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Tuning rectangular microstrip antenna through scan and zoom algorithm

Qinglian Zhang^{1,2}, Xin Zhang^{1,2*}  and Yupeng Li^{1,2}

Abstract

Microstrip antennas have been widely studied and can be applied to a large number of wide frequency domain in wireless communication. Microstrip antennas are featured with light weight, small volume, and low cost advantages. Planar or spatial structures could substantially affect the frequency reliability and sidelobe level of microstrip antennas. Designing high performance microstrip antennas requires the tuning of the length and width of microstrip patch, the equivalent permittivity, the feed position of the coaxial line, and so on. Although electromagnetic theory could provide a solution for antenna design, such solution is probably not optimal solution due to complex environment and the affection of multiple factors. This paper attempts to tuning the design of microstrip antennas by using scan and zoom algorithm. It does not require derivative information of antenna model. This algorithm consists of search space scan and search domain zoom stages. The effectiveness of the scan and zoom algorithm is firstly tested on mathematical functions. The algorithm is then verified on rectangular microstrip antenna design. Compared with theoretical solution, the novel algorithm attains better design solution. The algorithm can also be easily extended to tackle other antenna design problems.

Keywords: Microstrip antenna, Scan and zoom, Antenna design, Numerical optimization

1 Introduction

Radar sensor networks usually consist of a transmitting node and several receiving nodes. It is very useful in the context of passive localization and tracking. As a wireless network system, antenna arrays and radar elements are important to increase the diversity gain and reduce the probability of miss detection and false alarm [1–3]. How to design the antenna shape and deploy array elements is a science and art. Different designing methods and deploying manners are proposed to accurately detect targets [4–6].

The concept of microstrip antenna is first proposed in 1950s. With the development of a good model and application of copper and gold deposited dielectric substrate lithography technology, Munson and Howell made the earliest microstrip antenna in early 1970s. The advantages of microstrip antenna are light weight, small volume, low cost, convenient to connect with integrated circuit

and carrier, and so on. It has been deeply researched and applied to a large number of 100MHz–100GHz wide frequency domain on radar and radio equipments. In the field of microwave antenna, microstrip antenna has formed its own independent research direction.

To fulfill the need of wireless communication in radar sensor networks, ad hoc networks, or other wireless network systems [7, 8], it is necessary to design high gain, wideband, and reliable microstrip antennas. Generally, the design problem is resolved from two directions. One direction is to construct new antennas based on electromagnetic theory [9, 10]. The other is to simulate antenna model on computer and use optimization algorithms to design high performance antennas. Optimization algorithms are divided into deterministic algorithms and stochastic algorithms [11]. Deterministic algorithms such as gradient descent and Newton method converge very fast, though they require derivatives of objective functions [12–14]. Yu et al. studied a decomposition method for bound constrained optimization problems [15]. Stochastic algorithms such as evolutionary algorithms, particle swarm optimization [16, 17], and artificial bee colony converge slower than deterministic ones [18–20] though they

*Correspondence: ecemark@mail.tjnu.edu.cn

¹Tianjin Key Laboratory of Wireless Mobile Communications and Power Transmission, Tianjin Normal University, Tianjin, China

²College of Electronic and Communication Engineering, Tianjin Normal University, Tianjin, China

take objective functions as black-box, which makes these algorithms applicable to nearly all kinds of antenna design problems. Parallel execution of optimization algorithms could greatly save computational time [21, 22]. Hence, stochastic algorithms are becoming more and more popular in antenna designings.

Traditional deterministic methods or manual adjustment methods could not straightforwardly solve such antenna design problems. Thus, this study first constructs an optimization model for microstrip antenna. Second, we use scan and zoom algorithm to perform optimization. It is a heuristic algorithm and does not require derivatives of objective functions. Hence, it is applicable to simulation-based design problems. Scan and zoom algorithm consists of two main stages: (1) search space scan and (2) search domain zoom. Search space scan stage explores the whole search space and aims to find the domain of global optimum. Search domain zoom stage determines which domain worth more scanning and aims to refine current best solution. The advantages of scan and zoom algorithm are simple to implement and easy to use and does not introduce random factors. The proposed design framework is verified on both mathematical functions and rectangular microstrip antenna design problems.

In Section 2, the design of microstrip antenna and related works are presented. Section 3 gives the scan and zoom algorithm and the proposed design framework. Section 4 presents numerical results and discussions. The paper is concluded in Section 5.

2 Microstrip antenna design

Since 1970s, microstrip antenna has been widely studied; many design methods have been created and proposed. As shown in Fig. 1, a microstrip antenna is typically made up of a radiation patch attached to a dielectric substrate with a metal floor. Patch conductors are usually copper, aluminum, gold, etc. The shape of a patch can be arbitrary, but ordinary shape is the first choice for analysis simplification and performance evaluation.

Consider rectangular microstrip antenna as in Fig. 1, suppose the origin locates in the center of rectangular patch and establish coordinate system. Denote that l and

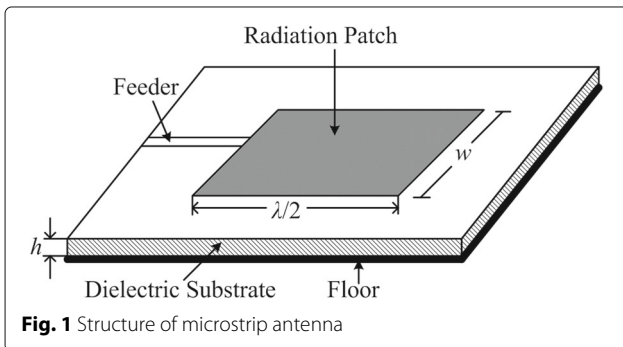


Fig. 1 Structure of microstrip antenna

w are the length and width of radiation patch. Denote that h is the thickness of substrate. Clearly, radiation patch, substrate, and ground pad can be equivalent to a low impedance microstrip transmission line with length l . It is an open circuit due to breaking off on both sides of transmission line. Based on equivalence principle, the design procedure is to determine l and w given ϵ_r, f_0 , and h , where f_0 represents the operating frequency of antenna and ϵ_r is the relative dielectric constant of the medium.

The width w of the rectangular microstrip patch can be calculated by the formula:

$$w = \frac{c}{2f_0} \sqrt{\frac{2}{1 + \epsilon_r}}, \quad (1)$$

where c represents the free-space velocity of light.

According to (1), given $\epsilon_r = 2.25$, $c = 3.0 \times 10^8$ m/s, $f_0 = 3$ GHz, w is approximately equal to 39.2 mm. Denote $w^* = 39.2$ mm. In general, when the width is chosen smaller than w^* , the radiation efficiency of the patch becomes lower; on the other hand, when the width is chosen greater than w^* , the radiation efficiency becomes higher, though it causes high changes of the distortion of the field.

The length l of the rectangular microstrip patch can be calculated by the formula:

$$l = \frac{c}{2f_0 \sqrt{\epsilon_{\text{eff}}}} - 2\Delta l, \quad (2)$$

where ϵ_{eff} represents equivalent permittivity and Δl is the length of equivalent radiation gap. The equivalent permittivity ϵ_{eff} can be calculated in accordance with the formula:

$$\epsilon_{\text{eff}} = \frac{\epsilon_r}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12h}{w}\right)^{-\frac{1}{2}}. \quad (3)$$

In (3), given $\epsilon_r = 2.25$, $w = w^* = 39.2$ mm, and $h = 5$ mm, ϵ_{eff} is about equal to 2.018. For the equivalent radiation slot length Δl , it can be calculated according to the formula:

$$\Delta l = 0.412h \frac{(\epsilon_{\text{eff}} + 0.3)(w/h + 0.264)}{(\epsilon_{\text{eff}} - 0.258)(w/h + 0.8)}. \quad (4)$$

In (4), given $\epsilon_{\text{eff}} = 2.018$, $w = w^* = 39.2$ mm, and $h = 5$ mm, Δl is about equal to 2.55 mm. Hence, in (2), given the above $c, f_0, \epsilon_{\text{eff}}$, and Δl , l approximates to 30 mm.

Based on traditional theoretical analysis, $w^* = 39.2$ and $l^* = 30$ are optimal solution for such a rectangular microstrip antenna design. Next, the design is modeled as a constrained optimization problem as follows:

$$\begin{aligned} & \min_{w, l, h} S(w, l, h) \\ & \text{s.t. } f_R = 3\text{GHz} \\ & \quad 29.2 \text{ mm} \leq w \leq 49.2 \text{ mm} , \\ & \quad 20 \text{ mm} \leq l \leq 40 \text{ mm} \\ & \quad 1 \text{ mm} \leq h \leq 11 \text{ mm} \end{aligned} \quad (5)$$

where w , l , and h are parameters to be tuned; f_R is the resonant frequency of the antenna; and $S(w, l, h)$ is the scattering parameter of the antenna. By minimizing S and assuring $f_R = f_0 = 3$ GHz, the design of rectangular microstrip antenna can be optimized.

Sobhani et al. proposed a tracking algorithm based on low-complexity particle filtering specifically tailored to radar sensor networks with one transmitter and several receivers [23]. Through studying the coverage problem of a bistatic radar sensor network, Gong et al. reported valuable insights into the placement of bistatic radars for barrier coverage [24]. Liang and Cheng proposed a knowledge-based persistent sensor network for estimating parameters in target radar cross section [25]. Han et al. analyzed relaying in multi-hop networks [26]. Alam et al. studied multiband microstrip patch antenna based on splitting method [27].

Chen et al. studied a low-profile and wide-beamwidth dual-polarized distributed microstrip antenna [28]. The proposed antenna operated at 2 and 2.2 GHz. Frequency bands and beamwidth were optimized by tuning positions of micro patches. Liu et al. studied a low-profile differential-fed dual-polarized microstrip antenna [29]. The proposed antenna operated at 1.71 to 1.85 GHz. It used a differentially feeding scheme to suppress even-order modes. Bandwidth enhancement was achieved by symmetrically arranging an array of shorting pins. The study in this paper differs from these researches in two aspects. First, antenna operating frequency is different. This paper focuses on 3 GHz microstrip antenna, though the method can also be expanded to other frequency. Second, the above two researches tune antenna mostly based on empirical experience, which could hardly be extended to handle other microstrip antenna types. This paper attempts to use scan and zoom algorithm to do optimization, which saves manual tuning of antenna parameters.

3 The used algorithm

The scan and zoom algorithm is given in this section as well as the proposed optimization framework.

3.1 Scan and zoom algorithm

Scan and zoom optimization algorithm (SZOA) was proposed by Venkataraman [30]. As shown in Fig. 2, the algorithm consists of two stages: (1) search space scan and (2) search domain zoom. At the scanning stage, sampling is done over whole search space. Alike to traditional non-linear programming methods [31–33], it is a deterministic operation without any random factors. The SZOA method is derivative free compared with Newton-type methods [34, 35]. Zoom stage is subdivided into narrowing search scope and enlarging the scope of search, which is based on the state of current optimal solution.

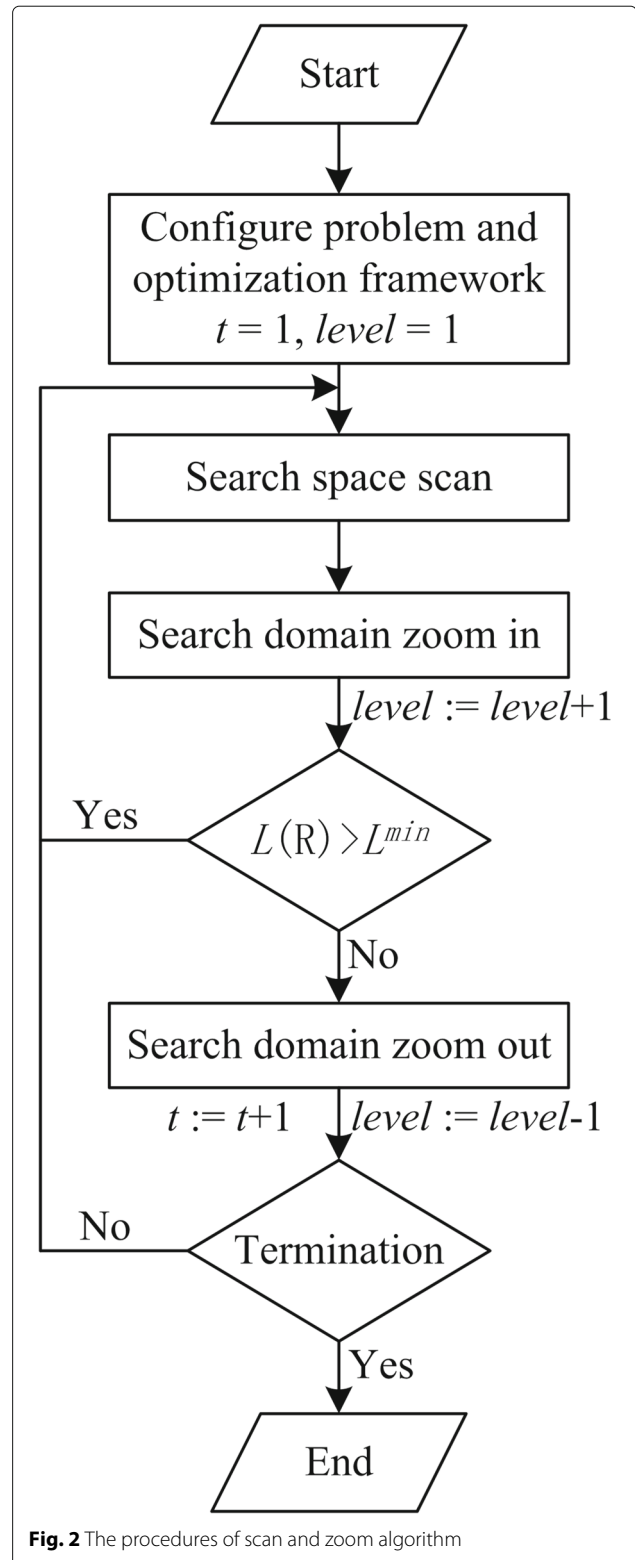


Fig. 2 The procedures of scan and zoom algorithm

The problem to be solved is considered as a black-box, which reduces the calculation operation of random number and improves the efficiency of execution compared with evolutionary algorithms.

The procedures of SZOA, as shown in Fig. 2, includes the following steps:

- Step 1: Initialize the SZOA method and design problem including the parameters and methods that need to be specified. For example, the search space Ω , the number of variables $D = 3$, the number of sampling points N_s , the iteration variable $t = 1$, the scanning layer $level = 1$, and the objective function S .
- Step 2: Scan stage. N_s sample points are taken with equal intervals in each dimension of the search space R , and at the initial time $R = \Omega$, R is divided into $(N_s - 1)D$ regions to form $N_s D$ sampling points. The sample points are evaluated based on model (5). Sort these points according to the minimization criterion, and mark each region formed by segmentation according to order.
- Step 3: Zoom in stage. The point with minimal function value is selected as the best choice at present. The region containing the point in the boundary as the reduced feasible space R , and mark the area corresponding to the search area has been searched.
- Step 4: If the length of the feasible space is greater than L_{min} , then the search subdivides one $level := level + 1$ and turn to step 2; otherwise, the area corresponding to the marked feasible space is searched and turn to step 5.
- Step 5: Zoom out stage. If the current level is still not the search area, then select all the sample points in the

region without minimum point as the current best choice in the point boundary region as the feasible space R , and mark the space corresponding to the area for search, go to step 2; otherwise, $level$ returns the previous layer of $level := level - 1$, in case all regions have been searched, go to step 6.

- Step 6: If all regions have been searched or met the pre-specified termination conditions, the method is terminated and output the best solution; otherwise, turn to step 2.

3.2 The proposed optimization framework

The design problem shown in (5) is a simulation-based model, which may be impossible using traditional optimization methods [36, 37]. Thus, an optimization framework is proposed by solving design problem based on SZOA. The framework is shown in Fig. 3.

The optimization framework is comprised by two parts. One is SZOA method and the other is microstrip antenna system. The former decides the parameter values for antenna size and shape and refines the fitness of parameter values in each iteration. The latter builds antenna system based on given parameter values, simulates the working of antenna system, and evaluates the efficiency of the resulting antenna.

As to algorithmic parameters of SZOA method, large N_s causes high explorative ability of the algorithm, whereas small N_s reduces such ability of searching whole space. Moreover, SZOA with larger $level$ has better exploitative ability than smaller value, whereas computational time also increases greatly as the increase of $level$.

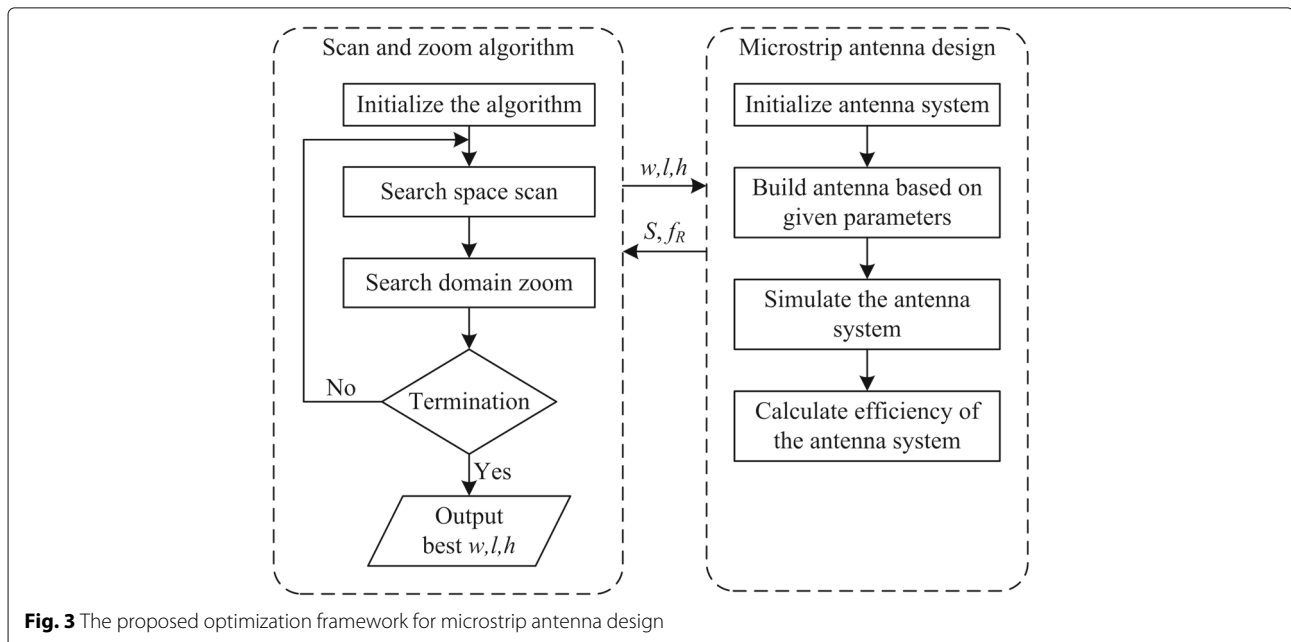


Fig. 3 The proposed optimization framework for microstrip antenna design

4 Results and discussion

In the numerical simulation, the SZOA algorithm is first tested on mathematical functions and compared with three other methods. They are pattern search (PS) [38], continuous non-revisiting genetic algorithm (cNrGA) [39], and hybrid chaotic quantum particle swarm optimization (HCQPSO) [40]. For SZOA, $N_s = \lfloor 10^{\lg(MFEN/D)/D} \rfloor$ and $l^{\min} = 10^{-6}$, where $MFEN$ represents the maximum function evaluation numbers. For PS, cNrGA, and HCQPSO, they are initialized by the default settings as in their papers. A set of six mathematical functions are taken as the first study. Functions as well as their properties are listed in Table 1. This table shows two unimodal functions and four multimodal functions used in simulation. D is set to 10 for these test functions. The SZOA algorithm is then tested on rectangular microstrip antenna design as shown in Section 4.2.

4.1 Results on mathematical functions

Table 2 shows the statistics of optimal objective function values attained by the four test algorithms. It can be seen from Table 2 that all algorithms find global optimum of f_1 . For the other functions, the SZOA algorithm attains smaller values than the PS, cNrGA, and HCQPSO algorithms. Compared PS with SZOA, it can be seen that for all functions, standard deviation (std) values of both algorithms are 0. This is because both algorithms do not contain random factors; hence, the same results are reached in each run. cNrGA and HCEPSO are two state of that art algorithms, though they are outperformed by the SZOA algorithm. For the multimodal functions, cNrGA and HCQPSO show large variance, on the other hand, SZOA not only finds smaller values, but also is very stable. Thus, it is able to conclude that the proposed optimization framework could be effective for the design of microstrip antenna design.

4.2 Results on microstrip antenna design

As in Section 2, $w^* = 39.2$ mm, $l^* = 30$ mm, and $h = 5$ mm are optimal setting based on electromagnetic theory. The antenna design is optimized by the proposed

optimization framework. The same parameter setting is used as in previous subsection.

First, let fix $w = w^*$ and $h = 5$ mm and set l as a parameter to be optimized by the proposed framework. Figure 4 shows the results compared theoretical solution and optimized solution. It can be seen from the figure that the SZOA algorithm finds better solution than the one computed based on theory. The parameter l is 30.25 mm which is slightly greater than l^* . In terms of objective function $S(w, l, h)$, theoretical solution is improved by 17.71%.

Second, set w , l , and h as three parameters to be optimized by the proposed framework. Figure 5 shows the results compared theoretical solution and optimized solution. It can be seen from the figure that the SZOA algorithm finds better solution than the one computed based on theory. The optimal parameters for w , l , and h are respectively 40.2, 30.125, and 5.375 mm. All values are greater than theoretical values. In terms of $S(w, l, h)$, theoretical solution is improved by 61.56%.

Therefore, the proposed framework is effective to solve microstrip antenna design. Moreover, theoretical solution is greatly improved by SZOA, which is verified both on one parameter and three parameters optimization.

5 Conclusions

Recently, radar sensor networks have been more and more widely used in various fields [41, 42]. To achieve good network stability and throughput of data transmission, antenna design is worthy of studying as it is a difficult and time-consuming task. Microstrip antenna design is considered in this paper. Different from existing approaches, this paper uses the SZOA algorithm to optimize the design problem. The contribution of this paper is twofolds. First, antenna design is formulated as a minimization problem (5). It is a simulation-based optimization problem; hence, stochastic algorithms should be used. Second, an optimization framework is proposed based on the SZOA algorithm. This algorithm does not use derivative information and does not involve random factors.

The usefulness of the SZOA algorithm is shown on six mathematical functions including two unimodal functions and four multimodal functions. It turns out that SZOA performs better than PS, cNrGA, and HCQPSO methods. There is no need to execute SZOA repeatedly as it returns the same result given the same setting. Moreover, the proposed framework is applied to tackle rectangular microstrip antenna design. Compared with theoretical optimal setting, the proposed framework can find better solution.

An overhead of the SZOA algorithm is that it requires sampling of each parameter, while the number of samples grows quickly with the increase of parameters. It is suggested to solve problems with less than 10 parameters.

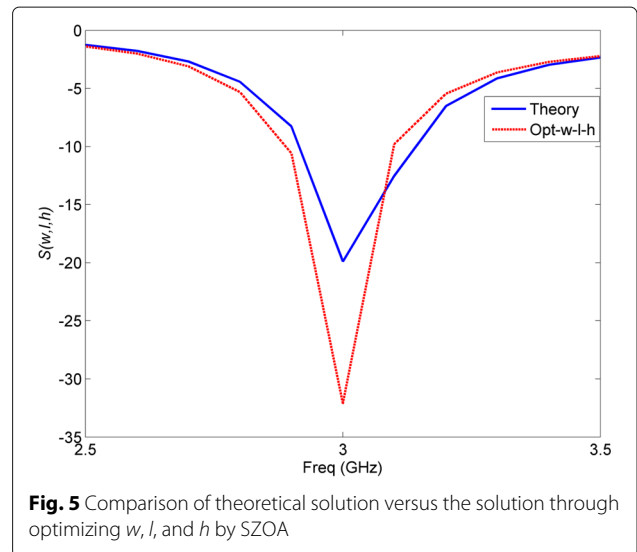
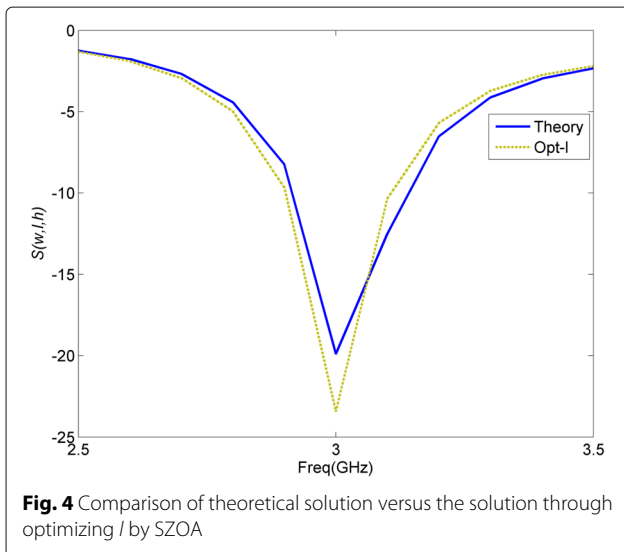
Table 1 Mathematical functions: two unimodal functions and four multimodal functions

Number	Function	Property
f_1	Spherical function	Unimodal, separable, scalable
f_2	Different power function	Unimodal, separable, scalable
f_3	Rastrigin function	Multimodal, separable, scalable
f_4	Rosenbrock function	Multimodal, nonseparable, scalable
f_5	Ackley function	Multimodal, nonseparable, scalable
f_6	Rotated Schwefel function	Multimodal, nonseparable, scalable

Table 2 Optimal function values found by PS, cNrGA, HCQPSO, and SZOA over 25 independent runs

$f(\cdot)$	Algorithm	min	med	max	std
f_1	PS	0.0000	0.0000	0.0000	0.0000
	cNrGA	0.0000	0.0000	0.0000	0.0000
	HCQPSO	0.0000	0.0000	0.0000	0.0000
	SZOA	0.0000	0.0000	0.0000	0.0000
f_2	PS	8.600E-3	8.600E-3	8.600E-3	0.0000
	cNrGA	1.369E-4	2.870E-3	2.560E-3	0.0077
	HCQPSO	7.250E-5	1.740E-4	2.850E-4	0.0001
	SZOA	3.210E-5	3.210E-5	3.210E-5	0.0000
f_3	PS	2.308E2	2.308E2	2.308E2	0.0000
	cNrGA	9.171E0	1.039E1	1.989E1	0.6293
	HCQPSO	9.660E0	1.863E1	3.404E2	7.7001
	SZOA	8.955E0	8.955E0	8.955E0	0.0000
f_4	PS	4.560E0	4.560E0	4.560E0	0.0000
	cNrGA	1.266E-1	3.280E1	7.460E1	32.3284
	HCQPSO	3.440E-2	6.260E0	1.008E1	4.7548
	SZOA	5.490E-4	5.490E-4	5.490E-4	0.0000
f_5	PS	2.059E1	2.059E1	2.059E1	0.0000
	cNrGA	2.027E1	2.035E1	2.045E1	0.0774
	HCQPSO	2.024E1	2.039E1	2.054E1	0.0790
	SZOA	2.023E1	2.023E1	2.023E1	0.0000
f_6	PS	1.840E3	1.840E3	1.840E3	0.0000
	cNrGA	5.916E2	6.667E2	1.185E3	300.8831
	HCQPSO	6.880E2	1.195E3	1.637E3	236.6575
	SZOA	5.799E2	5.799E2	5.799E2	0.0000

Minimum, median, maximum, and standard deviation are respectively abbreviated as min, med, max, and std



Abbreviations

cNrGA: Continuous non-revisiting genetic algorithm; HCQPPO: Hybrid chaotic quantum particle swarm optimization; PS: Pattern search; SZOA: Scan and zoom algorithm

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Availability of data and materials

Not applicable.

Authors' contributions

QZ implements the numerical simulation and collects the simulation results. XZ writes most of the paper. YL checks the numerical simulation and result analysis. All authors proofread the manuscript to reduce typos and grammar mistakes. All authors read and approved the final manuscript.

Authors' information

Qinglian Zhang majors in Communication Engineering in Tianjin Normal University (TJNU), Tianjin, China. She is working on antenna simulation and resonant frequency analysis.

Xin Zhang received his PhD in Electronic Engineering from City University of Hong Kong in 2013. Since 2015, he works as a lecturer at Tianjin Normal University. His main research interests are antenna design, resource allocation, evolutionary computation, and machine intelligence. He has published more than 40 technical papers on these subjects, including more than 30 papers in international journals.

Yupeng Li received the PhD degree in Communication and Information System in Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2015. He is currently working as a lecturer in Tianjin Key laboratory of Wireless Mobile Communications and Power Transmission, Tianjin Normal University (TJNU), Tianjin, China. His current research interests include antenna design, advanced modulation scheme, and coherent optical communication system.

Competing interests

The authors declare that they have no competing interests.

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