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Shaping the future of the application of quantum computing in intelligent transportation system

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Abstract: The intelligent transportation system (ITS) integrates a variety of advanced science and technology to support and monitor road traffic systems and accelerate the urbanization process of various countries. This paper analyzes the shortcomings of ITS, introduces the principle of quantum computing and the performance of universal quantum computer and special-purpose quantum computer, and shows how to use quantum advantages to improve the existing ITS. The application of quantum computer in transportation field is reviewed from three application directions: path planning, transportation operation management, and transportation facility layout. Due to the slow development of the current universal quantum computer, the D-Wave quantum machine is used as a breakthrough in the practical application. This paper makes it clear that quantum computing is a powerful tool to promote the development of ITS, emphasizes the importance and necessity of introducing quantum computing into intelligent transportation, and discusses the possible development direction in the future.

Key words: quantum computing; intelligent transportation; quantum annealing; D-wave quantum computer

1 Introduction

In order to solve the traffic problems caused by accelerated urbanization, the concept of intelligent transportation system came into being. Intelligent transportation system is an integrated system[1], which integrates computer technology, information technology, sensor technology, control technology, and other advanced technologies. It realizes the functions of intelligent transportation service, intelligent transportation management, and intelligent decision support by analyzing data[2], simulating state, and predicting phenomenon. The intelligent transportation system (ITS) highly integrates roads, vehicles, and users to realize the sustainability, high integration, high safety, and rapid response of transportation, so as to form a real-time, reliable, and efficient transportation system.

In the past few decades, ITS has become an effective method to improve the performance of vehicles on the road[3]. The goal of ITS is to provide road safety[4], comfortable driving and release the latest information about the road[5]. ITS has been widely used in road traffic flow guidance[6, 7], air traffic management[8], cargo transportation[9], automatic control of motor vehicles[10], emergency[11], intelligent scheduling[12], urban air pollution[13], ship navigation[14], vehicle communication[15], and other aspects, and has achieved certain results. However, it still has the following limitations:

(1) The speed of big data transmission and processing is slow, so it is difficult to realize real-time navigation of large-scale road network[16].

(2) There are loopholes in the software code and parameters of the road system, and the security cannot

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be guaranteed.

(3) For the abnormal, special events can not be completely accurately identified, resulting in traffic management lag, lack of reliability.

In view of the fact that the coherent superposition of quantum allows data to be calculated in parallel and exponentially doubled, the entanglement of quantum and the no-cloning theorem can ensure that data are absolutely safe in transmission and processing, and the quantum tunneling effect can jump out of local extremes with greater probability to obtain the global optimal solution[17] and other performances, quantum computing[18] is introduced into the intelligent transportation system to increase data processing speed, ensure data security, and enhance system reliability.

The rest of this paper is organized as follows. In Section 2, we introduce the core computing mode of quantum computer-quantum computing, and describe the principle and development process of universal quantum computer and special-purpose quantum computer respectively. Sections 3 and 4 introduce the applications of universal quantum computer and D-Wave quantum computer in three application directions: path planning, transportation operation management, and transportation facility layout, respectively. Section 5 summarizes the contribution of quantum computer to the transportation field, and proposes future development directions.

2 Quantum computer

Dennard Scaling law is approaching the physical limit, Moore’s law is coming to an end, and quantum computing is setting off a revolution in the digital field due to its exponentially accelerated performance.

2.1 Quantum computing

Quantum computing[19, 20] is an innovative computing model that uses quantum superposition, entanglement, and coherence to achieve quantum parallel computing. In quantum computing, the smallest storage unit is Qubit. Unlike classical bits, qubits not only have two linearly independent states $|0\rangle$ and $|1\rangle$, but also can prepare a linear superposition state of these two states. For example, the linear superposition state of a qubit is

$$|\phi\rangle = a|0\rangle + b|1\rangle \tag{1}$$

where a and b are complex numbers and meet the normalization condition $a^2 + b^2 = 1$. Similarly, n-bit qubits can be in 2^n states at the same time.

Based on the properties of coherence and superposition of quantum states, quantum computing realizes quantum parallel computing, which shows the advantage of exponential acceleration. Quantum computers that perform computational tasks based on the principles of quantum mechanics have applied this advantage to different fields through different quantum algorithms, and have shown the potential to surpass classical computers in certain specific fields. At present, quantum computer can be divided into universal quantum computer and special-purpose quantum computer.

2.2 Universal quantum computer

Universal quantum computer generally refers to the quantum computer based on quantum gate, which can realize different quantum algorithms through the construction and combination of different quantum gates, and has the properties of quantum superposition and quantum entanglement[21]. Any quantum algorithm can be realized by universal quantum computer. The operation of a universal quantum computer can be regarded as a large unitary operator, which is realized by a quantum circuit composed of a series of quantum gates. Quantum circuit is the most widely used computing model in universal quantum computer. It implements quantum computing by performing a series of logical operations on qubits. Quantum gate[22, 23] (also known as qubit gate and quantum logic gate) is the basis of quantum circuit, which performs unitary transformation on single qubit and double qubit. Quantum gate is equivalent to the logic gate in classical computer, but different from logic gate, quantum gate is reversible, which means that no energy is generated in calculation process. This is also the advantage of quantum computers over classical computers.

As early as 1980, Benioff first discovered the relationship between computation and quantum mechanics, and proposed the theory of making quantum computer[18]. In 1982, Feynman pointed out that the use of classical computer to simulate quantum mechanical systems requires exponential computing resources, and it might be possible to use actual quantum mechanical systems to simulate quantum phenomena to overcome these difficulties[24]. In 1985, Deutsch described the quantum computer model in theory for the first time and defined the quantum Turing machine, which laid the theoretical foundation for quantum computer research[25]. However, to prove that quantum computers have absolute advantages in computing power, it is necessary to find a quantum algorithm that can solve problems more effectively than classical computers. In 1994, Shor proposed a quantum algorithm for conducting the prime factorization-Shor's algorithm[26]. Shor's algorithm simplifies the factorization problem to the problem of finding the order, so that it only takes polynomial time to decompose the prime factors of large numbers, thus the NP problem in the classical computer is transformed into a P problem[27]. The emergence of Shor's algorithm has caused the upsurge of quantum computer research, and has brought threats and challenges to RSA public key system. Grover proposed Grover's algorithm for unstructured database search in 1997[28]. Grover's algorithm can find the elements that meet the specific requirements from the database containing N unordered data through $\sqrt{N}$ times of search, so as to accelerate the classical algorithm to the second power. Shor's algorithm and Grover's algorithm prove the powerful computing power of quantum computer. Since then, the development of quantum computer has accelerated, and it has changed from pure theoretical scientific research to engineering manufacturing. A variety of research and development ideas of quantum computing physics system have been put forward internationally, including superconducting qubit, ion trap, semiconductor quantum dot, optics, quantum topology, etc.

(1) Superconducting qubit

Superconducting qubit is one of the most promising methods to realize universal quantum computation, and its core device is Josephson junction. In 2015, the IBM team creatively used a square lattice of four qubits, and realized two kinds of error detection: bit flip and phase flip[29]. In 2016, Google and Quantum Technologies for Information Science of Basque University in Spain successfully developed a 9-qubit superconducting quantum computer[30]. In 2017, Intel announced the realization of a 17-qubit superconducting quantum chip. In the same year, IBM announced the advent of a 20-qubit quantum computer. In 2018, IBM demonstrated a 50-qubit superconducting quantum computing prototype. In the same year, Intel announced the realization of a 49-qubit superconducting quantum test chip "Tangle Lake". Not to be outdone, Google also launched the 72-qubit superconducting system "Bristlecone" in 2018. In January 2019, IBM released the 20-qubit superconducting quantum computing system-IBM Q System One; in September of the same year, Google announced that sycamore, a 53-qubit superconducting quantum computer, had completed the task of global supercomputer summit in about 10 000 years in 200 s, realizing "quantum hegemony". In June and August 2020, Honeywell and IBM successively announced that their quantum computer with 64 quantum volume performance ranked first in the world.

(2) Ion trap

The scheme of quantum computer using ion trap technology was first proposed by Cirac and Zoller in 1995[31]. In 2016, the University of Maryland and IonQ jointly released a 5-qubit programmable quantum computer based on ion trap technology[32]. In 2017, IonQ developed a 32-bit ion quantum computer prototype. In December 2018, IonQ announced a 79-bit ion trap quantum computer. In August 2020, Duke University and the University of Maryland jointly designed a fully connected 32-bit ion well quantum computer register that operates at low temperatures. In October, Honeywell launched the ion trap quantum computer, System Model H1, with 10 fully connected qubits and a quantum volume of 128, at the same time, IonQ announced that it will achieve the expected over 4 million quantum volume on the 32-qubit ion trap quantum computer.

Since the concept of quantum computer was put forward, researchers all over the world have made numerous attempts on various implementation schemes of quantum computer, but limited to the immature performance of universal quantum computer, such as the precision of universal quantum devices, the scalability of qubits, quantum error correction, the feasibility of quantum manipulation, and quantum connectivity, the commercialization process of universal quantum computer is slow.

2.3 Special-purpose quantum computer

In universal quantum computers, qubits require unitary transformation through logic gates, which make quantum superposition less efficient. Therefore, physicists hope to create a quantum computer that does not require logic gates, but uses the characteristics of quantum systems to solve specific types of problems. This kind of quantum computing model is called special-purpose quantum computer (or quantum simulator).

In November 2017, Harvard University researchers proposed to use a 51-atom quantum simulator to detect many-body dynamics[33]. In 2017, a research team from the Institute of Quantum Research and the National Institute of Standards and Technology used the 53-qubit quantum simulator to study the phase transition of Ising-type quantum magnets[34]. In the same year, Pan, a professor at the University of Science and Technology of China, and his colleague Lu, together with other researchers in the Shanghai Institute of Microsystems and Information Technology, Chinese Academy of Sciences researched a quantum computing model, which achieved the first Bose sampling experiment with tolerate photon loss[35].

The most typical special-purpose quantum computer is the commercial D-Wave special-purpose quantum computer which has a strong development momentum in recent years. After the early release of 4 Qubits, 16 Qubits, and 28 Qubits quantum annealed chips, D-Wave system company released the world’s first commercial quantum computer, D-Wave one, in May 2011, and released a new quantum computer every 2–3 years. As of December 2020, five generations of quantum computers, including D-Wave One, D-Wave Two, D-Wave 2X, D-Wave 2000Q, and D-Wave Advantage, have been released. The hardware development of each generation has made a leap forward, as shown in Fig. 1.

As can be seen from Fig. 1, the newly launched D-Wave Advantage quantum computer adopts a new topology-Pegasus[36]. Compared with the Chimera topology used in previous generations, the connectivity of Pegasus has increased by 2.5 times. In addition, the combination more than doubles the number of qubits, making it possible to solve larger and more complex

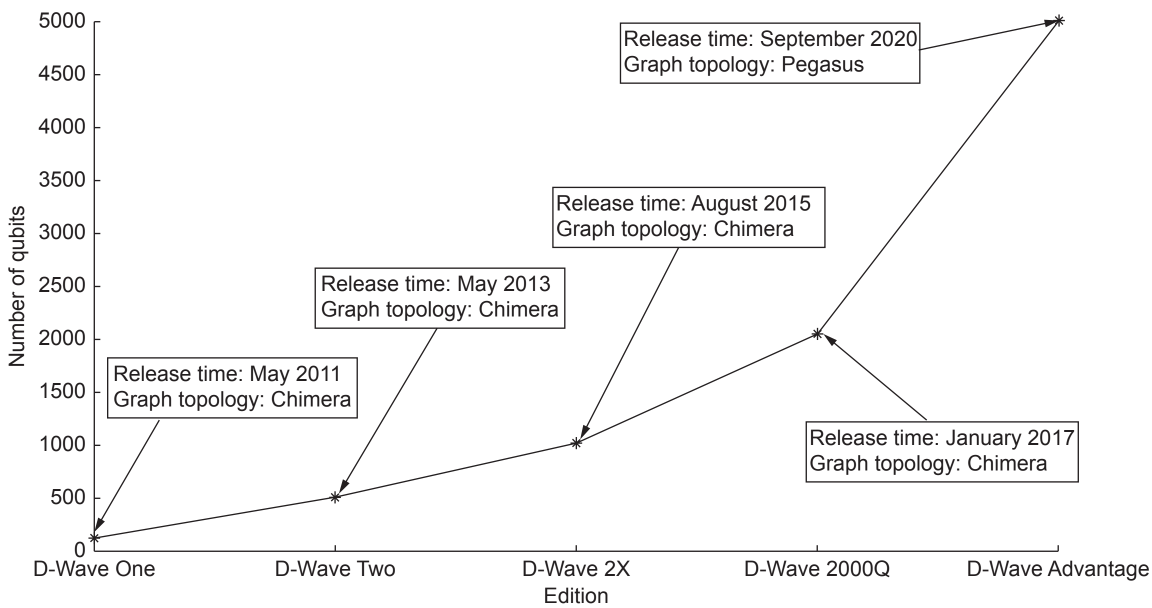

Fig. 1 D-wave quantum computer hardware development.

problems directly on the Advantage QPU.

D-Wave is an adiabatic quantum computer, based on superconducting qubit, using quantum mechanical effect, and showing quantum advantage through quantum annealing algorithm[37, 38]. Quantum annealing is an artificial intelligence algorithm with quantum effects, which uses quantum tunneling effect to find the global minimum corresponding to the optimal or close to the optimal solution[39–43]. The quantum annealing algorithm is based on the principle of quantum adiabatic annealing: under adiabatic conditions, the quantum state evolves slowly from the initial eigenstate (ground state) to the final state. As long as the evolution is slow enough, the system can always maintain the eigenvalue of the problem Hamiltonian State, until the end of evolution[44–47]. Quantum tunneling makes D-Wave have the ability to cross the potential barrier that classical algorithms (such as simulated annealing algorithm) do not have, so it is expected to jump out of the local sub-optimal solution and further approach the global optimal solution, as shown in Fig. 2. Through the quantum tunneling effect, D-Wave can solve some NP-hard combinatorial optimization problems in polynomial time.

The D-Wave quantum computer mainly solves combinatorial optimization problems. In order to find the global minimum of the energy function of the problem by using the characteristics of quantum adiabatic evolution, the problem to be optimized needs to be represented by Ising model (or equivalent quadratic unconstrained binary optimization (QUBO)).

In general, any optimization problem that can be

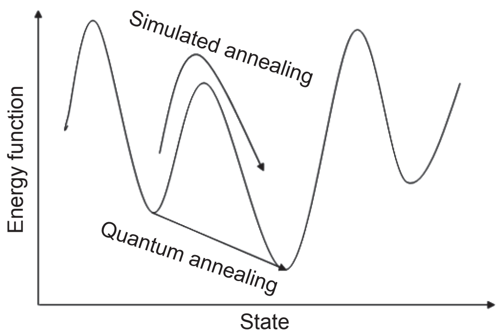

Fig. 2 Advantage of quantum annealing over simulated annealing.

mapped to this form can be solved by quantum annealing. The Hamilton function of Ising model can be expressed as[48, 49]

$$H_{Ising} = -\sum_{i} h_i s_i + \sum_{i,j} J_{i,j} s_i s_j \quad (2)$$

where $s_i \in \{-1, 1\}$, represents the Ising spin of the i-th qubit. h_i represents the weight of the i-th qubit, $J_{i,j}$ represents the coupling strength between qubits i and j. If s_i in Eq. (2) is replaced by $s_i = 1 - 2x_i$, the Hamiltonian function of the QUBO model is obtained.

In order to make it more convenient for users to use D-Wave for project development, D-Wave system also provides a series of quantum products, such as quantum cloud service Leap[50], Ocean Software Development Suite, open source software tool qbsolv[51], etc. The D-Wave system has been used by Lockheed Martin, Los Alamos National Laboratory, Volkswagen, the Quantum Artificial Intelligence Lab, DENSO, and other organizations around the world. More than 250 users have developed early applications on D-Wave, covering optimization[52], Artificial Intelligence[53, 54], Election Modeling[55], Material Science[56], Biology[57], Traffic Scheduling[58, 59], Preventive Health Care[60], Cryptography[61], etc. In the near future, D-Wave has the potential to solve more complex problems for more users in more fields.

3 Application of universal quantum computer in intelligent transportation

Although quantum computing is still in its infancy, its powerful performance in computing, storage, and information processing has helped it to be applied to transportation, communication security, intelligent optimization, new energy material[62], and other fields. Depending on the quantum advantage, quantum computer has been used in the field of intelligent transportation, such as path planning, transportation operation management, and transportation facility layout and so on, and has achieved remarkable results.

3.1 Using universal quantum computer to solve path planning problem

In 2009, Zhao et al.[63] from Zhejiang University of Technology established a mathematical programming model for capacitated vehicle routing problem, and solved it by using quantum evolutionary algorithm with quantum rotation gate and cataclysm operation. Quantum evolutionary algorithm uses two-dimensional 0−1 observation matrix to encode, uses quantum rotation gate to update, and introduces cataclysm operation to jump out of the local optimal solution. By comparing the results of quantum evolutionary algorithm with genetic algorithm and particle swarm optimization, this paper demonstrates that the proposed algorithm has better performance in search success rate, error, and global search ability. However, because the paper adopts a simplified static model in transportation, it can not describe the random changes in the actual transportation process in real time and dynamically.

In 2011, Liu and Zhou[64] from Northeast Petroleum University applied quantum particle swarm optimization (QPSO) algorithm to the optimization of transportation problems. The concept of particle swarm optimization (PSO)[65] was first proposed by Eberhart and Kennedy in 1995 in order to simulate the social behavior of birds and fish. The quantum particle swarm optimization algorithm uses position vector to describe the movement state of particles. Each element represents the order of transportation to each location according to its value. The transportation path is represented by the change of particle position. The mathematical model of transportation path is established by setting constraints, and the optimal solution is found through iteration. Compared with the traditional genetic algorithm, quantum particle swarm optimization algorithm speeds up the convergence speed and improves the accuracy of the optimal solution.

In 2012, in order to solve the multi-objective vehicle routing problem considering customer satisfaction (MVRPCS), Zhang et al.[66] from Zhejiang University proposed an adaptive grid multi-objective quantum evolutionary algorithm (MOQEA) on the premise of considering both customer satisfaction and travel cost. MOQEA uses the improved fuzzy due-time window to express user satisfaction, encodes chromosomes, and obtains multiple non-dominant solution sets, namely Pareto optimal solution sets. In order to realize the diversity of solution set, the adaptive grid is introduced to adjust the current grid number automatically according to the distribution of previous generation solution sets. Decision makers will use these solutions to select the optimal vehicle routing scheme according to their expected customer satisfaction and travel cost minimization ratio. Finally, MOQEA is applied to the benchmark problem in the standard sample library of multiple depot vehicle routing problem with time windows (MDVRPTW), and compared with the hybrid multiobjective evolutionary algorithm (HMOEA). It is concluded that MOQEA is effective for MVRPCS and superior to HMOEA.

In 2012, Wang et al.[67] from Hong Kong Polytechnic University proposed a hybrid algorithm-improved quantum-inspired evolutionary algorithm (IQEA), which combines quantum-inspired evolutionary algorithm (QEA) with greed heuristics method to expand the function of standard quantum-inspired evolutionary algorithm and solve complex problems with more constraints. The paper applies the IQEA algorithm to vehicle routing problems with time windows (VRPTW) in real life. VRPTW is an NP-Hard problem, and IQEA can speed up the solution time of large-scale problems. In dealing with the problem of consignment order, the upper level of IQEA cuts all the consignment sequences into the consignment subsequences according to the values of qubits, and the lower level applies the greed heuristics method to reconstruct the consignment subsequences to minimize the transportation cost. Although IQEA improves the performance of QEA, it still has limitations, such as being easy to fall into local optimization.

In 2018, Huang et al. from Zhengzhou University of Light Industry proposed a traffic prediction method based on modified ensemble empirical mode decomposition (MEEMD)[68] and quantum neural network (QNN)[69] according to the characteristics of long-range dependence and short-range dependence of real backbone network. Compared with the existing models, the model presented in this paper has higher prediction accuracy and better computational efficiency. In this paper, the traffic data sequence is preprocessed by MEEMD and decomposed into a finite number of intrinsic mode functions (IMF), then the IMF component is predicted by using the excellent nonlinear processing capability and convergence of quantum neural network. Finally the prediction results are comprehensively analyzed to obtain the final predicted value.

In 2019, Zhang et al. from Beijing Jiaotong University introduced an improved multi-objective quantum particle swarm optimization algorithm, which uses the advantage of quantum-behaved particle swarm optimization algorithm to obtain better search ability with fewer parameters to improve the global search ability and avoid being trapped in local optima[70]. Compared with other continuous multi-objective swarm intelligence algorithms, this algorithm obtains the real Pareto front which is closer to the design example of railway freight transportation route. The optimal Pareto front can provide the decision support for railway freight transportation path planning, reduce transportation cost, and optimize transportation quality.

In 2020, Zhang et al. proposed quantum genetic algorithm-learning vector quantization (QGA-LVQ) in order to predict the change of intelligent traffic flow[71]. It combines the advantages of simple structure and good clustering effect of learning vector quantization neural network with the global optimization ability of quantum genetic algorithm to overcome the shortcomings of LVQ neural network being sensitive to initial weights and easy to fall into local minimums. Aiming at five short-term traffic flow prediction problems, comparative experiments are carried out by using QGA-LVQ neural network, genetic algorithm-back propagation (GA-BP) neural network, and wavelet neural network, respectively. The results show that QGA-LVQ neural network is superior to the other two neural networks in prediction accuracy and convergence speed.

3.2 Using universal quantum computer to solve transportation operation management problem

In 2008, Sheu[72] inferred macroscopic traffic conditions by establishing a microscopic model describing the instantaneous decision-making behavior of drivers in the process of passing the accident scene in adjacent lanes. The model proposed in the paper divides driver behavior into three successive stages:

(1) **Initial stimulus:** According to the driver's actual psychology, the stimulus and pressure of the optical flow field represented by quantum mechanics are considered in the model.

(2) **Glancing-around car-following:** Quantum optical flow effect is used to model the following behavior of surrounding vehicles.

(3) **Incident-induced driving behavior:** Formulate the incident-induced driving behavior model. The quantum mechanics based method uses a microscopic model developed by integrating human factors and classical mechanics to simulate the driving law of a single vehicle, treating each vehicle as a single moving particle, and predicting the macroscopic traffic flow phenomenon by converging the dynamic motion characteristics of these particles, and it is applied to judge the psychological changes of drivers in the real abnormal traffic environment.

In 2013, Bernas and Wisniewska[73] from the University of Silesia proposed a quantum model to simulate traffic conditions and predict vehicle travel time. In the simulation, the vehicle can drive at different speeds. According to the probability of the vehicle passing through a specific point on the road, the moving position of the vehicle is estimated every second or a specified time interval. If vehicles represented by quantum states occupy the same position on the road or overtake each other, the model will correct the vehicle's position. The paper uses the cellular automata model to verify the proposed quantum model, and applies the verified quantum model to the simulation of the ambulance to estimate the travel time of the ambulance in real traffic. If this quantum model is applied to a quantum computer, the prediction result can be obtained in an instant.

In 2017, Dai and Wang[74] from Zhejiang Institute of Mechanical and Electrical Engineering, based on the actual situation of contemporary container transport vehicles and taking container transport as the research object, established a multi-objective mathematical programming model for the separation mode of tractor and trailer of container transport vehicles, so as to improve the turnover efficiency of container transport vehicles at the port and solve the truck and trailer routing problem (TTRP). The paper establishes a mathematical model for this problem, proposes an optimization alorithm based on hybrid quantum evolution to obtain the Pareto solution of the two separated objectives in TTRP, and introduces a greedy strategy to improve the convergence speed. In order to overcome the shortcoming of premature convergence caused by random operation of quantum evolutionary algorithm, a local search algorithm based on node switching is adopted; in order to maintain the discreteness of the Pareto solution, an adaptive grid operator is designed. Finally, the hybrid quantum evolutionary algorithm is applied to examples for comparison and verification. The results show that compared with the traditional tractor trailer integrated algorithm and other algorithms, the algorithm can effectively reduce the number of transport vehicles and operating costs.

In 2018, Hu et al.[16] from Wuhan University broke through the limitations of urban traffic network scale and real-time navigation, and proposed a route guidance method based on quantum searching (RGQS). Aiming at the modeling of a closed multi-intersection urban traffic network, the paper constructs an RGQS method composed of the algorithm for parallel calculation of the utility value of the route navigation scheme and road network utility value quantum searching (RNUQS). RNUQS algorithm improves the quantum search algorithm (QSA)[75], breaks through the limitation of search speed, and proposes a quantum error detection strategy (QEDS) to find better search results. The paper carried out comparative experiments on a simple artificial road network and a real city road network, and evaluated the performance of the route navigation system with the utility value. Compared with the FAVOUR algorithm[76] and the shortest path algorithm, the RGQS method has more obvious advantages in urban traffic with larger scale and more congested road network.

In 2020, Xiao et al.[77] from Hubei University proposed a new traffic safety scheme to promote effective communication between vehicles, thereby alleviating traffic congestion and reducing traffic accidents. The scheme uses quantum secret sharing method to provide secure information transmission for vehicle communication system (VCS). The cooperative cluster-head vehicles share group key through secret sharing scheme to obtain traffic control information with orthogonal quantum state coding.

3.3 Using universal quantum computer to lay out transportation facilities

In 2015, Che et al.[78] from Northwestern Polytechnical University proposed an improved quantum-inspired evolutionary algorithm to solve the lane reservation problem (LRP), and proposed a method to evaluate the impact of reserved lanes on traffic. During the period of large-scale sports events, it is necessary to reserve lanes to complete the urgent traffic task under the condition of minimizing the overall traffic flow. Firstly, an integer linear programming is improved and its properties are analyzed, which can reduce the search space of the optimal solution. Then, an improved quantum-inspired evolutionary algorithm for large-scale problems is developed based on the derived analytic properties. Finally, IQEA is applied to 485 randomly generated instances. For large-scale problems with 500 nodes and 50 tasks, the method proposed in this paper can produce high-quality solutions in a relatively short time.

In 2018, Hu et al.[79] from Wuhan University proposed an enhanced Biham, Middleton and Levine (EBML) model, which introduced the timing scheduling optimization (TSO) algorithm based on quantum particle swarm optimization to the management of traffic light timing. For the first time, different two-way multi-lane road networks are mapped to the BML grid space, and the vehicle update rules for different grid points are given. Compared with the Biham, Middleton and Levine (BML), EBML has a more accurate simulation of urban traffic congestion, and expounds the interference of different roads such as overpasses, underground tunnels, and roads on traffic flow. Finally, the proposed algorithm is compared with differential search algorithm, genetic algorithm, comprehensive learning particle swarm optimization algorithm, and stochastic method. The experiment proves that the proposed algorithm can improve the congestion situation in different traffic environments.

In 2018, Huang et al.[80] from Hunan University proposed a planning model that considers net present value (NPV) and life cycle cost (LCC) for the location and scale of electric vehicle charging stations. In order to obtain optimal economic benefits, the model comprehensively considers the constraints of distribution network, transportation network, and users. This paper presents an economic analysis framework of charging station. Based on voronoi diagram, it partitions the service area of charging station, intercepts the flow on the origin-destination (O-D) line and fixed nodes, and calculates the load of the area through the intercepted flow to determine the capacity of charging station. On the basis of considering NPV and LCC methods, quantum genetic algorithm is adopted to make the model have good convergence. At the end of the paper, the model is simulated for various scenarios, and the results prove that the model can effectively improve the economic benefits of the charging station.

Limited by the number of qubits, quantum fault tolerance, quantum controllability, hardware scalability, and other performance, practical universal quantum computer has not yet come out, only stays in the laboratory stage. The applications of universal quantum computer in the field of intelligent transportation mostly focuses on the research and improvement of quantum algorithm.

4 Application of special-purpose quantum computer in intelligent transportation

At present, due to the fact that quantum bits cannot satisfy the consumption of physical resources, the lack of connectivity between quanta, the low precision of quantum control, the weak hardware scalability, and other problems, the development of universal quantum computer is slow, and it still needs a long time to realize the practical application. Since the launch of the first quantum computing hardware D-Wave One in May 2011, a large number of scholars have seen the hope of quantum computer practicality, and have developed corresponding quantum algorithms and carried out experimental tests. The subsequent launch of a series of quantum products such as Leap quantum cloud service and Ocean software development kit provides a more convenient development platform for non-professional quantum technicians and remote developers, and promotes the promotion of D-Wave quantum computers and the development of related applications. D-wave quantum computer uses the principle of quantum dynamics to realize and accelerate the NP hard problem which can not be well solved by classical algorithms. The core principle of D-wave is quantum annealing algorithm, which is an artificial intelligence algorithm with quantum effect. Its quantum tunneling effect can jump out of the local optimal solution, approach or even obtain the global optimal solution in the exponential search problem. Using the characteristics of quantum adiabatic evolution, D-Wave quantum computers can help solve various discrete combination optimization problems. In recent years, it has also demonstrated its huge quantum power in the field of intelligent transportation.

4.1 Using special-purpose quantum computer to solve path planning problem

In 2017, Volkswagen Group cooperated with D-Wave Systems, and Florian Neukart et al. used quantum annealing algorithms to deal with traffic flow optimization problems in the real world, and mapped the problems to D-Wave 2X for solution[58]. The problem to be optimized in this paper is to minimize the travel time of a vehicle between its origin and destination, and minimize the congestion of all road sections. In this paper, T-Drive trajectory dataset of taxi GPS coordinates is used, D-Wave system is taken as an optimizer, and all traffic data are processed by hybrid solution of classical computer and quantum computer. The workflow is as follows:

(1) Use OSMnx API to extract the road map of Beijing from OpenStreetMap on the classic computer, map the vehicle coordinates of T-Drive to each street

of the road to determine the source and destination node of each vehicle, and extract three candidate alternative routes between the two nodes.

(2) Using the route of vehicles to determine the area of traffic jam in the map, and try to determine an effective alternative route for each vehicle in the congestion area.

(3) In order to solve the problem by using D-Wave's quantum processing unit (QPU), the traffic flow minimization problem must be represented by QUBO form. In this paper, the variable q_{ij} is used to represent the path j of car i, considering the constraints, the QUBO expression of the cost function Obj of all roads can be obtained as follows:

$$Obj = \sum_{s\in S}((\sum_{i}\sum_{j}\sum_{s\in S_j} q_{ij})^2) + \lambda \sum_{i}(\sum_{j} q_{ij} - 1)^2 \qquad (3)$$

where λ is the scale parameter, S is the set of all street segments in the map, and s is a certain street segment in the map.

(4) Represent Eq. (3) as a quadratic upper-triangular matrix and embed it in D-Wave 2X QPU. Considering that the number of logical variables that need to be embedded is greater than the functional qubits in QPU, the open source development tool qbsolv is used to divide the QUBO instance into subQUBO and solve the subQUBO. Finally, the solution results of each subQUBO are combined to form the solution of the QUBO instance. This plan is to reduce the path congestion under the premise of the path planning for each vehicle.

(5) Repeat steps (2) to (4) until no traffic congestion is found.

Through comparison experiments, it was found that the congestion degree of the road optimized by D-Wave was greatly reduced compared with the road randomly assigned by vehicles. All the 50 experiments optimized by qbsolv solved the problem of traffic congestion. However, the main body of the traffic flow problem simulated in this paper is only taxis, without considering the impact of road facilities, road communication, and other traffic participants on the traffic flow, and the objective of optimization is only to minimize the degree of road congestion.

In 2017, Syrichas and Crispin[81] from Manchester Metropolitan University proposed an empirical method for the vehicle routing problem with a large amount of data, using the measurement of vehicle runtime behavior to adjust the existing value of the meta-heuristic control parameter, reducing the complexity of adjust the control parameters for large instances, and improving the defect that the success rate of previous vehicle routing problem based on quantum annealing is less than 10%. The paper presents a method to adjust the Hamiltonian, which treats the term describing the interaction energy as a constant, simplifies the optimization process of control parameters, and makes quantum annealing suitable for very large instances. Theoretically, the method proposed in the paper can also be applied to other vehicle routing problems.

In 2019, Volkswagen Group launched the world's first traffic optimization pilot project using quantum computer to predict passenger flow and optimize routes in Lisbon, Portugal. The project uses D-Wave quantum computer to test the quantum navigation of 9 buses, 26 stops, and 4 bus lines. With quantum advantage, millions of real-time data can be considered in milliseconds, and calculation results can be obtained almost in real time. At the WebSummit Technology Conference in Lisbon from November 4th to 8th, the project will center on the conference venue and provide traffic guidance for thousands of passengers.

In 2020, Stollenwerk et al.[82] from German Aerospace Center described the problem as a combinatorial optimization problem in order to solve the strategic conflict problem in air traffic management, mapped it into QUBO form, and embedded it into classical solver, D-Wave 2X and D-Wave 2000Q for comparison test, respectively. In order to solve the air traffic congestion and save fuel costs, the paper arranges the optimal flight trajectory for each flight under the forecast of wind to minimize the total fuel cost of all routes, that is, to find wind-optimal trajectory. When there are multiple flights coexisting, the wind-optimal trajectory problem is likely to conflict, that is, two or more flights will exceed the safe distance between them. Therefore, the paper preprocesses the input trajectory data and modifies the trajectory to reduce the number of potential conflicts.

The wind-optimal trajectory problem is a combinatorial optimization problem. The paper uses the wind optimization trajectory of the transatlantic flight to construct a conflict graph and solve it with the quantum annealing algorithm. The nodes of the conflict graph represent flights, and the edges represent a potential conflict between the flights represented by the connected nodes. Considering the constraints, the total cost function is established. Then, the total cost function is embedded in D-Wave and considering the hardware constraints of D-Wave machine, this paper only considers the take-off delay and ignores the maneuver to keep the number of variables small. After using classical solver, D-Wave 2X and D-Wave 2000Q quantum chip to test the hardness of the example, it is concluded that the optimal solution of the current subproblem is obtained with 99% probability within 1 s of annealing time. If there are more than 12 flights, it is difficult to find a conflict-free solution.

In 2019, Irie et al.[83] from DENSO proposed a QUBO formula for capacitated vehicle routing problem (CVRP) considering time, state, and capacity. The CVRP proposed in the paper is equipped with a schedule to describe the time evolution of each vehicle, which realizes various strict time constraints. Since the concepts of capacity and time are similar, a capacity constraint, capacity-qubit, can be introduced to achieve capacity limitation. By increasing or decreasing the capacitated variable, the operator can increase or decrease the capacity according to the city where the vehicle arrives. As an additional benefit of capacity-qubits, state descriptions can also be obtained, and various driving rules can be formulated according to each state of the vehicle, such as operating cost and time-duration. The paper uses the D-Wave 2000Q quantum annealing machine to verify the proposed QUBO formula. The result shows that the QUBO system with less than 90 logical qubits can be embedded in D-Wave 2000Q for calculation.

4.2 Using special-purpose quantum computer to solve transportation operation management problem

In 2013, Crispin and Syrichas[84] from Manchester Metropolitan University applied the quantum annealing algorithm to the solution of CVRP in order to reduce the transportation cost and improve the customer service level. CVRP is a kind of vehicle routing problem with the maximum capacity of the goods contained in the vehicle. Using Path-Integral Monte Carlo (PIMC), the quantum system is mapped to a classical model composed of P ferromagnetically coupled spin matrices. According to a set of spin matrices, the CVRP problem is coded and the parameters are adjusted. The quantum tunneling effect of quantum annealing is used to generate an effective solution. The paper applies the quantum annealing CVRP algorithm (QACVRP) and the fixed temperature SA algorithm to a series of benchmark examples, respectively. The results show that QACVRP can obtain the best known solution (BKS) in all cases studied in this paper; in most cases, the success rate of quantum annealing algorithm is higher than that of simulated annealing algorithm.

4.3 Using special-purpose quantum computer to lay out transportation facilities

In 2019, Stollenwerk et al.[85] from the German Aerospace Center considered the use of quantum annealing to optimize the flight-to-gate assignment in order to reduce the total transit time for passengers. Using binary decision variables to encode the flight-to-gate assignment is a quadratic assignment problem, and its model is NP-hard, which is difficult to solve with classic methods. Therefore, the objective function is considered to be transformed into Qubo form, which is optimized and solved by D-Wave 2000Q quantum annealer. In this paper, the real data and simulation data of the airport are substituted into the objective function to solve the problem, but limited by the physical qubits provided by D-Wave 2000Q, only small data volume and small scale problems are studied. In order to reduce the accuracy requirements of examples, bin packing is used for coefficients. In the future research, the influence of bin packing on solution quality will be further studied.

In 2019, Hussain et al.[86] proposed a real-time traffic signal optimal control method based on artificial gridstructured road network and mapped it to the D-Wave system. The purpose is to maximize the traffic flow in the minimum time and minimize the total time of all vehicles waiting for the red light by controlling the traffic signal of the road network. The paper assumes that the road is a square grid with identical intersections, defines six vehicle driving modes for each intersection, and each mode is activated in a specified way. In view of the limited connectivity between qubits in D-Wave architecture, the paper adopts the hybrid solution method of classical and quantum computer. The workflow is as follows:

(1) Regardless of the route of any vehicle, only the classical computer is used to process data such as road length, speed limit, flow density, and synchronization signal.

(2) After a fixed time interval, the cost function in the form of QUBO is constructed by using the pre-processed data on the classical computer. When the cost function is the smallest, it corresponds to the optimal configuration of traffic signals at a specific time.

(3) Mapping the QUBO matrix to D-Wave QPU, for over-large problems or arbitrary connection problems, decompose them into sub-problems, and then map the sub-problems into the D-Wave QPU to solve in pieces.

(4) Every time a QUBO instance is solved, a new traffic signal configuration can be obtained, the traffic data of each segment are simulated, the traffic density data are updated, and the signals required for the next step are determined.

(5) Repeat steps (2)−(4) until the global optimal solution is obtained. The results of the paper prove that it is feasible for D-Wave to execute instances with a large number of variables and strict time requirements. Just as in the traffic signal optimal control example of this paper, a QUBO instance can be obtained every 5−10 s through D-Wave.

In 2020, Inoue et al.[59] from Toyota Central R&D Laboratory proposed a method to optimize the global control of traffic signals in urban traffic using D-Wave 2000Q, with the aim of minimizing the imbalance of global traffic flow in two orthogonal directions. In the paper, the road is represented by grid network, and the driving state of the car is controlled by the traffic signal at each intersection. Suppose that each signal has two states: north-south or east-west, and each car goes straight or turns at an intersection with equal probability. The goal of this paper is to adjust the traffic signal status of each intersection to make the whole traffic network the most smooth. This is a combinatorial optimization problem. In order to solve this problem on D-Wave, the paper expresses the problem as the Hamiltonian form of the Ising model. Since D-Wave 2000Q can process up to 64 variables at a time, and the number of roads is $\sqrt{64} = 8$, the number of roads involved in this question has exceeded 8, so it is necessary to use graph partitioning technology to subdivide the original problem, and then embedded into D-Wave chimera structure for solution. The paper uses local control, optimal control with simulated annealing, and optimal control with quantum annealing to optimize the problem, respectively. The comparison results of the three traffic control methods show that the performance of quantum annealing optimal control is the best in the steady state. In addition, the paper also found the theoretical correspondence between local and global control, and proposed the necessity of signal cooperative control of traffic flow.

In 2020, Wang et al.[87] from Shanghai University proposed to combine D-Wave quantum annealing, brain-like cognitive concept, and classical computing to build a hybrid computing architecture-quantum & brain-inspired hybrid-computing framework (QBIHCF), and combine clustering algorithms to form quantum & brain-inspired clustering algorithm (QBICA) to solve urban taxi stands location problem. Firstly, the paper extracts and preprocesses the taxi passenger boarding point data information, maps the coordinate data to the map for visualization, analyzes the distribution characteristics of coordinate points, finds the “key points” of the boarding points, and initializes the cluster center of the dataset[88]. Then calculate the driving distance similarity and angle similarity of each coordinate point and the cluster center point. Based on the similarity, the objective function in the form of QUBO is established. The QUBO model is solved by the quantum annealing algorithm of the quantum computer, the clustering center is updated according to the results, and the iteration is repeated until convergence, that is, the clustering result remains unchanged. Finally, the method proposed in this paper is compared with the K-means algorithm, and the results show that QBICA effectively overcomes the defect of being sensitive to the initial point and has stronger robustness.

5 Conclusion

Although the intelligent transportation system has made great achievements and considerable progress, it still has shortcomings in large-scale complex road network information processing, real-time control, road network capacity, infrastructure settings, and urban layout planning. Benefiting from the huge advantages of parallel computing, quantum entanglement and quantum tunneling in exponential acceleration, and secure communication and global optimization, a large number of researchers have applied quantum computing to the field of intelligent transportation to optimize and improve traffic performance. The application of quantum computing in the field of intelligent transportation still needs to overcome many technical obstacles. For example, the general quantum computer is limited by the current situation of low quantum bits, which makes it difficult to process large-scale traffic data. Due to its model structure, special-purpose quantum computer is a little weak in representing complex traffic environment.

This paper collects a large amount of relevant literature, and divides the applications in the field of transportation into three aspects: path planning problems, transportation operation management problems, and transportation facility layout problems, as shown in Fig. 3, and respectively from two aspects: the universal quantum computer and special-purpose quantum computer to the research results are summarized, emphasizing the quantum computing in intelligent transportation system motivated and innovative.

Since the universal quantum computer has not yet

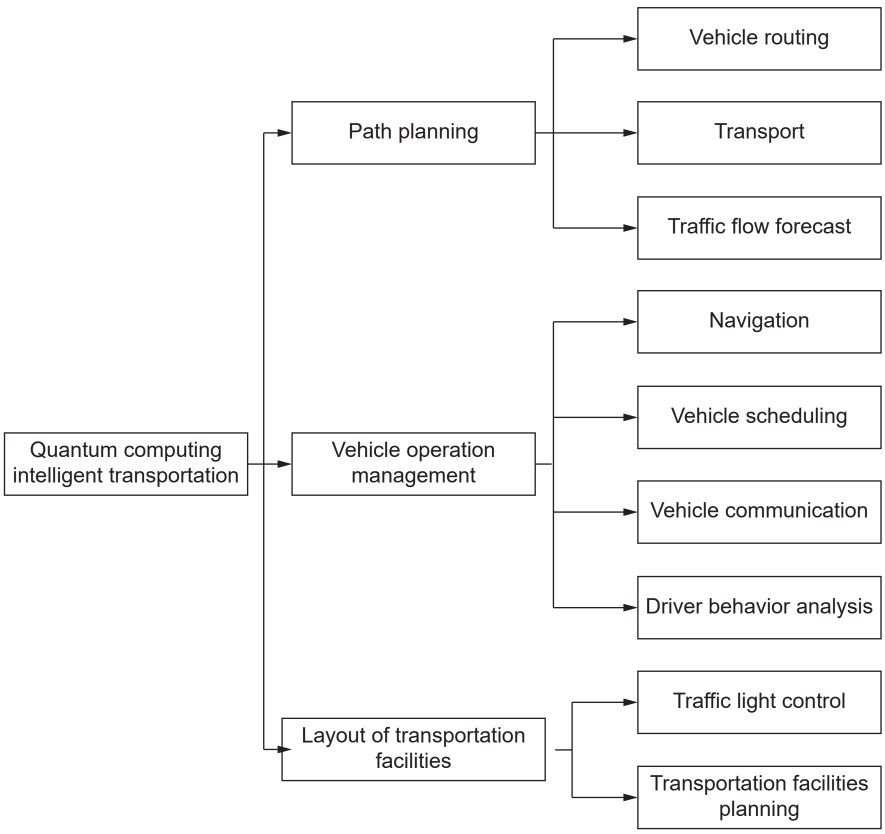

Fig. 3 Application of quantum computing in the field of intelligent transportation.

come out of the laboratory and is still far from being practical, most of its applications in the field of intelligent transportation are algorithm improvement and performance optimization, while the killer application and the demonstration of quantum advantages in practical applications are still challenges. Special-purpose quantum computer, especially D-Wave quantum computer, has been successfully commercialized, and has performed well in the field of intelligent transportation. D-wave quantum artificial intelligence in the future can be further studied and improved in the field of intelligent transportation for the following aspects:

(1) Urban traffic is full of large amounts of data and information. In the construction of smart city system, consider the integration of multiple data and information, comprehensively consider the impact of incentives on urban traffic, and build an information sharing and processing platform.

(2) Explore the hybrid architecture of quantum computer and classical computer, and explore the potential of multidisciplinary research.

(3) Explore the modularization of hybrid computing architecture of quantum algorithm and other intelligent algorithms.

(4) Aiming at the existing optimization algorithm, how to set the coefficient reasonably to reduce the system complexity and accelerate the convergence speed of the algorithm.

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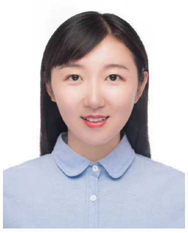

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