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SPECIAL SECTION ON NEW WAVEFORM DESIGN AND AIR-INTERFACE FOR FUTURE HETEROGENEOUS NETWORK TOWARDS 5G

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The Design of Microstrip Array Antenna and Its Optimization by a Memetic Method

XIN ZHANG, (Member, IEEE), MEIJIAO LIN, XIU ZHANG, (Member, IEEE), AND YANG LI
Tianjin Key Laboratory of Wireless Mobile Communications and Power Transmission, Tianjin Normal University, Tianjin 300387, China

Corresponding authors: Xiu Zhang (zhang210@126.com) and Yang Li (liyang_tongxin@163.com)

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ABSTRACT Microstrip antenna has been designed and applied to many practical scenarios for wireless communications. To meet the increasing requirements of wireless communication and quality of service, array antenna design deserves studying and analyzing. A novel design of 2.45-GHz microstrip array antenna has been proposed in the paper. The novel array antenna is composed by a planar layout of elements, coaxial feeders and circular feed points. The array antenna is designed to satisfy practical requirements, including frequency channel, voltage standing wave ratio, impedance matching, and signal loss rate. A memetic of genetic algorithm and the quasi-Newton method is proposed to effectively solve the design model. Numerical simulations are performed by the five optimization methods and two array sizes. The results show that the proposed design is able to produce qualified microstrip array antenna for usage. The proposed memetic method is more effective than the other four methods. The microstrip array antenna will be useful for practical wireless communication systems.

INDEX TERMS Array antenna, genetic algorithm, microstrip antenna, quasi-Newton method, wireless sensor.

I. INTRODUCTION

Internet of things (IoT) enlarges the concept of Internet. It is a network of combined by different areas, such as manufacturing factionaries, energy management systems, data collection devices, wireless communications, etc [1]–[3]. The fifth-generation (5G) mobile communication is a necessary part of IoT. More convenient wireless communication and high quality of service (QoS) can be provided by 5G. In such systems, sensor networks like array antennas is worthy further studying to ensure wireless communications among "things" be more efficient and in time [4].

The development history of microstrip antenna is relatively short [5], [6]. The concept of microstrip antenna was proposed by Deschamps in the 1950s. In the beginning, the concept did not attract much attention. By the 1970s, due to the development of printing technology and the emergence of various excellent dielectric materials, aircraft also had a great demand for low-profile antennas. In 1972, Munson and Howell developed the first batch of microstrip antenna that could be used in practice. Since then, microstrip antenna has attracted the attention of researchers. The University of New Mexico held a global conference on microstrip antennas in 1979. In 1981, a special collection of microstrip antennas was published by the IEEE Antennas and Propagation Society. This event opened up a new prospect of microstrip antenna research [7]–[9].

Microstrip antenna has many advantages such as small volume size, light weight, easy to conformal with carriers [10]. It has been widely used in broadband from 100 MHz to 50GHz such as remote sensing, wireless communication, and radar systems. However, it has some disadvantages such as narrow bandwidth, low gain, and bad directionality. To overcome these shortcomings, array antenna is a good solution which means array elements are arranged regularly. This can improve antenna gain and directionality of antenna.

Resonant antenna is a popular microstrip antenna type. It includes dipole antenna, slot antenna, and patch antenna. In this paper, patch antenna is taken to build an array antenna. Planar structure of patch antenna is used and each patch is independently fed. This causes great robustness of array antenna. The array antenna network is optimized to obtain

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eligible performance. The optimization of this paper concerns the length, width and location of the feed network. Optimizing these parameters is useful to reduce cost for manufacturing antennas and assure high QoS for users. Thus, such optimal design is very important to industry.

Compared with previous researches, the contributions of this paper are:

(1) The microstrip array antenna is modeled as an optimization problem with practical constraints. In the model, the scatter loss of array elements is minimized, and hence the network robustness is maximized.

(2) A memetic method is proposed for the optimization problem. It combines global search property of genetic algorithm and local search property of quasi-Newton method.

(3) Three array antenna sizes are tested to conclude the performance of the designed method. Moreover, the designed method is also compared with four other methods.

The state-of-the-art related works are described in detail in Section II. The designed array antenna model and its discussion are shown in Section III. The proposed memetic method for solving the designed model is shown in Section IV. Section V shows simulation configuration and results. The conclusion is drawn in Section VI.

II. RELATED WORKS OF MICROSTRIP ARRAY ANTENNA

In general, microstrip antenna is composed of a ground plate, a metal conductor with a certain shape, and a radiation element. The thickness of ground plate is much smaller than the wavelength. The length of the radiation element is about one half of the wavelength. Microstrip antenna has two kinds of feeding modes. One is the side feeding of the microstrip line, and the other is the back feeding of the coaxial probe to the patch.

Compared with single microstrip antenna, array antenna is affected by mutual coupling effect and the type of feed network. Moreover, return loss of array antenna is also stronger than single antenna. On the other hand, array antenna is able to obtain much higher gain than single antenna. Good directionality makes array antenna more acceptable in practice than single antenna.

Zhang et al. studied microstrip antenna design by scan and zoom method [11]. Two parameters of antenna patch were considered in their research. Some researchers have studied microstrip patch and slot antenna with high gain, wave velocity steering and broadband characteristics. In [12], the authors found that the asymmetric e-patch antenna design was most suitable because of its small size and high gain. In [13], the authors reported a new method for the design of broadband dual-polarization antennas using short dipoles, integrated balance bars and cross feeders. Experiments show that the antenna has broadband impedance bandwidth and good unidirectional radiation characteristics. In [14], a new on-chip antenna structure was designed to improve power gain and radiation efficiency. The result demonstrated the practicability of the low-cost receiver front end [14]. In [15], the authors studied a low-attitude omni-directional patch antenna with good radiation and filtering performance. Without extra filter circuit, the filter function is successfully integrated into patch antenna [15]. In [16], the authors reported a new type of integrated waveguide four-direction inverse phase filter power distributor. The proposed 1×4 antenna array could achieve high selectivity, symmetric radiation mode and low cross-polarization level in millimeter wave band [16].

In [17], the authors employed the travelling wave feed system, which may also provide symmetrical side-lobes for half-wavelength uniform spacing of slots. In 2015, Jung reported a robust global optimization approach for design of plasmonic waveguide [18]. The method was used to lessen the fabrication uncertainty effect and improve the reliability in design process while retaining high optical performance. The numerical results showed that the proposed method provided a useful design procedure for plasmonic waveguides with high performance and improved reliability [18]. In 2016, Scott et al. proposed a method for determining the permittivity and permeability for specimens with high refractive index [19]. The variable shape was also investigated. The method was validated by supporting measurements from a stripline cavity and coaxial airline. The results demonstrated the method was able to handle frequency dispersive and high index materials [19]. In the same year, there was an article that said an exact and efficient full wave numerical method was presented [20]. The method was based on genetic algorithm to design waveguide directional couplers with patterned apertures. In the proposed design procedure, magnetic field integral equation, for the waveguide directional coupler with patterned aperture, was derived and solved for magnetic current of aperture to calculate scattering parameters of the structure [20].

III. PROBLEM MODELING

An example of microstrip antenna is shown in Figure 1. Such antenna is popular due to ease of design, low cost to fabricate, and narrow bandwidth.

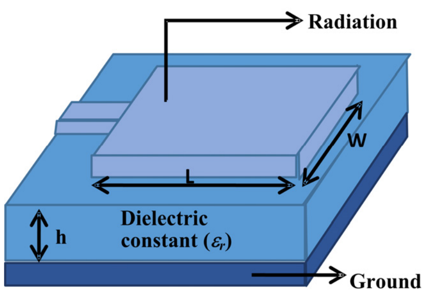

FIGURE 1. An example of microstrip antenna structure.

Since 2.45GHz frequency band is widely used in industrial, scientific, and medical fields, this paper attempts to study microstrip array antenna design at 2.45GHz. In microstrip array antenna, multiple elements cause return loss, which would trade off network gain. To fulfill practical requirements, three metrics are considered in the paper. These are input return loss, voltage standing wave ratio, and impedance matching.

Input return loss, voltage standing wave ratio and normalized impedance matching are very important parameters in microstrip patch array, and the optimization will be judged from these three results. Input return loss (S_{11}) refers to the ratio of incident power to reflected power (generally expressed as dB value); In other words, how much energy is reflected back to the source, and the smaller the better.

Voltage standing wave ratio (VSWR) refers to the voltage ratio of peak value to valley value. When VSWR is equal to 1 (expressed numerically in dB), it means that the impedance of the feeder and the antenna is completely matched. At this time, all high-frequency energy is radiated out by the antenna and there is no reflection loss of energy. When the standing wave ratio is infinite, it means total reflection, and the energy is not radiated out at all. In mobile communication systems, the closer VSWR is to 1, the better. Standing wave ratio is generally required to be less than 1.5, but in practical applications, VSWR should be less than 1.2. Too large VSWR will reduce the coverage of the base station and increase the interference in the system, which will affect the service performance of the base station.

Impedance matching reflects the power transmission relationship between the input circuit and the output circuit. Maximum power transfer is achieved when the circuit is impedance matched. On the contrary, when the circuit impedance mismatches, not only cannot get the maximum power transmission, but also may cause damage to the circuit.

An example of 2×2 microstrip array antenna is shown in Figure 2. In general, such array antenna consists of four parameters. They are the length (x_l) and width (x_w) of a patch, the feeding distance (x_f) between feeding point and patch center, and the distance (x_d) between array elements. In Figure 2, parameters x_l, x_w, x_f, and x_d are respectively 25 mm, 35 mm, 8.5 mm, and 100 mm.

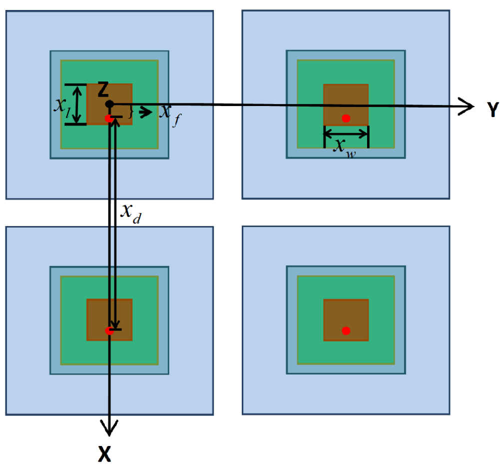

FIGURE 2. An example of 2×2 microstrip antenna network structure.

In this paper, input return loss S_{11} is taken as the objective function in array antenna design. Working frequency is set as 2.45 GHz, and impedance has to match 50 Ω for practical applications. For example, impedance at 49 Ω may not have significant difference with impedance at 51 Ω, though, they have equal difference from 50 Ω. In such case, it is hard to measure solution quality. Thus, only S_{11} is chosen as objective; both VSWR and impedance are taken as constraint conditions in network design. Based on empirical experience, x_d is set as half wavelength to simplify the model. x_l, x_w, and x_f are taken as decision variables. Thus, the design model is expressed as in (1).

$$\begin{aligned} \min \quad & S_{11}\left(x_l, x_w, x_f\right) \\ s.t. \quad & \text{Frequency}\left(x_l, x_w, x_f\right) = 2.45\text{GHz} \\ & \left|VSWR\left(x_l, x_w, x_f\right) - 1\right| \le 0.1 \\ & \left|\frac{z\left(x_l, x_w, x_f\right)}{z_0} - 1\right| \le 0.1 \\ & x_l^{\min}\text{mm} \le x_l \le x_l^{\max}\text{mm} \\ & x_w^{\min}\text{mm} \le x_w \le x_w^{\max}\text{mm} \\ & x_f^{\min}\text{mm} \le x_f \le x_f^{\max}\text{mm}, \end{aligned} \tag{1}$$

where z is impedance and $z_0 = 50$ Ω is the characteristic impedance level. Theoretically, ideal value of VSWR is equal to 1, and ideal impedance z is equal to z_0. However, such values cannot be met in practical applications. Thus, a relaxation of 0.1 is allowed as in (1). The relaxation could be set to other values based on the requirements of applications.

Input return loss S_{11} stands for the signal power loss from transmitting end to receiving end. Thus, minimizing S_{11} is equivalent to maximizing the efficiency of antenna system. In general, the minimal frequency point of S_{11} is the best feed point; such point is also the best frequency point of antenna gain. Moreover, our design is not restrained to a specific scenario, be it wide band or narrow band application. For a specific scenario, polarization, antenna gain and bandwidth constraints can be added to our design model. The model can also be solved by the memetic method. Design model (1) aims to minimize input return loss under the constraints of resonant frequency and impedance. In (1), s.t. is "subject to", i.e., S_{11} is subject to some constraints. The ranges of decision variables x_l, x_w, and x_f are determined by empirical experience.

Based on antenna propagation theory, ideal values of x_l, x_w, and x_f could be computed. This setting is a good start for solving design model (1). The formula for computing theoretical values is:

$$x_w = \frac{c}{2f_0}\left(\frac{\varepsilon_r+1}{2}\right)^{-\frac{1}{2}}, \tag{2}$$

$$x_l = \frac{c}{2f_0\sqrt{\varepsilon_e}} - \frac{0.824h\,(\varepsilon_e+0.3)\left(x_w/h+0.264\right)}{(\varepsilon_e-0.258)\left(x_w/h+0.8\right)}, \tag{3}$$

$$x_f = \frac{x_l}{2\sqrt{\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{x_l}\right)^{-1/2}}}, \tag{4}$$

$$x_d = \frac{\lambda}{1+|\sin\theta_0|}, \tag{5}$$

where $c = 3 \times 10^8$ m/s, $f_0 = 2.45$GHz, ε_r and h are given in Figure 1. θ_0 is the maximum sweeping direction of beam. Details of these (2), (3), (4) and (5) can be found in [7]–[9].

An optimization method is required to resolve design model (1). Given first order and/or second order differential, deterministic methods can be used [21]–[26]. In case differentials were not available, stochastic methods can be used [27]–[30].

IV. THE MEMETIC METHOD

An optimization algorithm is required to resolve the problem model. Although many such algorithms have been reported and analyzed, it is still useful to design a novel method combining the advantages of stochastic algorithms and deterministic algorithms. On the one hand, genetic algorithm (GA) is a famous stochastic algorithm which simulates natural evolution of species [31]. It has good global search ability, though it costs a great much number of iterations to converge. On the other hand, quasi-Newton (QN) method is a famous deterministic algorithm which is a variant of Newton optimization method [32]. It has fast convergence rate, though, it is easy to trap in local optima for complex multimodal problems. Thus, it is meaningful to combine the strengths of the two methods. In this paper, the idea is QN method searches in trust regions; while such regions are provided by GA. The memetic method is named as MGAQN and is described in the following.

A. PROCEDURES OF THE MEMETIC METHOD

The work flow of the memetic method is shown in Figure 3. In the beginning, initialization of the method is done. Then, crossover operator and mutation operator are executed for GA to refine trust regions. It suggests a potential trust region for the search of QN method. The QN method starts in trust region and returns the found solution to GA. The cycle is repeated until termination criterion is reached.

In each iteration, the fitness of a solution is evaluated based on problem model. For minimization problem, a better feasible solution must have smaller function value compared with another solution. Based on this rule, GA is able to refine good solutions in each cycle. QN method also uses this rule to find good solution.

B. THE USED GENETIC ALGORITHM

The GA method makes use of the following formula to produce a possible solution $\mathbf{x}_i$:

$$\mathbf{x}_i = \mathbf{x}^{\min} + \mathbf{r}_i \left(\mathbf{x}^{\max} - \mathbf{x}^{\min}\right), \tag{6}$$

where $\mathbf{x}^{\min}$ and $\mathbf{x}^{\max}$ are the boundaries of search space, and $\mathbf{r}_i$ is uniformly random numbers between 0 and 1. In crossover operation, the GA method makes use of the following formula to perform crossover. Denote Cr as crossover rate. Denote $\mathbf{x}_s$ and $\mathbf{x}_t$ as two parent solutions.

$$x_{ij} = \begin{cases} x_{sj}, & \textit{if } Cr < r_j \\ x_{tj}, & \textit{otherwise}, \end{cases} \tag{7}$$

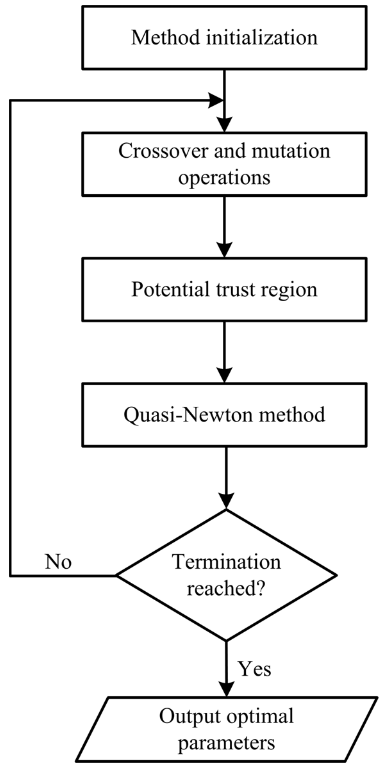

FIGURE 3. Flow chart of the memetic method.

where r_j is a random number between 0 and 1. In the mutation operation, the GA method makes use the following formula to perform mutation. Denote p_m as mutation rate. Denote $\mathbf{x}_m$ as a parent solution.

$$x_{ij} = \begin{cases} x_{ij} + r_{j2}\left(x_{ij} - x_{mj}\right), & \textit{if } r_{j1} < p_m \\ x_{ij}, & \textit{otherwise}, \end{cases} \tag{8}$$

where r_{j1} and r_{j2} are a random number between 0 and 1.

C. THE USED QUASI-NEWTON METHOD

Generally, QN method requires twice differentials of problem model. However, twice differentials of array antenna are not available as it is a simulation-based model. Hence, a derivative free QN method is used [32]. This method uses Broyden updating equation and direct line search.

$$\mathbf{x}_i^{new} = \mathbf{x}_i + \alpha_i \mathbf{d}_i, \tag{9}$$

where α_i is step size and $\mathbf{d}_i$ is Broyden-type direction. Direction $\mathbf{d}_i = -\mathbf{H}_i g_i$ has to satisfy $\mathbf{x}_i + \mathbf{d}_i \in \Omega$. Hessian matrix $\mathbf{H}_i$ and gradient vector g_i are computed by finite difference method.

Note that finite difference method might not be able to approximate function derivatives. On the other hand, considering the GA method could gradually converge to global optima, the trust regions that it suggested become smaller and smaller. This means step size would become smaller with the iteration going on. Hence, finite difference method is more accurate in the later evolution stage than in the former evolution stage.

D. UPDATING TRUST REGIONS

Trust region in this paper differs from trust region optimization method as in [33], [34]. As in problem model, there are a few parameters to be optimized. It is not a large scale optimization problem. Trust region is encoded to a chromosome in GA. For each parameter, its boundaries are encoded as two genes. Thus, a trust region of D parameters causes $2D$ additional genes in a chromosome. In this way, region size could be adapted with the evolution process of parameters.

Initially, boundaries of trust region are set to boundaries of search space. These genes also evolve through crossover and mutation operations as the problem parameters do. As shown in Figure 3, QN is activated in each cycle of the memetic method. When activating the QN method, the trust region of the fittest solution is used. When the best solution has not been improved for a number of iterations, the MGAQN method would be terminated.

V. NUMERICAL EXPERIMENT

This section gives the experimental settings and results. The array antenna design is resolved by different methods. Comparisons among these methods are also given.

A. EXPERIMENTAL SETTING

Numerical experiment is based on software simulation. It is conducted on a computer server with 2 CPU and 32 Gb memory. To study model (1) and discuss the effectiveness of the memetic method, it is reasonable to compare with other methods. This paper takes GA, pattern search (PS) [35], QN, sequential nonlinear programming (SNLP) [36] as comparison methods. These methods and the proposed MGAQN method are used to do experiment.

For the five methods, two termination criteria are used. One termination criterion is the best solution could not be improved for 10 iterations. The other termination criterion is a maximum number of 100 iterations. A method is terminated not matter which criterion is reached. In general, the MGAQN method is a memetic of the GA and the QN. Hence, it costs more computational operations than the GA and the QN. The computational complexity of the MGAQN method is also greater than the complexity of the GA and the QN.

As in array antenna, mutual coupling effect exists among patch elements. Parameter x_d affects the strength of mutual coupling. This paper considers uniformly array antenna. Thus, x_d is set as half wavelength. Such setting could avoid grating lobes and attain good directivity. In the simulations, x_l, x_w, and x_f are taken as variables to optimize. The ranges and theoretical values x_l, x_w, and x_f are given in Table 1.

B. ANALYSIS OF 2×2 MICROSTRIP ARRAY MODEL

For the 2×2 array antenna, the optimization is divided to three cases. Case 1 takes x_l as variable while x_w and x_f are set as default values as in Table 1. Case 2 takes x_l and x_w as variables while x_f is set as default. Case 3 takes x_l, x_w, and x_f as variables. Here default values refer to the theoretical values computed by (2)-(5).

TABLE 1. Ranges and theoretical values of decision variables.

Decision variable	Minimum (mm)	Maximum (mm)	Theoretical (mm)
x_l	23	30	28.130
x_w	33	37	34.097
x_f	6.5	10.5	8.500

The optimization results of case 1, case 2 and case 3 are shown in Table 2, Table 3 and Table 4, respectively. These tables give the optimal solutions found by the five methods. In these tables, *NI* stands for normalized impedance.

TABLE 2. Results for 2×2 array model found by five methods for optimizing x_l.

Method	S_{11}	*VSWR*	*NI*
GA	-27.032	1.093	1.066
PS	-25.068	1.118	1.044
QN	-27.032	1.093	1.066
SNLP	-33.190	1.045	0.982
MGAQN	-38.511	1.024	0.979

TABLE 3. Results for 2×2 array model found by five methods for optimizing x_l and x_w.

Method	S_{11}	*VSWR*	*NI*
GA	-27.426	1.089	1.056
PS	-27.426	1.089	1.056
QN	-27.426	1.089	1.056
SNLP	-44.659	1.012	1.003
MGAQN	-47.298	1.009	1.002

TABLE 4. Results for 2×2 Array Model Found by Five Methods for Optimizing x_l, x_w, and$_f$ x_f.

Method	S_{11}	*VSWR*	*NI*
GA	-28.602	1.077	1.056
PS	-27.426	1.089	1.056
QN	-27.426	1.089	1.056
SNLP	-44.659	1.012	1.003
MGAQN	-47.298	1.009	1.002

As shown in Table 2, the minimum value obtained by MGAQN method is the minimum among the five methods. At this time, the length of microstrip patch is 28.130mm, and the minimum value of S_{11} is -38.51 dB. At the same time, we found that the optimized results of GA, QN and PS were the same, the optimized length was 28mm, and the minimum value of S_{11} was -25.07 dB. This is because of the limitations of the methods. The GA, QN and PS methods prematurely converge and have fewer optimization points; hence they obtain the same results. From Table 2, except PS method, the other methods satisfy the VSWR constraint. Let further analyze normalized impedance matching. For *NI*, all methods satisfy this constraint.

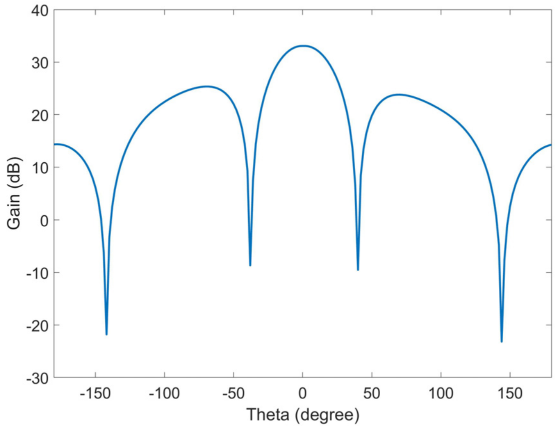

FIGURE 4. Case 1: Antenna array pattern obtained by MGAQN.

Antenna array pattern of case 1 is shown in Figure 4. It can be seen from Figure 4 that the total gain can be above 30 dB. Moreover, band width of main lobe also reaches the general requirements in applications. Such amplitude shows that antenna array is able to work well in applications. After optimization of case 1, we found that MGAQN is the best method to optimize the 2×2 microstrip patch array.

Next, let us use these five methods to resolve case 2. The optimization process is similar to case 1. Table 3 shows the results found by the five methods. It can be seen from the table that MGAQN is still the best one for case 2. The x_l and x_w is 28.13 mm and 34.10 mm. As can be seen from Table 3, the VSWR value at this time is 1.009, which is also the smallest value compared with other methods. And the value is close to 1, indicating that the impedance matches well at this time. It can be seen from Table 3 that the normalized impedance value is 1.002, which is close to 1, further indicating that the impedance matches 50 Ω very well at this time.

Next, let us use these five methods to resolve case 3. Table 4 shows the results found by the five methods. It can be seen from the table that MGAQN is still the best for case 3. At this time, the S_{11} value is −47.30 dB. Figure 5 shows the S_{11} curves of the five methods. All methods can satisfy 2.45 GHz frequency constraint. The curve of VSWR and *NI* under MGAQN was analyzed. It can be seen from Table 4 that the value of VSWR and NI is 1.009 and 1.002, respectively. We find that these two values are the same as case 2. Figure 6 shows the VSWR values by using the MGAQN method. The method reaches the best VSWR value when it satisfies 2.45 GHz constraint. Figure 7 shows the *NI* of the MGAQN method. It shows that the MGAQN method matches 50 Ω very well.

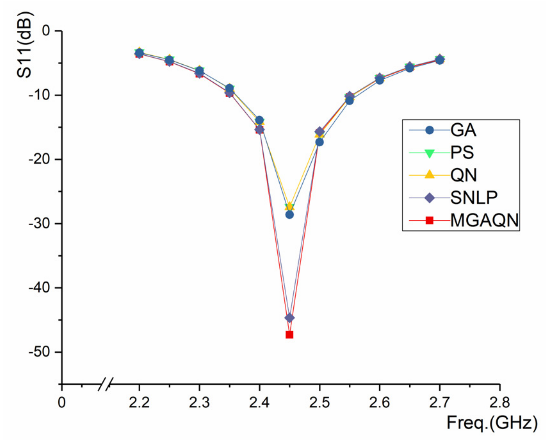

FIGURE 5. Case 3: S_{11} curves obtained by the five optimization methods.

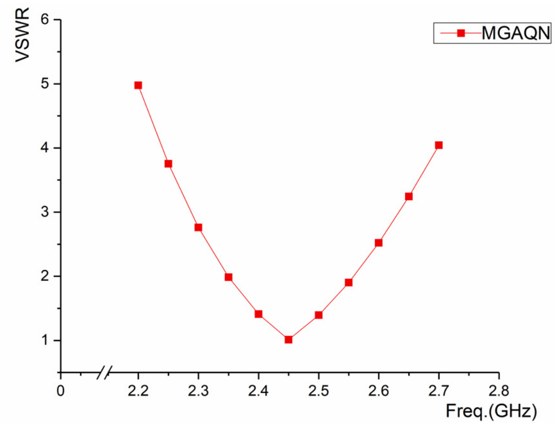

FIGURE 6. Case 3: VSWR curve for the MGAQN method.

TABLE 5. Results for 8×8 Array Model Found by Five Methods for Optimizing x_l, x_w, and x_f.

Method	S_{11}	*VSWR*	*NI*
GA	-23.683	1.140	1.129
PS	-23.683	1.140	1.129
QN	-23.683	1.140	1.129
SNLP	-41.394	1.017	1.040
MGAQN	-59.484	1.002	1.031

After summarizing these three cases, it can be concluded that the MGAQN method is more applicable in solving 2×2 microstrip array antenna than the others.

C. ANALYSIS OF 8×8 MICROSTRIP ARRAY MODEL

After optimizing the 2×2 microstrip patch array, the 8×8 microstrip array model is optimized. The initial model of 8×8 was drawn on the basis of 2×2. Its array spacing and optimization interval are the same. In this case, x_l, x_w, and x_f are taken as decision variables.

The results are given in Table 5. In the process of resolving 8×8 array model, it is found that the S_{11} curve obtained after

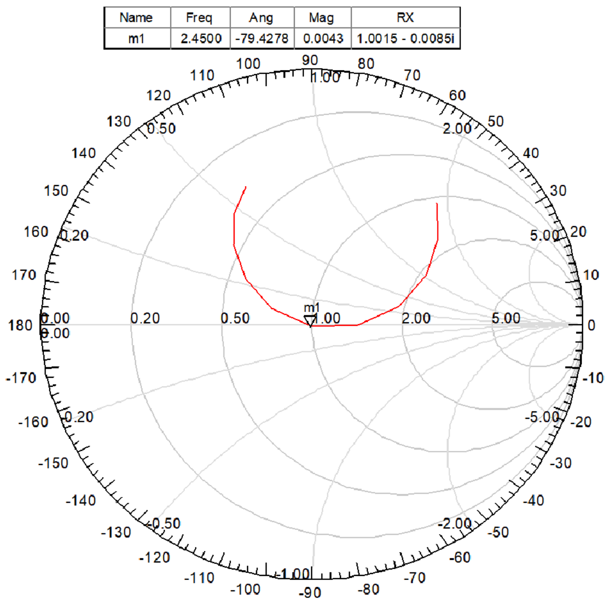

FIGURE 7. Case 3: Normalized impedance matching in the MGAQN method.

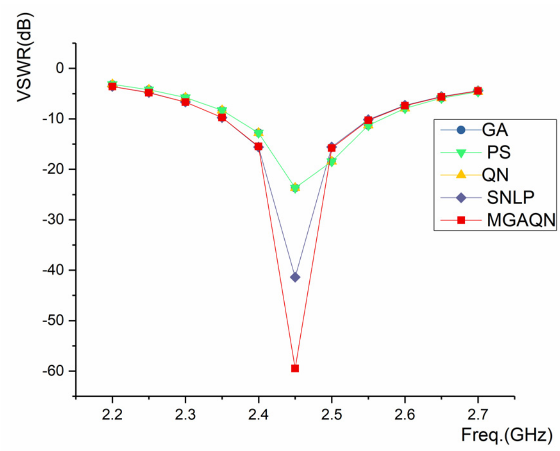

FIGURE 8. S_{11} curves obtained by the five optimization methods.

optimization is analyzed. When the MGAQN method is used for optimization, the value of S_{11} is the smallest among the five methods. It is −59.48 dB. At the same time, the VSWR value is 1.002 and the NI value is 1.031.

Figure 8 shows the S_{11} curves of the five methods. It can be seen that all methods satisfy the 2.45 GHz constraint. Figure 9 shows the VSWR values of the MGAQN method. It reaches the minimum point at 2.45 GHz frequency. Figure 10 shows the NI matching of the MGAQN method. It can be seen that the MGAQN method matches 50 Ω very well.

After analyzing the 8×8 array model, it can be concluded that the GA, PS and QN methods are not able to satisfy VSWR and impedance matching constraints. The MGAQN method is the best one among these methods.

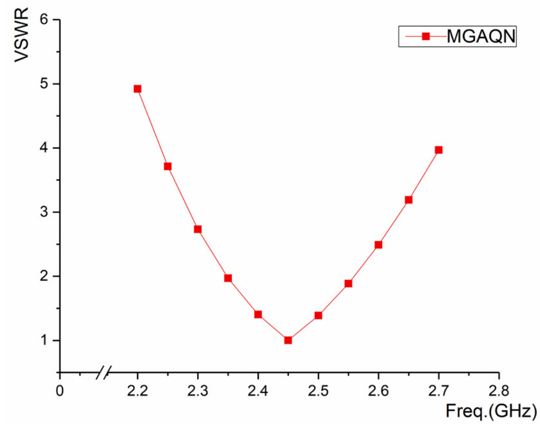

FIGURE 9. VSWR curve for the MGAQN method.

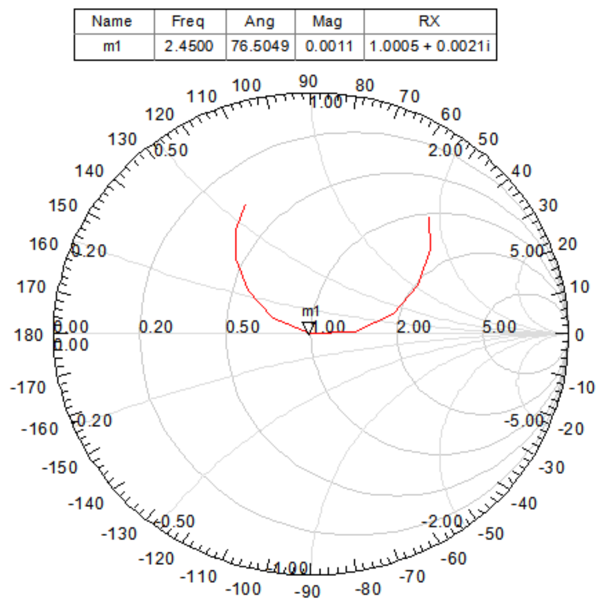

FIGURE 10. Normalized impedance matching in the MGAQN method.

TABLE 6. Results for 16×16 array model found by five methods for optimizing x_l, x_w, and x_f.

Method	S_{11}	*VSWR*	*NI*
GA	-27.426	1.089	1.056
PS	-27.426	1.089	1.056
QN	-27.426	1.089	1.056
SNLP	-35.796	1.033	1.026
MGAQN	-44.936	1.011	0.9887

D. ANALYSIS OF 16×16 MICROSTRIP ARRAY MODEL

After optimizing the 8×8 microstrip patch array, the 16×16 array model is optimized. The whole process is similar to the process of 2×2 and 8×8 array models. In this case, x_l, x_w, and x_f are taken as decision variables.

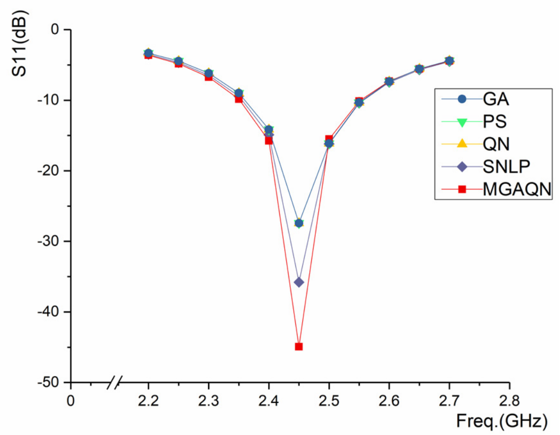

FIGURE 11. S_{11} **curves obtained by the five optimization methods.**

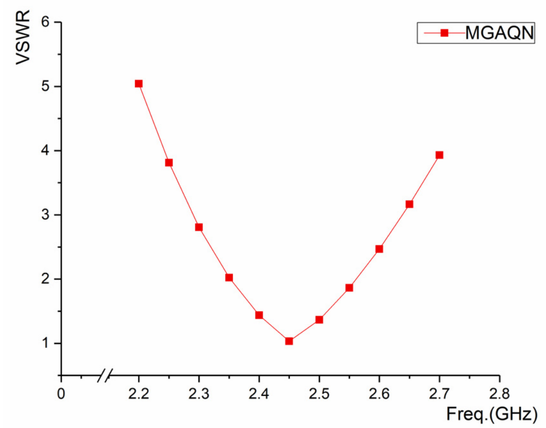

FIGURE 12. **VSWR curve for the MGAQN method.**

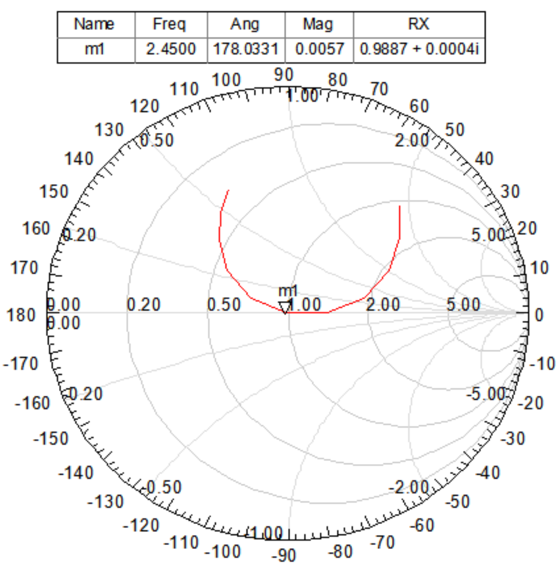

FIGURE 13. **Normalized impedance matching in the MGAQN method.**

The results are given in Table 6. It can be seen from the table that the minimum value of S_{11} obtained by these five optimization methods is the MGAQN method. It is −44.94 dB. The VSWR value was 1.011, and the NI value is 0.989.

Figure 11 shows the S_{11} curves of the five methods. It can be seen that all methods satisfy the 2.45 GHz constraint. The MGAQN method is the best, and the SNLP method is the second best. The other three methods attain the similar results. Figure 12 shows the VSWR values of the MGAQN method. It reaches the minimum point at 2.45 GHz frequency. Figure 13 shows the NI matching of the MGAQN method. It can be seen that the MGAQN method matches 50 Ω very well.

After analyzing the 16×16 array model, it can be concluded that the five methods are able to resolve the design model. The MGAQN method is better than the other methods.

VI. CONCLUSION

Microstrip antenna has many disadvantages such as narrow bandwidth, low gain, and bad directionality. To overcome these shortcomings, array antenna is a good solution which means array elements are arranged regularly. This can improve antenna gain and directionality of antenna. In this paper, patch antenna is taken to build an array antenna. Planar structure of patch antenna is used and each patch is independently fed. This causes great robustness of array antenna.

In this paper, the length, width and feeding distance of array antenna is taken as parameters. Application requirements could be satisfied by constraining working frequency, voltage standing wave ratio and impedance matching. Input return loss is set as objective to be minimized. Thus, a design model is constructed for array antenna. The array antenna network is optimized to obtain eligible performance. To solve the problem, a memetic method is proposed by combining genetic algorithm and quasi-Newton method. Moreover, four other methods are also taken to solve the design model. In numerical experiment, different array antenna sizes are tested. It is found that the design model can be resolved by the five optimization methods. For 8×8 array antenna, genetic algorithm, pattern search and quasi-Newton method could not found feasible solution to the problem. While the SNLP and the proposed MGAQN methods are able to find potential solutions. In all cases, the MGAQN method attains the best solution compared with other methods. Thus, the design model is meaningful and useful for practical applications. The proposed method is better suitable to resolve the model.

This study provides a simple method for array antenna research. In the future, we will continue to demonstrate this research and expand the array size to large scale to provide high QoS in 5G wireless communications and IoT. Optimization methods like particle swarm optimization [37], [38] can also be considered to solve design problems.

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XIN ZHANG received the B.Sc. degree from Ludong University, in 2006, the M.Sc. degree from the Shandong University of Science and Technology, in 2009, and the Ph.D. degree from the City University of Hong Kong, in 2013. Since 2015, he has been a Lecturer with Tianjin Normal University. He has published more than 50 technical papers, including over 30 papers in international journals. His main research interests include resource allocation, evolutionary computation, and antenna design.

MEIJIAO LIN is currently pursuing the degree in communication engineering from Tianjin Normal University, where she is also with the Tianjin Key Laboratory of Wireless Mobile Communications and Power Transmission. She attended many competitions in science and technology and won good results. Her main research interests include radio energy transmission, antenna design, and optimization.

XIU ZHANG received the B.Eng. and M.Eng. degrees in biomedical engineering from the Hebei University of Technology, Tianjin, China, in 2006 and 2009, respectively, and the Ph.D. degree in electrical engineering from The Hong Kong Polytechnic University, in 2012, where she completed her Postdoctoral research work, in 2015. She is currently an Associate Professor with Tianjin Normal University. Her research interests include numerical methods of electromagnetic field computation, novel wireless energy transfer systems, and wireless network optimization.

YANG LI received the B.E. and M.E. degrees from the College of Information Technology and Science, Nankai University, Tianjin, in 2008 and 2012, respectively, and the Ph.D. degree from the Department of Engineering, Tohoku University, Sendai, in 2017. He is currently with the College of Electronic and Communication Engineering, Tianjin Normal University. His research interests include antenna design, electromagnetic wave propagation, and sensor networks.