties such as frequency, radiation pattern or polarization can be changed dynamically by external control. In most cases, the external control is implemented with switches such as PIN diodes [1], field effect transistors (FETs) [2], micro electro mechanical system (MEMS) switches [3], and so on. To increase the antenna reconfigurability, the number of switches has to be increased. As a result, the number of antenna configurations according to the combination of different states of all the switches is also increased. However, the number of antenna configurations is an exponential function of the number of switches and increases faster as the number of switches increases, especially when a lot of switches are used. A mentionable shortcoming with this kind of antenna is that increasing the number of switches renders finding optimum solutions to different application scenarios much difficultly and slowly, due to the extremely large number of antenna configurations. The cost is also strongly affected by the large number of high-quality switches required, together with complex biasing networks and control circuitry. This is also true of reconfigurable reflectarrays, which have a lot of switches to adjust the delay [4].

With the increasing complexity caused by the increasing number of the switches, the problem of optimizing the overall structure of the antenna was investigated through various methods. If the switches are not evenly deployed in the antenna or some switches that do not affect the properties of the antenna a lot are removed, fewer switches could provide almost the same reconfigurability as the evenly deployed switches do. Several clever methods have been reported to remain the reconfiguration properties while minimizing the number of necessary switches, so as to release the burden of configurations finding and financial cost [5-8].

The approaches to reducing the number of switches of frequency reconfigurable antennas can

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be categorized into two groups. The first group intuitively deploys the switches based on the mechanism of antennas. The Ref. [5] mitigates the inherent complexity of pixel antennas by including multiple sized pixels divided over driven and parasitic regions. The asymmetric pin layout is used in [6] to preclude any duplicated states. The second group uses optimization techniques to search the best number and positions of switches according to a fitness function. Graph models are developed and formulated to reduce the number of switches and parts in the antenna structure [7]. Moreover, optimizations via genetic algorithms and evolutionary algorithms have received widespread attention and have been successfully applied in the reconfigurable antenna design [8].

This paper presents a method of reducing the complexity of the antenna while still fulfilling the requirements of the reconfigurability by removing the switches with less effect on the reconfigurability of the antenna. The effect of each switch is evaluated by the correlation coefficients of the two envelopes of frequency responses of the antenna. During the evaluating process, the switch to be determined is turned on and off, respectively; whereas, the other switches are in ON and OFF states randomly to provide sufficient number of antenna configurations. During the processing of discriminating the switches, the antenna properties of a large number of configurations should be computed, of which it happens to other optimization methods. Since the computation burden of full-wave simulations for each configuration is too heavy, the multi-port network method using the Y matrix is applied to compute the properties of the antenna under different configurations, and the full-wave simulation is only used to get the Y matrix of the antenna at the beginning of the optimization. The simulation results show that the proposed method works efficiently in choosing the best 8 switches from 40 switches.

II. THE PROPOSED METHOD

The optimization scheme of discriminating the switches with more importance can be divided into three steps:

1). assuming the antenna as a multi-port network and filling the Y matrix;

2). computing the importance of the switches on the return loss of the antenna;

3). removing the switches with less importance and verifying the optimized structure.

This paper is focused on the frequency reconfigurable antennas, so only the input impedance of the antenna under different configurations is computed. The multi-port method can also be used to analyze the radiation-pattern reconfigurability of antennas [9]. To do that, the importance of the switches on the radiation pattern has to be considered, yet this would not change the structure of the procedure.

A. Multi-port network method

Since the full-wave simulation is time-consuming and a large number of simulations are needed during the optimization, it is not practical to perform the full-wave simulation for every antenna configuration. Multi-port network method is especially efficient for such case [8,9]. In spite of the fact that to fill the Y matrix is time-consuming, it does not contribute much to the overall computation time because it is only calculated once at the beginning of the optimization.

The multi-port method is achieved by considering both the actual feeding port and the switches as simulation ports, so that the antenna is considered as an (N+1)-port network, N being the number of switches presented in the structure. The port model of the structure is shown in Fig. 1. In this way, the Y matrix of the structure is then used to compute the input impedance of the antenna.

The method of moment (MoM) analysis is especially efficient in dealing with the problem. In this paper, the MoM simulations are performed by FEKO, a computational electromagnetics software product developed by EM Software & Systems - S.A. (Pty) Ltd. The simulations run with a unit voltage source across the kth port and short circuits on the other ports, yielding current $y_{jk}=i_j$, where i_j is the current flowing into the jth port, y_{jk} is the element at the jth row and kth column of the Y matrix. Repeating this procedure successively for each port (k=1, 2, 3, …, N+1), the Y matrix is filled.

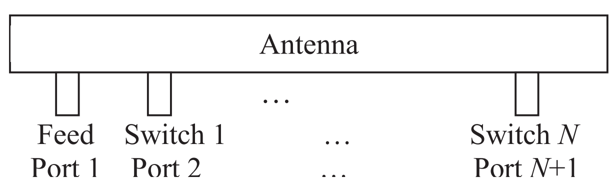


Fig. 1. Port model of the structure.

Y matrices are used to present the relation between the vector of voltages and the vector of currents on the ports, as:

$$\mathbf{i} = \mathbf{Y}\mathbf{v}. \quad (1)$$

Here, the Y matrix can be partitioned into blocks as follows:

$$\begin{bmatrix} i_1 \\ \mathbf{i}_2 \end{bmatrix} = \begin{bmatrix} y_{11} & \mathbf{y}_{12} \\ \mathbf{y}_{21} & \mathbf{Y}_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ \mathbf{v}_2 \end{bmatrix}, \quad (2)$$

where i_1 and v_1 are the scalar current and voltage of port 1 on the feed, $\mathbf{i}_2$ and $\mathbf{v}_2$ are the vectors of currents and voltages on the reconfigurable ports from 2 to N+1, respectively. In Eq. (2), the Y matrix is partitioned into four sub-matrices corresponding to the feed and the reconfigurable ports.

The Y matrix is then used to compute the input impedance of the antenna for any switch state by terminating port k+1 with admittance $y_{L,k}$, k=1, 2, …, N. For an ideal switch, the corresponding switch port is terminated in short circuit for ON state and open circuit for OFF state; for a real switch, the port is terminated in the appropriate ON/OFF impedance. In this paper, for analysis simplicity we only consider the switch with ideal characteristics.

Due to the definition of the polarities of the voltage and current on each port, the current and voltage of each port satisfy:

$$i_{k+1} = -y_{L,k} v_{k+1}. \quad (3)$$

It can be also expressed in the form of matrix:

$$\mathbf{i}_2 = -\mathbf{Y}_L \mathbf{v}_2, \quad (4)$$

where $\mathbf{Y}_L$ is a diagonal matrix with $Y_{L,kk}=y_{L,k}$.

Combining (2) and (4), the input admittance looking into the feed for the given terminations at the reconfigurable ports is:

$$y_{in} = \frac{v_1}{i_1} = y_{11} - \mathbf{y}_{12}\left(\mathbf{Y}_{22} + \mathbf{Y}_L\right)^{-1}\mathbf{y}_{21}. \quad (5)$$

The reflection coefficients are then given by:

$$\Gamma = \left(1 - y_{in} Z_0\right) / \left(1 + y_{in} Z_0\right), \quad (6)$$

where Z_0=50 Ω is the normalizing port impedance of the antenna.

For any switch state and any ON/OFF characteristics of the switch, the antenna reflection coefficients can be obtained from the multi-port structure in Fig. 2 and Eq. (6). Comparing with results from full-wave simulations, the above network-analysis technique is more efficient and the simulation procedure is not constrained by the number or type of configurable elements. In this way, it only needs to compute the Y matrix of the multi-port structure once at the start, which is then used to analyze all the possible switch states. The performance is not constrained by practical limitations of existing switch technology, biasing, substrate losses, etc.

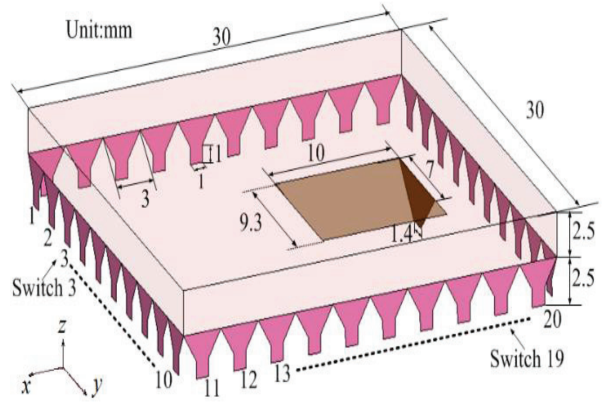


Fig. 2. Initial structure (ground plane removed) [8].

B. Importance of the switches

The importance of one switch means how much this switch impacts on the properties of the antenna or how big the difference of the properties of the antenna when the switch is in ON and OFF states, respectively. However, the difference of the properties of the antenna caused by one switch should not be too big. For example, if the antenna cannot work properly in the whole band of interest when one switch is in ON state, this switch ought to be always tuned off or be removed and should not be treated as a reconfigurable port, although the antenna works properly at some frequency when the switch is in OFF state. This happens when a switch is placed too close to the feed port. Obviously, a switch cannot be placed too close to the feed port, otherwise the antenna will be shorted.

Here, the importance of the switches to a frequency reconfigurable antenna is evaluated as follows:

1). selecting sufficient number of antenna configurations by turning the switches on and off randomly;
2). computing the reflection coefficients of all the selected antenna configurations by the multi-port network method;
3). categorizing all the antenna configurations into two groups for each switch according to the ON and OFF states of this switch;
4). obtaining the two envelopes for the two configuration groups of each switch by the

minimum reflection coefficients obtainable at every frequency in the band from the data in each group;

5). evaluating the importance of each switch by the correlation coefficients of the two envelopes of the switch to be determined.

After the five steps, an evaluation for discrepancy of each pair of envelopes is established by the correlation coefficients to determine the importance of this switch on the antenna, which is expressed as follows:

$$\rho_{X,Y} = \frac{E(XY) - E(X)E(Y)}{\sqrt{E(X^2) - E^2(X)}\sqrt{E(Y^2) - E^2(Y)}}, \quad (7)$$

where X and Y stand for the envelops of the reflection coefficients curves when the switch to be determined remains ON state and OFF state, respectively, E is the expectation, and $\rho_{X,Y}$ is the correlation coefficients of them. In mathematics, correlation coefficients are a measure of the interdependence of two random variables that ranges in value from −1 to +1, indicating perfect negative correlation at −1, absence of correlation at zero, and perfect positive correlation at +1. Herein, the correlation coefficients are factors which determine the relative importance of the switch on the antenna. Obviously, the switch with lower correlation coefficient has a greater effect since the two states make greater different performance of the antenna.

C. Final structure

Suppose that the proposed structure has N switches, then, the number of antenna configurations is 2^N. When N is big, the 2^N is much bigger. So the sufficient number of configurations that is used to determine the importance of the switch is M, which is less than 2^N. After one switch with least importance is eliminated, the state of this switch is always fixed. Therefore the number of configurations to be computed is no longer M but $M/2$, which is not sufficient enough. To eliminate another switch, the number of configurations has to be replenished up to M again with another $M/2$ new configurations, which are randomly selected and different from the previous configurations. When there are only a few more switches left and the overall number of configurations is less than M, all the configurations are used.

III. OPTIMIZATION RESULTS

To verify the concept of this method, a frequency reconfigurable antenna in [8] is optimized.

Figure 2 shows the geometry of the reconfigurable antenna with 40 switches to be reduced. It consists of a 30 mm × 30 mm square patch in air 5 mm above the ground plane, and a planar L-feed in air 2.5 mm above the ground plane. The horizontal part of the L-feed is a 9.3 mm × 7 mm rectangle, and the L-feed is connected to a 50 Ω SMA connector below the ground plane via a vertical tapering strip. The square patch is circumscribed by a 2.5-mm-wide strip with its top touching the edge of the patch. The patch and the strip are equipped with 40 tapered shorting straps connecting to the ground plane via switches. There are 10 evenly-spaced straps on each side. The reconfigurability is achieved by switches that connect each tapered strap to the ground plane. The ground plane is assumed to be infinite in extend.

The structure was firstly adopted in [8]. In Ref. [8], the optimization procedure was carried with a globe optimizer (genetic algorithm), a local optimizer (1-bit neighborhood) for the geometry, and exhaustive search for the switching patterns. The fitness function is constructed as a combination of the structural complexity of the antenna and the return loss over the entire frequency band. The same structure is used here because it has been verified working well as a frequency reconfigurable antenna in the entire band by [8] and it provides an optimized result obtained by other technique to compare with.

The 40 switches shown in Fig. 2 are uniformly distributed around the four edges of the patch. However, uniform distribution is a suboptimal geometry in terms of complexity, because the contribution of each switch to the antenna reconfigurability is not uniform. Some switches which are with more importance might have a much stronger influence over the antenna performance than those at other locations. Through only these switches with more importance, the antenna might have nearly the same reconfigurability compared with the antenna having all the 40 switches.

The performance of the prototype in Fig. 2 was simulated through FEKO in the band of 1.7 to 2.7

GHz at each of 101 frequencies. Although the multi-port network method is used, the antenna is not treated as a multi-port antenna in FEKO because the time consumed for simulating multi-port antennas is proportional to the square of the number of ports. Here, the antenna is assumed only having one port.

Each port among the actual feed and the reconfigurable ports is assigned as the feed, and all the other ports are shorted. If a unit voltage source is applied across the feed, then the currents through all the ports form one column of the Y matrix. After all the ports have been selected as a feed individually, the Y matrix is filled. Every element in the Y matrix is not a single number. Each one consists of the admittances at all the frequencies.

Using Eq. (5) and assuming that the value of $y_{L,k}$ is 0 when the kth switch is in OFF state and is infinite when in ON state for ideal switches, the frequency responses can be calculated in all cases. If non-ideal switches are terminated, the $y_{L,k}$ should be substituted with the actual admittances.

Obviously, the switches operate in a binary state (ON or OFF). All the switches provide 2^{40} configurations to the antenna. It is not possible to determine the reflection coefficients for all 2^{40} configurations. Thus, a random sample of 100,000 without repeat are applied, which can almost represent the tendency of the overall configurations according to the Monte Carlo Methods.

On the basis of simulation results, 100,000 configurations can provide a very good matching within the band of 1.7 to 2.7 GHz as shown in Fig. 3. The thin curves represent the reflection coefficients for the 100,000 configurations, and the thick curve is their envelope. The envelope is the minimum reflection coefficients obtained at every frequency in the band from the 100,000 curves of reflection coefficients, which is the key concern during the process of discriminating switches.

It can be seen from Fig. 3 that the envelope distributes in the band of 1.7 to 2.7 GHz without any gap. Now, we expect to simplify the original structure by reducing the number of switches while still retaining the frequency reconfigurability in the same band. The optimization is firstly carried out by means of comparing correlation coefficients of reflection coefficient envelops.

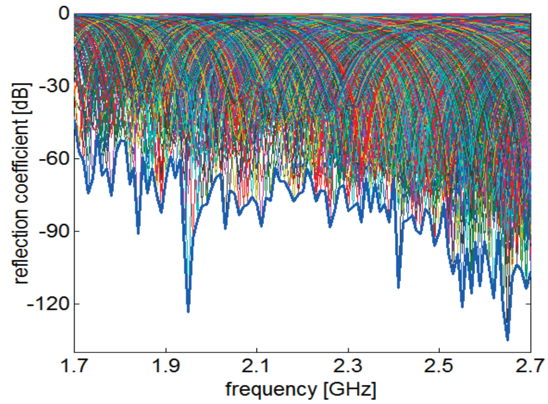
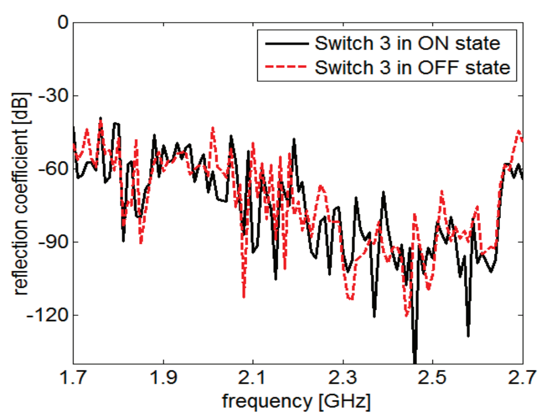


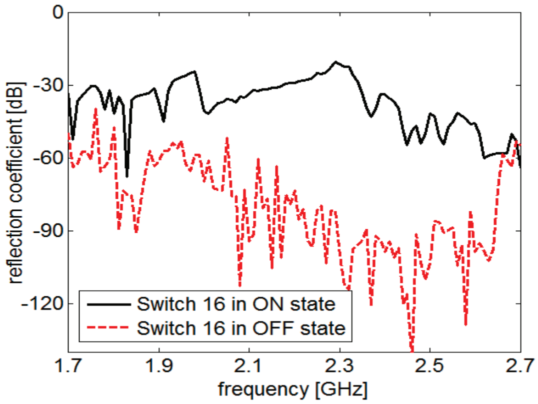
Fig. 3. Curves of a random sample of 100,000 configurations and their envelope.

As an example, to illustrate the importance of switches, Fig. 4 shows two pairs of envelopes of 100,000 configurations according to switch 3 and 16 (their positions are shown in Fig. 2) when they are in ON and OFF states. The discrepancy of each pair of envelopes represents the impact of the switch on the antenna.

As alluded before, a merit figure is obtained to evaluate the importance of switch. The correlation coefficient of the two envelopes of switch 3 (Fig. 4 (a)) is 0.3432, and that of switch 16 (Fig. 4 (b)) is 0.0540. It is obvious that switch 16 has a stronger impact on the antenna.



(a)



(b)

Fig. 4. Envelopes of curves of 100,000 configurations according to: (a) switch 3, and (b) switch 16.

The correction coefficients of each pair of two envelopes of all switches are given in Table 1 in descending order. As Ref. [8], 8 switches are left in the final structure. The 8 switches with the least correlation coefficients are 19, 14, 16, 35, 37, 8, 20, and 5. The antenna structure with these 8 switches is shown in Fig. 5. The simulated performance of the optimum structure is shown in Fig. 6; the thin curves represent the reflection coefficient of each switch configuration, and the thick envelope is the best performance obtained by 2^8 switch configurations. It can be observed that a very low reflection coefficient in the band can be achieved (the envelope is < -20 dB) for every frequency. Compared with the work reported in Ref. [8], the thin curves of the reflection coefficients for each switch configuration from the final structure are more evenly distributed over the band.

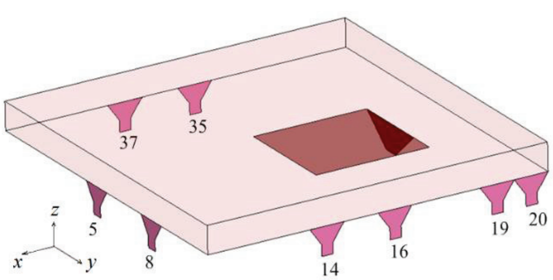


Fig. 5. Final structure (ground plane removed).

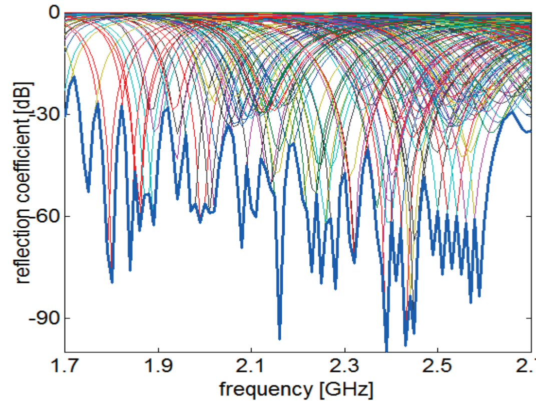
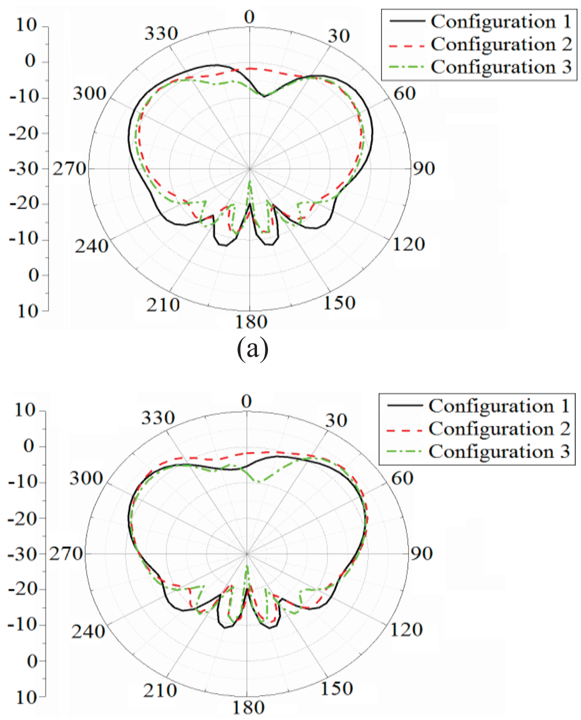


Fig. 6. The performance of the final structure from simulation.

Table 1: Correlation coefficients of 40 switches in descending order

Number of Switches	40	22	3	32	2
Correlation Coefficient	0.401	0.355	0.343	0.326	0.319
Number of Switches	31	34	30	29	39
Correlation Coefficient	0.281	0.265	0.241	0.236	0.235
Number of Switches	11	21	1	23	33
Correlation Coefficient	0.235	0.234	0.231	0.219	0.217
Number of Switches	13	24	4	27	38
Correlation Coefficient	0.214	0.209	0.208	0.198	0.185
Number of Switches	36	28	9	12	7
Correlation Coefficient	0.184	0.181	0.171	0.165	0.157
Number of Switches	26	10	6	18	25
Correlation Coefficient	0.156	0.154	0.134	0.131	0.131
Number of Switches	17	15	19	14	16
Correlation Coefficient	0.122	0.120	0.115	0.114	0.112
Number of Switches	35	37	8	20	5
Correlation Coefficient	0.101	0.096	0.094	0.084	0.014

Antenna radiation pattern simulation was also performed for three different configurations at the frequencies of 1.84 GHz, 2.22 GHz and 2.57 GHz, respectively. Figure 7 shows the simulated radiation patterns in *x-z* plane and *y-z* plane at the three certain frequencies. The simulated reflection coefficients of the proposed antenna of the 3 different configurations are plotted in Fig. 8. The states of the 8 switches of 3 antenna configurations are listed in Table 2 as a binary word where 0 and 1 represent OFF and ON states, respectively.



(a)

(b)

Fig. 7. Simulated gain of the proposed antenna of the 3 different configurations in: (a) *x-z* plane, and (b) *y-z* plane.

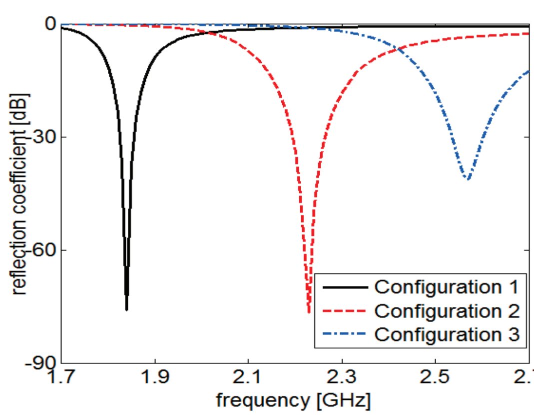


Fig. 8. Reflection coefficients of the proposed antenna of the 3 different configurations.

Table 2: States of the 8 switches of the antenna

Antenna Configuration	Resonant Frequency	States of 8 Switches (0 represents OFF, and 1 represents ON states)							
		19	14	16	35	37	8	20	5
1	1.84 GHz	1	0	0	0	0	1	0	0
2	2.22 GHz	1	1	0	0	0	0	1	0
3	2.57 GHz	1	0	0	0	1	0	1	1

IV. CONCLUSION

In this paper, a new method was presented to simplify reconfigurable antennas by reducing their number of switches which is based on the network analysis and the correlation coefficients. The network analysis is applied for filling the Y matrix and computing the reflection coefficients of the antenna. The correlation coefficients are used to determine the influence of the switches on the antenna. In this way, the reconfigurability of the frequency reconfigurable antenna almost remains the same after removing the switches with less importance. This optimization approach is an efficient tool to reduce the number of switches in reconfigurable antenna structures even though a big number of switches need to be reduced. In addition, this method is also suitable for optimizing radiation-pattern reconfigurable antennas.

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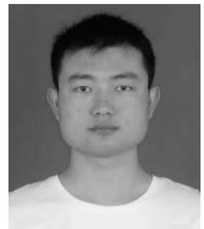

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