Directional Modulation Based on a Quantum Genetic Algorithm for a Multiple-Reflection Model

Yuwei Huang[1, 2], Xiubo Chen[1, 3, *], Kaiguo Yuan[1, 3], Jianyi Zhang[4] and Biao Liu[2]

Abstract: Directional modulation is one of the hot topics in data security researches. To fulfill the requirements of communication security in wireless environment with multiple paths, this study takes into account the factors of reflections and antenna radiation pattern for directional modulation. Unlike other previous works, a novel multiple-reflection model, which is more realistic and complex than simplified two-ray reflection models, is proposed based on two reflectors. Another focus is a quantum genetic algorithm applied to optimize antenna excitation in a phased directional modulation antenna array. The quantum approach has strengths in convergence speed and the globe searching ability for the complicated model with the large-size antenna array and multiple paths. From this, a phased directional modulation transmission system can be optimized as regards communication safety and improve performance based on the constraint of the pattern of the antenna array. Our work can spur applications of the quantum evolutionary algorithm in directional modulation technology, which is also studied.

Keywords: Directional modulation, quantum genetic algorithm, phased antenna array, multiple reflection.

1 Introduction

With the wide application of mobile communication and wireless networks, the illegal interception of broadcast information is a cause of increasing concern. The urgent need to protect legitimate users from being tapped has focused more attention on the physical security layer. A key technology to enhance the security of wireless communication is directional modulation (DM), which keeps the constellation mapping in the desired direction, while scrambling it at other locations.

A near-field direct antenna modulation (NFDAM) technique considers the direct radiation beam and several scattered beams reflected by the reconfigurable near-field parasitic structure to scramble the signal amplitude and phase in unsafe communication directions in the far field [Babakhani, Rutledge and Hajimiri (2008, 2009)]. Subsequently,

[1] Information Security Center, State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications, Beijing, 100876, China.

[2] Beijing Electronic Science and Technology Institute, Beijing, 100070, China.

[3] Sate Key Laboratory of Public Big Data, Guizhou University, Guiyang, 550025, China.

[4] School of Computing and Informatics, The University of Louisiana at Lafayette, Lafayette, LA 70503, USA.

[*] Corresponding Author: Xiubo Chen. Email: xb_chen@bupt.edu.cn.

Received: 12 February 2020; Accepted: 21 April 2020.

DM arrays are more easily synthesized than parasitic DM structures by combining the antenna excitation and far-field for DM system performance [Daly and Bernhard (2010)]. The phased array was adopted to synthesize digital modulation by shifting the phase [Daly and Bernhard (2009); Daly, Daly and Bernhard (2010)]. A pattern synthesis approach was applied to a DM system to ensure that constellation patterns were correct in specific communication directions, while conserving energy dispersal in other directions [Ding and Fusco (2013)]. However, there is the problem that an eavesdropper is in line with or close to the intended direction. To enhance data transmission security, researchers have studied a multi-path model in which the signal is received through both line-of-sight (LOS) and reflected paths in a simplified two-ray model [Shi and Tennant (2013); Ding and Fusco (2015)]. Also, the optimization of antenna arrays has been explored based on methods such as particle swarm and genetic algorithms [Ding and Fusco (2013); Ling, Zhu, Ser et al. (2012); Cen, Ser, Cen et al. (2010)].

With the development of quantum technology, research is focused in many areas [Xu, Xiao, Li et al. (2019); Qu, Cheng, Liu et al. (2019)]. The application of quantum mechanics introduces possible applications in secure communications, image steganography, and other fields [Qu, Wu, Wang et al. (2017); Qu, Li, Xu et al. (2019)].

The evolution algorithm has caught comprehensive attention because of its solving ability and extensivead aptability used in complex optimization questions [Qin, Huang and Suganthan (2009); Tian (2018)]. The genetic algorithm (GA) is a random search algorithm based on evolutionary theory, with the shortcomings of slow convergence and local optimal solutions [Mahdi and Bryan (2008)]. The researches of genetic algorithm are focused on new fields and technologies, such as cloud computing [Ma, Pang, Zhang et al. (2019)] and quantum technology. The quantum genetic algorithm (QGA) introduced some ideas of quantum computing, such as qubits and superposition of states, to GA, leading to rapid convergence and good global search capability [Xiong, Chen, Miao et al. (2004); Xing, Pan and Zuo (2007); Yang, Zhan and Tian (2013); Zhou and Cao (2014)].

The aforementioned research has promoted the DM technology mainly in free space or in the environment with one reflector. However, real communication tends to be more complicated, with multiple reflectors producing many types of reflection paths. This study is devoted to extending the DM system to a multiple-path model that is more complex than the two-ray model used in previous studies. We adopt a model with two reflectors, which contains multiple paths of LOS, single reflection, and double reflection. In addition, the quantum genetic algorithm is brought into the design of a DM antenna array to achieve the combined optimization goal of communication safety and the pattern of the antenna array. The scheme shows the advantages of the quantum evolutionary algorithm in phased DM technology.

The remainder of this study is organized as follows: Section 2 discusses the main principles of the QGA and the phased DM antenna array. The proposed multiple-reflection model is detailed in Section 3. The DM system design based on our model is shown in Section 4. The simulation and analysis of the model are discussed in Section 5. We summarize the study in Section 6.

2 Principle of the quantum genetic algorithm and phased DM Array

2.1 Quantum genetic algorithm

The quantum genetic algorithm based on qubits and superposition of quantum mechanics states can express chromosomes with quantum states. Based on the core concept of quantum coding and quantum gates, the algorithm shows superiority with effective development and searching ability. The quantum genetic algorithm has a wide range of applications, mainly in the fields of combination optimization, function optimization, signal processing, automatic control, and digital communication.

2.1.1 Quantum coding

The most prominent departure of a quantum genetic algorithm from a traditional genetic algorithm is that feasible solutions are encoded as qubits instead of bits. Different from classical approaches, a gene on a chromosome is expressed by qubits as an indeterminate value. A qubit can represent any superposition state, which can be expressed as follows:

$$|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle, \tag{1}$$

$$|\varphi\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}, \tag{2}$$

where $|\alpha|^2$ and $|\beta|^2$ are respectively the probabilities that the qubit will be found in a '0' or '1' state. The probability amplitude meets the condition:

$$|\alpha|^2 + |\beta|^2 = 1. \tag{3}$$

If a chromosome has three qubits whose respective pairs of probability amplitudes are as follows:

$$\begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{2\sqrt{2}}{3} & \frac{\sqrt{2}}{2} \\ \frac{1}{2} & \frac{1}{3} & \frac{\sqrt{2}}{2} \end{pmatrix}, \tag{4}$$

then the state and probability of this chromosome can be represented as follows:

$$\begin{aligned} &\sqrt{3}/3|000\rangle + \sqrt{3}/3|001\rangle + \sqrt{6}/12|010\rangle + \sqrt{6}/12|011\rangle + \\ &1/3|100\rangle + 1/3|101\rangle + \sqrt{2}/12|110\rangle + \sqrt{2}/12|111\rangle \end{aligned}. \tag{5}$$

It can be observed that in quantum computing, the chromosome has eight states, while in classical methods, a chromosome can only represent one state. So, a chromosome containing m qubits can involve 2^m states. Hence the application of the quantum genetic algorithm achieves the expansion of population diversity with a smaller population size to promote convergence.

In a quantum genetic algorithm, multiple quantum chromosomes together form a population,

$$Q(t)=\{q_1^{\,t},\ q_2^{\,t},\ \cdots\cdots q_n^{\,t}\}, \tag{6}$$

where q_i^t represents a chromosome of iteration t, and n is the population size. Then

$$q_i^{\,t} = \begin{pmatrix} \alpha_1^{\,t} \Big| \alpha_2^{\,t} \Big| \cdots & \Big| \alpha_m^{\,t} \\ \beta_1^{\,t} \Big| \beta_2^{\,t} \Big| & \Big| \beta_m^{\,t} \end{pmatrix}, \tag{7}$$

where m is the length of the chromosome, that is, the number of qubits.

2.1.2 QGA flow

Population initialization is first performed, where the probability amplitudes $|\alpha|^2$ and $|\beta|^2$ of all of the qubits of all chromosomes are distributed in all possible superimposed states with the same probability. Second, the measurement is adopted by randomly generating a number in [0, 1] and judging it. If the random number is larger than $|\alpha|^2$, then the qubit value is 1, and otherwise it is 0. In this way, a set of binary solutions is generated from the original initialized population, given by

$$P(t) = \{x_1^{\,t}, x_2^{\,t}, \cdots, x_n^{\,t}\}, \tag{8}$$

where $x_j^{\,t}$ is the measurement value of the jth chromosome in the tth generation, expressed as a binary string of length n, where n is the number of qubits on a chromosome. The solution from the above operation is brought into the fitness evaluation process, whose fitness function is designed for the solved problem. We choose the optimal individual as the target value for the evolution. Finally, we judge whether the fitness value or the number of iterations has reached its threshold. If so, then the algorithm is terminated. Otherwise, the rotation for the quantum gate and the crossover and mutation for quantum bits will be performed in the evolution in order to acquire the updated population. We repeat the above measurement and fitness evaluation, and if the optimal individual degenerates, then we retain the original optimal individual, and otherwise we replace it as the target of the next population evolution.

2.2 Phased antenna array for DM

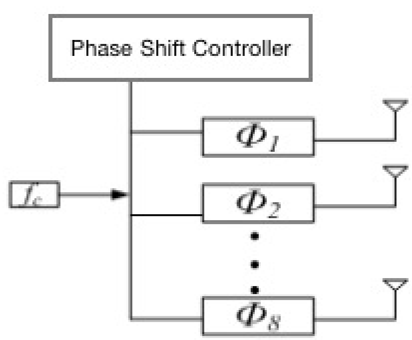

Figure 1: Phased array architecture

The transmitter structure of a phased DM array is shown in Fig. 1. Taking an eight-element linear antenna array as an example of a transmitting system, the antenna is located at an equivalent distance $\lambda/2$, where λ is the carrier wavelength of the transmitted signal, whose phase, as controlled by the phase shifter, is adjusted with the transmitted signal. In the desired direction, the legal receiver combines the signals sent by each antenna at the transmitter to synthesize the correct information. We adopt a QPSK system to modulate the DM signal, where a legal user in the desired direction can form a standard QPSK constellation pattern, and an eavesdropper only obtains the scramble constellation. The received signals can be calculated by the following equation:

$$E_i(\theta)=\sum_{k=1}^{8} e^{j[\phi_k(i)+\beta d_k \sin(\theta)]}, \tag{9}$$

where $\beta = 2\pi/\lambda$ is the propagation constant, θ is the transmission angle (0° along the y-axis), $\phi_k(i)$ is the phase shift of the *k*th antenna for the *i*th QPSK signal, and d_k is the distance from the first element to the *k*th antenna element:

$$d_k = (k-1) * \frac{\lambda}{2}. \tag{10}$$

3 Multiple-reflection model

3.1 Model with two reflectors

As shown in Fig. 2, multiple antennas are used to transmit the signal from the transmitter *T* to a desired receiver *R*. In the proposed model, a passive eavesdropper *E* who tries to intercept the signal can exist at any position. We assume the eavesdropper and desired user adopt one antenna to receive the information.

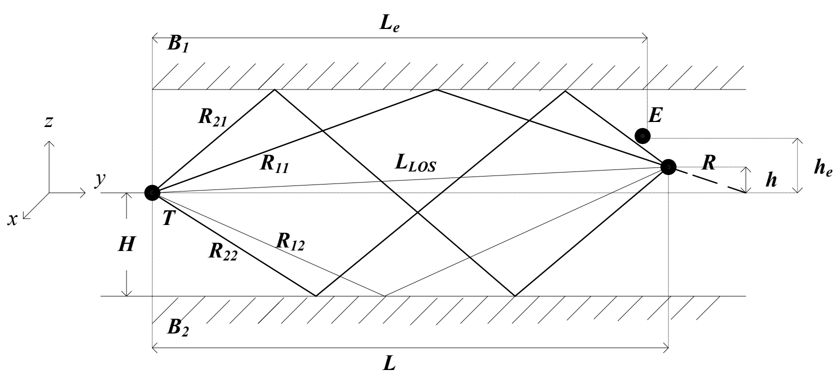

Figure 2: Multiple-path model with two reflectors

There are two reflectors proposed to generate the required reflection paths, marked by B_1 and B_2. As shown in Fig. 2, they are located at distance *H* from the transmitter antennas in opposite vertical directions. In the proposed model, the reflectors created at the boundary are assumed to be ideal without the consideration of a reflection coefficient.

The legal recipient *R* is at a horizontal distance *L* from the transmission antenna *T* at the vertical height $h \in [-H, H]$, given by

$$R_P = R_P(L,h). \tag{11}$$

The eavesdropper, who receives the information without destroying or interfering with communication between legitimate users, is marked as E, with horizontal and vertical distance L_e and h_e, respectively. The position is expressed as follows:

$$E_p = E_p(L_e, h_e)\ h_e \in [-H, H]. \tag{12}$$

3.2 Calculation for multiple paths

There are two types of paths for electromagnetic wave propagation in the proposed model: the LOS path and the reflection path. There can be multiple reflection paths, such as primary reflection and secondary reflection. With different reflection surfaces, reflections can occur on any one (B_1 or B_2 in the case of two surfaces), and generate different paths at different transmission angles and propagation distances, such as R_{11} and R_{12}. In this situation, the signal acquired by the receiver is a superposition of all paths, including the LOS path, primary reflection path, and secondary reflection path.

For information transmitted to the desired user R, the LOS path can be formulated as follows:

$$L_{Los} = \sqrt{L^2 + h^2}$$

$$\theta_{Los} = \arctan(\frac{h}{L}) \qquad \theta_{Los} \in (-90°, 90°), \tag{13}$$

where L_{Los} and θ_{Los} are the length and transmitted angle, respectively, for this path.

For propagation with one reflection, when the signal from the transmitter is incident on the surface of the reflection boundary, the reflection path can be expressed as follows:

$$L_{R11} = \sqrt{L^2 + (2H - h)^2} \tag{14}$$

$$L_{R12} = \sqrt{L^2 + (2H + h)^2}, \tag{15}$$

where L_{R11} (L_{R12}) represents the first reflection occurring on reflector B_1 (B_2). The horizontal transmitted angle deviation from the y-axis for paths R_{11} and R_{12} are given by:

$$\theta_{R11} = \arctan(\frac{2H - h}{L}) \tag{16}$$

$$\theta_{R12} = -\arctan(\frac{2H + h}{L}), \tag{17}$$

respectively. For the secondary reflection path, the electromagnetic wave reaches the receiver after reflections on surfaces B_1 and B_2. Due to the different angles of the emission, the signal may first be incident on reflective surface B_1 and then arrive at reflective surface B_2, or vice versa. Therefore, there are two secondary reflection paths, which can be expressed as follows:

$$L_{R21} = \sqrt{L^2 + (4H + h)^2} \tag{18}$$

$$L_{R22} = \sqrt{L^2 + (4H - h)^2}, \tag{19}$$

where L_{R21} (L_{R22}) represents the first reflection occurring on reflector B_1 (B_2), and the other reflection is on B_2 (B_1). The transmitted angle for the paths R_{21} and R_{22} are given, respectively, by:

$$\theta_{R21} = \arctan(\frac{4H+h}{L}) \tag{20}$$

$$\theta_{R22} = -\arctan(\frac{4H-h}{L}) . \tag{21}$$

For the eavesdropping channel, the signal path intercepted by the eavesdropper is the sum of the line-of-sight path and the various reflection paths between the sender and the eavesdropper. Assuming the eavesdropper is anywhere near the legal recipient, the calculations of the path length and transmission are similar to those for legal recipients.

With the difference of multiple reflection paths, the attenuation and phase vary with the reflections and the propagation distance. The power attenuation ratio of reflection paths and the LOS path can be expressed as follows:

$$Att_{Rmn} = \frac{L_{Los}}{L_{Rmn}} \quad m,n \in \{1,2\} , \tag{22}$$

where Rmn means reflected paths, including one or two reflection paths.

Assume that both reflection surfaces are perfect and the distance is a multiple of the wavelength λ. Then the phase can vary as follows:

$$Phase_{Rmn} = r * \pi + 2\pi * remainder(L_{Rmn}) , \tag{23}$$

where r is the number of reflections, and *remainder* is the remainder when L_{Rmn} is divided by the wavelength.

Considering the reflection paths based on (9), the sum of the paths received in the desired direction can be expressed as follows:

$$E_R^i = \sum_{m,n=1}^{2} E_i(\theta) * Att_{Rmn} * e^{jPhase_{Rmn}} . \tag{24}$$

In conclusion, the synthesized signal involving all paths in the multiple-reflection model can be summarized as follows:

$$E_{sum} = E_i + E_R^i . \tag{25}$$

For simplification, all calculations above are based on a double-reflection model. The multiple-reflection model can be applied generally for any number of reflections. The derivation is similar to that above.

4 System design based on multiple-reflection model

4.1 Fitness function for QPSK

The purpose of directional modulation of a phased antenna array is to adjust the phase shift values of each antenna by the phase controller. As a result, a user in the desired direction correctly synthesizes the signal, while an eavesdropper away from that direction can only receive the distorted signal.

The standard constellation point of the QPSK signal is shown as follows:

$$F_i = e^{\frac{j(2i-1)\pi}{4}}, \; i = \{1,2,3,4\}, \tag{26}$$

where *i* denotes the four QPSK signals.

In our design, it is desirable that the constellation received by the intended user is consistent with the standard constellation. Therefore, the fitness function should be designed with a task to make the received signal as close as possible to the standard constellation. As an optimization target, we can constrain it by:

$$\min_{\phi_1\phi_2\phi_3\phi_4\phi_5\phi_6\phi_7\phi_8} \left\{ S = \left| E_{sum} - F_i \right|^2 \right\}$$

$$Fit_1 = \left| E_{sum} - F_i \right|^2. \tag{27}$$

4.2 Optimization target for main lobe direction

In the discussed model, if the main lobe of the antenna array is in an undesired direction or far from the desired direction, then more signals carrying stronger energy from the transmitting antennas will interact with the wall to generate a reflection, which changes the original propagation path to cause larger path loss, or they will propagate in other directions, which fail to reach the receiver's position. In either case, the total energy received by the receiver will be greatly affected. Therefore, the main lobe of the pattern is taken as a consideration in the design of the fitness function, whose direction is limited to a range such that the energy goes in the desired direction as much as possible. With less energy loss and reflection, the signal arriving at the directed user can carry stronger energy.

According to the desired direction, the main lobe of the antenna array pattern can be limited to the range $\theta_{lobe} \in [-\sigma, \sigma]$, where σ is any angle chosen based on a specific problem, $\sigma \in [-90°, 90°]$. The fitness function can be formulated as follows:

$$Fit_2 = \begin{cases} 0, & \theta_{lobe} \in [-\sigma, \sigma] \\ \chi, & \theta_{lobe} \notin [-\sigma, \sigma], \end{cases} \tag{28}$$

where χ must be far greater than the relevant fitness value.

Finally, the total fitness function is an optimization target for the QPSK signal and the main lobe direction of the antenna pattern:

$$Fitness = w_1 Fit_1 + w_2 Fit_2, \tag{29}$$

where w_1 and w_2 respectively represent the weights of Fit_1 and Fit_2.

5 DM based on QGA synthesis results

Based on the above model and analysis, an optimization algorithm can be adopted to design and optimize the phased antenna array as the DM transmitter, which minimizes the designed fitness function in Section 4. Because this optimization goal involves multiple issues and variables, it may have a complex and nonlinear solution that may be difficult to achieve using classical optimization algorithms that can fall into local optimization. Therefore, this paper studies a quantum genetic algorithm to search for the solution in order to achieve global convergence. For the phased DM system, the phase shift values for each antenna play a key role as the optimization variables in the search for a solution.

We take as an example an eight-element half-wavelength spaced linear array as a transmitter to send a QPSK signal, whose antenna excitations are calculated through the QGA in the multiple-reflection model. In our simulation, H is set to 60λ and L to 200λ. The main lobe for the desired pattern is along the LOS direction with a range from $-30°$ to $30°$. An eavesdropper at the position $E_p(180\lambda,20\lambda)$ intends to passively intercept information when the receiver R *(assume* $R_P(200\lambda,10\lambda)$*)* is communicating with the transmitter.

The resulting phase configurations are presented in Tab. 1. In Fig. 3, the modulated signals at the desired receiver, sent by the eight-antenna array with the optimized phase shift values, are compared to the standard constellation. We can clearly see that the signals in the intended direction are completely coincident with the transmitted signal, proving that the complete information can be obtained by the legal receiver with secure communication. It can be observed from Fig. 3 that the constellation pattern at the position deviating from the desired direction is severely scrambled to prevent information leakage, which enhances the security of the system.

On the basis of the above designed transmitter system, not only can the desired recipient correctly decode the transmitted information, but the main lobe of the transmitting antennas is also limited to the range between $-30°$ and $30°$. The electromagnetic wave propagates in this direction to transmit more power and avoid too much power loss and path loss. The antenna array patterns for four QPSK signals are drawn in Fig. 4. The four main lobes are limited in the range from $-20°$ to $0°$, which meets the demands of the optimization goal to concentrate transmission power and reduce energy loss.

Table 1: Optimization result of phase shift values

QPSK signal	Phased antenna array							
	1	2	3	4	5	6	7	8
F_1	220°	232°	277°	238°	294°	78°	19°	83°
F_2	84°	149°	103°	76°	207°	228°	237°	332°
F_3	295°	332°	319°	48°	319°	215°	199°	355°
F_4	282°	262°	209°	48°	222°	326°	270°	285°

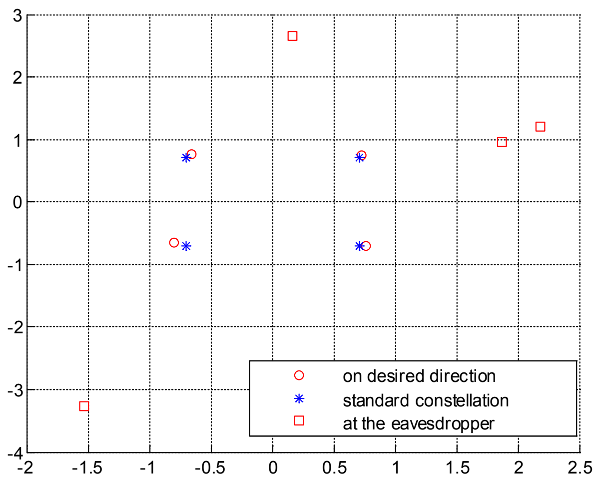

Figure 3: Constellation of receiver and eavesdropper: the red circle represents the received signal in the desired direction, the blue star means the standard constellation, and the red square is the signal intercepted by the eavesdropper

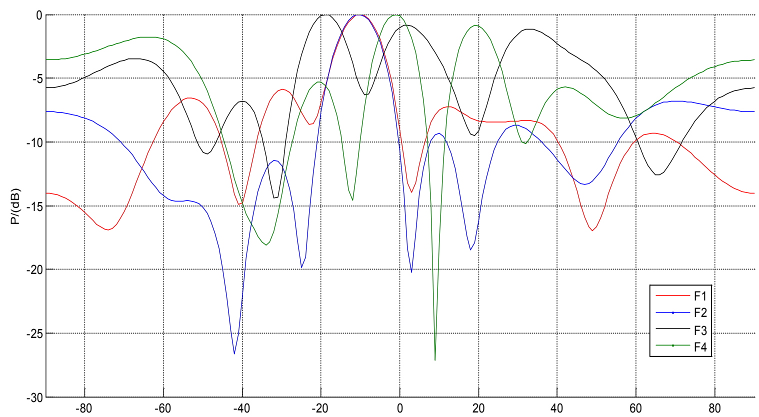

Figure 4: Pattern of the phased array antenna for four signals modulated by QPSK

In Fig. 5, the processes of searching the solution for QGA and the genetic algorithm (GA) are compared in the proposed model. With the same population and number of iterations, QGA evolves much faster than traditional GA, approaching the optimal solution in the 25th generation, while GA converges near the 63rd generation. In addition, QGA finds the optimal direction by the fifth generation, much faster than GA, which takes about 30 generations. The quantum genetic algorithm has great advantages in solving this problem, since it converges quickly and has a strong searching ability. Especially in a small population, it can quickly reach the global optimal solution to save running time. Moreover, for the case of multiple reflection paths (more than two reflections) in the general model and a larger antenna array size, a greater advantage will be exhibited.

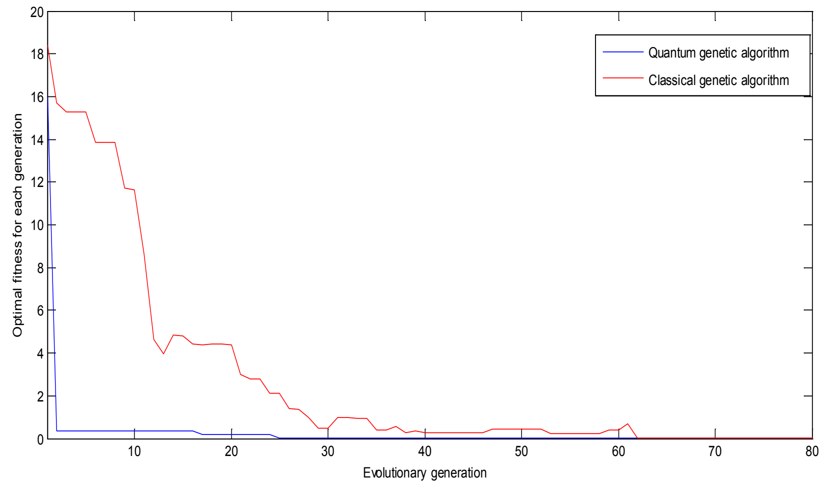

Figure 5: Comparison of genetic algorithm and quantum genetic algorithm

Compared to other research, this study conveys the novel idea that the directional modulation and pattern synthesis to achieve secure and efficient communication should be taken into consideration in the evolution algorithm. Owing to different types of paths in actual conditions, the calculation becomes more complicated than in the simplified model. The quantum approach provides an effective way to solve this problem. Our work shows the advantages in optimization performance of a faster speed and better solution, as well as the complex simulation in a multi-path model.

6 Conclusion

Considering the LOS path, single-reflection, and double-reflection paths, this study proposes a multiple-path model, which can be extended to the general case of multiple reflections close to a real complex environment. Combining the antenna pattern and phased array direction modulation in our model, the quantum genetic algorithm is utilized to optimize the phase shift value of the antenna array with excellent convergence performance and optimization ability. To sum up, this work explores the application of a quantum genetic algorithm in a complex environment with multiple reflection paths, to ensure secure communication and reduce the loss caused by the reflections and paths.

Acknowledgment: First and foremost, I would like to show my deepest gratitude to my supervisor, Dr. Xiubo Chen, who has provided me with valuable guidance in every stage of the writing of this thesis. I would also like to thank all my teachers who have helped me to develop the fundamental and essential academic competence. My sincere appreciation also goes to my colleagues from Beijing electronic science and technology institute, who participated this study with great cooperation. Last but not least, we thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

Funding Statement: This work was supported by the NSFC (Grant Nos. 61671087, 61962009 and 61003287), the Fok Ying Tong Education Foundation (Grant No. 131067), the Major Scientific and Technological Special Project of Guizhou Province (Grant No. 20183001), the Foundation of State Key Laboratory of Public Big Data (Grant No. 2018BDKFJJ018), the High-quality and Cutting-edge Disciplines Construction Project for Universities in Beijing (Internet Information, Communication University of China), the Fundamental Research Funds for the Central Universities (Nos. 2019XD-A02, 328201915, 328201917 and 328201916).

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

References

Babakhani, A.; Rutledge, D. B.; Hajimiri, A. (2008): Transmitter architectures based on near-field direct antenna modulation. *IEEE Journal of Solid-State Circuits*, vol. 43, no. 12, pp. 2674-2692.

Babakhani, A.; Rutledge, D. B.; Hajimiri, A. (2009): Near-field direct antenna modulation. *IEEE Microwave Magazine*, vol. 10, no. 1, pp. 36-46.

Cen, L.; Ser, W.; Cen, W.; Yu, Z. L. (2010): Linear sparse array synthesis via convex optimization. *IEEE International Symposium on Circuits and Systems*, pp. 4233-4236.

Daly, M. P.; Bernhard, J. T. (2009): Directional modulation technique for phased arrays. *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 9, pp. 2633-2640.

Daly, M. P.; Bernhard, J. T. (2010): Beamsteering in pattern reconfigurable arrays using directional modulation. *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 7, pp. 2259-2265.

Daly, M. P.; Daly, E. L.; Bernhard, J. T. (2010): Demonstration of directional modulation using a phased array. *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 5, pp. 1545-1550.

Ding, Y.; Fusco, V. (2013): Directional modulation transmitter radiation pattern considerations. *IET Microwaves Antennas & Propagation*, vol. 7, no. 15, pp. 1201-1206.

Ding, Y.; Fusco, V. (2013): Directional modulation transmitter synthesis using particle swarm optimization. *Loughborough Antennas & Propagation Conference*, pp. 500-503.

Ding, Y.; Fusco, V. F. (2015): MIMO inspired synthesis of directional modulation systems. *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 580-584.

Ling, C.; Zhu, L. Y.; Ser, W.; Wei, C. (2012): Linear aperiodic array synthesis using an improved genetic Aalgorithm. *IEEE Transactions on Antennas & Propagation*, vol. 60, no. 2, pp. 895-902.

Ma, T.; Pang, S. C.; Zhang, W. G.; Hao, S. H. (2019): Virtual machine based on genetic algorithm used in time and power-oriented cloud computing task scheduling. *Intelligent Automation and Soft Computing*, vol. 25, no. 3, pp. 605-613.

Mahdi, M. J.; Bryan, W. K. (2008): Optimal design and operation of irrigation pumping stations using mathematical programming and genetic algorithm. *Journal of Hydraulic Research*, vol. 46, no. 2, pp. 237-246.

Qin, A. K.; Huang, V. L.; Suganthan, P. N. (2009): Differential evolution algorithm with strategy adaptation for global numerical optimization. *IEEE Transactions on Evolutionary Computation*, vol. 13, no. 2, pp. 398-417.

Qu, Z. G.; Cheng, Z. W.; Liu, W. J.; Wang, X. J. (2019): A novel quantum image steganography algorithm based on exploiting modification direction. *Multimedia Tools and Applications*, vol. 78, pp. 7981-8001.

Qu, Z. G.; Li, Z. Y.; Xu, G.; Wu, S. Y.; Wang, X. J. (2019): Quantum image steganography protocol based on quantum image expansion and grover search algorithm. *IEEE Access*, vol. 7, pp. 50849-50857.

Qu, Z. G.; Wu, S. Y.; Wang, M. M.; Sun, L.; Wang, X. J. (2017): Effect of quantum noise on deterministic remote state preparation of an arbitrary two-particle state via various quantum entangled channels. *Quantum Information Processing*, vol. 16, no. 306, pp. 1-25.

Shi, H. Z.; Tennant, A. (2013): Secure communications based on directly modulated antenna arrays combined with multi-path. *Loughborough Antennas & Propagation Conference*, pp. 582-586.

Tian, D. P. (2018): Particle swarm optimization with chaos-based initialization for numerical optimization. *Intelligent Automation and Soft Computing*, vol. 24, no. 2, pp. 331-342.

Xing, H. L.; Pan, W.; Zuo, X. H. (2007): A novel improved quantum genetic algorithm for combinatorial optimization problems. *Acta Electronica Sinica,* vol. 35, no. 10, pp. 1999.

Xiong, Y.; Chen, H. H.; Miao, F. Y.; Wang, X. F. (2004): A quantum genetic algorithm to solve combinatorial optimization problem. *Acta Electronica Sinica*, vol. 32, no. 11, pp. 1855-1858.

Xu, G.; Xiao, K.; Li, Z. P.; Niu, X. X.; Ryan, M. (2019): Controlled secure direct communication protocol via the three-qubit partially entangled set of states. *Computers, Materials & Continua*, vol. 58, no. 3, pp. 809-827.

Yang, S. X.; Zhan, N. B.; Tian, L. H. (2013): An improved quantum genetic algorithm and its application. *Computer Engineering*, vol. 39, no. 5, pp. 196-199.

Zhou, R. G.; Cao, J. (2014): Quantum novel genetic algorithm based on parallel subpopulation computing and its application. *Artificial Intelligence Review*, vol. 41, no. 3, pp. 359-371.