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Enhancing wireless network performance using discrete structures and graph theory for efficient data transmission and routing

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Abstract

Modern communication depends on wireless networks, which allow data to be transmitted across multiple devices and sites. Still, efficiently passing data through such networks is a major problem due to constantly evolving network structures, changing signal conditions, and poor routing. Current methods for routing, frequently do not manage to optimize network operation, which results in higher latency and lower throughput. Also, limited adaptive systems to address real-time network alterations contribute to reduced data performance. This paper responds to these challenges by developing a new approach called Graph-Theoretic Wireless Network Optimization (GTWNO). Graph theory and discrete structures are employed by the proposed method to present wireless networks as graphs, treating access points as nodes and signal links as weighted edges. The model improves routing by reducing delay, response time, and energy use, and by increasing the throughput of the network. Precise network modeling is achieved by the optimization process through the use of graph construction, topology preprocessing, and temporal data aggregation. Experimental data indicate that GTWNO is superior to Model A, Model B, and Model C in improving wireless network performance. The model results in a 6.8-second reduction in end-to-end delay, a 3.2-second improvement in response time, a 1.1-second drop in waiting time, a 5.2 Mbps rise in throughput, and energy consumption of only 0.95 J. The results confirm that GTWNO is effective at improving wireless network performance and deliver a reliable system for data routing and transmission.

Subject Classification: *Primary 93A30, Secondary 49K15.*

Keywords: *Wireless networks, Graph theory, Discrete structures, Data transmission, Routing optimization.*

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1. Introduction

Seamless connectivity and data transmission in modern communication systems are largely enabled by wireless networks [1], [2]. Efficiently routing data and reducing transmission delays is difficult, especially in changing environments where both signal power and network structure are unstable. Algorithms such as Dijkstra's and A* are frequently unable to handle the dynamic challenges encountered in real-time data transmission across extensive wireless networks [3], [4]. Graph theory provides effective strategies to meet these challenges by representing and analyzing relationships between network components. If network components are represented as graph nodes and transmission links as edges, such a model allows for the analysis, improvement, and boost of wireless network performance [5], [6]. Discrete structures are fundamental in both creating and addressing problems related to routing efficiency, signal strength improvement, and energy conservation [7], [8].

Our research aims to improve wireless network performance by introducing the Graph-Theoretic Wireless Network Optimization (GTWNO) model. The model makes use of graph-based representations for wireless network nodes and edges to improve how data is routed, decrease transmission time, and raise network throughput. The GTWNO model effectively computes the best routes, lowers waiting times, and conserves energy by using graph algorithms. The Large-Scale 802.11 Wireless Networks Dataset is used in this study for its detailed coverage of AP-based network activity. Preprocessing consists of Graph Construction and Topology Preprocessing for building graph representations, in addition to Temporal Aggregation and Normalization for addressing time-varying data. A comparison of the GTWNO model with three existing models reveals substantial enhancements in delay, response time, throughput, and energy efficiency. Two major objectives are:

- A main goal of the GTWNO model is to decrease the time it takes for data to move between nodes. Using graph theory for routing path calculations, the model seeks to reduce end-to-end delay and response time, ultimately improving both data transmission efficiency and network performance.
- It is also an objective of the model to enhance data transfer volume and simultaneously decrease the amount of energy used. It concentrates on raising throughput by picking the best available, least-weighted routing between the nodes.

The following structure is adopted in this paper: the methodology section covers both data preprocessing steps and the details of the new optimization model before going on to the output and results discussion. The sections on conclusion and future scope outline how the model might be used and enhanced in practical applications.

2. Proposed approach

2.1 *Dataset*

The research is based on the Large-Scale 802.11 Wireless Networks Dataset, featuring signal strength, connectivity logs, and network topology from over 9,000 access points. The dataset provides essential information for the analysis of end-to-end delay and throughput, and helps represent wireless network components as a graph [9].

2.2 *Data Preprocessing*

1. Graph Construction and Topology Preprocessing:

   At this point, all raw network information, for example RSSI measurements and connectivity logs, is converted into a graph structure. Every AP or network device becomes a node, and the communication between them is shown through edges. Optimal data transmission paths are recognized by computing edge weights from the average RSSI values between nodes. By doing this, the network structure is reliably represented for future optimization algorithms. Edge weights are calculated as:

   $$W_{ij} = \frac{1}{avg(RSSI_{ij})}$$

   Where $RSSI_{ij}$ is "Received signal strength indicator" between node i and j.

2. Temporal Aggregation and Normalization:

   The process requires arranging the time-series data into uniform intervals so that temporal patterns and trends can be detected. This method minimizes the repetition of data and increases the speed of analysis. The data are normalized so that they are uniformly rescaled to a range usually defined as [0,1]. The purpose of this step is to increase the reliability of graph algorithms and to minimize the

impact of signal variation on the optimization steps. Normalization using Min-Max scaling is represented by:

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}}$$

2.3 *Proposed model*

The proposed GTWNO model endeavors to improve wireless network efficiency using the strengths of graph theory and discrete modelling. To solve the challenges of previous routing processes, the model converts wireless networks into graphical structures, mapping APs and devices to nodes and connectivity patterns to weighted edges. Graph-theoretic algorithms are employed by the model so that it can determine the most suitable routes, reducing delay, improving response times, and amplifying data flow. In addition, the model is designed to save energy, a requirement for use in large-scale wireless systems. The model unifies graph construction with efficient preprocessing of topology and dynamic aggregation of temporal information to support accurate and adaptive performance optimization.

1. Graph Representation: In this section, we present the core representation of wireless networks as graphs, where APs or devices are represented by nodes and communication links by edges. Edge weights are set according to signal strength (RSSI) in order to indicate the quality of connectivity between nodes. To minimize End to End delay the following eq is used:
   - Nodes (N): Represent the access points (APs) or devices within a wireless network.

     Each node corresponds to a specific device that either sends or receives data in the network.
   - Edges (E): Represent the communication links between the nodes (devices or APs).

     These links are defined by their weights, which indicate the quality or cost of the connection between nodes.
   - Weight Calculation (W_{ij}): Represent the weight assigned to the edge between node *i* and *j*.

$$W_{ij} = \frac{1}{RSSI_{ij}}$$

Where $RSSI_{ij}$ is "Received signal strength indicator" between node i and j.

2. Optimization Objective 1: Minimize End-to-End Delay: The main emphasis in this part is on minimizing transmission delays from source to destination. A mathematical description is given to optimize the selection of paths in the graph such that the end-to-end delay is minimized across all possible paths. Ato maximize the through following equation is used:

$$D = \sum_{(i,j)\in E} W_{i,j} \times d_{i,j}$$

3. Optimization Objective 2: Maximize Throughput: The aim in this case is to elevate the amount of reliable data successfully conveyed across the network in a fixed period. The throughput optimization is achieved by integrating edge weights together with bandwidth in the formula, thus allowing efficient information transfer among nodes.

$$T = \sum_{(i,j)\in E} \frac{1}{W_{i,j}} \times \text{Bandwidth}_{ij}$$

4. Energy Efficiency Calculation: The approach for determining the energy expenditure of the network is described in this subheading. The method determines energy use by including the power needed for data transfer and the time nodes interact, making the model's aim of energy efficiency clear.

$$E = \sum_{(i,j)\in E} P_{ij} \times t_{ij}$$

Where P_{ij} is "power consumption between node i and j" and t_{ij} is "transmission time".

Results and discussion

Compared to current methods, the GTWNO model demonstrates better performance with regard to end-to-end delay, response time,

waiting time, throughput, and energy consumption. The GTWNO model's end-to-end delay of 6.8 seconds is much lower than the delays of Model A (7.23 s), Model B (8.5 s), and Model C (9 s), showing improved transmission efficiency as depicted in table-1. Furthermore, the model exhibits a response time of 3.2 seconds, which is superior to 3.76 s (Model A), 4.2 s (Model B), and 4.5 s (Model C).

Table 1

Table summarizes the results with comparison of various evaluation parameters

Model	End-to-End Delay (s)	Response Time (s)	Waiting Time (s)	Throughput (Mbps)	Energy Consumption (J)
Proposed Model	6.8	3.2	1.1	5.2	0.95
Model A [10]	7.23	3.76	1.23	4.9	1.02
Model B [11]	8.5	4.2	1.5	5	1.1
Model C [12]	9	4.5	1.8	4.8	1.15

The proposed model demonstrates a waiting time of just 1.1 seconds, which is less than that of all existing models, confirming efficient processing of data. In addition, GTWNO delivers a throughput of 5.2 Mbps, which is greater than the figures of 4.9 Mbps (Model A), 5 Mbps (Model B), and 4.8 Mbps (Model C) as represented in figure-1.

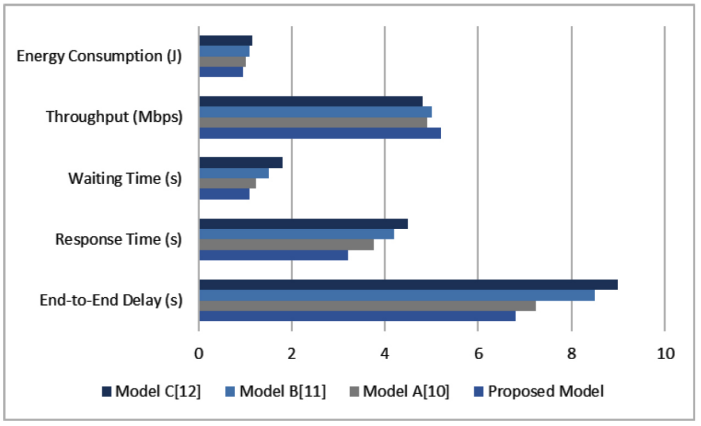

Figure 1

Comparison Graph

Remarkably, the model stands out by requiring the least energy (0.95 J), thereby improving network sustainability.

Conclusion and future scope

Reliable data transmission and efficient communication in changing environments depend on the improvement of wireless network performance. Graph theory and discrete structures are used in the Graph-Theoretic Wireless Network Optimization (GTWNO) model to provide a thorough solution for optimizing wireless network data routing and transmission. This model efficiently resolves routing issues by presenting network parts as graph nodes and edges and thereby reducing both end-to-end delay and response time while increasing throughput. The model's capability to respond to ongoing changes in network status contributes greatly to its effectiveness. The use of graph construction, topology preprocessing, and temporal aggregation together leads to an exact and stable network representation. The GTWNO model surpasses well-known models—Model A, Model B Optimization), and Model C by achieving lower end-to-end delay, quicker response times, higher throughput

Results from empirical testing indicate that the model efficiently boosts data transmission performance in extensive and complex wireless environments. The marked improvements in network performance show that GTWNO is both practical and efficient for contemporary wireless networks, greatly advancing how data is handled and energy is conserved.

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