IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 13, 2017, accepted February 28, 2018, date of publication March 5, 2018, date of current version March 19, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2812139

Methodology to Reduce the Number of Switches in Frequency Reconfigurable Antennas With Massive Switches

CHANGYING WU[1], (Member, IEEE), ZHOU YANG[1], YUSHENG LI[1], YUAN ZHANG[1], AND YEVHEN YASHCHYSHYN[2], (Senior Member, IEEE)

[1]School of Electronics and Information, Northwestern Polytechnical University, Xi'an 710072, China
[2]Institute of Radioelectronics, Warsaw University of Technology, Warsaw 00-665, Poland

Corresponding author: Changying Wu (aaawucy@nwpu.edu.cn)

ABSTRACT This paper proposes a new method for decreasing the complexity of reconfigurable antennas (RAs) with massive switches while increasing their reconfigurability. The proposed method is performed by removing the less important switches of an RA. Therefore, the RA only has a few important switches that have strong influences on the reconfigurability. The importance of a switch is evaluated by the minimum percentage of useful configurations (PUC). A monopole-type omni-directional frequency RA with 85 uniformly-distributed switches is optimized in this paper. For this type of antennas, a reflection coefficient less than -20 dB and a gain greater than 0 dBi at the same frequency makes a useful configuration. After reducing the switch number from 85 to 15, the complexity of the RA is greatly decreased while the reconfigurability is increased by more than 100 times within the band of 2 to 7 GHz. With only 15 optimally deployed switches, the PUC is significantly increased. Therefore, it is easy to find out the states of the switches to let the frequency RA work well at different frequencies. The results show that the proposed method is an efficient way to design RAs with switches in an optimal deployment.

INDEX TERMS Importance of switch, internal multi-port method (IMPM), percentage of useful configurations (PUC), reconfigurability, reconfigurable antenna (RA), switch deployment.

I. INTRODUCTION

Reconfigurable antennas (RAs) are capable of modifying dynamically their frequency and/or radiation properties in a controlled and reversible manner. To provide a dynamical response, in most cases, the reconfigurability is implemented with switches such as PIN diodes, field effect transistors (FETs), microelectromechanical system (MEMS) switches, and so on [1]–[9]. Due to their reconfigurability, RAs can be a good candidate for wireless applications, such as WLAN, MIMO system, mobile handset, radar, and satellite communication, etc [10]–[15].

Intrinsically, more switches provide higher reconfigurability. As the number of switches increases, the number of antenna configurations according to the combination of different states of all the switches is also increased. If there are N two-state switches in an RA, the number of antenna configurations is 2^N. The number of antenna configurations is an exponential function of the number of switches and increases significantly when many switches are used. There are some kinds of RAs that employ massive switches. They are named as pixel antennas [16], multifunctional antennas [17], self-structuring antennas [19], and evolving antennas [19]. An RA with massive switches can create a breakthrough in reconfiguration capabilities and application prospects, as well as offer drastic difficulties and complexities of physical implementation and numerical calculation.

Despite the improved reconfigurability, however, a mentionable shortcoming with this kind of antenna is that it is much difficult and slow to find the optimal solutions to different application scenarios with increased number of switches due to the extremely large number of antenna configurations. Although the internal multi-port method (IMPM) could be used to increase the calculation efficiency [20]–[22] and the genetic algorithm could be used to speed up the state localization [21]–[23], finding the suitable antenna configurations is still time-consuming.

Designers also need to pay extra attention to the deterioration of radiation performance caused by the complex biasing

2169-3536 © 2018 IEEE. Translations and content mining are permitted for academic research only.
Personal use is also permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

networks and control circuitry which are in the vicinity of radiation parts of RAs [24], [25]. Although there are some ways to reduce the number of bias lines, they are only applicable for particular types of RAs with few switches [26], [27]. If a large number of switches are used, especially being deployed two-dimensionally, ample efforts are needed for the switch biasing in antenna design and the effects of the biasing lines on the antenna performance remain difficult to deal with [28] and [29].

Due to 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. People want to achieve the same or higher reconfigurability with fewer switches. 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 biasing designing. These methods can be classified into two groups. The first group is the global search method. In this way, eight switches are selected from 40 uniformly-distributed switches by genetic algorithm [21] and correlation coefficient [30] to provide the same frequency coverage as the former 40-switch antenna does. The second way is based on the antenna mechanism. In [18], duplicate cases are avoided by asymmetric topology of switches. In [31], the switches away from the feed point are deployed much sparser because the switches near the feed point affect the antenna performance more than the switches away from the feed point do.

In this paper, to evidently decrease the difficulties and complexities of physical implementation and numerical calculation, the authors study on the impact of the deployment of switches on the reconfigurability of an RA with massive switches. A switch-by-switch reduction strategy is proposed to increase the reconfigurability by optimizing the switch deployment with a few switches of high importance. In Section II, we introduce the theory and main steps of the optimization procedure. Section III demonstrates a design example of a frequency RA with massive switches based on the method and gives the results. Finally, a conclusion is provided in Section IV.

II. THEORY

In the procedure of optimizing the switch deployment, the RA in study is assumed as a multi-port network. The IMPM is used to calculate the impedance and radiation properties of the RA with densely deployed switches. Then the percentage of useful configurations (PUC) is used as an objective function to evaluate the reconfigurability of the RA. If one switch is eliminated or fixed at a state, the PUC is then evaluated by other switches. Thanks to the quantitative criteria, the switches are ranked by their importance. The less importance of a switch, the higher PUC the other switches provide. After removing the less important switches, the RA only has the higher important switches. Therefore, the complexity is decreased and the reconfigurability is increased.

An omni-directional frequency RA is optimized in this paper. So the reconfigurability of the RA is evaluated mainly by the reflection coefficients. For radiation pattern RAs and polarization RAs, the reconfigurability should be evaluated by radiation properties as well as reflection coefficients. However, this would not change the procedure of optimization.

A. IMPM

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. The IMPM is especially efficient for analyzing RAs [20]–[22]. In spite of the fact that filling the Y-matrix or the Z-matrix is time-consuming, it does not contribute much to the overall calculation time because it is only calculated once at the beginning of the optimization. Once the Y-matrix or the Z-matrix is filled, it is very convenient to calculate the input impedance of the RA at any configuration.

The IMPM is implemented by considering both the actual feed 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. Let $\mathbf{I}$ and $\mathbf{V}$ be the vectors of current through and voltage across the $(N+1)$ ports, respectively. Z-matrices are used to present the relation between the vector of voltages and the vector of currents, as

$$\mathbf{V} = \mathbf{Z}\mathbf{I}. \tag{1}$$

The $\mathbf{Z}$ in (1) is an $(N+1) \times (N+1)$-matrix which can be filled with the help of FEKO, a general purpose 3D electromagnetic simulator developed by Altair Engineering. To get element z_{jk} of $\mathbf{Z}$, a unit current source is applied through the kth port and all other ports are in open circuit. As a result of that, the voltage v_{jk} across jth port equals z_{jk}, as

$$z_{jk} = v_{jk}. \tag{2}$$

Repeating the procedure successively for each port ($k = 1, 2, 3, \ldots, N+1$), the Z-matrix is filled.

The Z-matrix can be partitioned into blocks corresponding to the feed and the reconfigurable ports, as

$$\begin{bmatrix} v_1 \\ \mathbf{v}_2 \end{bmatrix} = \begin{bmatrix} z_{11} & \mathbf{z}_{12} \\ \mathbf{z}_{21} & \mathbf{Z}_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ \mathbf{i}_2 \end{bmatrix}. \tag{3}$$

In (3), v_1 and i_1 are the scalar voltage across and current through port 1 on the feed, respectively. $\mathbf{v}_2$ and $\mathbf{i}_2$ are $N \times 1$ vectors which present the voltages across and currents through the reconfigurable ports, respectively.

From (3), we have the input impedance of the antenna

$$Z_{in} = \frac{v_1}{i_1} = z_{11} - \mathbf{z}_{12}\left(\mathbf{Z}_{22} + \mathbf{Z}_L\right)^{-1}\mathbf{z}_{21}, \tag{4}$$

where $\mathbf{Z}_L$ is an $N \times N$ diagonal matrix with its diagonal elements representing the impedances of switches terminating the reconfigurable ports. Also, $\mathbf{Z}_L$ represents the configuration of the RA. For an ideal switch, the corresponding impedance is zero in short circuit for ON state and is infinity in open circuit for OFF state. For a real switch, the ports are terminated with appropriate ON/OFF state impedances. In this paper, the switches are assumed to be ideal for simplicity. The reflection coefficients are then given by

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} - Z_0}, \tag{5}$$

where Z_0 is the normalizing port impedance which is often 50 Ω.

From (3), we also have the currents through the reconfigurable ports

$$\mathbf{i}_2 = -\left(\mathbf{Z}_L + \mathbf{Z}_{22}\right)^{-1} \mathbf{z}_{21} i_1. \tag{6}$$

The realized radiation pattern of the RA for feed current i_1 is found using the superposition principle as

$$\mathbf{E}(\theta, \phi) = \sum_{k=1}^{N+1} i_k \mathbf{E}_k(\theta, \phi), \tag{7}$$

where i_k $(k = 2, \ldots, N+1)$ are elements of $\mathbf{i}_2$ in (6) while i_1 equals 1 A. $\mathbf{E}_k(\theta, \phi)$ is the radiation pattern of the RA when kth port is fed with current of 1 A and other ports are open circuit.

In the far field region, the ratio between the gain and the square of the magnitude of electric field is a constant for any antenna at a given frequency and direction so long as that both the input power and the distance between the field point and the antenna are the same. The constant ratio

$$C = \frac{G(\theta, \varphi)}{|E(\theta, \varphi)|^2} \tag{8}$$

can be easily calculated by theoretical formula or simulated by FEKO with any antenna. Then, the gain pattern of the RA is expressed as

$$G(\theta, \varphi) = \frac{C\,|\mathbf{E}(\theta, \varphi)|^2\left(1 - \Gamma^2\right)}{P_{in}} = \frac{C\,|\mathbf{E}(\theta, \varphi)|^2\left(1 - \Gamma^2\right)}{i_1^2 R_{in}/2} \tag{9}$$

where P_{in} is the input power, R_{in} is the real part of Z_{in}, and i_1 is always set as 1 A in this paper.

B. RECONFIGURABILITY

According to frequency RAs with massive switches, it is easy for one antenna to cover a wide operating band. However, it might take a long time to select a suitable configuration when the RA is in use because in most cases only a small percentage of the large number of configurations are useful configurations (It will be illustrated in Section III). For frequency RAs, a useful antenna configuration is defined as an antenna configuration that its input impedance matches well at a frequency in the operating band and its radiation pattern and polarization are as desired at the frequency. For practical use, the bandwidth of each resonance is also needed to define useful configurations. For radiation pattern and polarization RAs, there are similar definitions of useful antenna configurations which are not in the scope of this paper. An RA is highly reconfigurable if useful antenna configurations account for a great proportion of the entire massive antenna configurations at every frequency in the band. Provided the PUC is high, it is easy to find some sets of suitable switch states for the performance of the antenna we want. Furthermore, if one set of suitable switch states is failed due to the fact that some switches break down, a lot of other alternatives are available.

Quantitative criteria are needed in optimization. Since an RA with high reconfigurability has a high PUC, the criterion we used to present reconfigurability is the minimum PUC in the whole operating band. An N-switch RA has 2^N antenna configurations if each switch can be either turned in ON state and OFF state. Suppose there are M discrete frequencies in the operating band that the antenna needs to operate at, and each frequency is denoted as f_m $(m = 1, 2, \ldots, M)$. If U_m useful configurations out of the 2^N antenna configurations work well at f_m, the PUC p_m occurring at f_m is

$$p_m = U_m / 2^N. \tag{10}$$

However, the number of antenna configurations 2^N of an RA might be too big. It is impractical to check all the antenna configurations to find out the number of useful configurations. Therefore, a sufficient and practical number of antenna configurations S are used and p_m is then obtained by the number of useful antenna configurations out of S, as

$$p_m = U_m / S. \tag{11}$$

If there are more than 100 useful configurations U_m in S randomly chosen configurations, the error of calculating p_m with Eq. 11 instead of Eq. 10 is negligible. The minimum PUC is defined as the smallest p_m in the whole operating band

$$P_{\min} = \min(p_m \,|m = 1, 2, \ldots M). \tag{12}$$

C. IMPORTANCE OF SWITCHES

The importance of a switch means how the reconfigurability of an RA alters by changing the state of the switch. Use the pixel antenna proposed in [16] as an example which is redrawn in Fig. 1. There are 85 switches in this antenna. The side of each square pixel is 2.4 mm long and the overall size of the patches is 21.6 mm wide and 25.2 mm high. The uniform deployment of switches is suboptimal because the contribution of each switch to the antenna reconfigurability is not uniform. Switches located close to the feed port have a much stronger influence over the antenna performance than those at further location. It means that some switches are more important than others.

Three representative switches having typical kinds of influences on the antenna performance are used as examples to illustrate the importance of switches.

Switch A:

Suppose the RA has high reconfigurability, therefore the PUC is high in the whole operating band and the minimum PUC is high. When switch A is fixed at ON state and we let the RA traverse its configurations by other switches, the PUC caused by other switches except switch A is high in one part

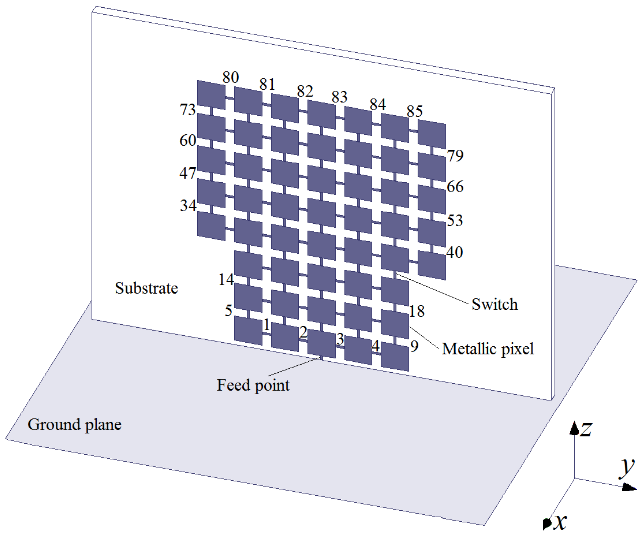


FIGURE 1. An RA with switches indexed.

of the operating band and low in the other part. Similarly, when switch A is fixed at OFF state, the distribution of the PUC with respect to frequency is reversed. No matter switch A is fixed at ON state or OFF state, the minimum PUC is always low even though the PUC is high at some frequencies. It means that the reconfigurability of the RA is not high without switch A. The most important switch should make the RA works well at some frequencies when it is in ON state. When it is in OFF state, some other frequencies work well. It is just the reason why we use switches in frequency RAs, which is to modify their frequencies dynamically.

Switch B:

The distribution of the PUC caused by other switches except switch B with respect to frequency and the minimum PUC are always the same regardless of whether switch B is fixed at ON state or OFF state. Introducing Switch B makes the number of useful configurations and the number of total configurations both doubled. Switch B is probably a switch at the farthest corners of an RA as the one shown in Fig. 1.

Switch C:

The PUC caused by other switches except switch C at any frequency in the operating band when switch C is fixed at one state (for example ON state) is higher than the PUC at the same frequency when switch C is fixed at the opposite state (for example OFF state). According to the example in the parentheses, the minimum PUC of the RA is noticeably higher when switch C is fixed at ON state than the minimum PUC when switch C is fixed at OFF state.

Based on the influences of switches A, B, and C on the antenna performance, switch A is the most important switch, switch C the least. It is quite understandable that switch A is the most important because switch A affects the performance of the RA a lot. It seems that switch C also affects the performance of the RA a lot. Actually, switch C should not be a switch because switch C always needs to remain at the same state when the RA is in use. So, it is better to take this switch away. Otherwise, the performance of the RA will be deteriorated seriously when switch C is broken and unfortunately is fixed at the unwanted state.

TABLE 1. The minimum PUC of an RA when one switch is fixed at a state.

Switch	State of the switch	Minimum PUC	Importance
A	ON state OFF state	Low Low	High
B	ON state OFF state	Medium Medium	Medium
C	ON state OFF state	High Low	Low

Table 1 gives the minimum PUC of an RA caused by other switches when one switch is fixed at one state. The minimum PUC is provided with other reconfigurable switches except the switch with fixed state. Switch A is the most important switch because when the switch is fixed at either state the minimum PUC caused by other switches is low. It means that Switch A should not be fixed at any state. Switch C is the least important switch because when the switch is fixed at a particular state the minimum PUC caused by other switches is high. Therefore, the importance of a switch is evaluated by the minimum PUC when the state of the switch is fixed.

D. SWITCH-BY-SWITCH REDUCTION STRATEGY

Higher minimum PUC indicates less important switch. If the least important switch is eliminated, the RA will provide higher minimum PUC with other switches. As a result of that, the reconfigurability of the RA is increased. Furthermore, since the number of switches is reduced, the complexity of the RA is decreased.

To make the switch reduction strategy efficiency, all the switches are ranked by their importance according to the minimum PUC. Then switch-by-switch, the least important switch is eliminated until the number of switches is reduced to a pre-determined number, the minimum PUC is increased to a pre-determined value, or the minimum PUC starts to decrease. After a switch is eliminated, the place where the switch was is replaced by a metallic strip if the minimum PUC is high when the switch was fixed at ON state, otherwise the place should be replaced by a gap. During the process of optimization, the biasing lines are not included.

III. NUMERICAL AND OPTIMIZATION RESULTS

The RA with uniformly distributed switches to be optimized is presented in Fig.1. It is a monopole-type antenna mounted perpendicularly over an infinite ground plane. The RA has 50 small metallic pixels with switches between every pair of adjacent pixels. The side length of each square pixel is 2.4 mm. The distance between each pair of adjacent pixels is 0.8 mm. To emulate a switch between two pixels in ON state, a 0.8 mm × 0.2 mm metallic strip is used to connect the two pixels. If the switch is in OFF state, the two pixels are disconnected by a small gap in the metallic strip. The pixels and strips are on the surface of a substrate with permittivity of 3.9 and thickness of 1 mm.

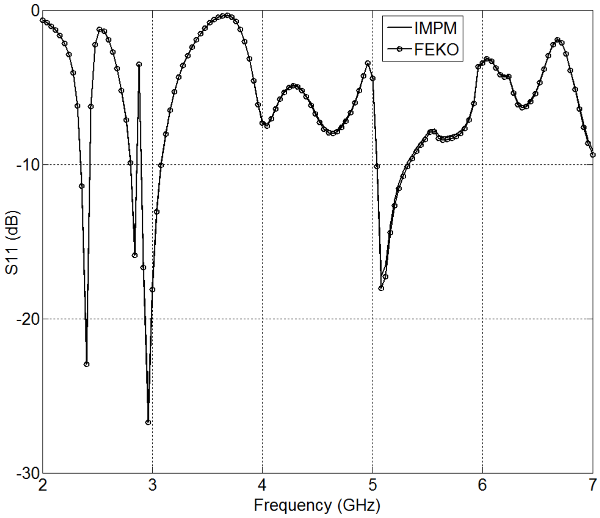


FIGURE 2. **The reflection coefficients obtained by the IMPM and FEKO of a randomly selected antenna configuration.**

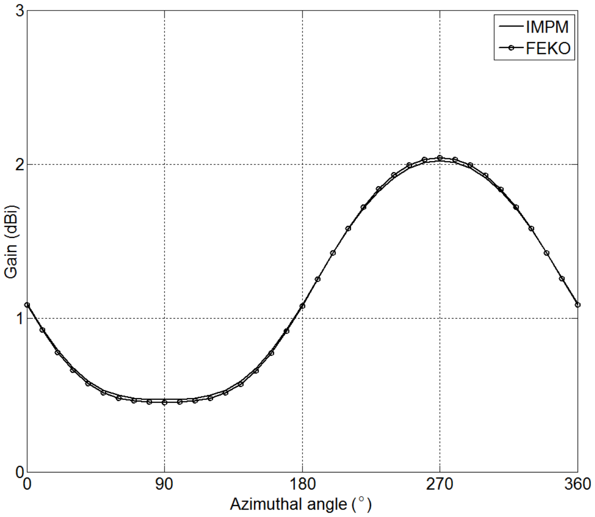


FIGURE 3. **The gain patterns obtained by the IMPM and FEKO at 3 GHz of the same antenna configuration.**

To verify the validity of the IMPM, the performance of the RA at a randomly chosen antenna configuration is obtained by both the IMPM and FEKO. The IMPM results are calculated by (5) and (9) for the reflection coefficient and the gain pattern, respectively. The reflection coefficients obtained by the IMPM and FEKO in Fig. 2 both show that the RA resonate well at 3 GHz. At this frequency, the gain patterns obtained by both the IMPM and FEKO are plotted in Fig. 3. The consistency in Fig. 2 and Fig. 3 shows the usefulness and accuracy of the IMPM. The application of IMPM in calculating reflection coefficients has also been verified in [20]–[22]. However, they only said the IMPM could be used to calculate radiation properties. To our best knowledge, this is the first time to really use the IMPM to calculate gain patterns. In the subsequent of the paper, therefore, the reflection coefficients and gain patterns will only be calculated by the IMPM.

The 85 switches provide 2^{85} configurations to the RA. It is impractical to calculate the performance for all antenna configurations. Thus, a random sample of 10,000,000 unique configurations is selected, which can almost represent the tendency of the overall configurations according to the Monte Carlo Method. The reflection coefficients in thin curves of the 10,000,000 configurations and their envelope in thick curve are shown in Fig. 4. The value of the envelope at every frequency is the minimum reflection coefficients among all curves in the operating band from the 10,000,000 curves of reflection coefficients. It can be seen from Fig. 4 that 10,000,000 configurations provide very good impedance matching within the band of 2 to 7 GHz.

The RA seems fine with Fig. 4 since the whole operating band is covered. However, Fig. 5 reveals another side of the RA. Using −20 dB as a threshold, if the reflection coefficient of a configuration at a frequency is less than −20 dB, it indicates that the configuration provides good impedance matching at the frequency. Neither the gain nor the polarization is considered in the good-impedance-matching configurations. The percentage of occurring of the good-impedance-matching configurations at every frequency is shown in Fig. 5. It can be seen that the distribution of the percentage is very uneven in the band. The percentage is extremely small at low frequencies. It might take a long time to locate a configuration which input impedance matches well at low frequencies.

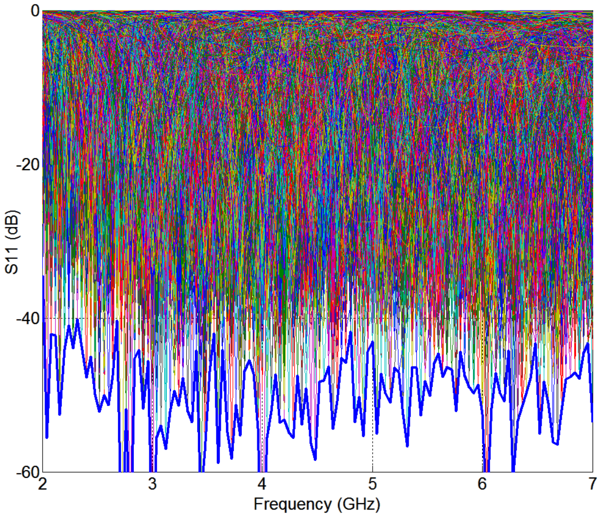


FIGURE 4. **Reflection coefficients of a random sample of 10,000,000 antenna configurations (thin curves) and their envelope (thick curve).**

The performance of gain patterns and polarization is also important for frequency RAs. The RA in Fig. 1 with infinite ground plane is always of vertical polarization in the horizontal plane. Suppose we need an omni-directional radiation pattern and the gain of the frequency RA is required to be greater than 0 dBi in the whole horizontal plane, then a reflection coefficient less than −20 dB and a gain greater than 0 dBi in the whole horizontal plane at the same frequency makes

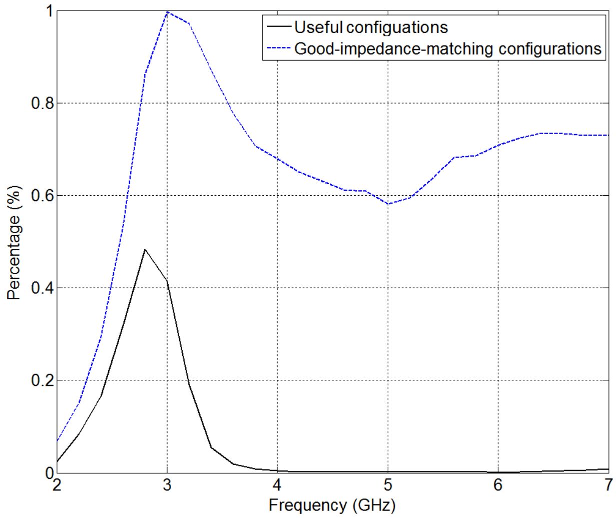


FIGURE 5. **The percentage of useful configurations and good-impedance-matching configurations.**

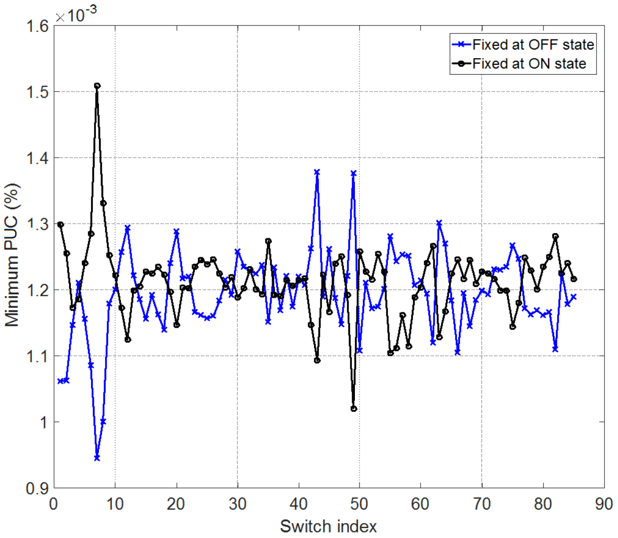


FIGURE 6. **The minimum PUC of the antenna in the case that the state of one switch is fixed.**

a useful configuration. The PUC at every frequency is also shown in Fig. 5. Since the useful configurations are defined as having good impedance matching and proper gain pattern and polarization, while good-impedance-matching configurations are defined only having good impedance matching. Therefore, the PUC is lower than the percentage of the good-impedance-matching configurations at every frequency, especially at high frequencies due to the fact that the antenna is higher than a half wavelength at these frequencies. In Fig. 5, the percentage of good-impedance-matching configurations at 6 GHz is 0.71%, while the PUC is only 0.0012% at the same frequency. It means that not all good-impedance-matching configurations could provide enough gain in the horizontal plane. The lowness of the minimum PUC implies that the reconfigurability of the RA is very low.

The reconfigurability is low because of the existence of too many less important switches. Although more switches might provide more useful configurations, these less important switches enlarge the denominator much more than the numerator of Eq. 10. Therefore, the reconfigurability could be increased by removing these less important switches. To illustrate the effect, Fig. 6 shows the minimum PUC of the antenna in the case that the state of one switch is fixed. There are two curves in Fig. 6. The abscissa values are switch indexes. The two ordinate values with respect to each abscissa value are the minimum PUC of the antenna while the corresponding switch is fixed at ON state and OFF state, respectively.

It can be seen from Fig. 6 that switch 7 is the least important switch. If switch 7 is fixed at ON state, the minimum PUC of the antenna is increased from 0.0012% to 0.0015%. The number 0.0012% is the minimum PUC caused by all 85 switches. As a result of that, it is better to replace switch 7 by a metallic strip to short the two connected pixels rather than to leave it as a switch. That means 84 switches can provide higher reconfigurability than 85 switches do if the least important switch is eliminated. It might be surprising at first sight that a switch at the closest position to the feed point is considered as the least important switch and should be eliminated first because we always say that switches located close to the feed port have a much stronger influence over the antenna performance than those at further locations. Strong-influence switches are not always high important switches. Fixing switch 7 at different states changes the resonant frequencies of the antenna a lot. So, it is a strong-influence switch. Fixing switch 7 at ON state makes the minimum PUC of the antenna much higher than fixing the switch at OFF state. So, it should be eliminated and is not a high important switch.

Switch 85 is at the top-right corner of the antenna where the current is the smallest in most cases. Obviously, this switch does not influence the performance much. If this switch is eliminated, the number of total antenna configurations is halved as well as the number of useful configurations. So, the PUC is almost the same no matter the switch in ON or OFF state and no matter with or without the switch. Although the effect of one switch in this area is trivial, the effect caused by a bunch of switches in this area all in together should not be neglected. Therefore, switch 85 is the medium important switch.

The average of the two curves in Fig. 6 slightly fluctuates around 0.0012%. The switch corresponding to the smallest average value is the most important switches in this stage. Since after one switch is eliminated the topology is changed, the most important switch in the next stage might not be the most important switch in the previous state. Therefore, we do not care which switch is the most important switch. We need to find out the least important switch and eliminate it. After one switch is eliminated, then find out the least important switch from the remaining switches again and eliminate it.

Also because the topology of the RA is changed by the elimination of the least important switch, the switches are not independent switches. The importance of a switch is

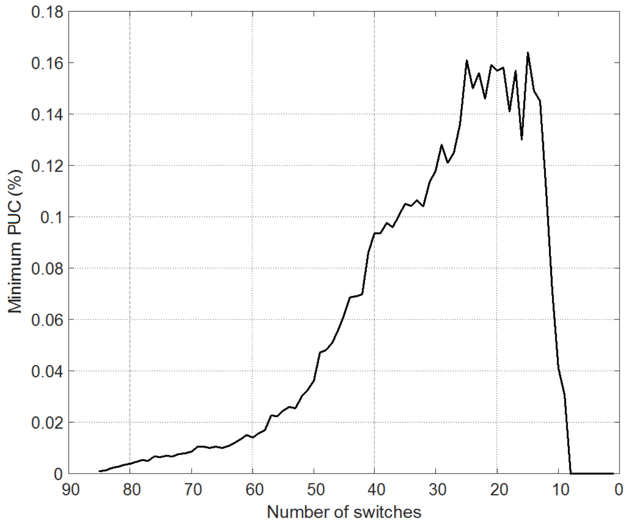


FIGURE 7. The minimum PUC of the RA with different number of switches.

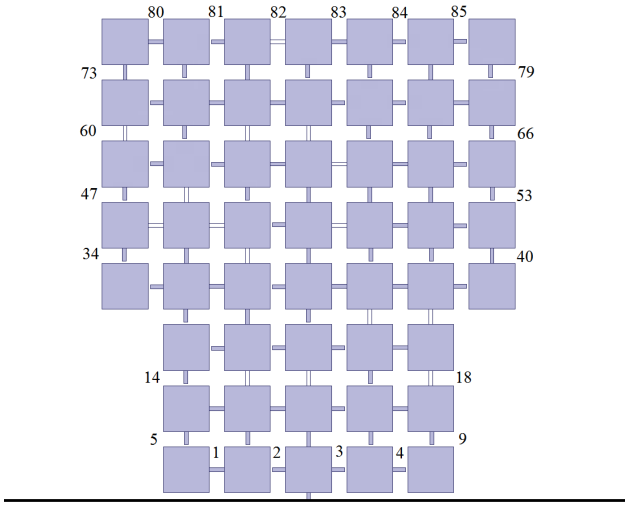


FIGURE 9. The final structure of the RA with 15 important switches highlighted in white.

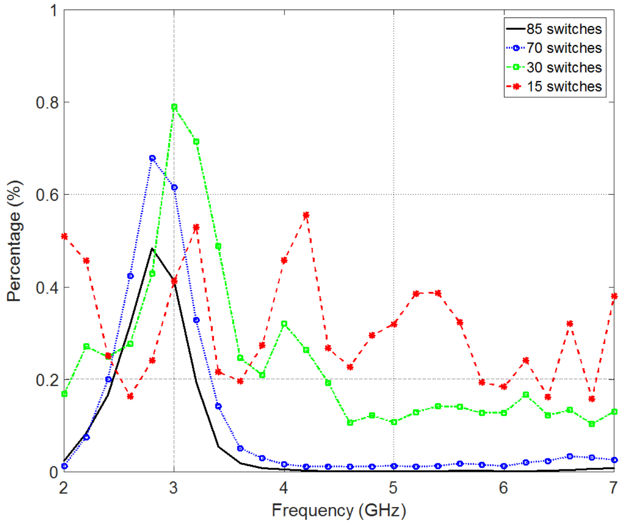


FIGURE 8. The PUC of the RA with different number of switches.

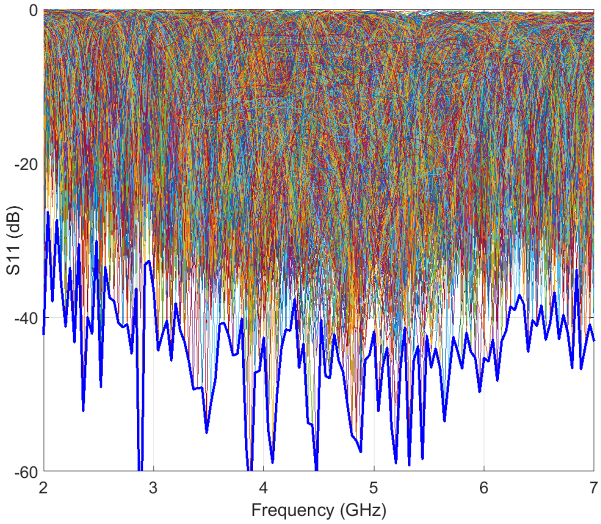
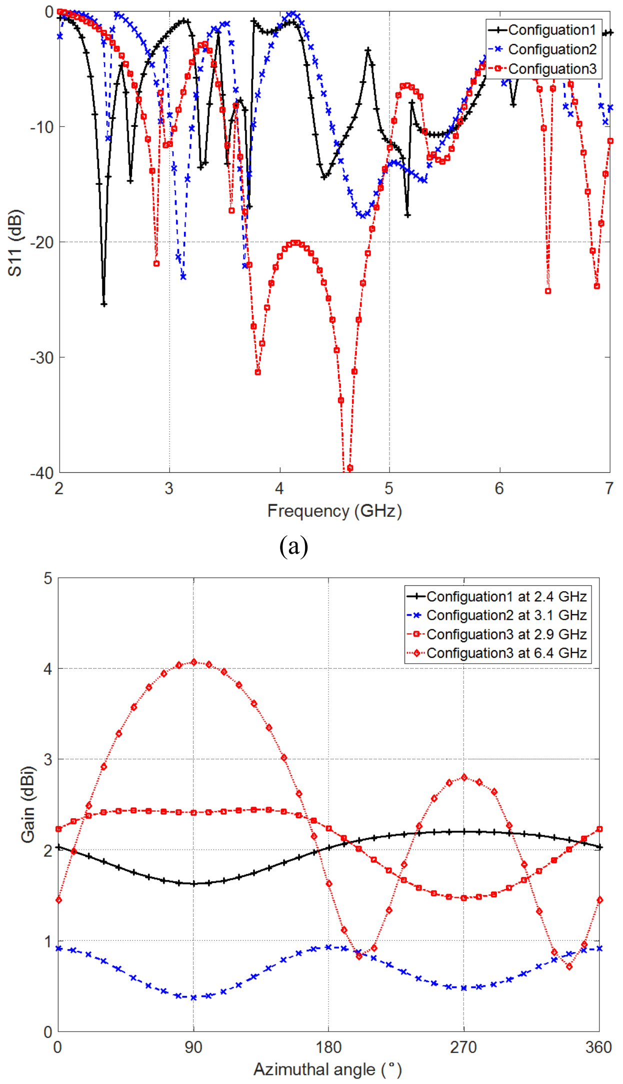


FIGURE 10. The reflection coefficients of the RA with 15 important switches (thin curves) and their envelope (thick curve).

determined by its own as well as by all other switches. Therefore, the least but one important switch in the previous stage might not be the least important switch in next stage after the previous least important switch is eliminated. The importance of the remaining switches changes with the changing of the RA topology and should be reevaluated.

Switch-by-switch, the least important switch is replaced by a metallic strip or a gap depending on the minimum PUC according to this switch. After one switch is eliminated, another set of sufficiently large number of configurations are selected randomly to evaluate the importance of the remaining switches. It is found that 10,000,000 configurations are sufficient to determine the first least important switch because there are more than 100 useful configurations in this set. The sufficiently large number is set as 10,000,000 at first. As the number of switches is being reducing, the number is eventually reduced to 1,000,000 and to 100,000 because the increasing of reconfigurability and the decreasing of the number of total configurations. When the number of switches reduced to 16, all the configurations are used to evaluate the importance of switches because 2^{16} is already less than 100,000.

The minimum PUC of the RA with different number of switches during the procedure of switch reduction is given in Fig. 7. The minimum PUC is keeping increasing (little fluctuation is ignored) with the reducing of the number of switches until the number of switches is less than 15. The increasing of PUC is mainly due to the fact that a lot of useless configurations are avoided. It means that the RA with 15 optimal-deployed switches provides the highest reconfigurability. When the number of switches is reduced to 8, the RA cannot work well at all the frequencies due to the fact that



(a)

(b)

FIGURE 11. The reflection coefficients and gain patterns of three useful configurations. (a) Reflection coefficients (b) Gain patterns.

TABLE 2. The states of switches, resonate frequency, and minimum gain in the horizontal plane of three antenna configurations.

Configuration	States of the switches	Resonant frequency (GHz)	Minimum gain (dBi)
1	000010001010110	2.4	1.6
2	110011010011101	3.1	0.4
3	101001101000011	2.9, 6.4	1.5, 0.7

State 1 represents OFF, and state 0 represents ON. The indexes of the 15 switches are 15, 16, 18, 26, 27, 36, 41, 42, 44, 48, 57, 60, 62, 63, and 82 which are highlighted in white in Fig. 9.

the minimum PUC is zero. The same trend is also observed in Fig. 8 where the curves of PUC of the RA with different number of switches are plotted. The final structure of the RA with the most important 15 switches is shown in Fig. 9. The places of the 15 switches are highlighted in white, and the eliminated switches are replaced by metallic strips and gaps according to the minimum PUC they caused. If the eliminated switches are replaced like that, the Z-matrix that is filled at first would not change in the process.

Both Fig. 7 and Fig. 8 show that the minimum PUC of the RA with 15 switches is 0.14% in the band of 2-7 GHz. It means that at least 46 out of $2^{15} = 32768$ configurations are useful configurations. At other frequencies, the number of useful configurations is even bigger. Fig. 10 gives the reflection coefficients and their envelope of the RA with final 15 switches. In this figure, not all reflection coefficients of total 32768 configurations are shown. Only reflection coefficients of useful configurations are plotted. It means that each curve has at least one resonant frequency where the reflection coefficient is less than -20 dB and the gain is greater than 0 dBi in the whole horizontal plane. It can be seen from Fig. 10 that the whole band is also fully covered with 15 switches. The envelope of S_{11} in Fig. 10 is higher compared with the envelope in Fig. 4. In despite of the envelope is higher, it is still under -20 dB which is the threshold for useful configurations.

To clearly show the frequency reconfigurable property of the proposed RA, Fig. 11 shows the reflection coefficients and gain patterns of three useful configurations. The states of the 15 remaining switches are given in Table 2. It can be seen that with different states of switches the antenna resonates at different frequencies. At some resonant frequencies, the reflection coefficient is less than -20 dB and the antenna radiates omni-directionally in the horizontal plane with its minimum gain greater than 0 dBi at these frequencies. It indicates that the antenna works as a frequency RA. For configuration 3, the antenna also matches well at 3.8 GHz, 4.6 GHz, and 6.9 GHz. However, at these frequencies the gain in the horizontal plane is less than 0 dBi. According to the definition of useful configurations in the paper, the antenna does not work well at these frequencies. It is same for the configuration 2 at 3.7 GHz.

IV. CONCLUSION

A frequency RA with massive switches is optimized for high reconfigurability. The measure of the reconfigurability is the minimum PUC in the whole operating band. Thanks to the optimization, the minimum PUC of the RA is increased more than 100 times from 0.0012% to 0.14% in the band of 2-7 GHz while the number of switches is reduced from 85 to 15. With a few high important switches, the states of the switches are easy to find out when the RA is to work for different functions which need different frequencies. The switch-by-switch reduction strategy is an efficient way to decrease the complexity of RA with a large number of switches while increasing the reconfigurability. The method is also suitable for optimizing radiation pattern RAs and polarization RAs as well as frequency RAs with band notches.

REFERENCES

[1] P.-Y. Qin, A. R. Weily, Y. J. Guo, and C.-H. Liang, "Polarization reconfigurable U-slot patch antenna," *IEEE Trans. Antennas Propag.*, vol. 58, no. 10, pp. 3383–3388, Oct. 2010.

[2] L.-Y. Ji, Y. J. Guo, P.-Y. Qin, S.-X. Gong, and R. Mittra, "A reconfigurable partially reflective surface (PRS) antenna for beam steering," *IEEE Trans. Antennas Propag.*, vol. 63, no. 6, pp. 2387–2395, Jun. 2015.

[3] M.-C. Tang, B. Zhou, and R. W. Ziolkowski, "Low-profile, electrically small, huygens source antenna with pattern-reconfigurability that covers the entire azimuthal plane," *IEEE Trans. Antennas Propag.*, vol. 65, no. 3, pp. 1063–1072, Mar. 2017.

[4] A. Petosa, "An overview of tuning techniques for frequency-agile antennas," *IEEE Antennas Propag. Mag.*, vol. 54, no. 5, pp. 271–296, Oct. 2012.

[5] Y. Yashchyshyn, K. Derzakowski, P. R. Bajurko, J. Marczewski, and S. Kozłowski, "Time-modulated reconfigurable antenna based on integrated s-PIN diodes for mm-Wave communication systems," *IEEE Trans. Antennas Propag.*, vol. 63, no. 9, pp. 4121–4131, Sep. 2015.

[6] P. Chawla and R. Khanna, "A new spiral frequency reconfigurable antenna with RF-MEMS switches for mobile RF front end," *Int. J. Appl. Electromag. Mech.*, vol. 47, no. 2, pp. 323–335, 2015.

[7] X. L. Yang, J. C. Lin, G. Chen, and F. L. Kong, "Frequency reconfigurable antenna for wireless communications using GaAs FET switch," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 807–810, Dec. 2015.

[8] C. Wu, T. Wang, A. Ren, and D. G. Michelson, "Implementation of reconfigurable patch antennas using reed switches," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1023–1026, 2011.

[9] J. S. Gibson, X. Liu, S. V. Georgakopoulos, J. J. Wie, T. H. Ware, and T. J. White, "Reconfigurable antennas based on self-morphing liquid crystalline elastomers," *IEEE Access*, vol. 4, pp. 2340–2348, 2016.

[10] M. C. Lim, S. K. A. Rahim, M. R. Hamid, A. A. Eteng, and M. F. Jamlos, "Frequency reconfigurable antenna for WLAN application," *Microw. Opt. Technol. Lett.*, vol. 59, no. 1, pp. 171–176, 2017.

[11] L. Di Palma, A. Clemente, L. Dussopt, R. Sauleau, P. Potier, and P. Pouliguen, "Radiation pattern synthesis for monopulse radar applications with a reconfigurable transmitarray antenna," *IEEE Trans. Antennas Propag.*, vol. 64, no. 9, pp. 4148–4154, Sep. 2016.

[12] C. G. Christodoulou, Y. Tawk, S. A. Lane, and S. R. Erwin, "Reconfigurable antennas for wireless and space applications," *Proc. IEEE*, vol. 100, no. 7, pp. 2250–2261, Jul. 2012.

[13] A. Khidre, K.-F. Lee, F. Yang, and A. Z. Elsherbeni, "Circular polarization reconfigurable wideband E-shaped patch antenna for wireless applications," *IEEE Trans. Antennas Propag.*, vol. 61, no. 2, pp. 960–964, Feb. 2013.

[14] Y. K. Park and Y. Sung, "A reconfigurable antenna for quad-band mobile handset applications," *IEEE Trans. Antennas Propag.*, vol. 60, no. 6, pp. 3003–3006, Jun. 2012.

[15] H.-B. Zhang, Y.-L. Ban, Y.-F. Qiang, J. Guo, and Z.-F. Yu, "Reconfigurable loop antenna with two parasitic grounded strips for WWAN/LTE unbroken-metal-rimmed smartphones," *IEEE Access*, vol. 5, pp. 4853–4858, 2017.

[16] D. Rodrigo and L. Jofre, "Frequency and radiation pattern reconfigurability of a multi-size pixel antenna," *IEEE Trans. Antennas Propag.*, vol. 60, no. 5, pp. 2219–2225, May 2012.

[17] X. Yuan *et al.*, "A parasitic layer-based reconfigurable antenna design by multi-objective optimization," *IEEE Trans. Antennas Propag.*, vol. 60, no. 6, pp. 2690–2701, Jun. 2012.

[18] L. Greetis, R. Ouedraogo, B. Greetis, and E. J. Rothwell, "A self-structuring patch antenna: Simulation and prototype," *IEEE Antennas Propag. Mag.*, vol. 52, no. 1, pp. 114–123, Feb. 2010.

[19] D. S. Linden, "A system for evolving antennas *in-situ*," in *Proc. 3rd NASA/DoD Workshop Evolvable Hardware*, Long Beach, CA, USA, Jul. 2001, pp. 249–255.

[20] R. Mehmood and J. W. Wallace, "Diminishing returns with increasing complexity in reconfigurable aperture antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 299–302, 2011.

[21] J. L. A. Quijano and G. Vecchi, "Optimization of an innovative type of compact frequency-reconfigurable antenna," *IEEE Trans. Antennas Propag.*, vol. 57, no. 1, pp. 9–18, Jan. 2009.

[22] S. Song and R. D. Murch, "An efficient approach for optimizing frequency reconfigurable pixel antennas using genetic algorithms," *IEEE Trans. Antennas Propag.*, vol. 62, no. 2, pp. 609–620, Feb. 2014.

[23] C. M. Coleman, E. J. Rothwell, and J. E. Ross, "Investigation of simulated annealing, ant-colony optimization, and genetic algorithms for self-structuring antennas," *IEEE Trans. Antennas Propag.*, vol. 52, no. 4, pp. 1007–1014, Apr. 2004.

[24] A. M. Yadav, C. J. Panagamuwa, and R. D. Seager, "Investigating the effects of control lines on a frequency reconfigurable patch antenna," in *Proc. Loughborough Antennas Propag. Conf.*, Loughborough, U.K., Nov. 2010, pp. 605–608.

[25] J. M. Kovitz, H. Rajagopalan, and Y. Rahmat-Samii, "Practical and cost-effective bias line implementations for reconfigurable antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1552–1555, 2012.

[26] D. E. Anagnostou and A. A. Gheethan, "A coplanar reconfigurable folded slot antenna without bias network for WLAN applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 1057–1060, 2009.

[27] N. Kingsley, D. E. Anagnostou, M. Tentzeris, and J. Papapolymerou, "RF MEMS sequentially reconfigurable sierpinski antenna on a flexible organic substrate with novel DC-biasing technique," *J. Microelectromech. Syst.*, vol. 16, no. 5, pp. 1185–1192, Oct. 2007.

[28] A. Besoli and F. De Flaviis, "A multifunctional reconfigurable pixeled antenna using MEMS technology on printed circuit board," *IEEE Trans. Antennas Propag.*, vol. 59, no. 12, pp. 4413–4424, Dec. 2011.

[29] D. Rodrigo, B. A. Cetiner, and L. Jofre, "Frequency, radiation pattern and polarization reconfigurable antenna using a parasitic pixel layer," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3422–3427, Jun. 2014.

[30] C.-Y. Wu, Y.-P. Ma, and J. Xu, "An efficient approach for reducing the complexity of reconfigurable antennas," *Appl. Comput. Electromagn.*, vol. 30, no. 2, pp. 237–244, Feb. 2015.

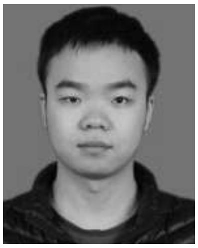
[31] B. T. Perry, E. J. Rothwell, and L. L. Nagy, "Analysis of switch failures in a self-structuring antenna system," *IEEE Antennas Wireless Propag. Lett.*, vol. 4, pp. 68–70, 2005.

CHANGYING WU (M'15) received the B.Eng. degree in electrical and electronic engineering, the M.Eng. degree in electromagnetic field and microwave technique and the Ph.D. degree (Hons.) in circuit and system, all from Northwestern Polytechnical University, Xi'an, China, in 1999, 2001, and 2004, respectively.

In 2011, he was a Visiting Scholar with the Radio Science Laboratory, Department of Electrical and Computer Engineering, The University of British Columbia, Canada. In 2015, he was a Visiting Scholar with the Department of Engineering and Digital Arts, University of Kent, U. K. Since 2004, he has been with the School of Electronics and Information, Northwestern Polytechnical University, where he is currently an Associate Professor. His research interests include antenna design and microwave measurement.

ZHOU YANG was born in Shangzhou, Shaanxi, China, in 1994. He received the B.Eng. degree in electrical and electronic engineering from Northwestern Polytechnical University, Xi'an, China, in 2016, where he is currently pursuing the M.Eng. degree in electromagnetic field and microwave technique.

His current research interests include antenna design and microwave measurement.



YUSHENG LI was born in Lezhi, Sichuan, China, in 1994. He received the B.Eng. degree in microelectronics from Northwestern Polytechnical University, Xi'an, China, in 2016, where he is currently pursuing the M.Eng. degree in electromagnetic field and microwave technique.

His current research interests include antenna design and microwave measurement.

YUAN ZHANG was born in Yanchuan, Shaanxi, China, in 1991. He received the B.Eng. degree in electrical and electronic engineering from Northwestern Polytechnical University, Xi'an, China, in 2014, where he is currently pursuing the M.Eng. degree in electromagnetic field and microwave technique.

His current research interests include antenna design and microwave measurement.

YEVHEN YASHCHYSHYN (M'96–SM'09) received the M.Sc. degree from the Lviv University of Technology, Lviv, Ukraine, in 1979, and the Ph.D. degree from the Moscow State Institute of Electronics and Mathematics, Moscow, Russia, in 1986, and the D.Sc. (Habilitation) degree in electronics from the Warsaw University of Technology, Warsaw, Poland, in 2006.

Since 1999, he has been with the Institute of Radioelectronics (IR), Warsaw University of Technology (WUT). In 2002, he became the Head of the Antenna Laboratory, and since 2009, he has been the Head of the Radiocommunication Division, IR, WUT. He has authored over 100 technical papers, authored or co-authored three books, and received nine patents. His research interests include antenna theory and techniques, smart beamforming, reconfigurable antennas, radio over fiber techniques, and materials characterization, including ferroelectric ceramic-polymers composites investigation up to subterahertz frequency.

Dr. Yashchyshyn was a recipient of the First Prize of EuMA on the 11th European Microwave Week for outstanding research and new concept of the reconfigurable antenna, Amsterdam, in 2008. He was a member of the Organizing Committee of the International Conference TCSET in 1998, a Reviewer of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES in2004, the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION in 2006, and the IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS in 2004. He was a Member of the Editorial Board of Izwestiya Wuzow Radioelektronika in 2009 and the Microwave and Radiolocation Section of the Electronics and Telecommunication Committee of the Polish Academy of Sciences in 2007, a TPC Member of the MIKON in 2009 and the European Wireless Conference EW in 2010, and a Member of the Scientific and Programme Committee of the Polish National Conference KKRRiT in 2009.

• • •