

Dynamic Load Impact on Protocols in Mesh: An ANOVA Test Evaluation

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Abstract

The presented paper offers an in-depth look at mesh routing protocols, focusing on how well they perform under different conditions of node density and mobility. To make accurate comparisons, the study uses robust non-parametric statistical methods, including the Kruskal-Wallis, Mann-Whitney, correlation and covariance tests, to pinpoint which protocols stand out across crucial Quality of Service (QoS) metrics. These metrics cover energy consumption, end-to-end delay, packet delivery ratio, throughput, and network overhead.

The research simulates several mesh network scenarios to collect important data for a comprehensive assessment of the reliability and effectiveness of each protocol. The Kruskal-Wallis test identifies large differences in performance across different circumstances. Following that, the Mann-Whitney test offers a closer look, comparing protocols in detail to identify those that work best under specific conditions.

The study finds that protocol performance can vary dramatically depending on network density and how mobile the nodes are. It outlines which protocols excel in more stable setups and which remain dependable in fast-changing, dynamic networks. For network designers and operators, these insights are incredibly valuable, offering practical guidance on optimizing performance in real-world deployments.

Furthermore, the research underscores why non-parametric statistical methods are so crucial. Network data often show high variability and don't always follow normal distribution patterns, making traditional parametric techniques less reliable. By choosing a more flexible and accurate approach, this study makes a meaningful contribution to wireless communication, providing a clearer picture of how different routing protocols hold up under real-world conditions.

Keywords

Mesh, AODV, KRUSKAL–WALLIS, One way ANOVA, Mann-Whitney, Correlation and Covariance

JEL Classification

L86, L63, L14, D85, C15

Introduction

The wireless connection uses wireless connectivity to exchange equipment information. Wireless network technologies remove the costly method of installing cables to communicate with devices in different locations. The wireless network could be either an infrastructure or an infrastructure-less network, depending on how one categorizes it (Maciej Piechowiak et al., n.d.). The wireless infrastructure network could comprise a cellular network or Wi-Fi Internet. The caller network needs base stations that are linked together between them. Unlike WIFI, the devices require internet and access points to connect to the Internet. However, some drawbacks come with those types of networks, such as high cost, low scalability, low privacy, and less reliability. The other uses and wireless networks or infrastructure-less networks, such as the mesh network, come with several advantages and uses such as transient communication, in emergency areas, military uses, and transform communication. Table 1 summarizes the difference between infrastructure and infrastructure-less in wireless communication (Alameri et al., 2022), (Alameri, Hubálovský, & Komarkova, 2021).

Despite their inherent advantages, both network categories confront distinct challenges. Infrastructure-based networks grapple with cost, scalability, privacy, and reliability issues, whereas infrastructure-less networks, such

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as mesh, navigate the complexities of security, network stability, and performance consistency. The importance of choosing the network type based on needs and limitations is highlighted in this situation to enhance the effectiveness and efficiency of wireless communication (Yuan Chai & Wenxiao Shi., 2017).

At the core of this discussion is the exploration of mesh networks which are self-organizing networks, with hop communication capabilities. These networks operate without an infrastructure and are well suited for handling large scale peer to peer distribution of computational resources. However, the mobility of mesh nodes presents challenges in maintaining network connectivity and stability that requiring routing protocols to navigate the network topology (Darroudi & Gomez, 2017), (Alameri & Komarkova, 2022).

This study focuses on using analysis to assess the performance of routing protocols in mesh network. By utilizing Network Simulator version 2 (NS-2) across node densities and routing protocols this research conducts an evaluation of protocol performance supported by a comprehensive statistical framework. Diving into the world of mesh routing protocols, this analysis pulls out all the stops with some slick ANOVA techniques, like the Kruskal Wallis and Mann-Whitney tests. Diving into the world of network protocols is a big challenge due to their mobility nature. That's where the trusty statistical approach comes into play, perfect for tackling the oddball data.

This study conducts a rigorous evaluation of multiple routing protocols under diverse network conditions, providing valuable insights into their performance and adaptability. It is all about getting to the heart of how these protocols perform when it comes to the Quality of Service (QoS) metrics that matter most—like how quickly data gets from the source node to the destination nodes, how reliable that delivery is, the speed of the data flow, and the extra burden it puts on the network.

This paper examines how the density of nodes, and their mobility patterns can seriously shake up protocol performance. These protocols go through a rigorous training program to see which one gives a better performance. This level of scrutiny is pushing the envelope in mesh technology, transforming our approach to network performance from the ground up.

By dissecting how different numbers of nodes and their movements affect network efficiency, this study uses a blend of statistical analysis and programming finesse to shed light on the best ways to beef up ad networks under various conditions. This thorough assessment aims to scrutinize routing protocols by analysing their performance metrics, within the non-parametric ANOVA framework. Using the Kruskal Wallis and Mann Whitney tests this study aims to identify the routing protocol through analysis adding valuable insights, to the field of wireless communication research.

Despite their benefits, mesh networks encounter considerable obstacles, especially in sustaining connection and enhancing performance amid fluctuating node density and mobility patterns. Routing protocols are essential for the efficiency and stability of networks. However, their performance can be significantly affected by network dynamics. This study seeks to fill the research vacuum by thoroughly assessing the efficacy of various prominent mesh routing protocols—AODV, DSR, DSDV, and ZRP—across diverse network situations.

The aims of this study are to: (1) examine the impact of differing node densities and mobility on the efficacy of these protocols, (2) employ robust non-parametric statistical techniques for precise evaluations, and (3) extract insights to guide the design and enhancement of future mesh networks. This research offers essential assistance for network designers and operators by reconciling theoretical performance with practical implementation.

Theoretical Background

Theory of mesh routing protocols

Mesh networks use routing protocols, each tailored to suit the infrastructure-less nature of the network. These protocols fall into three categories: reactive, proactive, and hybrid, each serving different networking challenges and needs. Reactive routing protocols, or "on-demand" protocols, establish routes when necessary and stop operating when those routes are no longer needed or available. This method reduces overhead by avoiding the maintenance of routes. On the other hand, routing protocols, often called "table-driven, maintain a routing table with updated information about all nodes in the network. This data is continuously shared among connected nodes to ensure each node has a view of the network topology (Karri et al., 2020).

Hybrid routing protocols combine elements from both reactive and proactive approaches. By merging the on-demand route discovery of protocols with the awareness of network topology seen in proactive protocols, hybrid protocols aim to enhance efficiency and responsiveness to changes in the network.

This study analyzes four known mesh routing protocols: Destination Sequenced Distance Vector (DSDV) (IEEE Control Systems Society et al., n.d.), Ad hoc On-Demand Distance Vector (AODV) (Ananthi & Jose, 2023), Zone Routing Protocol (ZRP) (Gasmi et al., 2020; Nithya et al., 2020), and Dynamic Source Routing (DSR).

This study aims to clarify the variations in how these methods work, shedding light on how they function and their appropriateness for network situations. Figure 1, summarizes how these routing methods are grouped, visually

showing how they fall into reactive, proactive, and hybrid types.

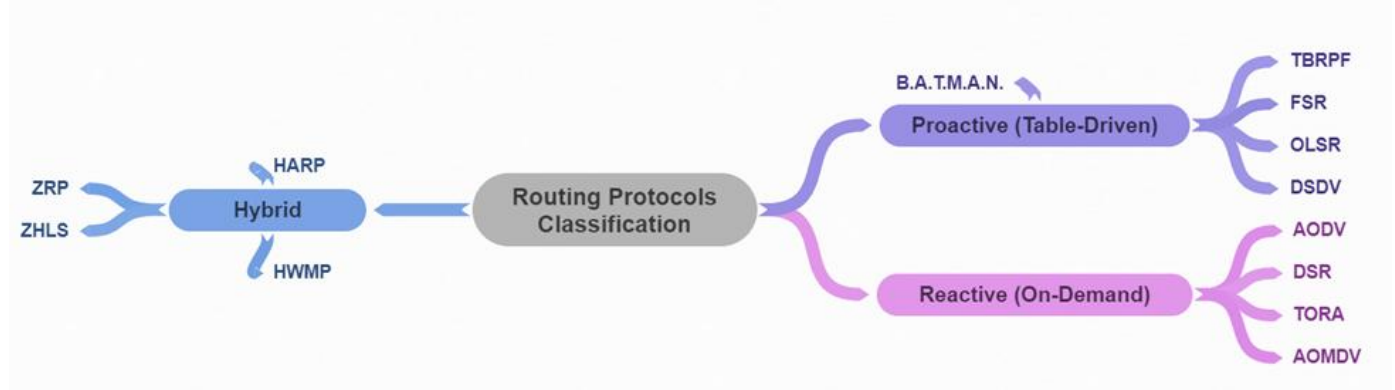


Fig. 1. Routing protocols Classification.

Mesh Protocols

Routing within mesh is characterized by the challenge of establishing a path between source nodes and destination nodes in a network that lacks a fixed infrastructure. Unlike traditional wired networks, which are static and stationary, MESHs require routing protocols that can adapt to the network's fluid topology. Classic wired network protocols such as Open Shortest Path First (OSPF) (Verma & Bhardwaj, 2016), Routing Information Protocol (RIP) (Raghavendra et al., 2022; Verma & Bhardwaj, 2016), Intermediate System to Intermediate System (IS-IS), and Enhanced Interior Gateway Routing Protocol (EIGRP) are ill-suited for MESHs due to their design for stable, wired environments. Consequently, MESH-specific routing protocols have been developed, falling into the three categories above: reactive, proactive, and hybrid, as detailed in Figure 1, and discussed throughout this paper.

Reactive protocols

In reactive routing protocols within MESHs, route discovery is not a continuous process but an on-demand strategy. This approach conserves network resources by avoiding the constant broadcasting of connectivity information. When a packet requires transmission, the reactive protocol initiates a route discovery phase, flooding the network with Route Request (RREQ) messages.

The AODV protocol represents this type of protocol. AODV reduces network congestion by sending out RREQs when needed. When an RREQ is received, the destination node or an intermediate node, with route details, replies with a Route Reply (RREP). A Route Error (RERR) is set off if a route is inaccessible, indicating the necessity for a route discovery process. The way AODV does things is pretty handy, dealing with each Route Request (RREQ) individually to keep the repeats down (Ananthi & Jose, 2023; Joon & Tomar, 2022; Yang et al., 2022).

The employment of AODV sequence numbers, as the authors focus on, is just to ensure the timelessness of routing data through the exchange of information. This is a better way in terms of the numbering system as it guarantees the propagation of routing information, taking no loops and leaving it updated. This can be found in what Zakrzewska remark that AODV retains hop details in the routing table and uses the strategy which is a hop-by-hop so that the intermediary nodes assist in delivering packets from source to destination (Zakrzewska et al., 2008).

An approach is offered by The Dynamic Source Routing (DSR) protocol. This protocol uses multiple reactive frameworks. DSR addresses bandwidth limitations in ad networks by avoiding frequent update messages seen in table-driven protocols (Sampoornam & Raaga Darshini, 2019; Sarao, 2018). Using a control packet mechanism, the on-demand routing process is managed to optimize network usage and minimize tasks. Reactive routing protocols such as AODV and DSR are tailored explicitly for routing in the mesh.

Proactive protocols

The main goal for this type of protocol is maintaining the most up-to-date path, which means monitoring routes and continually surveying for improvements. Optimally transmitting the flow distribution occurs as the path is determined as the packet reaches the host. An important example of a proactive protocol is a DSDV protocol (Gupta & Kumar, 2023; Kour et al., 2023).

DSDV is a mesh routing method that utilizes tables. Several other changes were made and applied to the DSDV algorithm following the Bellman-Ford algorithm. The routing table has three components: hops number, access nodes, and sequence number commissioned to the destination node. Sequence numbers differentiate routes that have already been declared stable from those in the process of being established and avoid loops. Routing tables are regularly broadcast to all the interconnected neighbouring nodes to keep them up to date or in case an essential update is performed in the table. It is preferable to send updates as a small batch rather than constantly to maintain

network stability. The routing table entry also contains a number that transmitter generates called a sequence number. The path selects the highest sequence number. When two or more paths have the same sequence number, the one with the better metric (i.e., the path with the shortest length) is chosen (Alameri, Komarkova, Al-Hadhrani, & Alkaraawi, 2023).

Table 1. Comparison of Infrastructure and mesh Wireless Network Modes.

Parameters	Infrastructure mode	Mesh mode
Fundamental Definition	There is no direct communication between wireless hosts. Instead, the communication must pass through access points APS, which means data transmission among devices is done by the APs	In an ad hoc network, the architecture is devoid of centralized hubs or connection points. Operating without access points, nodes or hosts in ad hoc mode establish direct peer-to-peer connections, facilitating a decentralized network topology.
Installation costs	Infrastructure mode is almost costly	There are almost no infrastructure costs
Connection Outdoors	APs represent a span or connection to other network devices	No physical infrastructure required where the node could be a client or server
Design Complexity	Most of the network employment is included in AP, and the client does not require much design effort	Since there is no prior coordination or server, we must use CSMA/CA with similar functions in all nodes
Hardware integrity	Infrastructure mode requires a backbone network	There is no need for backbone connectivity
Channel Access	Most WLANs employ TDMA (Time-division multiple access) technologies	In most of Ad-hoc types, WLANs utilize contention-based medium access control (MAC) protocols
Topology	A more fundamental benefit of the topology is that it can deliver software and utilities over wired networks	These types of Wi-Fi networks (Ad-hoc) are more creative because they require less equipment and set-up time

Hybrid protocols

These protocols merge and integrate the best attributes of the reactive and proactive routing protocols. Several features may be considered to design a protocol according to the needs. The hybrid protocols have been suggested in a paper by Nicklas Beijar which presented the ZRP routing protocols (Beijar, 2002).

ZRP: Utilizes reactive and proactive protocols in a hybrid system by proactively exploring nearby nodes and using reactive communication routing protocol features between nodes (Mittal & Kaur, 2009). A single config factor defines how the ZRP is designed for a given network. ZRP is a combination of two sub-routing protocols called Inter-zone Routing Protocol (IERP) and Intra zone Routing Protocol (IARP)(Haas et al., 2002).

The source table can recognize a path to the destination zone's entry through a constructive cache table lookup. IARP allows the path to be found by looking in the source zone using the cash routing table when it has already been sent a particular response time. When the source and destination are in the same area, IARP determines the path and sends the packets instantly. According to these advantage features, IARP is being used in the algorithm of ZRP routing protocols. The differences among AODV, DSDV, and ZRP routing protocols are highlighted in Table 2.

Table 2. Characteristics of routing protocols.

Protocol metrics	AODV	DSR	DSDV	ZRP
Multicast routes	No	Yes	No	Yes
Distributed	Yes	Yes	Yes	Yes
Flooding	Yes	Yes	Yes	No
Link Support	Yes	Yes	No	Yes
Multicast	Yes	No	No	Yes
Throughput	Yes, High	Yes	Yes, medium	Yes, medium
Routing overhead	Less	Yes, High	More	pretty big
Periodic	Yes, (Hello message)	No	Yes	Yes
Routes maintenance	Yes, RT	Yes	Yes, RT	Yes, RT

Approach and Techniques

This section of the paper describes the scenario, data gathering, and analysis process for MESH protocols in NS-2. NS-2 was selected on the grounds that this tool is openly available, free, and can easily support several MESH protocols such as AODV, DSR, and DSDV. Yet, ZRP is not one of them, and its implementation and setup within NS-2 were required by the authors. The simulator makes use predominantly of OTCL—Object Tool Command Language. This is a language that allows taking up wireless network simulations. This script, using OTCL, sets up a mesh scenario, with routing protocols, patterns of traffic, details of mobile nodes, output files viewed in the network animator NAM, trace files, and topology layout of the network.

Graph plotting was done using the design language MATLAB. Further, the results of the simulation were analysed using SPSS software, which is strong in statistics. During the simulation, the trace file thus generated was used to evaluate key metrics: throughput, packet delivery ratio, energy consumption, normalized routing overhead, and end-to-end delay.

Simulation Methodology

This paper uses the NS-2.35 network simulator to comprehensively assess the performance of mesh routing algorithms. NS-2 was selected for its adaptability and comprehensive support for simulating diverse wireless communication situations, which is essential for correctly depicting the behaviour of mesh networks.

Simulation played a key role in this paper; hence, its result has a direct impact on the experimental results of this study. A 1000x1000m cover area and the UDP protocol were used for this work. All the scenarios were simulated for 60 iterations each, totalling 180 iterations to reduce statistical discrepancies. Node mobility was modelled using the Random Waypoint (RWP) method, one of the major causes of network performance. Speeds up to 20 m/s were supported for the nodes' movements, whereas the simulations were carried out using 60 nodes, 80 nodes, and 100 nodes. This topology has been visualized under NAM—the NS-2 Network Animator—showing how node density and mobility may affect the efficiency of the network. In this paper, the adaptability and performance of mesh network protocols have been scrutinized under variable conditions.

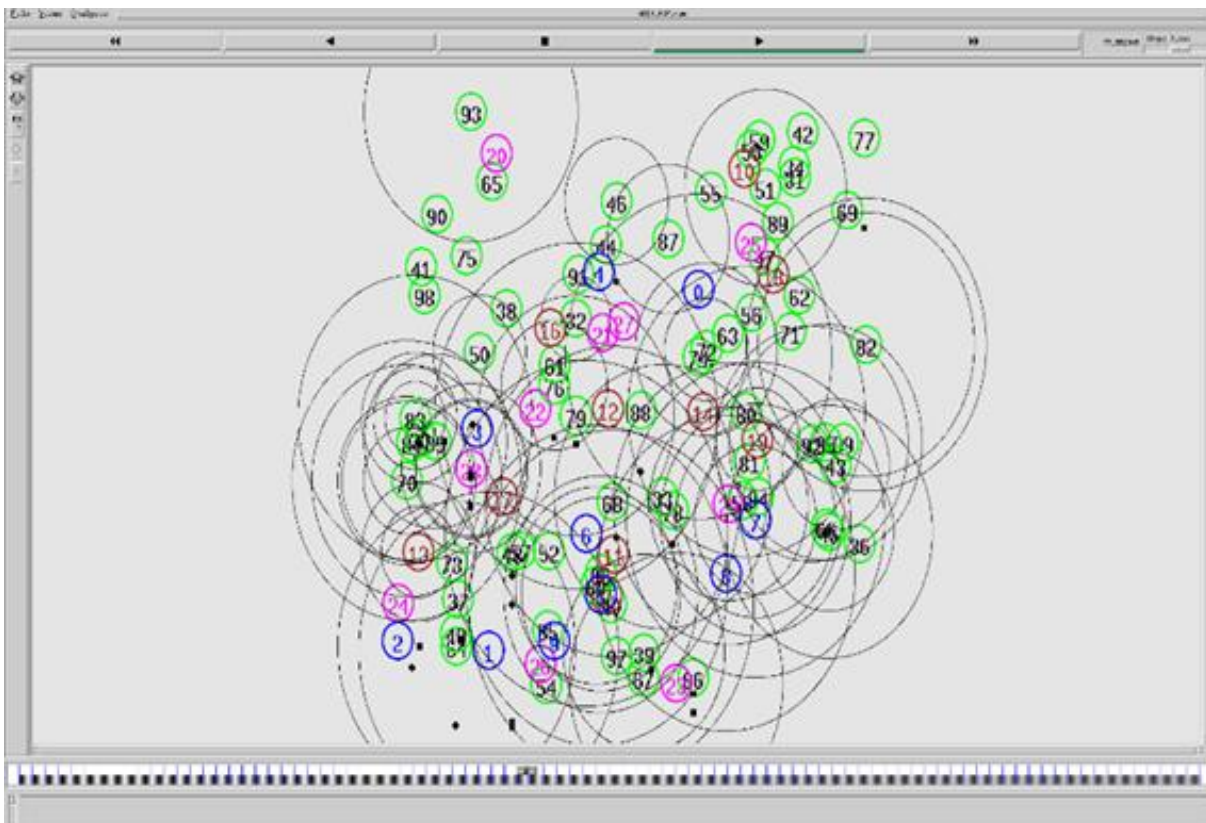


Fig. 2. Network Topology.

Benchmarking Routing Protocols: A Comparative Evaluation

This paper used several tools for data analysis: It made use of MATLAB in plotting, and it utilized Perl for extracting data from trace files. Performance metrics were computed based on a mathematical equation too. The work evaluated the performance of AODV, DSDV, and DSR to finally the ZRP, considering different numbers of nodes since the number of nodes is important regarding network efficiency. The simulations ran 180 times with different node counts. Key parameters and the network topology are given in Table 3.

Table 3. Simulation Parameters.

Parameter	Value
Simulator	NS-2.35
Channel type	Channel/Wireless channel
Simulation time	180 s
Simulation area	1000 m ²
Wireless transmission range	250 m
Packet type	CBR
Packet size	512 512 bytes/packet
Routing protocols	AODV, DSR, DSDV & ZRP
Number of nodes	60, 80 & 100
Number of iterations for parameter	180
Mobility Model	Random Waypoint
Antenna Type	Omni directional
Initial energy	100J
Pause time	4.0 s
Mobility speed	10 m/s

Comparative Simulation Analysis and Discussion

The presented study carried out two experimental environments designed with care to study the efficiency and scalability of different routing protocols. More precisely, it has focused on how those protocols handle node density changes. The main factors analyzed would be E-2-E delay, throughput, NRL, packet delivery ratio, energy consumption, and network lifetime. These metrics provide an overall view of network performance and help analyze how the networks adapt to higher node densities and more complexity. Combining these QoS metrics with statistical analysis can effectively depict how node density influences the overall efficiency of the network.

Simulation data are gathered by using NS-2 for AODV, DSR, DSDV, and ZRP routing protocols. Key metrics include: throughput, NRL, E-2-E delay, energy consumption (EC), network lifetime (NL), and packet delivery ratio.

Network Throughput

Network throughput is the total number of bits of raw data successfully transferred from one point over a network to another within a certain time. It is normally measured in bits per second, or higher units such as Mbps or Gbps. In short, it is a simple way to figure out how much data your network can process and deliver effectively, considering congestion, delays, and errors. It would mean that the network is performing well, in the sense that the throughput, with higher values, stands for data transferred without incidents. Equation NO 1, which is used for this purpose.

$$\text{Throughput} = \frac{\text{Total number of packets received}}{\text{Total Time}} \quad (1)$$

Normalized Routing Load (NRL)

This metric indicates the Maintaining connections between network devices sent during a simulation. The NRL can be calculated by Equation 2.

$$\text{NRL} = \frac{\sum \text{Routing packets}}{\sum \text{Packets received}} \quad (2)$$

Packet Delivery Ratio (PDR)

The Packet Delivery Ratio (PDR) is one of the key performance metrics for mesh networks and represents the ratio between packets/datas successfully delivered to final destination node and the total amount of packets sent by source node. This yields an understanding of how reliable and efficient the network is.

PDR Increase: The increased Packet Delivery Ratio signifies the better operation of the network, but it also means that the data packets are being dispatched to their destinations more effectively. destinations.

Reduced PDR: It indicates the existence of problems such as packet loss, due to congestion and/or node failure, or low routing efficiency. The PDR is an important metric for assessing network performance and is used to

Kruskal-Wallis Test Methodology

Extensive statistical analysis was done to find out the accuracy and validity of the results obtained. The authors have used one-way ANOVA tests to find performance differences between protocols. Since data distribution cannot be known, the Kruskal-Wallis test—a non-parametric form of ANOVA—has been considered in this regard. This test is effective for decomposing observations and finding out significant variations. In the case of two samples, the Kruskal-Wallis test reduces to the Mann-Whitney test.

Having established the importance and mechanics of the Kruskal-Wallis test, this paper forward to discuss the hypothesis testing framework and how statistical significance was determined for each metric.

Hypothesis Testing and Validation

The Kruskal-Wallis test has to be applied in observance of the proper conditions for obtaining accurate results. Data have to meet the criteria of independent measurement and homoscedasticity, although it is never required to reflect any normal pattern. This test finds its wide application in various fields of economic, biological, and computer science to establish the validity of a hypothesis.

The first step in hypothesis testing is the statement of the null hypothesis, H_0 . When the result of the statistical test gives a probability of less than 0.05, then and only then can the null hypothesis be rejected for the alternative hypothesis, H_1 . Standard distribution, Z , will enable comparisons to be made; further help may be obtained from critical regions regarding accepting or rejecting H_0 . If the value falls within the critical region, H_0 is rejected; otherwise, it is accepted.

Kruskal-Wallis ANOVA Test

The result of the Kruskal-Wallis test is a non-parametric method used to compare more than two independent samples. It evaluates whether the samples come from the same population by analyzing their distributions without assuming normality, as shown in equation 6.

$$Q = \frac{12}{n(n+1)} \sum_{i=1}^k \frac{R_i^2}{n_i} - 3(n+1) \quad (6)$$

where

- Q is the Kruskal-Wallis test statistic.
- n is the total number of observations across all samples (groups) in the test.
- k is the number of samples (groups).
- n_i is the number of observations in the i – th samples.
- R_i is the sum of the ranks for the i – th samples.

If Q exceeds the critical value from the chi-square distribution with $K-1$ degrees of freedom, the null hypothesis is rejected, indicating significant differences between the groups. With the presented hypothesis testing criteria clarified, presented paper next the analysis of throughput variability, detailing how statistical methods reveal performance differences among protocols

Analysis of Throughput Variability Using Kruskal-Wallis and Mann-Whitney

Throughput metric Using Kruskal-Wallis

Throughput is the amount of data received correctly in the simulation period. Based on the one-way ANOVA test with Kruskal-Wallis, the statistical results reject the null hypothesis with a p-value of less than 0.05, as depicted in Table 4, which indicates significant differences in throughput efficiency: in fact meaningful because Asymp. Sig > 0.05.

Table 4. ANOVA of throughput.

	Routing_Protocols	N	Mean
	AODV	180	540
	DSR	180	330
Values	DSDV	180	210
	ZRP	180	205
	Total	720	

The results of the throughput analysis, using a one-way ANOVA test, highlight how the four routing protocols—

AODV, DSR, DSDV, and ZRP—perform. AODV had the highest mean throughput of 540, with 180 observations per protocol, totalling 720 observations. This performance is attributed to AODV's dynamic, on-demand method of establishing routes, which selects the best paths and reduces delays, making it highly efficient for packet delivery.

DSDV and ZRP, however, show lower mean throughputs of 210 and 205, respectively. DSDV's performance is likely influenced by periodic updates that introduce delays and overhead. ZRP, a hybrid protocol combining proactive and reactive features, suffers from inefficiencies, especially due to the complexity of zone-based routing in dynamic networks.

In conclusion, AODV is the top choice for high-throughput environments, and DSR provides a good overall balance. Although DSDV and ZRP offer lower throughput, they may still be useful in situations where network stability and scalability are more critical than maximum throughput.

Table 5 presents the results of the Kruskal-Wallis H test—a non-parametric alternative to ANOVA—of four routing protocols in terms of throughput. The result gave a Kruskal-Wallis H value of 378.14 with $df = 3$, representing the number of groups minus one. Its Asymp. Sig. becomes absolutely 0.000, which normally should be < 0.001 . The very low value of p therefore constitutes evidence of significant differences in the throughput of the protocols, which in turn denotes that not all protocols are performing in the same way and that the differences done would therefore be statistically meaningful. It further indicates that the Asymp. Sig. of 0.000 revealed there were significant differences in throughput among the protocols; hence, it denied the null hypothesis. A Mann-Whitney test, therefore, was conducted to investigate these differences and had consequently shown remarkable performance differences by AODV and DSR protocols. Through subsequent steps of first using the Kruskal-Wallis test and a posterior Mann-Whitney test, clear comparisons of the protocols were derived as represented in Table 6. This result led us to conclude which type of protocols had this significant value by using the Non-parametric Tests -Mann-Whitney t -test, as shown in the next subsection between the AODV and DSR routing protocols.

Table 2. Kruskal-Wallis H Test for Throughput Comparison.

	Values
Kruskal-Wallis H	378.14
df	3
Asymp. Sig.	0.000

Throughput metric Using Mann-Whitney

The Mann-Whitney test, also called the Wilcoxon Rank Sum Test, is a non-parametric test used to compare two independent groups. It provides an estimate of whether the two groups are likely to come from the same distribution based on the differences between the variables of interest in each group. The generic question is whether the groups came from populations with different characteristics. Where is the Mann-Whitney test for AODV and DSR throughput shows the following values: Mann-Whitney U is 3599.000, Wilcoxon W equals 16479.000, Z-score is -11.127, and the two-tailed Asymp. Sig. is 0.000.

This is further demonstrated by the Mann-Whitney test results for AODV and DSR throughput, which show significant differences between the two groups. Similarly, comparing DSDV and ZRP protocols provides insight into their statistical relationship.

For comparing two groups, the Mann-Whitney test: Mann-Whitney U = 3599.000, Wilcoxon W = 16479.000, Z = -11.127, Asymp. Sig.) The p -value for the two-tailed test is 000. Since the p -value here is below .05, this can be taken as statistically significant at the 5% significance level. So, the null hypothesis is rejected and then we can say that there is a significant difference between both the groups.

The Mann-Whitney U statistic, Wilcoxon W statistic, Z-score and Asymptotic significance (2-tailed) for DSDV and ZRP comparison is 11622.500, 24502.500, -1.423 and respectively, 0.155 The results also did not reveal a significant difference between the DSDV and ZRP protocols, with all p -values being greater than 0.05. Hence in this case we fail to reject the null hypothesis.

While throughput is a critical measure of efficiency, it is equally important to analyze how well data packets are delivered, leading us to the assessment of PDR, NRL, and E-2-E delay across protocols.

Performance Metrics Analysis

Packet Delivery Ratio (PDR) Analysis

The evaluation of Packet Delivery Ratio (PDR) was conducted on four distinct routing protocols: AODV, DSR, DSDV, and ZRP. The ANOVA hypothesis test revealed a considerable variation among these methods, resulting in the rejection of the null hypothesis.

The AODV procedure recorded a PDR count of 160, a total of 15,800.32, an average of 95.6, and a variance of 15.2. Conversely, DSR had a smaller mean of 78.4 alongside a greater variance of 1,020.5. DSDV and ZRP had mean values of 53.9 and 48.7, respectively, with variances of 340.3 and 1,410.8. All the other nodes remained in PDR values below AODV and with a bigger variability like DSR and ZRP.

A non-parametric test (Kruskal-Wallis test) more suitable for data distribution not fulfilling normality condition, was used to confirm the absence of candidate genes above their expression threshold. Results indicated the Kruskal-Wallis H of 275.842 with three degrees of freedom, and Asymptotic Significance (two-tailed) value (.000). This effect confirms that there is a significant difference between the medians in which groups, and that the PDR distribution among treatments differ greatly.

A, The Mann-Whitney test was used to compare AODV against DSDV. Mann—Whitney U = 615.0, Wilcoxon W = 13800.0, Z = -15.225, Asymptotic Significance (two-tailed) =.000). This emphasizes an important difference between AODV and DSDV, which supports the rejection of H0.

Normalized Routing Load (NRL) Analysis

This included Normalized Routing Load (NRL), which was evidently quite different among the four protocols. According to results from the simulations, AODV performed much better than DSR with an average NRL of 40.3 and a variance of 800 when compared to DSR which had an average of roughly 2,950 with a variance of 21,000,000. On the other hand, DSDV protocol QoS had an average of 185 with a variability of 14,000 and the ZRP managed to showcase significantly higher average figure of 202,000. The ANOVA test indicated statistically significant differences at the 5% level, since the Asymptotic Significance value was below 0.05.

The Kruskal-Wallis test for NRL produced a H value of 350.473 with three degrees of freedom, and the Asymptotic Significance was 0.000. This further confirmed the significant disparities among the regimens. As for the statistical analyzes, Mann-Whitney test compared AODV with DSDV (Mann-Whitney value 1,400; Wilcoxon W= 14,400; Z=-14.05 and Asymptotic Significance (two-tailed) significance level equal to.000). It adds yet more weight to the very considerable differences observed among these approaches.

End-to-End Delay Analysis

One of the most common performance metrics studied was the end-to-end (E-2-E) latency. AODV average delay was 0.05 with a variance of 0.0025 and DSR reported average delay of 0.03 (Variance = 0.003). In the same context, the DSDV exhibited a markedly reduced average delay of 0.01 with negligible variance, while ZRP had a considerably elevated average delay of 4.0 with a variance of 41.0. The results resulted in the rejection of the null hypothesis due to the apparent observed variance.

Finally, the Mann-Whitney test comparing AODV with DSR demonstrated a significant difference, yielding a Mann-Whitney value of 5,500.5, a Wilcoxon W value of 18,500.5, a Z-score of -9.650, and an Asymptotic Significance value of 0.000. The final study confirmed significant performance disparities among the regimens across all essential criteria.

Evaluation Correlation and Covariance

Correlation measures the strength and direction of a linear relationship between two variables. The correlation coefficient (r) ranges from -1 to 1 as follows:

- $r = 1$ that is, if one variable increases, the other variable increases proportionately.
- $r = -1$ is perfect negative correlation. That is, if one variable increases, the other decreases proportionately.
- $r = 0$ no correlation, there is no linear relationship between the variables.

Covariance is the measure of the change of two variables together. Since covariance does not standardize the variables then value of covariance can be any.

Positive Covariance: When one variable increase then other variable tends to increase in value. Negative Covariance: If one variable increase then other variable tends to decrease in value. Magnitude: Since covariance is a measure that depends on the scale of variables, interpretation is not possible without its standardization, which is realized by correlation.

In fact, correlation and covariance can shed light on how node counts result in resultant energy consumption when performing energy analyses of network protocols, and whether energy consumption can scale predictably as the network grows.

Table 6 summarizes energy consumption by node count for each protocol to determine how energy consumption scales as network size increases.

Table 6. Correlation and Covariance of Node Count and Energy Consumption for Routing Protocols.

Protocol	Correlation	Covariance	Correlation Interpretation	Covariance Interpretation
AODV	0.888	21,600	A strong positive correlation, meaning that as the number of nodes increases, the energy consumption also increases significantly for AODV	The positive covariance indicates that as the number of nodes increases, energy consumption rises together with it.
ZRP	0.955	6,500	Very strong positive correlation to exhibit that the increment in node count strongly relates to an increase in energy consumption in ZRP.	In this case, however, the positive covariance will mean that a rise in nodes is strongly related to a rise in energy consumption.
DSDV	0.930	14,050	Strong positive correlation; this does point out that energy consumption significantly increases as node count increases for DSDV.	On the other hand, the positive covariance in this case indicates that with the node count, energy consumed rises for DSDV.
DSR	0.896	21,600	Strong positive correlation: the number of nodes highly influences energy consumption in DSR.	As with AODV, positive covariance in DSR indicates node count and energy consumption rise together.

Discussion and Comparative Analysis

The analysis showed that AODV was better than other protocols in throughput and packet delivery ratio, especially some scenarios with high node density and mobility. This was due to the on-demand route discovery of the AODV that reduces overhead and optimizes path selection. ZRP, with its hybrid mechanism was not efficient in networks where topologies changed rapidly due to the complexity of ZRP.

These findings have important practical implications. AODV adapts to changing conditions, such as the potential change in topology following a disaster (earthquake); AODV is therefore an ideal protocol for tracking and managing mobile devices within emergency situations such as disaster recovery or mobile Ad-hoc networks (MANET). However, it may be better for ZRP to prioritize more stable networks where the overhead of keeping proactive areas is adaptable.

AODV superior performance could be attributed to its reactive routing mechanism that creates routes only, when necessary, hence avoiding congestion and lesser delay. DSR is also good, but less efficient than AODV because of its source routing mechanism that can create delays because the information about a route will grow each time the network grows. While DSDV faced bottlenecks in high-density situations due to its periodic update dependence, ZRP never quite attained the balance between proactive and reactive designs effectively in practice.

In this research, the analysis is supplemented by statistical testing of those differences using a non-parametric method. Prior studies sometimes ignored such limits to ZRP, which this work seeks to highlight.

By aligning accurate simulations with advanced statistical analysis, this research provides an unprecedented understanding of protocol behavior. Future research could be focused on minimising AODV even more or usage of machine learning approaches for adaptive routing systems.

Conclusion

This work gives a complete investigation of all the various network parameters such as throughput, packet delivery ratio (PDR), normalized routing load (NRL), Energy Consumption EC and end-to-end delay for different mesh routing protocols that are AODV, DSR, DSDV and ZRP. Using a powerful statistical framework that involves the Kruskal-Wallis ANOVA and Mann-Whitney tests, our research provides a new understanding of why these protocols perform differently under different network conditions.

Clearly, AODV outperformed others based on all major performances and hence can be determined as the suitable protocol for dynamic and high-density mesh networks. The better performance is due to AODV reactive on-demand routing technique which improves data delivery and reduces delays. Conversely, ZRP resulted in the lowest performance for all scenarios as network size grew because of its hybrid architecture overhead and complexity. DSDV and DSR were also performed as moderate fashions but failed to outweigh AODV in terms of scalability & reliability.

The findings of this paper emphasize that due to the non-normality and heteroscedasticity nature of network data, it is necessary to use non-parametric statistical methods to correctly determine protocol performance in mesh networks. These large differences were also statistically tested (Kruskal-Wallis and Mann-Whitney tests) to confirm

the validity of our conclusions.

This dynamic behavior of the AODV protocol will be studied more deeply to improve routing. The proposed changes may fix the variation in link quality making it more efficient and robust. In addition, the optimization through adaptive routing using machine learning approaches will open new angles for improving mesh performance in various real-world conditions and applications including different mobility models.

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