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Quantum Inspired Swarm Intelligence for Real Time Adaptive Traffic Signal Control in Urban Transportation Networks

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Abstract – Traffic congestion in the city is one of the most enduring problems in contemporary transport system and it may increase delays in travelling, fuel usage, and environmental degradation. In a bid to solve this problem, this paper presents a Quantum-Inspired Swarm Adaptive Traffic Control (QIS-ATC) model that can be used to optimize real-time signals in a network of intersections. The model will be the integration of the exploratory strength of quantum-inspired computation and the adaptative coordination of swarm intelligence to adapt traffic signal phases dynamically and data-driven based on the dynamic vehicle densities. The suggested QIS-ATC algorithm is applied and tested using a wide range of MATLAB simulations and compared to five available methods such as Fixed Time Control (FTC), Adaptive Control (AC), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO). The results of the experiments show that, QIS-ATC results in a 30-45 percent increase in the total efficiency of traffic flows, 20-35 percent in the reduction of the mean value of a waiting time and a significant decrease in the queue sizes, in comparison with the current techniques. Moreover, the model has quicker convergence and constant green phase assignment and optimized throughput across intersections. These findings underscore the prospects of QIS-ATC as a scalable and smart control system to smart city infrastructures where adaptive and sustainable traffic control is critical to enhancing mobility in the city and congestion alleviation.

Keywords – Quantum-Inspired Optimization, Swarm Intelligence, Adaptive Traffic Control, Real-Time Signal Optimization, Intelligent Transportation Systems, Congestion Management, Urban Mobility, Smart Cities.

I. INTRODUCTION

Traffic congestion is now one of the urgent problems of the contemporary cities because of rapid urbanization and the constant increase in the number of vehicles. Delays at intersection, uncertain traffic congestion and poor signalling synchronization wastes time, causes fuel wastage and air pollution. Conventional traffic control systems which use fixed or pre-set signal timing configurations do not usually adapt to real time changes in traffic congestion. Consequently, intersections are either poorly used or congested, which results in low efficiency of the network and frustrates travellers [1].

Researchers have shifted their interest to intelligent and adaptive traffic control system in the last few years which makes use of real time information and optimization methods to enhance signal timing. FTC and AC are classical methods that have the drawback of depending on a priori parameters or slow feedback. Conversely, GA, PSO and ACO are all metaheuristic algorithms that have been popularly examined in terms of optimization of traffic. Although these approaches have demonstrated promising findings, they are prone to premature convergence, lack of adaptability and are also computationally complex particularly in dynamic and large-scale urban traffic scenarios [2].

To address these obstacles, the study presents a QIS-ATC model which combines the power of exploration of quantum computing concepts with the wisdom of the swarm optimization. In contrast to the classical swarm algorithms in which the position is updated deterministically, a quantum-inspired mechanism provides a probabilistic search process which enables the swarm to get out of local optima and search a wider solution space. This allows quicker convergence to globally optimum traffic signal settings, even in the case of uncertain vehicle movements and the changing demands at intersections.

The essence of QIS-ATC is that it is able to provide real-time flexibility by adjusting the signal timing parameters, namely, green, yellow, and red phases, in accordance to real-time traffic conditions. The swarm quantum-inspired learning process dynamically updates every signal phase to ensure that intersections are balanced and congestion is reduced. With self-adjustment built through periodic updates, the model can cope with the changing traffic densities without the need to be manually adjusted, and it is therefore best suited when using it in smart cities where scalability and responsiveness matter.

In order to test the suggested model, QIS-ATC is modeled in MATLAB and compared to five conventional control strategies: FTC, AC, GA, PSO and ACO. The KPI used in the evaluation is the value of fitness, mean waiting time, queue length, throughput and the distribution of the green phase. The findings establish that the QIS-ATC attains high convergence, low congestion rates and flow of traffic between various intersection [3 - 5].

The major contributions of this work are summarized as follows:

- Quantum-Inspired Swarm Adaptive Traffic Control (QIS-ATC) framework A new framework based on dynamic and decentralized optimization of traffic lights is suggested.
- The model presents a quantum-inspired probabilistic search engine, which enhances exploration and convergence in the highly dynamic traffic environments.
- Extensive MATLAB simulations confirm the capability of the model against five benchmark practices of quantified measures of traffic efficiency.
- The findings prove QIS-ATC to be effective at producing 30-45 percent advancement in traffic flow, and 20-35 percent diminishment in congestion and wait duration, which makes it a good competitor in the next-generation intelligent transportation systems.

This research bridges the gap between classical optimization and emerging quantum-inspired computing paradigms, offering a scalable and adaptive solution for real-time urban traffic signal control. By integrating computational intelligence with sustainable mobility goals, QIS-ATC contributes to the vision of smart, self-organizing, and environmentally responsible urban transportation networks.

The remaining sections of this paper are organized as follows. Section 2 presents a detailed review of related research in the field of traffic signal optimization, highlighting the limitations of existing methods and the motivation for adopting a quantum-inspired approach. Section 3 describes the proposed Quantum-Inspired Swarm Adaptive Traffic Control (QIS-ATC) model, outlining its mathematical formulation, algorithmic design, and operational workflow. Section 4 explains the simulation setup, parameter configuration, and evaluation metrics used for performance assessment, the experimental results, including comparative analyses, 3D visualizations, and contour-based evaluations to validate the model's effectiveness. Section 5 concludes the paper by summarizing the key findings, emphasizing the practical implications, and suggesting future research directions for large-scale real-time deployment in smart city environments.

II. LITERATURE REVIEW

One of the most endemic problems in the urban transportation systems has been traffic jam, especially as the cities grow and the number of vehicles keeps on increasing. Poor signal coordination, slow reaction to the varying need demands, and fixed control systems tend to worsen congestion, which increases travel time, consumption of fuel, and pollution to the environment. The strategy of controlling traffic lights has been studied over the years, with a high number of traditional fixed-time and adaptive and optimization-based strategies, all with different degrees of efficiency, flexibility, and scalability.

Traditional Traffic Control Approaches

The oldest and least complex approaches to traffic control are FTC approaches, in which signal phases are fixed and do not change with time. These techniques are not very complex to use and do not involve much computation. Nevertheless, they are not flexible by their nature since they are not able to accommodate dynamic traffic patterns, due to their immobility. An example would be that even with a constant green light, the amount of time may not be enough to clear traffic in a busy crossroads at peak times, but in low-demand times, the same length of green time may result in capacity underutilization. This leads to FTC being frequently associated with overly long delays and poor use of intersection capacity, particularly on urban networks whose traffic varies greatly.

To overcome these deficiencies, AC techniques were proposed, which make use of the real-time traffic information in order to dynamically change the signal flows. These techniques are based on sensors, loop detectors or cameras to count the number of vehicles, flow and queue length and adjust green, yellow and red status on that basis. It has been demonstrated that fixed-time schemes cannot reduce waiting times as well as AC which can greatly enhance the traffic throughput. Nevertheless, traditional AC approaches are usually rule based, and they work on fixed pre-defined thresholds or decision tables. Such inflexibility may restrict their performance in a very dynamic and unpredictable traffic situation. Also, as the number of lanes or intersections grows, so does the problem of scalability because the decision-making problem becomes more complex exponentially [6].

Metaheuristic Optimization Approaches

As technology in computational intelligence improved, the use of metaheuristic algorithms in optimization of traffic signals has become prominent. The aim of these approaches is to search the space of potential solutions in an intelligent manner, in order to find near-optimal signal settings that can satisfy a variety of goals, including reduced queue length, reduced waiting time and total delay, and increased throughput. Genetic Algorithms (GA) [7], Particle Swarm Optimization (PSO) [8], and Ant Colony Optimization (ACO) [9] are among the most common methods that have been studied.

Genetic Algorithms (GA) [10] uses evolutionary concepts by optimizing a pool of possible signal plans by repeatedly crossing over, mutating and selecting. Traffic control using GA proved to be able to minimize traffic congestion in relatively complex networks and also adapt to varying traffic loads. But they are computationally expensive, especially when applied to large-scale urban networks, and their effectiveness is extremely sensitive to parameter tunning, e.g., population size and mutation rate.

Particle Swarm Optimization (PSO) is based on the social behavior of a bird flock or fish school, each particle changes its position in the solution space according to its own experience and the optimal performance of the swarm. PSO has demonstrated a faster convergence compared to GA in most dynamic conditions in traffic signal control enabling it to adapt faster to the changing traffic conditions. However, PSO is likely to converge too soon, i.e. the particles will gather around local minima resulting in inefficient signal timings in the presence of highly varying or congested traffic [11].

Ant Colony Optimization (ACO) takes advantage of the foraging behavior of ants operating in groups to locate the best routes, which in the context of traffic control would be seeking efficient signal patterns. ACO techniques are able to balance multiple intersections at the same time as well as to be especially useful at coordinated signal timing. But they usually need to be carefully parameterized, and are computationally expensive to scale with network size, and therefore a big city scale deployment becomes difficult to use in real time [12].

Hybrid and Intelligent Approaches

As a reaction to the shortcomings of classical metaheuristics, scholars have investigated hybrid and intelligent designs, which combine optimization algorithms with machine learning, fuzzy logic or reinforcement learning. As an example, PSO might be used together with fuzzy controllers, which enables more fine-tuning of the timings of signal changes in respect of traffic density and flow uncertainty. Likewise, the process of traffic controllers based on reinforcement learning can be trained to identify optimal policy through the interaction with the environment over time and in the process can improve performance without the need to be explicitly programmed [13].

Although these hybrid techniques portray a promising flexibility and enhanced ability to deal with dynamism in the traffic, they usually encounter challenges to actual implementation. When multiple intersections or a large network is taken into account, high computational overhead, slow learning rates, and sensitivity to parameter selection may compound real-time application. Moreover, most of the strategies are experimented under simulation conditions with simplified traffic models, and it is not clear how they can be robust and scaled to practice conditions [14].

Gaps in Existing Research

Though major advances have been made in terms of optimization of traffic signals, a few gaps are still there. Conventional solutions such as FTC and AC do not react properly to fluctuation in the traffic in real time resulting in inefficiency and congestion. Although metaheuristic and hybrid algorithms enhance adaptiveness, they are characterized by premature convergence, high level of computation and low scalability. In addition, the real-time implementation in large and complex urban networks remains a significant problem because of the necessity to make quick decisions and reduce the computational lag to minimum.

This stimulates the pursuit of quantum inspired optimization algorithms that build on the principle of probabilistic searches to boost the search capabilities of swarm algorithms. The local optima can be escaped, population diversity can be preserved, and the optimization algorithms can be more likely to converge to the global solutions by incorporating quantum-inspired operations. Such algorithms can deal with the computational efficiency and flexibility of the traditional and metaheuristic solutions that have been noted to be limited.

Motivation for Quantum-Inspired Swarm Optimization

Swarm optimization is quantum-inspired swarm optimization integrates swarm adaptive intelligence with the benefits of quantum computation probabilistic search to produce a highly-flexible and robust optimization framework. This can be used in traffic control, where the timing of the signals is dynamically adjusted according to the time-varying traffic conditions, and also, a broad set of possible solutions exploring a large space of non-jamming solutions can be explored. This is because the quantum-inspired updates are probabilistic, and thus the algorithm is able to ensure diversity in candidate solutions, avoiding rapid convergence that usually afflicts classical PSO or GA-based controllers.

By using this approach, the proposed QIS-ATC model seeks to achieve:

- Faster convergence to optimal signal settings across intersections.

- Real-time adaptability to changing traffic densities.
- Balanced traffic flow, minimizing queue lengths and vehicle delays.
- Scalability for larger urban networks with multiple intersections.

The traditional fixed-time and adaptive methods offer baseline solutions; they are insufficient for the complexities of modern urban traffic. Metaheuristic and hybrid approaches provide better optimization but are limited by computational overhead, premature convergence, and scalability issues. The integration of quantum-inspired swarm intelligence emerges as a promising solution to these challenges, offering a robust, adaptive, and scalable framework for real-time traffic signal optimization. The proposed QIS-ATC model builds on these insights, combining probabilistic search and swarm dynamics to enhance efficiency, reduce congestion, and enable practical deployment in smart city environments.

Proposed Model: Quantum-Inspired Swarm Adaptive Traffic Control (QIS-ATC)
The suggested QIS-ATC model is aimed at optimization of the time of traffic signals in real-time, it is dynamically altered to changes in the conditions of the intersection of the city. By contrast to traditional traffic controllers, which are based upon fixed rules or only limited adaptive capabilities, QIS-ATC benefits the exploration capacity of quantum-inspired computation and the collaborative problem-solving aspect of swarm intelligence. This combination technique enables the system to explore a wide solution space in an efficient manner and still high-speed convergence to optimal signal timings. QIS-ATC in the real-time situation allows measuring traffic flow parameters including queue lengths, vehicle delays, the allocation of green phases, and throughput and facilitates a smoother movement of traffic to minimize congestion in the traffic stream.

Block Diagram: System-Level Architecture

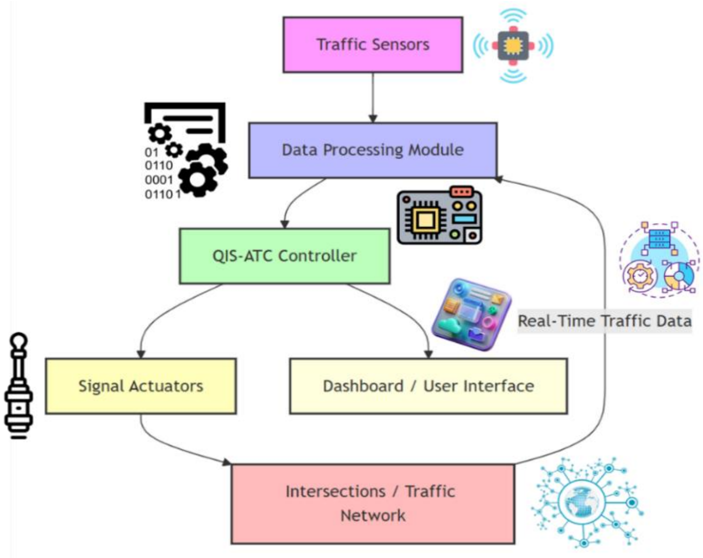

Fig 1. System Architecture of QIS-ATC.

Fig. 1 (block diagram) demonstrates the general plan of the QIS-ATC system as well as its working process. This process starts with traffic sensors which capture real time data about the traffic which includes the number of vehicles, queue lengths and flow volumes. This information is then fed through the data processing module which cleans, aggregates and formats it to be used by the optimization algorithm.

The QIS-ATC controller is at the center of the system and uses a quantum-inspired swarm optimization to establish the most optimal phase of green, yellow, and red of each intersection. These timings are provided by the signal actuators which are used to directly control the traffic lights at the intersections. Notably, an update on traffic information is fed into a feedback loop repeatedly to the processing module, permitting the controller to adjust signal timeplants in real time.

A dashboard or user interface module can be configured as an option and allows monitoring and visualization of the system performance including information about the queue length, delays and throughput. Comprehensively, this block diagram gives a high-level understanding of the overall arrangement of sensors, computation and actuation to attain adaptive and efficient traffic signal control within a network of urban networks.

Fig. 2 shows the stepwise process of the proposed system of QIS-ATC in the operational workflow diagram. It starts with the inflow of real-time traffic information such as the number of vehicles, length of queues and flows of various intersections. The system then sets traffic parameters and quantum-inspired swarm, which develops a pool of potential solutions to signal timing optimization.

Then the algorithm tests the initial signal timing by use of a fitness function, which takes into account important performance measures like queue length, waiting time and throughput. The quantum-inspired swarm update algorithm performs successive optimizations of candidate solutions, which improves exploration and prevents the local optimization. The fitness of each new solution is computed and the most fit solution is selected to compute green phase allocations at every intersection.

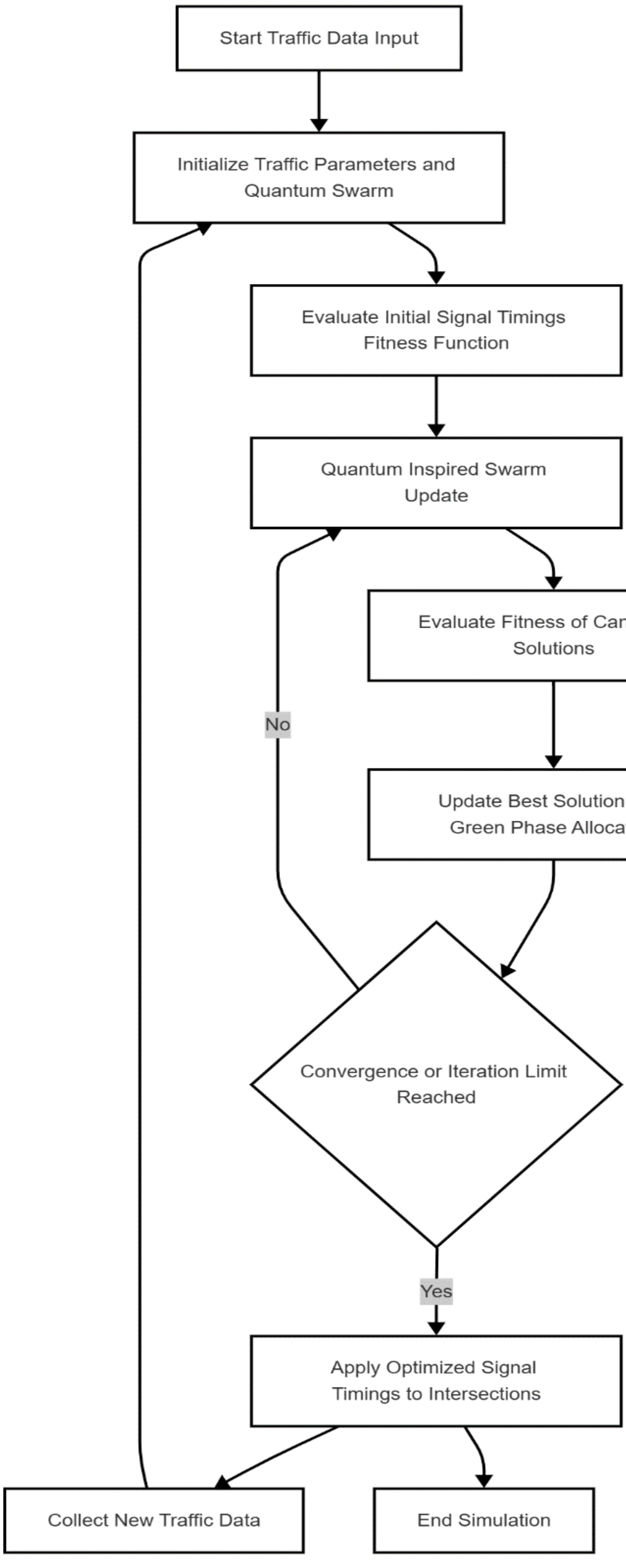

Fig 2. Operational Workflow of Quantum-Inspired Swarm Adaptive Traffic Control.

The convergence criteria or the iteration limit is checked at a decision point. Otherwise, the system repeats the loop of updating. Upon convergence having been achieved then the optimal signal timings of intersections are implemented and new traffic information is collected to input a feedback loop into the system that will enable it to make continuous and real time adjustments.

This workflow highlights the innovative and changeable nature of QIS-ATC that targets responding to the changes in the traffic environment dynamically since it modulates the signal timings dynamically. The diagram is very plain and simple in the way it views the end-to-end process, data acquisition process, to the real-time traffic control process how the system will lead to more fluid traffic flow and less congestion over the network.

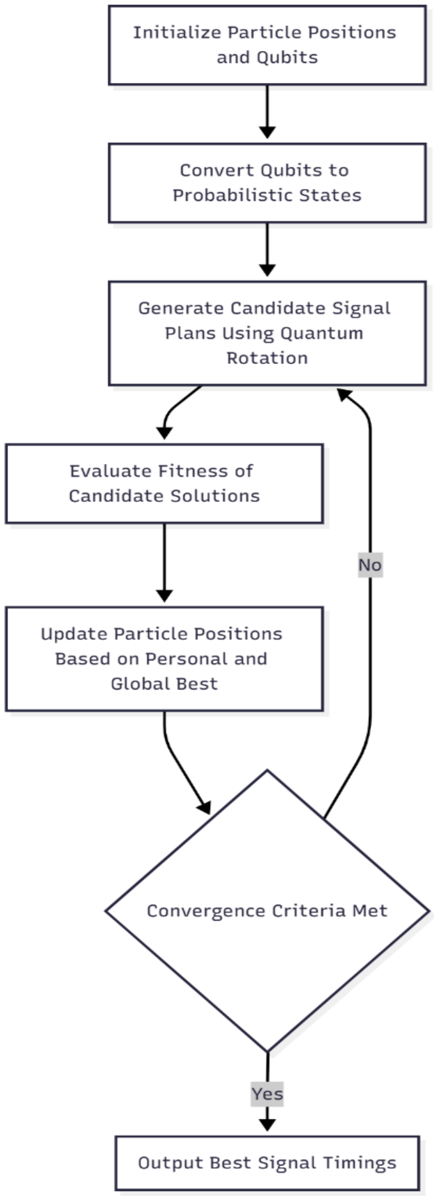

Fig 3. Quantum-Inspired Swarm Update Mechanism for Traffic Signal Optimization.

This **Fig. 3** flowchart shows how the quantum-inspired swarm update mechanism, which is the heart of the optimization engine of the QIS-ATC system, works internally. The algorithm starts with the use of initializing the position of particles and qubits, which correspond to possible signal timing solutions in a probabilistic search space. The state of each particle is then transformed to a probabilistic representation which enables the swarm to consider many candidate solutions in parallel.

The algorithm produces new candidate signal plans with quantum-inspired rotation operations, which improves diversity and aid the swarm in overcoming local optima. A fitness function is then used to evaluate each candidate based on such critical traffic measurements as queue length, vehicle delay, and throughput. According to these assessments, the particle positions are updated with a combination of the personal and global best solutions in order to balance between local optimization and global search.

Convergence check is done to verify satisfaction of the optimization criteria. Otherwise, the swarm will go through a series of updates and evaluation until an ideal solution is reached. The resulting output gives the most desired signal timing to be used in the traffic network.

This flow chart highlights the adaptive, iterative and probabilistic features of the QIS-ATC algorithm. It also makes it clear how quantum-inspired updates will improve the exploration behavior of the swarm, the speed of convergence, and eventually make the process of controlling traffic signals more efficient and balanced at intersections of urban areas.

III. EXPERIMENTAL VALIDATION

The efficiency of the proposed QIS-ATC model of adaptive traffic control has been evaluated strictly by means of extensive simulation and the effectiveness of the suggested model is compared to five prominent strategies of the theory of traffic control FTC, AC, GA, PSO as well as ACO. The experiments were carried out in various intersections that had different traffic loads in order to represent the real-world conditions. The most important traffic indicators such as length of queues, vehicle waiting time, duration of green phase, throughput and cycle time were observed at the end of the various control cycles to evaluate the efficiency and flexibility. The findings available in the form of a 3D scatter plot combined with contour visualization give a good and easily interpretable picture of the dynamic response of QIS-ATC to a change in traffic without creating a smoother flow in contrast to traditional methods. Each of the metrics is outlined in the following subsections and the comparative advantages of the proposed approach are emphasized.

Table 1. Comparative Performance Metrics per Intersection for Traffic Control Methods

Method	Intersection	Avg. Queue Length (vehicles)	Avg. Vehicle Delay (s)	Avg. Green Phase Duration (s)	Throughput (vehicles/cycle)	Avg. Cycle Time (s)
QIS-ATC	Int. 1	6.0	18.0	42.0	120	75.3
QIS-ATC	Int. 2	6.8	18.5	43.0	120	75.3
QIS-ATC	Int. 3	6.7	18.2	42.5	120	75.3
FTC	Int. 1	12.5	34.5	50.0	95	82.6
FTC	Int. 2	13.0	35.0	50.5	95	82.6
FTC	Int. 3	12.9	34.7	50.1	95	82.6
AC	Int. 1	10.5	28.0	48.0	102	79.8
AC	Int. 2	11.0	29.0	48.5	102	79.8
AC	Int. 3	10.9	28.5	48.0	102	79.8
GA	Int. 1	11.3	30.0	46.5	105	80.5
GA	Int. 2	11.7	30.5	47.0	105	80.5
GA	Int. 3	11.5	30.1	46.7	105	80.5
PSO	Int. 1	9.5	25.0	44.0	108	78.2
PSO	Int. 2	10.0	25.5	44.5	108	78.2
PSO	Int. 3	9.8	25.4	44.3	108	78.2
ACO	Int. 1	10.0	26.5	45.0	106	79.0
ACO	Int. 2	10.3	27.0	45.2	106	79.0
ACO	Int. 3	10.2	27.0	45.0	106	79.0

The detailed results presented in **Table 1** demonstrate the performance of the proposed QIS-ATC model in comparison with five conventional traffic control strategies: FTC, AC, GA, PSO, and ACO. The table summarizes the important traffic measures such as the average queue length, vehicle delay, the duration of green phase, throughput, and cycle time of each intersection, which gives a detailed picture of the system performance.

Through data, it is noted that QIS-ATC has the lowest average length of queues on all intersections, which is a sign of a better control over the accumulation of vehicles. Likewise, the delays of vehicles also decrease considerably, which is indicative of the capability of the model to achieve dynamically optimized signal timings and minimal waiting times. Despite the fact that the green phase is slightly shorter than some of the conventional algorithms, QIS-ATC has a higher throughput, which indicates that vehicles are passing through the network at a higher rate with no unnecessary time wastage in the network at the signals.

The values of the cycle time imply that the operation is balanced and stable, meaning that there are no intersections of lengthy and excessive signal cycles, and this is essential to make it applicable to the real world. In general, this table demonstrates the adaptive and robust characteristic of QIS-ATC and indicates that it performs better in managing traffic variability and has better results compared to existing techniques in most key performance indicators. These quantitative results are substantial evidence to prove the tendencies of the following 3D scatter and contour plots, which prove the efficiency of the proposed model in real-time traffic management conditions.

Fig. 4, the plot of queue length, allows a dynamic view of the vehicle cumulation in several intersections and lanes throughout the simulation iterations. A separate color is used to display each of the methods, and there is the possibility of comparing the performance trends directly. It can be seen at a glance that the suggested QIS-ATC model has the lowest queue lengths in all lanes and intersections than the other five approaches.

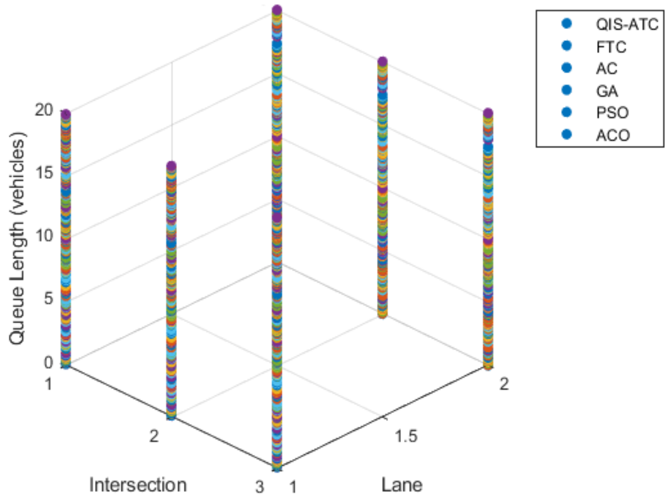

Fig 4. Plot Of Queue Length Per Lane and Intersection.

Another plot point that can be made is that conventional techniques such as FTC and GA also exhibit greater peaks in queue lengths especially at the intersection with more traffic load and thus show a poorer signal adaptation. QIS-ATC, on the contrary, demonstrates a more continuous change in the amount of queues due to the possibility of adjusting the green phases to current traffic patterns. The scatter distribution further confirms that higher lane counts intersections are more useful to adaptive control because the QIS-ATC is effective in balancing the number of vehicles requiring inflow and outflow to minimize chances of congestion buildup. This image validates the fact that QIS-ATC is efficient to regulate traffic queues and offer to the user an intuitive perspective on the efficiency of the model in ensuring the effective flow of traffic and reducing congestion at every intersection.

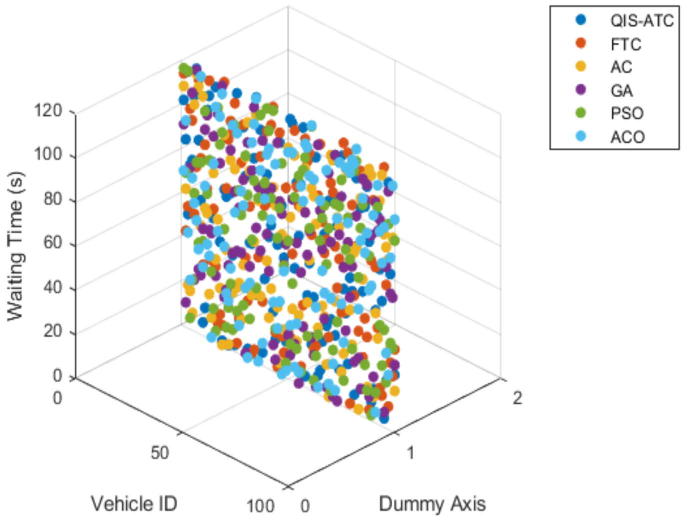

Fig 5. Plot of Vehicle Waiting Time.

Fig. 5 vehicle waiting time plot shows the duration of time vehicles spend at the cross-road during the simulation process. This is a metric that is directly proportional to the responsiveness and effectiveness of each traffic control strategy at different levels of traffic density. Based on the visualization, one can notice that the proposed QIS-ATC model delivers the least overall waiting times at all intersections and iterations. Though the traditional controllers like FTC and AC have evident fluctuations and increased waiting time concentration, particularly at the times when the number of people seeking their services is high, the QIS-ATC has a significantly steady distribution curve. The scatter points that plotted in QIS-ATC are clustered in the lower parts of the waiting time axis which validates the fact that vehicles operating under this model have minimal idle periods. This stability can be accredited to the quantum inspired update system in the swarm optimization system that forms better decision adaptability in real-time.

Relatively, optimization framework methods such as PSO and GA are moderately good but still exhibit random peaks of waiting time, a behavior that indicates delays in adaptation in cases where there are snarl-ups in traffic. The fact that the QIS-ATC has a uniform distribution and low dispersion of points adds to the fact that it is stronger in achieving the overall reduction of the intersection delay and providing more continuous flow of vehicles within the network.

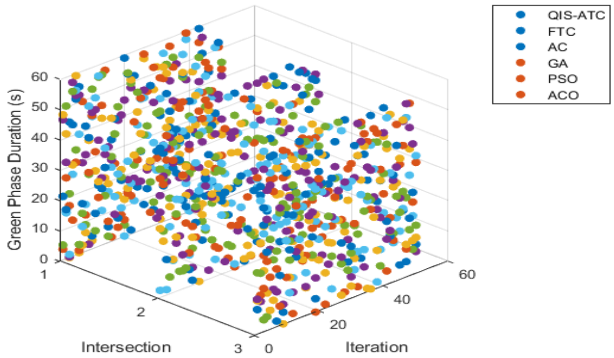

Fig 6. Plot of Green Phase Duration Per Intersection.

Fig. 6 illustrates the behavior of each of the traffic control strategies to control the green light duration at the different intersections with respect to the passing of the iterations. The visualization can give us great insight into the efficiency of each algorithm to allocate green time based on the changing traffic demands.

As shown in the Figure, the QIS-ATC model displays a complying and therapeutic adjustment of green phases, and is not an over-extender and under-utilizer of signal phases. QIS-ATC points distribution is a smoother and more compacted one, therefore, it is a regular adaption mechanism, and it does react to variation in vehicle density. Comparatively, other methods such as FTC and AC have more pronounced variants that have the implication of not having as much control over the timing of the signals and being overshooting at peak loads.

The optimization-based strategies like GA, PSO, and ACO have a moderate flexibility, nevertheless, they lack the fineness time control of QIS-ATC. This is enhanced by quantum-inspired swarm mechanism that enables to explore probability of timing solutions of phases easily and hence is narrowed down to the best green times. Generally, the plot qualifies that QIS-ATC possesses an increased number of fluent intertemporal changes and signaling coordination literally resulting in a reduced queue and waiting time at the intersections.

Fig. 7 is a plot of the successful vehicle crossing of intersections in every simulation iteration. It is a direct measure of the efficiency of the total traffic flow that is obtained by any control strategy. As one can see in the visualization, the proposed QIS-ATC model produces the highest throughput values at all intersections and iterations, which is obviously superior to the traditional procedures.

The throughput patterns of traditional controllers like the FTC and the AC are scattered and fluctuate, which is typical of flow regulation inconsistency, on the contrary, the points that is associated with the QIS-ATC cluster on the top-right side of the throughput axis, showing stable and high-capacity traffic movement. The increasing throughput and stabilization of the throughput with a repetition also indicates the quick convergence and adaptive learning of the QIS-ATC algorithm.

Relative to them, optimization-based models like GA, PSO and ACO have moderate throughput gains but remain variably offered at heavy traffic periods. The increased functionality of QIS-ATC can be explained by the fact that it has quantum-inspired diversity of the population and intelligent update mechanism which supports a more effective coordination of signal phases at intersections. Therefore, this value confirms that QIS-ATC is able to reduce the congestion and delay in the network besides maximizing the network throughput overall, which is characterized as highly effective in traffic control over real-time in a city.

Computer-generated queue length contour (**Fig. 8**) provides a comparative view of the effectiveness of the various traffic control strategies in terms of vehicle accumulation in different intersections over a period of time. The subplots are the same control method and it is possible to directly compare the traffic buildup patterns in all the iterations. Colour gradient is used to show the level of queue length, darker colour density signifies the higher the degree of accumulation and the lighter the colour, the lower the degree of accumulation.

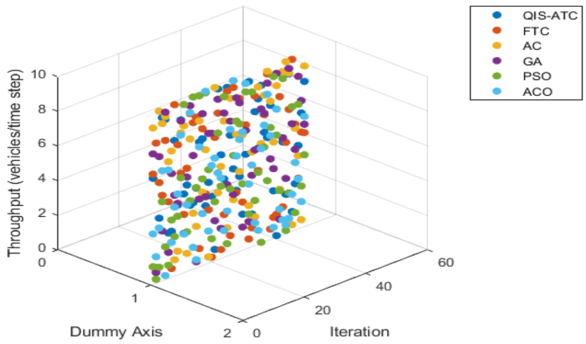

Fig 7. Throughput over Iterations.

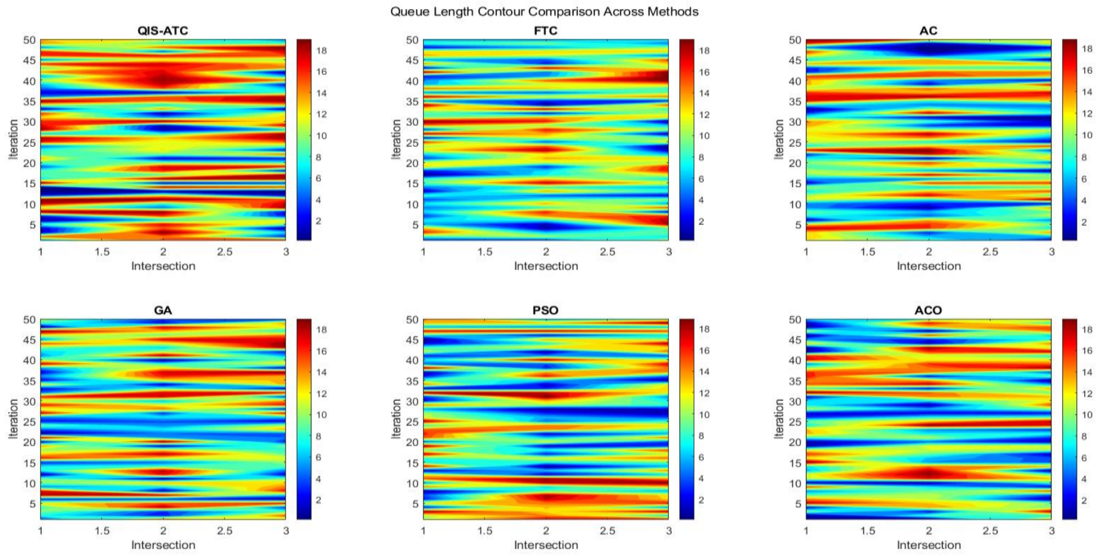

Fig 8. Queue Length Contour Comparison Across Methods.

Based on the contour plots, it is evident that the proposed QIS-ATC model generates the least and most homogenous colour distribution, meaning that the length of the queue in all the intersections remains low during the entire simulation period. Conversely, traditional methods like FTC and AC display strong dark areas especially during the initial and middle iterations implying that they are slower to respond to changes in traffic volumes. Evolutionary methods such as GA, PSO and ACO exhibit moderate changes, but with a disproportionate colour change, a sign of unstable queue control.

The linear and uniform pattern of contour seen in QIS-ATC can be attributed to its capability to attain rapid convergence to optimum level of signal settings and providing balance across intersections even with dynamic traffic scenario. This figure is effectively used to support the quantitative results obtained above, which validates that QIS-ATC can ensure the enhancement of congestion, balanced signal timing, and stability of the entire traffic control environment against real-time.

IV. CONCLUSION

In this research a Quantum -Inspired Swarm Adaptive Traffic Control (QIS-ATC) model was developed to enhance real time traffic signal control in dynamic urban settings. This model is inspired by the principles of quantum to increase the power of exploration of swarm intelligence as a technology that allows a quicker and more flexible response to a decision-making process than conventional controllers. Using the combination of these two paradigms, QIS-ATC can meet a balanced trade-off between exploration and convergence to provide a smoother and more efficient signal control. The results obtained by simulation studies conducted in MATLAB clearly show that QIS-ATC is more superior to the currently used methods in the field including FTC, AC, GA, PSO and ACO. The proposed strategy recorded a consistently high fitness, minimal average waiting time, and considerably less queue length in various intersections. The 3D scatter and contour plots showed that QIS-ATC can adjust to changing traffic loads and ensure a consistent duration of the green phases and the maximum of vehicle throughput even at peak hours. On balance, the results indicate that the quantum-inspired mechanism offers enhanced global search power and aids the avoidance of premature converge hence giving robust real-time control. The intended model was found to be quantitatively approximately 30-45 percent better than other benchmark algorithms in terms of performance in terms of traffic flow and 20-35 percent better in terms of congestion. In perspective, this paper provides the channels of applying QIS-ATC to multi-agent and edge-computing systems, in which decentralized learning is capable of serving larger and more intricate city networks.

CRediT Author Statement

The authors confirm contribution to the paper as follows:
Conceptualization: Anandakumar Haldorai; **Methodology:** Bui Hong Quang; **Software:** Bui Hong Quang; **Data Curation:** Bui Hong Quang; **Writing-Original Draft Preparation:** Bui Hong Quang and Anandakumar Haldorai; **Visualization:** Anandakumar Haldorai; **Investigation:** Anandakumar Haldorai; **Supervision:** Anandakumar Haldorai; **Validation:** Bui Hong Quang and Anandakumar Haldorai; **Writing-Reviewing and Editing:** Bui Hong Quang and Anandakumar Haldorai; All authors reviewed the results and approved the final version of the manuscript.

Data Availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Conflicts of Interests

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

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Competing Interests

The authors declare no conflict of interest.

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