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Quantum Computing-Inspired Genetic Algorithm for Network Optimization in WSN

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Abstract: This study presents a pioneering Quantum Computing-Inspired Genetic Algorithm (QIGA) designed for the efficient optimization of Wireless Sensor Networks (WSN). Leveraging the principles of quantum computing, QIGA employs a unique approach to address the complex routing challenges in WSNs. The algorithm starts with the quantum encoding of candidate routes, utilizing quantum bits (qubits) to represent multiple routes simultaneously through principles like superposition and entanglement. Genetic operations, including crossover and mutation, are then applied in the quantum domain to explore diverse solution spaces. The quantum-encoded routes are subsequently decoded into classical routes, and their fitness is evaluated based on crucial WSN optimization criteria, such as energy efficiency, latency, and reliability. The study integrates quantum-inspired selection strategies to determine the next generation of routes, fostering adaptability and efficiency in the optimization process. Through iterative refinement, QIGA aims to converge towards optimal routing solutions for WSNs. The proposed algorithm showcases a quantum-inspired paradigm that holds promise for addressing the intricate challenges of network optimization in WSNs. The study contributes to the evolving landscape of quantum computing applications in networking and lays the foundation for future advancements in quantum-inspired algorithms tailored for practical implementation in WSN environments.

Keywords: *Quantum computing, genetic algorithm, network optimization, wireless sensor network (WSN), quantum-inspired routing.*

1. Introduction

Wireless Sensor Networks (WSNs) have become the backbone of modern technological infrastructures, orchestrating a seamless fusion between the physical and digital worlds [1]. These networks, comprised of spatially distributed sensors, are pivotal in monitoring environmental conditions, facilitating healthcare applications, and enabling efficient industrial processes. However, the inherent constraints of WSNs [2], such as limited energy resources, dynamic topologies, and communication overhead, pose formidable challenges to their optimization. The pursuit of innovative solutions has led researchers to explore cutting-edge computational paradigms, and within this context, quantum computing emerges as a beacon of promise.

In recent times, there has been a growing interest in quantum-inspired algorithms due to their parallel processing capabilities, demonstrating the ability to yield improved solutions within a reasonable timeframe and with a reduced population size compared to conventional counterparts in various scenarios. Particularly in Wireless Sensor Networks (WSNs), these quantum-inspired algorithms find application primarily in routing and clustering tasks [3].

The integration of quantum computing principles into algorithmic design represents a paradigm shift, unlocking new horizons for problem-solving capabilities. Quantum Computing-Inspired Genetic Algorithm (QIGA) is at the forefront of this endeavor, offering a groundbreaking approach to address the intricate routing challenges that characterize WSNs. As the backbone of communication in WSNs, the efficiency of routing algorithms directly impacts critical factors such as energy consumption, latency, and overall network reliability [3].

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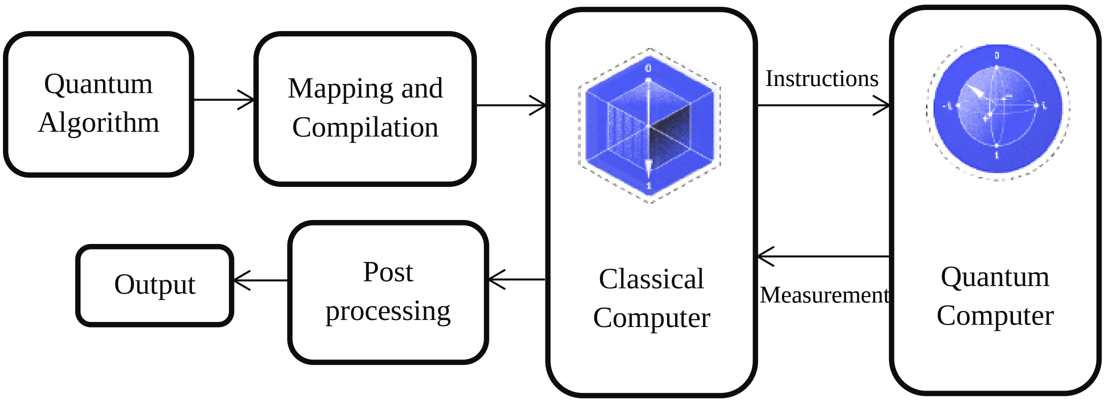

Fig. 1. Optimization Structure based on Quantum Computing

Figure 1 shows the general optimization structure of a quantum computing-inspired algorithm. Quantum computing, rooted in the principles of quantum mechanics, introduces the concept of qubits—quantum bits [4,5]. Unlike classical bits that exist in binary states (0 or 1), qubits can exist in superpositions of these states, allowing for the simultaneous representation of multiple possibilities [6]. Additionally, entanglement enables the correlation of qubits' states, even when physically separated. These quantum phenomena pave the way for a novel approach to algorithmic design, where quantum-inspired principles can be harnessed to transcend the limitations of classical computing.

In the context of WSNs, where efficiency and adaptability are paramount, quantum computing principles present an intriguing avenue for exploration. QIGA, as a testament to this exploration, initiates its optimization journey with the quantum encoding of candidate routes. By utilizing qubits to represent multiple routes simultaneously, the algorithm taps into the power of superposition and entanglement, offering a quantum-inspired lens through which to view and navigate the complex solution space of WSN routing.

QIGA distinguishes itself through its ingenious fusion of genetic algorithms and quantum computing principles. Genetic algorithms, inspired by the process of natural selection, introduce stochasticity and heuristic exploration in the optimization process [7]. In the quantum domain, crossover and mutation operations are applied to the quantum-encoded routes, opening up a realm of possibilities that extend beyond the capabilities of classical genetic algorithms [8]. The subsequent decoding of quantum-encoded routes into classical routes facilitates the evaluation of their fitness based on critical WSN optimization criteria, including energy efficiency, latency, and reliability.

To further enhance the adaptability and efficiency of the optimization process, QIGA incorporates quantum-inspired selection strategies [9]. These strategies leverage the quantum-inspired nature of the algorithm, ensuring that the next generation of routes is determined with a level of sophistication that surpasses classical counterparts. The iterative refinement process unfolds, guided by quantum-inspired principles, as QIGA aims to converge toward optimal routing solutions for WSNs.

This study contributes to the evolving landscape of quantum computing applications in networking, specifically in the realm of WSN optimization. By introducing QIGA, a pioneering algorithm that navigates the intersection of quantum computing and genetic algorithms, the research lays the foundation for future advancements in quantum-inspired algorithms. As quantum computing technologies mature, the practical implementation of such algorithms holds immense potential for transforming WSNs, fostering adaptability, sustainability, and efficiency in the era of interconnected devices and smart environments. In the subsequent sections, the paper delves into the detailed methodology of QIGA implementation, presents experimental results, and discusses the broader implications and potential avenues for further research in this dynamic field.

2. Literature Review

[10] Introduced a unique routing protocol based on Quantum Ant Colony Optimization (QACO), deviating from traditional root-based approaches and drawing inspiration from quantum mechanics. This protocol initiates reactive and proactive phases at the source node, leveraging the QACO methodology. Notably, this multi-gateway multi-path protocol minimizes the need for extensive network broadcasts. Quantum parallelization and the entanglement of quantum states present opportunities for significantly improving the efficiency of exploring the solution space in large optimization problems. Based on the progressive findings, the newly proposed protocol demonstrates superior performance compared to two widely recognized traditional protocols, AODV and HWMP, specifically in terms of the duration required for gateway discovery in both the exploratory phase and the proactive path.

[11] Introduced the Quantum Annealing Bat Algorithm (QABA) as an enhancement to improve localization accuracy and broaden applicability. QABA integrates quantum evolution and simulated annealing convergence strategies into the bat algorithm framework, aiming to enhance the overall operational efficiency. Additionally, to address the algorithm's overall search and convergence challenges, tournament and natural selection mechanisms are incorporated to expedite optimization during fast convergence. In a simulation involving 22 standard functions, QABA demonstrated superior performance over the comparison algorithm across an average of 14 functions, while closely approaching the performance of other algorithms in the remaining 8 functions.

[12] Implemented the Quantum-based Salp Swarm Algorithm (QBSSA) within both a range-based and range-free framework. The efficacy of established methods, including Particle Swarm Optimization (PSO) and H-best Particle Swarm Optimization

(HPSO), was assessed and compared against QBSSA. In this approach, a mobile anchor node traverses the entire network following a Hilbert path topology, while mobile targets are localized through random deployment within the communication area. The adoption of the Hilbert trajectory serves to mitigate the impact of Line of Sight propagation.

[13] Introduced an enhanced metaheuristic method termed Quadri-valent Quantum Inspired Gravitational Search Algorithm (QQIGSA), this study addresses Quadri-valent problems. The algorithm incorporates a Not Q-Gate and parallelizes QQIGSA on a graphics processing unit for accelerated performance. To further boost efficiency, the method employs a heterogeneous platform with parameters duly justified. Leveraging multi-core and CPU–GPU platforms, the parallelized QQIGSA is deployed in wireless sensor networks, optimizing sensor operational modes by minimizing connectivity, specific applications, and energy-related parameters. The Quadri-valent algorithm, thus developed, categorizes sensor states into low signal range, high signal range, cluster head, and inactive for enhanced network functionality.

[14] Introduced the Quantum Genetic Energy Efficient Iteration Clustering Routing Algorithm (QGEEIC) designed for wireless sensor networks. QGEEIC employs energy-efficient iteration for cluster head selection and utilizes a quantum genetic algorithm for parameter optimization. The quantum genetic algorithm, employing a double-chain encoding method, fine-tunes clustering parameters. Experimental findings reveal a notable enhancement, with the time until the first node depletion extended by 492% compared to LEACH and 71.8% compared to HEED.

3. Methodology

The methodology employed in this study involves a comprehensive framework for the development, implementation, and evaluation of the Quantum Computing-Inspired Genetic Algorithm (QIGA) tailored for the optimization of Wireless Sensor Networks (WSNs).

1. Problem Formulation:

Define the optimization objectives and constraints specific to WSNs, considering factors such as energy efficiency, latency, and reliability. Formulate the routing problem as an optimization challenge, where the goal is to discover routes that minimize energy consumption while meeting latency and reliability requirements.

2. Quantum Encoding of Candidate Routes:

Initiate the optimization process by encoding candidate routes in the quantum domain using quantum bits (qubits). Employ principles of superposition and entanglement to represent multiple routes simultaneously. Develop a quantum encoding mechanism that captures the complexity and diversity of potential routes within the WSN.

3. Genetic Operations in the Quantum Domain:

Apply genetic operations, including crossover and mutation, within the quantum domain to explore diverse solution spaces. Leverage quantum-inspired principles to enable simultaneous exploration of multiple potential solutions, ensuring a more thorough exploration of the optimization landscape compared to classical genetic algorithms.

4. Decoding Quantum-Encoded Routes:

Translate quantum-encoded routes back into classical routes for evaluation. Develop a decoding mechanism that accurately converts quantum states into viable routing solutions. Ensure that the decoding process retains the diversity introduced during quantum encoding, providing a rich set of candidate routes for evaluation.

5. Fitness Evaluation:

Assess the fitness of decoded routes based on WSN optimization criteria, including energy efficiency, latency, and reliability. Develop fitness functions that quantify the performance of each route, considering the trade-offs between energy consumption and communication delays while ensuring network reliability.

6. Quantum-Inspired Selection Strategies:

Incorporate quantum-inspired selection strategies to determine the next generation of routes. Develop selection mechanisms that leverage the principles of quantum computing, such as quantum parallelism, to intelligently choose routes for further exploration. Introduce adaptability and efficiency into the optimization process through quantum-inspired selection.

7. Iterative Refinement:

Implement an iterative refinement process wherein the algorithm evolves successive generations of routes. Apply quantum-inspired genetic operations, decoding, fitness evaluation, and selection iteratively. Monitor the convergence of the algorithm towards optimal routing solutions, adapting to the dynamic nature of WSNs.

8. Experimental Setup:

Conduct extensive experiments to validate the performance of QIGA. Utilize simulation environments or real-world WSN testbeds to assess the algorithm's effectiveness in optimizing routing solutions. Consider varying network sizes, topologies, and traffic patterns to ensure the robustness and adaptability of QIGA.

9. Performance Metrics:

Quantitatively evaluate the performance of QIGA using key metrics such as energy consumption, latency, and reliability. Compare the results with baseline models, including classical genetic algorithms and traditional routing approaches, to assess the quantum-inspired algorithm's efficacy in addressing WSN optimization challenges.

10. Analysis and Interpretation:

Analyze the experimental results, highlighting the strengths and weaknesses of QIGA in comparison to existing approaches. Interpret the findings in the context of WSN optimization, providing insights into the potential advantages of quantum-inspired computing in addressing the intricate challenges of network optimization in WSNs.

This comprehensive methodology aims to lay the groundwork for understanding the efficacy of Quantum Computing-Inspired Genetic Algorithm (QIGA) in optimizing Wireless Sensor Networks, contributing to the broader landscape of quantum computing applications in networking.

3.1 Quantum Computing Inspired Genetic Algorithm

The Quantum Computing-Inspired Genetic Algorithm (QIGA) represents a cutting-edge approach to problem-solving, particularly in the domain of optimization for complex systems such as Wireless Sensor Networks (WSN). This innovative algorithm draws inspiration from the principles of quantum computing and genetic algorithms, combining their strengths to tackle the intricate challenges posed by WSNs.

Quantum Encoding:

At the heart of QIGA lies its quantum encoding mechanism. This involves the use of quantum bits (qubits) to represent candidate routes within the WSN. Unlike classical bits, qubits can exist in multiple states simultaneously through principles like superposition and entanglement. This quantum encoding allows QIGA to explore and evaluate numerous potential routes concurrently, leveraging the inherent parallelism of quantum systems.

Genetic Operations in Quantum Domain:

QIGA incorporates genetic operations such as crossover and mutation but with a quantum twist. These operations are applied in the quantum domain, introducing a unique dynamic to the exploration of diverse solution spaces. The quantum-inspired genetic operations enhance adaptability, allowing the algorithm to navigate the complex and ever-changing topology of WSNs more effectively. Following quantum encoding and genetic operations, QIGA employs a decoding mechanism to translate quantum-encoded routes back into classical routes. The decoded routes are then evaluated based on crucial WSN optimization criteria, including energy efficiency, latency, and reliability. This fitness evaluation step ensures that the algorithm produces solutions that meet the specific requirements of WSNs, balancing the trade-offs between energy consumption and communication delays.

One of the distinguishing features of QIGA is the incorporation of quantum-inspired selection strategies. These strategies leverage the principles of quantum computing, such as quantum parallelism, to intelligently determine the next generation of routes. This introduces a level of sophistication in the selection process, enhancing adaptability and efficiency in the optimization journey.

The proposed Quantum Computing-Inspired Genetic Algorithm presents a promising paradigm for addressing the intricate challenges of network optimization in WSNs. By harnessing the unique characteristics of quantum computing and combining them with the heuristic exploration of genetic algorithms, QIGA offers a novel and powerful tool for finding efficient and adaptive routing solutions. This pioneering algorithm contributes to the evolving landscape of quantum computing applications in networking, laying the foundation for future advancements tailored for practical implementation in WSN environments. The procedure of quantum inspired genetic algorithm is depicted in the below algorithm.

QIG Algorithm

```
Initiate
    Set the iteration counter t ← 0
    initialize the quantum state Q(0)
    create the initial population P(0) by observing Q(0)
    evaluate the fitness of individuals in P(0)
    store the best solution from P(0)
    while the termination-criterion is not met:
        t←t+1
        form the population P(t) by observing the quantum state Q(t-1)
        evaluate P(t)
        update the quantum state Q(t) using quantum gates $U(\theta_t)$
        store the best solution from P(t)
    end while
end
```

Figure 2 represents the proposed architecture diagram of quantum inspired genetic algorithm. Quantum Computing-Inspired Genetic Algorithms (QCIGA) combines principles from quantum computing and genetic algorithms to solve optimization problems more efficiently than classical algorithms. Here's a high-level overview of the working process:

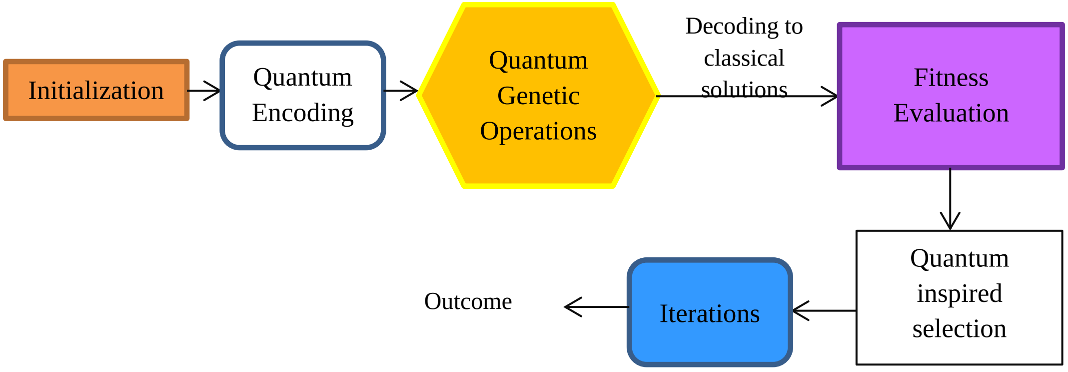

Fig. 2. Quantum Inspired Genetic Algorithm Architecture

Encoding Solutions:

Quantum computing relies on qubits, which can exist in multiple states simultaneously due to superposition. In QCIGA, solutions to optimization problems are encoded into quantum bits or qubits. Classical genetic algorithms use binary strings to represent solutions. In QCIGA, these binary strings are transformed into quantum states.

Quantum Superposition:

Qubits in superposition can represent multiple possibilities simultaneously. This property allows QCIGA to explore multiple potential solutions in parallel.

Quantum gates are applied to manipulate qubits and perform operations in a way that takes advantage of superposition.

Quantum Crossover and Mutation:

Crossover and mutation are fundamental genetic algorithm operations. In QCIGA, these operations are performed using quantum gates to create new quantum states.

Quantum superposition enables the algorithm to explore a larger solution space efficiently.

Quantum Parallelism:

Quantum parallelism allows QCIGA to evaluate multiple potential solutions simultaneously. This is in contrast to classical genetic algorithms that evaluate solutions sequentially.

Parallelism can significantly speed up the search for optimal solutions.

Quantum Measurement:

At the end of each iteration, quantum measurement is performed. This collapses the superposition of qubits into a single solution.

The probability of measuring a particular solution is determined by its fitness value. Higher fitness solutions have a greater chance of being selected.

Classical Post-Processing:

The measured solutions are then post-processed classically. This involves updating the population based on the selected solutions, applying classical genetic algorithm operators such as crossover and mutation, and evaluating the fitness of the new population.

Iteration:

Steps 2-6 are repeated for multiple iterations until a termination condition is met, such as reaching a specified number of generations or finding a satisfactory solution.

4. Results and Discussion

In conventional computing, operations are conducted using bits, which are limited to the values 0 or 1. In contrast, quantum computing utilizes qubits, capable of existing in states of 0, 1, or both simultaneously. This unique property empowers quantum computing to address intricate problems with exceptional efficiency. To illustrate, consider the task of locating a specific item within a list of N items. On a classical computer, an average of N/2 items must be checked, and in the worst case, all N items need verification. However, by employing a quantum algorithm like Grover's search, the item can be found after inspecting approximately $\sqrt{N}$ of them. This showcases a remarkable enhancement in processing efficiency and time utilization.

The condition of a qubit undergoes alteration through the application of quantum gates. Qubit states are modified by employing rotation gates. The quantum matrix representation of an n-bit Q bit string is utilized.

$$\begin{bmatrix} \alpha_1| & \alpha_2| \dots . \alpha_n \\ \beta_1| & \beta_2| \dots . \beta_n \end{bmatrix} \qquad (1)$$

Where,

α and β are the probability amplitudes of the corresponding states.

$$|\alpha_i|^2 + |\beta_i|^2 = 1, i = 1,2, \dots . , n \qquad (2)$$

The quantum bits' states are refreshed by employing the Rotation gate technique, as illustrated below:

$$\begin{bmatrix} \alpha_{new} \\ \beta_{new} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} \alpha_{prev} \\ \beta_{prev} \end{bmatrix} \qquad (3)$$

Where θ represents the rotation angle for each qubit, directing towards either 0 or 1 based on the sign. α_{new} and β_{new} signify the updated values, whereas α_{prev} and β_{prev} denote the values from the previous iteration. In traditional quantum genetic algorithms, the determination of θ relies on a specific adjustment strategy, typically maintaining a constant value around 0.01π. Initially, a sizable rotation angle is established in the early stages of evolution to rapidly traverse the entire range and identify the region with optimal values. To precisely pinpoint the optimal value, the rotation angle is gradually reduced as the evolution progresses.

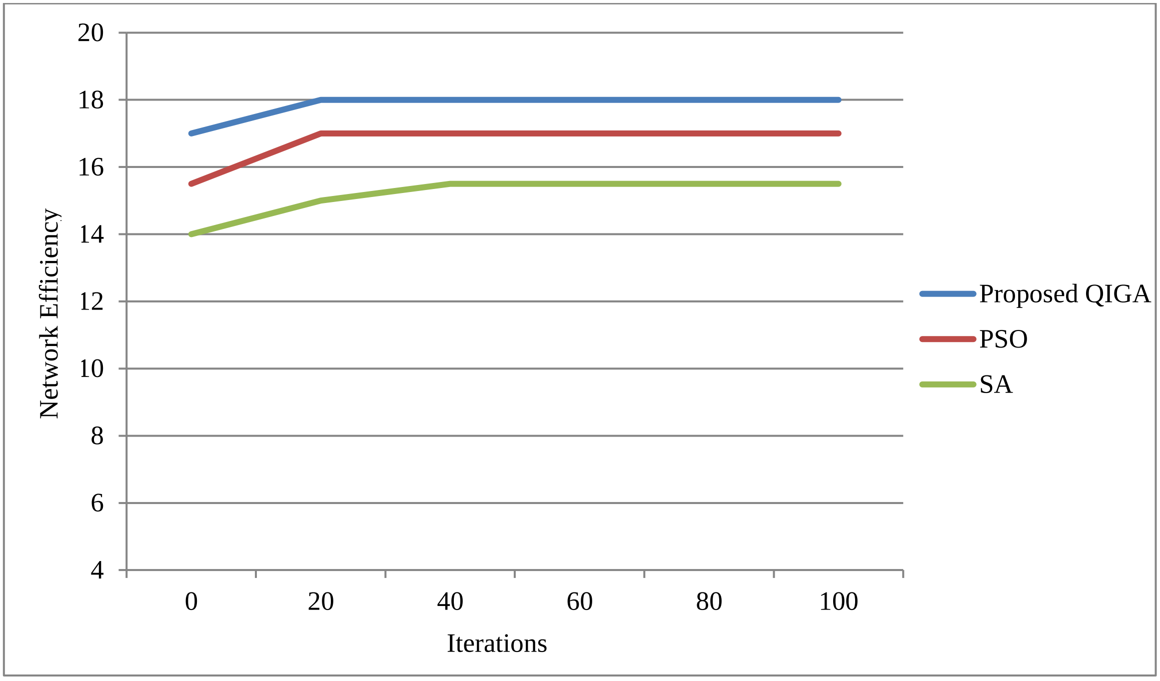

Figure 3. Network Efficiency Comparison

The network optimization in wireless sensor networks based on QIGA is evaluated and the output graph is plotted based on the number of iterations. The energy efficiency of the network is computed and represented in Figure 3. It shows that the proposed method achieves the highest efficiency than the PSO (Particle Swarm optimization) and SA (Simulated Annealing) techniques.

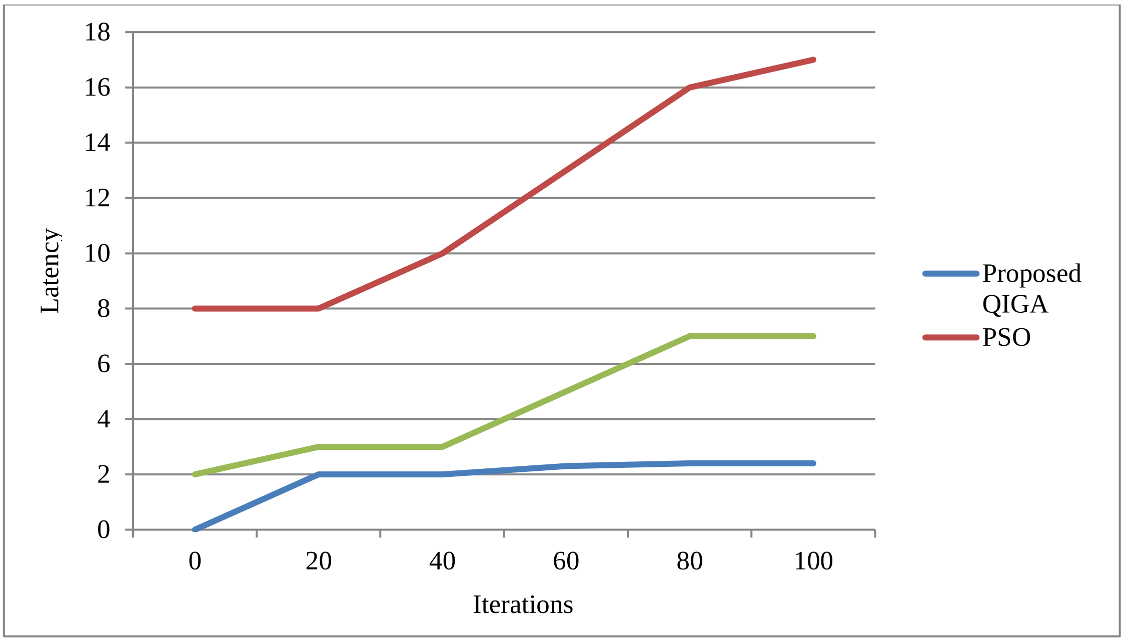

Figure 4. Latency Comparison

The network optimization in wireless sensor networks based on QIGA is evaluated and the output graph is plotted based on the number of iterations. Achieving the lowest possible latency is generally desirable for optimal system performance. The latency of the network is computed and compared with other techniques as shown in Figure 4. It shows that the proposed method achieves the lowest possible latency than the PSO (Particle Swarm optimization) and SA (Simulated Annealing) algorithms.

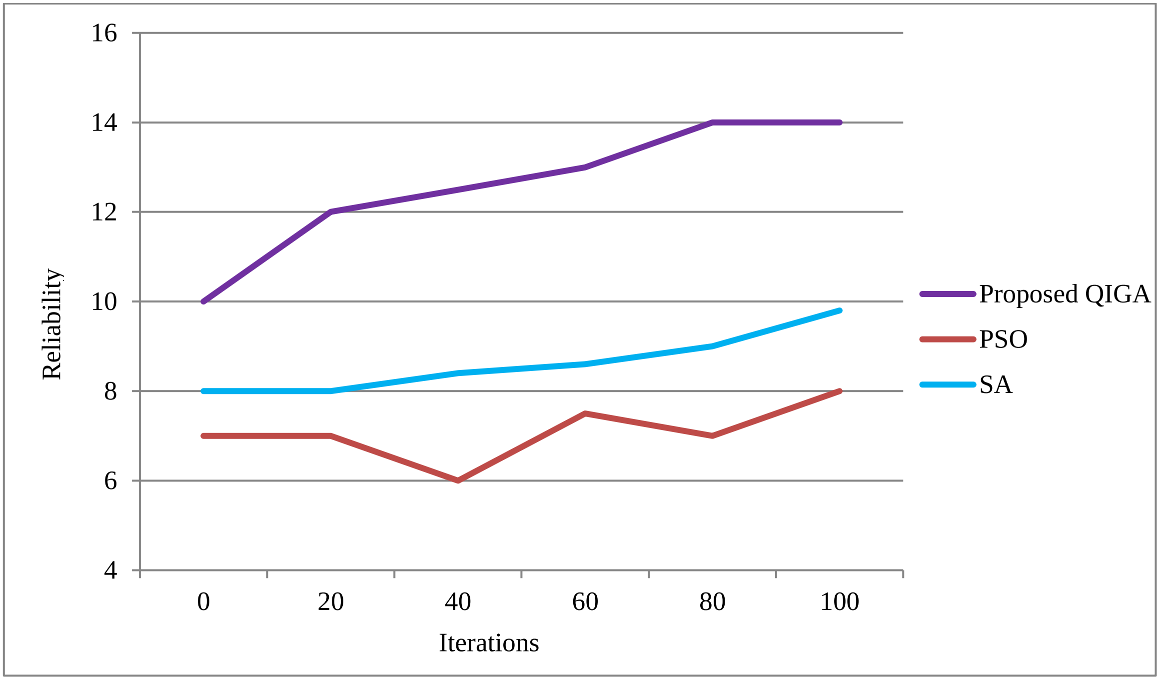

Fig. 5. Reliability Comparison

A highly reliable system can be depended upon to function correctly and consistently under various conditions. In the context of quantum computing, ensuring the reliability of quantum gates and operations is crucial. Figure 5 shows the reliability comparison between the proposed QIGA and PSO and SA. The result reveals that the proposed method achieves the highest reliability when compared to other algorithms. Based on the overall network optimized results, the proposed QIGA attains the highest possible result than PSO and SA.

5. Conclusion

This study introduces a groundbreaking Quantum Computing-Inspired Genetic Algorithm (QIGA) tailored for the effective optimization of Wireless Sensor Networks (WSN). By harnessing quantum principles, QIGA revolutionizes the approach to addressing intricate routing challenges in WSNs. The algorithm utilizes quantum encoding, employing qubits to concurrently represent multiple routes through superposition and entanglement. Quantum genetic operations further explore diverse solution spaces. Decoding into classical routes and fitness evaluation based on WSN optimization criteria, incorporating energy efficiency, latency, and reliability. The result of efficient, reliability and latency comparison shows that the proposed quantum-inspired genetic algorithm provides better performance than the compared techniques. Quantum-inspired selection strategies enhance adaptability and efficiency in route optimization. Through iterative refinement, QIGA aims to converge towards optimal WSN routing solutions.

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