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ROUTING METRIC AND PROTOCOL FOR WIRELESS MESH NETWORK BASED ON INFORMATION ENTROPY THEORY.

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In this work, the authors propose a routing algorithm based on information entropy theory for calculating the metric, considering the probability of packet loss. Information entropy theory serves as a robust foundation for evaluating uncertainty and disorder in data transmission, facilitating the development of a more resilient and intelligent routing strategy. In contrast to existing algorithms, the proposed approach enables a more accurate assessment of data transmission quality within the network, optimizing the routing process for maximum efficiency. The experimental results demonstrate a significant enhancement in network service quality while maintaining high performance. To validate the algorithm's effectiveness, a series of experiments were conducted, evaluating key performance metrics such as throughput, delay, and packet loss. A comparative analysis with established routing algorithms was also carried out, allowing for the assessment of advantages and drawbacks in relation to well-known algorithms. The findings suggest that the proposed algorithm surpasses traditional routing methods in optimizing data transmission quality and overall network efficiency.

Keywords: Routing, entropy, information, wireless mesh network.

1. Introduction

In the present day, wireless mesh networks (WMNs) are emerging as a rapidly deployed communication technology. This swift adoption can be attributed to several advantages, including easy and quick implementation, automatic self-recovery, dynamic self-organization, self-configuration, extensive network coverage, and cost-effectiveness. Furthermore, the versatility of WMNs makes them suitable for a wide range of applications, including broadband home networking, education, healthcare, building automation, disaster management, rescue operations, and military applications [1-4].

The WMN architecture consists of three carefully structured node layers. In the first layer, gateway nodes (GWs/Gws) are linked to the physical layer. Moving to the second layer, quasi-static wireless mesh routers (MRs/APs) fulfill the role of transmitting packets to and from mesh gateways. Finally, the third layer comprises mesh clients (MCs), including devices such as desktop computers, mobile phones, laptops, and various other wireless devices.

In general mesh routers have more sophisticated capabilities than mesh clients, such as multiple receive/transmit interfaces, higher transmitting power, infinite power supply. The data traffic in WMNs comprises gateway-oriented traffic and client-oriented traffic. In gateway-oriented traffic, data is transferred through a gateway to the Internet. In client-oriented traffic, the data packets are transmitted to the destination mesh client by multiple hops [5-6]. Currently, a lot of research has been done on routing issues in WMNs [7-15]. Routing protocol design is essential for the performance and reliability of WMNs. The primary goal of the routing protocols is to find reliable routes in multi-hop WMN that is deals with the highly unstable wireless medium. These days, more and more communication services require high throughput and little delay, so it is crucial to tackle the problem of traffic routing for throughput optimization and delay minimization in WMNs [11, 12]. In recent times, there has been a rising interest in the application of information entropy theory in routing for wireless networks [13, 14]. Information entropy methods offer a valuable framework to assess and improve the efficiency and reliability of data transmission in wireless networks. By quantifying uncertainty and disorder in network communication, these methods allow for a more comprehensive understanding of network dynamics, error detection, and quality of service optimization. Information entropy theory aids in identifying and mitigating potential vulnerabilities in routing protocols while enhancing the accuracy of performance metrics, such as throughput and overall network performance. Its adoption represents a promising direction for enhancing WMN routing in an era of growing data demands and network complexity [15-18].

In this work, a new algorithm, named Information entropy-based routing algorithm (IER), is proposed to calculate the routing metric based on information entropy theory. The method considers vulnerabilities observed in Dijkstra's algorithm, where an increase in complexity correlates with a higher probability of errors. For a more accurate assessment of errors in the communication channel, it is proposed to use the entropy method. Additionally, routing algorithms developed for WMNs, such as Optimized Link State Routing (OLSR) and Better Approach to Mobile Adhoc Networking (BATMAN), use broadcasting techniques to discover pathways. However, this approach often leads to network congestion, which, in turn, reduces throughput. It's also important to note that current routing algorithms designed for wireless ad hoc networks are not directly applicable to WMNs, as they haven't been optimized for the specific requirements of WMNs.

2. Routing Protocols

This section presents a concise overview of several prominent routing protocols developed for WMNs, with the aim of identifying vulnerabilities and strengths as a preliminary step before creating a new routing algorithm. Furthermore, the discussion of Dijkstra's algorithm is delved into as a benchmark for comparison with more specialized WMN routing protocols, enabling the evaluation of its applicability and constraints [19].

Numerous routing protocols have been proposed for wireless mesh networks, including Dynamic Source Routing (DSR), Ad-hoc On-Demand Distance Vector (AODV), Destination-Sequenced Distance Vector (DSDV), Optimized Link State Routing (OLSR), Better Approach to Mobile Adhoc Networking (BATMAN), Software-Defined Networking for Mesh Networks (SDNMesh), and Three-Stage Routing Algorithm (Three-Stage). Many of these protocols use broadcasting techniques to establish communication pathways, but this approach can be energy-consuming and lead to unnecessary overhead.

The OLSR protocol is a proactive, table-driven routing protocol designed for use in mobile ad-hoc networks (MANETs) and wireless mesh networks (WMNs). OLSR aims to efficiently determine and maintain routes in a network where nodes can move and change their connections frequently. It was developed to address the challenges of routing in dynamic, self-organizing, and multi-hop wireless networks. OLSR represents an enhancement of the traditional link state protocol, designed specifically for mobile ad hoc networks and wireless networks.

First, OLSR is a proactive routing protocol, which means it maintains routes at all times. This proactive nature reduces route discovery latency, making it suitable for applications that require low-latency communication. Secondly, OLSR optimizes control message overhead using Multipoint Relays (MPRs), reducing the number of nodes that need to rebroadcast control messages. This optimization reduces the impact on the available network bandwidth and power resources.

Also, OLSR is well-suited for multi-hop wireless networks, making it ideal for wireless mesh networks, ad-hoc networks, and other scenarios where nodes need to relay data across multiple hops. OLSR also can work with existing IP networks and can be easily integrated with the Internet Protocol (IP), enabling seamless communication with other IP-based devices. However, it comes with certain vulnerabilities and limitations such as limited scalability, resource consumption, static MPR selection, security concerns, inapplicability for all scenarios, and lack of QoS Guarantees. OLSR can face scalability issues in large networks due to its proactive nature. Maintaining routing information for all nodes in the network can lead to excessive control overhead, which may not be practical in highly dynamic and large-scale environments.

The proactive approach of OLSR results in higher resource consumption, both in terms of memory and processing power. This can be a concern in resource-constrained devices, such as sensor nodes. Also, OLSR's Multipoint Relay (MPR) selection is typically static, meaning that MPRs are selected during the initial setup and do not adapt to changing network conditions. This can lead to suboptimal routing in dynamic networks. (OLSR) protocol faces security vulnerabilities as it lacks robust built-in security mechanisms, making it susceptible to attacks such as spoofing, eavesdropping, and denial of service. To ensure secure operation, additional security mechanisms like encryption and authentication must be added. Furthermore, OLSR may not be the optimal choice for all types of wireless networks. In scenarios involving

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highly mobile networks or rapidly changing network topologies, alternative routing protocols like AODV (Ad Hoc On-Demand Distance Vector) might be more suitable due to their adaptability and responsiveness to dynamic network conditions. Moreover, while OLSR can be extended to consider Quality of Service (QoS) metrics, it does not inherently provide strong QoS guarantees. This limitation makes it less suitable for applications with stringent QoS requirements, where the assurance of specific performance characteristics is of utmost importance [20-22].

The BATMAN is a proactive, table-driven routing protocol designed for wireless ad-hoc networks and mobile mesh networks. BATMAN aims to provide efficient and reliable communication in scenarios where nodes can move, and the network topology changes frequently. BATMAN (Better Approach to Mobile Ad-Hoc Networking) offers numerous advantages in wireless mesh and ad-hoc networks. It is a proactive routing protocol that maintains up-to-date routing information, reducing route discovery latency and facilitating low-latency communication. BATMAN excels in multi-hop environments, making it ideal for wireless mesh networks, where data must traverse multiple nodes to reach their destination. Its innovative Originator-based routing approach minimizes control message overhead by allowing nodes to select Originators that relay information, enhancing network efficiency.

BATMAN is known for its ease of use with minimal configuration requirements, making it accessible to a broad range of users and applications. Additionally, it provides adaptability to various wireless environments, supports mesh networking, and can be integrated with the Internet Protocol (IP) for broader internet connectivity. Extensions such as BATMAN-ADV can enhance security with features like encryption and authentication, adding to its versatility and robustness. BATMAN (Better Approach to Mobile Ad-Hoc Networking) has notable limitations. While it offers proactive routing, it can encounter scalability issues in large networks due to control message overhead, potentially affecting network performance. Its resource consumption, including memory and processing power, can be demanding and may not be suitable for resource-constrained devices. Security concerns are a drawback, as BATMAN lacks strong built-in security mechanisms by default, leaving it vulnerable to various attacks. Moreover, it may not be the optimal choice for highly mobile or rapidly changing network scenarios, where other routing protocols might provide more adaptability and responsiveness. Lastly, BATMAN does not inherently guarantee Quality of Service (QoS), making it less appropriate for applications requiring strict QoS requirements, which need assurance of specific performance characteristics. Consideration of these limitations is essential when selecting BATMAN as a routing protocol in various network deployments [23, 24].

SDNMesh is a routing protocol designed to enhance the capabilities of the OpenFlow protocol, enabling its application in Wireless Mesh Networks (WMNs) with their dynamic characteristics. It involves the modification of the OpenFlow client to align with the proposed routing architecture. SDNMesh operates in two phases: the first phase establishes routes from the controller to switches, which may not be optimal in terms of latency, while the second phase optimizes these initially inefficient routes, introducing some additional delay. This protocol addresses challenges like link or node failures, which are common in wireless environments. To support its functionalities, an OpenDaylight controller is integrated into the network, enabling the controller to gather information from Mesh Access Points (MAPs) and form a global network view. SDNMesh provides a stepwise approach to routing, focusing initially on establishing connections between the controller and all the switches in the network, followed by setting up routing paths between the SDN controller and connected switches, ultimately ensuring efficient data transmission between switches.

The Three-Stage routing algorithm is a specialized approach designed to address routing challenges within Software-Defined Networking (SDN)-based Wireless Mesh Networks (WMNs), particularly in the context of Smart Grid communication and power grid management. This algorithm extends the capabilities of the OpenFlow protocol to adapt to the dynamic nature of WMNs. It operates in three key stages: First, it focuses on establishing connections between all switches in the SDN-based wireless mesh network and at least one controller, utilizing an OpenFlow-based routing algorithm and network flooding. Once initial connections are established, the second stage optimizes routing paths, introducing new alternatives, including shortest and load-balanced routes. Finally, the third stage addresses routing among switches, ensuring efficient data transmission. The Three-Stage routing algorithm emphasizes cost-effectiveness, low latency, and network-aware communication, making it well-suited for providing coverage in challenging environments, such as power systems in rural and disaster-prone areas [25, 26].

Dijkstra's algorithm is an algorithm used to find the shortest path between two nodes in a weighted graph. It was developed by Dutch computer scientist Edsger Dijkstra and is one of the most widely used methods in networking and telecommunications. Dijkstra's algorithm operates on the principle of finding the shortest path in a weighted graph. It begins with an initial node, setting its distance to itself as zero and all other nodes as distances to infinity. The algorithm iteratively selects the unvisited node with the smallest known distance, evaluates the distances to its adjacent nodes, and updates them if a shorter path is found. This process continues until all nodes are marked as visited or until the shortest path to a specific destination node is discovered. Once completed, the algorithm allows for determining the shortest path to any node by tracing the sequence of nodes and their distances from the initial node. Dijkstra's algorithm offers several key advantages, making it a valuable tool in various applications. It guarantees the discovery of the shortest path in graphs with non-negative edge weights, ensuring optimal route selection. Its versatility allows it to be applied to a wide range of real-world problems, from transportation and logistics to computer network routing. The algorithm excels in providing accurate results, making it suitable for critical applications where precision is essential. Also, Dijkstra's algorithm is relatively simple to understand and implement, making it accessible to a broad audience of users, from novice programmers to experts in route optimization. Despite its effectiveness, Dijkstra's algorithm has notable vulnerabilities that must be considered when applying it to certain scenarios.

First and foremost, it cannot handle graphs with negative edge weights, as it assumes non-negativity, and attempting to use it in such cases can result in incorrect results. Additionally, the algorithm focuses on finding the shortest path from a single source node to all other nodes, making it less suitable for problems that require simultaneous determination of multiple sources or destinations. While its time complexity can be improved with the use of a priority queue, Dijkstra's algorithm remains inefficient for large graphs, leading to increased computational demands. Furthermore, its memory usage can be high in large-scale applications, as it requires storing and updating distances for all nodes. Lastly, the algorithm is not suitable for graphs with negative weight cycles, as it may get stuck in an infinite loop in such scenarios [27, 28].

3. The proposed routing method

The fundamental principle of the Information entropy-based routing algorithm (IER) centers on channel multiplication, providing it with the capability to adeptly manage errors and efficiently handle packet loss during data transmission. To implement the proposed routing algorithm, the initial step involves calculating the distance between nodes, defined as the shortest length between the nodes u and v. Consider Fig. 1 which illustrates a cascade-connected network configuration featuring routers $R1$, $R2$, and $R3$, interconnected through channels (ch1 and ch2), where potential errors can occur. This diagram visually portrays the sequential connections between the routers, underscoring the cascading nature of their arrangement.

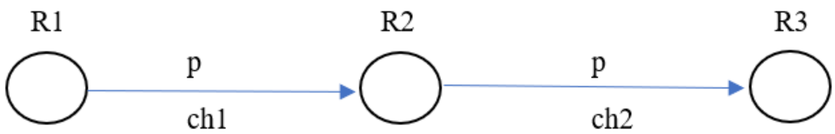

Fig.1. An example of cascade-connected routers.

Each channel has error probabilities that depend on the distances between routers (Fig. 1). To find the distances, the following equation is used:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}, \quad (1)$$

where d represents the distance between the two routers, $(x_1,\ x_2)$ are the coordinates of the first router, $(y_1,\ y_2)$ are the coordinates of the second router.

The calculation of received power (P_r) is crucial for assessing the quality of the received signal in communication networks. It helps in determining whether the signal is strong enough to ensure reliable communication and to identify potential issues such as signal degradation or interference. The received power (P_r) can be calculated using the Friis transmission equation. It is expressed as:

$$P_r = \frac{P_t G_t G_r(\lambda^2)}{(4\pi d)^2}, \quad (2)$$

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where P_r is the received power, P_t is the transmitted power, G_t is the gain of the transmitting antenna, G_r is the gain of the receiving antenna, λ is the wavelength of the signal, d is the distance between the transmitter and receiver.

The free-space path loss equation, also known as the Friis transmission equation, is used to calculate the loss of signal power as it propagates through free space.

$$\frac{P_r}{P_t} = D_t D_r \left(\frac{\lambda}{4\pi d}\right)^2, \quad (3)$$

where D_t is the directivity of the transmitting routers antenna, D_r is the directivity of the receiving routers antenna, λ is the signal wavelength, d is the distance between the antenna routers.

Next, both the Signal-to-Noise Ratio (SNR) and the Bit Error Rate (BER) can be derived. SNR is a ratio that compares the strength of the received signal to the background noise, while BER quantifies the likelihood of errors in the received data. Since p represents the probability of an error, it is indeed equal to the BER. The equation for BER depends on the modulation scheme and channel model but can generally be expressed as:

$$p = BER = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}}), \quad (4)$$

where $erfc$ is the complementary error function.

Next, cascade-connected channels are examined, and their error probabilities (Fig. 2) are calculated. The model and analysis of cascade-connected channels are presented in [29].

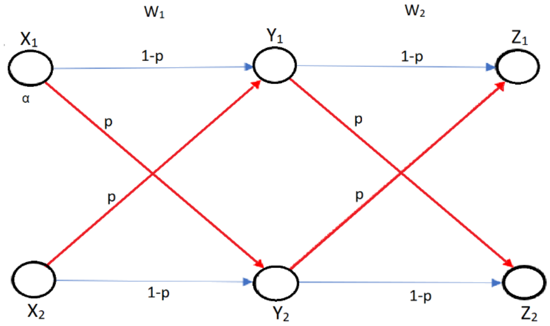

Fig.2. Cascading channels.

The channels are considered as matrices and multiplied accordingly. The matrix representing the conditional probabilities for this model is provided below:

$$P(R_3/R_1) = \begin{bmatrix} 1-p & p \\ p & 1-p \end{bmatrix} \begin{bmatrix} 1-p & p \\ p & 1-p \end{bmatrix}, \quad (5)$$

where p is probability of error.

The total probability n cascade-connected channels are defined as follows:

$$P = P\left(\frac{R_N}{R_1}\right) = \prod_{i-1}^{N} \begin{bmatrix} 1-p & p \\ p & 1-p \end{bmatrix} = \begin{bmatrix} 1-p_N & p_N \\ p_N & 1-p_N \end{bmatrix}, \quad (6)$$

where, p is probability of error of each cascade, p_N – total probability of N cascade-connected channels.

In the following step the total entropy of the channel path is calculated. The total entropy of the channel path characterizes the degree of uncertainty or information content associated with the transmission through a particular route. The total entropy of the channel path is defined as:

$$H_N(p) = -p_N \ln p_N - (1-p_N)\ln(1-p_N), \quad (7)$$

The subsequent step involves selecting the path with the minimum entropy among calculated entropies. This decision-making process is guided by the principle of minimizing unpredictability or disorder in the information associated with the chosen path. By prioritizing paths with minimized uncertainty, the algorithm is designed to optimize the flow of data, leading to higher throughput, and improved overall network performance. In the final step we defined throughput according to the following equation:

$$C = 1 - H_N(p_N), \tag{8}$$

where C is throughput, p_N is total probability of N cascade-connected channels and H_N is total total entropy of the channel path.

Here, a brief description of the proposed method is presented. To implement the IER, the following steps need to be performed:

1) Find distance (d) between routers;
2) Define received power (P_r);
3) Find SNR and BER of each channel;
4) Choose 10 random paths between source and target;
5) Define entropy of each path;
6) Choose path with minimum entropy;
7) Determining the throughput of the route.

4. Experimental evaluation

To assess the effectiveness of the IER algorithm, a simulation model of a WMN with 200 nodes was constructed using Python. The performance of the IER algorithm was benchmarked against several established routing protocols, including OLSR, BATMAN, and SDN based routing, Three-Stage algorithm, and the classic Dijkstra's algorithm. This comparative analysis was focused on key performance metrics: throughput, as illustrated in Figure 3 (a, b); Packet Loss Ratio, depicted in Figure 4; and Delay, shown in Figure 5. The simulations were carried out under varying network sizes, with WMN node counts of 10, 50, 100, 150, and 200, to obtain a comprehensive set of data on the three-performance metrics of interest: throughput, packet loss ratio, and average delay.

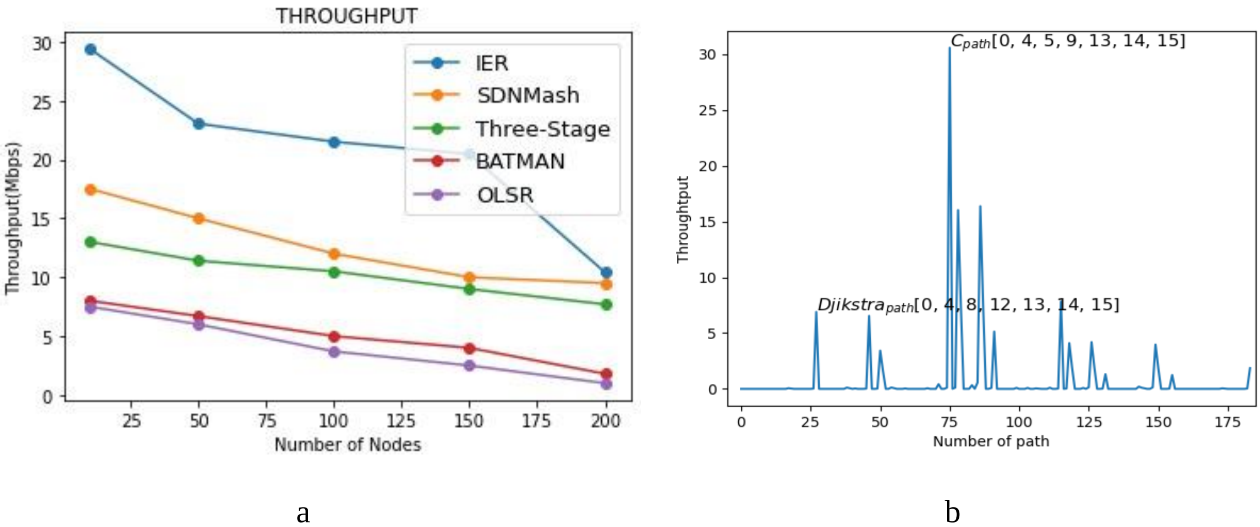

Fig.3. Throughput: a) of IER, SDNMash, Three-Stage, BATMAN and OLSR algorithms; b) of Dijkstra's algorithm

Figure 3 (a) presents the throughput measurements for each of the evaluated protocols − IER, OLSR, BATMAN, Three-Stage, and Dijkstra's across different network sizes. The data indicates that the IER algorithm consistently achieves higher throughput than the other protocols, demonstrating its efficiency in handling network traffic. Additionally, Figure 3 (b) further explores the throughput performance for the IER and Dijkstra's algorithms by showing the path with the highest throughput between node 0-15 within 20

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nodes in WMN. This comparison highlights the IER algorithm's superior capability in identifying and utilizing the most efficient paths for data transmission, resulting in optimal network performance.

Packet loss is a critical metric for gauging the efficacy of routing protocols in optimizing data exchanges between network nodes. According to the Fig. 4 the IER protocol demonstrates superior performance in maintaining low packet loss rates across various network sizes. The OLSR protocol, in contrast, exhibits the highest rate of packet loss, suggesting a slower convergence and less efficient path optimization. Following OLSR, BATMAN also shows a considerable packet loss, potentially due to longer intervals between routing information updates and the lack of a mechanism to minimize communication overhead. It is observed that the packet loss increases with the network size for these protocols. Such increase underscores the influence of two pivotal factors on packet loss rates: the proficiency of a routing protocol in path optimization and its associated communication overhead. Moreover, network interference often plays a substantial role in packet loss, with the likelihood of data collisions and the reception of corrupted packets increasing as the network becomes more congested. Thus, a routing protocol's design must balance path efficiency and overhead to mitigate packet loss, especially in larger and more complex networks where interference is more prevalent.

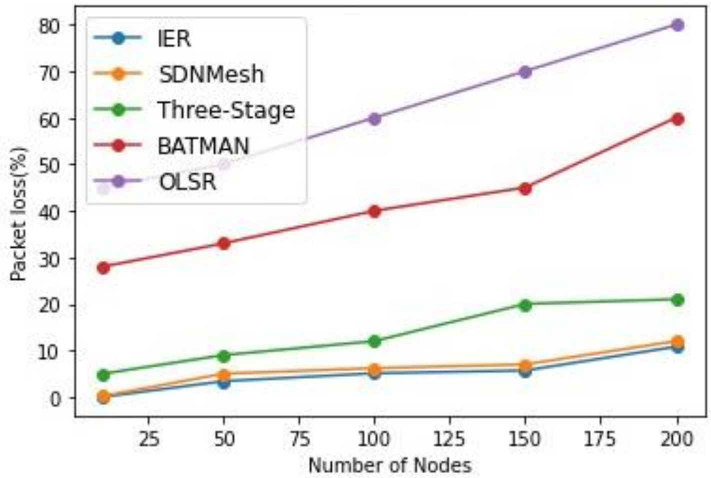

Fig.4 Packet loss ratio.

Fig. 5 evidently illustrates the relationship between network load and delay, indicating that as the load increases, so does the latency in packet delivery. Delay is defined as the duration it takes for a packet to travel from a source mesh client to a destination mesh client within the network.

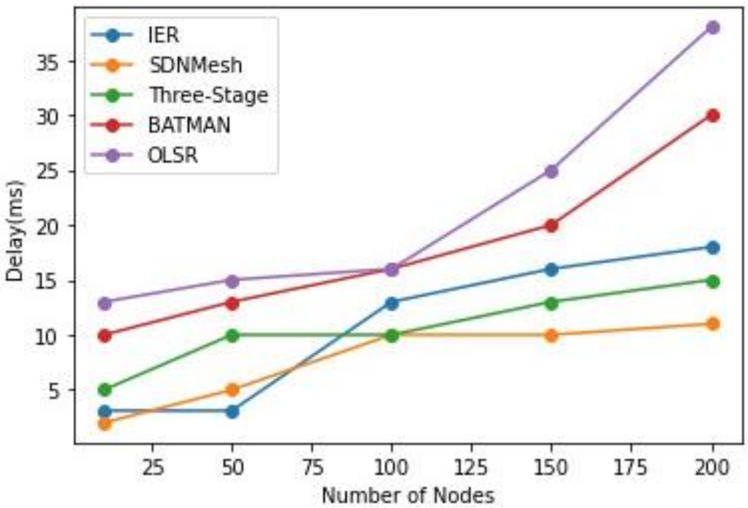

Fig.5 Deley.

The Fig, 5 demonstrates that the IER protocol exhibits commendable performance in terms of lower delays when compared to OLSR and BATMAN, showcasing its efficiency in quicker data packet delivery under various loads. However, it is important to note that while IER outperforms OLSR and BATMAN, it is slightly outshined by the Three-Stage and SDN Mesh routing protocols, which exhibit even lower delay times.In summary, the IER algorithm exhibits strong performance in throughput and packet loss metrics, suggesting it is robust and efficient, especially in WMN. However, there is space for improvement in delay handling where it is currently outpaced by Three-Stage and SDNMesh protocols. Overall, the IER algorithm emerges as a highly competent and reliable choice for WMNs, particularly distinguished by its scalability and resilience to network load and interference. Its design balances path efficiency and communication overhead adeptly, making it a strong contender in the field of advanced routing protocols.

5. Conclusion

The innovative Information Entropy-based Routing (IER) algorithm introduced in this paper represents a significant breakthrough in the domain of network routing. Grounded in the principles of information entropy theory, the IER algorithm leverages the probabilistic nature of packet loss to quantify the uncertainty in data transmission, thereby fostering a more intelligent and resilient routing framework. The experimental findings underscore the algorithm's efficacy, demonstrating its ability to enhance network service quality markedly. When juxtaposed against conventional routing algorithms such as Dijkstra, OLSR, BATMAN, SDNMesh, and Three-Stage, the IER algorithm not only competes effectively but often surpasses these established protocols across critical performance metrics such as throughput, delay, and packet loss. The IER algorithm has been shown to offer a more precise assessment of transmission quality, contributing to an optimized routing process that bolsters network efficiency. While the IER algorithm may trail slightly behind the Three-Stage and SDNMesh protocols in delay metrics, its overall high performance, and the significant improvements it brings to network service quality mark it as a superior choice for contemporary and future WMN applications.

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