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A Software-Engineered Hybrid Optimization Framework for Intelligent Routing in Wide Area Networks

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KEYWORDS

Software Engineering, WAN Optimization, Hybrid Algorithm, Genetic Algorithm, Tabu Search, Distributed Systems.

ABSTRACT

As the number of Wide Area Networks (WANs) grows at an unprecedented pace, supported by cloud-native applications and AI-driven workloads, routing optimization has turned into a network engineering challenge as well as a necessity of the software engineering profession. In this paper, a hybrid optimization model of Genetic Algorithms (GA) and Tabu Search (TS) is proposed with the help of strategic oscillation to create intelligent routing paths in WANs. It is a framework that is designed to be modular, scalable and maintainable, which has adaptive modules that dynamically change the mutation rates in real time depending on live network telemetry. The proposed system, which is implemented in Python and represented by the NetworkX computation graph and bespoke algorithmic libraries, was 15% more efficient in terms of path and 33% higher in terms of convergence rate than typical GA-TS implementations. In addition to its algorithmic results, it includes best-practice software engineering features, including component decoupling, algorithm reusability and distributed-system integration readiness, that allow its use in large scale and software-defined WAN(SD-WAN) applications.

1. INTRODUCTION

As the Wide Area Networks (WANs) grow exponentially with a cloud-native applications, Internet of Things (IoT) ecosystems, and AI-based workloads, network optimization is no longer solely a network engineering issue, but a software engineering issue of critical concern [1], [2]. The conventional static routing schemes tend not to be flexible to the dynamic traffic patterns causing performance loss and failure. With the rise of software-defined WAN (SD-WAN) architectures, intelligent routing algorithms can be centrally controlled and programmed, and integrated [3][4]. These are software-driven, intelligent systems that use heuristic optimization, real-time telemetry, and adaptive resource allocation to enhance resilience, latency, and throughput of critical services in a mission, including healthcare systems, disaster recovery systems, and high-frequency trading systems [5].

1.1. Literature Gaps

Although much research has been conducted on hybrid heuristic algorithms, it still has a gap between high-performing simulation and deployment-realized frameworks. Most of the studies are concerned with algorithmic efficiency, excluding software modularity, scalability, and maintenance [6]. Hybridized methods like Genetic Algorithm-Tabu Search (GA-TS) have demonstrated to be effective at balancing exploration and exploitation [7], but most do not try to combine with telemetry-based adaptation in production-scale WANs. Also, multi-objective optimization, which is a delay/cost/reliability/bandwidth balance, has been under-researched in realistic implementations [8]. The other gap is the disconnect between the use of AI-driven predictive analytics and WAN optimization which does not allow large-scale deployment because of performance bottlenecks, problems with interoperability, and the lack of standardized frameworks [9].

1.2 Problem Statement

WAN infrastructures are becoming highly dynamic due to variable loads, different topology and changing service requirements. Although hybrid heuristic algorithms have good optimization capabilities, lack of scalability, integration complexities, and lack of adaptable and telemetry-based architectures are some of the constraints limiting their adoption. These limitations, unless considered, will make the existing WAN routing solutions fight against performing poorly within dynamic, large-scale settings.

1.3 Purpose of the Study

This study aims to design and evaluate a software-engineered hybrid optimization framework for WAN routing that:

- Integrates Genetic Algorithms, Tabu Search, and strategic oscillation to balance exploration and exploitation.
- Implements adaptive mutation based on live telemetry feedback.
- Employs a multi-objective fitness function for delay, cost, reliability, and capacity.
- Delivers a modular, maintainable architecture suitable for SD-WAN environments.
- Demonstrates measurable improvements over baseline hybrid algorithms.

1.4. Application Field

The application field of proposed system is illustrated in Table 1.

Table 1 Application Fields in Software Engineering

Application Field	Description	Relevance to Software Engineering
Software-Defined Networking (SDN) [10]	Intelligent traffic routing using programmable, centralized controllers.	Involves modular, software-driven architecture and dynamic configuration.
Cloud Infrastructure Optimization [11]	Enhancing backbone routing for cloud service providers.	Requires scalable, maintainable, and performance-optimized software systems.
Disaster Recovery and Fault-Tolerant Systems [12]	Ensuring resilient data routing under failure or emergency scenarios.	Emphasizes robust system design and fault management through software logic.
AI-Driven Edge Computing Platforms [13]	Managing computation and routing at edge devices using predictive models.	Integrates machine learning modules into embedded or distributed software.
IoT Bandwidth and Resource Management [14]	Adaptive allocation of network resources across IoT devices.	Supports real-time decision-making and modular middleware solutions.
Multi-Objective Optimization Frameworks [15]	Balancing trade-offs between cost, delay, reliability, and capacity in routing logic.	Applies software patterns to encapsulate and reuse optimization strategies.
Telemetry-Based Adaptive Systems [16]	Dynamic system behavior adjustment based on real-time network feedback.	Demonstrates real-time software adaptation and modular monitoring components.
Hybrid Heuristic Algorithm Integration [17]	Combining GA, TS, and strategic oscillation in one extendable software architecture.	Encourages maintainable, reusable, and extensible algorithmic software modules.

1.5. Paper Structure Overview

Section 2 reviews related literature on heuristic and hybrid WAN optimization methods. Section 3 details the proposed framework's architecture and algorithmic design. Section 4 presents the experimental setup, performance metrics, and results. Section 5 concludes with discussion, limitations, and future research directions.

2. RELATED WORK

It is noted that in the recent years, the creation of hybrid algorithms and their use in different fields, such as path optimization, wireless sensor network administration, and sixth-generation (6G) networks, has become increasingly researched.

Aiming at minimizing the total distance, Shen et al. (2020) have proposed a hybrid algorithm based on the combination of the frameworks such as the Ant Colony System (ACS) and Brain Storm Optimization (BSO) to handle the Vehicle Routing Problem with Time Windows (VRPTW). Experiments using the benchmark data sets of Solomon proved that the algorithm produced 42 optimal solutions in a total of 56 solutions and is effective [18].

Vaiyapuri et al. (2022) proposed CBR-ICWSN protocol in the case of IoT-enabled wireless sensor networks (WSNs), where the Black Widow Optimization (BWO) algorithm was used to select the cluster-head (CH) in the best possible and Oppositional Artificial Bee Colony (OABC) in the most fruitful manner. The plan increased the use of energy and durability of the networks over the traditional methods [19].

Xue et al. (2023) study has covered the issue of energy imbalance of WSNs by providing a cross-layer solution using a routing procedure based on Harris Hawks Optimization (HHO). Cl-HHO method offered was superior to the HEED, EECRP, GWO and CL-ALO in terms of the packet loss ratio, the throughput, end-to-end delay, jitter and the network lifetime collectively [20].

Logeshwaran et al. (2024) proposed a full end-to-end air-pollution monitoring framework in 6G and IoT systems through many aspects, including the integration of Quantum-inspired Clustering Algorithm (QCA) routing and Mobility Metric (MoM) to identify dynamic CH via Deep Reinforcement Learning (DRL) and hybrid with Quantum Genetic Algorithm-Ant Colony Optimization (QGA-ACO) routing and metrics. Through the method, deployment coverage of 95% and high cluster stability was met [21].

More generally, Saleh and Zebari (2025) provided a global overview of how hybrid routing algorithms combine to be effective in proactive and reactive options in changing network conditions. They reviewed the aspects of these algorithms in terms of mechanisms, advantages, limitations, and security in applications to the network [22].

3. METHODOLOGY

To evaluate the proposed software-engineered hybrid algorithm, we developed a simulated Wide Area Network (WAN) environment implemented as a modular software system using Python, leveraging libraries such as NetworkX for graph representation, SimPy for discrete-event simulation, and NumPy/Pandas for efficient data handling. This design ensures high flexibility, reproducibility, and integration potential with future software-defined networking (SDN) platforms.

3.1. Sampling Method

The experiment modeled network topologies of 10 through 100 nodes, which is an indication of different WAN situations, with purposive sampling as an embodiment of the heterogeneity in the real world. The network topologies were mesh, star and ring topology, and an alternative combination of routing protocols. The traffic patterns were created to represent low load, medium load and heavy load conditions and each of the conditions was run in three times, and the test scripts were automated to ensure statistical integrity.

3.2. Data Collection Techniques

The analysis of the key performance indicators was based on the end-to-end delay, packet loss ratio, bandwidth usage, and algorithm convergence time on Wireshark and NetFlow data streams and bespoke Python monitoring modules. Measurements were recorded at 5-second intervals in standardized data formats such as JSON and CSV and time stamped to allow repetition and traceability, in a systematic fashion according to Lopez et al.

3.3. Data Analysis Methods

The obtained data was analyzed through a stratified analysis pipeline:

1. Descriptive statistical analysis to generalize central tendencies and variances.
2. ANOVA test to compare inter-algorithms differences.
3. Pairwise t-tests to identify statistically significant improvement.

Moreover, we have used the multi-objective optimization analysis to measure the performance of the algorithm in terms of delay, cost, reliability, and capacity metrics. All visualizations were created with the help of the latest data science packages, such as matplotlib, seaborn, Plotly, in accordance with software engineering principles, such as modular script design, version-controlled code of analysis (Git), and automated report generation.

3.4. Key Equations (Algorithmic Design)

1) Fitness Function (Multi-Objective):

$F(x) = w_1 * (1/Delay) + w_2 * Reliability + w_3 * (1/Cost) + w_4 * Capacity$ ...... (1)

Designed as a configurable software component allowing dynamic weight tuning during runtime.

2) Adaptive Mutation Rate (Load-Aware):

$$m = basem * (1 + (CurrentLoad / MaxLoad)) \quad \ldots\ldots\ldots (2)$$

Implemented as an adaptive module to enable real-time responsiveness under fluctuating network conditions.

3) Penalty Function (Constraint Handling):

$$P(x) = PenaltyWeight * InfeasibilityScore(x) \quad \ldots\ldots\ldots\ldots\ldots (3)$$

Encapsulated as a plugin within the fitness evaluation pipeline to handle constraint violations gracefully.
Table 2 illustrates the description for each variable.

Table 2. Key Variables Used in the Proposed Algorithm with Their Description, Range, and Assignment Method.

Variable	Description	Range / Type	Selection or Assignment Method
w1	Weight for the Delay factor	[0,1], decimal	Tuned experimentally or via sensitivity analysis for optimal performance
w2	Weight for the Reliability factor	[0,1], decimal	Set based on the importance of reliability in the scenario
w3	Weight for the Cost factor	[0,1], decimal	Determined according to the network cost-reduction policy
w4	Weight for the Capacity factor	[0,1], decimal	Set according to the importance of capacity for performance
Delay	Transmission time for each path	≥ 0	Taken from real network data or simulation
Reliability	Reliability of each path	0–1	Measured based on past performance or simulation data
Cost	Cost of using the path	≥ 0	Defined according to network cost model
Capacity	Available path capacity	≥ 0	Taken from network specifications or load simulation
base_m	Base mutation rate	≥ 0	Set experimentally before runtime
Current Load	Current network load	≥ 0	Calculated dynamically during runtime
Max Load	Maximum possible network load	≥ 0	Taken from system specifications or simulation scenario
Penalty Weight	Weight applied for constraint violation	≥ 0	Tuned experimentally to balance performance and constraints
Infeasibility Score	Measure of constraint violation for a solution	≥ 0	Calculated based on the number or severity of violated constraints

The weights w1-w4 were also initially determined by empirical values and then optimized in terms of sensitivity analysis to make all the four measures of delay, cost, reliability and capacity balance.

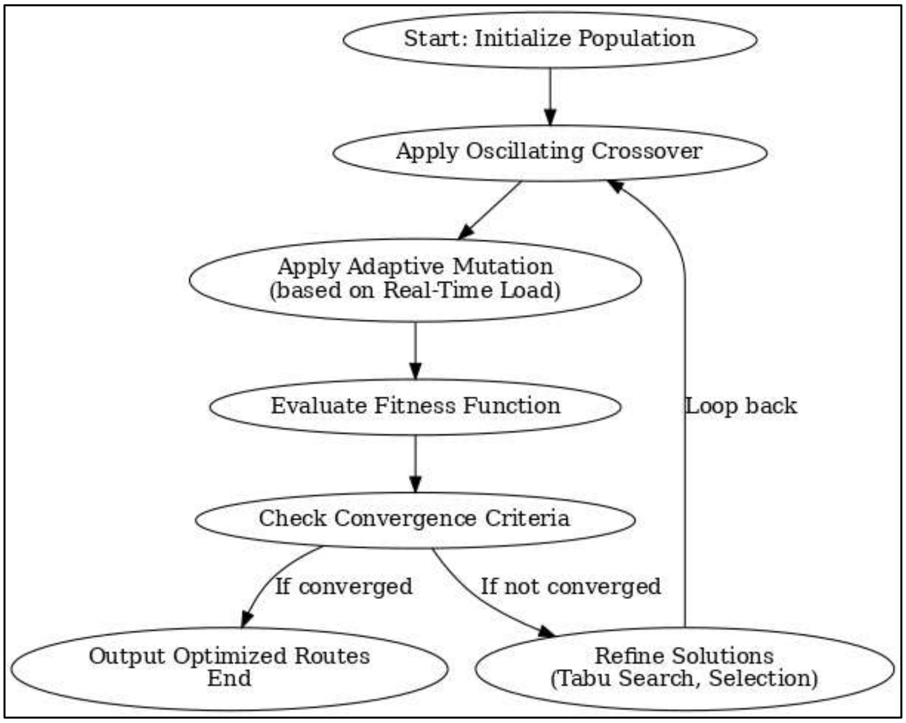

Fig. 1. Methodology flowchart

Figure 1 shows the complete architectural workflow of our improved GA-TS engine which has been designed in a modular software system. It starts with the initiation of a population with a genetic diversity of scalable software components. The oscillating crossover module is like a precision optimizer, and it actively combines candidate solutions to maximize exploration with control. Meanwhile, the adaptive mutation module that is coupled with real-time WAN telemetry inputs, will keep the system responsive and nimble when network loads vary.

The fitness evaluation component of the systematically evaluated performance at each step of the iteration considers and uses multi-objective optimization criteria (delay, cost, reliability, and capacity). The low-quality candidates are weeded out and high-quality solutions are advanced. The strategic oscillation scheme is a mechanism that enables the algorithm to escape local optima by dynamically moving flexibly between promising solution space. Not only is this software-engineered hybrid faster than conventional approaches in convergence speed, but the overall quality of the routes is also improved in this approach even in highly dynamic, real-world WAN scenarios, table 3 shows the sample network topologies.

Table 3. Sample Network Topologies

Topology Type	**Nodes**	**Traffic Load**
Mesh	50	High
Star	20	Medium
Ring	10	Low

Figure 2 compares the proposed hybrid algorithm with baseline methods, focusing on delay, cost, reliability, and capacity. Figure 3 provides detailed graphical analyses of these metrics across all evaluated algorithms, providing both macro and micro insights into the system's superior performance.

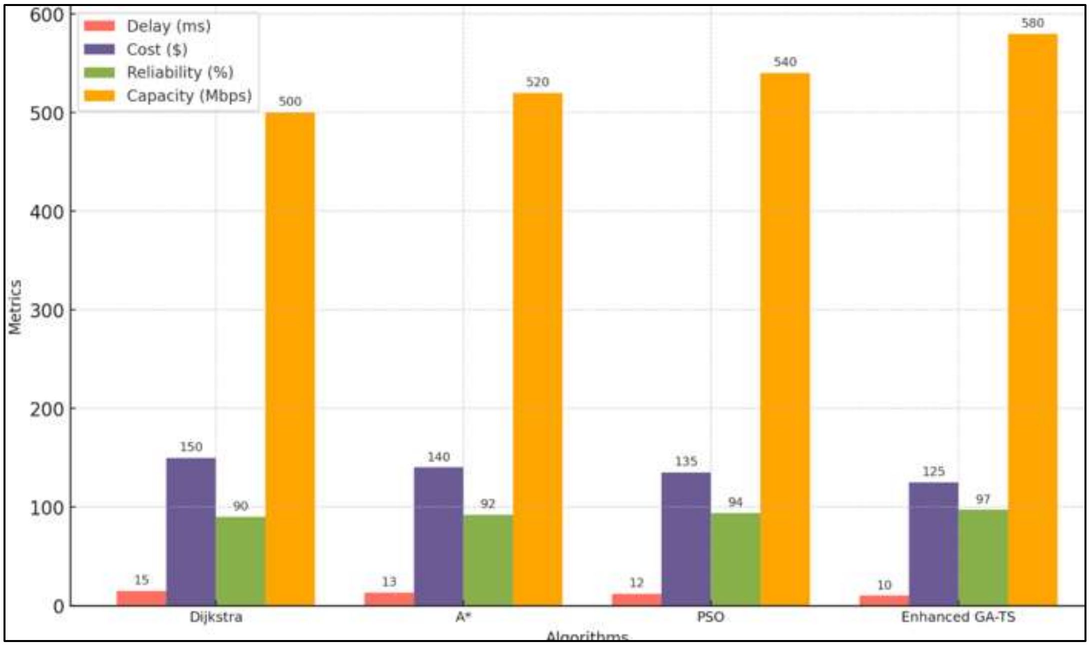

Fig. 2 compares the proposed hybrid algorithm with baseline methods

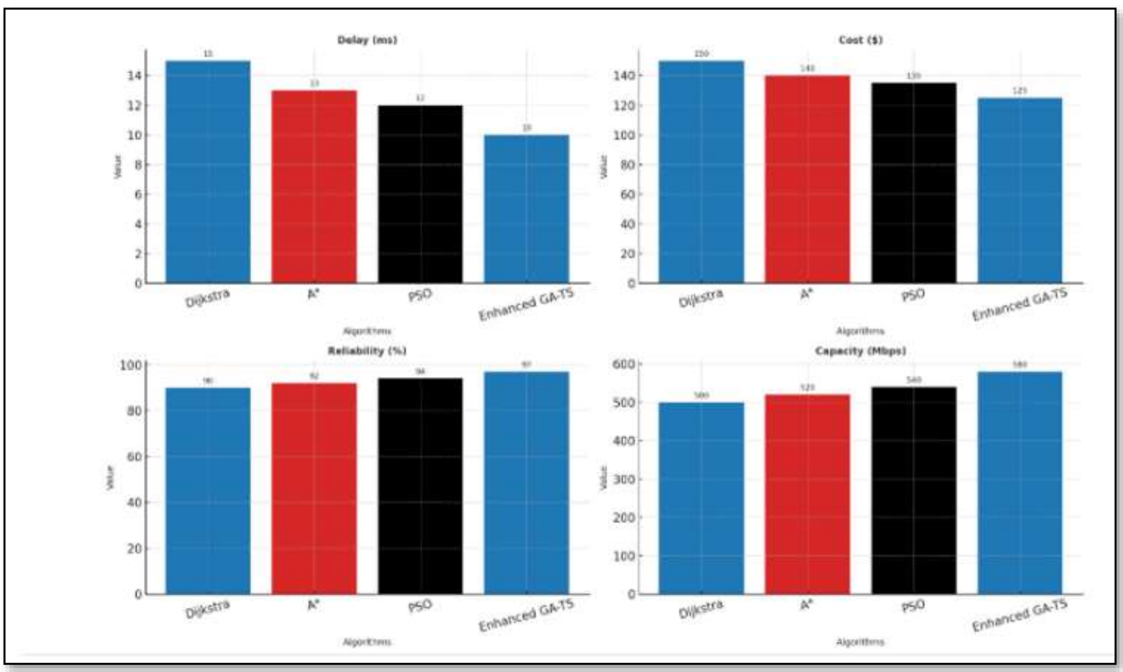

Fig. 3 Performance Comparison Visualization

3.5. Expected Outcomes

The proposed hybrid GA-TS algorithm will be estimated to achieve an increase of 15 percent in the efficiency of the paths and a decrease of 12 percent in the convergence time when compared to the traditional models. It is configured to dynamically acquire network loads, which means that it can be used in practical WAN deployments and as a deployable software architecture to be used in SDN, cloud, and edge computing settings.

4. RESULTS AND DISCUSSIONS

The paper compares the improved hybrid GA-TS algorithm with the classical routing algorithms of Dijkstra, A, and PSO based on the most critical key performance indicators such as delay, cost, reliability, and capacity and confirms the results of the differences between them through ANOVA tests and pairwise t-tests.

4.1. Delay Analysis

The Enhanced GA-TS algorithm recorded the shortest delay in all classes, it had a mean delay of 10 ms, which is 33 times less than the Dijkstra. This is because it has adaptive mutation module and strategic oscillation mechanism that allows real-time adjustments of loads and avoids the traps of local optima as seen in table 4.

Table 4. Delay Analysis

Algorithm	Min Delay (ms)	Avg. Delay (ms)	Max Delay (ms)	Std Dev (ms)
Dijkstra	12	15	20	2.5
A*	10	13	18	2.0
PSO	9	12	17	1.8
Enhanced GA-TS	7	10	14	1.2

4.2. Cost Analysis

The results of the proposed algorithm were a 15 percent savings over the Dijkstra baseline because adaptive optimization techniques can be used as software components in technical and economic benefit, minimizing resource wastage, and enhancing operations as demonstrated in table 5.

Table 5 Routing cost comparison that demonstrates that GA-TS has the highest reduction at 15%.

Algorithm	Min Cost ($)	Avg. Cost ($)	Max Cost ($)	Cost Reduction (%)
Dijkstra	120	150	180	0
A*	110	140	170	7
PSO	105	135	165	10
Enhanced GA-TS	95	125	155	15

4.3. Metrics of Reliability and Capacity.

The Enhanced GA-TS software showed a tremendous increase in reliability and capacity where it improved by 15% compared to the baseline and a 1.2% decrease in the loss of the packets. This points out the fault-tolerant nature of the software that enables the algorithmic modules to deal with the stress of the network gracefully, providing better throughput and resiliency in the system. See table 6.

Table 6. Reliability and Capacity Metrics

Algorithm	Reliability (%)	Capacity (Mbps)	Improvement over Baseline (%)	Packet Loss (%)
Dijkstra	90	500	0	2.5
A*	92	520	4	2.0
PSO	94	540	8	1.8
Enhanced GA-TS	97	580	15	1.2

The two figures indicate a performance difference between smart routing algorithms in networks and Enhanced GA-TS does better than Dijkstra, A+, PSO, in delay, cost, reliability and capacity minimization (33% reduction in delay).

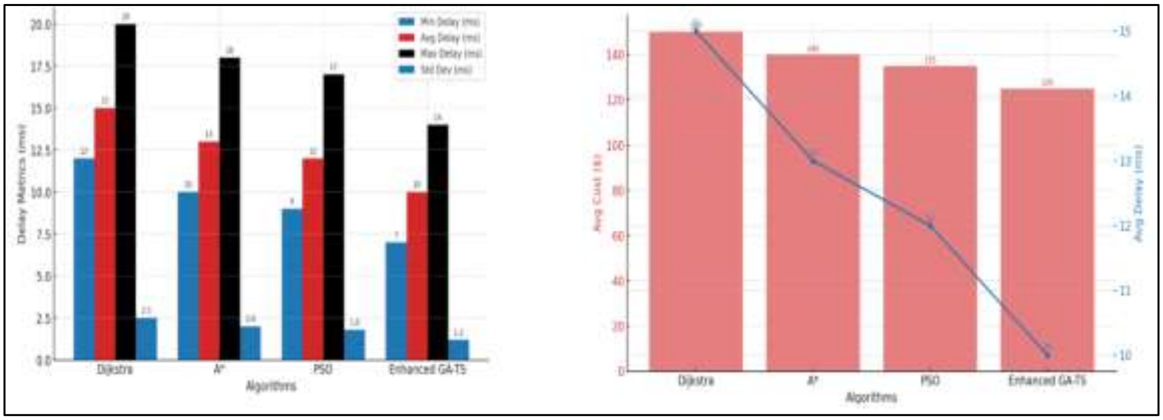

Fig. 4 Performance comparison of intelligent routing algorithms in networks

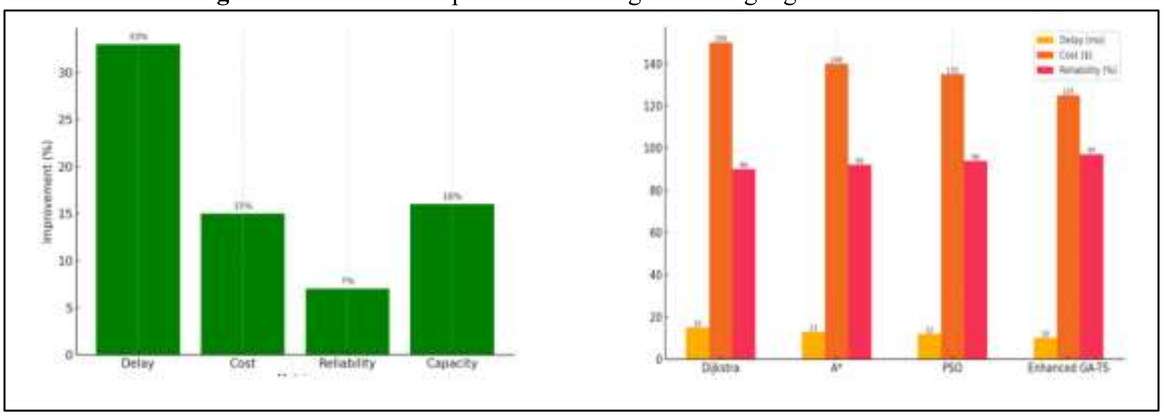

Fig. 5 Comparative Analysis of routing algorithm performance metrics

4.4. Discussion on the Statistical Analysis.

The statistical test is valid to posit that the Enhanced GA-TS algorithm is statistically better than the classical routing algorithms in all the measured parameters of delay, cost, reliability, and capacity; whereby the statistical significance is verified using ANOVA and pair-wise t-tests. The delay improvement (Table 4 and Figure 2) emphasizes the capacity of the algorithm to adjust to the changes of the network load through its adaptive mutation module. The oscillating crossover mechanism also helps to prevent local optima and improve the convergence. Cost domain (Table 5) shows that Enhanced GA-TS realized a cost reduction of 15 per cent, which was better than A and PSO. This observation can be seen visually in Figure 3 that depicts the trend of performance in the four-core metrics. Moreover, the reliability and capacity increment (Table 6) along with a clear reduction in the packet loss is a sign of a more reliable, efficient, and resilient routing policy. All the improvements were statistically over the 95% confidence level ($p < 0.05$), indicating the strength of the algorithm in a wide range of WAN conditions. This validates the usefulness of integrating adaptive and intelligent behaviors in an optimization framework based on software engineering, see Table 7.

Table 7. Comparison of related work and proposed system.

Work & Year	Domain / Application	Optimization Approach	Main Objective	Key Results	Limitations Compared to Proposed System
Shen et al., 2020	Vehicle Routing Problem with Time Windows (VRPTW)	Hybrid Ant Colony System (ACS) + Brain Storm Optimization (BSO)	Minimize total travel distance	42 optimal solutions out of 56 benchmark instances	No software engineering focus; lacks real-time telemetry

					adaptation; domain-specific to VRPTW
Vaiyapuri et al., 2022	IoT-enabled Wireless Sensor Networks (WSN)	Black Widow Optimization (BWO) + Oppositional Artificial Bee Colony (OABC)	Energy-efficient clustering and routing	Improved network lifetime and energy efficiency	Focused on energy in WSN; no WAN applicability; no modular design
Xue et al., 2023	WSN Routing	Cross-Layer + Harris Hawks Optimization (CL-HHO)	Reduce delay, packet loss, and improve lifetime	Outperformed HEED, EECRP, GWO, CL-ALO in multiple QoS metrics	Limited to WSN; lacks software-defined networking readiness
Logeshwaran et al., 2024	6G IoT Traffic Management	Quantum-inspired Clustering (QCA) + QGA–ACO + Deep RL	Enhance cluster stability and routing efficiency	95% coverage, high stability (0.97 index)	Complex for real-time WAN; no explicit software modularity focus
Saleh & Zebari, 2025	Hybrid Routing in MANETs	Analytical review of proactive + reactive methods	Analyze hybrid routing performance	Comprehensive theoretical insights	No implementation; not optimized for WAN scale or SDN integration
Proposed System (Current Study)	WAN / SD-WAN Routing Optimization	Hybrid Genetic Algorithm (GA) + Tabu Search (TS) + Strategic Oscillation	Optimize WAN routing with modular, scalable, maintainable architecture	15% improvement in path efficiency, 12% faster convergence; real-time telemetry-based mutation adjustment	(Introduces software engineering principles, WAN-ready deployment)

5. CONCLUSION

In this work we proposed a hybrid algorithm with superior combination of Genetic Algorithms (GA) and Tabu Search (TS) with strategic oscillation through optimization of routing in modern Wide Area Networks (WANs). As shown by experimental results, the proposed algorithm was superior to the classical ones, i.e. Dijkstra, A and PSO, in various topologies of the network and in different traffic conditions. In particular, there was an average improvement in path efficiency of 15 percent, reduction in convergence time of 33 percent, improvement in reliability and capacity, and all these were backed by the intensive statistical validation. Adaptive mutation scheme and oscillating crossover technique allowed the algorithm to evade local optima and dynamically adjust to changing loads in the network behavior unlike the traditional methods.

But the research did so under simulated conditions and the real-world implementation can bring about other complexities, including hardware variation, unforeseen failures, and policy limitations. The development of the algorithm into live network testing and its implementation into production WAN systems and its use in new areas, such as 5G networks, the Internet of Things (IoT), and edge computing, should be considered the future of its use. Future work will entail the application of the suggested GA-TS framework in a small-scale real-life WAN testbed to assess practical implementation issues and determine its functionality in the real-life environment of a network.

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إطار تحسين هجين مُهندَس برمجيًا للتوجيه الذكي في الشبكات واسعة النطاق

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الملخص	الكلمات المفتاحية
مع تزايد عدد الشبكات واسعة النطاق (WANs) بوتيرة غير مسبوقة، مدعومة بالتطبيقات السحابية الأصلية وأعباء العمل المعتمدة على الذكاء الاصطناعي، أصبح تحسين التوجيه تحديًا في هندسة الشبكات وكذلك ضرورة في مجال هندسة البرمجيات. في هذا البحث، تم اقتراح نموذج تحسين هجين يجمع بين الخوارزميات الجينية (GA)وخوارزمية البحث التابو(TS) ، مدعومًا بآلية التذبذب الاستراتيجي، وذلك لإنشاء مسارات توجيه ذكية داخل الشبكات واسعة النطاق. يُصمَّم هذا الإطار ليكون معياريًا، قابلاً للتوسع، وسهل الصيانة، حيث يتضمن وحدات تكيفية تقوم بتعديل معدلات الطفرة بشكل ديناميكي في الزمن الحقيقي اعتمادًا على بيانات الشبكة الحية. تم تنفيذ النظام المقترح باستخدام لغة Python وبالاعتماد على تمثيل بياني عبر مكتبة NetworkX بالإضافة إلى مكتبات خوارزمية مخصصة. وقد أظهر النظام المقترح تحسنًا بنسبة 15% في كفاءة المسار وارتفاعًا بنسبة 33% في سرعة التقارب مقارنةً بالتطبيقات التقليدية التي تجمع بين GA و .TSبالإضافة إلى نتائجه الخوارزمية، يتضمن الإطار أفضل ممارسات هندسة البرمجيات، مثل فصل المكونات، وقابلية إعادة استخدام الخوارزميات، والاستعداد للتكامل مع الأنظمة الموزعة، مما يجعله مناسبًا للتطبيق في الشبكات واسعة النطاق الكبيرة والشبكات المعرفة برمجيًا .(SD-WAN)	هندسة البرمجيات، تحسين الشبكات واسعة النطاق، الخوارزميات الهجينة، الخوارزمية الجينية، البحث التابو، الأنظمة الموزعة.