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A Novel Optimization Technique for Designing Frequency Reconfigurable Pixelated Planar Antenna

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***Abstract*—A novel method incorporating joint perturbation sensitivity analysis is proposed in this paper to design frequency reconfigurable planar antennas with a pixelated surface. Using our method, an antenna design having two switched working frequency bands and omnidirectional radiation patterns, is optimized. The simulation results verify its efficacy and potential computation efficiency.**

***Index Terms*—Optimization technique, sensitivity analysis, frequency reconfigurable antenna, pixel antenna.**

I. Introduction

Frequency reconfigurable antennas are increasingly playing important roles in advanced wireless communication systems [1]. One approach to achieve reconfigurability is by using the discretized or pixelated planar structure and its feature is its high design flexibility. The genetic algorithm (GA) has been widely used to find the optimal configuration of antennas implementing such structures [2], [3].

In this paper, a novel design strategy is proposed to optimize the pixelated planar antenna with frequency reconfigurability using perturbation sensitivity analysis based on [4]. In [4], the analysis method is only applied to fixed pixel antenna designs and this work extends its application scenarios to reconfiguration between two bands utilizing one PIN diode. Different from [4], the concept of joint perturbation sensitivity is introduced to simultaneously evaluate the influence of the hardwire configuration and the switch location on the antenna performance. A reconfigurable pixelated antenna is optimized by our proposed method as a verification example.

II. Antenna Structure

Fig. 1 (a) shows the structure of the frequency reconfigurable pixelated planar antenna used in this work, where the substrate is FR4 with $\epsilon_r = 4.4$ and thickness 1.6 mm. The entire rectangular metallic surface is discretized into 3×5 sub-elements with $Q = 22$ internal ports. The PIN diode SMP1345 from Skyworks is selected as the RF switch and its equivalent circuit models are provided in Fig. 1 (b) [5]. The internal multi-port method (IMPM) is used to efficiently calculate the electromagnetic characteristics of the antenna, where the load impedance connected to each internal port required is limited to either infinity ("open" hardwire) or zero ("short" hardwire) or computed from the equivalent circuits (RF switch) [3].

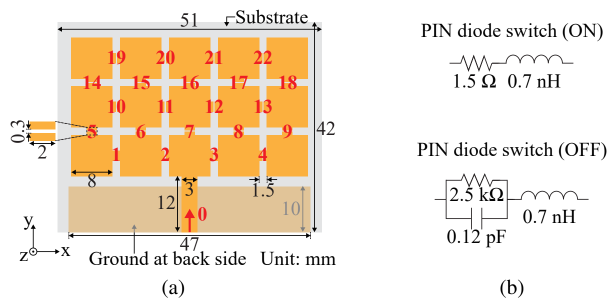

Fig. 1. (a) Geometry of the proposed antenna. Black and red numbers represent geometric dimensions and port numbers, respectively. The red arrow (port 0) indicates external feeding. (b) RF equivalent circuits of the PIN diode.

III. Formulation and Optimization Method

In this work, a single PIN diode (denoted as the switch in the following) is considered for performing reconfiguration between two frequency bands. The design vector is formed similarly to [3]. We use a row vector $\boldsymbol{x}_\mathrm{S}$ with $K = \lceil \log_2 22 \rceil = 5$ binary bits to denote the location of the RF switch and a $1\times Q$ binary vector $\boldsymbol{x}_\mathrm{L}$ to indicate the hardwire configuration, whose element is 1 for "open" and 0 for "short". The switch is located at port 1 if the corresponding decimal number of $\boldsymbol{x}_\mathrm{S}$ is 0, at the Qth port if it is larger than Q and at the internal port with number equal to decimal $\boldsymbol{x}_\mathrm{S}$ otherwise. Note that the binary bit in $\boldsymbol{x}_\mathrm{L}$, whose position is determined as the switch, is not used as its impedance will be replaced by that obtained from the equivalent circuits in Fig. 1 (b). It is kept here for clearness of port numbering and ease of programming. The complete design vector is $\boldsymbol{x} = [\boldsymbol{x}_\mathrm{L}, \boldsymbol{x}_\mathrm{S}]$. We assume that the switch is ON in $\boldsymbol{x}$ and use the vector $\overline{\boldsymbol{x}}$ to represent the antenna having the same configuration as $\boldsymbol{x}$ but with the OFF switch.

The frequency reconfigurable antenna is designed to operate at two switched frequency bands ($[f_1^{\mathrm{ON}} : f_U^{\mathrm{ON}}]$ when the switch is ON and $[f_1^{\mathrm{OFF}} : f_V^{\mathrm{OFF}}]$ when it is OFF). The objective function $g(\boldsymbol{x}, \overline{\boldsymbol{x}})$ to be minimized subject to $\boldsymbol{x} \in \{0,1\}^{27}$ can then be expressed as Eq. (1), where $S_{11}(\boldsymbol{x}, f)$ is S_{11} with antenna configuration $\boldsymbol{x}$ at frequency f in dB scale, all the t parameters are optimization thresholds and $[a]^+$ is the greater of either zero or a. The last two terms in Eq. (1) are for achieving omnidirectional radiation in the plane

$$
\begin{aligned}
g = &\sum_{u=1}^{U}\left[S_{11}\left(\boldsymbol{x}, f_u^{\mathrm{ON}}\right)-t_{\mathrm{S1}}\right]^{+}+\sum_{v=1}^{V}\left[-S_{11}\left(\boldsymbol{x}, f_v^{\mathrm{OFF}}\right)+t_{\mathrm{S2}}\right]^{+}+\sum_{v=1}^{V}\left[S_{11}\left(\overline{\boldsymbol{x}}, f_v^{\mathrm{OFF}}\right)-t_{\mathrm{S1}}\right]^{+}+\sum_{u=1}^{U}\left[-S_{11}\left(\overline{\boldsymbol{x}}, f_u^{\mathrm{ON}}\right)+t_{\mathrm{S2}}\right]^{+} \\
&+\left[\operatorname{range}\left(\mathbf{E}_{\boldsymbol{\phi}}\left(\boldsymbol{\theta}, \phi=\phi_r, \boldsymbol{x}, f_{\mathrm{c}}^{\mathrm{ON}}\right)\right)-t_{\mathrm{E}}\right]^{+}+\left[\operatorname{range}\left(\mathbf{E}_{\boldsymbol{\phi}}\left(\boldsymbol{\theta}, \phi=\phi_r, \overline{\boldsymbol{x}}, f_{\mathrm{c}}^{\mathrm{OFF}}\right)\right)-t_{\mathrm{E}}\right]^{+}. \qquad (1)
\end{aligned}
$$

$\phi = \phi_r$ at the two corresponding center frequencies ($f_{\mathrm{c}}^{\mathrm{ON}}$ for ON switch and $f_{\mathrm{c}}^{\mathrm{OFF}}$ for OFF switch) by diminishing the range (difference between maximum and minimum) of their horizontal components (dBi-scale $\mathbf{E}_{\boldsymbol{\phi}}$).

The optimization method proposed in this work is based on the concept of perturbation sensitivity analysis from [4]. Here we separate the binary bits representing the hardwire configuration and the switch location to calculate the n-bit joint perturbation sensitivity. n-bit joint perturbation sensitivity is defined here as the change in the objective function value caused by simultaneously changing up to n bits in $\boldsymbol{x}_{\mathrm{L}}$ and up to n bits in $\boldsymbol{x}_{\mathrm{S}}$ ($n \geq 1$). Algorithm 1 provides the complete optimization flow. During this iterative process, the algorithm converges towards the direction with the steepest decent and incorporates the effects of both hardwire connection and switch location. The larger n is, the better performance the algorithm has in terms of robustness and achieving the global optimum, as the search space increases and more candidates are considered, but more time is required.

Algorithm 1 Overall design steps of our proposed method.

1) Obtain a starting point $\boldsymbol{x}_{ini}$ by Monte Carlo method with 20 initial samples randomly generated.
2) For every possible combination of $m \in \{1, \ldots, n\}$ bits in $\boldsymbol{x}_{\mathrm{L}}$ and m bits in $\boldsymbol{x}_{\mathrm{S}}$, compute the difference between the objective function value after changing $2m$ bits in $\boldsymbol{x}$ (m bits in $\boldsymbol{x}_{\mathrm{L}}$ and m bits in $\boldsymbol{x}_{\mathrm{S}}$) and the original $g\left(\boldsymbol{x}_{ini}, \overline{\boldsymbol{x}}_{ini}\right)$. Store the joint perturbation sensitivities in vector $\boldsymbol{p}$.
3) Find the minimal joint perturbation sensitivity in $\boldsymbol{p}$ as $p_{\min}$.
4) Check the stop criterion. End the algorithm if $p_{\min} \geq 0$ and $\boldsymbol{x}_{ini}$ is the final design. Otherwise go to Step 5.
5) If $p_{\min} < 0$, find its corresponding perturbed design $\boldsymbol{x}_p$. End the algorithm if $g\left(\boldsymbol{x}_p, \overline{\boldsymbol{x}}_p\right) = 0$ and $\boldsymbol{x}_p$ is the final design, otherwise update $\boldsymbol{x}_{ini} = \boldsymbol{x}_p$ and go to Step 2.

IV. Design Example and Experimental Results

Utilizing our approach, an antenna is optimized by 2-bit joint perturbation sensitivity analysis operating at 2.3~2.5 GHz when the switch is ON ($f_{\mathrm{c}}^{\mathrm{ON}} = 2.4$ GHz) and 3.2~3.4 GHz when it is OFF ($f_{\mathrm{c}}^{\mathrm{OFF}} = 3.3$ GHz). The frequency sampling interval is 25 MHz so $U = V = 9$. We set $\phi_r = 0$, $t_{\mathrm{S1}} = -10$ dB, $t_{\mathrm{S2}} = -5$ dB and $t_{\mathrm{E}} = 1$ dB. The terms with t_{S2} are for the independence between the two switched PIN diode states.

After 5 iterations with 12120 ($20 + (5 \times 22 + 10 \times 231) \times 5$) objective function evaluations, the optimal design is obtained within 40 seconds using a computer with Core i7 CPU (1.80 GHz) and 16 GB RAM. The PIN diode is located at the internal port numbered 7 and the ports with "short" hardwires are [4,9,10,12,13,14,18,19,21,22], with all the others being "open". The simulated results are shown in Fig. 2. The final objective function value is 0.87 with a slight violation on the range of $\mathbf{E}_{\boldsymbol{\phi}}, \phi = 0$ (1.66 dB for ON switch and 1.21 dB for OFF switch). The good results obtained within a short time period verify the efficacy of our proposed method and its potential of being computationally efficient.

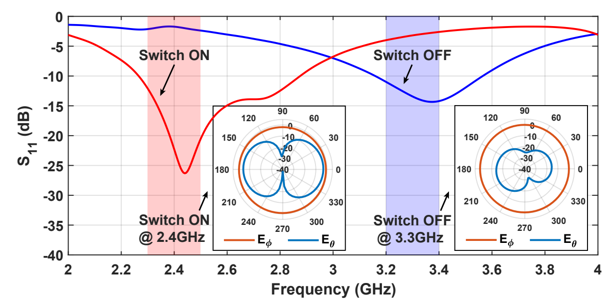

Fig. 2. Simulated S_{11} and radiation patterns at $\phi = 0$ for the optimized frequency reconfigurable antenna when the switch is in ON- and OFF-states.

V. Conclusions

A novel optimization technique is proposed to design a frequency reconfigurable antenna with pixelated sub-elements implementing the concept of joint perturbation sensitivity analysis. An antenna that utilizes one PIN diode realizing two switched working frequency bands with omnidirectional radiation patterns is designed through this new method and the simulation results prove its efficacy.

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