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ORIGINAL ARTICLE

Quantum algorithms: applications, criteria and metrics

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Abstract
In the field of data processing and IoT communication it is possible to develop more robust solutions by combining quantum algorithms with metaheuristics. Said solutions can be applied in the industry and be measured using metrics associated with complexity, efficiency, processing, and accuracy. An extensive bibliographical review is carried out to determine which is the most efficient and effective hybrid algorithm that can be applied to a real experimental case, which aims to improve communication to reduce occupational risks. Criteria, metrics, and experimental results were obtained, in which it is shown that the quantum genetic algorithm is better than the genetic algorithm. A detailed discussion on the objective function, the convergence to the global optimum, and the need to improve the obtained solutions is given. The conclusions raise new aspects that need investigation.

Keywords Quantum genetic algorithms · Communications · IoT · Industrial applications

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Abbreviations

CMISO	Cooperative multiple-input-single-output
DJ	Deutsch–Jozsa
GA	Genetic algorithms
IoT	Internet of Things
LoRa	Long range
LoRa Mesh	Long-range mesh network
LoRaWAN	Long-range wide-area network
PSO	Particle swarm optimization
QGA	Quantum genetic algorithms
QPSO	Quantum particle swarm optimization
RSSI	Received signal strength indicator
SNR	Signal-to-noise ratio
TTN	The Things Network
VoD	Ventilation on demand
WSN	Wireless sensor networks

Introduction

Wireless sensor networks (WSN), which correspond to sensing nodes connected to each other and deployed for performing a task, are among the solutions offered for systems being capable of quickly and reliably transmitting information from the edge of a network to the monitoring/control center [1]. The sensor data are shared with each other and used as input to a distributed estimation system for extracting the relevant information.

For the information used for decision-making in the mining industry to be effective, which works under extreme conditions in the operations, it is necessary to perform a fault diagnosis to avoid errors in the processing and output of data from the system [2].

On the other hand, Networks having a Long Range (LoRa) communication protocol, managed by a local server in the field or by an online cloud server over the internet [3], are capable of offering safe solution without a substantial increase in the energy consumption and using a wireless frequency spectrum without paying a license fee [4]. The network layer for LoRa may vary depending on the kind of topology with which the communications network is built. Long Range Wide Area Network (LoRaWAN) and Long Range Mesh network (LoRa Mesh) are some common topologies [5, 6].

The features of LoRa make it a relevant technology for use in Internet of Things (IoT) applications to exchange information at an acceptable speed with the cloud, for uploading and downloading data. IoT allows systems to be remotely detected and controlled, providing a greater integration between the physical world and computer-based systems, which in the long term provides greater efficiency, accuracy, and economic benefits. However, IoT has some limitations since the information is not encrypted, lacks security, and shows a low data transfer rate and a high latency time [7].

If the network is vulnerable, it can lead to cyber-attacks in which communication systems are corrupted and false information can be transmitted that changes the real data [8].

In wireless communication networks of smart industries in the primary sector, quantum-inspired optimization is increasingly used for solving complex problems. Quantum-inspired optimization is based on quantum mechanics and comprises the analysis, processing, and transmission of data in real-time [9, 10]. Quantum-inspired optimization is a concept of quantum computing and has the qubit as the minimal unit and the superposition of states (for example, an electron exists in all its possible states at the same time and simultaneously) [10]. The quantum provides a greater availability, scalability, and operativity to the balancing of the data loading in the cloud of the computing network working with IoT [11].

By means of quantum computing it is possible to solve problems that can not be solved using classical computing. It also allows the combination of quantum algorithms with databases and with more efficient querying algorithms for large amounts of data [12, 13]. Quantum systems are based on the postulates of quantum mechanics related to the Hilbert space, in which multiple target states may be superpositioned and more rapidly analyzed, since there is a probability vector showing the probability distribution among multiple states and the evolution of the transition matrix between states [12].

Quantum Genetic Algorithms (QGA) have been used to solve complex optimization problems in engineering, due to their great capacity for global computing in a shorter execution time, due to the search for their implicit parallel, and due to the smaller size of the population [14].

Quantum systems have advantages in the industry since they can minimize energy costs due to lower network traffic, improve performance with less delay latency, reduce the risks of failures in the information security field, and allow distributed use and analysis of IoT data in offline or limited connectivity environments [15]. It is possible to use the concepts of eigenvectors and eigenvalues of a Hilbert space together with an information system with multi-agents to improve decision-making, wherein robustness helps to capture a large amount of data in an environment that operates with disturbances from different sources with a dynamic and evolving environment [16].

Motivation

Underground mining is an important productive sector in Chile, in which productive activities are carried out daily in tunnels that require Ventilation on Demand (VoD) with sensors and actuators. These devices transmit data through the rocks, which usually generates losses in communication due to frequent cuts of optical fiber and the shortcomings that wireless systems present due to the lack of robustness of the configuration [17]. The loss of connectivity in mining tunnels is risky since, for example, forces workers to evacuate so that they do not get intoxicated by gases. It can also cause fatal accidents, silicosis, etc.

If communications fail and the current legal regulations related to the protection of life, physical integrity of people, facilities and infrastructure in which operational activities are carried out are not complied with, sanctions are applied to the mining company that generate economic costs in production. [18].

As a solution, it is necessary to find communication methods that are more secure and capable of transmitting information in a ventilation system in which data are captured with sensors, optimized with a hybrid quantum algorithm, monitored and controlled with a more robust communication support. If mining has resilient networks that can withstand failures and attacks, decisions can be made in real time to prevent risks and accidents in the workplace. It is required to look for technologies that improve communication and algorithms that provide advantages due to their accuracy, speed, effectiveness, and efficiency.

To determine which algorithm is more robust for a tunnel in underground mining, in the present work a bibliographic review of the methods, algorithms, and metrics is exposed in the next section. A communication method best matching the requirements of the underground mining environment is selected. With the selected method, in the subsequent section, an experimental case will be developed followed by which experimental results of the quantum genetic algorithm are given. Key aspects will be discussed next. Conclusions and future lines of research will be given in the final section.

Scope

The research is focused on determining a quantum algorithm that can be used experimentally to communicate a VoD system inside the tunnel. The work includes the design of the ventilation system with sensors and the optimisation of the quantum genetic algorithm (see "Conceptual design" in steps (1) and (2). It should be noted that future research will address the computer and software development that builds a monitoring and control system (see "Conceptual design" in step (3).

Literature review

To know in which areas quantum algorithms are applied and what are the parameters that could build metrics that can be used in communications with IoT, the literature review was performed on October 3, 2022, using the keywords `'quantum' AND 'optimization' AND 'IOT'`. Among the 54 results found, the sample presented in Table 1 was selected due to the close relation with the experimental case as developed in "Experiment".

Most repeated features in the quantum algorithms shown in Table 1 are classified in Table 2. The results show that in the Telecommunications field, most of the publications are related to data transmission networks and quantum heuristic algorithms.

A search with the Scripts in the Main Collection of Web of Science: `TS=(quantum AND IoT AND communication)` was performed on August 11, 2022, 2022, to determine which technologies have been studied in the area of communications with IoT. The results obtained in the in Table 3 show that the compatibility of the different technologies with the algorithms needs to be further studied and that, in general, IoT systems are considered as means to optimize resources.

Table 4 compares which metaheuristic method with and without quantum is more efficient. A search was carried out in the Web of Science, IEEE, and Scopus databases on October 20, 2022, with the keywords `'Quantum Algorithms' AND 'Metaheuristic Algorithm'`. Results were obtained for Metaheuristic Algorithms (10,463 on the Web of Science, 5257 on IEEE, and 19,049 on Scopus), and for Quantum Algorithms (27,139 on the Web of Science, 38,736 on Scopus, and 10,483 on IEEE).

The obtained results in Table 1 were used to create Table 5, in which the algorithms were classified according to the following criteria: complexity (efficiency), effectiveness, processing, and accuracy. It was observed that the algorithm that presented the greatest number of attributes is the quantum bee colony with 21.4%, followed by the quantum firefly colony algorithm with 19.6%. In third place appeared the quantum genetics and the firefly colony algorithm with 17.9%. It should be noted that the choice of the algorithm also depends on the field of the optimization problem being studied, as can be seen in Table 1.

As explained in "Experiment", the experiment was performed with the quantum genetic algorithm since it included the following criteria: data processing, mathematical modeling, and object detection.

Materials and methods

Basic representations

Unlike classical computing, quantum computing uses superposition and entanglement, in which the quantum states of two or more objects are to be described by a single state involving all objects in the system even when the objects are spatially separated; since the electron may be in any of the infinitely many intermediate quantum states between classical states 0 and 1 [62, 63]. In quantum computing, it is possible to prepare a system cold enough for the electron not being able to escape from the two levels with the lowest energy. As shown in Fig. 1 an atom can have two orbitals that simulate the behavior of a qubit. When the energy is not enough to change its orbit, the electron remains in an intermediate state, the superposition is broken (collapse or decoherence), and it is likely to pass to state 0 or 1.

Quantum computing has the advantage that it benefits from superposition or parallelism by considering all the paths at the same time, thus increasing its processing capacity. It can be represented by the qubit, which is the smallest unit of the Information Theory [64].

For representing the superposition for 1, 2 and n qubits, it is proposed [65]:

Table 1 Industrial areas with IoT quantum algorithm applications

Area	Description	Method/algorithm	Parameters
Telecommunication	An energy optimization model for IoT environments applied to a stochastic environment with a green communication framework is proposed. It aims to obtain sustainable development while safeguarding the environment. A monitoring system is created wherein the energy consumption and the cost generated by sensing, processing, and communication activities are relevant. Data communication consumes most of the energy of the sensors [19]	Quantum Energy Balancing in sensor-enabled IoT systems	Network lifespan, power consumption, dead nodes, and execution time
	A method of balance between energy efficiency and the provision of quality of service is proposed, which measures the permanence of certain standards in data services. It seeks to prioritize traffic between different devices connected to the same router, to determine that the proposed optimization algorithm generates a balance between network lifespan and performance [20]	Optimization of quantum particles swarm. Non-dominated sorting Genetic Algorithm	Network Lifespan and Outage Performance
	A fog-based protocol is created to produce secure routing. Fog-based is a cloud technology in which data is obtained with devices that are not directly uploaded to the cloud but are prepared in smaller decentralized data centers. The Quantum Firefly Optimization-based Multi-Objective Secure Routing protocol is obtained, thus allowing to produce better results in the metrics [21]	Quantum Firefly Optimization	Packet delivery, packet loss and average delay, energy consumption
	Research is made on the improvement of a particle swarm algorithm, with quantum mechanics to configure the optimal path. It is used in IoT applications with enhanced connectivity for network troubleshooting. Optimal solutions are obtained with a lower estimate of the proficiency function [22]	Quantum Particle Swarm Optimization (QPSO)	Number of nodes, transmission range, consumed energy, payload message, data length, and data transmission
	A high-performance clustering protocol is built: quantum clone whale optimization algorithm. The technique improves the communication system by obtaining high quality, according to its energy expenditure and the time of sending the information. It extends the lifespan of the network and effectively minimizes energy consumption [23]	Optimization of quantum clone whales	Network lifespan, energy distribution, and data transmission delay
	The development of a node location algorithm is studied and applied in a system of isotropic networks that seek to exceed the speed limits of a conventional network, for robust and precise technology. It is obtained a cost-effective alternative that uses GPS [24]	Salp Swarm of quantum behavior	Precision and robustness of network anisotropy
Medicine	A monitoring system based on the IoT and a WSN is created. They are applied in the medical care of infants and the elderly to improve the quality of life and reduce the electricity consumption of the system [25]	Quantum Particles Swarm Optimization	Data accuracy, algorithmic efficiency, and energy costs of routes
	With QPSO, it is possible to improve regression and update testing of IoT software applications and sensor networks. It seeks to improve robustness and reduce the cost of failure coverage, and it is applied to customer service in the health area. Better results are obtained than with the genetic and Particle Swarm Optimization (PSO) algorithm [26]	Optimization of particles swarm of quantum behavior	Coverage of failures and declarations, inclusiveness, and reduction of failure detection costs

Table 1 continued

Area	Description	Method/algorithm	Parameters
Road safety	In a sensor space with IoT applications in a stochastic environment, real-time data are taken and optimized by maximizing the accuracy of the data obtained from the process and improving reliability. A traffic and route monitoring system is generated [11]	Quantum Optimization with IoT	Data Cost, Data Accuracy, Data Reliability, and Data Time Efficiency
	Large amounts of IoT data are optimized in real-time. The methodology incorporates a real-time IoT sensor space, which is optimized with a quantum algorithm. The simulation in the vehicular traffic of a road is evaluated, and the results show temporal efficiency and performance parameters [27]	Quantum Computing Optimization	Data similarity, energy efficiency, accuracy, and reliability
Education	A planning system for the teacher is proposed, so as to achieve energy efficiency in the network of wireless sensors, assisted by IoT. It is classified into two types of student levels (outstanding and medium level), wherein the student evaluates what he or she learns from the teacher and the system is responsible for delivering the best educational programming according to his or her level by finding the best teachers for the student; thus obtaining an increase in the life capacity of the network [28]	Quantum Group Teaching Optimization	Average delay, Mean residual energy, packet loss rate, packet delivery ratio, and network lifespan

Table 2 Characterístics of quantum algorithms

Field	Algorithm	Optimization		
		Energy	Nodes	Data
Telecommunications	Quantum Energy Balancing in sensor-enabled IoT systems	✓	✓	×
	QPSO	✓	✓	✓
	Quantum Firefly Optimization	✓	✓	✓
	QPSO	✓	✓	✓
	Quantum clone whales	✓	×	✓
	Quantum Salp Swarm	×	✓	×
Medicine	QPSO	✓	×	✓
	QPSO	×	✓	✓
Road safety	Quantum methods and IoT	×	✓	✓
	Quantum Computing	✓	×	✓
Education	Quantum Group Teaching	✓	✓	✓

- Example ($n = 1$). For 1 qubit it is obtained the dimension 2^1.
- Example ($n = 2$). In the case of 2 qubits, 2^2 dimensions are obtained, corresponding to simultaneously having the combinations 00, 01, 10 y 11 [62].
  In the Bloch sphere shown in Fig. 2, the ψ state describing the linear combination of ket 0 and ket 1, given an orthonormal basis, is represented
  Regarding the mathematical formulation, the following linear combination is proposed [69].

$$\mid \psi\rangle = \alpha \mid 0\rangle + \beta \mid 1\rangle = \begin{pmatrix}\alpha\\0\end{pmatrix} + \begin{pmatrix}0\\\beta\end{pmatrix} = \begin{pmatrix}\alpha\\\beta\end{pmatrix} \tag{1}$$

With $\alpha \in \mathbb{C}$ and $\beta \in \mathbb{C}$
It is worth mentioning the probabilistic condition for the normed complex magnitudes α and β:

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

Table 3 Quantum-inspired communication and IoT methods

Method	Description	Technology	Algorithm
Quantum optimization	The information routing of IoT devices is optimized for minimizing the energy consumption of the sensors and extending the life span of the network. The metrics are compared and a better solution than other methods is obtained, related to the energy, measurement, and rotation angle [19]	IEEE 802.15.4 for WSN, with Personal Area Network Standard	Quantum metaheuristic with green communication
	The negative effect of the transmission power for enhancing the quality of service is minimized. In the results, a greater convergency speed than the PSO and QGA algorithms is obtained [29]	IoT devices according to a Cooperative Multiple-Input-Single-Output (CMISO) scheme	Coalition selection based on qubits
	With the CMISO and quantum PSO algorithms, the routing is optimized and the life span in local networks for short-range IoT is extended. The election of the optimal emitter-receiver cooperative device pair is improved [30]	IoT devices incorporating CMISO schemes	Coalition selection based on qubits (QPSO)
Post-quantum cryptography	The privacy in the IoT communication is improved with an algorithm for devices of greater power. Its performance is validated by means of attacks on the network using MIRAI bots and Xilinx IS14.5, with frequency, confidentiality, power, error, and latency metrics [31]	Xilinx ISE14.5 tool for IoT devices	Diffie Supersingular Multiplication
	Examines fundamental features and architectures of IoT systems, and, from this analysis, focus on the security of the systems with limited hardware resources [32]	Lattice in IoT devices security	Sensitive classification for cryptographic security
Object-oriented programming	With the algorithms based on Reliable Anchor Pairs and Salp Swarm of quantum behavior, the impact of the anisotropy in the localization of WSN with IoT is mitigated. The optimal node pairs are elected for minimizing the traffic in the network. The results show that greater accuracy and robustness are obtained [24]	Wireless sensor networks	Quantum Behavior Salp Swarm
	It is studied that post-quantum algorithms can be efficiently executed in the current hardware of IoT and that the IoT communication systems are secure enough when faced with the threats posed by quantum computers and Shor algorithm applications [33]	Post-quantum cryptosystems incorporated into IoT devices	Post-quantum encryption

WoS, https://www.webofscience.com/wos/woscc/summary/bca3dfd0-42d3-4113-bdce-faecdabd57e7-5c6a8b63/relevance/1, access on 8/11/2022

Wherein $|\alpha|^2$ is the probability of the qubit being in ket 0 y $|\beta|^2$ is the probability of the qubit being in ket 1 [61].

- Example for n. It is possible to have multiple qubits with 2^n dimensions. It is a quantum entanglement state with a higher correlation than classical systems.

Quantum systems

The evolution or dynamic of the qubits is determined by a unitary operator U, over the Hilbert vector space with finite or infinite dimension. The Hilbert space is based on the postulates of quantum mechanics [70–72].

It follows the following steps:

Step 1 Choose the system to be described. There is a system described by a unitary state vector $|\psi(t_i)\rangle$ belonging to a Hilbert vector space.

Step 2 Choose the possible system configurations. The system $\psi(t_i)$ changes of state U in time, and there is a linear transformation in which the quadratic sum of probabilities is maintained equal to 1

$$S_1 :|\psi(t_i)\rangle \xrightarrow{U} S_2 :|\psi(t_{i+1})\rangle. \quad (3)$$

With S_1 = system 1 and S_2 = system 2; $i = 1, 2, \ldots n$, $i \in \mathbb{N}$.

Equation (3) may be expressed as a dynamic matrix of the system.

Table 4 Criteria of quantum and non-quantum metaheuristic algorithms

Metaheuristic	Criteria	Quantum	Non quantum
Genetic Algorithms (GA)	Data processing	A visualization method for large amounts of data is proposed. It proposes a multi-objective GP-tSNE genetic programming approximation model, which has more understandable characteristics and higher quality mappings since it makes a deeper analysis by reducing the dimension of data. It is efficient on low complexity problems [34]	A QGA allows solving a weighted data problem in a cavity with a 3-channel sensor that detects the noise due to the suspended particle impact. Results are obtained with a high data processing capacity, using a variance metric for the input signal [35]
	Mathematical Modeling	The speed of convergence and the quality of the electromagnetic solution are improved with GA and the evolution strategy (ES). Mathematical modeling is performed related to circular polarization antennas at specific stations. More accurate and higher performance solutions are obtained [36]	The multi-objective cellular genetic algorithm with multi-objective optimization and the QGA are created for cellular automata. Discrete mathematical and computational modeling for the process with two possible states is provided. It differs from other metaheuristic algorithms in that it improves performance and the next generation depends on the cell and its surroundings [37]
	Detection of objects	With Genetic Programming (GP) a problem is solved for the detection of outgoing objects based on artificial intelligence and image processing as function of the semantics of objects. GP improves the interpretation of high-level features with a lower number of samples than deep convolution neural networks [38]	It proposes a diagnostic method of faults in rotational machinery, based on the vector support machine (SVM) optimized with QGA. The method is applied to fault detection in rotating machinery on an axis, obtaining a higher accuracy than the traditional SVM and GA [39]
	Energetic efficiency	With GA and the multi-threshold image processing method, a regional public energy management evaluation index system is created. With GA, more efficiency is obtained due to the lower cost of execution and storage of resource allocation data in the organization [40]	An improved multi-objective QGA is used to solve environmental pollution problems caused by electric cars on high-speed highways. A rate of self-consumption of clean energy and energy efficiency management strategies are proposed. It improves the rate of convergence, increases the diversity of the population, decreases energy costs and carbon emissions [41]
Ant Colony (ACA)	Data transmission for wireless sensors	To improve the efficiency of energy data, the problem of optimizing data transmission in networks connecting wireless sensors (WSN) is solved. It reduces energy consumption and increases the useful life of the network, the algorithm studied is more efficient than other bio-inspired algorithms [42]	Based on the evolutionary Quantum Ant Colony Algorithm (QACA), the coverage and transmission of self-organized wireless sensor networks are optimized. WSN monitors with fixed or environmental parameters of the environment. The results show that it improves target coverage and speed of convergence compared to the genetic algorithm [43]

Table 4 continued

Metaheuristic	Criteria	Quantum	Non quantum
	Logistics Optimization	Investigates a logistic problem of the traveling agent and route optimization, with ACA and PSO. The shortest path for the transfer of products is studied. It obtains greater efficacy than with ACA [44]	Based on the quantum ant algorithm (QACA), it solves the problem of combinatorial optimization of the backpack, which is commonly used with the genetic algorithm. QACA obtains probable states for small colonies and achieves an optimal solution by updating the pheromone and rotating the quantum gate. It has higher performance than QGA and GA [45]
	Data transmission for communication networks	ACA optimization improves transmission in wireless sensor networks (WSNs) that do not require physical infrastructure and maximizes WSN energy efficiency and lifespan. Higher efficiency is obtained than with conventional ACAs [46]	With QACA, a quantum system is created in which NP queries and the transmission of large amounts of data from distributed databases are optimized. It reduces query join costs, minimizes total execution time by improving convergence speed, avoiding falling into the local optimum, and has more goodness than ACA [47]
Firefly Colony (FA)	Device Routing	Integrates FA algorithms into photovoltaic systems, to improve global power peak tracking and routing with high accuracy. By maximizing power extraction in wind turbine systems, it achieves results with high accuracy and efficiency and with a tracking speed faster than conventional SAs [48]	With FA and quantum algorithms, it studies multicast routing in the quality of service of communication network transmission. It seeks to avoid premature convergence, has a variety of solutions, and greater efficiency than other algorithms [49]
	Image Segmentation	With cellular FA, image segmentation is optimized with 2D OTSU. Efficient results are obtained that are measured with the metrics of segmentation speed, accuracy, and anti-noise capacity [50]	With quantum FA (QFA), the segmentation of microscopic images used to identify critical diseases is optimized, and a high efficiency is obtained to generate segmentation improving the quality of the image of the hippocampus compared to other algorithms such as the chaotic firefly, bacterial foraging and the flight of the firefly with Levy [51]
	Performance Optimization	An FA is proposed that randomly selects elite fireflies similar to the genetic algorithm, to improve the speed of convergence and local search capacity with which a more robust solution is obtained. Gets better results than traditional FA and other metaheuristic algorithms [52]	Dirac's delta potential well model is optimized with QFA. Higher performance is obtained than the FA and exponential atmosphere algorithms [53]

Table 5 Classification of the key attributes of each quantum and metaheuristic algorithm

Type	Criteria	Complexity[a,e]	Efficacy[b,e]	Processing[c]	Accuracy[d]
GA	Data processing	✓	×	×	✓
	Mathematical Modelling	×	✓	×	✓
	Object detection	×	✓	×	✓
QGA	Data processing	✓	×	✓	✓
	Mathematical Modelling	✓	×	✓	✓
	Object detection	✓	✓	✓	✓
ACA	Data transmission for wireless sensors	✓	×	×	✓
	Logistic optimization	×	✓	×	✓
	Data transmission for communication networks	✓	✓	×	✓
QACA	Data transmission for wireless sensors	✓	✓	✓	✓
	Logistic optimization	✓	✓	✓	✓
	Data transmission for communication networks	✓	✓	✓	✓
FA	Device routing	✓	✓	×	✓
	Image segmentation	✓	✓	✓	✓
	Performance optimization	✓	✓	×	✓
QFA	Device routing	✓	×	×	✓
	Image segmentation	✓	✓	✓	✓
	Performance optimization	✓	✓	✓	✓

[a]Algorithm complexity or efficiency: rapidness of the internal decision, execution of the prediction and encoding [54, 55]
[b]Efficacy: The algorithm follows the procedures in an ordered and coherent way for achieving the objectives, has correct acceleration, stability, and scalability capacities [56, 57]
[c]Processing: Set of steps of an algorithm which show connection and synergy among them [58]
[d]Accuracy: The percentage obtained by comparing the resulting value of the computing algorithm with the theoretical algorithm (mathematical calculation) [59]
[e]Complexity and efficacy: uses less resources [60, 61]

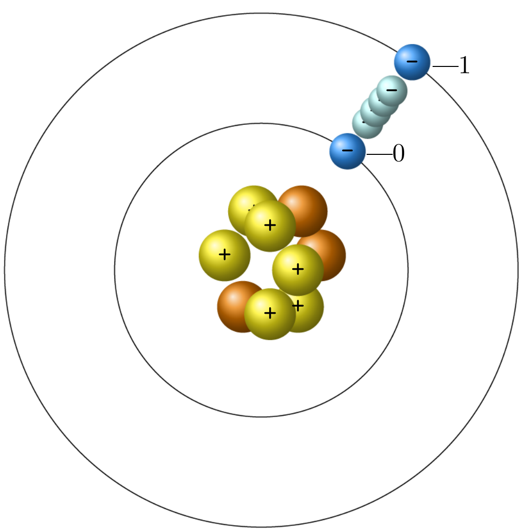

Fig. 1 Atom with 2 orbitals simulating 1 qubit

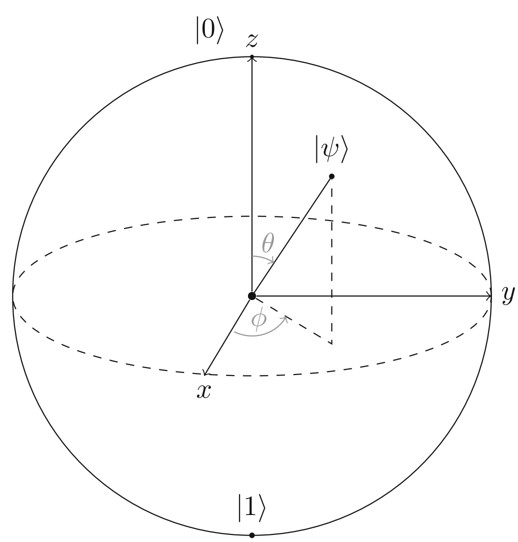

Fig. 2 Parallelism [66–68]

Step 3 Propose the dynamic of the system for explaining why it moves. For example, 3 hermitian or self-adjoint matrixes may be provided in a complex vector space V with a sesquilinear form $h : V \otimes V \to \mathbb{C}$, wherein h is antilinear (or conjugate linear). A hermitian form requires:

$$h(x, y) = \overline{h(y, x)}; \quad x, y \in V. \tag{4}$$

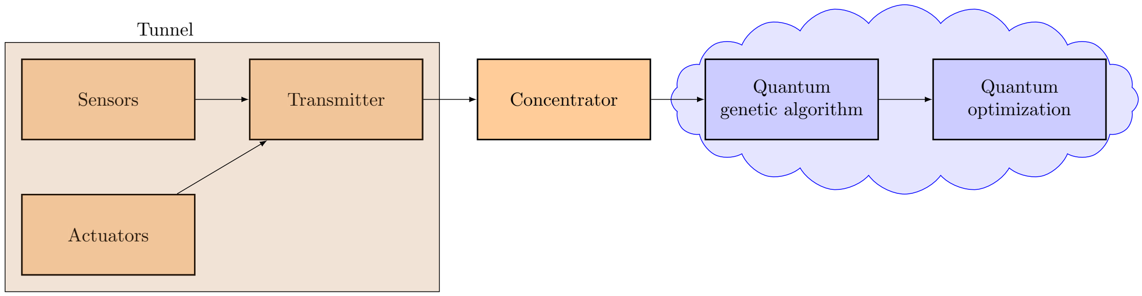

Fig. 3 General diagram of the experiment

Then, $E_i = V_i^H; i = 1, 2, 3$ is a real vector space with hermitian forms of V^H.

In a quantum system, an observable may be defined if the sum of the probabilities equals 1, that is, if it is known how many possible results there are in the observation, as shown in Eq. (5):

$$E_1 + E_2 + E_3 = 1. \tag{5}$$

It is possible to define the superposition and create two stable states A and B [73]:

$$E^A \rightarrow \mid A\rangle = \frac{\mid 0\rangle + \mid 1\rangle}{\sqrt{2}}; E^B \rightarrow \mid A\rangle = \frac{\mid 0\rangle - \mid 1\rangle}{\sqrt{2}}. \tag{6}$$

Step 4 Performing measurements.
With R the observable is measured and U shows the change in the state from system 1 to system 2:

$$S_1 \overset{U}{\rightarrow} S_2 \overset{R}{\rightarrow} P_i = \langle \psi \mid \widehat{E_i} \mid \psi \rangle. \tag{7}$$

In Eq. (7) the probabilities P_i with $i = 1, 2, 3$ for the three hermitian matrixes E_1, E_2, E_3, shown in step 2, are obtained. The notation for the self-adjoint hermitian operators $\widehat{E_i}$ is used:

$$\langle \psi \mid \widehat{E_i} \mid \psi \rangle.$$

Since $\widehat{E_i}$ is a Hermitian operator, both ket or bra may be used indistinctly. Hermitian operators have real eigenvalues and real, orthogonal eigenvectors [74].

The entanglement, until the time of the measurement, does not have a well-defined spin (measurement of the angular momentum due to the rotation of the particle about its own axis), and the variables of the system on which its value depends are not known. It is possible to know the state of an observable particle and its result as expressed by its probability.

Mathematical formulation

In this work, the results of the experiment shown in Fig. 3 are presented. Said experiment uses communication resources, which may be adapted to an underground mine. A scenario is created, in which a tunnel is provided with sensors and actuators that capture, store and transmit humidity, temperature, differential pressure, and CO_2 data. The devices are connected to a hub that sends a large amount of data to a central point, which is connected to the cloud computing infrastructure wherein a quantum genetic algorithm is applied and the quantum information is optimized.

Quantum Genetic Algorithms:. A QGA based on quantum mechanics is used. The algorithm searches for a global optimum from the chromosomes and the updating of the quantum gates [75].

Unlike the classical genetic algorithm in which the population evolves genetically by selecting, crossing, and mutating genes; QGA uses the method of chromosome evolution based on the quantum rotating door, increasing its performance and the interference crossover that provides a greater crossover of the [68] chromosomes.

In the evolutionary algorithm, it is possible to record a quantum chromosome gene with one or more qubits that can represent the probability of storing information in states 0, 1 or as a superposition of two quantum states [69] (see Eqs. (1) and (2)). By generalizing, as mentioned in the example of "Quantum systems" for n qubits, the chromosome with length n can be observed in 2^n states.

The quantum chromosome is updated from generation to generation to evolve the optimal individual [69]. As shown in Fig. 2, a quantum logic gate may be represented by a 2×2 matrix, wherein θ is the rotation angle:

$$\begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}. \tag{8}$$

The measurement process of each record allows changing the amplitude of the observable individual, wherein the search for the best solution is determined by updating the chromosome [76]. α y β are modified (see Eq. (1)) generat-

Fig. 4 **a** Installation of the communication system in the mine, **b** FSO transceiver within the mine tunnel, top: outside the tunnel, below: inside the tunnel

ing an entanglement and the best solution is obtained:

$$\begin{bmatrix} \alpha' \\ \beta' \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} x \begin{bmatrix} \alpha \\ \beta \end{bmatrix}. \tag{9}$$

In the encoding process, there is a chain of one or more input records for the measurement process of the observable [60]. The new quantum chromosome is obtained:

$$CQ = \begin{bmatrix} \alpha_1 \mid \alpha_2 \mid \cdots \mid \alpha_{n-1} \mid \alpha_n \\ \beta_1 \mid \beta_2 \mid \cdots \mid \beta_{n-1} \mid \beta_n \end{bmatrix} \tag{10}$$

wherein:

$$\mid \alpha \mid_i^2 + \mid \beta \mid_i^2 = 1 \,, \forall i = 1, 2, 3, \ldots, n. \tag{11}$$

The number of the population of quantum chromosomes is initialized:

$$\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}} \right). \tag{12}$$

A measurement is performed with a group of possible solutions according to the iteration in which the execution is [77]. The global optimum is sought, wherein each solution is particularly observed, saving the best value among the group of solutions [60].

Regarding the optimization formula to be used for the quantum genetic algorithm, the following are maximized in 3-D in real-time: the distance between the sensors Z_i with $i = 1, \ldots, 5$ being the environment or the neighborhood of the object of study X_k where k is the number of objects. Points in space that are close to a given point or that are close neighbors to a fixed point are sought [78].

It is had that by varying the time in a Δ_t it is possible to identify the optimal sensor for the object X_k in the algorithm Q. The optimization Q has stat-dynamic detection capabilities in a multi-object IoT environment, where the environment is stochastic and dynamic. The optimization Q also evaluates the IoT of the environment with respect to a specific object [15, 27].

The displacement is optimized with the following mathematical model [11]:

$$Q = \max \sum_{k=1}^{x} \sum_{j=1}^{z} \sum_{i=1}^{y} \left(w_{ijk} * \sqrt{Y_{ijk}} \right)^2. \tag{13}$$

With

$w_{ijk} \in (0, 1) \quad \forall i, j, k = (0, \ldots, 1)$ being the weight associated with the data.

Y_{ijk} being the environment parameters related to the object and the sensor.

Experiment

The feasibility of improving communications in an underground mining environment with an optimized quantum genetic algorithm will be studied in the experiment.

Description of the system

The experimental system represented in Fig. 3 has the following steps:

Step 1: data acquisition from humidity, gas, temperature, and pressure sensors. As shown in Fig. 4, the sensors are installed at a uniform distance from each other, such that the distance between devices is equidistant within a length of the measured environment. An object having a non-zero measurement probability within the environment is detected and controlled with an Arduino Mega 2560 microcontroller and a TTGO T-Beam Rev1 LoRa Node. The ID, key, frequency, and spread are obtained from each device.

With the radiofrequency nodes in the tunnel, the sensor information is sent to a hub with a fixed position, and an IoT network is built. The physical system is formed by a LoRaWAN Gateway (Raspberry pi + 3B + Hat Dragino PG 1301), a Gigabit Switch, and a Raspberry Pi 4. Three sensor nodes, among which two move away from the hub at regular distance intervals and one is kept at a fixed distance from the hub are configured for obtaining the data. The information is sent from each LoRa node to the hub, which sends the data to the local server.

At the next connection interface stage between sensors, the metrics Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR), associated with the range, instrument reach length (span), and response time variables, are obtained. For each sensor, the following attributes are captured: ID, name, description size, sensor, and device. The data are sent to the central hub and the Backhaul block.

Step 2: Optimization of the Quantum Genetic Algorithms. The data sent through the Backhaul block are received and the IoT devices are connected to a cloud server acting as a data repository in real-time. The "cloud" is a combination between The Things Network (TTN) server, that manages the LoRaWAN communication and computing services at a local server, wherein the services of optimization of the quantum-genetic algorithm are stored.

A quantum-genetic algorithm is built based on the methods of [79–81] and the IBM Quantum experience platform in the Cirq Python library. The quantum circuit is built inspired by the Deutsch–Jozsa (DJ) theory, which improves the distribution of the quantum keys that provide autonomy and robustness [82]. The DJ theory searches the optimum value of the objective function and can be used with the Hadamard logic gate (represented in Fig. 2 and Eq. (14) that allows quantum superposition with equally probable states.

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}. \tag{14}$$

The Hadamard gate is obtained as a linear combination of Pauli matrices and the Pauli gate may operate as a Not gate. It is to be mentioned that the Not gate is the one performing the chromosomic variation and may transform the probability amplitudes of the selected qubits, according to the probability of random mutation, to increase the diversity of the population and reduce the premature convergence, providing robustness since losses of a great part of the information of

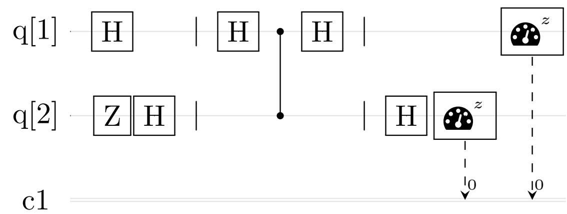

Fig. 5 Quantum System, Software IBM Q https://quantum-computing.ibm.com/composer/files/6a178b3b75b834bdc4531221f05ef24d2dccd6901192b1edf50c8be7a2104f7b

the population are avoided [61, 83]. The gates are combined and a quantum system as shown in Fig. 5 is built.

The experiment follows the iterative process shown in Fig. 6, which determines the global solution of the maximization problem [68]. The chromosome of the algorithm comes from the creation of a random vector matrix that generates the individual selection process and their genetic crossing. The aim of the process is to vary the chromosome among generations and has a mutation step that preserves the genetic diversity of the population [35, 60].

For modeling the quantum-genetic algorithm, an adaptation of Eq. (10) will be used as an evaluation or fitness function. Since the algorithm to be modeled is a kind of learning algorithm, it is possible to use neural networks [84, 85].

For accelerating the creation of neural networks and training the model (Fig. 7), the open source Python library keras^{GA} is included in Eq. (15). It is to be mentioned that the prediction is generated depending on the object (for example, people or vehicles working in the tunnel) and the parameters: SNR, RSSI, distance, and a random binary number used for generating the chromosome:

$$Q = \max \sum_{k=1}^{x} \sum_{j=1}^{z} \sum_{i=1}^{y} \left(w_{ijk} * \sqrt{\text{keras}^{\text{GA}}} \right)^2. \tag{15}$$

With

$$w_{i,j,k}, \epsilon, (0,1) \quad \forall, i, j, k, = (0, \ldots, 1)$$
$$\text{keras}^{\text{GA}} : \text{ parameter } Y \text{ in 3-D.}$$

Experimental results

The GA and QGA algorithms were tested with the objective function shown in Eq. (15) and the database obtained from the laboratory with the parameters SNR, RSSI, the distance and binary number. Ten iterations of five generations each are generated and, as shown in Fig. 8a and b, the quantum genetic

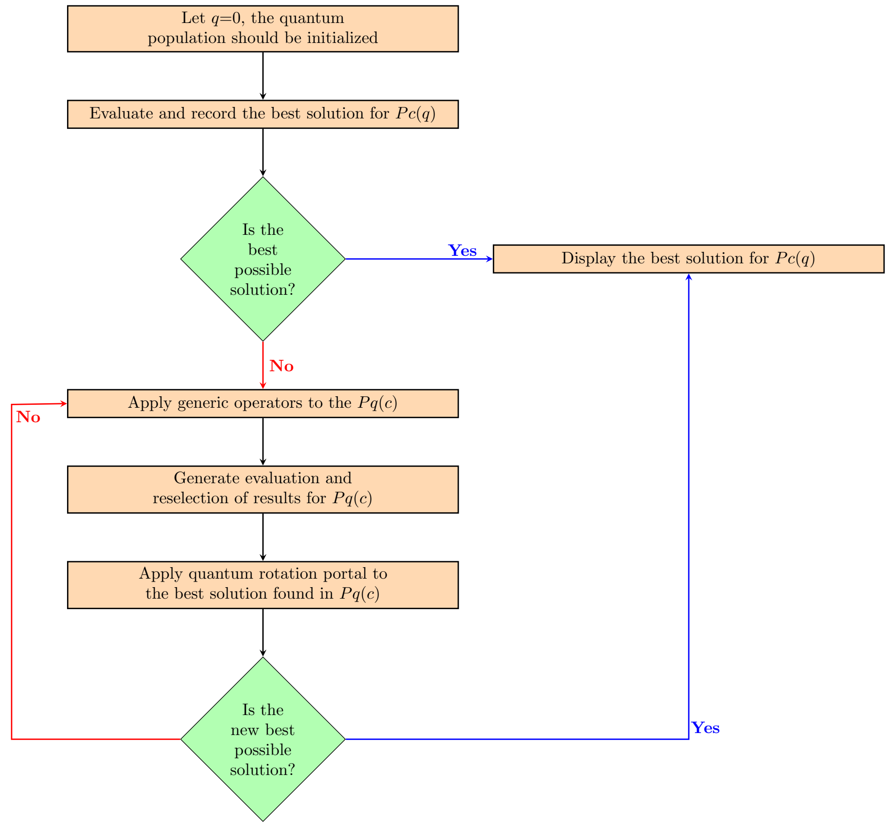

Fig. 6 Selection process. $Pc(q)$ corresponds to the quantum population defined according to the input record defined as qubits. $Pq(c)$ corresponds to the quantum population defined according to the genetic operators for the recorded chromosome. Based on [81]

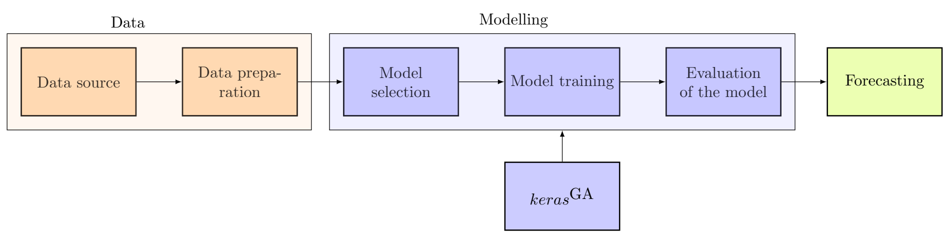

Fig. 7 Forecast

algorithm obtains a higher fitness and a shorter computation time than the GA.

Figure 9a shows the distribution of the results. It is observed that GA converges rapidly in the second generation with values close to 1.5173. In relation to QGA, it can be seen in Fig. 9b that the values found are relatively lower at the beginning, and in generation 4 it approaches the global optimum close to 1.9365.

By comparing the metrics in Table 6, the following advantages of using the quantum genetic algorithm are observed: it gets a higher accuracy, it has a higher computed true experimental value for the objective function, and it is more efficient since a better performance in less average time and costs is obtained.

Finally, in the experiment, the following considerations were taken:

- A sensor package is not located at a point in the environment, at a shorter distance than another package of the same type.
- Considering the technical specifications of the sensors since the precision and accuracy can be improved for the sensor package closest to the object.

Discussion

Analysis of QGA and its optimization function

In nonlinear optimization problems, effective and efficient strategies are required for solving complex problems [86]. It is important to find local optima that give a better solution in the search space than those used as regional strategies that are close to the objective function [87].

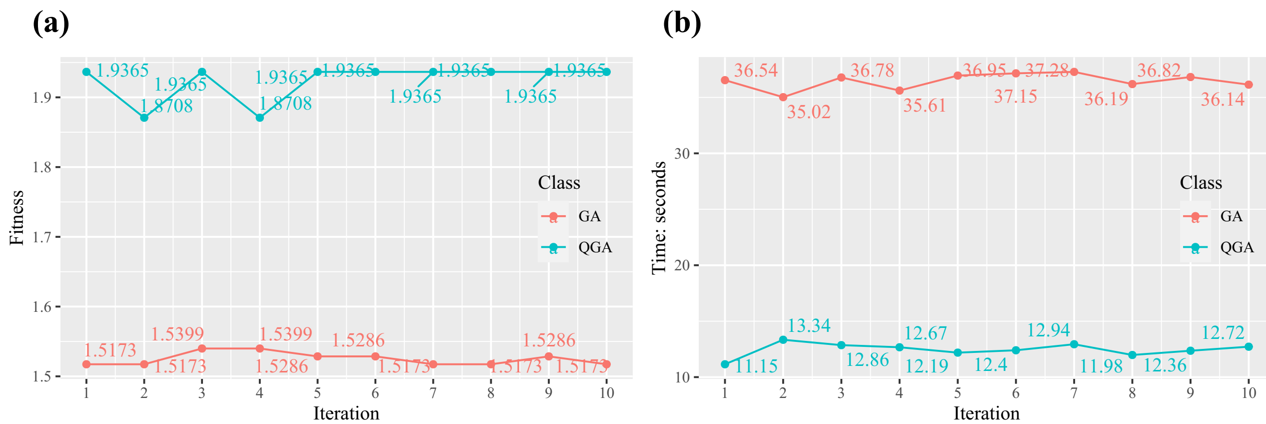

Fig. 8 **a** Fitness and **b** time

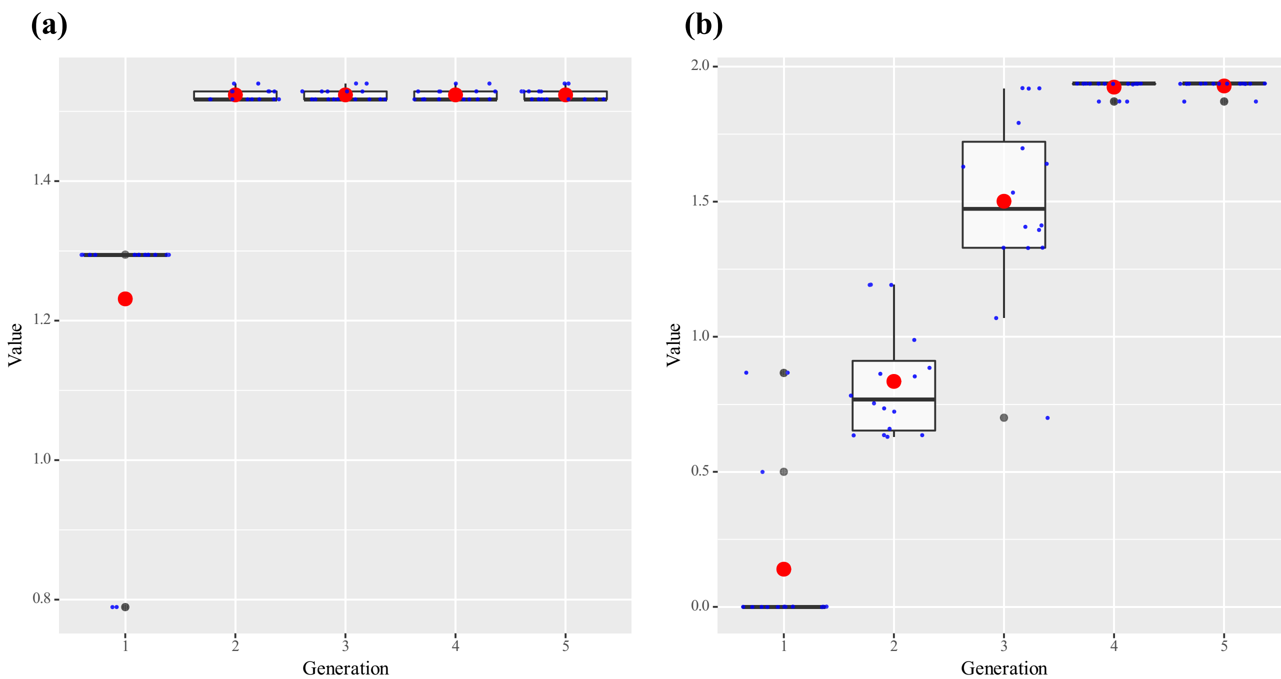

Fig. 9 **a** GA and **b** QGA. The red dot represents the average

Table 6 Comparative table

Metrics	GA	QGA
Real optimization value	1.9365	1.9365
Experimental optimization value	1.5252	1.9234
Algorithm performance [%]	78.76	99.32
Average response time [s]	36.45	12.46

In relation to the experiment, a rapid convergence was observed that could be caused by entanglement [88]. It should be said that the speed of convergence would not ensure the existence of the optimum and in the case the optimum strays from the local solutions, the solutions could not have a global convergence [89]. On the other hand, in a quantum algorithm, it is possible to have different tuning strategies of the quantum revolving door that could prematurely converge locally at a slow rate, in a state of stagnation [69].

In the optimization function, further analysis of the chromosome function of the quantum genetic algorithm is required [84]. It is necessary to improve the quantum genetic

Table 7 Analysis of advantages and disadvantages of quantum systems

Criteria	Advantages	Disadvantages
Computing tasks	More efficient with quantum properties than in traditional systems. This is because in quantum systems 2^n superposition components are involved in a single state, whereas in classical systems 2^n possible states are described by n bits [90]	Traditional computers can neither read nor store a quantum state, therefore the greater efficiency for performing the tasks is not verified [91]
Algorithm processing	Most of the information is not accessible to reading by other means and it has great processing and execution speed capacities for solving stochastic problems [58, 90]	The processing of information requires complex coding, with an important hardware overload, for performing efficient quantum processes in a robust system [92]
Integrated data	By simulating evolution with quantum entanglement, it is possible to exponentially increase the amount of data needed to describe the state, therefore significantly decreasing the execution time [90]	The quality of the information is not ensured, therefore, falsification and collusion errors can occur due to malicious information emitters [93]
Execution environment	If entanglement is physically performed in a general state of the quantum or classical system of 2^n levels, linear resources are required [90]	There is a dependence on the quantum platform responsible for generating entanglement, establishing a reliable quantum link between two connected nodes. The entanglement must be one of the basic service elements offered by a system being executed in a quantum network node [94]
Non-locality action	The quantum entanglement does not depend on the non-locality [95]	The characteristics of non-classical correlations, non-locality, and entanglement show direct influence on each other, generating a non-locality dependence [96]
Algorithm implementation	The quantum algorithm provides a greater accuracy in the response by operating between different energy levels, which in the case of electrons is low [97]	Each algorithm must be built based on a quantum circuit model and validated according to the problem to be addressed. Therefore a specific quantum algorithm cannot be extrapolated to a different context [98]

algorithm by analyzing other optimization functions on the chromosome, which do not use only the fitness function as the traditional genetic algorithm and which deliver solutions that have fast convergence to the local optimum. It is noted that different scenarios can be generated in which: (1) the quantum bit of the chromosome is not close to the optimum or (2) in case it is in the optimum, a new chromosome is generated that can move away from the current optimum and affect the convergence of the algorithm [68].

More research is needed on hybrid quantum algorithms, wherein metaheuristics that generate a global search and optimization methods that perform an efficient local search are combined [89].

On the other hand, since the quantum genetic algorithm is integrated into a communications system as shown in Fig. 4, it can exhibit the advantages and disadvantages that are exposed in Table 7.

Feasibility technological

QGA

In the experiment it was possible to generate the QGA algorithm since with the Python Numpy library the spin vector is built and the quantum superposition simulation is performed. Qiskit, SymPy and QuTIP are used to build the quantum circuits and implement the quantum algorithms.

Future research will use IBM Quantum Experience to bring the code to the mining company's Amazon Web Services (AWS) and Google Cloud Platform (GCP) cloud monitoring service platforms.

Conceptual design

Figure 10 shows the QGA conceptual model that includes the following steps: (1) the tunnels within the IoT network in mining with the sensors that extract environmental data from the ventilation system; (2) the genetic quantum optimization space which will be hosted in the industrial routers; (3) a control center that will monitor in real time the environmental variables to make timely decisions and avoid risks, for example, if there is excess CO_2, a backup fan could be alerted or activated.

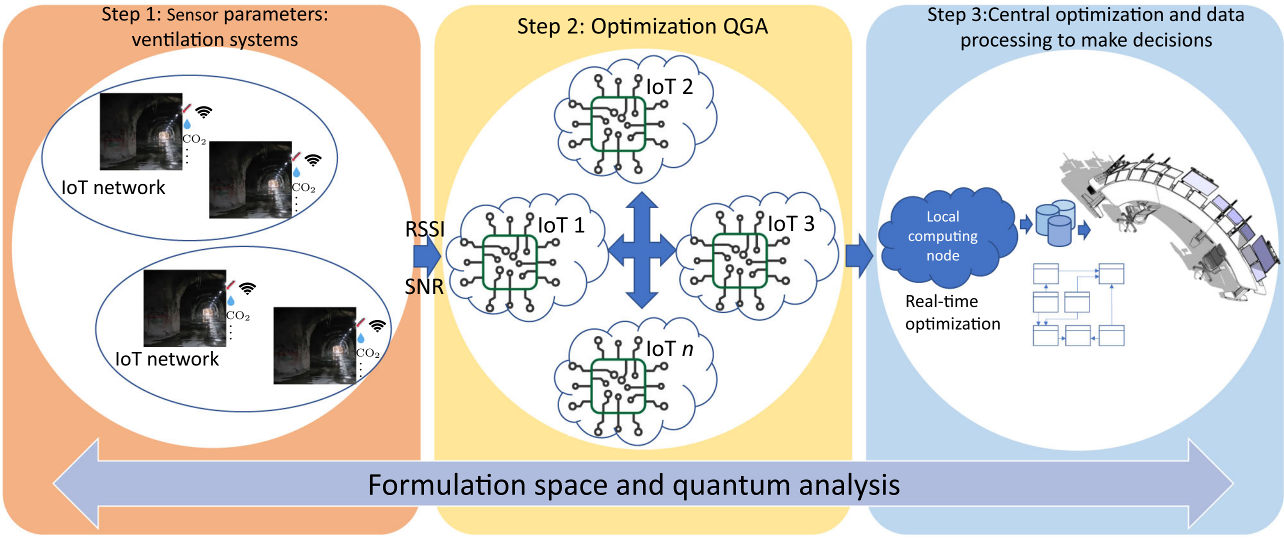

Fig. 10 QGA conceptual model

Advantages and limitations

Advantages

As mentioned in "Literature review", it is feasible to use quantum genetic algorithms in the field of telecommunications which are more robust than conventional algorithms. It is observed that QGA meets the criteria required for the implementation of the experiment shown in "Experiment" since it can process data, performs mathematical modeling, detects objects and can determine energy efficiency (see Table 4).

Another advantage is that incorporating QGA in the communication system makes data transmission more robust and ensures a higher percentage of availability of ventilation systems inside a mine. By receiving more reliable, real-time data on flows within the mine (air flow rates, gas concentrations, temperature conditions, etc.), decision-making and information management would be more efficient and effective [99]. Secure and robust communication would allow for real-time reporting of hazards and timely evacuation of workers [17].

Limitations

Another limitation is that the implementation of QGA depends on the execution environment. In the experiment described in "Experiment", it was complex to build a QGA runtime environment that could be adapted to a real mining tunnel situation. Many tests were performed in the laboratory to determine which parameters and/or metrics of the sensors and actuators comply with the postulates of quantum mechanics which requires uncertain and non-deterministic data. RSSI and SNR metrics associated with range, span and response time were selected.

Another difficulty was the creation of the database with unstructured information; it was necessary to clean and structure the data so that it could be processed with the quantum genetic optimization algorithm.

On the other hand, to develop a system such as the one shown in Fig. 10 a multidisciplinary group is required since knowledge of different areas related to: Quantum Mechanics, Heuristic Optimization, Electronics, Informatics and Computing and with the knowledge of Data Management to help in the decision-making process.

Conclusions

In this bibliographical review it is shown that there are more practical than analytical cases that have been studied in the field of quantum computing, and that there has not been enough research regarding the quantum approach compared to other traditional methods [10]. In addition, in Tables 1 and 5 it was determined that Telecommunications is the industry field in which quantum algorithms with IoT have been analyzed the most; and that it is possible to obtain metrics for object detection, data processing, and data modeling.

In "Literature review" it was shown that it is possible to use hybrid algorithms that work with metaheuristics and quantum computing. Despite the fact that there are industrial applications in the literature, it has been difficult to understand how they can be applied to a real case since it is necessary to have knowledge and understanding of different fields, such as: quantum mechanics, metaheuristics, function optimization, programming, data analytics, and electrical engineering.

Despite the multidisciplinary nature of the case study presented in this work, it was possible to integrate experimental data obtained with sensors with input parameters of the quantum genetic algorithm to obtain results that are close to the global optimum.

It is necessary to continue investigating and analyzing other optimization functions that could provide more effective and efficient local optimal solutions. If better solutions are obtained, more secure communication in an underground tunnel environment could be obtained with more robust support. This could be implemented into a monitoring and control system that allows to provide safe and optimum environmental conditions for workers as they move through the mine, due to, for example, the timely and safe connection that would exist with the ventilation system.

In the future, new methods and protocols are required to transmit quantum information securely and in real time, so that in the future it will be possible to have a quantum internet in companies to ensure communication between the sender and receiver [100]. With quantum, it would be possible to group quantum devices in a network in the cloud, and it would also be possible to change the configuration currently used in mining to transmit data over the internet with fibre-optic cable networks with short-range coverage that require repeaters (a situation that generates vulnerability) [101].

In our opinion, it should be noted that with the influence of artificial intelligence, there is a growing need for communications systems that are more secure for data transmission and that can withstand the changes brought about by the larger 5 G technology. With quantum, data could be sent over long distances, with secure cryptography.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest in the publication of this paper.

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