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Modification of the AODV Routing Discovery Mechanism in Wireless Mesh Networks

Doctoral DISSERTATION

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Annotation

This thesis offers a comprehensive analysis of Wireless Mesh Networks (WMNs), crucial in the evolution of advanced wireless technologies like Wireless Sensor Networks, the Internet of Things, and the Internet of Vehicles. It highlights WMNs' unique characteristics, such as self-configuration and scalability, while addressing their dynamic nature, posing challenges for routing protocols. The thesis explores the limitations of the Ad hoc On-Demand Distance Vector (AODV) protocol and introduces the Fuzzy Control Energy Efficient (FCEE) routing protocol as a solution. FCEE, integrating fuzzy logic with AODV, enhances network efficiency and longevity, demonstrating superiority over traditional protocols in terms of throughput, energy efficiency, and quality of service metrics.

This work stands out for its innovative approach to **applying informatics** principles to wireless communications, mainly designing adaptive routing solutions for WMNs. This thesis effectively demonstrates the FCEE protocol's advantages through rigorous simulations, showing its potential to improve link stability and network performance. This thesis is significant for its contribution to the field of wireless communications and **Applied Informatics**, offering a novel perspective on tackling routing challenges in WMNs and highlighting the importance of data-driven decision-making in modern networking environments. It sets a precedent for future research at the intersection of networking and informatics.

Keywords: Wireless Mesh Network, Routing Protocols, Protocol Evolution, FCEE, Fuzzy Logic.

Název: Modifikace mechanismu vyhledávání směrování protokolu AODV v bezdrátových Mesh sítích

Anotace: Disertační práce komplexně analyzuje bezdrátové mesh sítě (WMN), které jsou klíčové pro další vývoj pokročilých bezdrátových technologií, například bezdrátové senzorové sítě, Internet věcí a Internet vozidel. Jsou zdůrazněny jedinečné vlastnosti WMN, jako je autokonfigurace a škálovatelnost, a je charakterizována jejich dynamická povaha, které je výzvou pro směrovací protokoly. Dále práce zkoumá omezení protokolu Ad Hoc On-Demand Distance Vector (AODV) a představuje protokol Fuzzy Control Energy Efficient (FCEE) jako nově navržené řešení. Protokol FCEE, který integruje fuzzy logiku s AODV, zvyšuje efektivitu a životnost sítě, poskytuje lepší výsledky ve srovnání s tradičními protokoly v následujících metrikách kvality služby: propustnost a energetická efektivita. Tato práce se nabízí inovativní přístup k aplikaci principů informatiky v oblasti bezdrátové komunikace, zejména tím, že navrhuje adaptivní řešení směrování pro WMN. Výhody protokolu FCEE jsou názorně ukázány pomoci simulací, které demonstrují potenciál protokolu FCEE vylepšit stabilitu spojení a výkon sítě. Tímto práce přispívá k rozvoji bezdrátových technologií a aplikované informatiky, nabízí nový pohled na řešení výzev směrování ve WMN a zdůrazňuje důležitost datově řízeného rozhodování v moderních síťových prostředích.

Klíčová Slova: Bezdrátová mesh síť, Směrovací protokoly, Vývoj protokolu, FCEE, Fuzzy logika.

Abstract

Wireless Mesh Networks (WMNs) are increasingly significant in the evolution of advanced wireless communication technologies like Wireless Sensor Networks (WSN), the Internet of Things (IoT), and the Internet of Vehicles (IoV). These networks have robust features such as multi-hop routing, self-configuration, self-healing, and scalability, are revolutionizing the networking domain. However, the dynamic nature of WMNs, characterized by changeable link qualities, shows significant variables for routing protocols, even in the context of static nodes.

This thesis begins with a detailed exploration of WMNs, identifying their essential challenges and underscoring the critical need for advanced routing mechanisms. Employing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Framework, an Ad hoc On-Demand Distance Vector (AODV) protocol analysis is conducted, showing its potential and limitations. The Fuzzy Control Energy Efficient (FCEE) routing protocol is introduced in response to address the challenge of routing protocol in a mesh network. This novel integration of fuzzy logic with the AODV protocol significantly enhances network efficiency and long lifetime.

Within the area of **Applied Informatics**, this thesis emphasizes the application of informatics principles to design a responsive routing solution for WMNs. This solution is adaptive to network variations and detects optimal paths by leveraging complex performance metrics that aptly reflect the shades of wireless links. Traditional metrics, such as hop count, fail to address the multifaceted objectives of WMNs, which span across optimizing throughput, Packet Delivery Ratio (PDR), Average End-to-End delay (E-2-E delay), node survival rates, energy consumptions, and other quality of service (QoS).

As presented in this thesis, the FCEE routing model is a beacon of innovation in **Applied Informatics**. FCEE integrates the fuzzy logic approach with the AODV protocol, substantially increasing network resilience and efficiency. The protocol innovates by incorporating a memory channel powered by fuzzy logic to intelligently manage packet broadcasts based on the nodes' energy reserves, enhancing the network's operational lifetime and performance.

The **FCEE** protocol shows its superiority over conventional AODV and other modern routing protocols through rigorous experimental simulations. Its reliability, reduced latency, robust link stability, and extended route viability stand out. The FCEE protocol notably surpasses AODV in average throughput and energy efficiency, and further advancements in PDR, normalized routing load, and goodput further confirm its dominance.

This thesis transcends the boundaries of traditional network routing solutions by employing **Applied Informatics** approaches. It emphasizes the significance of data-driven decision-making and integrating cognitive computing concepts, such as fuzzy logic, to address the complexities of modern

networking environments. The introduction of the FCEE protocol marks a groundbreaking advancement in **Applied Informatics**, tackling the continuing challenges of WMN routing and paving the way for WMNs to fully harness their capabilities fully, thereby enabling reliable, efficient, and scalable wireless communications in an interconnected world.

In summary, this thesis not only contributes a novel routing protocol to the field of wireless communications but also serves as a testament to the transformative power of **Applied Informatics** in solving real-world problems. It underscores the importance of multidisciplinary approaches in technological innovation and sets an advance for future research in the convergence of networking and informatics.

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"If you Receive Advice, Show your Acknowledgments."
-Prophet **Muhammad** (peace be upon him)

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Contents

List of Acronyms

ACO Ant Colony Optimization

AODV Ad hoc On-Demand Distance Vector

AOMDV An Optimized Ad-hoc On-demand Multipath Distance Vector

AP Access Point

ARP Address Resolution Protocol

CBR Constant Bit Rate

DSDV Destination-Sequenced Distance-Vector

DSN Destination Sequence Number

DSR Dynamic Source Routing

E-2-E delay End-to-End Delay

EC Energy Consumption

Enhanced-Ant-AODV Enhanced-Ant-AODV

FCEE Fuzzy Control Energy Efficient

FLC Fuzzy Logic Controller

IoT Internet of Things

IoV Internet of Vehicles

IRAODV Intelligent Routing AODV

MAC Medium Access Control

MANET mobile ad hoc network

MANETs mobile ad hoc networks

MC Mesh Clients

MRS Mesh Routers

NAM Network Animator

NRL Normalized Routing Load

OLSR Optimized Link State Routing

PDF Packet Delivery Fraction

PLR Packet Loss Ratio

PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses

RREP Route Reply

RREQ Route Requests

RSD Relative Standard Deviation

RSSI Received Signal Strength Indication

RWP Random Waypoint

SPF Shortest-Path-First

SSAODV Signal Strength-Based Ad-Hoc On-Demand Distance Vector

STAB-AODV STAB-AODV

TCP Transmission Control Protocol

UDP User Datagram Protocol

WMN Wireless Mesh Network

WMNs Wireless Mesh Networks

WSN Wireless Sensor Networks

ZRP Zone Routing Protocol

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Introduction

Wireless communication technologies have become increasingly indispensable due to their unparalleled mobility, deployment flexibility, cost-efficiency, and ease of implementation (Majumdar, 2018) & (Mowla et al., 2022). Specifically, Wireless Local Area Networks (WLANs), which are founded on the IEEE 802.11 suite of standards, has gained significant traction. The formation of these standards, spearheaded by Working Group 11 of the IEEE Standards Committee, has been instrumental in shaping the landscape of wireless communications. One notable milestone was the approval of the IEEE 802.11b standard in 1999, which revolutionized the market by offering an elevated data transfer rate of up to 11 Mbps. The superior throughput capabilities of this standard, coupled with its economic feasibility, have cemented its status as the prevailing WLAN technology (Prameela and Daniel, 2016).

Emerging as an evolutionary advancement of conventional wireless technologies, WMNs offer a plethora of functionalities and convenient access, thereby fulfilling the increasingly complex demands of modern communication systems. WMNs extend the capabilities of existing wireless architectures, including cellular networks, wireless sensor networks, and mobile ad hoc networks (MANETs), to support a more diverse range of applications.

In the prevailing WLAN configurations based on IEEE 802.11 standards, network architecture often relies on a centralized Access Point (AP). While this model decentralizes channel access, it inadvertently funnels all network traffic through the AP, which limits scalability and bandwidth. WMNs effectively mitigate this constraint by enabling APs to function in a mesh topology, where they can relay packets among themselves through a shared gateway. However, this architecture is not without its challenges, notably the potential for bandwidth reduction when multiple users access the network concurrently (Agrawal et al., 2022) & (Bilal and Khan, 2019).

WMNs are frequently classified as a specialized subset of MANET due to their shared characteristics, primarily stemming from the absence of a wired backbone. In WMNs, each node serves dual functions: as a host and as a wireless router. However, unlike in MANETs, WMNs distinguish between end hosts and routing nodes, which are typically stationary. The traffic patterns in WMNs also exhibit unique characteristics, mainly centring around data flow between end users and the network gateway, thus differentiating them from MANETs where traffic can circulate between node pairs (Al-Karaki, Al-Mashaqbeh, and Bataineh, 2017).

The networking industry has shown heightened interest in WMNs mainly because of their inherent merits, such as multi-hop routing, self-configuration, and self-healing capabilities. Furthermore, WMNs offer robust reliability and scalability, which make them well-suited for a broad spectrum of applications. These networks also present significant advantages in terms of initial setup costs, ease of maintenance, and operational robustness. Significantly, the mesh architecture can be incrementally expanded, allowing scalable performance to meet evolving needs (Sanyal, Kar, and Roy, 2020).

Motivation

In the wake of rapid technological advancements in wireless communications, the IoT has gained monumental importance, leading to a proliferation of interconnected devices. This has subsequently highlighted the critical role of WMNs in providing robust, inter-device communication and seamless connectivity to broader networks, including cellular networks and the Internet. WMNs, with their self-configuring, infrastructure-independent architecture and multi-hop wireless communication capabilities, emerge as a compelling solution for many applications.

However, the burgeoning complexity of contemporary mesh networks, accentuated by the exponential growth of big data and IoT, poses significant challenges. These encompass the management of voluminous data, the optimization of routing protocols, and the assurance of dependable, efficient communication. Conventional networking methodologies often fail to address these challenges, especially in resource-intensive and time-sensitive scenarios.

The imperative animates this research to augment mesh network performance in the dynamic landscape of variable network conditions and developing application requirements. The objective is to formulate dynamic and adaptive network management frameworks and routing solutions capable of efficiently navigating diverse network conditions while supporting resource-intensive applications.

This research focuses on enhancing the AODV routing protocol, a powerful utilized algorithm in mesh networks. Although AODV stands out in on-demand route discovery and is proficient in identifying optimal paths between nodes, it shows limitations in adaptability and decision-making in ever-changing mesh network environments.

This thesis supports incorporating fuzzy logic methodologies into the AODV protocol to improve these drawbacks. Fuzzy logic, a perceptive mathematical framework designed to manage ambiguity and uncertainty, is invaluable in handling imprecise routing metrics. The planned integration aims to develop adaptable routing strategies adapted to diverse network conditions, elevating overall network performance.

Another motivation for this research is the escalating integration of IoT and its complexities. The large influx of IoT devices generates substantial amounts of data, necessitating efficient data management solutions within mesh networks. This research is designed to address the complexities engendered by IoT within the context of mesh networking.

Furthermore, conventional static membership functions in routing protocols often prove insufficient for adapting to dynamic network conditions. This research proposes the implementation of dynamic membership functions based on fuzzy logic, thereby fostering enhanced routing performance and overall network efficiency.

In conclusion, this thesis is driven by the goal of optimizing the AODV routing protocol's performance within mesh networks through the integration of fuzzy logic and dynamic membership functions. This approach seeks to address the challenges presented by the proliferation of IoT devices and enhance the efficiency and reliability of communication in modern wireless networks.

Thesis Outline

This thesis is structured to explore the AODV in the context of Wireless Mesh Network (WMN) comprehensively.

Chapter 1, delves into an overview of WMN, elucidating their inherent characteristics and architectural framework. While an array of routing metrics and protocols crucial to WMN are touched upon, significant emphasis is placed on the AODV due to its centrality to this research.

Chapter 2, presents an overview of the primary goal of the dissertation, which is the introduction of an adaptive routing protocol that combines the AODV routing protocol with fuzzy logic. It also enumerates the methods and tools utilized in the thesis.

Chapter 3, presents a systematic and rigorous analysis of the extensions of the AODV protocol. Utilizing the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, the chapter adheres to the highest academic standards to ensure the integrity and scholarly rigor of the review process. The chapter begins with an identification phase, using significant scientific search engines like Scopus, and includes a comprehensive selection of major journals, conferences, and workshops relevant to the AODV protocol. The systematic review process is detailed, following the Cochrane process and PRISMA guidelines to ensure a transparent and comprehensive literature examination. Critical phases of the PRISMA framework are outlined, including the criteria for eligibility, the integration phase, and the analysis of the methodological soundness of the studies. The chapter emphasizes excluding non-generalizable studies, informal literature, and articles without clear quality indicators. The results of the PRISMA framework analysis are summarized, highlighting the formal validity of the AODV extensions and proposing potential future initiatives and recommendations based on the findings. The chapter also discusses the limitations and challenges of using fuzzy logic in routing protocols.

Chapter 4, The chapter begins by explaining the role of fuzzy logic in improving wireless network routing. It introduces the idea that, unlike traditional methods, fuzzy logic can handle uncertain and variable network conditions more effectively.

Delving into the theoretical underpinnings of the subject, the chapter provides a comprehensive overview of fuzzy sets and membership functions. It contrasts the binary nature of classical set theory with the gradient-based approach of fuzzy logic, where elements possess degrees of membership. This section is crucial as it explains how fuzzy logic allows for a more flexible representation of concepts such as ”low energy” or ”high throughput,” particularly relevant in wireless networks.

After laying the groundwork, the chapter dives into how fuzzy logic is used in the protocol. It discusses turning fuzzy logic decisions into concrete actions, focusing on the Center of Gravity method as an example.

The central part of the chapter looks at the improvements made to the broadcast forwarding algorithm thanks to fuzzy logic. It talks about how the algorithm can adjust itself based on the current state of the network, which helps it make better decisions about sending data. The chapter concludes by mentioning that the next part of the work will evaluate how well the new fuzzy logic-based method works compared to other methods. It sets the stage for a detailed analysis that will look at the performance of the new approach in different situations.

Chapter 5, offers a comprehensive investigation of the FCEE protocol within the NS-2 simulation framework. It begins with a justification for using simulation-based approaches, highlighting the NS-2 simulator’s capabilities for modeling complex network scenarios and integrating new modules.

Also, 5, introduces the NS-2 simulator, the significant tool selected for evaluating the efficiency of the Fuzzy Control Energy Efficient (FCEE) routing algorithm and the other software and language programming scripts, including (TCL, AWK, Perl and MATLAB). A significant part of the chapter is dedicated to the methodology, which includes a thorough description of the simulation environment and the specific modifications made to adapt the NS-2 framework to the FCEE protocol. This includes the integration of enhanced trace and logging functionalities, configuration files tailored for the FCEE protocol, and tools for generating node positions and movements. The chapter then delves into the performance evaluation of the FCEE protocol, comparing it against standard AODV and other variations. It outlines the scenarios used for testing, which cover different network densities, traffic patterns, and node velocities. The performance metrics used for evaluation include throughput, delay, routing overhead, packet delivery ratio, packet loss ratio, and energy consumption. Furthermore, the chapter discusses the mobility model used in the simulations, providing a comprehensive description and justification for the assumptions made. It also showcases the detailed inventory of adapted files and modules, emphasizing the commitment to accuracy and meticulous documentation. In addition, it provides a clear and straightforward structure, summarizing the key aspects of the FCEE protocol’s integration into the NS-2 framework and its performance evaluation.

Chapter 6, begins by discussing the use of simulation models to examine the efficiency of the FCEE protocol within the NS-2 simulation framework. It justifies using NS-2 due to its ability to model complex network scenarios and integrate new modules, which is essential for testing the FCEE protocol.

It then details the methodology, describing the simulation environment and the modifications made to adapt NS-2 to the FCEE protocol. This includes enhanced trace and logging functionalities, configuration files specific to the FCEE protocol, and tools for node position and movement generation.

The chapter proceeds to evaluate the performance of the FCEE protocol against standard AODV and other modern versions of the AODV. It outlines the scenarios used for testing, which include different network densities, traffic patterns, and node velocities. The performance metrics used for evaluation are energy consumption, throughput, delay, routing overhead, packet delivery ratio, and packet loss ratio,

A comprehensive results analysis and discussion section follows, where scenarios such as Scenario 7.4, 7.4, and 7.4 are detailed. For example, Scenario A provides a comprehensive analysis of the simulation outcomes, specifically focusing on the performance of the FCEE protocol.

The chapter also includes a statistical analysis section, underscoring the importance of statistical methods in ensuring the robustness and adaptability of routing protocols in dynamic network environments. It discusses statistical measures such as mean, median, and standard deviation.

Chapter 7, Presents a contribution and conclusion from the work carried out. Analyzes the research insights, providing a comprehensive summary of the thesis undertaken. Additionally, it outlines possible directions for future research, paving the way for further academic directions.

1

State of the Art

Contents

Overview

This chapter investigates the significant landscape of wireless communication, emphasizing the important need for efficient, robust, and reliable routing mechanisms in WMNs. Also, this chapter includes but is not limited to optimization techniques for routing protocols, clustering algorithms, ant colony route analysis, and AODV routing optimization. This chapter aims to synthesize these foundational insights. The focus is on subtly examining WMNs and their associated routing protocols, particularly the AODV routing protocol.

1.1 Wireless Mesh Network (WMN)

Wireless Mesh Networks (WMNs) represent an emergent paradigm in multi-hop wireless technology, consisting of wireless access points (APs) that enable robust connectivity and seamless communication among wireless clients via multi-hop wireless routes. These networks can be further integrated with the Internet through specialized gateway routers. Serving as the mesh nodes, these APs can operate on various wireless technologies, such as Wi-Fi and WiMAX, and can be interconnected hierarchically (Agrawal et al., 2022; Rajya Lakshmi, Ribeiro, and Jain, 2015).

WMNs exhibit several characteristics common to Ad Hoc networks. For instance, each network node functions as a host and a wireless router. However, WMNs distinguish themselves from Ad Hoc networks in that they have separate end hosts and routing nodes, with the latter generally being stationary. This architectural distinction enhances the reliability and redundancy of WMNs. In node failure, the remaining nodes can communicate directly or through one or more intermediary nodes (Asgari et al., 2015).

Clients can interface with WMN routers through standard networking protocols like Ethernet, IEEE 802.11, and Bluetooth. Moreover, WMNs are versatile enough to be implemented using a range of wireless technologies, including but not limited to IEEE 802.11, IEEE 802.16, and cellular technologies. In most applications, WMNs serve as a conduit to infrastructure networks, typically offering Internet connectivity via a gateway.

WMNs offer advantages over traditional broadband Internet access technologies such as cable modems and xDSL. Specifically, WMNs require a substantially lower initial investment and can be deployed more rapidly. Compared to fixed Wireless Metropolitan Area Networks (WMANs), such as those based on IEEE 802.16, WMNs offer enhanced coverage areas, particularly in densely built urban environments with physical obstructions like trees and buildings. Furthermore, WMNs provide increased reliability by offering multiple alternative routes to circumvent failed nodes and poor links (Mohammed and Othman, 2023).

In addition to these benefits, certain WMN implementations also support mobile user access. Unlike Wireless Local Area Networks (WLANs), which necessitate separate wired network connectivity for each AP, WMNs allow APs to be strategically placed within range. This enables them to forward packets to and from a shared gateway, simplifying the network architecture. However, it is essential to note that this configuration may reduce network capacity, as nodes must handle their traffic and forward traffic to other nodes (Vasudeva and Sood, 2018). Several key characteristics of WMNs significantly impact routing and deserve close attention:

- **Scalability and Reliability:** Scalability is a pivotal concern for WMNs. The network's overall performance and reliability are theoretically proportional to the number of participating nodes. The absence of scalability support could lead to a marked degradation in network performance as the network expands. Reliability, another crucial design element, can be quantified through metrics like terminal-pair reliability, representing the likelihood of successful communication between two network terminals. Effective routing protocols should be capable of swiftly rerouting around failed nodes and broken links (Hu, Cai, and Pan, 2021).

- **Latency:** In applications that require real-time communication, such as VoIP or streaming media, the latency introduced by multi-hop communication can be a critical issue. Routing protocols must be designed to minimize this latency (Hu, Cai, and Pan, 2021).
- **Network Connectivity:** The robustness of WMNs is mainly attributable to their mesh connectivity. Managing this connectivity for optimal reliability and redundancy is a critical operational aspect. To maintain a reliable mesh network, algorithms for network self-organization and topology control are essential (K.C, 2016).
- **Quality of Service (QoS):** Addressing QoS in WMNs is challenging due to the potential for interference among closely situated nodes. WMNs often support broadband services with diverse QoS requirements. Therefore, routing protocols must consider additional performance metrics beyond end-to-end delay and fairness, such as delay jitter, aggregate throughput, per-node throughput, and packet loss ratios (Duong, Binh, and Ngo, 2022).
- **Energy Efficiency:** In many WMN deployments, especially those in remote or hard-to-reach areas, energy efficiency is a critical factor. Nodes may be battery-powered, and efficient energy utilization can significantly extend the network's operational lifespan (Sun, 2016).
- **Self-Configuration:** WMNs are inherently self-configuring. Any node joining the network is automatically integrated into the mesh topology, eliminating the need for manual configuration. This feature also enables the network to reconfigure itself as needed (Hamrioui et al., 2022).
- **Self-Healing:** WMNs can reorganize and continue functioning even when one or more nodes are compromised or relocated. This ensures the network remains operational without requiring human intervention for message rerouting (Saleem, Johnson, and Ramasubramanian, 2013).
- **Gateways:** In most Wireless Mesh Networks (WMNs) architecture, specialized nodes known as gateways serve a pivotal role. These gateways are strategically positioned to form the network's backbone and are primarily responsible for facilitating connectivity between mesh clients and external networks, most commonly the Internet (Mohammed and Othman, 2023).

- **Traffic Patterns:** Contrary to the prevalent assumption in Ad Hoc networks, where any node is equally likely to act as either the source or the destination of network traffic, WMNs exhibit a distinct traffic pattern. Specifically, the network traffic flow in WMNs is generally directed from mesh clients toward external networks, such as the Internet, via the gateways above (Mahajan, HariKrishnan, and Kotecha, 2022).
- **Security and Privacy:** WMNs often need to provide secure communication channels. This involves encryption and secure routing protocols that can resist various types of attacks like eavesdropping, spoofing, and man-in-the-middle attacks (Al-Anzi, 2022).
- **Interoperability:** WMNs often comprise heterogeneous devices that may use different wireless technologies. The ability of these devices to work together seamlessly is crucial for the network's overall performance (Al-Anzi, 2022).
- **Load Balancing:** In WMNs, some nodes may handle disproportionate network traffic, leading to bottlenecks. Effective load-balancing strategies are essential to distributing network traffic evenly across nodes (Asgari et al., 2015).
- **Fault Tolerance:** Beyond self-healing, WMNs often incorporate additional fault tolerance mechanisms to handle hardware failures, data errors, and other unexpected issues without requiring manual intervention (Gogoi, Ghoshal, and Manna, 2023).
- **Mobility Management:** While many WMNs are relatively static, some deployments may involve mobile nodes. Effective mobility management strategies are needed to handle the associated challenges, such as route instability and increased control message overhead.
- **Bandwidth Optimization:** Given that wireless bandwidth is a limited resource, WMNs must employ strategies to use the available bandwidth efficiently. This could involve techniques like channel bonding, adaptive modulation, and coding (Nawaf, Allen, and Rana, 2017).
- **Geographical Coverage:** WMNs are often praised for their extensive geographical coverage, particularly in challenging environments where traditional networking infrastructure is difficult to deploy (Taleb et al., 2022).

Unlike Ad Hoc networks, WMNs have specialized gateway nodes that form the network backbone and facilitate Internet connectivity for mesh clients. Additionally, the traffic patterns in WMNs are generally directed from mesh clients to the Internet via these gateways, unlike in Ad Hoc networks where any node could serve as either the source or destination of traffic. Lastly, WMNs can accommodate stationary nodes, often mounted on fixed structures like lamp posts or rooftops, and mobile nodes that can roam within the network's coverage area.

1.1.1 Wireless Mesh Network Architectures

WMNs consist of radio nodes, systematically classified into Mesh Clients (MC) and Mesh Routers (MRS), as depicted in Figure 1.1. Each node in the network performs dual roles: it acts both as a host and as a router. This dual-role architecture enables the network to extend its coverage via multi-hop communication strategies. Unlike conventional wireless routers, which mainly function as gateways or repeaters, MRS in WMNs have advanced routing capabilities. Some MRS are even furnished with multiple wireless interfaces. In contrast, MC contribute to the network's routing capabilities but lacks gateway or bridge functionalities and typically has a single wireless interface.

The primary design goal of WMNs is to optimize mobility for MC while ensuring that MRS remain relatively static. This design philosophy aims to leverage the strengths of both mobile and static nodes to achieve a balanced and efficient network.

To further understand the versatility and adaptability of WMNs, it is instructive to examine their architectural diversity. The architecture of WMNs can be segmented into three distinct categories:

- **Infrastructure/Backbone:** In Infrastructure/Backbone WMNs, as depicted in Figure 1.1, mesh routers create a backbone that facilitates client access. Here, mesh clients are passive in the routing and forwarding of packets. They connect via mesh routers, which integrate WMNs with existing wireless networks. This is made possible through the gateway and bridge functionalities embedded in mesh routers. Clients must interface with base stations connected to mesh routers via Ethernet if different radio technologies are in play (Mohammed and Othman, 2023).
- **Client WMNs:** Mesh clients form a peer-to-peer network and actively participate in routing functions. This architecture reduces the need for a separate mesh router. Packets destined for a particular node traverse multiple nodes before reaching their final destination. Typically, Client WMNs operate on a single type of radio technology, making them akin to conventional Ad Hoc networks. However, this architecture places additional responsibilities on end-user devices, such as routing and self-configuration (Chai and Zeng, 2021).
- **Hybrid WMNs:** This architecture amalgamates infrastructure with client meshing characteristics, wherein mesh clients have the dual capability of direct intercommunication or network access through mesh routers. Data transmission to the intended destination is facilitated by both the client mesh and the backbone infrastructure. The infrastructure element of this system provides interconnectivity to a diverse array of networks, encompassing the Internet, Wi-Fi, WiMAX, and sensor networks, thereby augmenting internal connectivity and extending coverage within the Wireless Mesh Network (WMN) (Chai, Shi, and Shi, 2017).

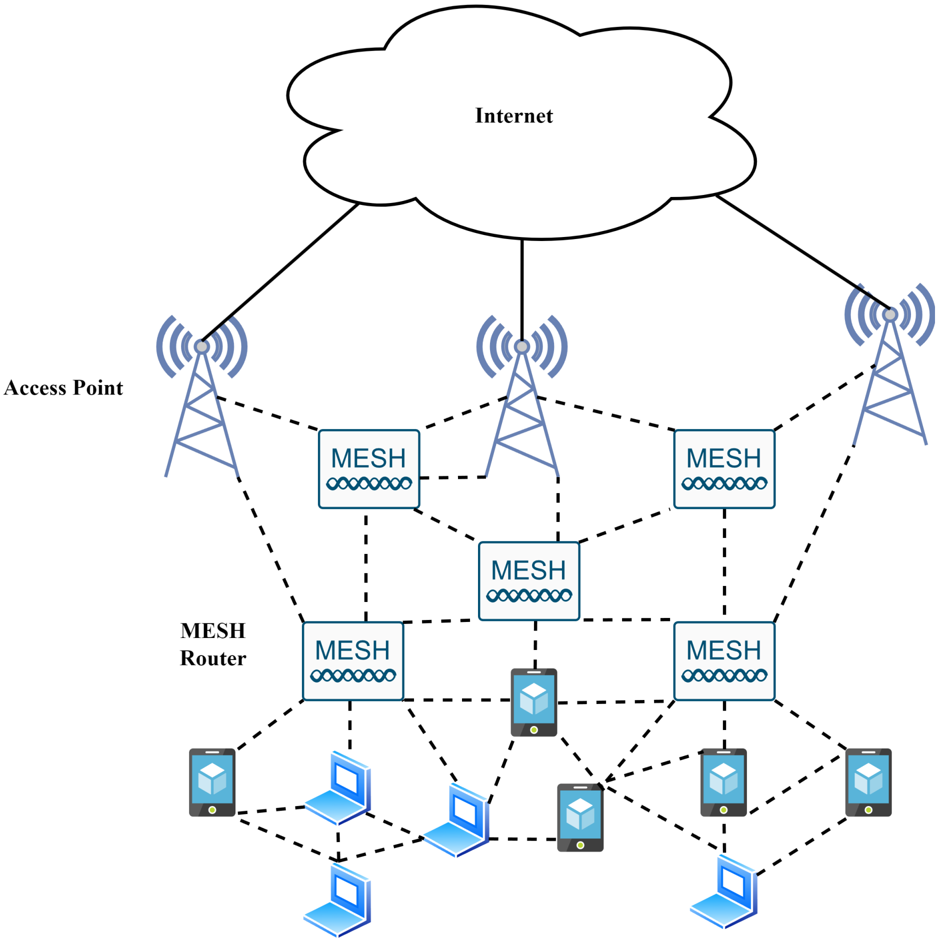


Figure 1.1: Wireless Mesh Network Architectures.

(Alameri, Komarkova, Al-Hadhrami, and Lotfi, 2022)

1.1.2 WMN Topology and Routing

The topology and routing mechanisms of WMNs are pivotal components that dictate the network's performance, scalability, and reliability. WMNs typically employ a multi-hop architecture, where data packets traverse through several nodes to get to their destination. This architecture inherently differs from traditional wireless networks, usually consisting of a single hop between the client and the access point. The multi-hop nature of WMNs introduces complexities but also offers advantages such as extended coverage and fault tolerance.

Regarding topology, WMNs might be broadly categorized to three categories: Infrastructure/Backbone WMNs, Client WMNs, and Hybrid WMNs. Infrastructure WMNs comprise mesh routers that form the backbone, providing connectivity to mesh clients. On the other hand, client WMNs lacks a dedicated router backbone; instead, the clients perform the routing. Hybrid WMNs combine elements of both, offering a flexible and robust solution. The choice of topology directly impacts the network's performance metrics, including latency, throughput, and fault tolerance.

Routing in WMNs is another critical aspect that requires careful consideration. Unlike traditional networks, where routing is generally static, WMNs often employ dynamic routing protocols to adapt to the network's ever-changing topology. The AODV and the Optimized Link State Routing (OLSR) protocols are commonly used in WMNs. AODV is a reactive protocol, which establishes a route only when needed, thus reducing the control message overhead. OLSR is a proactive protocol where routes are pre-established, allowing for quicker data packet transmission but at the cost of increased control message overhead (Abolhasan, Hagelstein, and Wang, 2009; Wang, Xie, and Agrawal, 2009).

The hexagonal topology, often used in simulations and theoretical models, provides an idealized but useful framework for studying WMNs, Figure 1.2, which depicts our concern's topology. In such a topology, each node has an equal number of neighbours at equidistant locations, allowing for uniform distribution of network resources and facilitating more accurate performance evaluations.

In summary, the topology and routing mechanisms are integral to the design and operation of WMNs. They influence key performance indicators and thus require meticulous planning and optimization. The multi-hop architecture and dynamic routing protocols offer a flexible yet complex environment well-suited for various applications, ranging from broadband home networking to emergency response systems.

1.1.3 The Design Goal of WMNs

The design goals of WMNs are multifaceted, aiming to address the challenges and limitations inherent in traditional wireless networks while capitalizing on the advantages of mesh topology. These goals can be broadly categorized into performance, scalability, reliability, and adaptability.

1.2 Overview of Routing Protocols

WMNs have appeared as a versatile and robust solution for various networking scenarios, ranging from residential to large-scale industrial applications. The efficacy of a WMN is intrinsically linked to its routing protocols, which govern how data packets traverse through the network. This section presents a comprehensive review of the several types of routing protocols commonly employed in WMNs, focusing on their operational characteristics, advantages, and limitations. Figure 1.3, illustrates the different routing protocols based on their operational characteristics. Next, this thesis explores specific types of routing protocols in more detail, including proactive, reactive, and hybrid protocols, along with the emerging concept of cross-layer design.

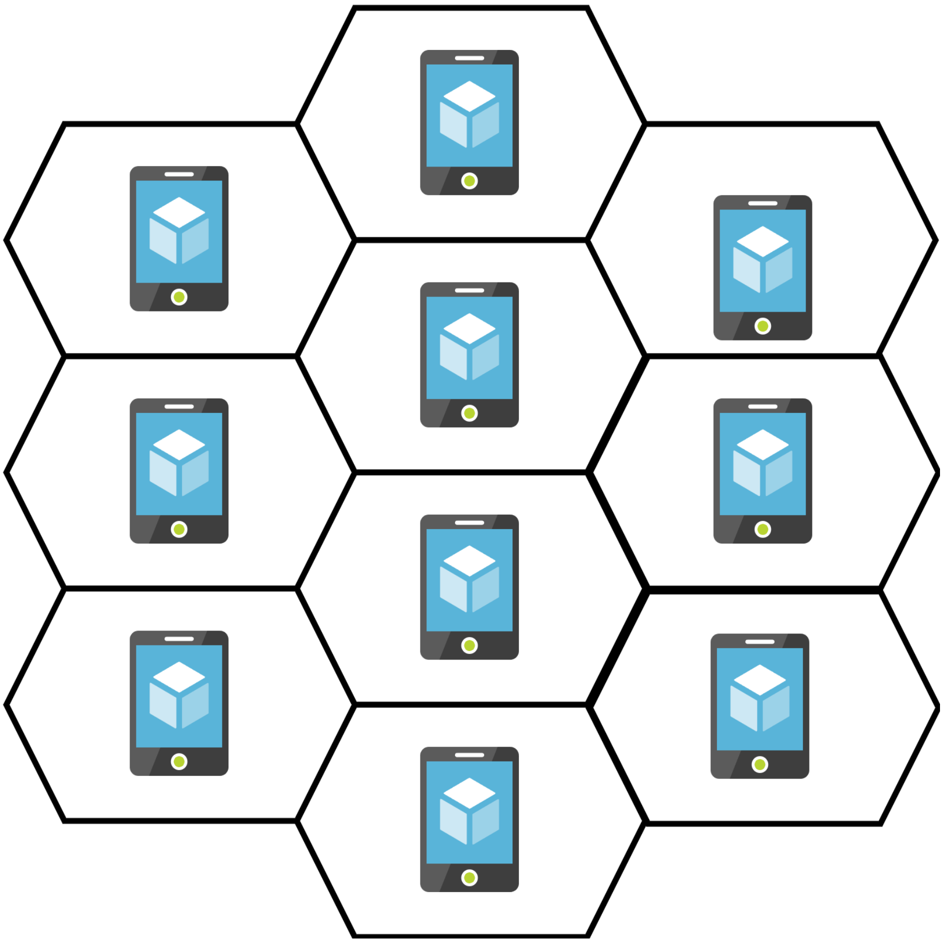


Figure 1.2: WMN Topology.
(Alameri, Komarkova, Al-Hadhrami, and Lotfi, 2022)

Proactive Routing Protocols: Those protocols maintain up-to-date routing tables at each node, such as OLSR and Destination-Sequenced Distance-Vector (DSDV) (Bugarcic, Malnar, and Jevtic, 2019). These tables are updated periodically or upon network topology changes, ensuring routes are immediately available.

Reactive Routing Protocols: Reactive or on-demand routing protocols, including AODV and Dynamic Source Routing (DSR), initiate route discovery only when a node needs to send data to a destination for which it does not already have a path. These protocols are generally more scalable and better suited for dynamic environments where network topology changes frequently (Alameri and Komarkova, 2019).

Hybrid Routing Protocols: This type of routing protocol, such as Zone Routing Protocol (ZRP), aims to integrate the best features of both proactive and reactive approaches. In these protocols, nodes within a certain proximity use proactive routing, while nodes farther away are reached using reactive routing. This dual approach aims to balance the trade-offs between latency and overhead (Alameri, Hubálovskỳ, and Komarkova, 2021).

Figure 1.3: Routing Protocols Classification.

Cross-Layer Design: Besides these primary categories, cross-layer design has gained attention for its potential to improve network performance. Cross-layer design enables more informed and adaptive routing decisions by allowing information exchange between different network stack layers. This is particularly useful in WMNs, where network conditions vary widely and rapidly (Alameri, Komarkova, Al-Hadhrami, and Lotfi, 2022) & (Ramadhan, 2010).

Specialized Protocols: Some WMNs employ specialized routing protocols designed to meet specific needs, such as Quality of Service (QoS) guarantees, energy efficiency, or support for mobile nodes. These specialized protocols often modify or extend existing proactive or reactive protocols to achieve their objectives (Alameri, Komarkova, and Al-Hadhrami, 2023).

In summary, the choice of routing protocol can significantly impact the performance, scalability, and reliability of a Wireless Mesh Network (WMN). Therefore, selecting an appropriate routing protocol is a critical design decision considering various factors, including network size, mobility patterns, and specific application requirements. The subsequent sections of this thesis will delve deeper into the intricacies of the AODV routing protocol, providing a detailed analysis of its operation, advantages, and potential areas for improvement.

1.2.1 Destination-Sequenced Distance-Vector Routing (DSDV)

The DSDV protocol is founded on the distributed Bellman-Ford algorithm. This routing technique was among the earliest proactive solutions designed for mesh networks. It ensures loop-free routing tables by incorporating destination-assigned sequence numbers. Each mobile node maintains a routing table with the following hop addresses, hop counts, and sequence numbers. Periodic updates are broadcasted to keep consistent tables, with sequence numbers preventing routing loops. DSDV employs two types of update packets: ”full dump” and ”incremental” packets. Full dump packets carry the complete routing table, while incremental packets transmit only the changed information since the last full dump. Nodes maintain an additional table to store incremental routing information. The protocol relies on preferred neighbours for each destination and forwards data packets accordingly. Routes with the most recent sequence numbers are chosen, and settling time is used to optimize routes by delaying routing updates. However, DSDV consumes bandwidth and power due to regular table updates, making it less appropriate for highly dynamic networks. DSDV is an early proactive routing solution suitable for small-scale ad hoc networks (Wang et al., 2017; Narra et al., 2011).

1.2.2 Open Shortest Path First (OSPF)

OSPF is a link-state protocol for routing TCP/IP networks. Routers exchange information about their connections and construct a shortest path tree to calculate routing tables. The protocol includes the Hello, Election, Flooding, and Shortest-Path-First (SPF) algorithms (Al-Musawi et al., 2020). Messages establish neighbours, while the SPF algorithm computes the shortest paths. A Designated Router (DR) and Backup Designated Router (BDR) are elected for broadcast networks. Flooding ensures consistent topology information, and OSPF selects the cheapest route. OSPF supports variable length subnetting and areas for reduced routing traffic (Gunavathie and Umamaheswari, 2024).

1.2.3 The Wireless Routing Protocol (WRP)

The Weighted Routing Protocol (WRP) is a table-based protocol that maintains routing information among network nodes. It incorporates a second-to-last hop concept and utilizes distance and predecessor information to prevent routing loops. In this framework, every node sustains a quartet of tabular records: a table for distance metrics, a routing table, a ledger detailing the cost associated with various links, and a catalog for the management of message retransmissions, known as the Message Retransmission List (MRL). Routing tables are exchanged through periodic and triggered update messages, allowing nodes to update their paths based on received information. However, the WRP protocol suffers from high control traffic overhead, periodic Hello messages, and memory-intensive table maintenance (Mohiuddin, Khan, and Engelbrecht, 2016; Nurhaida, Ramayanti, and Nur, 2019; Kurniawan and Prihanto, 2022).

1.2.4 Zone Routing Protocol (ZRP)

The ZRP represents an innovative hybrid framework that integrates the attributes of both proactive and reactive routing mechanisms. This protocol delineates the network into distinct routing zones, within which each node proactively administers routes in its immediate vicinity. Internal zone routing is managed via the Intrazone Routing Protocol (IARP), whereas the Interzone Routing Protocol (IERP) facilitates routing across different zones (Alameri, Komarkova, and Ramadhan, 2021).

Within the scope of IARP, nodes ascertain the shortest paths and maintain routes to all other nodes in the same zone. This necessitates nodes possessing knowledge confined to the network topology of their respective routing zones, with topological updates disseminated solely within those zones. The IARP does not prescribe a specific routing protocol, accommodating various proactive strategies such as distance vector or link-state routing.

Conversely, IERP orchestrates route discovery across distinct zones, activating when the source and destination nodes do not reside within the same zone. This process involves the propagation of a Route Requests (RREQ) message to the zone's border nodes, reiterating until the destination node is located. Subsequently, a Route Reply (RREP) message is relayed back to the source node, delineating the discovered route.

ZRP capitalizes on the strengths of proactive and reactive protocols, adeptly initiating route queries for distant nodes and swiftly establishing routes within the local zone. It curtails the volume of query messages by confining them to the zone's edge nodes. Unlike purely proactive protocols, ZRP restricts the broadcast of topological alterations to the vicinity of the change, thereby enhancing efficiency. Nonetheless, the protocol's flexibility in IARP selection implies that nodes might need to accommodate multiple routing protocols to ensure compatibility with various IARPs (Shah et al., 2021; Beijar, 2002; Kurode et al., 2021).

1.2.5 Temporally Ordered Routing Algorithm (TORA)

The TORA is a robust and adaptable distributed routing protocol predicated on the principles of the link reversal algorithm. Tailored for dynamic mobile networks with high node density, TORA facilitates on-demand route discovery and sustains multiple pathways for each pair of source and destination (Alameri and Komarkova, 2021). It effectively reduces communication overhead by confining responses to alterations in network topology. Employing a 'height' metric to ascertain the orientation of links, TORA preserves a directed acyclic graph (DAG) oriented towards each destination, thereby optimizing route maintenance and efficiency (Nurwarsito and Umam, 2020).

1.2.6 Optimized Link State Routing Protocol (OLSR)

The protocol, tailored for ad hoc networks, functions as a proactive, table-driven IP routing protocol that orchestrates systematically disseminating network topology data among all nodes. As a proactive link-state routing protocol, it employs Hello and Topology Control (TC) messages to uncover and broadcast link-state data across the network (Saini and Sharma, 2020). A pivotal feature of the OLSR protocol is the multipoint relay (MPR) strategy, which designates specific nodes to propagate messages during the broadcast process. This strategy leverages the topology data from these nodes to calculate the most direct routes to all nodes within the network, thus markedly diminishing the message overhead in contrast to conventional flooding techniques. MPRs are selected from one-hop neighbors with established symmetric bidirectional links, promoting efficient routing and mitigating complications associated with unidirectional links. The MPRs are crucial in effectively distributing control messages throughout the network (Alameri and Komarkova, 2021).

The OLSR protocol is underpinned by three core processes: neighbor detection via regular Hello message exchanges, streamlined control message dissemination through MPRs, and the derivation of optimal routes employing the shortest-path algorithm. Neighbor detection is crucial for recognizing alterations within a node's immediate network vicinity. Hello messages, transmitted at regular intervals, include the sender's address, a roster of its neighbors, and the status of the links (e.g., asymmetric or symmetric). The MPR mechanism guarantees that topology information reaches every node efficiently without redundant broadcasting or retransmissions. Nodes independently elect a set of MPRs, thereby reducing the overhead associated with message flooding. The optimal routing paths are computed through the periodic dispatch of TC messages by nodes with non-empty MPR sets. These messages convey the originating node's address and its MPR selection, enabling all MPRs to acquire the necessary reachability information. By applying the shortest path algorithm to the selectively constructed topology graph, nodes are able to determine the most efficient routes. The relevance of topology information is time-bound, necessitating its removal upon the expiration of its validity period (Kazakov, 2023).

The OLSR protocol offers several advantages, particularly in large and dense networks. Using MPRs enhances optimization compared to classic link-state algorithms. It enables the rapid establishment of connections. However, periodic network discovery represents a disadvantage, as it can impose continuous calculation and memory burdens, particularly for resource-constrained devices running OLSR implementations (Yang et al., 2023).

1.2.7 Dynamic Source Routing (DSR)

The DSR protocol is an on-demand routing system designed for Ad Hoc networks. It has two main parts: finding routes and keeping them current. DSR's route discovery method effectively identifies a route from the source to the destination, with each packet en route carrying the addresses of the nodes through which it passes (Guo et al., 2022).

A node with the DSR protocol intending to send a packet first consults its Route Cache Table for an existing route. Without a suitable path, the node initiates route discovery by broadcasting an RREQ packet. Nodes further propagate this packet unless they are the destination or have a route to the destination in their cache. Nodes without a route to the destination append their address to the RREQ before rebroadcasting, while nodes with a known route send an RREP, linking the discovered route to the cached route.

Each RREQ is uniquely marked with an identification number and includes the identifiers of the source and destination, along with the addresses of the intermediate nodes it has encountered. To prevent unnecessary retransmissions, nodes discard RREQs bearing an ID they have previously processed. When the RREQ reaches the destination node, it responds with an RREP back to the source, indicating the path the RREQ has taken. The source node, upon receipt of the RREP, caches this route to streamline future communications to the same destination.

As the source node sends data packets to the destination, intermediate nodes passively gather routing data, storing the routes from the RREP headers in their caches. This passive learning facilitates the maintenance of an informed and efficient routing structure within the network (Ramadhan, 2010).

1.2.8 Ad-Hoc On-Demand Distance Vector (AODV)

The AODV routing protocol (Perkins, Belding-Royer, and Das, 2003), is a widely used routing algorithm in MANETs and WMNs. It is designed to adapt dynamically to varying network topologies and conditions, making it particularly suitable for networks where nodes are mobile and topology can change rapidly. AODV is an on-demand, reactive routing protocol that establishes routes between nodes only when needed. It employs a table-driven approach, where each node maintains a routing table that stores essential information about active routes to various destinations (Alameri, Komarkova, and Al-Hadhrami, 2023). The routing table contains several key pieces of information:

- **Hop Count:** The number of intermediate nodes through which a packet must pass to reach the destination.
- **Sequence Number:** A unique identifier that ensures the freshness of the route information.
- **Next Hop:** The immediate neighbour node to which packets for a specific destination should be forwarded.

The routing protocol serves as the core for enabling effective communication among routers, thereby facilitating the selection of optimal paths between any two nodes within a computer network. The AODV routing protocol is specifically engineered to mitigate routing loop scenarios where data packets circulate endlessly within the network without reaching their intended destinations. Notably, AODV protocol operates autonomously, requiring no external stimuli, and is robust enough to function in environments characterized by multiple mobile nodes. These protocols are resilient to various network challenges, including packet loss, link failure, and node mobility.

Each node within the network maintains a routing table that includes essential parameters such as the hop count, sequence number, and the next hop node. The hop count indicates the current distance to the destination node, while the sequence number functions as a unique identifier to ensure the freshness of the route information. In the event of link breakage, the AODV protocol promptly notifies the affected nodes, allowing them to invalidate routes traversing the disrupted link. Importantly, the AODV protocol allows the destination node to generate a unique sequence number, which is subsequently incorporated into the route information disseminated to the requesting nodes (Alameri and Komarkova, 2019).

AODV Routing Methodology

Figure 1.4, graphically delineates the operational dynamics of the AODV protocol. It elucidates the route establishment process within an ad hoc network, highlighting the transmission of Route Request (RREQ) and Route Reply (RREP) packets among the nodes. Within the AODV framework, a node requiring a route to another node disseminates an RREQ packet, which encapsulates the originating node's address, the intended destination's address, and a distinctive request identifier. As the RREQ packet permeates the network, each recipient node formulates a reverse path leading to the source node. This reverse path is pivotal for transmitting an RREP packet back to the source node, whether directly from the destination node or via an intermediate node that maintains a current route to the destination. Upon reception of an RREP packet, the source node establishes a direct route to the destination (Alameri, Komarkova, Al-Hadhrami, and Alkaraawi, 2023).

The AODV protocol's reactive nature is advantageous for wireless networks as it potentially minimizes network overhead compared to proactive routing protocols (Bondre and Dorle, 2017). Nonetheless, it is not without its challenges, which include possible delays in route discovery and the necessity to sustain routes amidst the mobility of nodes. AODV secures a route between source and destination using a hop-by-hop routing approach. With this foundational comprehension of AODV, we dissect the specific routing methodologies it employs. The AODV routing mechanism's comprehensive process can be bifurcated into two principal phases.

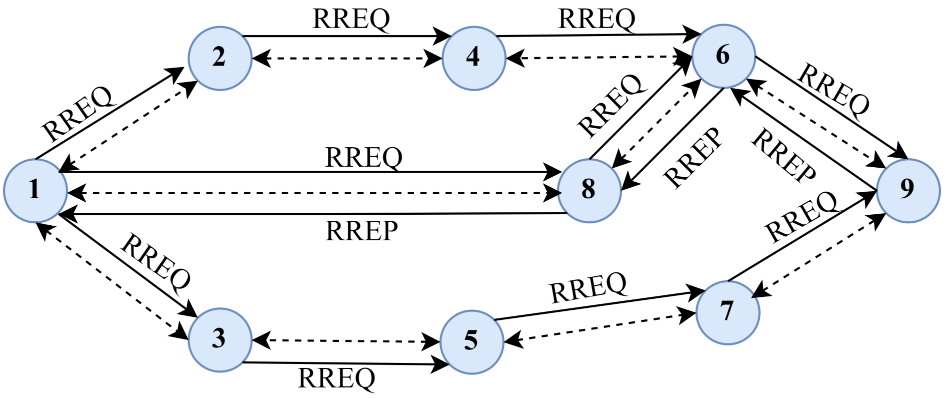


Figure 1.4: AODV Protocol in Process.

(Alameri, Komarkova, Al-Hadhrami, and Lotfi, 2022)

- **Discovery of Routes:** In the context of route discovery within Wireless Mesh Networks (WMNs), the source node initiates communication by attempting to dispatch a packet to a designated destination node. It consults its routing table to ascertain the existence of a current route to the destination node, as the routing table should ideally hold this information. Should the routing table contain the requisite route information, the source node transmits the packet to the next hop on the path to the intended destination. Conversely, if the routing table lacks the necessary route, the source node commences the route discovery process to establish a new path to the destination node (Alameri, Komarkova, Al-Hadhrami, and Lotfi, 2022).

  The route discovery is set in motion by creating a Route Request (RREQ) packet, which includes the source node's IP address and current sequence number, as well as the destination node's IP address and the last known sequence number. Additionally, the RREQ packet is assigned a unique broadcast ID, which is incremented with each new RREQ packet issued by the source node. Following the generation of an RREQ packet, the source node disseminates the packet and activates a timer to await a response.

  As depicted in Figure 1.5, the route discovery procedure in the Ad hoc On-Demand Distance Vector (AODV) protocol is illustrated. Upon receipt of an RREQ packet, a node examines its validity by inspecting the source node's IP address and the broadcast ID. Each node maintains a record of the broadcast ID and the source node's IP address for a specified duration. To respond to the RREQ packet, a node must determine, via its routing table, whether it has an available route to the destination. The RREQ packet also conveys the destination's sequence number, preventing routing loops, thereby ensuring that any route relayed back to the source node is based on up-to-date information.

If a node meets the criteria above, it issues an acknowledgment by directing an RREP packet back to the source node through unicast transmission. This process ensures that the route information is current and valid, facilitating effective communication within the network (Alameri, Komarkova, and Al-Hadhrami, 2023).

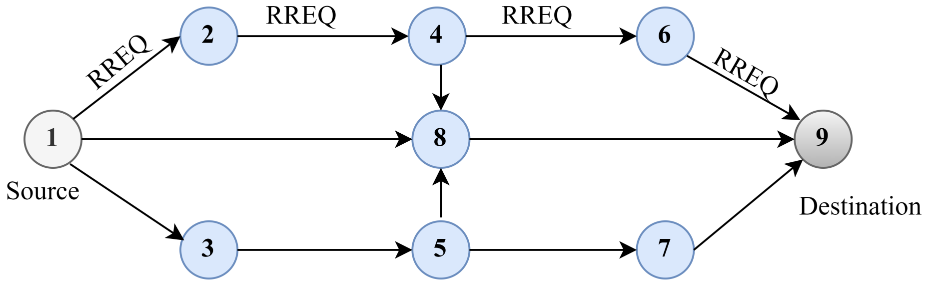


Figure 1.5: The Route Discovery Process in AODV.
(Alameri, Komarkova, Al-Hadhrami, and Lotfi, 2022)

In summary, When a source node wishes to communicate with a destination node for which it does not have a valid route, it initiates the route discovery process. This begins with the creation of a RREQ packet. The RREQ packet contains several fields, including:

- Source IP Address
- Destination IP Address
- Source Sequence Number
- Destination Sequence Number
- Broadcast ID: A unique identifier for this particular RREQ.

The source node broadcasts the RREQ packet to its immediate neighbours. Each neighbour, upon receiving the RREQ, performs several actions:

- Reverse Route Creation: The neighbour returns a reverse route entry to the source node in its routing table. This is used for sending RREP back to the source.
- RREQ Propagation: If the neighbour is not the destination and does not have a valid route to the destination, it forwards the RREQ to its neighbours, effectively propagating the request through the network.

- **Maintenance of Routes:** After establishing a route between a source and a specific destination within a wireless network, the mobility of nodes affects only those routes that traverse the nodes situated on an active path. Should mobility disrupt the route during data transmission, the source node is compelled to initiate a fresh route discovery process to formulate a new pathway to the destination. In such events, the impacted source nodes emit either a Route Reply (RREP) or a Route Error (RERR) message. The RERR message, triggered by the upstream node, enumerates destinations inaccessible due to link failures. Upon receipt, this message is disseminated to adjacent nodes, which designate their routes to the affected destination as inactive, effectively setting the route cost to the destination as infinite (Alameri, Komarkova, Al-Hadhrami, and Lotfi, 2022).

  Conversely, suppose the source node receives an RREP. In that case, an alternative route has been identified, prompting the source node to recommence the route discovery process to secure a viable route as required.

  Illustrated in Figure 1.6, is the process of source route discovery. Route maintenance is achievable through two strategies. The primary strategy involves the source node broadcasting an RREQ to its neighbors, detailing the IP addresses of the source and destination, along with their respective sequence numbers and a broadcast ID. Should the destination node respond with an RREP, the source node acquires the route information via an intermediary node.

  Alternatively, route maintenance may be conducted locally by an intermediary node that seeks to restore a disrupted link. This node projects an RREQ to its immediate neighbors directed towards the destination. When the destination node receives this RREQ, it responds with an RREP to the intermediary node, thereby reestablishing the route between the source and the destination (Alameri, Komarkova, Al-Hadhrami, and Lotfi, 2022).

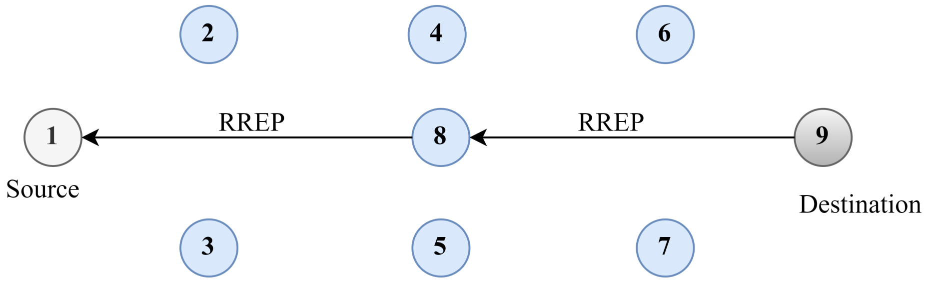


Figure 1.6: The RREP Process.
(Alameri, Komarkova, Al-Hadhrami, and Lotfi, 2022)

The significance of studying routing protocols, especially the AODV) protocol remains high in the realms of WMNs, MANETs, and other specialized applications. As we venture further into the complexities of WMNs, it becomes increasingly important to scrutinize the routing protocols that serve as the backbone of these decentralized and dynamic networks. While traditional broadband technologies offer valuable solutions, they often do not fully address the unique challenges WMNs present. Therefore, the upcoming section will focus on a comprehensive review of scholarly research that critically evaluates the performance of the standard AODV protocol. We will compare AODV to other routing protocols and examine its efficacy under various network conditions and performance metrics to understand how AODV can best meet the specialized requirements of WMNs.

1.3 Advanced Routing Mechanisms in AODV: A Comparative Analysis

The importance of studying routing protocols like AODV in WMNs, MANETs, and other related applications continues to be high.

This section will examine research papers critically assessing how well AODV performs. We will compare AODV to other routing protocols and explore how it works under different network conditions. Specifically, this chapter will evaluate the protocol's efficiency by considering factors such as the number of nodes, node speed, and network size. We will focus on measuring key performance indicators like throughput, end-to-end delay, packet delivery ratio, energy use, and routing overhead.

1.3.1 AODV under statistical analysis approach

The statistical analysis in this study was crucial in evaluating the performance of various routing protocols in mobile ad hoc networks (MANETs). The researchers used mathematical statistics to study and evaluate the behavior of transmitted data and measure the efficiency of the protocol based on the simulation results and the standard deviation of the data. This analysis allowed them to identify the strengths and weaknesses of each protocol in terms of throughput, energy consumption, delay, and packet drop rate. For instance, the AODV routing protocol performed well regarding throughput and energy consumption, while DSR had a lower delay. The AntHocNet protocol, on the other hand, showed high delay and fluctuating behavior in packet drop rate. These findings suggest the need for further research to improve the performance of routing protocols (Alameri and Komarkova, 2022).

1.3.2 Ant Colony Optimization and AODV performance

The paper "Performance and Statistical Analysis of Ant Colony Route in mobile ad hoc network (MANET) explores Ant Colony Optimization (ACO) as an alternative technique for routing in

MANET (Alameri, 2019). This study discusses how MANETs are becoming increasingly crucial in areas such as emergency response and healthcare. It highlights the challenges of dynamic topology, energy consumption, and packet drop rates in MANETs. The study conducted a comparative analysis of various routing protocols An Optimized Ad-hoc On-demand Multipath Distance Vector (AOMDV), DSR, AODV, and AntHocNet—focusing on their Quality of Service (QoS) and statistical performance. One of the main conclusions was that AODV outperforms other protocols in metrics like throughput and packet delivery ratio, particularly in small to medium-sized networks. Despite ACO's potential, the paper calls for further improvements and research, especially concerning AODV.

1.3.3 Single vs. Multiple Path Protocol of AODV

This study investigates the impact of various routing protocols on the performance of MANET (Alameri, Komarkova, and Ramadhan, 2021). The study compares three widely used routing protocols: AODV, AOMDV, and OLSR. The authors employed network simulation software to evaluate key performance metrics, including data throughput, packet delivery ratio, routing overhead, and end-to-end delay.

The findings reveal that the AODV protocol, which utilizes a single-path routing mechanism, outperformed the multi-path protocols OLSR and AOMDV in several aspects. Specifically, AODV demonstrated superior data throughput and packet delivery ratios while requiring minimal routing overhead. However, multi-path protocols exhibited a slight advantage in terms of end-to-end delay.

Upon scaling the network by increasing the number of devices, AODV maintained its high performance. In contrast, OLSR experienced declining data throughput and packet delivery ratios. Interestingly, AOMDV's end-to-end delay improved as the network size increased. The study also highlighted that the performance of OLSR was particularly sensitive to the number of devices in the network, leading to reduced data throughput and increased latency. AOMDV was found to be faster in data transmission compared to both AODV and OLSR. Regarding routing overhead, AODV was the most efficient among the three protocols. In conclusion, the authors advocate for further research into the AODV protocol, particularly focusing on its behaviour under various network conditions and its adaptability to unstable connections (Alameri, Komarkova, and Ramadhan, 2021).

1.3.4 Routing in Geographic Information Systems (GIS)

The paper ”Network Routing Issues in Global Geographic Information Systems” discusses the suitability of different routing protocols for Geographic Information Systems (GIS). After conducting simulation-based comparative studies, the paper highlights that AODV has a lower packet drop rate, higher throughput, and better service quality than its counterparts, making it more suitable for GIS applications where real-time data acquisition is crucial (Alameri and Komarkova, 2021).

1.3.5 In-depth Comparative Assessment of Various Parameters in the AODV Protocol

This study conducts a comprehensive comparative analysis of routing protocols in MANETs, a type of network where each device operates independently and is free to move. Utilizing the NS-2.35 simulation tool, the study evaluates the performance of four prominent routing protocols: AODV, DSR, DSDV, and ZRP.

The evaluation criteria include key performance metrics such as throughput, which measures the amount of successfully transmitted data; end-to-end delay, indicating the time taken for data to reach its destination; packet delivery ratio, which quantifies the success rate of data delivery; and remaining energy, which assesses the energy efficiency of the devices post-transmission.

AODV is the most effective among the protocols examined, demonstrating superior throughput and a higher packet delivery ratio. The paper also offers a balanced discussion on the advantages and disadvantages of each protocol while referencing previous research in the field for a more holistic understanding (Alameri and Komarkova, 2021).

1.3.6 Influence of Node Speed on Routing Protocol Performance

This study presents an empirical investigation into the impact of node velocity on the efficacy of various routing protocols in MANETs, a type of network characterized by transient and dynamic connections. Utilizing a network simulation tool, the study rigorously evaluated the performance of four established routing protocols, AODV, DSDV, DSR, and ZRP, under varying node speeds.

Key performance metrics were employed for this evaluation, including throughput, which quantifies the volume of successful data transmission; end-to-end delay, measuring the time required for data to traverse the network; packet loss, indicating the amount of data lost during transmission; and energy consumption, assessing the power utilization of the network.

The findings reveal a notable correlation between node speed and the performance of routing protocols. Specifically, the AODV protocol emerged as the most efficient in terms of throughput and packet loss, signifying its capability to transmit the highest volume of data with minimal loss. Conversely, the ZRP protocol was found to be the most energy-efficient.

The study concludes that an increase in node speed adversely affects the performance of routing protocols, underscoring the need for adaptive strategies in MANETs (Alameri, Komarkova, Al-Hadhrami, and Hussein, 2023). Section 1.4, is For further discussion on routing protocols suitable for various wireless network conditions.

1.4 Routing Protocols in WMNs

Selecting an appropriate routing protocol is a pivotal consideration in wireless networks, as it dictates how the network's topology is formed, configured, and maintained. Nodes within the network need to collect topology data to facilitate effective communication, a process that can be either reactive or proactive. Reactive routing protocols, such as AODV and DSR, initiate route discovery only when communication between nodes is required. These protocols typically use the least number of hops to establish a route. Studies indicate that reactive approaches yield better throughput and lower latency, particularly in WMNs, where the topology is dynamic and nodes are mobile (Choudhary et al., 2022; Perkins, Belding-Royer, and Das, 2003).

On the other hand, proactive routing protocols like DSDV, and Wireless Routing Protocol (WRP) maintain up-to-date routing tables by regularly broadcasting routing information (Chavan and Venkataram, 2022). This ensures that routes are readily available when needed. The ongoing research in WMNs routing aims to identify new performance metrics that can enhance the efficiency of these protocols. Factors such as available bandwidth, link load, and packet loss ratio must be considered when selecting or designing an optimal routing protocol for WMNs.

While protocols improved for the MANET like AODV, and DSR apply to WMNs due to their similar characteristics, specialized routing protocols are also being developed to leverage the unique features of WMNs. These include protocols focused on multi-radio routing regarding their channel selection mechanisms and hierarchical routing protocols. For instance, Kodialam and others have introduced channel assignment and routing algorithms that define the capacity regions between specific source and destination pairs, assuming rapid channel-switching capabilities (Kodialam and Nandagopal, 2005). Raniwala and colleagues have suggested a centralized approach to channel assignment and multi-path routing based on traffic loads, assuming non-switchable channels (Junior et al., 2022). Alicherry and the team has tackled the channel assignment and routing issue by considering interference constraints, aiming to allocate wireless capacity among clients to optimize network throughput (Appini and Reddy, 2023) & (Ramadhan, 2010).

1.5 Summary

This chapter has provided a comprehensive overview of WMNs and their routing protocols. It has intricately dissected the topology of WMNs, exploring the various routing mechanisms that underpin these networks. The chapter has illuminated the challenges that pervade WMN routing, underscoring the criticality of addressing these impediments to engineer efficient and reliable routing solutions. The AODV routing protocol and its discovery mechanisms have been exhaustively discussed, yielding a deep understanding of its functionalities and implications. These insights offer valuable guidance for network designers and researchers striving to create enhanced routing solutions tailored to meet the unique demands of WMNs.

The revelations from this chapter hint at the vast potential for future research and development in this field. Chapter 3, will systematically review enhancements to the AODV extension, meticulously analyzing the existing literature to unearth gaps and opportunities for further advancement in this domain.

2

Aim, Objectives and Methods

Aim

This dissertation primarily aims to focus on the innovation and introduction of an adaptive routing protocol, Utilizing both the AODV protocol and fuzzy logic. It begins with a critical evaluation of existing routing protocols within mesh networks, followed by an exploration of diverse techniques aimed at their enhancement. The overarching objective is to refine key performance metrics, including energy consumption, routing overhead, end-to-end delay, packet delivery ratio, node survival, packet loss ratio, and network throughput, specifically within mesh networks utilizing the AODV protocol.

Furthermore, this work aims to extend the network lifetime in Wireless Mesh Networks (WMNs). By introducing efficient routing mechanisms designed for energy conservation and other Quality of Service (QoS), the work aims to enhance the network's operational lifespan and ensure consistent performance.

To achieve this aim, the dissertation addresses several objectives.

Objectives

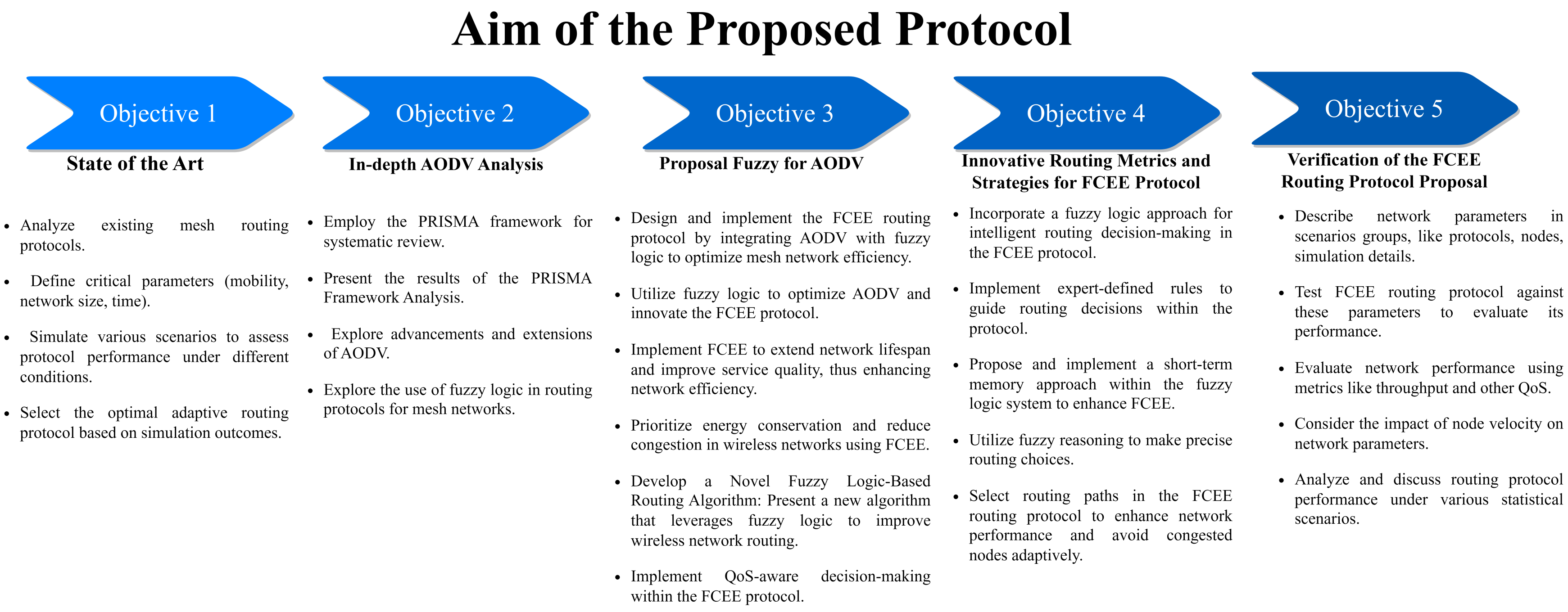
- **Objective 1 - State of the Art:** Conduct evaluations of prevailing mesh routing protocols across different scenarios, delving deep into the influence of critical parameters such as mobility, network size, and time. These evaluations aim to select the optimal adaptive routing protocol for superior performance enhancements under varying conditions. The outcomes from these simulations will be used to confirm the decision to select the routing protocols.
- **Objective 2 - In-depth AODV Analysis:** A novel investigation into the constraints and utilities of mesh routing protocols, focusing on the AODV routing protocol. Utilize the PRISMA Framework to systematically investigate the challenges, limitations, and utilities of the AODV routing protocol in mesh networks, providing a foundation for introducing an enhanced protocol.

- **Objective 3 - Proposal Fuzzy for AODV:** Innovate and introduce a highly efficient routing protocol for wireless mesh networks by integrating the AODV protocol with the Fuzzy logic approach, leading to the Fuzzy Control Energy Efficient (FCEE) Routing Protocol. This innovative protocol will be rigorously compared with the standard AODV and other prevalent modern routing protocols to underscore its performance and efficiency.

- **Objective 4 - Innovative Routing Metrics and Strategies for FCEE Protocol:** Propose a novel approach to introduce new routing metrics and path selection strategies. Lead to design strategies uniquely tailored to congested nodes, enhancing throughput and the other QoS parameters in mesh networks.

- **Objective 5 - Verification of the FCEE Routing Protocol Proposal:** Employ robust statistical methods and examine the node variety impact and gateway configurations to systematically analyze the simulation performance data to examine the proposed FCEE protocol. This will give insights into its scalability and efficiency in large-scale mesh networks.

Diagram 2.1, illustrates the objectives and methodology behind a proposed protocol aimed at enhancing wireless network routing. The five primary objectives encompass understanding the current state of routing protocols, an in-depth analysis using the PRISMA framework, introducing a novel approach combining AODV and fuzzy logic, proposing new metrics for path selection, and employing statistical methods to assess network performance. Each objective delves into specific strategies and outcomes, providing a comprehensive roadmap for the protocol's development and evaluation.



Aim of the Proposed Protocol

Objective 1

State of the Art

- Analyze existing mesh routing protocols.
- Define critical parameters (mobility, network size, time).
- Simulate various scenarios to assess protocol performance under different conditions.
- Select the optimal adaptive routing protocol based on simulation outcomes.

Objective 2

In-depth AODV Analysis

- Employ the PRISMA framework for systematic review.
- Present the results of the PRISMA Framework Analysis.
- Explore advancements and extensions of AODV.
- Explore the use of fuzzy logic in routing protocols for mesh networks.

Objective 3

Proposal Fuzzy for AODV

- Design and implement the FCEE routing protocol by integrating AODV with fuzzy logic to optimize mesh network efficiency.
- Utilize fuzzy logic to optimize AODV and innovate the FCEE protocol.
- Implement FCEE to extend network lifespan and improve service quality, thus enhancing network efficiency.
- Prioritize energy conservation and reduce congestion in wireless networks using FCEE.
- Develop a Novel Fuzzy Logic-Based Routing Algorithm: Present a new algorithm that leverages fuzzy logic to improve wireless network routing.
- Implement QoS-aware decision-making within the FCEE protocol.

Objective 4

Innovative Routing Metrics and Strategies for FCEE Protocol

- Incorporate a fuzzy logic approach for intelligent routing decision-making in the FCEE protocol.
- Implement expert-defined rules to guide routing decisions within the protocol.
- Propose and implement a short-term memory approach within the fuzzy logic system to enhance FCEE.
- Utilize fuzzy reasoning to make precise routing choices.
- Select routing paths in the FCEE routing protocol to enhance network performance and avoid congested nodes adaptively.

Objective 5

Verification of the FCEE Routing Protocol Proposal

- Describe network parameters in scenarios groups, like protocols, nodes, simulation details.
- Test FCEE routing protocol against these parameters to evaluate its performance.
- Evaluate network performance using metrics like throughput and other QoS.
- Consider the impact of node velocity on network parameters.
- Analyze and discuss routing protocol performance under various statistical scenarios.

Figure 2.1: Five-Step Framework for Wireless Network Protocol Enhancement.

Table 2.1, Provides an outline summary detailing each objective and its related chapter. Additionally, the table highlights the specific paper addressing each objective and pinpoints the chapter where the objective and research questions are discussed in depth.

Table 2.1: Overview of Objectives, and Chapter References.

Objective	Chapter	Publication
Objective 1	Chapter 1	[C1], [C2], [C3], [C4] & [C5]
Objective 2	Chapter 3	[B1] & [J2]
Objective 3	Chapter 4	[J1] & [J3]
Objective 4	Chapter 4	[J3]
Objective 5	Chapter 4, Chapter 5, Chapter 6, Appendix A, Appendix B & Appendix C & [B2]	

Used Methods and Tools

The methodology to enhance the Ad hoc On-Demand Distance Vector (AODV) routing protocol using fuzzy logic involves several steps, methods and tools.

- **Introduction to Fuzzy Logic in AODV:** The aim is to integrate Fuzzy Logic into the Ad hoc On-Demand Distance Vector (AODV) routing protocol to enhance its performance and adaptability in wireless mesh networks. Fuzzy logic offers human-like decision-making capabilities, allowing the protocol to perform better in dynamic networks. Integrating AODV with fuzzy logic and the memory channel results in a novel approach to the Fuzzy Control Energy Efficient (FCEE) routing protocol.

- **Development of the FCEE Routing Protocol:** (FCEE) routing protocol emphasizes energy efficiency and congestion management. By amalgamating the reliability of AODV with the energy rules and fuzzy logic approach, the resulting algorithm promises efficient routing. Depending on the packet type, the FCEE protocol employs fuzzy rules to determine its destination. Simulations in NS-2 were used to evaluate the proposal.
  - The FCEE routing protocol focuses on energy efficiency and congestion mitigation.
  - Intermediate Nodes: Concentrating on the energy capacity of these nodes on the transmission paths.
  - Metrics Used: Energy level and last broadcast are pivotal metrics for optimal data packet transfer paths.

- **Introduction of the Short-term Memory Channel:** A novel ”short-term memory” approach is proposed, leveraging crucial information like energy level and last broadcast to refine decision-making. This system retains relevant data to facilitate more informed decisions.
- **Evaluation of FCEE:** An accurate evaluation is executed to evaluate the effectiveness of FCEE against other modern routing protocols and the standard AODV.
  - Simulation Setup: The NS-2 simulator, known for its comprehensive documentation and efficacy, is configured. NS-2 models are developed to appraise the FCEE metrics within various routing protocols. Different simulation scenarios are run, tweaking parameters like node density, transmission range, and traffic type.
  - Performance Metrics: Several metrics, including Network Throughput, PDR, E-2-E delay, Nodes Survived, PLR, NRL, Average Energy Consumption, Goodput, and PDF are gauged. Detailed data is available in Appendixes (7.4, 7.4, 7.4) and scenarios (5.4.3, 5.4.3, 5.4.3, 5.4.3).
  - Statistical Analysis: Rigorous statistical techniques are employed to gauge FCEE’s performance under diverse conditions. Results, which are elaborated in 6 and Appendix 5.4.3, underscore FCEE’s superiority.
  - Data Interpretation: Post-simulation, PERL and AWK scripting languages, alongside statistical tools, are utilized for data analysis.
  - Large-Scale Testing: The FCEE path selection algorithm undergoes evaluation in a network framework of 60 and 100 nodes, different network sizes, different traffic patterns, different parameters evaluation, different node speeds, and different routing protocols to ascertain its scalability and robustness.

Tools and Software

This thesis utilized several advanced tools and software, each carefully selected to achieve the aims and objectives of the current work efficiently. These technological resources have been significant in data collection, analysis, and simulation, providing a robust foundation for the research. Detailed below is a comprehensive list of the software and tools deployed, which have been pivotal in facilitating a thorough investigation and enabling a subtle understanding of the subject matter during the examination.

Software

- NS-2.35
- C++
- MATLAB R2021a
- TCL 8.6
- Awk 4.1.3
- Perl 5
- SPSS Statistics V-28

Tools

- Cbrgen
- NAM
- Setdest

In addition, figure 2.2, illustrates a scheme depicting the relationships between various tasks and the tools and software utilized to accomplish them in network simulation and analysis of FCEE.

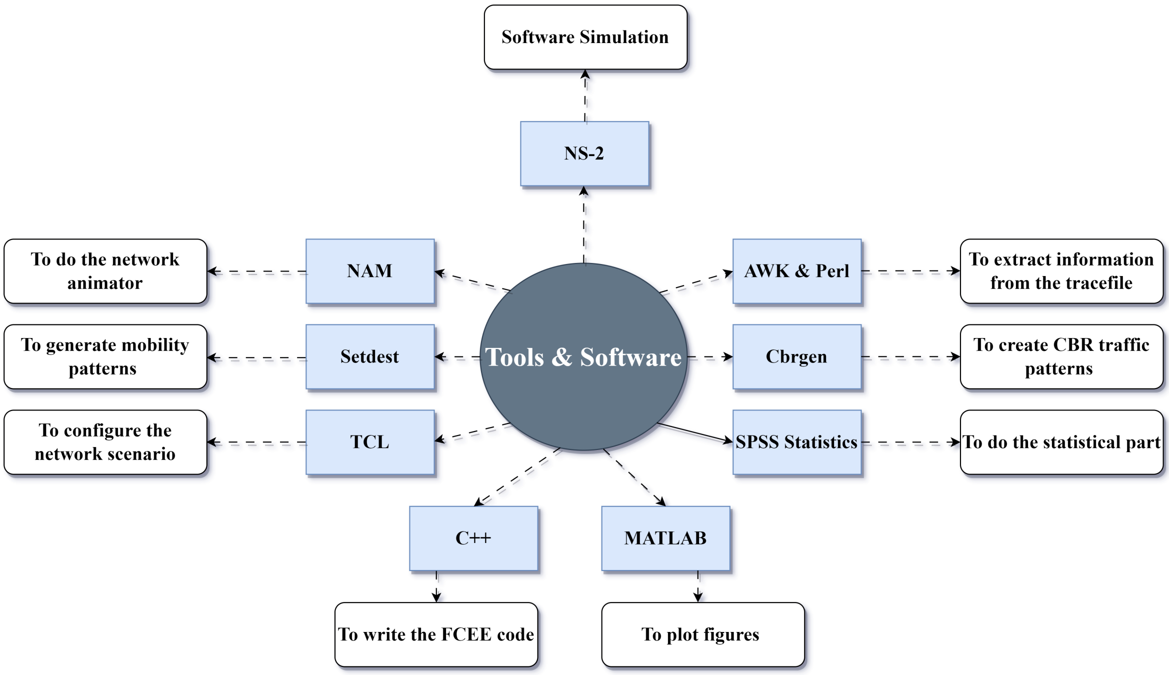


Figure 2.2: Mapping of Network Simulation Tasks to Associated Tools & Software.

3

An In-Depth Analysis and Discussion on the Extension of AODV Protocol

Contents

Overview

This chapter utilized significant scientific search engines, including ScienceDirect, Web of Science, and Scopus, as primary sources, to gain a comprehensive understanding of the subject. The selection of these sources aimed to include all major journals, conferences, and workshops relevant to the subject, acknowledged by the scientific community or deemed appropriate by publishers. The combined results from these databases yielded the examined papers, focusing on investigating AODV extensions using the PRISMA framework.

This resolution confers enhanced robustness upon the proposed research. It ensures the integrity of the selected scholarly articles, given that the thesis eschews the incorporation of grey literature such as preliminary reports, works in progress, technical notes, or presentation slides. These sources often present challenges in evaluating their scholarly merit, as delineated herein.

3.1 PRISMA Framework

The conduct of a systematic review within this thesis adhered to the highest academic standards, following the well-established Cochrane process. Employing the esteemed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, this thesis document meticulously captured and reported the essential components necessary for a comprehensive and transparent systematic review. The PRISMA framework, built upon the foundation of existing evidence and methodological best practices, provides a minimum set of requirements that must be meticulously addressed in systematic reviews and meta-analyses. This research endeavor ensured the integrity, reliability, and scholarly rigor essential for conducting a thorough and well-documented review by adhering to these guidelines.

In summary, this thesis's systematic review embodies the highest academic rigor standards, employing the Cochrane process and adhering to the PRISMA guidelines to investigate the AODV extension and find the gaps. By meticulously addressing each essential component and ensuring transparency and comprehensiveness, this research endeavor provides a robust and authoritative examination of the available evidence, making a valuable contribution to the present body of Information in the field. PRISMA methodology involves the following steps.

3.1.1 Protocol and Registration

This thesis followed the Cochrane process for a systematic review. It carefully selected and included relevant studies, extracted and combined data, and rigorously evaluated the quality of the studies. The systematic and transparent nature of the review process not only enhances the credibility and validity of the findings but also allows for replication and future research building upon this comprehensive foundation.

3.1.2 Identification Stage

The structured analytical process commenced with a meticulous exploration of scholarly works, as depicted in Figure 3.1, which illustrates the primary databases scrutinized for seminal literature on the Ad hoc On-Demand Distance Vector (AODV) protocol, complemented by exhaustive searches in the ScienceDirect, Web of Science, and Scopus databases.

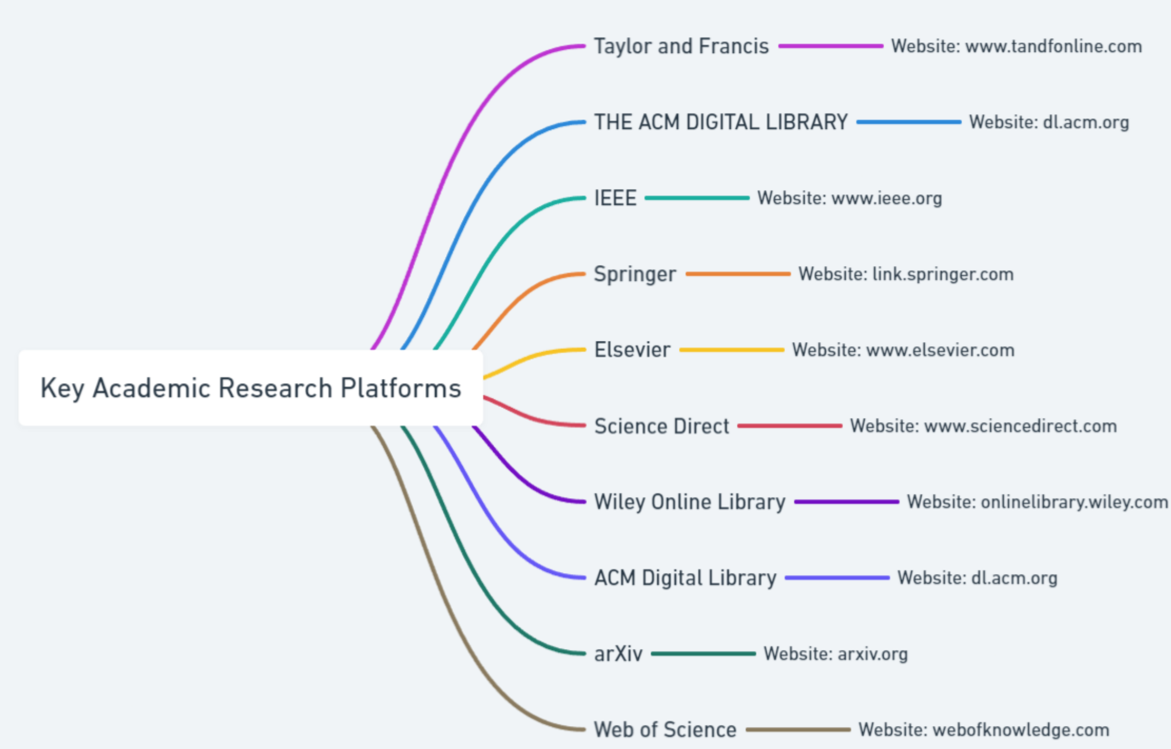


Figure 3.1: Academic Research Libraries and Databases.

The figure presents a meticulously crafted mind map that delineates a selection of paramount academic research databases pivotal for the scholarly community. Central to the diagram is the overarching title 'Academic Research Libraries and Databases,' which is the connection from which all branches flow. From this core are ten principal nodes, each signifying a distinguished repository of scholarly literature. These nodes are:

1. **Taylor and Francis:** A venerable institution in academic publishing, offering a vast repository of journals and articles across diverse disciplines.
2. **THE ACM DIGITAL LIBRARY:** The hub for computing and information technology literature, providing access to a wealth of conference proceedings, journals, and newsletters.
3. **IEEE:** A premier organization in the engineering domain, offering extensive resources, including standards, journals, and conference papers.

4. **Springer:** Renowned for its expansive coverage in science, technology, and medicine, Springer's database is a treasure trove of research papers and books.
5. **Elsevier:** A global leader in information analytics, Elsevier's platforms support many scientific and medical research initiatives.
6. **Science Direct:** Operated by Elsevier, this is a leading web-based science, technology, and medical research gateway, hosting a substantial corpus of publication content.
7. **Wiley Online Library:** An extensive store offering a broad range of scholarly resources across various scientific, technical, and medical fields.
8. **ACM Digital Library** The go-to digital collection for the computing and IT sectors, filled with a comprehensive selection of research papers and materials from conferences.
9. **ArXiv:** A freely available digital archive that houses a wide range of academic papers in physics, mathematics, computer science, and related quantitative fields.
10. **Web of Science:** A comprehensive research interface that connects users to several databases, supporting detailed investigation into scholarly works across multiple disciplines.

Non-peer-reviewed materials, such as conference summaries, drafts, and incomplete articles, were omitted from consideration. A systematic examination of the database inventories was undertaken. Experts in the field were categorized as researchers and contributors. For each database, the titles and abstracts of publications were scrutinized for keywords pertinent to the focal issues, specifically "AODV." The search yielded research papers penned in English from the year 1900 through 2022. The subsequent section delineates the precise criteria employed in the screening of the identified literature.

3.1.3 Screening Criteria

In the screening phase, each article was subjected to a thorough appraisal to ascertain its relevance for the systematic literature review. A panel of four scholars undertook this evaluation, each independently examining the content of the articles to decide on their suitability for inclusion—the curation of academic papers adhered to established search protocols. A collection of potentially impactful studies was compiled after excluding articles that contributed no novel insights. Further scrutiny of titles and abstracts led to the exclusion of research that did not meet the relevance criteria, yielding a distilled set of studies of critical importance. Excluded from this selection were documents whose recommendations were tailored to specific applications, thus lacking the broad applicability required for inclusion.

3.1.4 Eligibility Criteria

At the eligibility stage, a comprehensive evaluation of each article was performed. This thesis meticulously extracted and examined the recommendations posited within each study, along with the specific research conducted to substantiate these recommendations. Articles were excluded from this analysis if they presented design guidelines that were either excessively broad for the scope of this work or too complex for the researchers (coders) to interpret effectively.

Various data management tools were employed to maintain an organized record throughout the identification and screening processes. t the eligibility stage, a comprehensive evaluation of each article was performed. This thesis meticulously extracted and examined the recommendations posited within each study and the specific research conducted to substantiate these recommendations. Articles were excluded from this analysis if they presented design guidelines that were either excessively broad for the scope of this work or too complex for the researchers (coders) to interpret effectively. Various data management tools were employed to maintain an organized record throughout the identification and screening processes. Using Excel spreadsheets facilitated collaboration among the researchers, allowing for the efficient storage, retrieval, and annotation of information about the articles under review. This collaborative platform also supported the systematic analysis of the data.

3.1.5 Integration Stage

A rigorous qualitative assessment was conducted by the thesis to categorize the design guidelines more accurately and to prepare the coded data for addressing the thesis questions underpinning the systematic literature review. Although this study predominantly reviews Ad hoc On-Demand Distance Vector (AODV) research published since the early 20th century, it offers a contemporary overview of the field. It is evident from this investigation that literature on modifications to AODV routing protocols within Wireless Mesh Networks (WMN) and Mobile Ad hoc Networks (MANET) has seen a notable increase since the beginning of the 21st century.

Criteria for inclusion and exclusion were meticulously applied to distinguish between pertinent and irrelevant studies, incorporating all alterations to AODV routing protocols in WMNs into the sample framework. Additionally, this systematic review encompasses several recent contributions to AODV modifications in MANETs relevant to this discourse. The criteria were predicated upon specific research themes, alterations to AODV routing protocols in WMNs, the temporal span of publication from 1900 to 2022, and discernible user engagement rates, among other targeted factors. Implementing stringent guidelines for the inclusion and exclusion of studies guaranteed the selection of only the most relevant papers, facilitating a comprehensive analysis that remained faithful to the posed research questions.

Inclusion parameters were established with a precise research focus as a fundamental prerequisite, encompassing modifications to AODV routing protocols in WMNs, the scope of the study, and the availability of the publication report to the public within the specified date range. The qualitative analysis was primarily focused on the abstracts of papers that did not meet the inclusion criteria and were not subject to the exclusion parameters. The present work face a thorough vetting process to ensure compliance with the eligibility criteria.

3.1.6 Assessing Research Methodology and Quality

In the final data collection stage, the requisite information was meticulously compiled, and any discrepancies among the authors were deliberated and resolved. Consequently, the authors synthesized the findings of these articles. The interpretative analysis and categorization of the articles yielded a plethora of vital insights, which, in turn, laid the groundwork for numerous prospective initiatives and recommendations.

The thesis was conducted precisely, focusing on the alterations to AODV routing within wireless mesh networks. A significant challenge was the oblique representation of methodologies in the abstracts and method sections, necessitating adherence to the PRISMA framework.

Thus, the thesis necessitated a comprehensive examination of the full text of the papers to discern the specific methodologies employed in modifying the AODV routing discovery process pertinent to the requisites of wireless mesh networks. This section articulates the findings of our literature review concerning the initial research questions posed.

3.1.7 Results of PRISMA Framework Analysis

This section confirms the formal validity of the AODV protocol, encapsulating the findings in a representational summary. Furthermore, the subsequent segment of this inquiry conducts a thorough exploration of the methods employed in the organization and extraction of data, thereby extending the initial findings of the thesis.

3.1.8 Examination of Data Filtering and Extraction Processes

From an initial pool of over 1,000 articles, 627 were selected for preliminary scrutiny in the search and identification phase. These articles were methodically evaluated against the study's database criteria. An in-depth review of 175 full-text articles was then undertaken to discern their suitability during the eligibility assessment. This review led to the exclusion of 50 articles deemed too broad or vague to yield valuable insights into the modifications to the AODV routing discovery mechanics within wireless mesh networks.

The remaining 125 articles were identified as pertinent to the modification of AODV routing discovery mechanics in wireless mesh networks. After the information retrieval phase, as depicted in the PRISMA flow diagram, this collection was meticulously examined to distill data related to the modifications in AODV routing discovery mechanics in WMNs and the empirical validation of the design guidelines. After thoroughly evaluating titles and abstracts, 125 articles were deemed potentially valuable.

Figure 3.2, illustrates the PRISMA-based methodology employed in this thesis to elucidate the selection of relevant papers. This study builds upon interdisciplinary literature analysis in this domain, reviewing meta-analytical studies on mobile learning from the 1900s to 2022, thus providing an overview of recent research trends. The analysis indicates that modifying AODV routing discovery mechanics in wireless mesh networks is dynamic, with a steady increase in publications since the early 20th century.

Data were collected independently by this thesis, with any discrepancies resolved through consultation with a third analyst, ensuring a consensus was reached. The final data collection stage involved reconciling differences among the study's authors and compiling the selected articles. Through the translation and categorization of the papers, a multitude of critical insights were garnered. Consequently, a series of potential future projects and guidelines have been proposed. The thesis was conducted with due diligence, providing a robust foundation for modifications to the AODV routing discovery mechanics in wireless mesh networks. A challenge was the lack of explicit methodological descriptions in the abstracts and method sections per the PRISMA approach. This required a comprehensive review of the entire content of the articles to ascertain the precise nature of the modifications to the AODV routing discovery mechanics for the assessment criteria in WMNs. This meticulous part of the selection process was time-intensive but crucial to ensuring the relevance of the publications included.

The data gathering was conducted independently by the researchers, adhering to established protocols and meticulous record-keeping. Discrepancies were mediated through consultations with a third

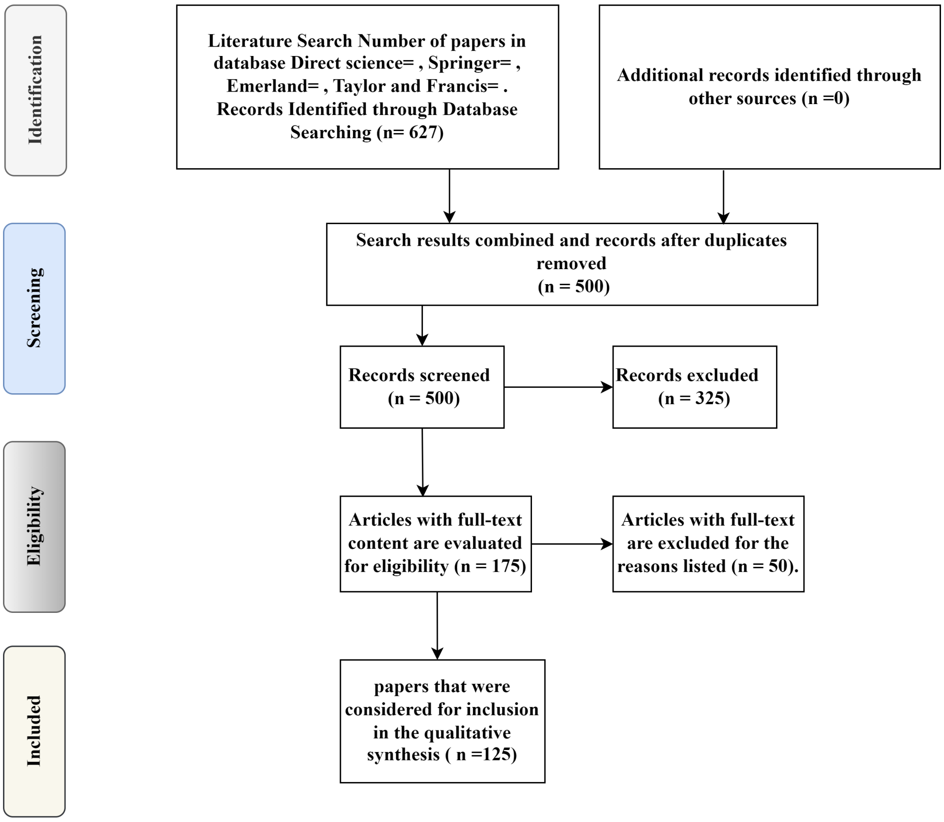


Figure 3.2: A Flow Diagram of PRISMA's Technique.

analyst, culminating in a unified agreement after thorough deliberation. In the concluding data acquisition phase, all necessary details were amassed, and any variances among the study's contributors were duly reconciled. Subsequently, the authors curated a compilation of 125 pertinent articles. This dissertation has encapsulated a wealth of critical concepts through the translation and organization of these documents. The subsequent segment elucidates the precise criteria and approach for selecting research studies.

3.1.9 Methodology for selection Studies

In constructing this dissertation, constructive feedback played a pivotal role in the meticulous development and refinement of the selection criteria for research papers. In alignment with the standards set forth by previous scholarly reviews, the studies were systematically categorized as either ”significant” or ”insignificant.” This splitting was based on clear criteria for what to include and leave out. These criteria considered how formal the literature was, explicitly leaving out informal reports, works in progress, technical notes, and presentations.

Furthermore, several articles were omitted due to their publication in indexes not recognized by the academic community. A discernible uptick in the volume of literature about the AODV protocol

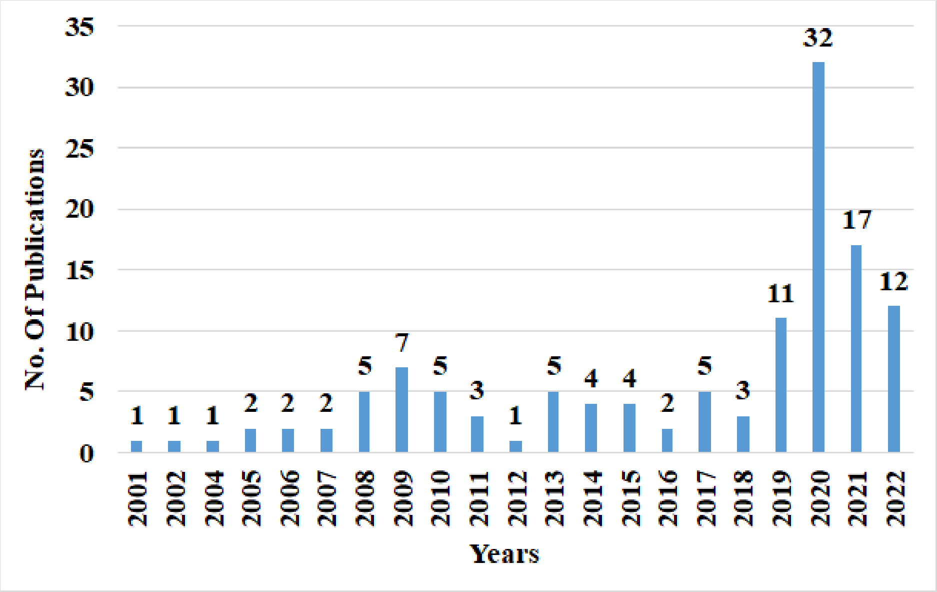


Figure 3.3: Selective Paper Publication by Years.

has been noted in recent times, as illustrated in Figure 3.3. It is essential to acknowledge that the data for the year 2022 might not be exhaustive, given the expected lag in indexing and the availability of publications from that year. The search, executed in June 2022, revealed that a substantial majority of the publications (N = 72 out of 125) had seen a significant rise in frequency from 2019 to 2022.

3.1.10 Routing protocol analysis

Peizhao Hu conducted a comprehensive analysis of the performance of simulated routing protocols, as documented in the study by (Hu, Pirzada, and Portmann, 2006). This examination involved a series of evaluations to determine the efficacy of the AODV protocol under varying conditions of mobility and network traffic. The initial evaluation adjusted the mesh mobility parameters from a standstill to a velocity of 20 meters per second, with a consistent transmission rate of 512 kilobits per second. The subsequent evaluation escalated the transmission rate incrementally from 256 kilobits per second to 4 megabits per second, while the velocity of the mesh clients was maintained at 5 meters per second. In the first scenario, the results derived from the NS2 simulator are denoted as AODV-NS2, whereas the outcomes from the testbed using the MNE are designated as AODVMNE.

In the scholarly work by (Alameri and Komarkova, 2022), the researchers conducted an assessment of the efficacy of various routing protocols within MANETs utilizing the NS-2 simulator. This evaluation employed mathematical-statistical methods to analyze the behavior of transmitted data and quantify the efficiency of the protocols based on simulation outcomes and the data set's standard deviation. The study incorporated several performance metrics that are also utilized in the current research, including packet drop rate (PDR), network throughput, and energy consumption. It was observed that the AODV routing protocol exhibited superior performance in terms of PDR, network throughput, and energy efficiency.

The Early Unidirectionality Detection and Avoidance (EUDA) framework enhances the efficiency and performance of routing in heterogeneous ad hoc networks by proactively identifying and circumventing unidirectional links. This advancement is particularly evident in the reduction of routing overhead and the minimization of end-to-end delay. The framework distinguishes itself from conventional routing protocols by offering improved throughput, reduced overhead, and decreased latency. Nevertheless, a significant challenge in current routing methodologies within heterogeneous ad hoc networks is the absence of robust mechanisms for the early detection and avoidance of unidirectional links. Traditional routing protocols frequently presuppose a uniformity in node characteristics, an assumption that often does not hold in practical environments. This discrepancy can lead to notable inefficiencies, manifesting as diminished throughput, increased overhead, and extended latency (Ko, Lee, and Lee, 2004).

While certain studies, such as those by (Suhaimi, Mamat, and Azzuhri, 2010), have proposed novel route recovery mechanisms for the AODV algorithm to address the challenge of broken links, these studies did not conduct a comparative analysis of the impact on network performance across various levels of node mobility, traffic load, and different sets of source-destination pairs, as originally delineated in the foundational AODV Request For Comments. The subsequent section delineates the local route recovery process of AODV as documented in these studies, providing a comparative evaluation and synthesis of the results. Suhazlan Suhaimi's research specifically scrutinized the AODV's performance in scenarios of connection failure attributable to node mobility, employing NS-2 simulations to investigate the subsequent route recovery procedures (Suhaimi, Mamat, and Azzuhri, 2010).

In the study by (Sarkar, Choudhury, and Majumder, 2021), the authors elucidate the correlation between the destination node, the source links of the tripartite agreements, and the density of nodes within a given network area. The research posits that the performance metrics of the Enhanced Ant protocol markedly surpass those of the conventional Dynamic Source Routing (DSR) protocol and the Ant Colony Optimization (ACO) algorithm (Sarkar, Choudhury, and Majumder, 2021). Furthermore, implementing an ACO-based routing enhancement expedites network operations within mesh networks effectively.

In the research by (Li and Peng, 2020), the investigators quantified the average communicative latency and the throughput across three distinct network configurations. The simulation established a fixed number of nodes within a specified area, from which a random assortment of source and destination nodes was generated. Subsequently, the network's connectivity was expanded to evaluate the communicative delays simulated by the three protocols, focusing on the augmented network's performance. The Ant protocol demonstrated a more pronounced effect in the simulations. The study proceeded to simulate the requisite transmission power for each protocol under varying network connectivity conditions, yielding results that indicated a superior rate of successful transmissions for the multi-path transmission protocol compared to standard network propagation methods. The Fortified Ant protocol exhibited promising performance, suggesting its potential for enhanced functionality within mesh networks. The findings revealed that the Fortified Ant protocol significantly outperformed the traditional Ant Colony Optimization (ACO) regarding connection establishment speed. The protocol demonstrated reduced end-to-end delays and improved packet delivery rates, outstripping the performance of both the AODV and AOMDV networks. The simulations were conducted to assess the influence of network scale, latency, and packet delivery efficacy on various routing protocols pertinent to Vehicular Ad-hoc Networks (VANETs), such as AODV, DSR, DSDV, and AOMDV, utilizing the NS-2 simulator. Simulation tools like NS3 and NS2 facilitated comparative analyses. Prior studies incorporated diverse mobility models to more accurately mirror real-world network scenarios. Examining various routing protocols provided insights into the optimal protocol selection for different network conditions across multiple scenarios (Li and Peng, 2020).

3.1.11 In-Depth Critical Analysis of Routing Protocols

In the domain of vehicular mesh networks, the distinctive attributes present considerable complexities in the routing paradigm. In light of the burgeoning Internet of Vehicles (IoV) landscape, alongside the emergence of autonomous and interconnected vehicular technologies, there arises a spectrum of innovative technological solutions catering to diverse service quality exigencies, which, in turn, engender intricate challenges in data transmission. To date, a multitude of routing protocols has been advanced to facilitate such networked interchanges. Protocols such as the Ad-Hoc On-demand Distance Vector (AODV), Dynamic Source Routing Protocol (DSR), Optimum Link State Routing (OLSR), and Destination-Sequenced Distance-Vector Routing Protocol (DSDV) are prevalent. This study conducts a rigorous examination of the AODV routing mechanisms tailored for Wireless Mesh Networks (WMNs) and their subsequent adaptations.

The investigation commences with an exploration of Wireless Mesh Network (WMN) architectures and the foundational principles of routing functions. WMNs have garnered considerable scholarly interest in recent years due to their promise of integrating a diverse array of wireless networks. Contemporary studies have focused on WMNs in the context of advanced communication systems driven by the demand for rapid and high-capacity content delivery. However, the protocols proposed for these networks have not been scrutinized to the same extent despite their potential to enhance the efficiency and reliability of mobile ad-hoc networks significantly.

The Ad-Hoc On-demand Distance Vector (AODV) protocol, characterized as reactive, is particularly suited to networks that require minimal computational resources and experience low traffic volumes. AODV's design minimizes overhead for nodes that are not active, which, while beneficial under light traffic conditions, becomes a liability as network load escalates. The absence of comprehensive network topology knowledge further impedes AODV's performance. Literature reviews indicate that traditional AODV's responsiveness and adaptability to dynamic information are limited. Consequently, this study reviews the literature to elucidate modifications to the AODV routing protocol within wireless mesh networks.

Earlier research has documented amendments to AODV to enhance the dissemination of route request messages, resulting in an augmented variant termed AODV EXT. This contrasts with probability-based approaches that assign a static likelihood to each node without ensuring total network coverage. The methodologies reviewed in prior studies and this paper advocate for reducing redundant re-transmissions along routing paths, borrowing from comprehensive range routing algorithms with node pruning techniques, thus ensuring connectivity and robustness in routing paths beyond what traditional wireless network protocols can guarantee.

This study's findings are juxtaposed with the routing protocol delineated by Maaza and Khelifa for the Energy Reversed Ad-Hoc On-Demand Distance Vector (ERAODV), which exhibits up to 1.7% increased energy efficiency compared to the conventional AODV Request EXT. AODV EXT demonstrates a data throughput enhancement exceeding 19% over the standard AODV and 10% over ERAODV. The research by (Khelifa and Maaza, 2010) also reveals that constructive agreement protocols underperform in more extensive networks, though they excel in smaller-scale communications. Conversely, reactive protocols exhibit superior performance in expansive network environments. Due to the significant costs associated with path discovery and node mobility, both protocol classes face challenges in vast mobile networks. Compared to traditional protocols, a hybrid approach, such as AODV, necessitates a strategy that precludes inefficient re-transmissions based on the transmitting node's vicinity densities, which have shown promising results. This research underscores the imperative for ad-hoc network protocols to be meticulously calibrated to accommodate varying traffic patterns and application requirements for optimal efficiency.

Drawing upon the systematic literature review and the Comprehensive analyses presented in this thesis, it is clear that the ad hoc On-Demand Distance Vector (AODV) routing protocol offers a range of advantages over other widely used protocols. AODV stands out primarily due to its exceptional scalability, efficiently managing large and diverse network topologies. Its design ensures loop-free routing, significantly enhancing the reliability and efficiency of data transmission paths. Moreover, AODV excels in rapid route establishment, a vital feature in dynamic network environments where quick adaptation is crucial. The protocol also adeptly supports unicast and multicast traffic, demonstrating its versatility. Additionally, AODV's approach reduces control overhead, optimizing network performance, especially in bandwidth-constrained environments. Its robustness in adapting to changing network conditions and its interoperability across various network configurations further highlight its comprehensive applicability and effectiveness as a routing protocol. Here are some of the main advantages of AODV:

- **Scalability:** AODV is highly scalable and well-suited for large ad hoc networks. It efficiently manages network resources by establishing routes on-demand, reducing overhead, and ensuring efficient network capacity utilization.
- **Loop-free Routing:** AODV guarantees loop-free routing through sequence numbers. This ensures that packets are routed along correct paths without encountering looping or inconsistency issues, enhancing the reliability and stability of the network.
- **Quick Route Establishment:** The Ad-Hoc On-Demand Distance Vector (AODV) protocol reduces the latency associated with route formation by utilizing a demand-driven discovery process. Upon transmitting data from a source to a destination, AODV activates a route discovery procedure that adeptly ascertains and institutes the most direct pathway connecting the source and destination nodes.
- **Support for Unicast and Multicast:** AODV supports unicast and multicast communication. It can efficiently establish routes for both types of traffic, allowing for effective communication among individual and group nodes in the network.
- **Reduced Control Overhead:** AODV minimizes control overhead by maintaining routing information only for active routes. It does not require periodic exchange of control messages throughout the network, which helps conserve network resources and reduces unnecessary communication overhead.
- **Robustness in Dynamic Environments:** AODV is well-adapted to dynamic and changing ad hoc network environments. It can effectively handle the mobility of nodes, link failures, and network topology changes, ensuring continuous connectivity and route availability.
- **Interoperability:** AODV's interoperability with other routing protocols makes compatibility with other devices and systems possible. Because of this compatibility, new devices can be easily added to and integrated into preexisting networks.

AODV generally presents a harmonious equilibrium among effectiveness, capacity to accommodate growth, and flexibility. It is a suitable alternative to ad hoc networks that exhibit fluctuating network conditions, dynamic topologies, and resource limitations.

3.2 Extensions of AODV: A Comprehensive Review

This thesis has precisely investigated the augmentation of the Analysis, Design, Optimization, and Verification (ADOV) framework by extensively exploring extensions and variants. These scholarly pursuits are predominantly anchored in specific methodological approaches that have been systematically engaged to refine the existing framework. The collection of proposed variants has been subjected to a meticulous analytical stratification, yielding ten distinct categories that span a wide array of domains, including quality, multipath, energy, security, and routing strategy. This categorization is founded upon a comprehensive compendium of techniques, each contributing to a refined comprehension of the complex and multifaceted nature of the ADOV framework.

In this section, a detailed analysis of prior studies focusing on the limitations of the AODV routing protocol is provided. The review of existing academic literature reveals several extensions and variants that have been proposed to enhance the ADOV framework. The proposed variants have been organized into fifteen categories, four of which are particularly pertinent to the research delineated herein. Figure 3.4, provides an illustrative representation of the common strategies employed in developing these ADOV extensions.

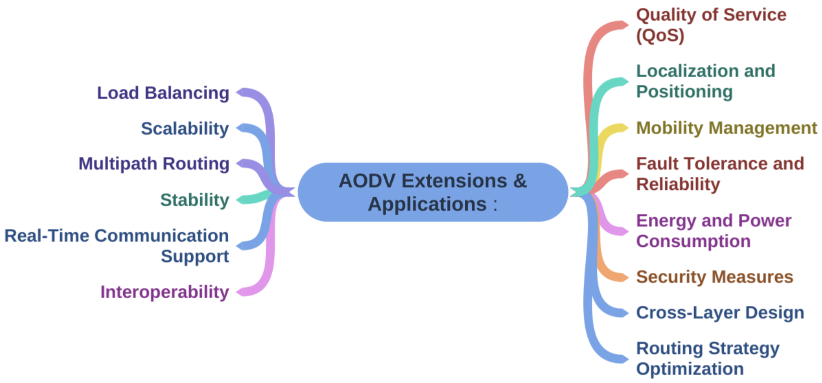


Figure 3.4: AODV Extensions Categories.

This section is based on analysing the AODV protocol and its extensions. This search report briefly overviews the AODV protocol utilized in WMNs and several research topics. Agents are small packets that move across the network, collecting data about networks and nodes. The study systematically examines Quality of Service (QoS), energy and power consumption, Routing Strategy Optimization, Dynamic Routing Discovery, and AODV stability. These domains involve various techniques and extensions, and those categories are related to the proposed work. Specific proposals might be classified under more than one category, underscoring the multifarious nature of these extensions within the context of the overarching ADOV framework.

3.2.1 Quality of Service (QoS):

Quality of Service (QoS) denotes the capability of a network protocol to differentiate and regulate diverse traffic streams following their distinct requirements. In the context of AODV, QoS enables the protocol to prioritize and allocate network resources to certain applications or data streams, improving performance. Protocols like Multi-Objective AODV (MOAODV), DPAODV, ERAODV, ABAODV, MAAODVACO, OAMAODV, OAODV, IPAAODV, QAODV, and others are proposed to improve QoS in AODV. QoS supports several levels of quality in the connection, like network throughput, delay, packet delivery ratio, jitter, etc.

MultiObjective AODV (MOAODV): This extension enhances MANET routing quality, dependability, and energy efficiency through various methods like MOAODV algorithm, Ant Colony Optimization (ACO) algorithm, and Bee Colony Optimization algorithm (Jinil Persis and Paul Robert, 2017). These methods combine multiple routing objectives using an arc meta-criterion function. In this study, various routing objectives are combined using an arc meta-criterion function, and Equation X is used to enhance the AODV routing protocol.

Energy ReverseAODV (ERAODV): The current research's outcomes may be juxtaposed with the routing mechanism delineated by (Khelifa and Maaza, 2010) known as Energy Reversed Ad-Hoc On-Demand Distance Vector (ERAODV), which demonstrates an enhancement of up to 1.7% in energy efficiency over the Ad-Hoc On-Demand Distance Vector Request EXT. Regarding data throughput, the AODV EXT variant exhibits an improvement exceeding 19% relative to the conventional AODV and surpasses the ER-AODV by 10%.

Agent-BasedAODV (ABAODV:) The extant literature delineates strategies for route restoration within the AODV framework in response to link failures. However, it does not adequately address the comparative significance of Quality of Service (QoS) across networks. The Agent-Based AODV (ABAODV) protocol, as proposed by (Bairwa and Joshi, 2020), facilitates the local management of trust information, thereby minimizing ancillary messaging and temporal delays. This protocol employs a multi-agent system at each node, comprising two monitoring agents and one routing agent, and introduces a novel algorithm for calculating trust values.

(Kurian and Ramasamy, 2021), introduced a trust-oriented secure routing mechanism that mitigates the trust scores of nodes engaged in flooding or non-cooperative behaviors. Practical simulations indicate that this approach diminishes the overhead associated with control messages by 4% and enhances the efficacy of service discovery by 13%.

ModifiedAODV (MAODV): Anantapur and Patil (Anantapur and Patil, 2021) have developed an Ant Colony Optimization (ACO)-enhanced secure routing protocol for Mobile Ad-hoc Networks (MANETs), which selects the most efficient route by evaluating four critical metrics: residual energy, trustworthiness, nodal degree, and distance. This ACO-refined AODV variant, termed Modified AODV based on Ant Colony Optimization (MAAODVACO), is designed to reduce latency and augment the Packet Delivery Ratio (PDR), while ensuring secure data transmission pathways that are resilient to blackhole attacks.

Optimized Adaptive Multi-path (OAMAODV): (Deepa, Krishna Priya, and Sivakumar, 2020) introduced an Optimized Adaptive Multi-path AODV (OAM-AODV) that enhances data transmission continuity by preemptively predicting link failures and seamlessly transitioning to an alternative optimal route. This proactive approach not only elevates the network's throughput by diminishing the frequency of route discoveries but also curtails the packet drop ratio by obviating the need for immediate route re-establishment after every link disruption.

OptimizesAODV (OAODV): Author optimizes-AODV protocol for Bluetooth Low-Energy (BLE) mesh networks. Standard BLE mesh networks typically use flooding for multi-hop communications, leading to network overheads and delays. The proposed Optimized AODV (OAODV) aims to make the protocol more efficient for BLE communication, reducing end-to-end delay and overheads. Despite the improvements, there are areas where the OAODV protocol falls short or could be further enhanced where the PDR of OAODV is lower than the mesh protocol, indicating a need for improvement in reliability (Ghori et al., 2021).

Improved Priority Aware AODV (IPAAODV): (Nallayam Perumal and Selvi, 2022), have developed IPAAODV, a protocol that addresses the challenges posed by the velocity of mobile nodes within a network, particularly when mobility exceeds 2 m/s. This protocol incorporates a dual-threshold mechanism: initially, it enforces a velocity cap to foster route stability, and subsequently, it implements a data rate threshold to prioritize high-importance data streams while suspending lower-importance streams when the cumulative bandwidth usage surpasses the set threshold. The empirical evidence suggests that IPAAODV surpasses both the conventional AODV and PAAODV in terms of throughput, packet delivery ratio (PDR), and end-to-end delay (EED). This is in contrast to existing priority-aware strategies that rely on connection-oriented methods, which tend to exhibit inconsistent throughput and increased latency as the velocity of mobile nodes rises above certain thresholds.

WAODV (WAITAODV): Checkhar et al. (Chekhar et al., 2021), introduced an innovative protocol known as WAODV (WAITAODV), which empowers nodes within a network with self-regulatory capabilities. Under this protocol, nodes autonomously determine whether to retransmit a Route Request (RREQ), discard it, or delay its broadcast based on the statistical data of neighboring nodes. This strategy is designed to reduce the frequency of broadcasts by certain nodes, thereby mitigating network congestion over time and enhancing the efficiency of the local recovery stage among neighboring nodes.

QoSDriven AODV (QAODV): (Avudaiammal, Vathsan, and Sivashanmugam, 2022), have directed scholarly scrutiny toward Quality of Service (QoS) within network protocols, proposing a QoS-oriented hoc on-demand Distance Vector (QAODV) routing protocol. This protocol integrates a power constraint factor alongside the distance metric. Empirical evaluations indicate a 14.28% enhancement in throughput, a reduction of 27.83% in latency, and an 11.6% decrease in packet loss when juxtaposed with the traditional AODV. The protocol operates by disseminating Route Request (RREQ) packets across the network, with each node updating power levels and hop count. Upon the retrieval of Route Reply (RREP), the destination node assesses the transmitting node's power, discarding routes that fall below a certain energy threshold. Selection for communication is conferred upon routes surpassing this threshold. Should the power of an adjacent node decline beneath this limit, the protocol initiates a fresh route discovery. This methodology presents a potential for expansion to encompass mobile nodes and aligns with the practical deployment of the AODV protocol as delineated in RFC 3561 (Perkins, 2004).

StableAODV (STABAODV): In their research, (Pandey and Singh, 2022) introduce an enhancement to the Ad-Hoc On-Demand Distance Vector (AODV) protocol for Mobile Ad-Hoc Networks (MANETs), termed StableAODV (STABAODV). This protocol innovates by incorporating a 'route stability factor', a novel metric derived from the count of active connections, to evaluate the dependability of a route. The STABAODV protocol utilizes this stability factor to select routes, aiming to augment the network's efficiency and diminish the incidence of route failures. Additionally, the protocol implements a mechanism to address route failures and curtail the volume of control messages required for route discovery. Simulation outcomes demonstrate that the STABAODV protocol surpasses the conventional AODV regarding packet delivery ratio, end-to-end delay, and routing overhead.

Signal StrengthBased (SSAODV): In the study by (Manjhi and Patel, 2012), the Signal Strength-Based Ad-Hoc On-Demand Distance Vector (SSAODV) protocol is introduced, tailored for Mobile Ad-Hoc Networks (MANETs). This protocol integrates a route selection algorithm that prioritizes signal strength and link quality to optimize network performance. It utilizes a predefined threshold to assess signal strength, thereby ascertaining the integrity of the links. Subsequently, it identifies the most effective transmission route by favoring paths with superior signal strength. A novel metric, termed the ”Neighbourhood Knowledge Factor,” has been developed to refine the route selection process, taking into account the number of nodes knowledgeable about the optimal route. Utilizing NS-2 simulations, the study benchmarks the SSAODV against the traditional AODV protocol. The results indicate that SSAODV surpasses AODV in metrics such as packet delivery ratio, end-to-end delay, and routing overhead. These findings underscore the SSAODV protocol’s potential to significantly enhance MANET efficiency by leveraging signal strength and link quality for more reliable route determination.

Intelligent Routing AODV (IRAODV): (Anand and Sasikala, 2019), have introduced an innovative routing protocol known as IRAODV, which is predicated on the establishment of routes on an as-needed basis. The protocol is designed to optimize network performance by prioritizing signal strength and link quality in the route selection process. It employs a predetermined threshold for evaluating signal strength to ensure the robustness of the links. The protocol then selects the most advantageous route for data transmission, choosing paths that exhibit the strongest signal. To enhance the route selection mechanism, a new metric called the ”Neighbourhood Knowledge Factor” has been formulated. This factor takes into account the quantity of nodes that possess information about the most efficient route, thereby facilitating a more informed route choice. Comparative analysis using NS-2 simulations positions IRAODV as superior to the conventional AODV protocol in terms of packet delivery ratio, end-to-end delay, and routing overhead. The empirical evidence from this study suggests that IRAODV holds promise for improving the efficacy of MANETs by utilizing signal strength and link quality as critical determinants for establishing more stable and reliable routes.

Probabilistic AODV (PAODV) protocol: The Probabilistic AODV (PAODV) protocol modifies the standard AODV protocol, designed to address network congestion issues (Nissar, Naja, and Jamali, 2015). Utilizing probabilistic techniques, PAODV determines whether a node should broadcast a RREQ packet. The protocol becomes particularly effective under increased network traffic conditions. In such scenarios, each node typically has multiple adjacent nodes, increasing the likelihood of discovering multiple routes. Consequently, the number of RREQ packets disseminated into the network decreases, alleviating congestion. This process is iteratively performed until the network reaches a less congested state. It is worth noting that the protocol initially introduces a higher level of delay due to the maximum probability of sending RREQ packets in a less congested network. The probability decreases as the network becomes more congested, reducing the protocol’s overhead.

Modification of AODV RREQ Mechanism: In the proposed modification to the standard AODV routing protocol, the Route Request (RREQ) mechanism undergoes significant changes to optimize network performance. Unlike the standard AODV, which broadcasts RREQ packets to all nodes, the modified scheme employs a node table to maintain information about hop nodes. This table enables the selection of a subset of neighboring nodes for message transmission, with the selection criteria dynamically adjusted based on service properties and application requirements. When the density of neighboring nodes meets specific conditions, each network node initiates an RREQ message. This selective broadcasting minimizes network congestion by reducing unnecessary transmissions. Upon receiving an RREQ packet, an intermediate node examines the packet's path list, where its path is highlighted. If the node is among those selected to forward RREQ packets, its path is included in the path list. This decision-making process considers the density of intermediate nodes, allowing RREQ forwarding only under specific criteria. The proposed modification reduces transmission overhead, particularly as neighbouring nodes increase. While this selective approach enhances the likelihood of achieving full network coverage, it does so at the cost of increased complexity (Nissar, Naja, and Jamali, 2015).

Neighbour PAODV (Nb-PAODV) protocol: A novel feature has been introduced in an extension to the PAODV protocol, resulting in the Neighbour-PAODV (Nb-PAODV) protocol (Bugarcic, Malnar, and Jevtic, 2019). This feature involves the addition of a specific parameter, denoted as 'p,' which governs the probability of rebroadcasting RREQ packets during the route discovery phase. The parameter 'p' is calculated using a formula, as the referenced study outlines. In the formula 3.1, Nb represents the number of neighbours for the node initiating the packet transmission. Since each node in the AODV protocol maintains a list of its neighbours in its routing table, determining the value of 'p' during runtime becomes straightforward. This probabilistic approach addresses the limitations of the original PAODV protocol. Specifically, the probability of rebroadcasting an RREQ packet is inversely proportional to the number of neighbours a node has. Therefore, as the number of neighbours increases, the probability of 'p' decreases, and vice versa. Importantly, this is not a sectional calculation; each node possesses its own 'p' and 'Nb' values, which are stored in the routing table.

$$p = 1/Nb \tag{3.1}$$

Enhanced Metric AODV (EM-AODV): The proposed metric introduces a robust framework for evaluating the stability of paths, incorporating three key parameters: "affinity," "available bandwidth," and "battery level." By integrating these parameters into the routing decision process, the EM-AODV protocol ensures enhanced performance. In order to achieve efficient load sharing, EM-AODV maintains multiple paths to the destination. Upon receiving route replies, the source node diligently computes the enhanced metric 'M' using the following prescribed formula in 3.2:

$$M_i = (A\text{„}min\text{''}^{i}) + (B\text{„}min\text{''}^{i}) + (BP\text{„}max\text{''}^{i}) \tag{3.2}$$

The calculation of the enhanced metric 'M' in EM-AODV incorporates parameters such maximum consumed battery power along the pat (BPi max), 'i', minimum affinity value along the path (Aimin), and minimum available bandwidth along the path (Bimin). This comprehensive metric aims to improve routing decisions by considering path stability and resource characteristics (Thanthry, Kaki, and Pendse, 2006).

AODV based on Link Failure Prediction (AODVLFP): Li et al. on (Li, Liu, and Jiang, 2008), developed an extension to the AODV routing protocol, AODV-LFP. This extension primarily focuses on enhancing the performance of network communications by significantly reducing latency and improving the efficiency of packet delivery. The objective of AODV-LFP is to optimize the routing process to minimize the time taken for data packets to travel from their source to their destination, thereby improving the overall responsiveness and reliability of the network.

However, the research conducted by Li et al. has certain limitations. One of the critical shortcomings is the lack of a comprehensive comparative analysis between AODV-LFP and the classical AODV protocol. Such a comparison is crucial to understanding the relative advantages or improvements that AODV-LFP offers over the standard protocol. Without this comparative analysis, it is challenging to gauge the effectiveness of the AODV-LFP extension in his scenarios and its potential impact on network performance. Moreover, the study does not delve into the potential limitations or drawbacks of the proposed protocol. Understanding the limitations is essential for network administrators and engineers when considering the implementation of this protocol in specific environments.

Table 3.1, provides a comprehensive summary of additional AODV extension protocols that are specifically relevant to this category.

3.2.2 AODV Energy and Power Consumption Extensions

DynamicPower AODV (DPAODV): The study by (Bamhdi, 2020) presents an enhancement to the Adaptive On-Demand Distance Vector (AODV) routing protocol, termed Density-Preserving AODV (DP-AODV), which incorporates transmission power control to modulate node density. This modification demonstrates superior performance metrics, including packet delivery ratio, reduced packet loss, and latency, when juxtaposed with the conventional AODV protocol. The research utilizes two-ray ground and freeway mobility models across different node densities (75, 100, 150, 200), pro-

Table 3.1: AODV QoS and Performance Extensions.

Source	**AODV Extensions**	**Optimization**	**Limitations**
(Avudaiammal, Vathsan, and Sivashanmugam, 2022)	QoS-AODV	Enhance QoS within a wireless mesh network	Potential inefficiency in routing discovery, where strict conditions on bandwidth and delay may lead to discarding possibly viable routes
(Kok et al., 2013)	EAOMDV-MIMC	improved Network's Lifetime	Increasing the average end-to-end delay, and the total energy consumed
(Li, Liu, and Jiang, 2008)	AODV-LFP	Reduced latency and enhanced packet delivery	Not providing a thorough comparison between AODV LFP and classic AODV, nor does it address the protocol's potential limitation
(Glabbeek et al., 2016)	Algebra-AODV	In this study, an enhanced variant of the AODV protocol, integrating the rules of Algebra for Wireless Networks (AWN), is presented and examined.	The authors abstract from timing issues, which means they cannot make claims on routing loops resulting from the premature expiration of routing table entries
(Tarapiah, Aziz, and Atalla, 2017)	AODV	The researchers investigated measurement instruments for protocols associated with two distinct mobility models, employing NS-2 VANET simulators for this purpose—an aggregate sum of packets transmitted across all nodes in the network.	this context refers to the need for comprehensive performance analysis of VANET networks, the limitations of existing routing protocols, and the potential for further research in areas such as energy consumption and the use of different simulators
(Hassan et al., 2021)	GEO-TAODV	Comparing the QoS terms	The presented scenarios lack a comprehensive and comprehensive protocol analysis
(Bamhdi, 2020)	DP-AODV	Enhance QoS performance	The challenge is represented by transmitting a packet at a given power without exhausting the connection link
(Khelifa and Maaza, 2010)	ER-AODV	Enhance QoS performance	The proposed protocol establishes routes based on minimum hop count, which can have a negative impact when the number of communications increases
(Dogra et al., 2018)	Queue-AODV	Reduced traffic	Congestion and packet dropping can cause retransmissions and lower network performance
(Mai, Rodriguez, and Wang, 2018)	CC-AODV	manage network congestion	Does not analyze the power consumption of the CC-AODV protocol compared to AODV. The study cites power consumption as a performance parameter but does not provide results or analysis
(Srivastava and Raut, 2019)	AODV+	Enhance QoS within a wireless mesh network	A lack of consistency, as evidenced by an increase in delay proportional to the number of nodes
(Duong et al., 2023)	RLI-AODV	Improved the QoS the protocol designed for 5G mobile MANET	High traffic loads, QoS requirements, and performance indicators like throughput, end-to-end delay, and SNIR may cause these constraints
(Ali, Abdalla, and Abbas, 2018)	MAODV	overhead controlling	Flooding route request (RREQ) signals to build routes increase network overhead
(Darabkh et al., 2018a)	MDA-AODV	A stable path reduces link breakage	Requires all nodes to have GPS and omnidirectional antenna, which may not be possible. Also, the proposed protocol performance to current techniques

viding robust evidence of DP-AODV's efficacy over the standard AODV through simulation results. The fidelity of these results is bolstered by the single-path transmission approach employed by both protocols, ensuring a realistic and precise analytical comparison.

The simulations, which encompassed diverse traffic and mobility patterns, revealed a consistent enhancement in packet delivery ratio with DP-AODV across all node densities, registering improvements ranging from 12% to 31%. Moreover, the protocol's dynamic transmission power management led to a noticeable reduction in packet loss rates and latency, with the latter experiencing a decrease from 54% to 52%. These improvements underscore DP-AODV's superiority in routing efficiency and reduced transmission delay compared to the standard AODV.

Despite these advancements, the study acknowledges certain limitations. The behavior of DP-AODV under multi-path transmission scenarios remains unexplored, and the protocol exhibits increased overhead with the scaling of network size. This overhead, which escalates with node density, warrants further investigation, particularly in scenarios with a high number of nodes. (Bamhdi, 2020) work calls for additional research to evaluate the protocol's overhead in relation to varying node densities, thereby providing a comprehensive understanding of DP-AODV's scalability and performance in more complex network environments.

Energy ReverseAODV (ERAODV): The findings of (Khelifa and Maaza, 2010), elucidate that while constructive agreement protocols may exhibit efficacy in communication, their performance is suboptimal within the context of expansive networks. Conversely, reactive protocols demonstrate enhanced functionality across extensive network topologies. The dualistic nature of these protocols, however, results in diminished performance in vast mobile networks due to the substantial costs associated with path establishment and node mobility. In contrast, the AODV protocol, a hybrid solution, has been recommended to mitigate such inefficiencies by precluding redundant transmissions based on the transmitting node's status. The research further reveals that adjusting the density of neighborhood nodes yields promising results. It is imperative, therefore, that protocols are meticulously calibrated to maximize efficiency within Ad-Hoc networks, tailored to accommodate diverse traffic patterns and application requirements.

HopPower(PHAODV): In their scholarly work, (Ket and Hippargi, 2016) introduced the Hop-Power based AODV (HPAODV), a routing protocol that adjudicates active route selection by considering dual criteria: the energy levels and the hop count of neighboring nodes. Upon rigorous testing and comparative analysis with the conventional AODV, the HPAODV demonstrated a marked improvement in reducing end-to-end delay. The protocols underwent evaluation under a variety of network conditions, encompassing diverse network scales and mobility velocities, wherein HPAODV consistently exhibited enhanced performance.

Power Aware HeterogeneousAODV (PHAODV): The authors of (Safa, Karam, and Moussa, 2014), proposed PHAODV to utilize available resources effectively. The protocol aims to achieve load balancing among heterogeneous networks by creating an optimized routing path that considers each sensor node's energy status. The routing path for data communication is determined by selecting the path from the existing routing table that minimizes energy consumption. Consequently, all sensor nodes continuously monitor the immediate fluctuations in energy levels. In addition, implementing a link-aware dynamic threshold mitigates the issue of route exhaustion and effectively decreases the occurrence of route error messages. Nevertheless, this particular protocol exhibits a higher level of overhead, resulting in potential energy depletion concerns within the network.

Energy Aware Routing Protocol(AODVEA): The paper of (Ket and Hippargi, 2016), introduces two modified versions of the AODV protocol, namely AODVEA (Energy Aware Routing Protocol) and AODVM (Modified AODV), to increase the network's lifetime by considering the nodal energy of each node before forwarding a Route Request packet. *AODVEA:* The protocol integrates a local forwarding mechanism predicated on a nodal energy threshold for intermediate nodes, and it adopts a routing strategy based on the max-min energy algorithm to optimize route selection. *AODVM:* The study conducts a comparative analysis of novel protocols vis-a-vis the established Ad-hoc On-demand Distance Vector (AODV), employing metrics such as network longevity, mean throughput, and mean latency. Findings indicate that the Modified AODV (AODVM) outperforms the standard AODV, delivering superior throughput and extended network durability, alongside reduced latency in comparison to the Enhanced AODV (AODVEA).

The paper identifies a gap in existing routing protocols, including AODV, where node energy threshold is not considered in making forwarding decisions, and routing is not based on node residual energy. This lack of energy consideration can lead to quicker energy depletion in nodes, reducing the overall network lifetime.

Improved gossipAODV (gossipAODV): In the realm of Mobile Low-Duty Wireless Sensor Networks (MLDWSNs), precise localization is of paramount importance. The study by (Bethi and Moparthi, 2022) introduces an enhanced version of the distance vector protocol predicated on a gossip-based mechanism. This refined protocol effectively obviates the transmission of superfluous data during node discovery. It adeptly addresses the complications engendered by clock drifts in nodes. Empirical evidence from the study indicates enhancements across various metrics, notably in the reduction of discovery delay, optimization of wake-up scheduling, and diminution of energy expenditure.

Modified AODV (MoAODV): In the scholarly work of (Pandey and Singh, 2021), a Decision Factor (DF) based Modified AODV (MOAODV) routing protocol is delineated. This protocol incorporates a decision-making algorithm predicated on two pivotal parameters: the residual energy of nodes and the signal power. To ascertain the energy status of adjacent nodes, 'Hello' messages are disseminated periodically. Upon receipt of such a message, a node will update its directory, contingent upon the sender's residual energy surpassing a predetermined threshold, thereby mitigating the superfluous dissemination of route requests. The dynamic nature of Mobile Ad-Hoc Networks (MANETs) is characterized by fluctuating topology, mobility, and scalability and is further constrained by factors such as node energy, latency, and reliability. Nodes within the network may assume various operational states—transmitting, receiving, idle, or sleep—with the transmission state being the most energy-intensive. Given that all nodes are powered by batteries with finite reserves, energy conservation is of critical importance.

Enhanced AODV (ENHAODV): (Pandey and Singh, 2022), elucidate a pioneering routing algorithm, ENHAODV, which prioritizes the selection of an efficacious route by evaluating the quality of both links and nodes during the route discovery phase. In this scheme, nodes are equipped with a registry of proximate nodes characterized by robust energy levels, thereby fostering the establishment of more stable routes within a Mobile Ad-Hoc Network (MANET) milieu. The ENHAODV protocol enhances the traditional 'Hello' packet system by incorporating additional data, including the sender's coordinates for distance computation and residual energy levels. Simulations corroborate that ENHAODV surpasses the conventional AODV in terms of throughput, packet delivery ratio, and normalized routing load, while concurrently diminishing delay.

In the realm of the Internet of Underwater Things (IoUT), which is burgeoning due to interests in oceanic exploration, security, industrial development, and military applications, (Bhattacharjya, Alam, and De, 2019) have proposed an energy-efficient Underwater Wireless Sensor Network (UWSN) architecture. The longevity of such networks is paramount, necessitating the design of energy-conscious systems that operate on minimal energy. This approach leverages multi-hop transmission and assesses the efficacy of various protocols, including AODV, Zone Routing Protocol (ZRP), and Interzone Routing Protocol (IERP), across different packet sizes. The evaluation metrics include average jitter, throughput, packet loss, energy consumption, and average delay, providing a comprehensive analysis of protocol performance.

This type of AODV extension can be classified under Energy Efficiency Optimization and Underwater Networking. The focus on energy-aware systems, multi-hop transmission, and the specific application to underwater environments places this work in a specialized category that combines energy conservation with the unique challenges and opportunities underwater communication and exploration presents.

Energy Efficient QlearningAODV (EAQAODV): In their 2022 study, (Joon and Tomar, 2022) introduce the EAQAODV protocol, an advanced routing mechanism that employs a Q-learning-based reward system to select cluster heads. This innovative approach to Ad-hoc On-demand Distance Vector (AODV) routing facilitates the determination of the most favorable path by considering many criteria, including residual energy, communication range, authorized channel access, hop count, and trustworthiness. The protocol is designed with the potential for adaptation to mobile nodes, and it presents an opportunity for future research to mitigate the interference effects associated with node mobility. The EAQAODV protocol is crafted to address the challenges of network longevity and performance within cognitive radio sensor networks. By leveraging a Q-learning algorithm for path optimization, the protocol demonstrates enhanced metrics regarding average end-to-end latency, energy efficiency, and overall network durability when juxtaposed with pre-existing methodologies.

Multi-Objective Simulated Annealing (MOSAAODV): The manuscript delineates the development of an enhanced Ad-hoc On-demand Distance Vector (AODV) routing protocol, termed MOSAAODV, which is predicated on the principles of multi-objective optimization via simulated annealing. This novel protocol is tailored explicitly for Ad-hoc networks, focusing on identifying optimal routing paths that concurrently address path congestion and robustness. The MOSAAODV protocol employs a dual-objective optimization framework, factoring in the inter-nodal distance, the traffic load on nodes, and the energy reserves of node batteries. It establishes fitness functions for both path congestion and robustness, with the overarching goal of prolonging the network's operational lifespan and enhancing resource distribution efficacy. Empirical analyses have demonstrated that MOSAAODV reduces packet loss rates and augments the longevity of paths, thereby contributing to an overall elevation in network performance (Wu, Wei, and Li, 2021).

FuzzyAODV: In the study by (Choudhary et al., 2022), a refined Ad-hoc On-demand Distance Vector (AODV) routing protocol is introduced, incorporating fuzzy logic to evaluate multiple parameters. These parameters include the residual energy of nodes, the anticipated longevity of links, node velocity, hop count, and bandwidth, all of which are integral to determining the most viable routing path. The trust metric, derived from these considerations, is instrumental in selecting subsequent nodes in the network. The probability of link failure is mitigated through this multi-metric fuzzy logic approach. A set of binary linguistic variables is employed to encode the five input parameters, while the output, representing the node's trust level, is categorized into five distinct linguistic values. The authors have constructed seven fuzzy logic rules for calculating the trust metric. The study acknowledges the potential for incorporating additional metrics and factors to refine this protocol in future research endeavors.

BiogeographyBased OptimizationAODV (AODV-BBO): The concept of this paper revolves around integrating AODV with Multiprotocol Label Switching (MPLS) to improve energy efficiency and reduce end-to-end delay in the network. AODV-BBO is a revolutionary method proposed in this research to construct an efficient route in an MPLS-MANET. This method combines Ad hoc On-Demand Distance Vector (AODV) with biogeography-based optimization (BBO) (Jayaramu and Banga, 2020).

The improvement for the routing network comes from the use of MPLS, which provides fast packet forwarding with better Quality of Service (QoS) and enables efficient data forwarding along with bandwidth reservation for traffic flows with different QoS requirements. The AODVBBO methodology further enhances performance by reducing the MPLSMANET's end-to-end delay and energy consumption.

Enhanced Power AwareAODV (EPAAODV): The concept of this paper revolves around the challenges and solutions in (Mafirabadza, Makausi, and Khatri, 2016). The paper discusses the issues of high end-to-end delay, network partitioning, and excessive power consumption in MANETs due to increased hop count and network organization changes. It also highlights the two main routing protocols implemented in MANETs, Reactive and Proactive, and their strengths and weaknesses.

The paper proposes several improvements to the routing protocol. For instance, it discusses the Transmission Power Approach and Load Distribution Approach to minimize energy consumption during active communication. It also introduces the Sleep/Power down method for energy consumption minimization during inactivity. Furthermore, the paper proposes using an EPAAODV protocol, showing a better packet delivery ratio, throughput, and less energy consumption than conventional AODV. However, the paper also identifies several gaps and weaknesses. One primary concern is the latency issue in reactive protocols. Additionally, many routing protocols focus mainly on latency and less on energy consumption, which can lead to nodes draining all of them. Tabel 3.2, summarize other AODV energy consumption extensions.

Table 3.2: AODV Energy Consumption Extensions.

Source	**AODV Extensions**	**Optimization**	**Limitations**
(Kanakaris, Ndzi, and Ovaliadis, 2011)	AODV-EXT	Improving throughput and packet drop rate	Further investigation is justified to comprehensively understand and analyze the aspects of energy consumption.
(Darabkh et al., 2018a)	MA-DP-AODV-AHM	Improve routing performance in VANETs by reducing control overhead, end-to-end delay, and energy consumption	The protocol's performance must be analyzed in numerous scenarios and conditions to discover shortcomings or opportunities for improvement
(Joshi and Biradar, 2021)	GEO-TAODV	Energy efficiency Improvement	The proposed protocols may have scalability and network size limits
(Damodar et al., 2018)	ENL-AODV	Improves the efficiency of the network and power consumptions	examines the minimum hop count when determining routes, without considering nodes' energy and load. This can cause unreliable pathways and inefficient network use
(Abu-Ein and Nader, 2014)	PH-AODV	Improve the network throughput and PDR	This study lacks to compare PH-AODV to the original AODV protocol based on performance parameters such as energy consumption
(Zhaoxiao, Tingrui, and Wenli, 2009)	EAODV	It improves packet delivery ratio, reduces average end-to-end time, and reduces routing overhead	Energy-aware routing technologies include EAODV. This effort neglects QoS, security, and scalability
(Chettibi and Chikhi, 2016)AODV-BBO	Enhance energy consumption	The performance of the P2R2 scheme is mainly dependent on the node's mobility	These limitations could potentially
(Mafirabadza, Makausi, and Khatri, 2016)	EPA-AODV	Minimize energy consumption	The latency issue in the proposed protocol

3.2.3 Routing Strategy Optimization and Dynamic Routing Discovery

The vitality of efficient routing strategies and dynamic routing discovery in the network is emphasized. We delve into strategies such as BypassAODV, AODVVD, ACOAODV, and NeighborhoodDensityAODV. These strategies optimize route selection by incorporating elements like link quality, energy consumption, congestion, and reliability. We emphasize the importance of dynamic routing optimization to cater to varying use cases, scenarios, and network requirements. The summary of the Routing Strategy Optimization of AODV extensions is presented in Table 3.3.

BYPASSAODV: A cross-layer approach involving the integration of AODV and bypass file is employed to enhance MAC-interaction in (Alshanyour and Baroudi, 2010). This design identifies packet transformation loss and triggers the local repair process within the routing layer. When a failure link repair occurs, the bypass setting is activated with the upstream node's permission, establishing a connection between the bypass and the downstream node among another node. This bypass system reduces the radius of typologies and routing overheads, addressing inherent problems in AODV, such as unnecessary error recovery, non-optimal reconstructed routes, and high routing overheads. This focus on routing strategy optimization through the proposed bypass mechanism results in increased goodput and a reduced packet drop ratio. In essence, BypassAODV aligns with the category of Routing Strategy Optimization, with no clear evidence that it fits within Multipath Routing.

The modification to the traditional AODV mechanism, as suggested in the referenced work, has led to the introduction of two-hop service information and renaming RREQ and RREP as SREQ and SREP, respectively. Certain parameters like energy, mobility, and message broadcasting affect Ad-Hoc network efficiency, and AODV's neglect of node energy in the route discovery process can lead to transmission failures and increased energy consumption.

AODV Velocity and Dynamic (AODV VD): The network overhead and route discovery control packages are reduced in another variation called AODV-VD in (Haider Alani and Alsaqour, 2020). Nodes are categorized as either reliable or unreliable based on an initial probability-based velocity vector. Reliable nodes are marked by their superior broadcasting capabilities. The AODVVD scheme builds upon the existing Ad-hoc On-demand Distance Vector (AODV) routing protocol. It introduces a dynamically probabilistic route discovery approach that selects reliable nodes to avoid link breaks and reduce congestion. The scheme minimises redundant retransmissions by utilizing exponential math functions to resolve probability values dynamically. It improves network performance regarding end-to-end latency, average throughput, packet transmission ratio, and overhead ratio. The paper identifies the challenge of broadcasting control packets in MANETs, leading to increased overhead and decreased network performance. Traditional AODV does not adequately address this issue, particularly in high-mobility scenarios. The paper also suggests future exploration of the proposed scheme with different reactive protocol types, such as DSR, and using different mobility models in various environments.

Ant Colony Optimization (ACO AODV): An extension to the Ad-hoc On-Demand Distance Vector (AODV) routing protocol incorporates the Ant Colony Optimization (ACO) mechanism to enhance routing in Mobile Ad-hoc Networks (MANETs) in (Nancharaiah and Mohan, 2014). This approach considers factors such as link quality, congestion, residual energy, and the number of hops for optimal route selection. The unique ACO mechanism, modeled after ant behavior in pathfinding, involves calculating a pheromone count value based on metrics like Received Signal Strength, Congestion, Residual Energy, and Hop-count. Despite its innovative approach, the proposal has certain drawbacks, such as disregarding energy conservation in route selection, leading to inefficient energy usage, and increased packet size due to appended path information, resulting in higher overhead.

Neighborhood-DensityAODV (NDAODV): In the context of Wide Area Networked Environments (WANETs), characterized by their dynamic and scalable nature, the Neighborhood Density AODV (NDAODV) protocol has been developed to mitigate the typically high overhead associated with such networks. NDAODV enhances the traditional AODV routing protocol by integrating the Expected Transmission Time (ETX) metric, prioritizing reliable transmission over mere hop count. This approach significantly curtails the Route Request (RREQ) process by factoring in the density of neighboring nodes. Empirical evidence within scholarly research demonstrates the process for calculating the optimal neighbor density. Comparative analyses between the NDAODV, standard AODV, and Probabilistic AODV protocols have been conducted, focusing on key performance indicators, including network overhead, Packet Delivery Ratio (PDR), throughput, and jitter(Malnar and Jevtic, 2022).

The paper introduces an improvement to the Ad hoc On-Demand Distance Vector (AODV) protocol, called Neighborhood-Density AODV (NDAODV), specifically designed for large-scale dynamic Wireless Ad hoc NETworks (WANETs). The improvement involves using Power Light Reverse ETX (PLRE) instead of the traditional hop-count metric to enhance reliability and reduce routing overhead.

Drone Assisted AODV (DA AODV): The burgeoning field of the Internet of Vehicles (IoV), an offshoot of the Internet of Things (IoT), is garnering increasing interest as technological advancements continue to evolve. Vehicle Ad-hoc Networks (VANETs) facilitate communication among mobile entities within an infrastructure-independent milieu. Unmanned Aerial Vehicles (UAVs), including drones, are being deployed for a myriad of applications ranging from surveillance and cinematography to security and environmental monitoring. In this context, Afzal et al. (2021) have introduced enhancements to traditional routing protocols, presenting Drone Assisted Destination-Sequenced Distance Vector (DADSDV), Drone Assisted Optimized Link State Routing (DA-OLSR), and Drone Assisted Ad-hoc

On-demand Distance Vector (DAAODV). These protocols were tested within simulated environments measuring 300 by 1500 meters and 300 by 6000 meters. The drone-assisted routing mechanisms demonstrated notable improvements in performance metrics when compared to their conventional counterparts (Afzal et al., 2021).

Trust Based Secure Multipath Routing AODV(TBSMR): The proposed TBSMR protocol extends the AODV protocol to provide secure and efficient routing in (Sirajuddin et al., 2021). It addresses congestion handling, secure routing through trusted nodes, multipath routing, and packet loss reduction. The improvement in this work is the integration of various properties into a single protocol to enhance the quality of service (QoS) in MANETs. By considering factors like congestion control, malicious node detection, packet loss reduction, and available battery power of nodes, the TBSMR protocol aims to improve the efficiency and reliability of packet transmissions. The TBSMR protocol falls under the category of QoS-based routing protocols for MANETs. It focuses on enhancing the QoS by addressing the limitations of the AODV protocol and incorporating features like congestion control, secure routing, multipath routing, and packet loss reduction.

One potential weakness or gap in this work is that it does not explicitly mention how the proposed protocol handles specific security attacks, such as black or wormhole attacks. While it mentions the need for secure routing through trusted nodes, further details on the mechanisms used to detect and mitigate these attacks would be beneficial.

Table 3.3: Routing Strateg Extensions.

Source	**AODV Extensions**	**Optimization**	**Limitations**
(Sirmollo and Bitew, 2021)	MARA-AODV	Enhance the routeing strategy of the network	This approach ignores nodes' redundant rebroadcasting packets, which may cause connection breakdown
(Yang and Liu, 2017)	GA-AODV	Enhancement of Network Performance	The modification improves average latency, packet received rate, and routing recovery frequency, but it does not solve genetic algorithm optimization limits or trade-offs
(Sherif and Salini, 2023)	Chimp-CoCoWa-AODV	The network route discovery and QoS has been improved	These algorithms' performance and scalability in diverse network conditions should be examined
(Sarkar, Choudhury, and Majumder, 2021)	E-Ant-AODV	Optimal path selection	Lack of emphasis on energy consumption
(Sirajuddin et al., 2021)	TBSMR-AODV	Path selection enhancement	Lack of emphasis on security attacks
(Afzal et al., 2021)	DA-AODV	Enhanced network efficiency with the assistance of aerial nodes	Implementation of the strategy by varying transmission ranges and grid sizes & Exploration of the impact of topological constraint changes

3.2.4 AODV Stability Extension

Stability, a crucial aspect of network performance, is explored in the context of AODV. Ensuring consistent and less frequently changing routes is challenging in dynamic networks. AODV Stability Extensions, encompassing Handling Mobility, Error Recovery, Balancing Overhead, Energy Efficiency, and Resilience to Attacks, are examined. We present extensions like RAODV, REMA, and AgentAODV that enhance route stability through factors such as active load, energy constraints, and mobility patterns. Table 3.4, summarizes AODV extensions in this aspect.

Reverse AODV (RAODV): In their seminal work, (Dsouza and Manjaiah, 2020) introduced the Reverse Ad-hoc On-demand Distance Vector (RAODV) protocol, which innovatively incorporates the active load of network paths during the route discovery phase, favoring the selection of less congested pathways. Distinct from the conventional AODV protocol, where Route Request (RREQ) messages elicit unicast Route Reply (RREP) messages from the destination node, RAODV employs a broadcasting approach for RREP messages. Given the highly dynamic topology of Mobile Ad-hoc Networks (MANETs), where nodes may spontaneously join or depart from the network, RAODV addresses the critical need to disseminate new route information promptly upon the integration of a node. However, this protocol must also contend with the potential for escalated network congestion, a consequence of the increased broadcast activity that accompanies the simultaneous joining of multiple nodes.

Regional Energy and Mobility Aware AODV (REMA): In their 2017 study, (Shi, Chai, and Liu, 2017) introduced the Regional Energy and Mobility Aware (REMA) routing protocol, which addresses the pivotal influence of energy limitations and node mobility on network lifetime and route stability within hybrid networks—factors often overlooked by traditional routing protocols. REMA judiciously selects network service routes based on regional energy reserves and the degree of node dispersion, with preference given to areas characterized by higher residual energy and lower dispersion levels, thereby contributing to an extended network lifespan. Additionally, the protocol evaluates node stability, favoring nodes with lower average mobility and minimal dispersion, as high mobility and dispersion are associated with increased link failures. The initial study was conducted using a single radio client, indicating the potential for future research to expand the protocol's application to environments with multiple clients.

AgentAODV (AAODV): Congestion-Aware Routing in MANETs: The paper modifies the RAODV routing algorithm known as CRAODV (Congestion Aware Reverse AODV) to enhance performance during the route discovery process. It does this by considering the active load of the path, thereby choosing a less congested route. The result is a decrease in packet loss and an improvement in throughput. *CRAODV:* This new protocol considers node mobility and congestion when discovering a route. It is designed to offer better throughput and packet delivery ratio while reducing delays during transmission. In essence, CRAODV represents an optimization over the traditional approach, and its effectiveness has been demonstrated in a small network environment.

Another innovative protocol discussed is AAODV, inspired by the well-known AODV protocol but with integrated features like Expected Transmission Time (ETT) and hop count. Unlike traditional protocols like AODV and DSR, AAODV uses agents to calculate the ETT of the route, taking both the ETT metrics and hop count into consideration. This holistic approach enables the selection of the most cost-efficient routes, significantly enhancing performance in terms of throughput and latency. Simulation results clearly show that AAODV surpasses traditional protocols (Nguyen et al., 2021).

The existing routing protocols in MANET, such as AODV and DSR, face challenges in achieving high performance due to the mobile nature of network nodes and the lack of reliance on central devices like base stations. The paper identifies a need for a more efficient routing protocol that can handle the unique characteristics of MANET, including rapid flexibility and self-configuration. The paper also acknowledges that the proposed protocol has not been thoroughly studied for energy consumption evaluation, indicating an area for future research.

Table 3.4: AODV Stability Extension.

Source	**AODV Extensions**	**Optimization**	**Limitations**
(Srivastava and Raut, 2019)	AODV+	Improves stability, packet losses, and end-to-end delay	AODV+ performance is inconsistent and delays as the number of nodes rises
(Huang et al., 2022)	AODV-NLS-ETX	Improves route stability	The ND-AODV-ETX protocol's link is less reliable than the AODV-NLS-ETX protocol, resulting in a negative trend in PDR during extensive speed change periods
(Yamarthy, Subramanyam, and Prasad, 2016)	MLR	refined the approach to minimize the average end-to-end delay and augment the Packet Delivery Ratio while concurrently diminishing the normalized routing load	integrated various traffic patterns and conducted scalable simulations to elucidate the impact of network dimensions and node quantity on the Machine Learning-based Routing (MLR) scheme

Traditional routing schemes often suffer from limited battery capacity, dynamic topology, and node mobility, leading to frequent link breakage and increased latency and routing overheads. Existing improvements to routing schemes have not adequately addressed the need for stable and energy-efficient routes.

With these advancements in routing protocols for MANETs, exploring the potential of fuzzy logic becomes crucial. Therefore, the subsequent subsection, ”Fuzzy Logic in Routing Protocols for mesh,” delves into applying fuzzy logic in addressing challenges and improving network performance through intelligent decision-making.

3.3 Fuzzy Logic in Routing Protocols for mesh

Fuzzy logic, an artificial intelligence subset, has seen a significant surge in application since its initial adoption by Japanese technologists, notably revolutionizing the electric industry with its capacity to address non-linear problems. Introduced by L.A. Zadeh, fuzzy systems have become a cornerstone in soft computing, finding extensive use across various industrial applications (Dernoncourt, 2013).

Within the domain of ad hoc networks, enhancing quality-of-service (QoS) metrics is imperative. QoS, a measure of network performance, encompasses parameters such as end-to-end delay, packet loss, and overhead and is critical for quantitatively improving network resources. The Fuzzyvan-QoS model, implemented across various protocols, is one such innovation aimed at elevating network QoS. In the architecture of networks, the allocation of priority and weights has been instrumental in refining the QoS of foundational systems (Mchergui, Moulahi, and Nasri, 2020).

Disruptions and unreliable routing frequently beset wireless mobile networks. In dynamic ad hoc networks, selecting a stable path is fraught with challenges due to the ever-evolving positions of nodes. The adoption of fuzzy logic in routing enhances network efficiency, with autonomous agents aiding in the identification of the most viable path. This approach has been juxtaposed with traditional AODV routing in a comparative study, demonstrating the efficacy of fuzzy systems in optimizing decision-making processes (Miri and Tabatabaei, 2020).

Fuzzy logic’s influence extends across various sectors, including control systems, uncrewed aerial vehicles (UAVs), electric machines, mesh networks, and communication channels, underscoring its role in product engineering and design. Beyond its technical applications, fuzzy logic’s principles of reasoning, akin to Boolean logic, are applied in medicine, business, automotive technology, and natural language processing, enabling professionals to navigate uncertainties with enhanced decision-making capabilities.

Given fuzzy logic's established significance and versatility, this thesis will delve into its specialized application within routing protocols, exploring its potential to refine and optimize network communications.

3.3.1 Fuzzy Logic Approach in Routing Protocols

Fuzzy logic emerges as a powerful tool in addressing the challenges posed by dynamic networks. This thesis introduces the concept of fuzzy logic and its applications in enhancing Quality of Service (QoS) metrics and energy consumption. The utilization of fuzzy logic in routing protocols is explored, highlighting its ability to make intelligent decisions in uncertain environments. The application of fuzzy logic in various routing scenarios, from optimizing link-state routing to improving cellular communication channels, underscores its potential for addressing challenges in mesh networks. Several studies in this subsection presented to show the effect of Fuzzy logic in this aspect, as shown below.

A study by the author (Rahmani et al., 2022), proposed a fuzzy logic-based AODV routing protocol that considers multiple parameters, including the node's residual energy, link expiration time, speed, hop count, and bandwidth, to determine the optimal path. The trust value computed based on these parameters guides the selection of the next node, reducing the likelihood of link failure. The fuzzy rule base for trust estimation employs binary linguistic variables for inputs and different linguistic values for the output. Further enhancements can be explored by considering additional metrics and factors.

Another approach presented in (Gowtham and Subramaniam, 2019), introduces a fuzzy logic-based routing mechanism for AODV, enhancing system stability. Trust values for intermediate nodes establishing routes between source and destination nodes are determined based on input variables such as remaining energy, speed, and hop count. Performance evaluation using the NS-2.35 simulator demonstrated that the proposed fuzzy AODV algorithm outperformed AODV and MBCR routing protocols regarding throughput, packet delivery ratio, average end-to-end delay, and average routing load, even in highly mobile environments.

To enhance the efficacy of the AODV routing protocol, the methodology proposed by Nihad Abbas employs a fuzzy logic framework, prioritizing nodes with superior credibility to ascertain the optimal routing path. Another proposed multipath protocol, Fibonacci Multipath Load Balancing (FMLB) (Abbas, Ilkan, and Ozen, 2015), arranges K distinct routes in rising order based on the required number of hops and assigns weights using the Fibonacci sequence. The number of packets transmitted through each path depends on the data size within the packet.

In the context of optimized link-state routing, fuzzy logic is incorporated into the FLBHITPEOLSR protocol (Vikkurty and Pallam Shetty, 2020), to enhance the transmission of the hello packet in communication channels. The proposed technique considers mobile network inputs such as size and mobility pattern to compute the hello interval time, resulting in improved delay, throughput, and load balancing. With the increasing popularity of 5G cellular communication in MANETs, a fuzzy logic-based activation strategy selection is employed to design the channel state information feedback method, adapting different traffic load management techniques and enhancing communication channels in cellular networks.

Fuzzy logic is widely used as a controller to evaluate route stability in MANETs. The proposed fuzzy systems utilize input and output variables for inference and fuzzification. For example, a fuzzy modified multipath approach using AODV routing controls data packets, discarding paths that are not utilized during communication. Heuristic-based routing, such as fuzzy-based on-demand routing, increases battery lifetime and channel stability (Sarao, 2018; Tabatabaei, Teshnehlab, and Mirabedini, 2015; Sireesha and Pallam Shetty, 2016). Studies comparing traditional routing protocols with fuzzy logic-based routing protocols consistently demonstrate the latter's superiority in parameters such as throughput, network delay, route discovery, packet delivery ratio, and routing overhead (Gunjan et al., 2020). Different simulation tools, including OPNET, NS2, and OMNET++, have been used in these studies. Additionally, fuzzy logic has proven valuable in solving the mobile vehicular routing problem, particularly in transmitting medical materials within hospitals. Experiments at Chang Gung Children's Hospital compare fuzzy methods with other programming techniques, showcasing the optimal solution fuzzy logic offers for addressing the weighted problem in Ad-Hoc networks (Sheng et al., 2006).

Overall, integrating fuzzy logic into routing protocols offers promising results for improving performance, stability, and efficiency in various network scenarios. With the demonstrated benefits of applying fuzzy logic to routing protocols, it is clear that this approach holds promise for addressing the challenges faced in mesh networks.

3.3.2 Limitations and Challenges of Using Fuzzy Logic in Routing Protocols

While applying fuzzy logic in routing protocols has proven promising results in enhancing network performance and adaptability, it is essential to examine the limitations and challenges associated with its use critically. This subsection provides a comprehensive overview of the drawbacks of incorporating fuzzy logic into network routing protocols (Alameri, Komarkova, and Al-Hadhrami, 2023). Specifically, it delves into issues related to computational complexity, scalability, compatibility with existing systems, accuracy, and resource overhead. Furthermore, it highlights the ways for future research to address these challenges, thereby offering a balanced perspective essential for any rigorous academic study.

- **Scalability and Real-world Applications**

  Fuzzy logic-based routing protocols often excel in simulated environments. However, the scalability of these protocols in larger, more complex real-world networks remains a subject of investigation. Factors like network heterogeneity and unpredictable environmental conditions pose challenges to the direct application of fuzzy logic.

- **Compatibility with Existing Infrastructure**

  Another challenge lies in the compatibility of fuzzy logic-based solutions with existing network infrastructures. Fuzzy logic systems may require specialized hardware or software adaptations, hindering their widespread adoption.

- **Accuracy and Reliability**

  Fuzzy logic allows for imprecision and deals well with uncertainty, but there's a trade-off between flexibility and accuracy. The use of linguistic variables and rule-based systems might sometimes lead to decisions that are not as accurate as those derived from precise mathematical models.

- **Resource Overhead**

  Implementing fuzzy logic in routing protocols introduces additional parameters and rules, increasing the size of routing tables and messages. This overhead can potentially negate some of the performance gains achieved through optimized routing.

- **Future Research Directions**

  Given these limitations and challenges, future research could focus on optimizing the computational aspects of fuzzy logic systems, developing scalable models, and assessing the reliability and compatibility of these systems in real-world scenarios.

3.4 Summary

This chapter provides a comprehensive systematic literature evaluation conducted to identify emerging research trends concerning the dynamics and modifications of the AODV routing discovery mechanism in wireless mesh networks. This study critically reviews the proposed extensions and modifications to the AODV routing protocol, providing an in-depth analysis of its key components. By synthesizing the existing body of knowledge, this systematic study reveals that the AODV routing protocol has been extensively investigated, demonstrating a thorough understanding of its functionalities and limitations.

Despite the substantial progress made in the evolution of the AODV protocol, several limitations persist in the newer versions. These include challenges related to broadcasting efficiency, inadequate path discovery, data packet duplication, longer routes, and limited control over information distribution. Furthermore, it has been observed that the related works suffer from network delay, energy consumption, and increased overhead due to the routing discovery operation. These findings underscore the need for further improvements and refinements to the AODV protocol, particularly in unreliable mesh networks with limited resources.

To address these limitations and enhance the overall performance of the mesh network, this study highlights the potential benefits of incorporating fuzzy logic techniques. Fuzzy logic, renowned for handling imprecise and uncertain routing metrics, offers a promising avenue for optimizing the AODV protocol.

By identifying the existing limitations and emphasizing the potential of fuzzy logic, this research highlights the need for further advancements in the field. Future directions can include improvements in the AODV routing protocol based on the fuzzy approach. Therefore, Chapter 4, explores the integration of fuzzy logic with the AODV routing protocol. This approach enhances adaptability and performance in dynamic networks, introducing the Fuzzy Control Energy Efficient (FCEE) routing protocol. Chapter 4, presents the framework's design, implementation, and evaluation, aiming to address the limitations of conventional protocols in wireless mesh networks.

4

Proposed Fuzzy Logic Enhancement for AODV

Contents

Overview

In the rapidly evolving domain of wireless mesh networks, the quest for efficient and reliable routing remains a paramount challenge. While traditional algorithms have made significant strides, they often challenge the uncertainties and dynamism inherent to these networks. This chapter delves into a modern approach that seeks to address these challenges by integrating the principles of fuzzy logic with the Ad-hoc On-demand Distance Vector (AODV) routing protocol.

Building on this foundation, the chapter explores the meticulous methodology behind the fusion of fuzzy logic with the AODV routing protocol. This integration promises enhanced adaptability and superior performance in dynamic network environments. Central to this chapter is the introduction of the Fuzzy Control Energy Efficient (FCEE) routing protocol. Appropriate for wireless mesh network architectures, FCEE is a testament to fuzzy logic's potential in revolutionizing routing protocols.

As the chapter progresses, it becomes evident that integrating fuzzy logic into wireless mesh network routing protocols is a technical endeavour and an exploration into replicating nuanced human decision-making processes in computer networks.

4.1 Fuzzy Logic-Based Routing Framework

The field of fuzzy logic systems is experiencing rapid expansion, marked by the emergence of new applications and groundbreaking results. Fuzzy logic, renowned for its ability to navigate uncertainties, has significantly bolstered routing protocols and services by facilitating complex logical operations.

Fuzzy logic, a form of reasoning that facilitates rational decision-making in the presence of uncertainty and imprecision, was conceptualized by Zadeh during the 1960s (Zadeh, 1965). At the same time, he was affiliated with the University of California. Since its inception, the fuzzy theory has undergone rapid evolution and widespread application. Diverging from computers that rely on precise numerical values represented as binary digits or Boolean logic, the human mind can engage in reasoning amidst ambiguous circumstances. Humans possess the invaluable trait of common sense, enabling them to navigate partially valid scenarios. By employing fuzzy logic, computers gain the ability to grasp elusive concepts, thus facilitating the development of technologies capable of discerning and assessing nebulous situations. In instances where predefined algorithms fail to dictate system responses, fuzzy logic assumes control, drawing upon its common-sense-like attributes. Before diving into the concepts of fuzzy sets, it's essential to understand the traditional binary perspective on set theory. A key component of fuzzy set theory is the membership function, which quantifies the degree of belongingness of an element to a set.

4.2 Fuzzy Sets and Their Corresponding Membership Functions

In the realm of classical set theory, the membership of an element within a set is treated as a binary concept: an element either belongs to a set or does not. However, the foundations of fuzzy set theory introduce a departure from this binary perspective, allowing for partial membership. Fuzzy set theory, an extension and generalization of classical set theory, also called crisp set theory, addresses this nuanced perspective. A crisp set, denoted as X in classical set theory, typically consists of a finite, countable, or uncountable collection of elements or objects, i.e., x X. Each element is assigned a binary membership status within the set. However, in practical contexts, the membership of elements in sets cannot be precisely delineated as a binary value of either 1 or 0 (Bose, Maulik, and Sarkar, 2024) & (Dubois and Prade, 1990).

Fuzzy set theory (FST) endeavours to express imprecise and uncertain information, overcoming the limitations of classical set theory. In the context of wireless mesh networks, representing concepts such as ”low energy” or ”high throughput” using conventional (classical) set theory becomes challenging. The fuzzy set theory offers a solution by introducing a membership function, quantifying the degree to which each element belongs to a set. A fuzzy set denoted as ’A’ within a discourse universe X is defined as follows in 4.1:

$$A = (x, \eta_A(x)) \mid \forall x \in X, \text{ where } \eta_A(x) \tag{4.1}$$

In the context of a doctoral thesis, it is imperative to establish that A(x) denotes the membership function of x concerning the fuzzy set A. This elucidation is further exemplified in Figure 4.1, which serves to represent the said membership function visually.

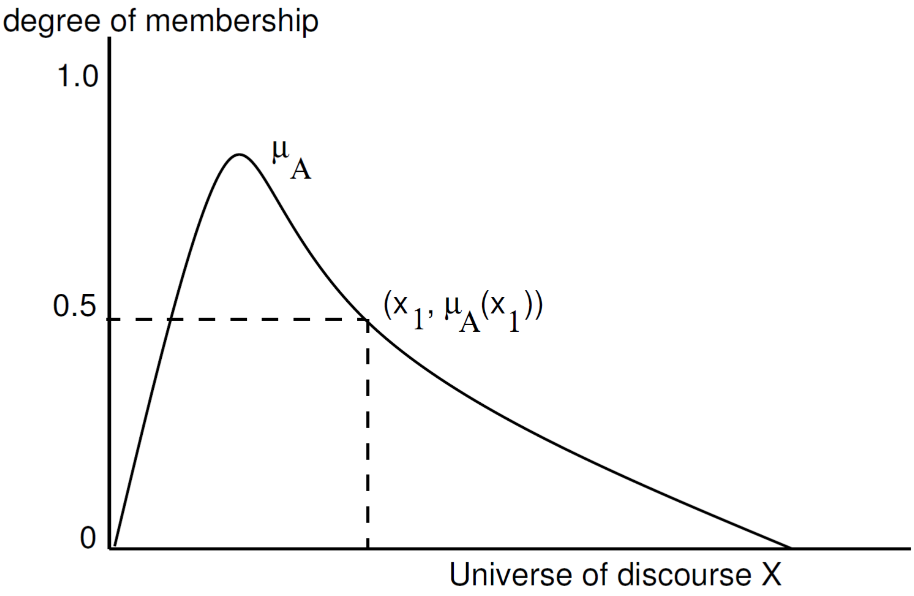


Figure 4.1: Membership Function of A.

While the theoretical foundations of fuzzy reasoning are rooted in mathematics, its practical applications are vast and varied, especially in computer networks.

4.3 Fuzzy Reasoning and Linguistic Variables in AODV

Building on this, fuzzy logic has been recognized as a mathematical framework specifically designed to formalize human reasoning processes. Fuzzy reasoning is rooted in the theoretical underpinnings of fuzzy sets, encompassing a wide range of disciplines, including Artificial Intelligence, information processing, and diverse branches of mathematics such as logic, graph theory, topology, and optimization. The application of fuzzy logic has witnessed a remarkable surge since the 1990s, spanning domains such as production, finance, marketing, and other decision-making contexts, as well as microcontroller-based systems in household appliances and largescale process control systems (Zhang et al., 2017) & (Carlsson and Fullér, 2001). When confronted with systems characterized by nonlinearities and the absence of reliable analytical models, fuzzy logic control has emerged as an immensely promising methodology. Undoubtedly, fuzzy inference represents a stride towards simulating human cognition.

Fuzzy logic techniques' primary advantage is the principles of fuzzy sets. They excel at addressing intricate, nonlinear, and vaguely defined problems. The efficacy of fuzzy sets resides in their capacity to encompass qualitative knowledge and expertise about system behavior and dynamics. This distinctive capability renders fuzzy logic systems indispensable in gaining a transparent and tangible qualitative understanding of systems that defy precise mathematical modeling. Moreover, fuzzy schemes can serve as enablers for other approaches or independently function as self-reliant methodologies, offering a plethora of alternative structures and schemes.

Furthermore, fuzzy logic emerged as a mathematical framework to formalize human reasoning processes. Unlike classical reasoning, which confines propositions to binary truth values, fuzzy logic employs the concept of linguistic variables and inference rules to establish a nuanced approximation of the truth. Linguistic variables pertain to variables whose values are expressed in natural or artificial language, encompassing words or phrases. In this linguistic context, domain experts have the flexibility to construct language rules, leveraging hedge words such as ”more,” ”many,” and ”few,” and connectors such as AND, OR, and NOT, among others. These constructs enable the formulation of language-based rules revolving around linguistic variables.

By incorporating linguistic variables and inference rules, fuzzy logic allows for a more comprehensive and refined representation of knowledge. At the heart of fuzzy logic lies its rules set, known as fuzzy rules, which play a pivotal role in achieving desired effects. It bridges the gap between formal mathematical expressions and the nuances inherent in human reasoning. When confronted with imprecise or ambiguous information, fuzzy logic provides a mechanism to capture the inherent vagueness and uncertainty. It enables experts to harness their expertise and encode it into a system that facilitates approximate reasoning.

The inference engine, a vital component of fuzzy logic, operates by employing these linguistic variables and rules to expedite the process of approximate reasoning. The inference engine facilitates efficient and effective decision-making using linguistic context and its associated constructs, even when precise quantitative measurements are lacking or difficult to ascertain.

In summary, fuzzy logic represents a significant departure from classical reasoning by accommodating linguistic variables and rules. This allows it to capture the richness and imprecision inherent in human cognition. It provides a robust framework for approximate reasoning and decision-making, empowering experts to translate their expertise into computational systems capable of handling complex and uncertain scenarios. The strength of fuzzy reasoning is particularly evident in its use of linguistic variables. These particular types of variables derive their values from words or phrases, which can belong to natural or artificial languages. Linguistic variables have several key attributes:

- It has a name
- It has a set of values
- Universe of Discourse, a set of all possible values
- Syntactic Rules
- Semantic Rules

4.4 Fuzzy Logic Operations and Rules

In the context of this thesis, fuzzy rules are formulated as ”if and else” clauses, capturing the established relationship between linguistic variables and their corresponding outcomes.

In order to ensure robustness and dependability, the fuzzy rules set adopted in this study is grounded in a wealth of communication experience. These rules, presented in Table 3, are meticulously constructed with domain experts’ valuable insights and expertise. By tapping into their profound knowledge, the fuzzy rules encapsulate the intricate nuances of the problem domain, allowing for effective decision-making and reliable system performance. Formulating fuzzy rules is a meticulous process that draws upon practical experience and rigorous simulation experiments. These independent rules serve as a guiding framework, facilitating achieving desired outcomes. Through the sound design and selection of fuzzy rules, the system can harness the collective wisdom of domain experts, combining it with computational capabilities to effectively address the complexities inherent in the problem at hand.

Overall, applying fuzzy rules within the fuzzy logic framework empowers this thesis to deliver high reliability in problem-solving. By harnessing the insights and experiences of experts, the chosen set of fuzzy rules serves as a robust foundation for decision-making, enabling the system to navigate complex scenarios and deliver accurate and dependable outcomes.

4.4.1 Fuzzy Logic: Bridging the Gap in Decision Making

Unlike binary logic, which deals in absolutes (true or false), fuzzy logic accommodates degrees of truth. This is particularly beneficial for wireless networks, where conditions are in constant flux, and decisions often lie in the gray area. The following subsection gives an overview of the fuzzy logic system in a computer network.

4.4.2 Fuzzy Logic System

Fuzzy logic has been widely applied across diverse domains, such as aerospace, medicine, and computer networks. This doctoral thesis presents an innovative, intelligent routing mechanism employing fuzzy logic for dynamic topology networks. The devised system seamlessly integrates fuzzy logic principles with a memory channel to ensure the delivery of high-quality services within mesh networks. The fundamental constituents of a typical fuzzy logic system encompass a Fuzzifier, Knowledge Base, Inference Engine, and Defuzzifier (Hamd et al., 2023).

This thesis revolves around developing an intelligent routing mechanism grounded in fuzzy logic tailored to address the intricate challenges posed by dynamic topology networks. In these networks, effective traffic management is indispensable due to the diverse range of supported services and the imperative for efficient resource utilization.

To ensure the stipulated quality of service, two pivotal functions, namely fuzzy logic and a memory channel, were harnessed within the mesh network architecture. Empirical findings substantiate that the performance of the proposed mechanism surpasses that of conventional routing algorithms. Figure 4.2, graphically represents the fuzzy logic-based control system, elucidating the core components.

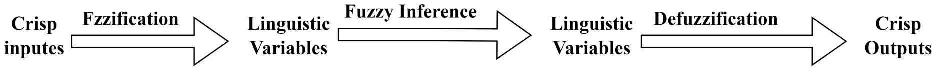


Figure 4.2: Fuzzy Logic System Architecture.

- **Fuzzifier:** For my doctoral thesis, I have employed a fuzzifier module, which is designed to transform traditional crisp data inputs into their corresponding fuzzy sets, enabling the subsequent application of fuzzy logic methodologies.

- **Fuzzy Rules:** The knowledge base stores all the fuzzy rules, which consist of if-then statements or user-defined directives that guide the decision-making process.

- **Inference Engine:** The pivotal element of the fuzzy logic system is the component responsible for mapping the outcomes to the input set and determining the applicable rules for specific inputs. The process involves determining the percentage of conformity between the input provided and the established rules. The inference engine handles the deliberation and selection of a course of action. The result of the inference engine is a fuzzy set.

- **Defuzzifier:** It transforms the fuzzy set into traditional crisp values again. The present model represents the antithesis of the Fuzzification procedure. The fuzzy sets that are produced by the interface engine are subsequently transformed into precise numerical values. The crisp values obtained represent the outputs of the fuzzy logic system.

The architecture of the Fuzzy Logic System is both accessible and comprehensible. The algorithms can be succinctly characterized with minimal data input, resulting in low memory usage. These inherent advantages establish the application of fuzzy logic system techniques as an optimal choice for facilitating the decision-making process.

4.4.3 Proposed Architecture of Fuzzy Control Energy Efficient (FCEE) Routing Protocol

Fuzzy logic has been integrated into enhancing the Fuzzy Control Energy Efficient (FCEE) Routing Protocol, with a specific emphasis on assessing the energy reserves of intermediary nodes within the transmission routes. The routing path is meticulously chosen based on predefined criteria to optimize both the network's lifespan and its quality of service (QoS). In the context of mesh networks, an effective routing strategy involves the identification of the most efficient transmission paths, extending the network's operational duration.

To achieve this objective, two crucial metrics, namely energy levels and the history of prior broadcasts, are employed to select optimal routes for data packet transmission. This selection process primarily concerns the comprehensive evaluation of the cumulative energy capacity available among the intermediary nodes along these designated paths.

4.4.4 Proposed Short-term Memory Channel Based Fuzzy Logic System

The FCEE routing protocol significantly enhances wireless mesh networks, addressing congestion and energy efficiency concerns. By integrating fuzzy logic, the protocol can handle uncertain and dynamic network conditions. A novel ”short-term memory” approach is proposed to augment the system’s decision-making, using critical information like energy level and last broadcast.

The proposed architectural framework is then implemented atop the existing AODV routing protocol. The FCEE routing protocol is a pivotal contribution to wireless mesh networks, addressing the challenges associated with congestion and energy efficiency. By incorporating fuzzy logic principles, the protocol exhibits the capability to handle uncertain and dynamic network conditions, thereby enhancing the overall performance and reliability of the network. A short-term memory approach is introduced to further enhance the fuzzy logic system’s efficacy. This innovative mechanism enables the system to retain and utilize relevant information, such as energy level and last broadcast, facilitating more informed decision-making processes. Figure 4.3, represents the overview of the short memory approach. Incorporating short-term memory within the fuzzy logic framework empowers the system to adapt to evolving network dynamics, ultimately improving routing efficiency and congestion management.

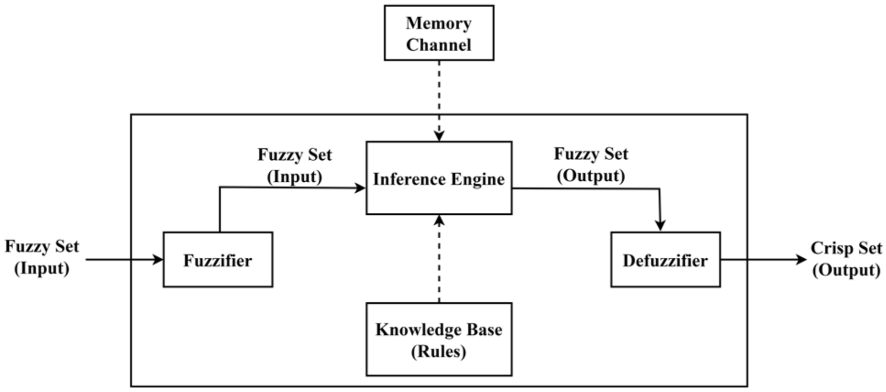


Figure 4.3: Proposed Memory Channel Based Fuzzy Logic System.

Subsequently, the proposed architecture is seamlessly integrated into the widely employed AODV routing protocol. This integration leverages the strengths of the FCEE and AODV protocols, synergistically combining their functionalities to attain a more robust and efficient routing solution. Through this integration, the thesis establishes a comprehensive framework that harnesses the advantages of fuzzy logic and builds upon the existing foundation of the AODV protocol, culminating in a sophisticated routing mechanism tailored to wireless mesh networks.

The presented thesis introduces the FCEE routing protocol, augmented with a short-term memory approach, and successfully integrates it with the AODV routing protocol. This endeavour contributes to advancing routing techniques in wireless mesh networks, offering improved performance, adaptability, and congestion management capabilities.

In the conceptual model advanced within this research, a memory channel is employed to preserve and manage the node's state information. Specifically, this thesis adopts the broadcast packet parameter as a critical component of the node's state representation. Given the primary objective of designing a congestion-tolerant routing protocol, it is crucial to acknowledge that broadcast packets significantly influence network throughput and can serve as a prominent source of congestion and packet loss within any given network context. To address this challenge, the proposed model leverages the node's remaining energy level and the information about the most recent broadcast packet transmission as crucial decision-making factors. By assessing these parameters, the model determines whether the node should be responsible for forwarding the broadcast packet or abstain from doing so. In essence, the integration of fuzzy logic principles guides the inference engine's decision-making process, enabling the establishment of a coherent and contextually informed routing protocol.

To expound on the specific decision rules employed by the inference engine, Table 4.1, outlines the fuzzy rules harnessed within the proposed model. These rules serve as a guiding framework for the inference engine, facilitating the interpretation of the node's state information and informing the ultimate decision regarding forwarding broadcast packets. By adhering to these carefully crafted fuzzy rules, the model attains an adaptive and congestion-aware routing mechanism, enhancing the overall robustness and performance of the network.

Incorporating a memory channel and utilizing the broadcast packet parameter as state information epitomizes a critical facet of the proposed model. Through the intelligent application of fuzzy logic and the utilization of well-defined fuzzy rules, this thesis endeavors to devise an innovative congestion-tolerant routing protocol that optimizes network performance, mitigates congestion-related issues, and safeguards against packet loss in wireless mesh networks.

Table 4.1: Fuzzy Rules.

Rules	Energy Level	Last Broadcast	Decision (Forward Broadcast)
Rule 1	High	Yes	Yes
Rule 2	High	No	Yes
Rule 3	Good	Yes	No
Rule 4	Good	No	Yes
Rule 5	Average	Yes	No
Rule 6	Average	No	Yes
Rule 7	Low	Yes	No
Rule 8	Low	No	Yes

Dynamic Thresholds: By introducing dynamic thresholds, the protocol enables more informed routing decisions, reducing congestion and enhancing network efficiency.

4.4.5 Fuzzification

As depicted in Figure 4.3, the fuzzifier module is pivotal in facilitating the fuzzification process by leveraging the membership function outlined in Equation 4.2. This equation serves as the key determinant for evaluating the membership level of each node. In the context of this thesis, the establishment of four linguistic variables, namely (i) high, (ii) good, (iii) average, and (iv) low, enable a comprehensive expression of the node's energy level. The formulation of Equation 4.2, is provided below, wherein scalar values such as 'p', 'q', 'r', and 's' play a crucial role in precisely configuring the membership function. Specifically, 'p' and 'q' form the trapezoid's base, while 'r' and 's' shape its upper section. Incorporating these scalar values ensures the accurate representation of the energy level membership.

$$\mu(x) = \begin{cases} 0 & \text{if } x \leq p \\ \frac{x-p}{r-p} & \text{if } p \leq x \leq r \\ 1 & \text{if } r \leq x \leq s \\ \frac{q-x}{q-s} & \text{if } s \leq x \leq q \\ 0 & \text{if } q \leq x \end{cases} \tag{4.2}$$

The thesis presents a tabulated representation of the fuzzification process in Table 4.2, guiding the precise definition of the steps involved and establishing a systematic framework for evaluating node energy levels.

Table 4.2: Fuzzification.

Remaining Energy (RE)	**Energy Level**
If a node has RE greater than 75%	High
If a node has RE greater than (or equal to) 50%, and less than 75%	Good
If a node has RE greater than (or equal to) 25%, and less than 50%	Average
If a node has RE less than 25%	Low

The presented thesis employs the fuzzifier module, augmented by the membership function encapsulated in Equation 4.2, to undertake the essential fuzzification process. As this thesis outlines, incorporating linguistic variables and scalar values empowers researchers to effectively capture and represent the node's energy level within the fuzzy logic system (FLS). The tabulated format, furnished in Table 4.2, is a comprehensive reference, ensuring consistency and accuracy throughout the fuzzification process. Figure 4.4, shows the Membership function for the Proposed FLS of the energy levels.

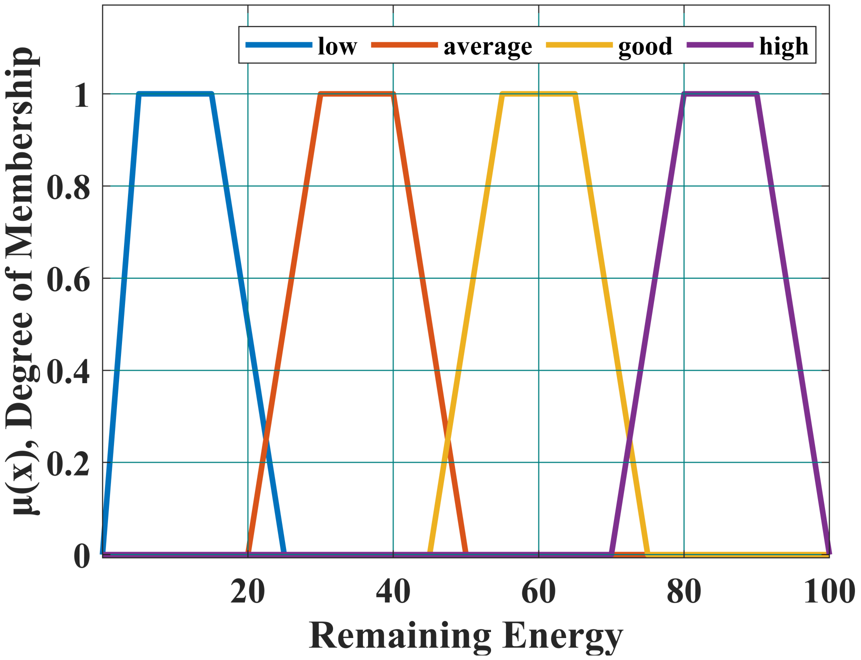


Figure 4.4: Membership Function for Proposed FLS.

4.4.6 Defuzzification Methods

Fuzzy rule-based systems analyze linguistic if-then rules through a sequence of operations, including fuzzification, inference, and composition. These operations yield fuzzy results, necessitating a subsequent transformation into precise, crisp outputs. To achieve this transformation, the process of defuzzification is employed. Defuzzification converts the fuzzified output into a singular crisp value corresponding to a specific fuzzy set (Chakraverty, Sahoo, and Mahato, 2019). Within the realm of the Fuzzy Logic Controller (FLC), this defuzzified value serves as a representation of the action required to regulate the underlying process. There are several known methods of defuzzification, such as:

- Center of Sums Method (COS)
- Center of gravity (COG) / Centroid of Area (COA) Method
- Center of Area / Bisector of Area Method (BOA)
- Weighted Average Method
- Maxima Methods
- First of Maxima Method (FOM)
- Last of Maxima Method (LOM)
- Mean of Maxima Method (MOM)

The present work utilizes the center of gravity (COG) approach for the implementation of defuzzification. The primary idea underlying the utilization of the COG technique involves the identification of the center of gravity and the enclosed region of the abscissa within the membership function curve as the output.

Center of Gravity (COG) Method

In the proposed routing protocol, the conversion of a fuzzy set to a crisp set is achieved using the Center of Gravity (COG) method. The COG approach is a common technique used in fuzzy logic systems to convert the fuzzy output of a system into a crisp value. It is employed to determine a representative value that best captures the overall behaviour or characteristic of the fuzzy set.

The COG method calculates the centre point of the area under the fuzzy membership function curve, taking into account the degree of membership of each element within the fuzzy set. By determining the weighted average of the fuzzy set's elements, the COG method provides a crisp output that encapsulates the general information embedded in the fuzzy set. In the context of the proposed routing protocol, the COG method is applied to convert the fuzzy output obtained from the inference engine, which determines whether a node should forward a broadcast packet or not, into a crisp decision. By employing the COG method, the protocol can obtain an unambiguous decision that guides the routing behaviour.

The COG method smoothly transitions from the fuzzy logic-based decision-making process to a crisp and actionable output. By converting the fuzzy set into a crisp set, the routing protocol can effectively determine the most suitable course of action for each node, enhancing the efficiency and performance of the overall network.

It is worth noting that the COG method relies on accurately representing the fuzzy membership functions and their corresponding degree of membership values. Therefore, the design and calibration of these fuzzy membership functions play a crucial role in ensuring the reliability and effectiveness of the COG conversion process.

The fundamental premise of the Center of Gravity (CoG) method, as elucidated by (Subbotin and Voskoglou, 2014) & (Subbotin, 2014), revolves around the identification of the point at which a vertical line labeled as $X*$ divides the aggregate into two equal masses. This approach is particularly applicable when μ_c is defined utilizing discrete Membership Functions, as represented in Equation 4.3.

$$x^{*}=\frac{\sum_{i=1}^{n}\mu_c\left(x_i\right)\cdot x_i}{\sum_{i=1}^{n}\mu_c\left(x_i\right)} \tag{4.3}$$

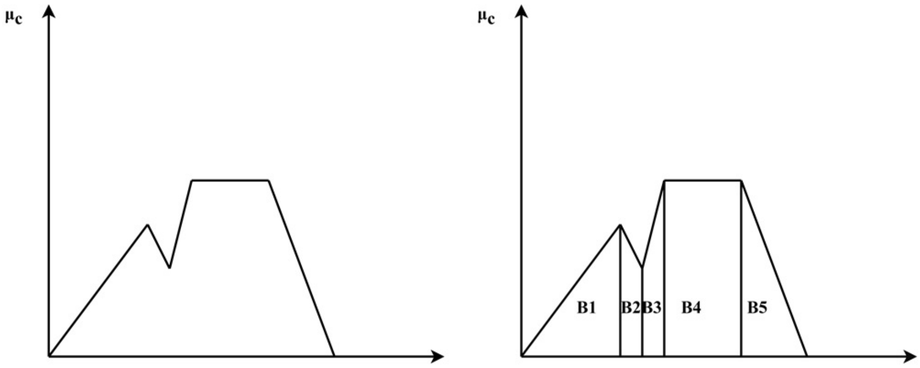


Figure 4.5: CoG Method for Defuzzification.

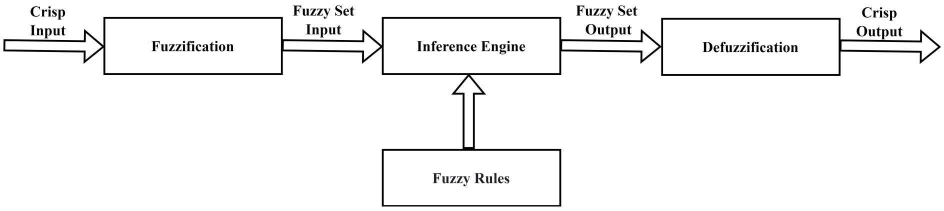


Figure 4.6: Defuzzification Step.

This methodology yields a precise outcome based on the center of gravity of the fuzzy set. The entire region encompassed by the membership function distribution, which characterizes the cumulative control action, is partitioned into distinct subregions, typically trapezoidal in our case. Each subregion's area and its corresponding center of gravity, known as the centroid, are computed. The summation of these individual subregion areas is subsequently employed to ascertain the defuzzified value for a discrete fuzzy set. Figure 4.5, illustrates the Center of Gravity (CoG) method employed for defuzzification.

Let B_i and X_i denote the ith sub-region's area and center of gravity, as shown in Equation 4.4.

$$x^* = \frac{\sum_{i=1}^{n} B_i \cdot x_i}{\sum_{i=1}^{n} B_i} \tag{4.4}$$

The process of defuzzification involves the conversion of a linguistic outcome into a numerical value, as shown in figure 4.6. Adopting the COG method in the proposed routing protocol enables the conversion of fuzzy outputs into crisp decisions, allowing for precise and unambiguous routing actions.

This conversion mechanism enhances the protocol's ability to effectively handle the uncertainties and imprecisions associated with the decision-making process, contributing to the overall efficiency and performance of the wireless mesh network.

4.5 Protocol basics

The frequent broadcasting required by the destination-sequenced distance vector (DSDV) for establishing and upkeep routes in networks results in a high overhead of $O(n^2)$, where n represents the total number of nodes within the network.

To enhance the performance of the Destination-Sequenced Distance Vector (DSDV) routing protocol, the AODV protocol has been proposed. The primary goal of AODV is to reduce the number of broadcasts on the network by implementing an on-demand route creation mechanism. The AODV protocol is classified as a reactive routing protocol, wherein each node functions as a router. Routes are established as needed and are solely maintained for their utilization. To guarantee the absence of loops, the AODV routing protocol employs the Destination Sequence Number (DSN) concept. Each node in the network maintains a monotonically increasing number, as described in the reference. The AODV protocol is classified as a destination-based routing protocol, wherein a node must only possess knowledge of the next hop to forward packets to the intended destination. All nodes involved in the network assume a flat structure and have similar roles.

However, like other protocols, AODV has its share of weaknesses or gaps identified in the literature over time. Here are some of the commonly recognized shortcomings of the AODV protocol:

Route Maintenance: The AODV is an on-demand protocol, it might not have an alternative route immediately available when a link on the current course fails, which can lead to increased latency.

Overhead: The route discovery process can introduce significant overhead, especially in high-mobility scenarios, as RREQ (Route Request) and RREP (Route Reply) packets flood the network.

Battery Consumption: Constant route discoveries and maintenance can drain the batteries of mobile nodes quickly, reducing the overall lifetime of the network. For those reasons, the presented thesis introduces the FCEE approach to addressing all those challenges.

For the above reasons, this doctoral thesis introduces the FCEE methodology meticulously designed to address these multifaceted challenges.

4.5.1 FCEE Proposed scheme

The foundational principles of the Ad hoc On-Demand Distance Vector (AODV) protocol are comprehensively delineated in (Marina and Das, 2001). This reference served as the basis for the further development of AODV and led to the introduction of the new approach termed ”FCEE”. The FCEE features its proclivity to ascertain and sustain routes exclusively on a need basis, thereby maximizing efficiency. The foundational operations encompassed by the FCEE protocol envelop the following:

1. Route discovery mechanism
2. Establishment of both forward and reverse paths
3. Meticulous management of routing tables
4. Ensuring localized connectivity
5. Robust path maintenance
6. FCEE forwards the broadcast based on their rules.

The communication packets integral to the $FCEE$ protocol are Route-request $RREQ$, Route-reply $RREP$, and Route-error $RERR$. In scenarios where a source node denoted as SRC anticipates data transmission to a destination notated as DST but lacks a pre-established route, it triggers the route discovery process via the broadcast of an $RREQ$ packet. This packet encapsulates vital attributes such as route request ID (RREQ_ID), IP addresses denominated as (SRC_IP and DST_IP), sequence numbers for both originator and recipient represented as (SRC_SEQ and DST_SEQ), the cumulative hop count H_c, and assorted request flags F_q.

Upon intercepting an $RREQ$, the immediate neighbouring node, or N_h, evaluates the destination in the $RREQ$. Should N_h align with DST, a direct unicast $RREP$ is dispatched to SRC, enriched with pertinent details like IP addresses (SRC_IP, DST_IP), the sequence number of the destination (DST_SEQ), a designated lifetime T_l, reply flags F_r, prefix dimensions P_s, and the cumulative hop count. Intriguingly, if N_h isn't identical to DST but possesses knowledge of a feasible route, it transmits an $RREP$ to SRC. Conversely, intermediary nodes, or N_i, bereft of routes to DST, propagate the $RREQ$ to their neighbours, augmenting the Hc in the process. The protocol efficiently eschews redundant broadcasts by ascertaining that N_i discards duplicate RREQs. A noteworthy outcome of nodes intercepting the $RREQ$ is formulating a reverse path to SRC, culminating in a unicast conduit from DST back to SRC. The subsequent unicast $RREP$ phase from DST to SRC witnesses the instigation of a forward path, paving the way from SRC to DST. The $AODV$ protocol prioritizes paths based on their hop counts, endorsing routes with minimal counts. For a path p spanning from node S to node D with a link distance denoted by i_j, the associated cost, C_p, is as described in Equation 4.5.

$$C_p = \sum_{(i,j)\in p} d_{ij} \forall \left(d_{i,i+1} = 1\right) \tag{4.5}$$

In scenarios involving active routing, nodes might leverage 'hello' messages to foster cognizance of proximate connectivity. These messages, symbolized as HELLO, are specialized RREP broadcasts with a hop count demarcated at unity, given in 4.4. Given a stipulated hello loss L_h and a defined interval I_h, the vitality or lifetime of this 'hello' message notated as P_h can be mathematically represented as given in Equation 4.6.

$$P_h = L_h \times I_h \tag{4.6}$$

An essential feature of the $FCEE$ protocol lies in its proactive route update mechanism. This framework ensures the acquisition of the most contemporary routes while simultaneously eliminating potential loops. This is actualized when the sequence number of the destination and the associated hop count resonates with the conditions outlined in Equation 4.7.

Navigating to the field of route maintenance, the protocol is primed to tackle unforeseen link breakages or route errors. In such events, the $FCEE$ protocol deploys the $RERR$ message to inform the impacted nodes. This $RERR$ packet is populated with details such as the count of unreachable destinations (UNR_DST_CNT), the IP addresses deemed unreachable (UNR_DST_IP), and their corresponding sequence numbers (UNR_DST_SEQ).

$$\begin{aligned}
&\text{if } (SEQ_i < SEQ_j) \text{ or } ((SEQ_i = SEQ_j) \text{ and } (Hc_i > Hc_j)) \text{ then}\\
&SEQ_i = SEQ_j,\\
&Hc_i = Hc_j + 1,\\
&\text{Next\_hop} = j.
\end{aligned} \tag{4.7}$$

The introduction of $FCEE$ accentuates the importance of energy capacity in intermediate nodes along transmission paths. With the primary focus on energy efficiency and mitigating congestion, $FCEE$ employs a fuzzy logic system to choose optimal paths for data transfer, considering factors like the energy level and the last broadcast.

The significance of this approach is magnified with the integration of a novel "short-term memory" channel in 4.4.4. This channel retains critical information such as energy level and the last broadcast, enriching the system's decision-making capability. As represented in Figure 4.3, this short-term memory channel assists the system in swiftly adapting to network changes, optimizing routing efficiency.

Leveraging the fuzzification process as depicted in Figure 4.3, linguistic variables, namely high, good, average, and low, are used to articulate the node's energy level. Table 4.2, systematically delineates the fuzzification process, outlining the energy levels based on the remaining energy RE.

One of the standout features of the $FCEE$ approach is its adeptness at managing network congestion, especially at the intermediate or routing nodes. $FCEE$ efficiently controls this broadcast by exploiting its fuzzy logic system coupled with the memory channel. On packet reception, after routine operational tasks like error or checking validation, and checksum calculations, the routing subsystem discerns the packet's destination. Depending on whether the packet is for the receiving node, another node, or a broadcast packet, the $FCEE$ protocol kicks into action. Based on the fuzzy rules from Table 4.2, the output is determined, paving the way for an informed routing decision. Integrating $AODV$ and $FCEE$ creates a routing algorithm with good efficiency.

By combining the routing mechanisms of $AODV$ with the energy rules and fuzzy logic approach of $FCEE$, this algorithm ensures optimal performance in wireless mesh networks. The $FCEE$ focus on energy efficiency and congestion alleviation, coupled with the reliability and dynamism of the $AODV$ protocol, results in a robust routing solution tailored for modern mesh networks. The following subsections describe the $FCEE$ approach in detail.

4.5.2 Integration of Fuzzy Logic in AODV

Integrating fuzzy logic in the AODV routing protocol presents a promising approach to enhance performance and adaptability in dynamic wireless mesh networks. Fuzzy logic is a powerful tool to incorporate human-like decision-making capabilities into the protocol, enabling it to effectively handle uncertainties, imprecisions, and non-linearities inherent in such environments.

Integrating fuzzy logic into the AODV protocol enables it to use linguistic variables and fuzzy rules for smarter routing decisions. This approach captures qualitative network aspects like ”low energy” or ”average energy,” which are difficult to define with traditional logic. Fuzzy rules, central to this integration, are structured as ”if-then” clauses, linking linguistic variables to specific actions in the routing protocol. Expert knowledge of fuzzy rules, optimizing AODV protocol's route selection based on current network conditions, as shown in Table 4.2 and Table 4.1.

The mechanism within the fuzzy logic integration allows the AODV protocol to reason and draw conclusions based on linguistic variables and fuzzy rules. The protocol can perform fuzzy reasoning and generate crisp outputs that guide the routing decisions by employing algorithms such as the information of the current thesis. The algorithm for the route discovery mechanism of the protocol is presented in Algorithm 1 and 2, and the corresponding notations are provided in Table 4.3.

Algorithm 1 FCEE Route Discovery Algorithm Based AODV Algorithm.

```
procedure ShouldRebroadcast(Energy_Level, Last_Broadcast)
    if Energy_Level == high $\vee$(Energy_Level == good $\wedge$Last_Broadcast != forwarded) $\vee$(Energy_Level == average $\wedge$Last_Broadcast != forwarded) $\vee$(Energy_Level == low $\wedge$Last_Broadcast != forwarded) then
        return true
    else
        return false
    end if
end procedure
Input: Control packets: Rreq, Rrep, Rerr; Destination ID: DestID; Energy level: Energy_Level; Last broadcast status: Last_Broadcast
Output: Ri
if S has route to D then
    send to next hop towards D
    return Ri
else
    S creates Rreq
    Hc $\leftarrow$ 0
    broadcast Rreq
    I $\leftarrow$ {nodes receiving Rreq from S}
    for i $\in$ I do
        if Ci == Rreq then
            if Invalid Rreq then
                discard old or duplicate
                continue
            end if
            if Ni == D then
                Dest seq (Rrep) $\leftarrow$ Dest seq (D)
                Hc (Rrep) $\leftarrow$ 0
                send Rrep to S
                return Ri
            else if Ni has active route to D then
                Dest seq (Rrep) $\leftarrow$ Dest seq (Ni)
                Hc(Rrep) $\leftarrow$ Hc (Ni to D)
                send Rrep to S
                if G == TRUE then
                    send gratuitous Rrep to D
                end if
            else
                RT $\leftarrow$ Org seq (Rreq)
                Hc $\leftarrow$ Hc + 1
                if ShouldRebroadcast(Energy_Level, Last_Broadcast) then
                    rebroadcast Rreq
                end if
            end if
        else if Ci == Rerr then
            mark route invalid
        end if
    end for
    update RT of S
    send to next hop towards D
end if
return Ri
```

Algorithm 2, outlines the FCEE method, optimized for efficient packet routing within a network. Upon receipt of a packet, the algorithm first determines if the destination ID $DestID$ matches the next hop ID $Nexthopid$. If a match is found, the packet is successfully received, and the process concludes. Otherwise, the proposed protocol is initiated. In cases where the destination ID corresponds to a unicast address $unicastadd$, the packet is dispatched directly to the targeted node. However, the algorithm introduces an energy-centric decision-making component when the last broadcast is forwarded. Here, based on the node's energy level — whether it is high, good, average, or otherwise — the algorithm will decide whether to forward the broadcast or not. In essence, this approach balances the need for efficient routing with the consideration of energy conservation, ensuring that packets are relayed effectively without depleting node energy resources unnecessarily.

Algorithm 2 FCEE_ALGORITHM_Based On_Fuzzy_Approach.

```
Input: DesID, NextHopID, Last_Broadcast, Energy_Level
Output: Action (Receive Packet, Send Packet, Forward Broadcast, Do Not Forward)
if DesID == NextHopID then
    Action = "Packet Received"
    STOP
else if DesID == unicastAdd then
    Action = "Send packet to targeted node"
    STOP
else if Last_Broadcast == forwarded then
    if Energy_Level == high then
        Action = "Forward the broadcast"
    else if Energy_Level == good OR Energy_Level == average then
        Action = "Do not Forward the broadcast"
    else
        Action = "Do not Forward the broadcast"
    end if
else
    Action = "Forward broadcast"
end if
```

Table 4.3: Notation used in FCEE Algorithm.

Symbol	**Description**
Rreq	Request control packet for route discovery
Rrep	Reply control packet for found route
Rerr	Error control packet for route errors
DestID	Destination node's ID
Energy_Level	Energy level of the node (High, Good, Average, Low)
Last_Broadcast	Status of the last broadcast (Forwarded or Not Forwarded)
S	Source node
D	Destination node
Ni	Neighbor node i
Unicastadd	unicast address
Nexthopid	next hop ID
DestID	Destination ID
NextHopID	Next Hop ID
unicastAdd	Unicast Address
Energy_Level	Energy Level
Last_Broadcast	Last Broadcast
Hc	Hop count
I	Set of nodes receiving control packet Ci
RT	Routing table of the node
Ri	Route information from source to destination
Ci	Control packet
GratuitousRREPFlag	Flag indicating if a gratis RREP must be sent
G	Flag for check if a gratis RREP must be sent

4.5.3 FCEE Flowchart

Network congestion often happens at specific points within the network, which we call intermediate nodes or routing nodes. These nodes are responsible for figuring out the best path for data to travel through the network. Another reason for congestion is when there is a lot of broadcast traffic, especially in networks with lots of broadcasting. To address this issue, we have the Fuzzy Control Energy Efficient (FCEE) routing protocol. It uses fuzzy logic and memory channels to handle broadcast traffic better. This helps reduce the load on the network and lowers congestion. Flowchart explaining how *FCEE*

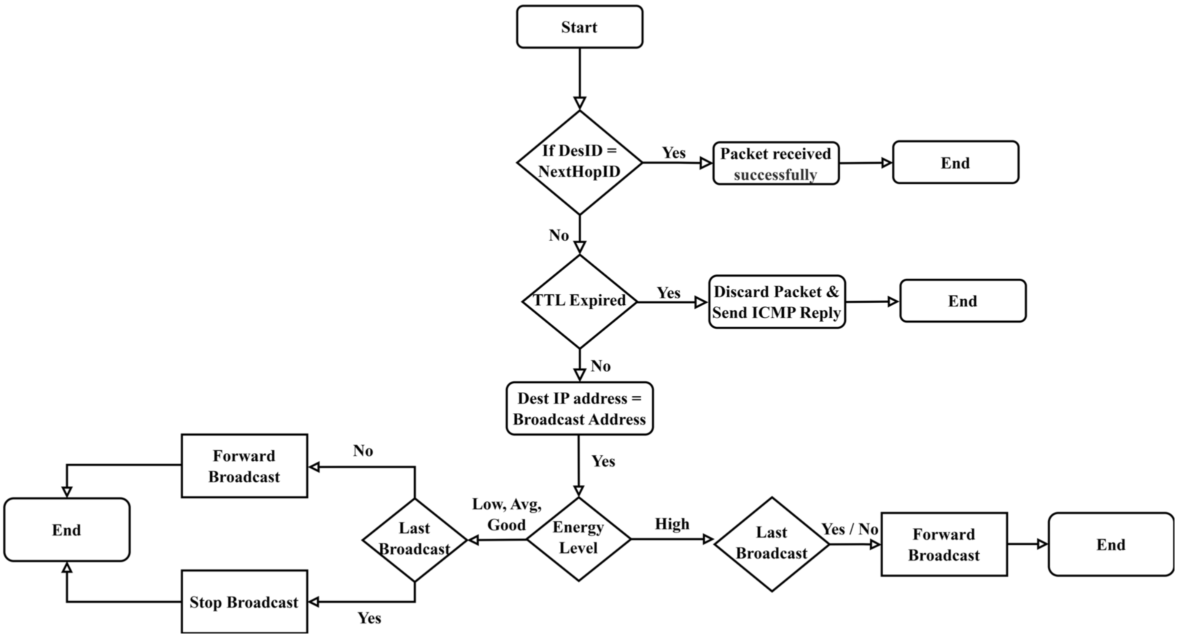


Figure 4.7: Fuzzy Control Energy Efficient (FCEE) Algorithm Flowchart.

works in Figure 4.7, but understanding the whole process requires breaking down the steps it takes.

Here is how it works: When a device, often called a node, receives data from the wireless channel, it goes through several steps in the network stack. Think of this like a series of tasks. First, there is the data link layer that checks for errors, corrects them, and makes sure the data is synchronized. Then, as the data moves up the network stack, it gets processed at layers called Layers III and IV. These layers do things like checking for errors in the data, looking at things like the Time-To-Live (TTL) field, and deciding where the data should go next. Layer IV, also known as the transport layer, makes sure the data gets from one end of the network to the other without any problems by using techniques like checksums to find and fix errors.

The decisions made during these processes are essential because they determine what happens next. If the device that receives the data is the one it was meant for (the destination), then the data goes to the proper application or service.

However, if the data needs to go to other devices in the network, that is where the FCEE routing protocol comes in. If the destination is a specific device, FCEE quickly sends the data there. However, if the destination is a ”broadcast” address, FCEE checks its memory to see what happened with the last broadcast data. In both cases, whether the last broadcast data was sent or not, FCEE makes decisions based on some fuzzy rules that are detailed in Tables 4.2 4.1. These rules help FCEE figure out what to do, and then it carries out those decisions.

Decision-making in routing isn’t black and white. By introducing dynamic thresholds, the protocol can make more informed decisions about forwarding broadcasts, leading to reduced network congestion and improved efficiency, as shown in both tables 4.2 & 4.1.

The provided algorithm 2, can be divided into three main parts:

1. **Packet Reception and Destination Check**
    - The algorithm begins by receiving a packet.
    - It checks if the destination ID $DestID$ matches the next hop ID $Nexthopid$.
    - If there is a match, the algorithm stops, and the packet is received.
2. **Proposed Protocol Initialization and Unicast Check**
    - The proposed protocol is started if the destination ID $DestID$ does not match the next hop ID $Nexthopid$.
    - The algorithm checks if the destination ID $DestID$ is a unicast address, indicating a targeted node.
    - If it is a unicast address, the packet is sent directly to the targeted node, and the algorithm stops.
3. **Broadcast Forwarding Decision**
    - If the last broadcast $Last\_BoradCast$ was forwarded, the algorithm evaluates the energy level of the node $Energy\_Level$ to determine whether to forward the broadcast or not.
    - If the energy level is high, the broadcast is forwarded.
    - The broadcast is not forwarded if the energy level is good or average.
    - The broadcast is not forwarded if the energy level is low.
    - If the last broadcast $Last\_BoradCast$ was not forwarded, the broadcast is forwarded regardless of the energy level.

Figure 4.8, presents a simulation illustrating data packet transmission within a mesh network, employing the FCEE protocol. This representation underscores the protocol's efficacy in such network configurations.

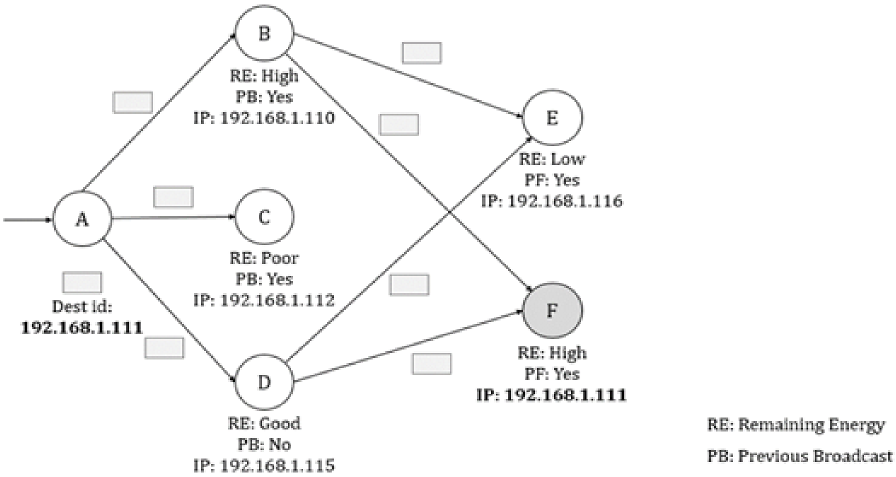


Figure 4.8: Example Acenario of Route Selection Process of FCEE.

4.6 Enhancements for Fuzzy-Controlled Broadcast Forwarding Algorithm

The following subsections now focus on enhancements that optimize routing in wireless networks. However, several enhancements have been implemented to enhance its performance and adaptability. This subsection explores improvements to the algorithm that have been made to optimize its effectiveness in delivering broadcast packets while considering dynamic network conditions and resource constraints.

4.6.1 Adaptive Membership Functions

One enhancement involves adapting membership functions used in the fuzzy logic system. By dynamically adjusting the shape and parameters of the membership functions based on network parameters such as node density, link quality, or energy levels, the algorithm can better capture the varying degrees of uncertainty and make more informed broadcast forwarding decisions. The adaptive membership function can be expressed in Equation 4.8:

$$\mu(x) = f(x) \tag{4.8}$$

where μ(x) represents the membership degree of an input variable x, and $f(x)$ represents the adaptively adjusted membership function.

4.6.2 Dynamic Thresholds

Building on the concept of adaptive membership functions, this subsection delves into another pivotal aspect: dynamic thresholds. This approach can significantly enhance the decision-making process for broadcast forwarding. Instead of relying on fixed energy level thresholds, the algorithm can dynamically adjust the thresholds based on the overall network energy or the energy distribution among neighbouring nodes. This ensures that the broadcast forwarding decisions are sensitive to the energy conditions of the specific network environment. The dynamic threshold calculation can be expressed in Equation 4.9.

$$T = E_{\mathrm{avg}} * k \tag{4.9}$$

where T represents the dynamic threshold, E.avg represents the average energy level in the network, and k is a scaling factor that adjusts the threshold sensitivity. Figure 4.9, shows the Dynamic Thresholds.

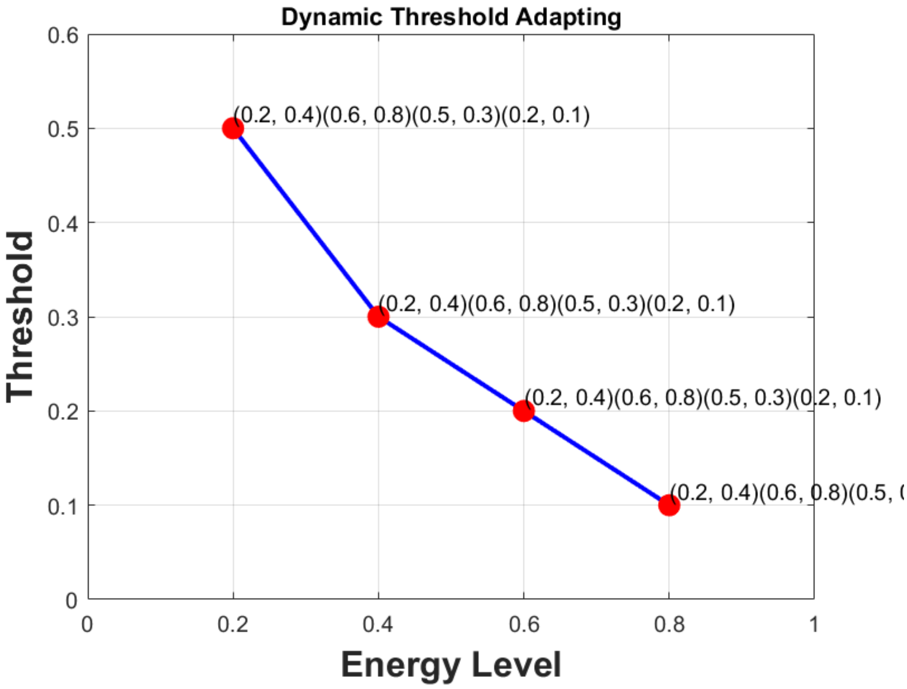


Figure 4.9: Dynamic Thresholds.

The graph's horizontal axis denotes the energy states, encompassing a continuum from 0 to 1. The energy level denotes the residual energy of a node within the network. The vertical axis denotes the thresholds, which range from 0 to 1. Whether a node should forward a broadcast packet depends on the energy level, as the threshold dictates. The plot's blue line represents the dynamic threshold curve that adjusts according to the network energy conditions. The curve shows how the threshold value changes as the energy level varies.

4.6.3 Congestion Awareness

To address congestion-related challenges, the algorithm has been enhanced with congestion awareness, as illustrated in Equation 4.10. By monitoring network congestion levels and using congestion-related metrics such as packet loss rate or buffer occupancy, the algorithm can dynamically adjust the broadcast forwarding decisions to alleviate congestion hotspots and ensure smoother data transmission.

$$\begin{aligned}\text{IF Congestion\_Level} \geq \text{Threshold THEN Forward\_Broadcast,}\\ \text{ELSE Do\_Not\_Forward\_Broadcast}\end{aligned} \tag{4.10}$$

where $Congestion\_Level$ represents the congestion level, Threshold is a predefined threshold value. Figure 4.10, shows the $congestion - aware$ decision.

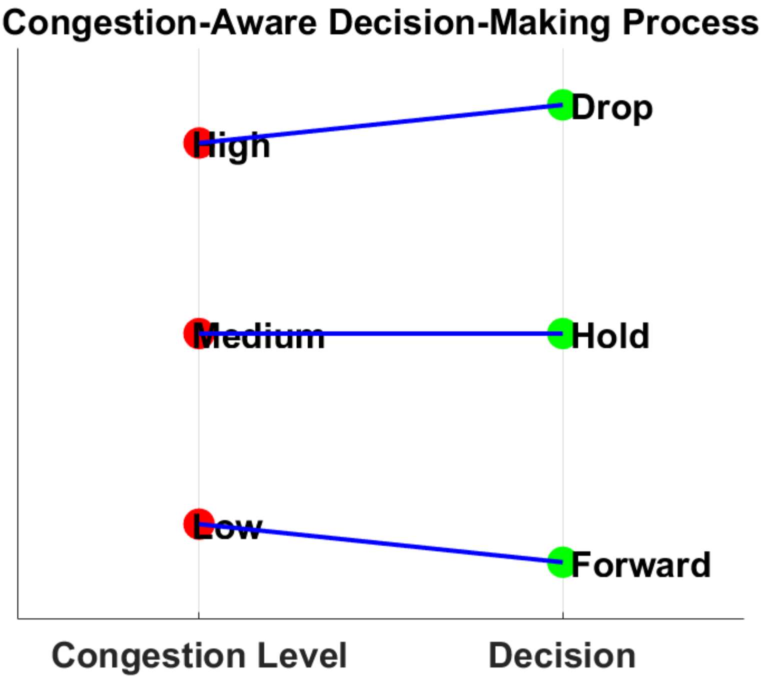


Figure 4.10: Illustrating the Congestion-Aware Decision-Making Process.

Figure 4.10, visually demonstrates how the proposed algorithm adapts its decisions in response to varying congestion levels. The algorithm enables efficient network management by mapping congestion levels to specific actions. The clear and intuitive illustration aids in understanding the relationship between congestion levels and decision outcomes, facilitating effective congestion control and optimization in the network.

4.6.4 Quality of Service (QoS) Considerations

A further enhancement to the FCEE algorithm is the integration of QoS considerations, ensuring that broadcast packets are prioritized based on their associated requirements. The algorithm can prioritize certain broadcast packets based on their associated QoS requirements by incorporating QoS metrics such as packet delay, throughput, or reliability. This ensures that high-priority applications or traffic flows receive appropriate handling and resource allocation, improving overall network performance, as shown in Equation 4.11. Figure 4.11, shows this process.

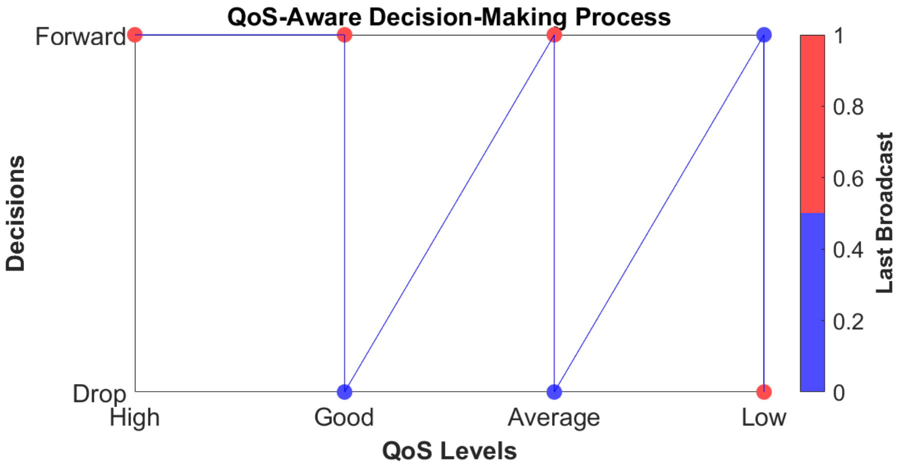


Figure 4.11: Illustration of the QoS-Aware Decision-Making Process.

$$\text{IF } QoS\_Metric \geq \text{Threshold THEN Forward\_Broadcast,} \\ \text{ELSE Do\_Not\_Forward\_Broadcast} \tag{4.11}$$

Figure 4.11, illustrates the QoS-aware decision-making process concisely and transparently. The graph presents different QoS levels on the x-axis and decisions on the y-axis. Each marker represents a specific combination of QoS level and decision. The colour of the markers indicates the status of the last broadcast, with blue indicating not forwarded and red indicating forwarded. The lines connecting the markers depict decision transitions based on the QoS level. This graph enables a straightforward interpretation of the decision based on a given QoS level and the status of the last broadcast.

The proposed enhancements refine the fuzzy-controlled broadcast forwarding algorithm and equip it to adapt seamlessly to the ever-changing dynamics of wireless networks. By considering factors such as adaptive membership functions, dynamic thresholds, congestion awareness, and QoS considerations, the algorithm can achieve enhanced performance, robustness, and adaptability in delivering broadcast packets efficiently while meeting the requirements of various network scenarios.

4.7 Summary

The Fuzzy Logic-Based Routing Framework is a pioneering approach proposed in this research study to enhance the performance and adaptability of routing protocols in wireless mesh networks. This chapter presents a comprehensive exploration of the design and implementation of the framework, which leverages the power of fuzzy logic for efficient route selection, with an overview description of the modification introduced to the AODV routing protocol. The chapter establishes the background and motivation for developing a new routing framework based on fuzzy logic.

The design of the fuzzy logic-based routing framework is detailed, elucidating the system architecture and the construction of the fuzzy rule base. The chapter explains the methodology for designing membership functions and the rule-firing mechanism. It also presents the fuzzy inference engine responsible for route selection based on the network's dynamic conditions.

Based on the concepts and discussions from Chapter 4, chapter 5 explores more deeply the intricacies of network simulation models, focusing on the Network Simulator Version 2 (NS-2). It provides a comprehensive overview of the mobile nodes, the modifications made within the NS-2 simulator framework, and the mobility model employed.

Chapter 5, also explores the vital role of Transmission Control Protocol (TCP). In addition, the User Datagram Protocol (UDP) is used in this thesis for network simulations, emphasizing the importance of selecting the appropriate traffic models for accurate simulation outcomes. It further elaborates on using Constant Bit Rate (CBR) and Pareto distribution traffic models in mesh networks and their interaction with the FCEE routing protocol.

The methodology section outlines the simulation process, data analysis techniques, performance evaluation criteria, and scenario classification. It also discusses the assumptions made in the simulation model. The chapter 5, concludes with a discussion on the resilience of network connectivity and the impact of node speed on the FCEE routing protocol, setting the stage for more detailed analysis in the next chapter.

5

SIMULATION MODEL

Contents

Overview

The present chapter elucidates the simulation model, the simulator settings, and the underlying assumptions integrated into the discrete event simulator known as Network Simulator Version 2 (NS-2). The NS-2 simulation models have been meticulously crafted to undertake a thorough evaluation and scrutiny of the effectiveness of the FCEE metric within diverse routing protocols, encompassing AODV, DSR, AODV and Intelligent Routing AODV (IRAODV) (Anand and Sasikala, 2019), Enhanced-Ant-AODV (Sarkar, Choudhury, and Majumder, 2021), Stable-AODV (STAB-AODV) (Pandey and Singh, 2022), and Signal Strength-Based Ad-Hoc On-Demand Distance Vector (SSAODV) (Manjhi and Patel, 2012). These investigations are conducted within the intricate realm of a Wireless Mesh Network (WMN) environment. The study accurately classifies the various scenarios that are systematically grouped based on their distinctive arrangements. In the following sections of this chapter, these arrangements will be expounded upon comprehensively, fostering a deeper comprehension of the research findings.

5.1 Justification for Utilizing an Approach Based on Simulation

This thesis involves a distributed mechanism that requires extensive testing. The presented thesis conducted a comprehensive evaluation of the FCEE path selection algorithm within a robust network framework, which included 60 and 100 nodes strategically positioned across the network topology to achieve our objectives. This study assessed this routing protocol through a comparative analysis with alternative methods. Additionally, this thesis needed to test the new metric with different numbers of nodes in various network positions, and this work made adjustments to parameters like network size, node speed, and simulation time to gauge the effectiveness of the new FCEE metric under diverse scenarios. We also examined how this metric performed with TCP/UDP transport protocols.

To adequately analyze the FCEE metric's performance, we generated 500 random network topologies for each scenario. However, conducting all these tests experimentally would have been impractical due to the scale and complexity of the required test network. It would also have been extremely time-consuming. Therefore, we opted for computer simulation as a more feasible and practical alternative. Computer simulation allows us to maintain complete control over the simulation environment, eliminating any unpredictable outcomes resulting from signal propagation variations.

To ensure an accurate investigation and analysis of the FCEE metric's performance, we generated 500 random topologies for each possible situation in this study. In the following subsection, this work outlines the network modeling approach used in this thesis.

5.1.1 Network Modeling

The NS-2 simulator, a widely recognized software application extensively employed by commercial and research communities, is a valuable tool for conducting simulations encompassing diverse network environments. Within the scope of this research, the selection of NS-2 was based on a comprehensive survey which confirmed its efficacy and meticulous documentation, making it an ideal choice for modelling purposes. Additionally, the flexibility and ease of incorporating new modules and the capability to simulate large-scale scenarios further enhance its appeal. This study entailed the evaluation of multiple scenarios, which were meticulously generated within the simulation tools and network testbed. Two specific session types, namely Constant Bit Rate (CBR) and file transfer protocol (FTP), were employed to facilitate the assessment process.

Utilizing the ”freeware” version of NS-2 adds further allure to researchers, as it provides an accessible platform for investigation. Moreover, the comprehensive suite of NS-2 modules surpasses that of

OPNET Modeler regarding features such as Open-Source Nature, Flexibility and Extensibility, Community Support, and functionalities, rendering it particularly appealing to researchers specializing in network analysis and exploration (Zhang and Lu, 2020). In addition, The NS2 provides several advantages, such as enabling testing of new network protocols, allowing for efficient experimentation with various network configurations, providing accurate results for network performance analysis, providing hands-on experience for students, and finally, enabling understanding of complex network concepts through simulations. While network modeling provides a broad overview, the presented thesis utilized NS-2 as a tool for this task. Where NS-2 offers specific functionalities, this thesis will explore them in this chapter.

5.1.2 Network Modeling Using NS-2

The underlying architecture of NS2 is depicted in Figure 5.1, showcasing its fundamental structure. NS-2, a software tool widely utilized by the research and commercial communities, offers a command known as "NS," which serves as the entry point, requiring a single input parameter denoting the title of a Tcl simulation scripting document. In many instances, a simulation trace file is generated to facilitate the plotting of graphs or the creation of animations. NS-2 comprises two essential languages: Common C++, and Object-oriented Tool Command Language (OTcl) (Issariyakul et al., 2009) & (Khelifi et al., 2019). While C++ defines the internal workings of the simulation, serving as the backend, OTcl is responsible for assembling and configuring objects and scheduling discrete events, functioning as the front. The integration of C++ and OTcl is facilitated through TclCL. Variables in the OTcl domain, when mapped to a C++ object, are commonly referred to as handles. Conceptually, a handle is a string (e.g., "_o10") within the OTcl domain, devoid of inherent functionality. Instead, the functionality, such as packet reception, is defined within the corresponding mapped C++ object (e.g., an instance of the Connector class). Within the OTcl domain, a handle acts as an interface, enabling interaction with users and other OTcl objects. It may define its procedures and variables to facilitate this interaction. It is worth noting that member procedures and variables in the OTcl domain are referred to as instance procedures and instance variables, respectively. Therefore, it is highly recommended that readers familiarize themselves with C++ and OTcl languages. Readers are encouraged to refer for detailed information on C++ (Raza et al., 2017) & (Ramadhan, 2010).

NS2 provides a comprehensive collection of built-in C++ classes, typically employed to configure simulations using Tcl scripts. However, advanced users may need more than these objects for specific needs. In such cases, they can develop their own C++ classes and utilize the OTcl configuration interface to instantiate objects from these custom classes. Following the simulation, NS-2 generates text-based simulation results. Network Animator (NAM) and XGraph are commonly employed to interpret and visualize these results graphically and interactively.

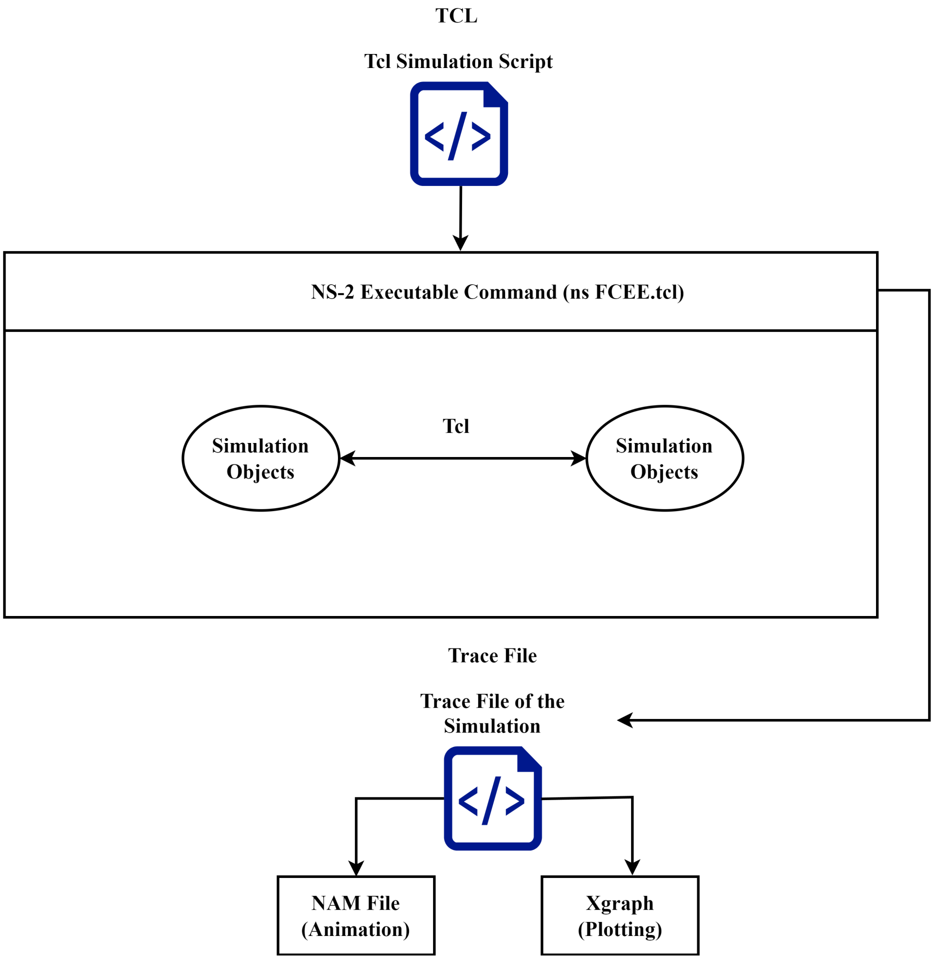


Figure 5.1: Architecture of the NS-2.

The Perl programming language has been used to extract the information from the trace file. Each topology comprises a single gateway and several nodes distributed randomly across the network coverage area as well described in this thesis. All generated topologies were imported into NS-2 to run the simulated topologies. The generated results were exported for analysis to Perl and AWK, the latter developed by Aho, Weinberger, and Kernighan, to process the trace file information. MATLAB, a numerical computing environment developed by MathWorks, offers capabilities such as matrix manipulation, plotting of functions and data, and implementation of algorithms. The MATLAB language was used to plot the figures. An essential aspect of our network model in NS-2 involves the incorporation of mobile nodes, which will be discussed in detail in a subsequent subsection dedicated to mobile nodes.

5.1.3 Mobile nodes

In the dynamic realm of network simulations, mobile nodes are indispensable. They emulate real-world scenarios, with their movements and interactions profoundly shaping network dynamics. It's essential to represent them accurately.

The NS-2 simulation defines mobile nodes with specific movement patterns, speeds, and trajectories, emulating real-world devices like smartphones and tablets. Their mobility is characterized by parameters such as speed, pause time, and movement direction. The current thesis employed the Random Waypoint Mobility Model in the NS2 framework, allowing nodes to select their destination randomly and move towards it at a uniformly distributed speed between the set minimum and maximum values.

The modeling is categorized into three layers for the FCEE routing protocol in NS2, an enhanced version of the AODV protocol for mesh networks. The modeling under NS2 for the FCEE routing protocol, an updated version of the AODV protocol for mesh networks, is divided into three levels: the application layer, the network layer, which houses the routing protocol, and the MAC/PHY layer, as depicted in figure 5.2.

- **Application Layer:** The Application layer, positioned at the OSI model's pinnacle, delivers application services directly to users. It ensures seamless communication between user applications and the underlying protocol layers. In the context of the FCEE protocol, the specific role of the Application layer is influenced by the protocol's design and implementation. Particularly, the Application layer in the FCEE protocol emphasizes Quality of Service (QoS).

  This layer outlines specific QoS requirements for data transmission. Subsequently, the FCEE protocol leverages these requirements to make informed routing decisions, ensuring the transmitted data adheres to the stipulated QoS standards.

- **Network Layer:** This is the heart of the node model, housing the routing protocol. It integrates modifications to the traditional AODV protocol, leveraging fuzzy logic techniques to refine routing decisions tailored for mesh networks.

- **MAC/PHY Layer:** The packet flow within the network layer can either originate from higher-layer applications or ascend from the MAC and PHY layers. To ascertain the best forwarding path, these packets undergo **('IP routing process')**. If a packet doesn't have a clear route, it is channeled to the **('mesh_mgr')** and **('FCEE_rte')** processes. These processes, enriched with the fuzzy logic enhancements of the FCEE protocol, determine the optimal route. The packet then proceeds to the **('ip_dispatch')** process for transmission.

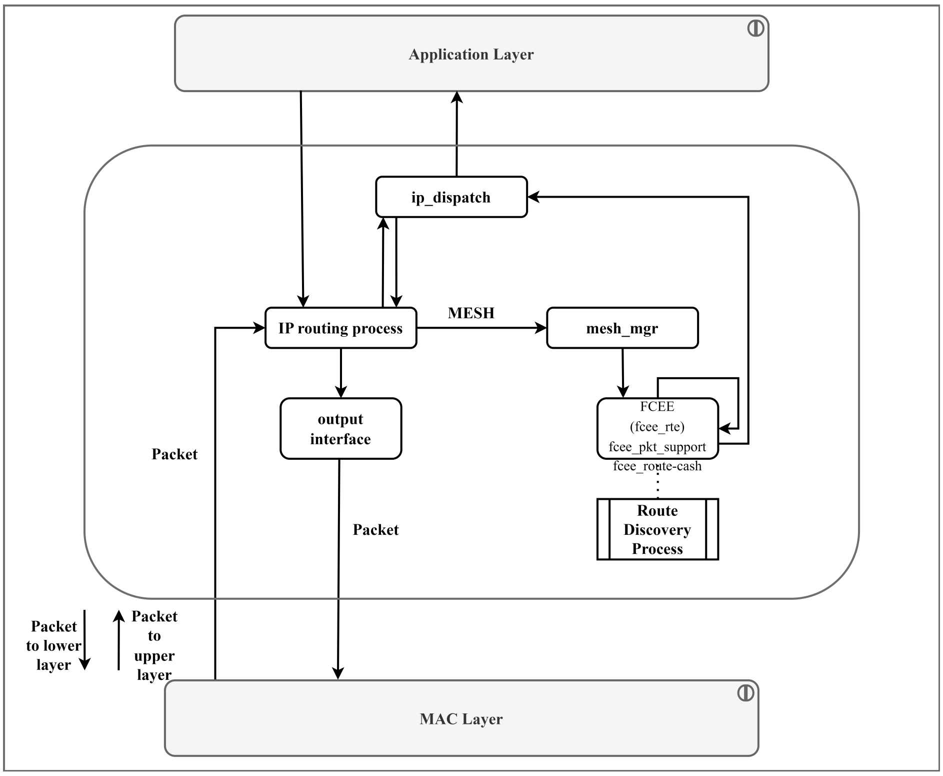


Figure 5.2: Data Traffic Packet Flow of FCEE Protocol.

Mobile nodes are equipped with unique capabilities tailored for mobile networking. Figure 5.3, illustrates a mobile node within NS2, equipped with an agent for packet processing. The primary distinction between wired and mobile nodes is their communication mode. While wired nodes use links, mobile nodes operate via wireless channels. Mobile nodes, unlike their wired counterparts, can move within a topology. Key components of a mobile node include:

- Address Classifier: Directs packets to either the port classifier or routing agent.
- Destination Node: Receives packets from the link layer, classifying them based on address.
- Port Classifier: Allocates packets to agents connected to the mobile node.
- Routing Agent: Manages routing tables and packet forwarding.
- Link Layer: Converts network addresses to hardware addresses.
- Address Resolution Protocol (ARP): Maps network addresses to MAC addresses.
- Interface Queue: Stores packets set for transmission.
- Medium Access Control (MAC): Regulates access to the wireless channel.
- Wireless Network Interface: Manages packet transmission and reception.

- Radio Propagation Model: Determines if a network interface can receive a signal packet.
- Wireless Medium: Distributes packets.

To effectively simulate mobile nodes within NS-2, the presented thesis made necessary modifications to the default settings, as depicted in figure 5.3.

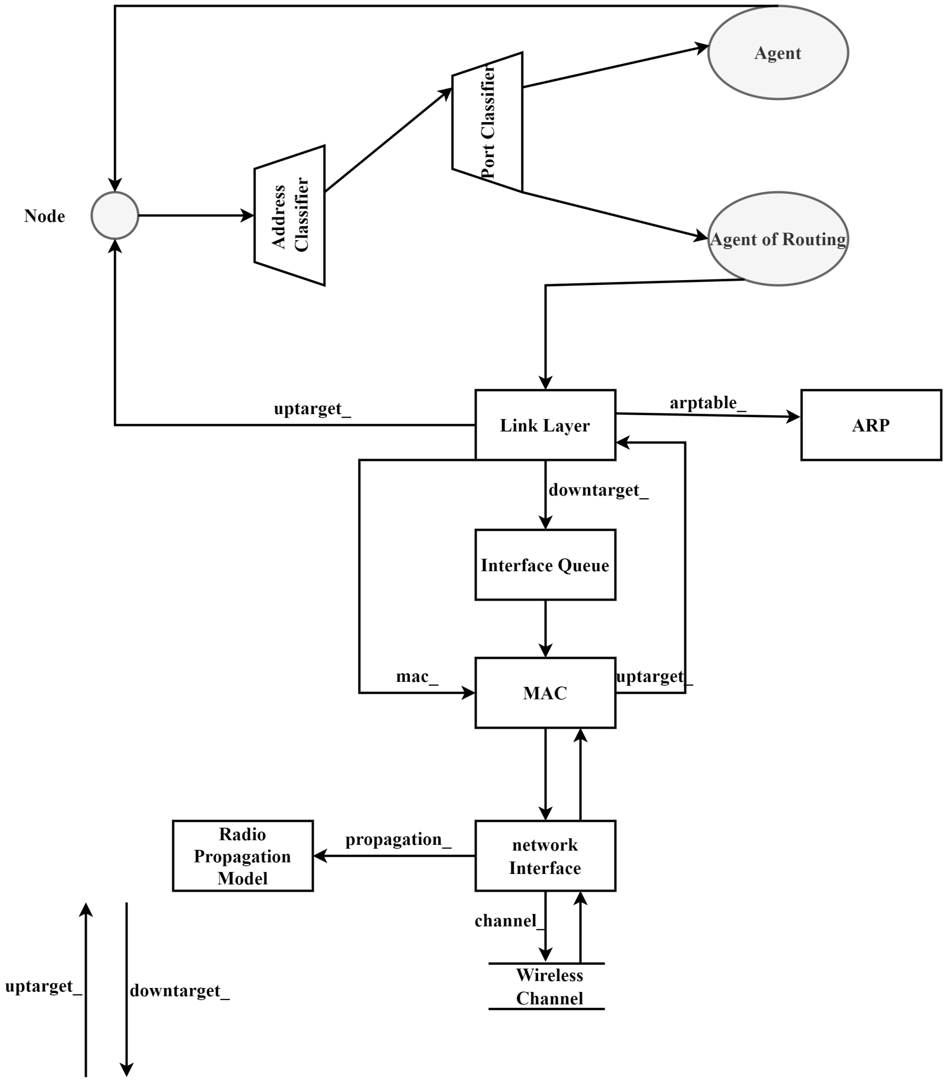


Figure 5.3: Illustrative of a Mobile Node in NS-2, (Issariyakul et al., 2009).

Table 5.1, shows the values and descriptions of the FCEE node configuration.

Table 5.1: FCEE Node Config Overview.

Option	**ConfigParam**	**Details**
-meshRouting	routingAgent_	FCEE (Routing Protocol)
-llType	lltype_	LL (Link Layer Type)
-macType	macType_	Mac/802_11 (MAC Type)
-ifqType	ifqType_	Queue/DropTail/PriQueue (Interface Queue Type)
-ifqLen	ifqlen_	450 packets (Max Packet in ifq)
-antType	antType_	Antenna/OmniAntenna (Antenna Model)
-propType	propType_	Propagation/TwoRayGround (Radio-Propagation Model)
-phyType	phyType_	Phy/WirelessPhy (Network Interface Type)
-channelType	channelType_	Channel/WirelessChannel (Channel Type)
-topoInstance	topoInstance_	FCEE.tcl
-agentTrace	agentTrace_	ON
-routerTrace	routerTrace_	ON
-macTrace	macTrace_	ON
-movementTrace	movementTrace_	On
-energymodel	EnergyModel	ON

5.1.4 Modified files within the NS-2 Simulator Framework

Several modifications were indispensable to adapt the NS-2 simulator to our specific research needs, particularly in the realm of mobile nodes and network dynamics. Central to the simulation framework is the Tcl scripting file, a primary input conduit for the simulator. This file encompasses an ASCII trace file, systematically structured to chronicle network-level events, segmented by pertinent fields.

Further enhancing this is integrating the Network Animator (NAM) visualization tool. NAM provides invaluable real-time visualization of network nodes, acting as a pivotal instrument for verifying the veracity and integrity of the simulations. The culmination of the simulation process produces an output: results meticulously catalogued in a text format. Figure 5.4, visually represents the adapted modules within the NS-2 framework. Significantly, the Fuzzy Control Energy Efficient (FCEE) routing protocol, built upon the AODV protocol foundation, is actualized through adept C++ programming within the NS-2 environment. Concurrently, Tool Command Language (TCL) scripts play an instrumental role in delineating complex simulation scenarios, synergistically aligning with the C++ framework.

Figure 5.4, elucidates the architectural integration of the extensions within the NS-2 framework. This integration epitomizes our commitment to accuracy, underscoring the meticulousness characterizing our research endeavours. Figure 5.4, showcases a detailed inventory of the adapted files and modules, paving the way for advanced functionalities within the NS-2 framework.

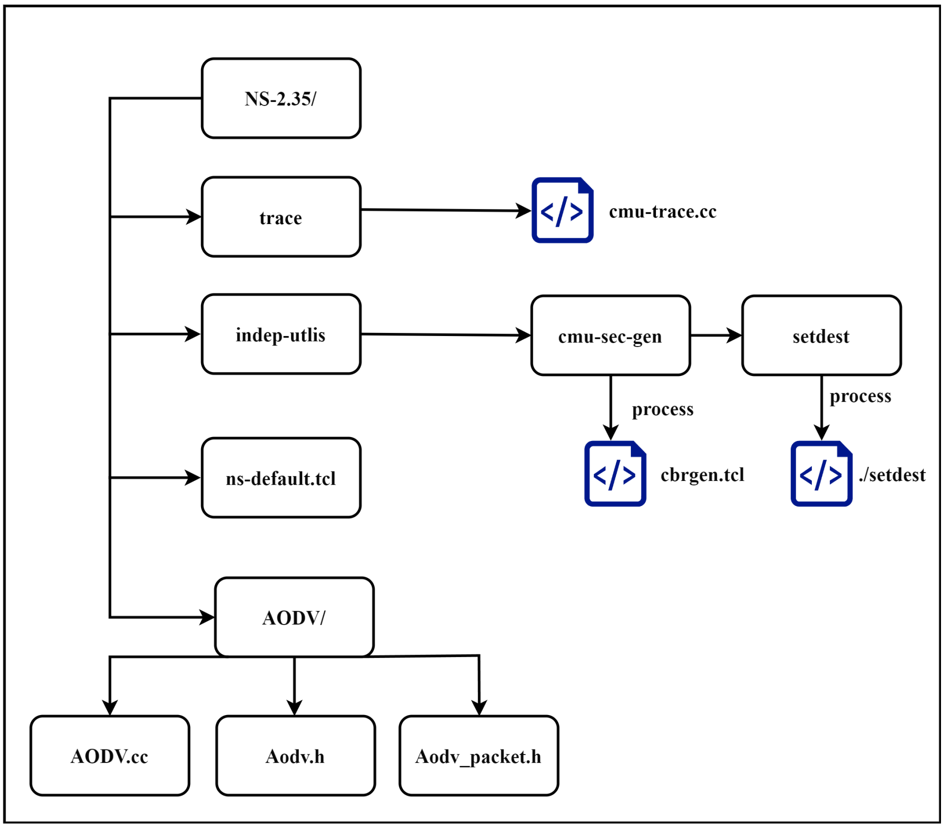


Figure 5.4: Modified files within the NS-2 Simulator Framework.

The associated files with the modified modules encompass:

- **[Aodv/aodv.cc:]** This file integrates the transmission and reception of the ”hello” messages, standard AODV functions, and routing table updates. It effectively manages node-specific information, including implementing timers, routing agents, and TCL hooks. Importantly, the original AODV implementation in this file has been adapted to incorporate the features of the FCEE routing protocol. FCEE enhances the AODV protocol by introducing advanced route maintenance strategies and energy efficiency mechanisms.

- **[aodv.h:]** This file defines the structure and functionalities associated with mobile nodes. It includes methods like getDistance (double x, double y) for calculating distances between nodes. The file also manages data related to neighbouring nodes, such as their count, flags, and a table detailing their attributes. Furthermore, it specifies a list of neighbours, capturing details like their IDs, transmission power, and respective distances.
- **[aodv_packet.h:]** This header file defines the AODV reply header, detailing attributes such as xpos, ypos, and transmission power. It ensures the protocol's packet structure is consistently maintained and interpreted across the network nodes.
- **[cmutrace.cc:]** This file incorporates enhanced trace and logging functionalities specifically designed to capture energy consumption events and other critical metrics relevant to the FCEE protocol with precision.
- **[NSdefault.tcl:]** This configuration file is tailored for the FCEE protocol, allowing researchers to experiment with diverse configurations within the NS-2 framework.

- **[setdest:]** Utilized to generate node positions, movement speeds, and directions as shown below.

```
setdest -v 2-n $numnodes -p $pt -M $maxspeed -t $simtime -x $maxx -y $maxy
```

- **[Cbrgen:]**This tool orchestrates node connections, stipulating the maximum connections and designating agent types between nodes, Which is shown below.

```
ns cbrgen.tcl [-type cbr|tcp] [-nn nodes] [-seed seed] [-mc connections] [-rate rate]
```

Each adaptation within the NS-2 framework has been meticulously documented, promoting traceability and facilitating wider adoption. These modifications are essential in aligning the simulator's performance with the intended network model, especially regarding the dynamics of mobile nodes.

The enhancements to the NS-2 framework markedly elevate its ability to simulate the complex behaviors of mobile nodes with high accuracy. This progress is vital for establishing a robust foundation for the research methodology, ensuring that the simulations reflect real-world conditions. The following subsection will delve deeply into the mobility model, outlining the vital changes needed to boost the simulations' precision. This approach guarantees that the simulations are theoretically robust, practically applicable, and dependable.

5.1.5 Mobility Model

Random mobility models, such as Random Way Point, Random Walk (random direction), Free Way, and Manhattan, are significant in the emulation of the networks. As far as current understanding goes, there is a lack of analytical research that calculates the anticipated number of hops for pathways in a mesh network under conditions of random mobility.

The FCEE routing protocol uses the RWP mobility model, which is widely used for mobility in network simulations and is commonly employed within the NS-2 framework. The RWP model establishes random waypoints and velocities to simulate node movement in a network. In the RWP model, each node selects a random destination within the simulation area and moves towards that destination with a predefined velocity. Once the node reaches its destination, it pauses for a specific duration before selecting a new random destination and velocity.

The RWP mobility model stands out for its stochastic nature and uncorrelated node motion. The analysis does not take into account any particular mobility patterns or limitations. The simulation area allows for unconstrained movement of nodes, thereby generating dynamic and realistic scenarios for network simulations.

As per the findings of (Younes and Albalawi, 2020), it has been observed that the distribution of X_1 or X_2 in the Random Waypoint Mobility Model is non-uniform in the long run. The probability distribution function for the position of a point X_n in motion along a line of length L, as shown in Equation 5.1.

$$f_{X_n}\left(x_n\right)=\frac{6}{L^2}x_n+\frac{6}{L^3}x_n^2 0\leq x_n\leq L \tag{5.1}$$

Given the independent and identically distributed nature of X_1 and X_2, the probability distribution function *pdf* that describes the location of the two points can be determined, as shown in equation 5.2.

$$f_{X_1X_2}\left(x_1,x_2\right)=f_{X_1}\left(x_1\right)\cdot f_{X_2}\left(x_2\right)0\leq x_1\leq L,0\leq x_2\leq L \tag{5.2}$$

The integral of the joint probability density function $f_{X_1X_2}(x_1,x_2)$, over the appropriate range for $S=|x_2-x_1|$, yields the cumulative distribution function (CDF). This function quantifies the probability that the distance S is less than or equal to a specific value d, as specified in Equation 5.3.

$$\begin{gathered}P(s\leq d)=\iint f_{X_1X_2}\left(x_1,x_2\right)dx_2dx_1=\iint f_{X_1}\left(x_1\right)f_{X_2}\left(x_2\right)dx_2dx_1\\=\int_0^d\int_0^{d+x_1}f_{X_1}\left(x_1\right)f_{X_2}\left(x_2\right)dx_2dx_1+\int_d^{L-d}\int_{x_1-d}^{d+x_1}f_{X_1}\left(x_1\right)f_{X_2}\left(x_2\right)dx_2dx_1+\\\int_{L-dx_1-d}^{L}\int_{X_1}^{L}\left(x_1\right)f_{X_2}\left(x_2\right)dx_2dx_1\end{gathered} \tag{5.3}$$

Upon evaluating the integrals in the final equation, the resulting outcome is as follows in equation 5.4.

$$P(S \leq d) = \frac{12d}{5L} - \frac{4d^3}{L^3} + \frac{3d^4}{L^4} - \frac{2d^6}{5L^6} \tag{5.4}$$

The probability density function $f(d)$ of d can be defined as the derivative of the Equation 5.5, described in equation 5.5 (Younes and Albalawi, 2020).

$$f(d) = \frac{12}{5L} - \frac{12d^2}{L^3} + \frac{12d^3}{L^4} - \frac{12d^5}{5L^6} \tag{5.5}$$

While modeling mobility is vital, choosing traffic models, such as TCP and UDP, plays a pivotal role in the simulation's outcome. The next chapter describes in detail the traffic models that are used in this thesis.

5.2 An Examination of TCP and UDP

The Transmission Control Protocol (TCP) is a fundamental mechanism that ensures reliable and ordered delivery of byte streams between source-destination pairs. It is the backbone for numerous Internet applications, including widely used services such as the World Wide Web, email, and file transfer. While the User Datagram Protocol (UDP) caters to applications prioritizing reduced latency over guaranteed reliability. Unlike TCP, UDP operates in a connectionless and unreliable manner without establishing virtual circuits or requiring acknowledgments. It simply transmits messages.

TCP provides a point-to-point communication channel, ideal for applications that demand reliable data transfer. Its performance relies on a subset of algorithms and techniques, notably flow control and congestion control. Flow control governs the rate at which data is transmitted between senders and receivers, ensuring a balance in a data flow. Congestion control, on the other hand, involves interpreting network signals to adjust transmission rates, preventing network congestion. TCP also employs mechanisms such as timeouts and retransmissions to address error control. By combining error detection and error correction, TCP guarantees successful data transmission, even though delays can be significant, especially in real-time applications.

However, it should be noted that TCP implementations often focus on optimizing performance within wired networks, neglecting the distinctive characteristics of wireless networks. This oversight can lead to suboptimal TCP performance in wireless environments. Unlike wired networks, where packet losses are typically attributed to network congestion, wireless networks experience losses due to various factors, including routing failures, network partitions, and high bit error rates. Attempting congestion control in such scenarios, particularly when employing TCP, results in poor performance. Furthermore, the intricate interactions among TCP, the media access control (MAC) layer, and routing algorithms significantly impact end-to-end performance (Karmakar, Chattopadhyay, and Chakraborty, 2017) & (Shenoy, Kumari M, and Shenoy, 2019).

The use of TCP in a wireless network causes a sharp decline in the network's overall throughput as the number of hops on a route rises. Several factors, such as MAC layer collisions and inappropriate route recovery timers in the routing protocol, contribute to this (Chakraborty and Nandi, 2014). The UDP was chosen to mitigate the potential adverse interactions between the newly proposed route selection rule based on the FCEE metric and TCP. The study chose UDP to avoid any adverse effects of the new route selection rule on TCP performance.

In summary, TCP and UDP serve distinct purposes in network communication. While TCP ensures reliability and orderly delivery, UDP prioritizes low latency. The characteristics of wireless networks necessitate careful consideration when implementing TCP, as the assumptions made for wired networks do not hold. By investigating the interplay between TCP, MAC layer, and routing algorithms, this thesis sheds light on the challenges faced in achieving optimal performance in wireless networks. It highlights the advantages of using UDP to avoid potential detrimental effects on TCP performance.

The selection of these traffic models ensures a comprehensive and realistic simulation, allowing for a deeper understanding of network dynamics.

5.3 Traffic models in Mesh Networks

In the intricate landscape of mesh networks, where each node can function as a router, the role of traffic models becomes paramount. These protocols are not merely facilitators of communication; they are the linchpins that ensure the efficacy and reliability of data transmission. By judiciously determining optimal paths for data flow, they manage potential network congestion, guarantee equitable resource distribution, and enhance the network's overall performance. Beyond these functions, traffic models adeptly address challenges such as packet loss, latency, and the intricacies of route discovery, thereby fortifying communication robustness within mesh networks. Within the scope of this thesis, particular emphasis is placed on the Constant Bit Rate (CBR) and Paretotraffic models, illuminating their pivotal roles in mesh network communication.

5.3.1 Constant Bit Rate (CBR)

The term Constant Bit Rate (CBR) traffic originates from the realm of Asynchronous Transfer Mode (ATM) and denotes a transmission paradigm where data is conveyed at a consistent bit rate. A CBR stream is thus characterized by the transmission of data in packets of a fixed size, separated by fixed intervals. Notably, the sender of a CBR stream does not endeavor to ascertain the successful reception of transmitted data by the destination, nor does it make any attempts to ascertain the existence of the destination itself. Consequently, the absence of a connection establishment phase is a defining feature, as the traffic propagates from the source to the destination without feedback from the destination or intermediate nodes.

The distinctive characteristics of CBR and TCP traffic impose diverse conditions and challenges on mesh networks. TCP traffic, being reliant on bidirectional communication, necessitates the availability of two-way traffic between the source and the destination for the successful delivery of data. This requirement encompasses the connection establishment and subsequent data transfer phases. In contrast, CBR traffic exhibits a more streamlined communication pattern, where unidirectional traffic exclusively between the source and the destination is sufficient. To accommodate the requirements of TCP traffic, it becomes imperative for the underlying routing protocol in mesh to ensure the availability of effective dual routes for each end connection. The presence of these redundant routes serves as a means to enhance the reliability and robustness of TCP-based communication in MANETs. The redundant routes act as backup paths, enabling the system to circumvent failures or disruptions in the network, thereby sustaining continuous bidirectional traffic flow.

In contrast, the more straightforward communication demands of CBR traffic necessitate the establishment of only a single route per data stream. As CBR traffic does not require bidirectional communication channels, the routing protocol's primary objective in this context is to determine an optimal and stable route from the source to the destination. The routing protocol must carefully consider link quality, path stability, and energy efficiency to select the most suitable route for transmitting the CBR data stream. By recognizing and addressing the differing requirements of CBR and TCP traffic, meshs can be effectively designed and optimized to support the specific needs of each traffic type. Establishing appropriate routing mechanisms that facilitate reliable bidirectional communication for TCP traffic and efficiently determining unidirectional routes for CBR traffic contributes to the mesh's overall performance and functionality in diverse scenarios and applications. The FCEE routing protocol addresses the distinct conditions CBR and TCP traffic impose in the mesh network. The protocol is designed to adapt to the specific requirements of each traffic type while maximizing energy efficiency. In the case of TCP traffic, which necessitates bidirectional communication, the

FCEE routing protocol ensures the availability of dual routes for each end connection.

By maintaining multiple routes, the protocol enhances the fault tolerance and reliability of TCP-based communication in the mesh. In the event of a link failure or disruption, the FCEE protocol leverages the redundant routes to reroute the bidirectional traffic swiftly, minimizing the impact on the connection and ensuring continuous data delivery.

Conversely, the FCEE routing protocol focuses on establishing an optimized and stable unidirectional route per data stream when dealing with CBR traffic. It carefully evaluates parameters such as link quality, path stability, and energy efficiency to select the most suitable route for transmitting the CBR data. By efficiently determining a single route for CBR traffic, the FCEE protocol minimizes routing overhead and conserves energy resources in the mesh. The FCEE routing protocol thus serves as a vital component in mesh, seamlessly accommodating the distinct requirements of both CBR and TCP traffic. By integrating the protocol with the network infrastructure, researchers and practitioners can harness its capabilities to enhance the overall performance, energy efficiency, and reliability of MANETs in diverse scenarios. The FCEE routing protocol contributes to informed decision-making. It facilitates the effective utilization of CBR and TCP traffic in mesh, empowering researchers and practitioners to make informed decisions and optimize the utilization and expansion of the AODV protocol.

5.3.2 Pareto Distribution Traffic

The Pareto traffic model demonstrates an **ON/OFF** packet generation pattern commonly employed in analyzing network traffic dynamics. Within the ON period, the generation rate of packets exhibits variability following a Pareto distribution. The precise configuration of this distribution is achieved by manipulating its shape parameter. Notably, the traffic generators associated with the Pareto model encompass additional parameters such as the packet generation rate during the ON period and the durations of both the ON and OFF periods. Employing a Pareto traffic generator facilitates the simulation of various traffic sources, including multimedia, video, and voice data. This model effectively captures such traffic types' distinctive characteristics and statistical properties, enabling researchers and practitioners to understand their behavior within network environments (Wang et al., 2020).

By accurately tuning the parameters of the Pareto distribution and incorporating them into the traffic generation process, the Pareto traffic model serves as a valuable tool for studying and evaluating the performance of communication networks. Its ability to faithfully replicate the dynamics of multimedia, video, and voice traffic sources enhances the realism of simulations, allowing for the comprehensive analysis of network protocols, resource allocation strategies, and quality-of-service provisioning mechanisms (Darabkh et al., 2018b).

In summary, the Pareto traffic model, characterized by its ON/OFF packet generation pattern and the utilization of a Pareto distribution, provides a robust framework for simulating and studying multimedia, video, and voice traffic sources. By carefully configuring the model's parameters, researchers and practitioners can gain profound insights into the behavior of these traffic types, enabling informed decision-making and advancing communication network technologies. A random variable X is considered to adhere to the Pareto distribution when it conforms to the specified probability distribution function, as shown in the following Equation of 5.6.

$$f(x) = P(X > x) = \begin{cases} \left(\frac{x_m}{x}\right)^{\alpha}, & x \geq x_m \\ 1, & x < x_m \end{cases} \tag{5.6}$$

Where x_m denotes a scale parameter. By varying x_m and α, on-off traffic can be generated. The integration of the Pareto traffic model with the FCEE protocol in the context of mesh networks establishes a comprehensive framework for analyzing and optimizing network performance. The Pareto model, with its ON/OFF packet generation pattern, aptly simulates multimedia, video, and voice traffic sources. Concurrently, the FCEE protocol addresses challenges pertinent to energy efficiency in mesh networks.

The cooperation of the Pareto traffic model and the FCEE protocol offers researchers invaluable insights into multimedia, video, and voice traffic dynamics within mesh networks. This integration facilitates the evaluation of the FCEE protocol's adaptability in managing diverse traffic types.

Recognized for its adaptability and energy-efficient routing, the FCEE protocol enhances resource allocation and operational efficiency in mesh networks. With its dynamic communication strategies, it can adeptly cater to the Pareto traffic model's requirements, adjusting its routing and transmission parameters in response to the model's bursty traffic nature.

The integration of the Pareto model with the FCEE protocol also empowers researchers to assess the influence of the Pareto distribution parameters on network performance. By modulating the shape parameter and other distribution attributes, the adaptability and efficiency of the FCEE protocol can be meticulously analyzed.

This combined approach significantly augments the domain of mesh networks, elucidating the performance and scalability of the FCEE protocol concerning multimedia, video, and voice traffic. It paves the way for informed decision-making, steering researchers toward the effective deployment of the FCEE protocol in mesh networks.

This research rigorously examines the interplay between the Pareto and CBR traffic models and the FCEE and AODV protocols. The objective is to discern the protocols' behaviour and adaptability under diverse traffic conditions, focusing on metrics like packet delivery, energy efficiency, and overall network performance. The results of the routing protocol efficiency based on the traffic models are presented in Appendix 7.4, in extensive detail.

5.4 Methodology

The presented methodology serves as a comprehensive blueprint for the simulation process, meticulously detailing each phase, tool, and technique employed. The presented chapter initiated our research with the configuration of the NS-2 simulator, seamlessly integrating the modifications elucidated in the preceding sections. Subsequently, we meticulously defined our network's topology, delineating node placements, connections, and movement trajectories. At the heart of this methodology was the execution of diverse simulation scenarios. This work dynamically adjusted parameters such as node density, transmission range, and traffic type. Every simulation run was rigorously documented, capturing pivotal metrics like throughput, delay, and packet loss.

5.4.1 Data Analysis

Post-simulation, we transitioned into an intensive phase of data interpretation. Leveraging advanced using PERL and AWK scripting language tools with some statistical tools, this thesis presented the results that derive from the trace file information. This analytical phase was instrumental in comprehending the behavior of mobile nodes within our network and discerning the ramifications of our modifications to the NS-2 framework.

5.4.2 Performance Evaluation

The proposed chapter subjected the network's performance to a thorough examination across varied topologies, juxtaposing the efficacy of the **FCEE** protocol against benchmarks like standard **AODV**, **DSR**, **IRAODV** (Anand and Sasikala, 2019), **Enhanced-Ant-AODV** (Sarkar, Choudhury, and Majumder, 2021), **STAB-AODV** (Pandey and Singh, 2022), and **SSAODV** (Manjhi and Patel, 2012). The NS-2 modeller emerged as our tool of choice for these simulations. Central to our thesis was exploring the **FCEE's** performance across metrics such as average throughput, delay, routing overhead, packet delivery ratio, packet loss ratio, and average energy consumption within diverse wireless mesh network scenarios. This thesis meticulously designed these scenarios to gauge the performance implications of deploying the newly introduced **FCEE** routing protocol.

5.4.3 Scenario Classification

This chapter comprehensively explores various dimensions of network dynamics, encompassing network density, temporal variations in simulation, fluctuations in network size, traffic typologies, and the intricacies of node velocities and counts. This work has meticulously categorized our scenarios into distinct groups for methodological clarity analysis. Each of these groups epitomizes specific facets of the network, such as its dimensions, node count, and node velocity, as elucidated in Table 5.2. In every scenario, the MAC protocol employed was IEEE 802.11. For scenarios (5.4.3, 5.4.3, and 5.4.3), a singular gateway was utilized. Conversely, scenario **D** 6.4.4 incorporated both one and two gateways. While most scenarios were characterized by a node count of 100, scenario 5.4.3 was distinct with a configuration of 60 nodes. Also, the simulation parameters of scenario E are described with detailed results in Appendix 7.4.

Table 5.2: Classification of the Simulation Scenarios.

Scenario	Nodes speed	Routing protocols	Simulation Time	Topology Area	Traffic type
A	10 m/s	FCEE, AODV, IRAODV	300 sec	1000 x 1000 m	CBR
B	10, 20, 30, 40, 50 m/s	FCEE, STAB-AODV, SSAODV	150 sec	800 × 900 m	CBR
C	10 m/s	FCEE, AODV, Enhanced-Ant-AODV, DSR	200 sec	1800 X 840 m	CBR
D	10 m/s	FCEE, AODV	300 sec	1000 x 1000 m	CBR
E	10 m/s	FCEE, AODV	180 sec	1000 x 1000 m	CBR & Pareto

Scenarios of Group A:

Group A of this study investigates the performance of the FCEE technique in conjunction with both the standard AODV protocol and the Intelligent Routing AODV (IRAODV) protocol (Anand and Sasikala, 2019). The IRAODV strategy entails the utilization of an algorithm incorporated into the AODV protocol, which enhances its energy reduction capabilities.

To estimate distances in cases where access is limited or specialized equipment is unavailable, the Received Signal Strength Indication (RSSI) is employed (Carlsson et al., 2018). The RSSI is a standard metric in radio receiver technology, commonly used in wireless networking within the IEEE 802.11 protocol family. The FRIIS transmission formula based on RSSI measurements can calculate the distance. The present study will demonstrate the application of this intelligent technique through a practical example. When access is restricted or direct distance measurement is unfeasible, the RSSI is an alternative means of estimating distance. The RSSI value is typically hidden from end users of devices housing the receiver, but it is readily discernible to those employing wireless networking technologies, as shown in the following Equation 5.7 (Chatterjee and Das, 2015).

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^z d^2 L} \tag{5.7}$$

Several crucial parameters contribute to the computation of distance through RSSI, including the receiving power P_r, transmitting power P_t, a gain of the transmission antenna G_t, a gain of the receiving antenna G_r, wavelength (λ), system loss factor (L), and distance between antennas D. Two nodes aim to establish communication. In a MANET consisting of N nodes, the set of neighbouring nodes at a one-hop distance is denoted as A_i, the set of adjacent nodes at a two-hop distance as B_i, and the set of all distances as D_i. The X and Y axes are established accordingly.

The proposed procedure involves identifying central nodes within a given region and updating the corresponding table of individual nodes. Subsequently, a coordinator node is selected to transmit the packet once a predetermined number of nodes have received it. However, challenges such as route discovery overhead, routing loop formation, and lack of Quality of Service (QoS) support persist in IRAODV protocols. Scenario Group **A** is devised to address these challenges, where the FCEE parameters are set to match those of the IRAODV routing protocol for a proper comparison. Overall, this study aims to comprehensively analyze the weaknesses and limitations associated with the IRAODV protocol, propose the FCEE protocol as an enhanced solution, and evaluate its performance in terms of energy optimization.

Scenarios of Group B:

This study examines the effects of fluctuations in node speed on network behaviour, utilizing the FCEE as a metric for the routing discovery mechanism. This study investigated is done with a novel protocol names Stable-AODV (STAB-AODV) (Pandey and Singh, 2022). This study aims to compare the node speed impact of the FCEE with STAB-AODV and AODV, to enhance the quality of AODV routing, specifically in terms of throughput, PDR, delay, control message overhead, and normalized routing load.

The proposed methodology of STAB-AODV involved the selection of the subsequent hop through a comparison of residual energy and received signal quality against their corresponding dynamic threshold values. Additionally, the stability factor metric is incremented by one before processing the

RREQ packet. If a duplicate RREQ (Route Request) packet is received at a subsequent stage with a superior stability factor, said packet shall be deemed prioritized. Following establishing a route, every node transmits a hello packet to monitor the status of adjacent nodes. The receiving node of a *"hello"* message contains information solely on its nearby neighbours with minimized delay, as shown in equation 5.8.

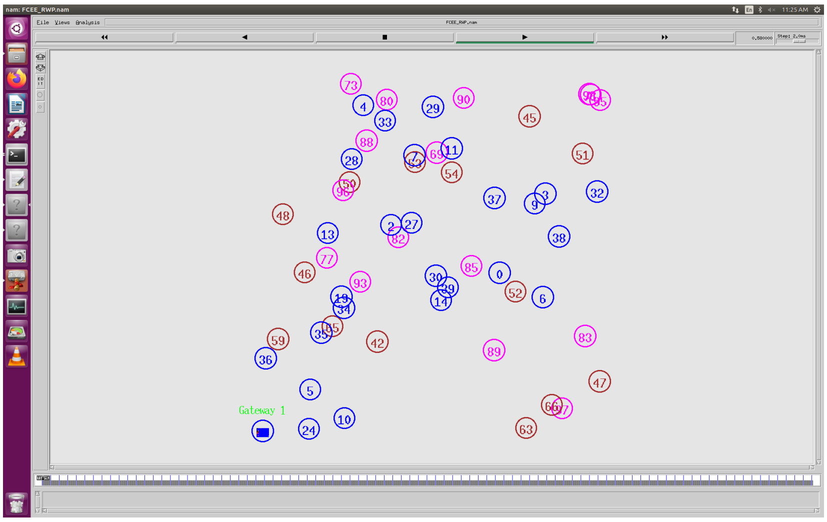
$$SS_{CURR} = \frac{(P_{tr}) \times (G_{tr}) \times (G_r) \times \left(h_r^2\right) \times \left(h_t^2\right)}{(d^4 \times L)} \tag{5.8}$$

where SS_CURR represents the power received by the node $Node_i$.
P_tr denotes the transmitted signal Power.
G_tr and G_r (with $G_tr = G_r = 1$) are the gains of the transmitter and receiver antennas, respectively.
The terms h_r^2 and h_t^2 (where $h_r = h_t = 1.5''$ m) represent the heights of the receiver and transmitter antennas, respectively.
L (with $L = 1$) signifies the Path Loss, and d is the distance between the transmitter and receiver.
The subsequent chapter details the simulation results, which underscore the superior efficiency of the FCEE compared to STAB-AODV.

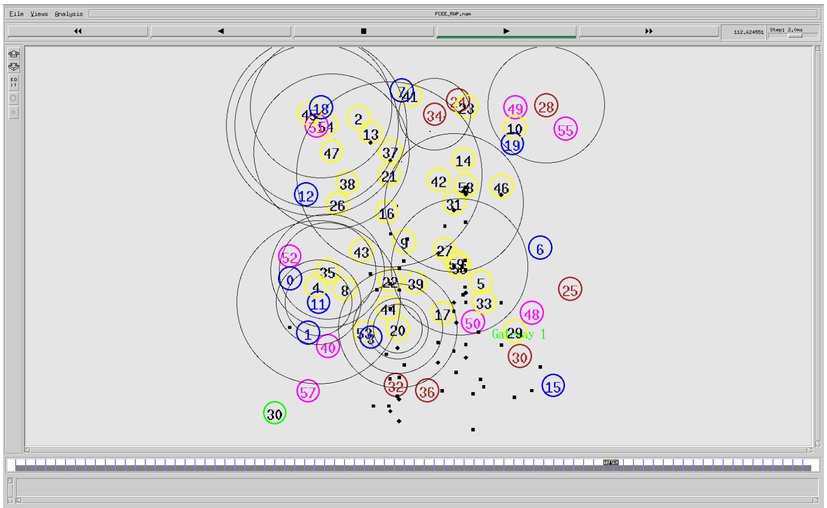
Scenarios of Group C:

This study entails a comprehensive analysis of the impact of node fluctuations on the performance of the modified AODV protocol in diverse scenarios. Specifically, the group has chosen to examine the efficiency of the FCEE technique and another novel routing protocol called Enhanced-Ant-AODV by employing a network comprising 100 nodes.

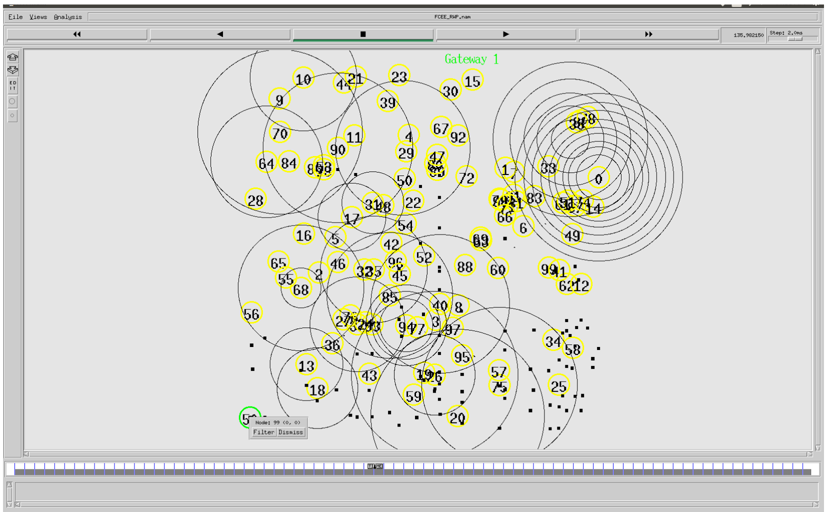
The Enhanced-Ant-AODV is based on an approach of enhancing Quality of Service (QoS) in mobile ad hoc network (MANET) by integrating Ant Colony Optimization (ACO) with AODV protocol to facilitate route selection (Sarkar, Choudhury, and Majumder, 2021). The optimal pathway for data transmission is determined by employing pheromone value within the ant colony mechanism integrated with AODV. The present study involves the computation of the pheromone value of a given route, which is determined by considering several factors, such as the end-to-end reliability of the path, congestion, number of hops, and residual energy of the nodes along the route. The data packet transmission process involves selecting the way with the highest pheromone value. Figure 5.5, Shows the scenarios group animation.



(a) Scenario A.



(b) Scenario B.



(c) Scenario C.

Figure 5.5: Scenarios Group Animation.

Scenarios of Group E:

In this comprehensive study, we delved deep into the complexities of the FCEE and AODV routing protocols, emphasizing their operational dynamics under distinct traffic patterns, namely Constant Bit Rate (CBR) and Pareto. By undertaking this comparison, we aimed to shed light on each protocol's potential advantages and limitations in different network scenarios. The methodology, data analysis, and detailed results of this comparative assessment have been carefully documented and can be accessed in Appendix 7.4. This appendix is a rich resource for those seeking an in-depth understanding of the performance metrics observed during our evaluations. The comprehensive results from the simulation of scenario E are meticulously detailed in Appendix 7.4.

5.4.4 Modeling Assumption

This section provides a comprehensive exposition and rationale for the various assumptions underpinning the simulation model employed in this study. The principal assumptions of the model are elucidated as follows:

Network Area and Node Density: The network area and the number of nodes within it are not constrained and are detailed in the accompanying table. The plane's boundary edges are open, precluding any reflections, and all nodes are distributed randomly across the plane. To attain varying node density values, adjustments are made to the transmission range of network nodes as required. The simulation system operates using a single, unchanging communication channel.

Variable Node Speeds in Mesh Networks: In a mesh network, where nodes engage in direct communication to relay data, the introduction of diverse node speeds can be advantageous for several reasons:

Enhanced Connectivity: Faster nodes can cross long distances in less time, connecting them to more neighbours. Connectivity improves network coverage and robustness.

Efficient Routing: Varying node speeds enhance mesh network routing. Relays or routers can forward data packets between slower nodes. Dynamic routing speeds and improves data delivery, optimizing network performance.

Load Balancing: Nodes with different speeds enable load balancing within the network. Higher-speed nodes can handle more data traffic and distribute the workload, preventing congestion and bottlenecks. Real-world mesh network nodes may have distinct mobility patterns. Nodes may be permanent or movable. The network can adapt to changing mobility patterns by allowing nodes to different speeds, providing continuous communication and data transmission.

Resilience to Failures: Nodes with various speeds can sustain network connectivity during node failures or disturbances. High-speed nodes can swiftly join or reroute data to compensate for slower or failed nodes. Resilience improves fault tolerance and network operation. Due to all the reasons above, the presented thesis Highlights the node speed impact of the FCEE routing protocol with the STAB-AODV, SSAODV, and AODV routing protocols.

The study utilized a traffic stream based on the User Datagram Protocol (UDP). The UDP protocol is characterized as a connectionless protocol that does not necessitate a pre-established connection between two endpoints before transmitting packets. In contrast, the transmission control protocol (TCP) necessitates initiating a connection between the sender and receiver before sending any data.

According to the reference, optimal network performance regarding global throughput can be attained through UDP. Nadine Hasan et al.(Hasan, Mishra, and Ray, 2022), introduced a simulation of stationary scenarios and found that the interactions among TCP, MAC, and routing protocols significantly impact the performance of a mesh network. To mitigate the potential interference arising from the coexistence of the novel routing selection approach utilizing the FCEE and the TCP, the utilization of UDP is implemented in this investigation as a means of circumventing the conflict that may arise from the deployment of two distinct flow control mechanisms within the network.

5.5 Summary

This chapter has carefully examined the complexities of simulating mobile nodes within a network using the NS-2 framework. The discourse presented herein establishes a foundation for an in-depth analysis of mobile node dynamics, achieved through judicious modifications and a rigorous methodology. As explained in chapter 6, our discoveries significantly impact network simulations.

6

Comprehensive Results Analysis and Discussion

Contents

Overview

This chapter presents a detailed analysis of the simulation outcomes of integrating a fuzzy logic principle into the AODV protocol's routing framework. The foundation of this principle is anchored in the advancements of the FCEE routing protocol.

Utilizing the NS-2 simulation platform, we systematically evaluate the efficacy of the AODV routing algorithm, now enhanced with the FCEE. This assessment positions the FCEE against a range of recognized protocols, such as the standard AODV, DSR, AODV and Intelligent Routing AODV (IRAODV) (Anand and Sasikala, 2019), Enhanced-Ant-AODV (Sarkar, Choudhury, and Majumder, 2021), Stable-AODV (STAB-AODV) (Pandey and Singh, 2022), and Signal Strength-Based Ad-Hoc On-Demand Distance Vector (SSAODV) (Manjhi and Patel, 2012).

The core objective of this chapter is to ascertain the performance merits of the FCEE about its peers. This is achieved through meticulous performance comparisons spanning various scenarios, with the finer details encapsulated in the ensuing table of 5.2.

Moreover, we undertake a precise comparative statistical analysis to delve deeper into the simulation outcomes of both the FCEE and AODV routing protocols. The overarching aim is to clarify the relative strengths and efficiencies of the FCEE compared to established protocols, achieved through rigorous statistical examination across multiple scenarios.

6.1 Simulation Model

This doctoral dissertation carefully evaluates the performance of the proposed scheme across diverse simulation scenarios. Utilizing NS2.35 for simulations, this research leverages its comprehensive support for many routing protocols tailored for wireless networks. The Network Simulator is a sophisticated, object-oriented simulation tool, harmoniously integrating the OTcl interpreter as its front-end interface and C++ as its computational back end.

Perl and *AWK* scripts are employed for data extraction from the trace file, with the subsequent visual representation crafted in MATLAB. MATLAB, renowned for its prowess in numerical computing and data visualization, is the chosen environment for graph plotting. Its widespread academic and industrial adoption can be attributed to its extensive plotting functions, user-friendly interface, and seamless integration with its myriad functionalities. MATLAB's capabilities are vast, from statistical analysis, curve fitting, and optimization to signal and image processing. As illustrated in Figure 6.1, users can effortlessly analyze data and generate insightful visualizations by harnessing these integrated features.

A proper comparative analysis anchors this research, juxtaposing the proposed protocol against established counterparts, including the AODV, IRAODV, STAB-AODV, SSAODV, and Enhanced-Ant-AODV protocols. The evaluation criteria encompass key metrics such as throughput, packet delivery ratio, end-to-end delay, and the proportion of active nodes. This performance assessment necessitated the strategic alteration of parameters, including the number of nodes, node velocity, and network data rates, while ensuring the consistency of other parameters.

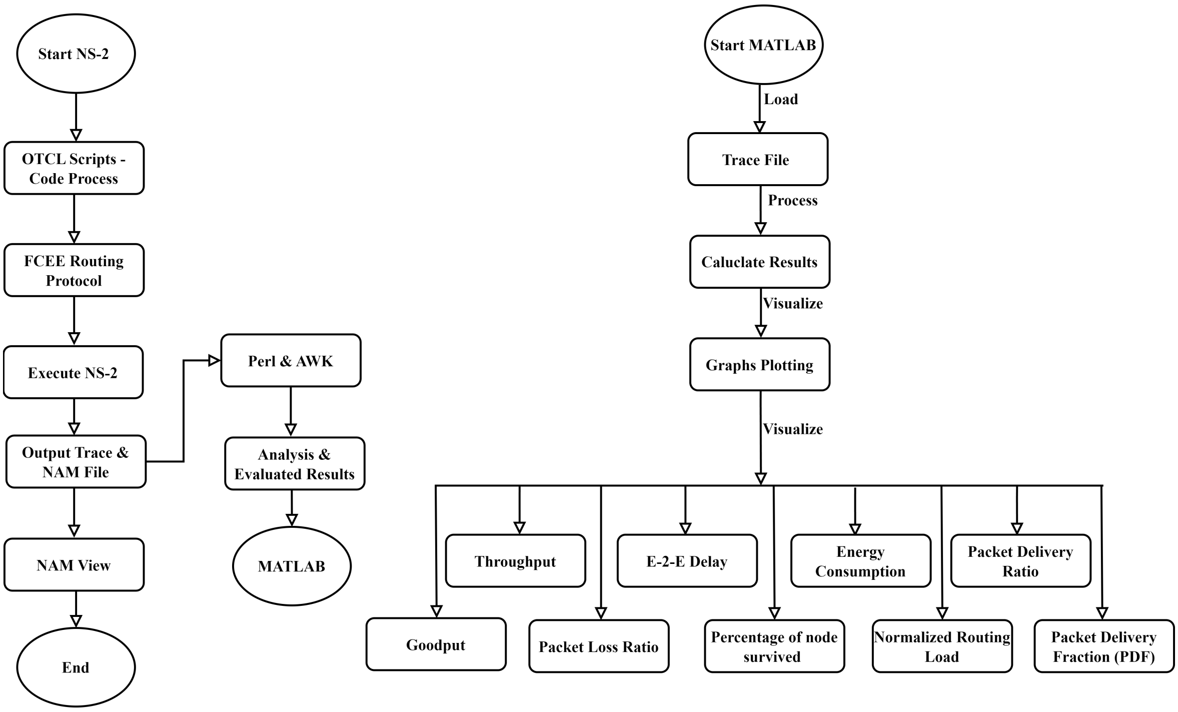


Figure 6.1: NS2 Structure & Code Operations.

6.2 Simulation Operation

The present study utilized the latest version of NS-2, specifically version 2.35, to generate two distinct types of trace files: simulation trace and Nam trace. The simulation trace file was subsequently employed for data analysis, whereas the Nam trace file was utilized with the network animator (Nam) utility to visualize the simulation process. Figure 6.1, illustrates the execution of the simulation using NS-2. The graphical representations were generated, and the trace files were analyzed using the MATLAB programming language due to its robust capabilities and the above-mentioned reasons. Furthermore, a custom Perl script was proposed in this study to calculate various metrics, including packet drop rate (PDR), throughput, average End-to-End Delay (E-2-E delay), average energy consumption, Normalized Routing Load (NRL), Packet Loss Ratio (PLR), percentage of node survival, goodput, packet delivery fraction (PDF), and network overhead, based on the trace files.

In addition, the simulation scripts were developed in OTcl, an object-oriented extension of TCL, to model and evaluate UDP protocols, routers, and other network components within the NS-2 software. Network scenarios were created using TCL scripts, ensuring consistent connection settings, node movement, and location implementation. Modifications were made to adjust the transmitting and receiving power of the nodes, aiming to optimize packet transmission. The simulation results were recorded in a trace file encompassing detailed network simulation information. The proposed protocol's effectiveness was compared against widely used AODV variant protocols and other routing protocols.

To emulate real-world dynamics, the simulation area initially featured a random distribution of nodes. Radio communications were permitted in all directions using omnidirectional antennas ranging from 250 meters per node. Node mobility was limited to a maximum speed of 10 meters per second. The Two-Ray Ground Reflection Model was employed to simulate radio wave propagation. The simulation's traffic sources were activated from the beginning and remained active throughout, generating continuous bit rate (CBR) traffic in UDP packets, each consisting of 512 bytes. To better reflect the dynamic nature of real-world scenarios, the simulation's stop period ranged from 1 to 10 seconds. In the current configuration, the power usage of each node was set to 1.15 W when idle, 1.2 W during transmission, and 1.6 W during reception. The movement of nodes followed a Random Waypoint (RWP) model generated by the Setdest tool, while the cbrgen utility facilitated the construction of random data transmission scenarios. Emphasizing performance analysis in the context of mobility, synthetic mobility models were employed to approximate real-world mobile entity behaviour. These models served as a valuable means to draw inferences regarding critical network characteristics. The mobility model defined the paths taken by the mobile nodes in the simulated experiment. Given that the performance of a routing protocol may vary depending on the mobility model, it represents an essential role in designing and implementing an adequate wireless infrastructure.

In most instances, the spatial distribution of mobile network nodes, as governed by the Random Waypoint (RWP) model, exhibited non-uniform characteristics. The velocity at which each node progressed towards its designated destination adhered to a normal distribution centered around zero meters per second, within the bounds of the maximum allowable speed. The selection of the RWP mobility model for this simulation stemmed from its close alignment with the mobility patterns commonly observed in mobile device users, thereby enhancing the fidelity of the wireless mesh network representation.

6.3 Parameters Evaluation

In mesh networks, nodes are typically distributed stochastically. This distribution can be visualized either on a three-dimensional sphere's surface with an area of 1 square meter or within an equivalent planar disk. This work seeks to understand the distinct influence of network edges.

Each node autonomously selects a destination for data transmission based on proximity to a randomly determined point, resulting in an average separation of approximately 1 meter between destinations.

Our framework suggests that nodes operate uniformly, with all transmissions at a consistent power level. To address the challenges of Arbitrary Networks, this work integrated a Protocol and Physical Model that considers interference.

The ensuing evaluation results are pivotal for mesh networks. This thesis assesses various parameters to determine routing protocol performance. Hence, this thesis aims to explore the dynamics of the FCEE routing protocols against these parameters.

6.3.1 Performance Metrics

The assessment of mesh networks can be conducted by employing a range of performance metrics to ascertain their efficiency, reliability, and effectiveness. Presented below are several prominent performance metrics commonly utilized for evaluating mesh networks. Several performance metrics have been considered while analyzing the protocols (FCEE, AODV, IRAODV, STAB-AODV, SSAODV, and Enhanced-Ant-AODV).

6.3.2 Network Throughput

The concept of throughput is conventionally characterized as the temporal mean of the number of bits per second that each node can convey to its intended recipient. Achieving a bit throughput rate per second for individual nodes is possible by implementing a spatial and temporal transmission scheduling scheme. This involves operating the network multi-hop and utilizing intermediate nodes for buffering during transmission delays. By doing so, each node can successfully transmit an average bit rate per second to its intended destination node.

The feasibility of specific throughput levels depends on node positioning, which often lacks a systematic pattern. This refers to the traffic destination at each node, defined within the PAC Learning Theory framework. The problem's inherent randomness allows for considering probabilities that approach zero. If certain deterministic constants exist, the throughput capacity of the Random Networks category can be estimated to be of the order of bits per second, as shown in equation 6.1 (Gupta and Kumar, 2000).

$$\begin{gathered}\lim_{n\to\infty} \operatorname{Prob}(\lambda(n) = cf(n) \text{ is feasible }) = 1 \\ \liminf_{n\to\infty} \operatorname{Prob}\left(\lambda(n) = c' f(n) \text{ is feasible }\right) < 1\end{gathered} \tag{6.1}$$

In summary, equation 6.2, is used to calculate the throughput capacity, where mathematically, the concept can be formally defined as:

$$\text{Throughput} \;=\frac{\text{No.of bytes received } * 8}{\text{Simulation time } \times 1024}\text{Kbps} \tag{6.2}$$

6.3.3 Packet Delivery Ratio (PDR)

The Packet Delivery Ratio (PDR) is a performance metric used to measure the effectiveness of packet transmission in mesh networks. It represents the ratio of successfully delivered packets to the total number of packets sent within the network (Rishiwal, Kush, and Verma, 2008) & (Sisodia, Singhal, and Khandal, 2017). PDR is calculated by dividing the number of successfully received packets by the total number of packets transmitted, expressed as a percentage. A higher PDR indicates a more reliable and efficient network, as more packets are successfully delivered to their intended destinations. In mesh networks, where multiple paths exist between source and destination nodes, PDR can vary depending on the routing algorithms, network congestion, node density, and other factors. By evaluating the PDR, researchers and network administrators can assess the network's ability to deliver data accurately and reliably. It is important to remember that although PDR offers valuable insights into the performance of packet delivery, it should be evaluated in conjunction with other metrics, such as latency, throughput, and network scalability, to obtain a comprehensive understanding of the overall network performance and its appropriateness for specific applications.

The mathematical calculation for determining the PDR in mesh networks involves dividing the count of successfully delivered packets by the total count of transmitted packets and multiplying the quotient by 100 to represent the PDR as a percentage, as shown in equation 6.3.

$$\text{PDR} = \frac{\sum \text{Received Data Units at D}}{\sum \text{Data Units Originated from S}} \tag{6.3}$$

Here, D refers to the destination, and S refers to the source.

6.3.4 Packet Loss Ratio (PLR)

In the area of computer networking, we assess the Packet Loss Ratio (PLR) to determine the percentage of data packets that do not successfully reach their intended destination when transmitted from one device to another (Setijadi, Purnama, Purnomo, et al., 2018) & (Kumar, Ramya, and Masillamani, 2010). In network communication, information is often segmented into smaller units called packets, which are then dispatched across the network. Regrettably, various factors may lead to the loss of some of these packets during transmission, resulting in data loss or communication delays (Kiran et al., 2018). The PLR is a metric that quantifies the proportion of lost packets relative to the total number of packets sent. This ratio is mathematically expressible through the following formula 6.4:

$$\text{PLR} = \left(\frac{\sum_{i=1}^{N} \mathbb{I}_{\text{loss}}(i)}{\sum_{i=1}^{N} 1} \right) \times 100\% \tag{6.4}$$

In this equation, PLR stands for Packet Loss Ratio. The term $\sum_{i=1}^{N} \mathbb{I}_{\text{loss}}(i)$ represents the summation of lost data units over N total transmissions, where $\mathbb{I}_{\text{loss}}(i)$ is an indicator function that equals 1 if the i-th data unit is lost and 0 otherwise. The denominator, $\sum_{i=1}^{N} 1$, denotes the total number of transmitted data units. The result is multiplied by 100 to express the ratio as a percentage.

For instance, if a mesh network transmitted 1,000 packets and 50 packets were lost or not successfully delivered, the PLR would be: $\text{PLR} = (50/1000) \times 100 = 5\%$

In this example, the PLR is 5%, indicating that 5% of the packets sent within the mesh network were lost or not successfully delivered. A high PLR value suggests poor network performance, as it signifies a significant loss of packets during transmission. This can result from network congestion, link failures, interference, or other factors affecting packet delivery. Minimizing the PLR is crucial for maintaining reliable communication and data transfer in mesh networks.

Through the diligent observation of the Packet Loss Rate (PLR) and the subsequent implementation of effective strategies to mitigate packet loss, such as the optimization of routing algorithms, the enhancement of network infrastructure, or the incorporation of error correction mechanisms, network administrators possess the ability to augment the overall performance and dependability of the mesh network. The FCEE is efficient regarding PLR, as shown in the simulation result, and superior to its peers from other routing protocols.

6.3.5 Normalized Routing Load (NRL)

The concept of Normalized Routing Load (NRL) in a mesh network pertains to a quantitative measure employed to assess the routing overhead or the quantity of control traffic produced by the routing protocol within the network (Desai and Patil, 2014). It provides insights into the efficiency of the routing protocol in terms of the number of signaling and control messages required to establish and maintain routes in the network. NRL is calculated by dividing the total number of routing control messages by the number of data packets successfully delivered, as shown in Equation 6.5.

$$NRL = (\text{ Total Routing Control Messages })/(\text{ Total Data Packets Delivered }) \tag{6.5}$$

The term ”Total Routing Control Messages” denotes the aggregate number of control messages produced by the routing protocol to establish, maintain, and update routes. The components mentioned above encompass signalling packets, route request packets, route reply packets, and additional control messages integral to the routing process.

On the other hand, FCEE is a routing protocol designed specifically for wireless mesh networks focusing on reducing energy consumption and improving network lifetime. The FCEE protocol incorporates fuzzy logic principles to enhance the decision-making process in route selection. It utilizes dynamic membership functions to adapt to changing network conditions and make contextually aware, real-time decisions. The FCEE protocol aims to optimize network performance by minimizing energy consumption, maximizing network throughput, and improving key performance metrics such as packet delivery ratio, end-to-end delay, and the number of nodes that remain operational over time.

The FCEE protocol presents a novel routing approach using fuzzy logic and dynamic membership functions in mesh networks. This thesis aims to enhance the energy efficiency and efficacy of the routing process, resulting in a prolonged network lifespan and improved network performance.

6.3.6 Average end to end delay (E-2-E Delay)

The concept of end-to-end delay in mesh networks pertains to the temporal duration required for a data packet to traverse from its originating node to its intended destination node (Sisodia, Singhal, and Khandal, 2017). The total delay in packet transmission encompasses various components, namely transmission delay, propagation delay, queuing delay, and processing delay. These factors collectively contribute to the overall delay experienced by the packet during its journey. The measurement of end-to-end delay holds significant importance in assessing a network’s efficiency, as it directly influences the speed and punctuality of data transmission. The presented work expresses the average end-to-end delay mathematically in Equation 6.6 (Sarma and Nandi, 2010).

$$\text{Avg. E2E Delay} = \frac{\sum_{i=1}^{N}(t_{\text{receive},i} - t_{\text{send},i})}{N}\ \text{ms} \tag{6.6}$$

Another objective of the **FCEE** routing protocol is to minimize the duration of end-to-end communication delays within mesh networks. The FCEE protocol utilizes fuzzy logic principles and dynamic membership functions to make informed decisions during the routing process. The FCEE protocol incorporates an analysis of dynamic network conditions and context awareness to make informed decisions in selecting routes that effectively minimize the end-to-end delay.

The FCEE protocol considers various factors, including link quality, traffic congestion, and node energy levels, to optimize routing decisions and minimize latency. This project aims to establish optimal routes that effectively reduce waiting times, circumvent congested pathways, and guarantee the prompt delivery of data packets—integrating fuzzy logic and adaptive decision-making within the FCEE protocol results in improved routing efficiency and reduced end-to-end delay within mesh networks.

The FCEE protocol aims to enhance network performance by employing energy-efficient and context-aware routing decisions, explicitly focusing on minimizing end-to-end delay. The FCEE protocol has the potential to enhance communication in mesh networks by efficiently managing the routing of data packets.

6.3.7 Average Energy Consumption

The issue of energy consumption at the network interface presents a formidable challenge for mobile computing devices, whether they operate within a base station infrastructure or as part of a standalone mesh network (Mafirabadza and Khatri, 2016) & (Ko, Lee, and Lee, 2004). Despite the widely acknowledged significance of energy consumption in mesh protocol design, its evaluation as a criterion has been largely overlooked. This scholarly thesis proposes the hypothesis that evaluations focused solely on the bandwidth utilized in route negotiation fail to address resource utilization in mesh protocols comprehensively (Feeney, 2001).

The assessment of energy consumption in network protocols necessitates achieving a delicate balance between two primary objectives: attaining an accurate estimation of energy usage and developing a comprehensive understanding of protocol behaviour. The accuracy of an energy consumption estimate in simulation is directly correlated with the degree of resemblance between the simulated environment and the actual hardware being emulated.

Examining energy consumption in network protocols is paramount within the FCEE routing protocol. The FCEE protocol is specifically designed to address the pressing issue of energy consumption in mobile computing devices, particularly in mesh networks. It recognizes the pivotal role of energy efficiency in maximizing the performance and longevity of mesh networks. In contrast to conventional evaluations prioritizing bandwidth utilization during route negotiation, the FCEE protocol integrates energy consumption as a critical criterion for comprehensive protocol assessment. It acknowledges that a thorough understanding and optimization of resource utilization in mesh protocols necessitate including energy consumption as a crucial factor. Through meticulous analysis of energy consumption, the FCEE protocol can identify energy-intensive protocol behaviours and uncover link-layer issues that significantly impact energy utilization within the ad hoc environment.

The FCEE protocol strives to balance the precise energy consumption estimation and a comprehensive understanding of protocol behaviour. It recognizes the indispensability of accurately estimating energy consumption in simulation by meticulously emulating the physical characteristics of the simulated hardware. Hence, the FCEE routing protocol is intrinsically intertwined with the discourse on energy consumption in network protocols. It endeavours to address the energy challenge by recognizing energy efficiency as a vital factor in protocol evaluation. Furthermore, it integrates energy consumption analysis into its design and optimization processes. By implementing the FCEE protocol, researchers and network designers can advance energy-efficient routing strategies, enhancing their operational effectiveness, durability, and ecological viability.

To calculate the Average Energy Consumption (EC) in the FCEE protocol within a mesh network, using these steps and Equation 6.7.

Given the energy metrics:

$$\begin{aligned} E_{\text{tx}} &: \text{Transmission Energy} \\ E_{\text{rx}} &: \text{Reception Energy} \\ E_{\text{idle}} &: \text{Idle Energy} \\ E_{\text{sleep}} &: \text{Sleep Energy} \end{aligned}$$

And the collected data:

$$\begin{aligned} N_{\text{tx}} &: \text{The aggregate sum of packets transmitted across all nodes in the network.} \\ N_{\text{rx}} &: \text{ The total sum of packets received by all nodes in the network} \\ T_{\text{idle}} &: \text{Total time nodes spent in idle mode} \\ T_{\text{sleep}} &: \text{Total time nodes spent in sleep mode} \end{aligned}$$

The total energy consumption for each activity is:

$$E_{\text{total,tx}} = E_{\text{tx}} \times N_{\text{tx}}$$

$$E_{\text{total,rx}} = E_{\text{rx}} \times N_{\text{rx}}$$

$$E_{\text{total,idle}} = E_{\text{idle}} \times T_{\text{idle}}$$

$$E_{\text{total,sleep}} = E_{\text{sleep}} \times T_{\text{sleep}}$$

The overall total energy consumption is:

$$E_{\text{total}} = E_{\text{total,tx}} + E_{\text{total,rx}} + E_{\text{total,idle}} + E_{\text{total,sleep}}$$

Finally, the Average Energy Consumption (EC) for N nodes is:

$$\text{EC} = \frac{E_{\text{total}}}{N} \tag{6.7}$$

The above formula 6.7, calculates the average energy consumption per node in the mesh network using the FCEE protocol.

6.3.8 Node Survival Percentage

The Percentage of Node Survived metric in a mesh network pertains to the ratio of nodes that maintain their operational and functional state over a specified time frame. The metric evaluates the network's ability to withstand and recover from node failures or disruptions, assessing its robustness and resilience.

The resultant percentage represents the node ratio that effectively maintained connectivity and functionality throughout the observation period. A more significant percentage indicates a network that exhibits greater resilience, as a more significant proportion of nodes have remained operational in the face of potential failures or disruptions.

The calculation can be mathematically calculated by Equation 6.8.

$$PNS = \left(\frac{N_{\text{active}}}{N_{\text{total}}}\right) \times 100 \tag{6.8}$$

Where:

$$N_{\text{active}} : \text{Number of nodes still active or operational}$$

$$N_{\text{total}} : \text{Initial Count of Network Nodes}$$

6.3.9 Goodput

In networking, the term ”goodput” pertains to measuring the effective rate at which messages are successfully transmitted and received across a given communication channel. The concept of goodput is presented by (Qiao and Choi, 2001). It's essentially the application-level throughput, which excludes protocol overhead and retransmissions. For a mesh network using the FCEE protocol, the goodput is calculated by this Equation 6.9:

$$\text{Goodput} = \frac{\text{Successfully received data (bits)}}{\text{Total transmission time (seconds)}} \tag{6.9}$$

To calculate the goodput for the FCEE protocol in a mesh network:

Successfully received data (bits): This is the total number of bits that have been successfully received at the destination without any errors and the bits used for protocol overhead.

Total transmission time (seconds): The duration encompassing the entire transmission process, commencing from the initiation of the first-bit transmission to the completion of the reception of the final bit.

6.3.10 Packet Delivery Fraction (PDF)

In a mesh network, the Packet Delivery Fraction (PDF) is a metric used to evaluate the proportion of successfully delivered packets compared to the total number of packets transmitted within the network. It measures the effectiveness and reliability of packet delivery in the mesh network.

The concept of PDF is mentioned by (Daas and Chikhi, 2018). The Packet Delivery Fraction is calculated by dividing the number of successfully delivered packets by the total number of packets transmitted. It represents the fraction or percentage of packets that reached their intended destination without loss or errors, as shown in equation 6.10.

$$\text{PDF} = \frac{\text{Packet Delivery Ratio} \times \text{Goodput}}{\text{Throughput}} \tag{6.10}$$

The PDF metric is important in assessing the quality of service (QoS) the mesh network provides. A high PDF value indicates a high level of packet delivery success, implying efficient routing, low packet loss, and reliable communication. Conversely, a low PDF value suggests congestion, network disruptions, or inefficient routing, leading to a higher packet loss rate.

6.4 Results and Discussion

This section offers an analysis and assessment of the simulation results of integrating a novel path selection rule. This rule incorporates the FCEE metric and its associated enhancements into the routing mechanisms of AODV, Intelligent Routing AODV (IRAODV) (Anand and Sasikala, 2019), STAB-AODV (STAB-AODV) & Signal Strength-Based Ad-Hoc On-Demand Distance Vector (SSAODV) (Pandey and Singh, 2022), and Enhanced-Ant-AODV (Enhanced-Ant-AODV) (Sarkar, Choudhury, and Majumder, 2021).

In evaluating the modified AODV routing algorithm ”FCEE” compared to the routing mentioned above protocols, the presented work employed NS-2.35 as a simulator software.

6.4.1 Scenario A, Results & Discussion

In the present study, denoted as Scenario 6.4.1, this section elucidates the simulation outcomes and provides a comprehensive analysis of the findings. Figure 6.2, shows an in-depth look at how the FCEE protocol and the Intelligent Routing protocol for IRAODV perform regarding network throughput. It is noteworthy to mention that both of these routing protocols hold significant importance in the domain of mesh networks.

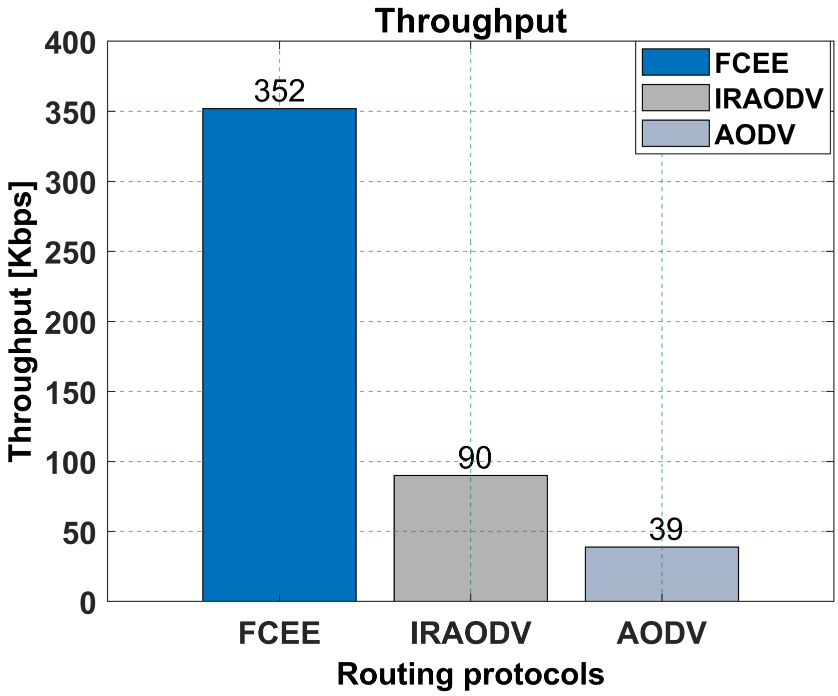


Figure 6.2: Network Throughput of Scenario **A**.

The FCEE protocol demonstrates superior network throughput, achieving 352 kbps compared to IRAODV's 90 kbps and AODV's 39 kbps. This signifies that FCEE can transmit more data within a given time frame than IRAODV and AODV. The key driver behind this enhanced throughput lies in introducing a memory channel, which effectively manages and reduces the number of broadcast packets.

Broadcast packets are bandwidth-intensive and necessitate substantial network resources. Nodes inherently process broadcast packets, leading to increased network load. Therefore, the proposed protocol attains higher throughput by curbing the proliferation of broadcast packets within the network. This aspect carries significant weight in selecting a routing protocol for a mesh network as it directly influences overall network performance.

However, it is crucial to acknowledge that network throughput should not be the sole determinant in routing protocol selection. Other factors, such as end-to-end delay (E-2-E delay), packet delivery ratio (PDR), and energy consumption (EC), warrant consideration in the analysis. This study aims to compute and assess these factors. In pursuing elevated throughput, it can be argued that FCEE emerges as a more advantageous choice for a mesh network.

The packet delivery ratio is a metric used to quantify the packet loss rate. A greater quantity of packets successfully delivered corresponds to a reduced incidence of packet loss. The packet delivery ratio results are presented in Figure 6.3. FCEE protocol exhibits a significantly superior packet delivery ratio (PDR) of 98% in contrast to the IRAODV protocol, which achieves a PDR of 68%.

Furthermore, the AODV protocol demonstrates a relatively lower PDR of 35%. This implies that the FCEE protocol has a higher capacity to successfully transmit data packets to their designated destination than the IRAODV protocol. This factor is essential in selecting a routing protocol for a mesh network, as it influences its reliability and performance. In the context above, the observed decrease in dropped packet percentage, approximately 2%, demonstrates favourable outcomes and renders FCEE a viable option for networks experiencing high traffic levels.

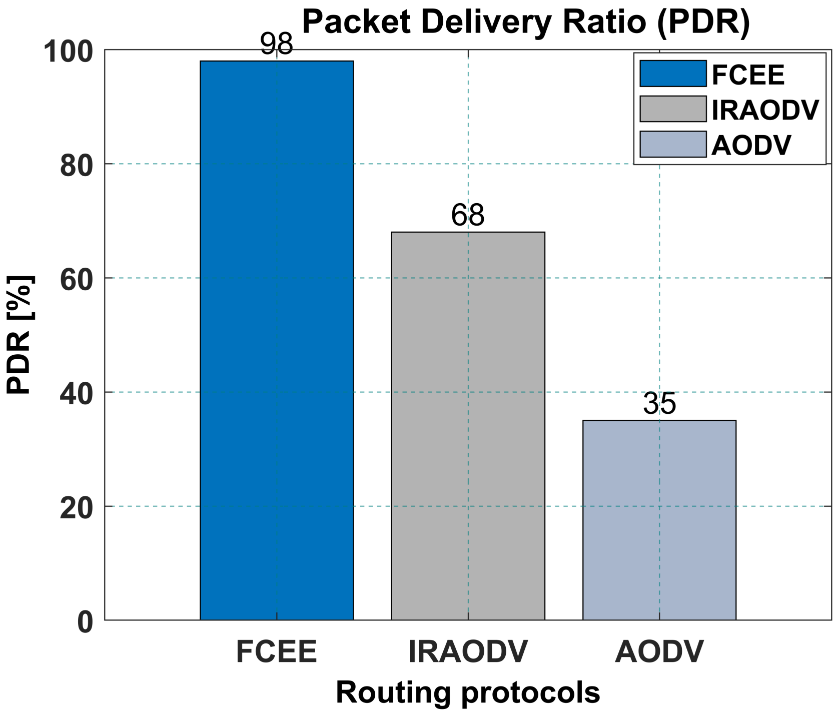


Figure 6.3: Packet Delivery Ratio of Scenario **A**

In comparison, the FCEE protocol exhibits a notably lower end-to-end delay of 13 ms, as opposed to the respective delays of 55 ms for the IRAODV protocol and 39 ms for the AODV protocol. This implies that the FCEE protocol exhibits a higher data transfer rate from a source to a destination than the IRAODV protocol. The consideration of this factor is of utmost importance in the selection of a routing protocol for a mesh network, as it has a direct impact on the overall performance of the network, particularly in the context of real-time applications such as voice and video communication, where achieving a minimal end-to-end delay is of critical significance. FCEE could be a more optimal selection for a mesh network requiring minimal end-to-end delays. The E-2-E delay in this specific network is illustrated in Figure 6.4.

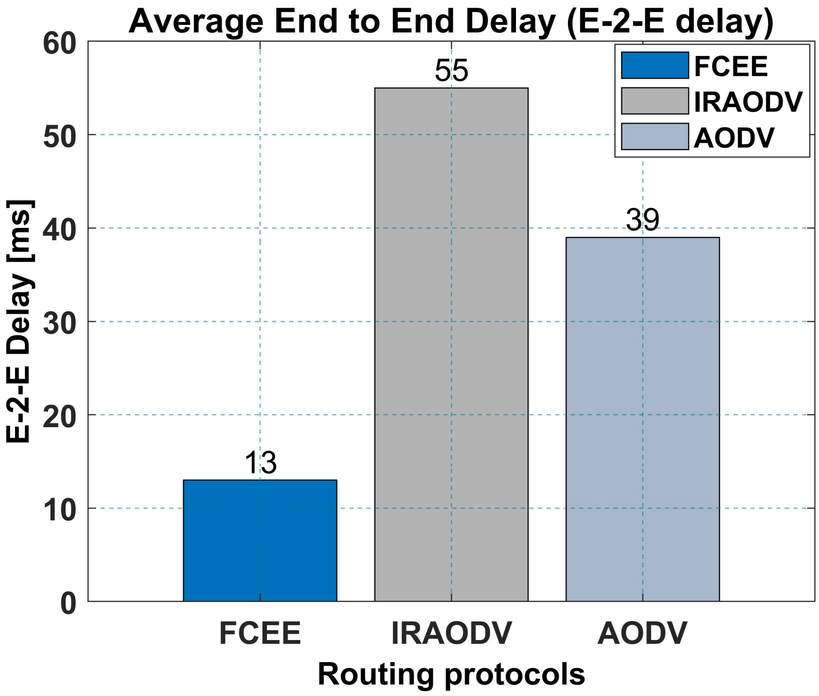


Figure 6.4: Average End to End Delay of Scenario **A**.

Energy consumption is a crucial consideration in selecting a routing protocol for a mesh network, as it directly impacts the lifespan of network nodes. In this context, our observations indicate that FCEE consumes 14 joules, whereas IRAODV consumes 40 joules, and AODV consumes 90 joules, as depicted in Figure 6.5. This disparity underscores FCEE's superior energy efficiency compared to IRAODV. FCEE's reduced energy consumption can be attributed to its routing mechanism.

In practical terms, adopting FCEE instead of IRAODV can substantially extend the operational lifespan of network nodes. This is especially advantageous for applications demanding prolonged network operation in resource-constrained environments. Regarding energy efficiency, FCEE, as a reactive routing protocol, may be advantageous over protocols like IRAODV. Incorporating fuzzy logic into the routing decision-making process may also contribute to energy conservation.

In summary, FCEE's reactive routing strategy, combined with fuzzy logic integration, diminishes routing overhead and conserves energy. This makes FCEE suitable for mesh networks with stringent energy consumption requirements and extended network longevity objectives. Nonetheless, as with any routing protocol selection, a comprehensive assessment of all factors and alignment with the network's specific needs remain essential.

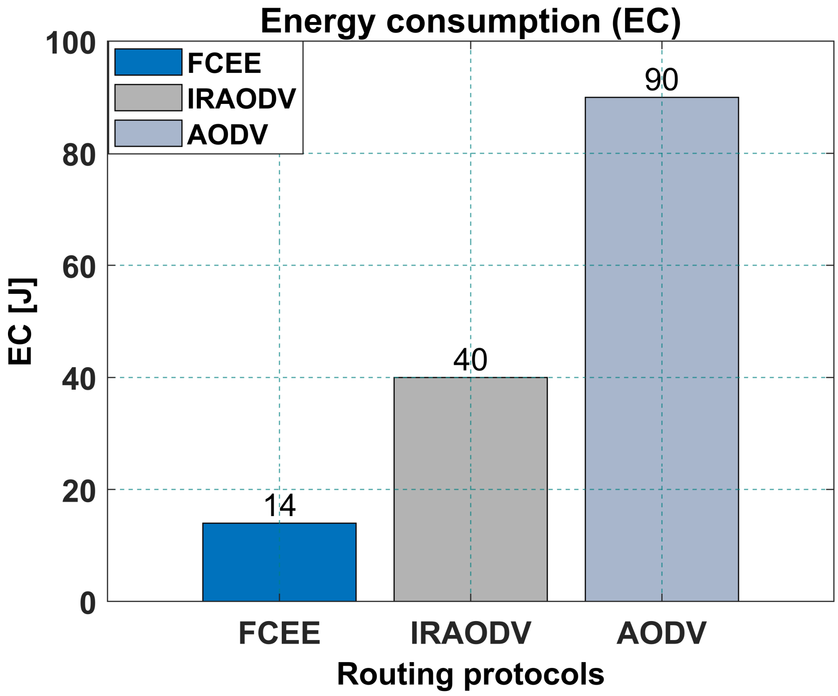


Figure 6.5: Energy Consumption of Scenario **A**.

Scenario 6.4.1, introduces the FCEE routing protocol for wireless mesh networks, leveraging the nuances of fuzzy logic. When benchmarked against reactive routing protocols like IRAODV (Anand and Sasikala, 2019), and AODV, FCEE showcases superior performance, achieving a minimal end-to-end delay and an impressive packet delivery ratio, all while maintaining energy efficiency.

6.4.2 Scenario B, Results & Discussion

This subsection, focusing on Scenario B (6.4.2), presents a comparative analysis between the proposed FCEE protocol, STAB-AODV, and SSAODV. Node speed plays a pivotal role in influencing various performance parameters in mesh networks, including throughput, Packet Loss Ratio (PLR), Packet Delivery Ratio (PDR), Normalized Routing Load (NRL), and average End-to-End (E-2-E) delay.

Mesh networks leverage mobile devices, often referred to as nodes, to establish communication pathways in the absence of a fixed infrastructure. The velocities of these nodes wield a significant impact on overall network efficiency. Nodes with high velocities can escalate network overhead due to frequent route discovery and maintenance message transmission. This heightened activity may lead to reduced network efficiency and hinder seamless communication. Moreover, elevated node velocities can elevate PLR and diminish PDR, as the likelihood of packet loss or drop during transmission surges.

Conversely, higher node velocities may enhance network throughput by expediting data transmission while nodes are in motion at greater speeds. Consequently, comprehending the influence of node velocity on the aforementioned performance parameters is imperative when designing and evaluating mesh networks. Network designers can optimize network performance across diverse operational scenarios by factoring in node speed.

Figures 6.6, 6.7, 6.8, 6.9, and 6.10 depict the impact of varying node speeds on PDR, PLR, throughput, NRL, and E-2-E delay, respectively. Node speeds range from 10 m/s to 50 m/s, with increments of 10, encompassing values of 10, 20, 30, 40, and 50. The network comprises 60 nodes.

Packet Delivery Ratio (PDR) denotes the percentage of successfully transmitted packets compared to the total dispatched packets. Data analysis reveals that the FCEE protocol attains the highest PDR, with STAB-AODV and SSAODV closely following suit. This observation underscores FCEE's ability to transmit a substantial number of packets successfully, a credit to its efficient routing mechanism (as illustrated in Figure 6.6). Conversely, SSAODV exhibits a relatively lower PDR, attributable to its less efficient routing mechanism.

Packet Loss Ratio (PLR) quantifies the ratio of lost packets to the total transmitted packets. Data analysis indicates that STAB-AODV and SSAODV exhibit comparable performance. However, the STAB-AODV protocol shows a slightly higher PLR when node speeds are lower, while the SSAODV protocol records a slightly higher ratio at higher node speeds. This discrepancy arises from the distinct routing mechanisms employed by the two protocols.

The PLR serves as a critical metric, influencing the suitability of a routing protocol for specific applications, particularly those necessitating reliable and swift packet transmission.

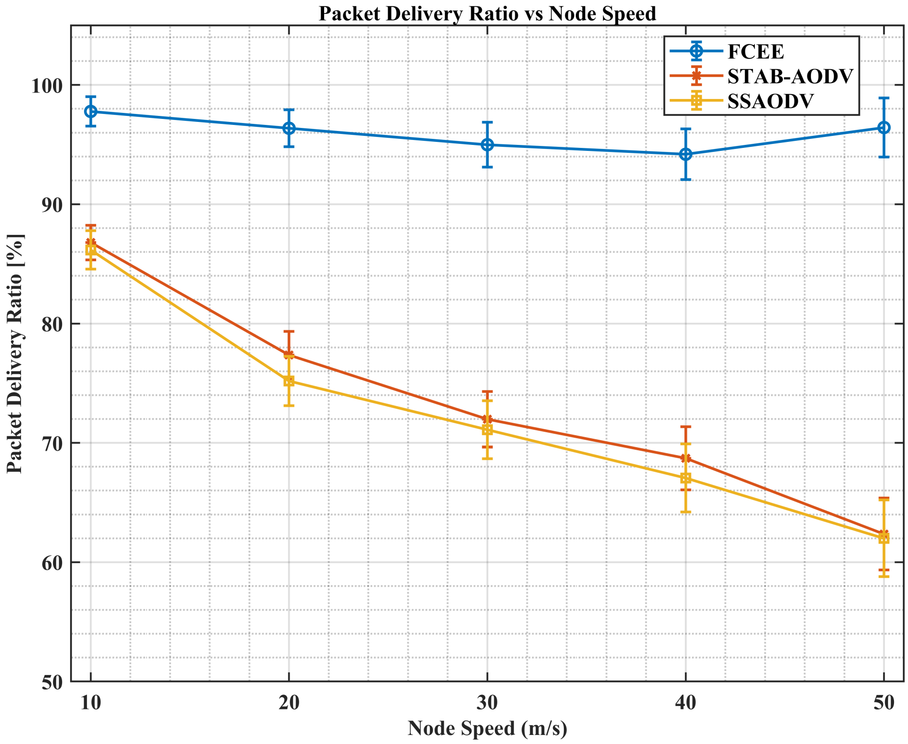


Figure 6.6: Packet Delivery Ratio of Scenario **B**.

The Packet Loss Ratio (PLR) refers to the proportion of lost packets relative to the total number of transmitted packets. Data analysis reveals that STAB-AODV and SSAODV exhibited similar performance trends. Nonetheless, STAB-AODV displayed a slightly elevated packet loss ratio at lower node speeds, while SSAODV demonstrated a slightly higher ratio at higher node speeds, as illustrated in Figure 6.7. This divergence in performance can be attributed to the distinct routing mechanisms employed by these two protocols.

Evaluating the effectiveness of a routing protocol for applications that necessitate dependable and timely packet transmission hinges on the packet loss ratio. This metric assumes critical significance when assessing network performance and reliability.

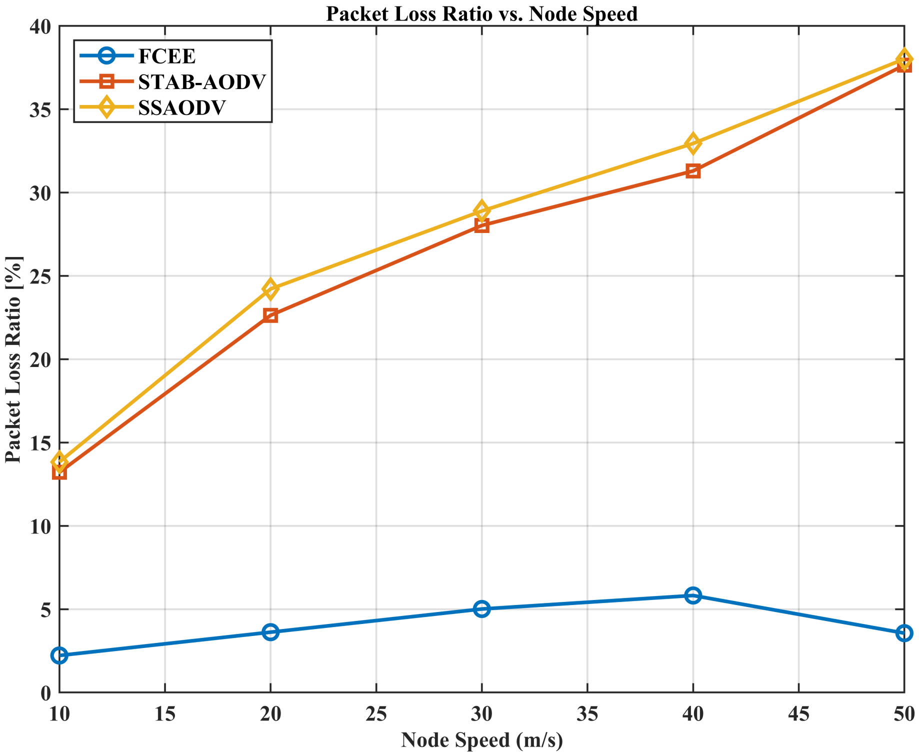


Figure 6.7: Packet Loss Ratio of Scenario **B**.

Figure 6.8 illustrates the Normalized Routing Load (NRL) of three distinct routing protocols: FCEE, STAB-AODV, and SSAODV, as a function of node speed within a mesh network. NRL quantifies the average number of control packets dispatched by a node for each transmitted data packet, serving as a measure of the routing protocol's overhead.

The graph demonstrates that increasing node speed results in higher NRL values for all three protocols. For FCEE, NRL ranges from 4.41 at 10 m/s to 5.93 at 50 m/s. In the case of STAB-AODV, NRL ranges from 360.39 at 10 m/s to 585.54 at 50 m/s, while SSAODV exhibits a range from 382.81 at 10 m/s to 627.42 at 50 m/s.

Notably, FCEE consistently maintains the lowest NRL among the three protocols, followed by SSAODV and STAB-AODV, across all node speed settings.

This graph underscores the paramount importance of efficient routing protocols in mesh networks, particularly in scenarios with high node speeds, where control packet overhead can significantly influence network performance.

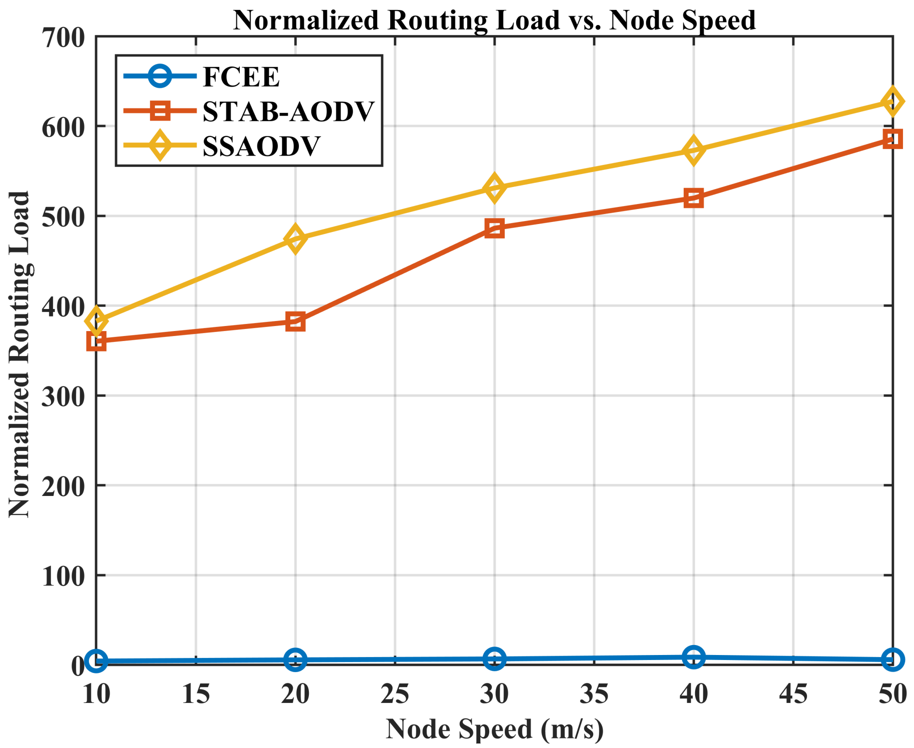


Figure 6.8: Normalized Routing Load of Scenario **B**.

The investigation reveals that as node speeds escalate, the throughput of all evaluated schemes declines. Nevertheless, the proposed protocol outperforms the others, as indicated in Figure 6.9. This superiority can be attributed to the acceleration of node mobility with higher speeds, resulting in connectivity disruptions and subsequent throughput deterioration. In contrast, the FCEE scheme, which factors in residual energy and intermediate node congestion during path selection, offers more stable routes, ultimately mitigating congestion.

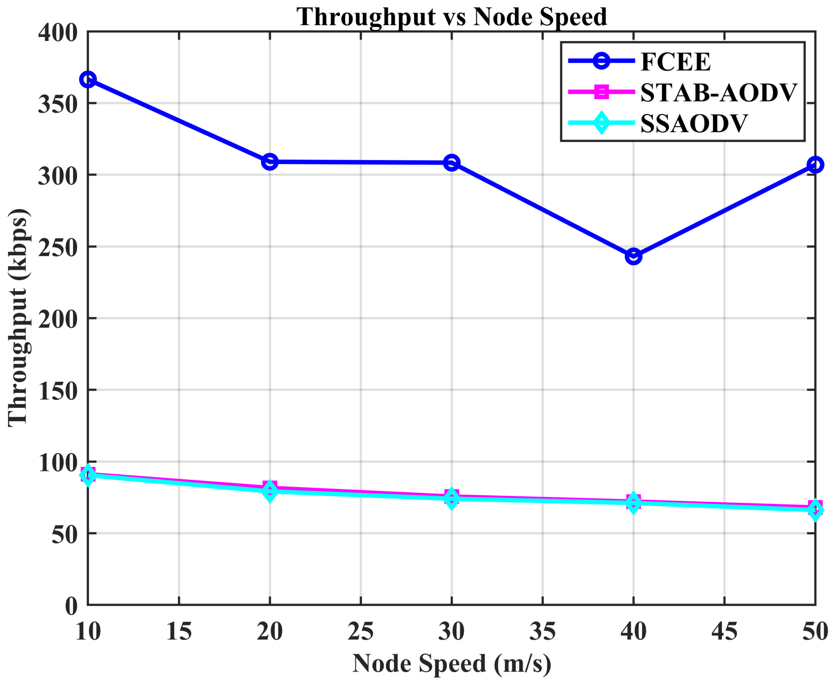


Figure 6.9: Throughput in kbps vs Node Speed of Scenario **B**.

The end-to-end delay results, as depicted in Figure 6.10, highlight that FCEE consistently exhibits the lowest delay across all speeds, with an average delay of 0.054 seconds. In contrast, STAB-AODV and SSAODV demonstrate similar delay performance, with average delays of 0.062 milliseconds and 0.076 seconds, respectively. Notably, at lower speeds (10 and 20 m/s), STAB-AODV marginally outperforms SSAODV in terms of delay, but as node speed increases, SSAODV shows improved delay performance.

In summary, the end-to-end delay results underscore FCEE as the optimal protocol for minimizing delay, while STAB-AODV and SSAODV exhibit comparable performance with slightly higher delay.

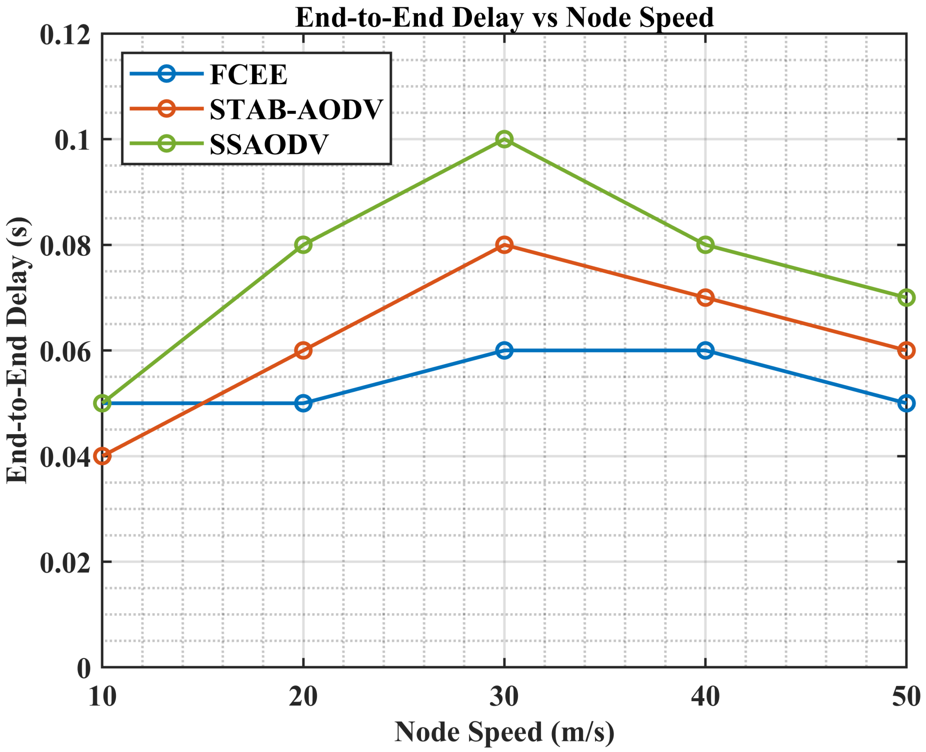


Figure 6.10: End-2-End Delay of Scenario **B**.

In Scenario 6.4.2, the FCEE routing scheme was introduced for mesh networks. A comparative analysis of FCEE, STAB-AODV & SSAODV (Pandey and Singh, 2022), revealed distinct performance variations across different metrics, especially with changing node speeds. Notably, FCEE consistently outshined the other protocols in throughput and maintained the lowest normalized routing load and packet loss ratio across all node speeds. While the end-to-end delay was comparable among the three, slight variations favoured STAB-AODV at lower speeds and SSAODV at higher speeds. For applications prioritizing minimal packet loss or routing overhead, FCEE emerges as the prime choice, underscoring its potential to enhance mesh network performance.

6.4.3 Scenario C, Results & Discussion

In Scenario 6.4.3, an experimental framework is utilized to assess the performance of the proposed protocol under diverse network conditions. This assessment encompasses the FCEE, Dynamic Source Routing (DSR), Ad hoc On-Demand Distance Vector (AODV), and Enhanced-Ant-AODV protocols. The Enhanced-Ant-AODV, a fusion of AODV with Ant Colony Optimization (ACO), offers an innovative route selection strategy, enhancing Quality of Service (QoS). Route determination within the ant colony hinges on the pheromone value of each path in the AODV protocol. This value is derived by assessing route reliability, considering factors like congestion, and node residual energy. Simulation outcomes distinctly highlight the superior performance of the proposed scheme over AODV, DSR, and Enhanced-Ant-AODV in terms of FCEE. Relevant network parameters for Scenario **C** are detailed in Table 6.1.

The comprehensive analysis of the findings scenario 6.4.3, are illustrated in Appendix 7.4. This scenario contains a comprehensive examination and comparative assessment of the FCEE protocol alongside three reactive routing protocols, AODV, DSR, and Enhanced-Ant-AODV(Sarkar, Choudhury, and Majumder, 2021). The evaluation of the proposed protocol scheme, in conjunction with the aforementioned reactive protocols, has been mentioned, conducted, and analyzed. This rigorous evaluation thoroughly investigates multiple performance metrics, such as packet delivery ratio, throughput, average end-to-end delay, and the percentage of operational nodes.

Table 6.1: Network Parameters of Scenario C.

Parameter	**Value/Type**
Network Simulator & Software	NS-2, MATLAB, C++, Perl, AWK
Channel type	Wireless channel
Node Number	100
Simulation Network Size	1800 m X 840 m
Time	200 s
Routing Protocols	FCEE, DSR, AODV, & Enhanced-Ant-AODV
Mobility model	Random Waypoint
Propagation model	Propagation/Free Space
Agent type	UDP
Application Protocol	CBR
Network protocol	IPv4
Node Speed	10 m/sec

The simulation results clearly confirm the superiority of FCEE over its counterparts across these various performance metrics. FCEE consistently outperforms the other routing protocols, validating its efficiency in optimizing network performance, as shown in Appendix 7.4.

6.4.4 Scenario of Group D

A comprehensive investigation was conducted to investigate the performance of the FCEE across varied network configurations, as delineated in the above scenarios. Furthermore, this scenario underscores the influence of the gateway on the performance metrics of both the FREE and AODV protocols.

WMNs are meticulously designed to ensure seamless connectivity for mesh clients, acting as a bridge to the Internet. Integrating specialized nodes, often called gateways, is paramount in shaping the foundational architecture of WMNs, guaranteeing consistent connectivity for mesh clients. This research is methodically segmented into four distinct scenarios. One such scenario positions a singular gateway at the network's centre as presented in Figure 6.11.

In contrast, the subsequent scenarios deploy two gateways: one situated at the network's edge and the other anchored centrally, as illustrated in Figure 6.12. In each scenario, a group of 100 nodes is evenly and randomly distributed throughout the network. Each node is configured with a packet size of 512 bytes, transmitting at a rate of five packets per second.

In addition, the presented work suggested the scenario of group D's four gateways, which are distributed at the network edge of a 1000 m * 1000 m area in Figure 6.13.

In the proposed work, gateways are strategically positioned to ensure optimal coverage and connectivity. The distribution of the gateways is as follows:

One Gateway: Located at the centre of the network.

Two Gateway: Positioned at the centre, and another one is located at the top edge as shown in Figure 6.12.

Four Gateway The gates of this network are positioned on the network's edges, as depicted in Figure 6.13.

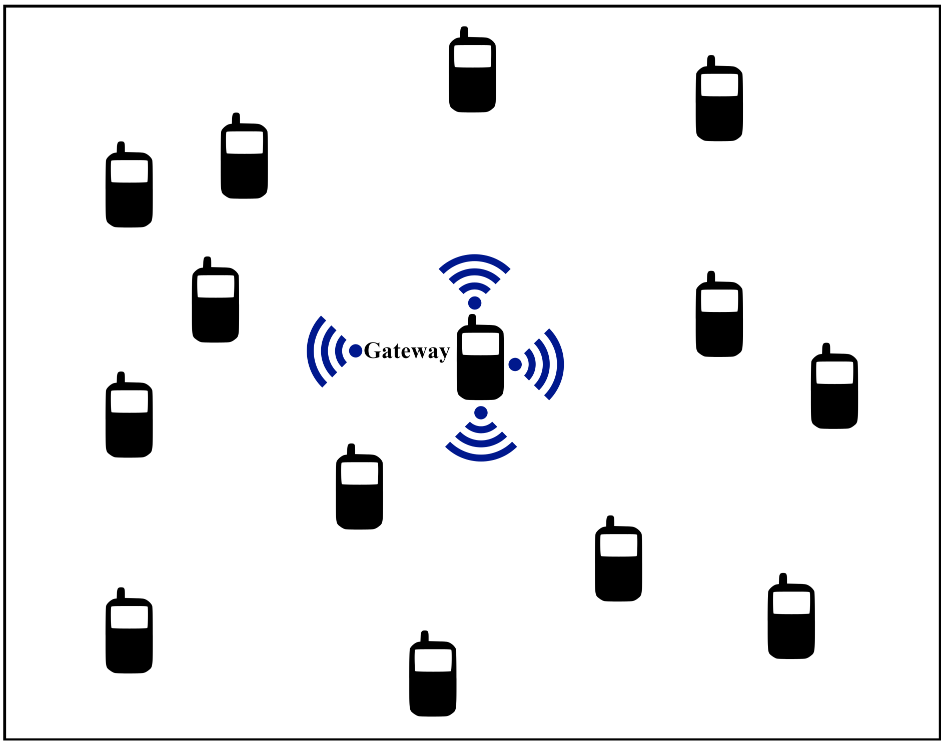


Figure 6.11: Central Gateway Node Topology .

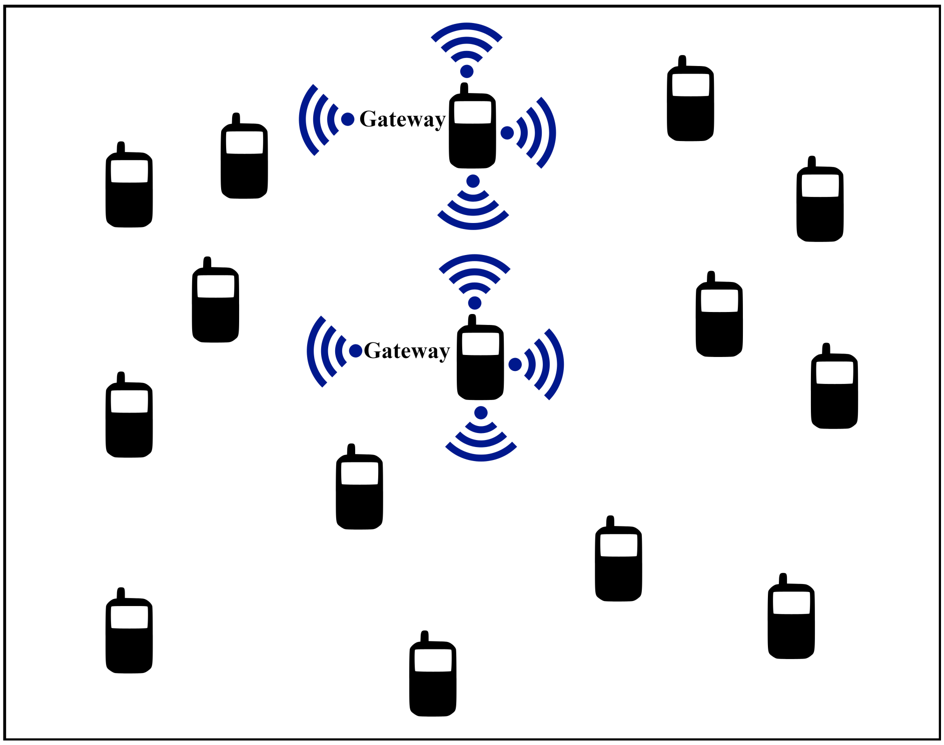


Figure 6.12: Two Gateway Node Topology.

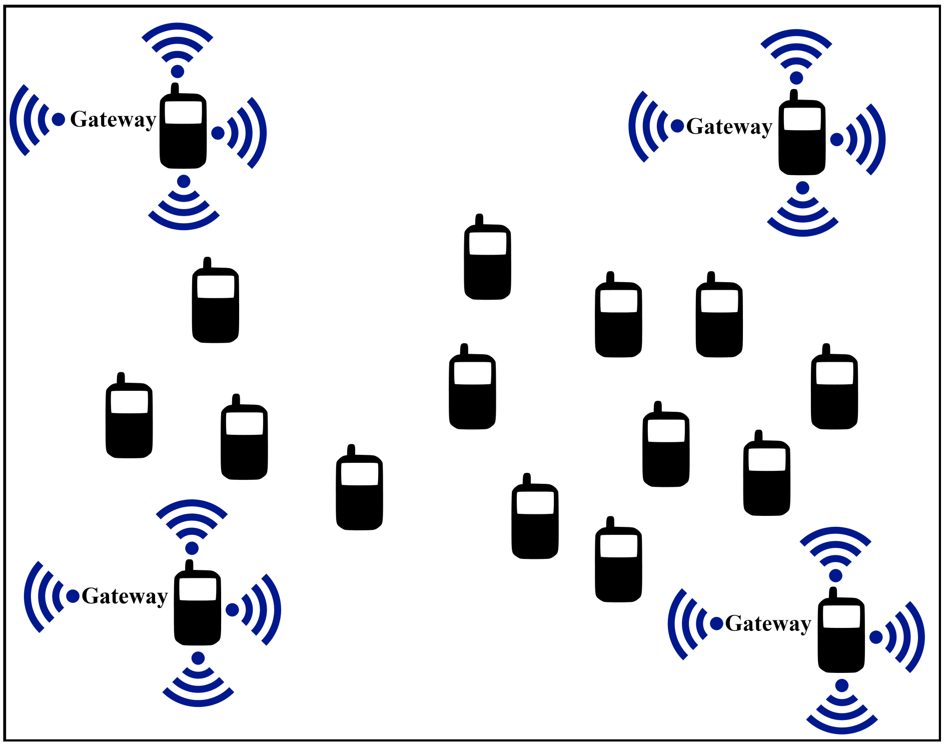


Figure 6.13: Four Gateway Node Topology .

Placing the gateways at the corners of the network area could maximize their coverage and ensure that devices within the area have optimal access to the gateways. This configuration helps distribute the gateways evenly and minimizes the distance between any point in the network and the nearest gateway, reducing potential connectivity issues. The figures above present an overview of the four gateways distribution through the network area. This study seeks to offer valuable insights into the performance and efficiency of the A FCEE in various gateway deployment scenarios within WMNs through the implementation of a rigorous and well-structured approach.

Table 6.2, below illustrates some of the main characteristics of the network parameters of scenario group D. The efficient operation of computer networks relies on effective routing protocols and gateway configurations. The diversity of the number of gateways plays a crucial role in optimizing network performance. This chapter presents a detailed analysis and discussion of the impact of gateway diversity on network performance metrics, specifically focusing on throughput, packet delivery ratio (PDR), E-2-E delay, energy consumption, remaining energy, normalized routing load, goodput, nodes survived, and Packet Delivery Fraction (PDF).

Table 6.2: Simulation Parameters.

Parameter	**Value/Type**
Routing Protocols	FCEE & AODV
Number of Nodes	100
Radio model	Two-ray Ground
Node Positioning	Randomly across the network
Gateway Position	Centre
No of Gateway	1, 2, & 4
Simulation Time	180 (Sec)
Simulation Area size	1000 m × 1000 m
Network Simulator	NS-2.35
Performance Metrics	Throughput, Packet Delivery Ratio, End-to-end delay, Energy Consumption, Normalized Routing Load
Antenna Model	Omni-Antenna
Channel	Wireless channel
Application Traffic	CBR
Physical/MAC layer	IEEE 802.11
Iteration	250

The analysis considers two commonly used routing protocols, AODV and FCEE, and examines their performance under various gateway configurations and locations, the results presented in Appendix 7.4. Appendix 7.4, showcases figures that elucidate the performance of the routing protocols, emphasizing the pivotal role of gateways in influencing the efficiency of these protocols.

Gateway diversity's analysis of routing protocols and locations offers critical insights into network performance. The number of gateways notably influences performance metrics. While AODV shows variable performance based on the number of gateways, FCEE remains consistent, making it suitable for multi-gateway networks. The study underscores the advantages of gateway diversity in energy efficiency and network stability. Both protocols, especially with multiple gateways, ensure robust network connectivity. These insights aid network planners determine the optimal number and placement of gateways. In summary, gateway configurations are pivotal in optimizing network efficiency and performance. This analysis also emphasizes the importance of the standard deviation metric, with detailed evaluations in section 6.5.

In addition, the detailed results of the simulation for scenario E are thoroughly presented in Appendix 7.4.

6.5 Statistics Analysis

Statistical analysis is essential in evaluating and optimizing routing protocols within computer networks. By employing rigorous statistical methods, researchers can accurately measure the performance of different routing algorithms under various conditions, ensuring that data transmission is efficient and reliable. Such analyses offer insights into a protocol's behavior, strengths, and potential weaknesses, facilitating informed decisions when designing or optimizing network infrastructures. Furthermore, the importance of statistical analysis extends beyond mere performance metrics; it aids in predicting the scalability, robustness, and adaptability of routing protocols in dynamic network environments. In essence, statistical analysis is the backbone for ensuring that routing protocols can meet the ever-evolving demands of modern communication systems, guaranteeing seamless connectivity and optimal data flow.

6.5.1 Mean

The mean or average is a fundamental measure of central tendency, encapsulating the typical or average value within a dataset. This statistical metric offers a singular value that succinctly synthesizes the overarching magnitude or level of the data under consideration. By capturing the representative nature of a dataset, the mean enables researchers to derive valuable insights and draw meaningful conclusions from the collected information. Equation 6.11 is used to calculate the mean.

$$\bar{X} = \frac{1}{N} \sum_{i=1}^{N} x_i \tag{6.11}$$

Where $\bar{X}$ represents the mean, N is the total number of observations, and x_i represents each individual value in the dataset.

While widely used, the arithmetic mean is sensitive to extreme values or outliers present in the dataset. Such outliers can skew the mean, potentially misrepresenting the central tendency, especially in datasets with non-normal distributions or other complex characteristics. In such scenarios, alternative measures of central tendency, like the median or mode, might offer a more accurate representation.

6.5.2 Median

The median is a statistical measure of central tendency representing a given dataset's middle value. The data is partitioned into two equal halves, with 50% of the values positioned below and 50% positioned above the median. The median is frequently employed as a substitute for the mean when the dataset exhibits outliers or a non-symmetrical distribution, equation 6.12, is used to calculate it.

$$\text{Median} = \frac{\text{value at position } \left(\frac{n}{2}\right) + \text{value at position } \left(\frac{n}{2}+1\right)}{2} \tag{6.12}$$

The Relative Standard Deviation (RSD) quantifies the extent to which a set of numbers varies concerning its mean. RSD can be computed by dividing the standard deviation by the mean of the dataset. A higher RSD indicates a more significant deviation of numbers from the mean, signifying greater variability, whereas a lower RSD suggests that the numbers closely cluster around the mean. RSD proves especially valuable when comparing the dispersion of datasets characterized by distinct scales or units of measurement, as expressed in Equation 6.13.

The formula for calculating the RSD is as follows:

$$RSD = \left(\frac{\sigma}{\mu}\right) \times 100 \tag{6.13}$$

Where:

- σ is the standard deviation of the dataset.
- μ is the mean of the dataset.

The result is expressed as a percentage, indicating the relative variability concerning the mean.

6.5.3 Standard Deviation

The standard deviation is a statistical measure that quantifies the dispersion or variability of a dataset. In the context of packet drop count, it provides insights into the consistency and stability of the network performance. A higher standard deviation indicates more significant variability in packet drops, while a lower standard deviation suggests more consistent performance. In our analysis, we have calculated the drop count standard deviation for each gateway configuration in the FCEE and AODV protocols. Table 6.3, shows the examine the results:

Table 6.3: Throughput Comparison: FCEE vs. AODV with Gateway Variants.

Routing Protocol	**One Gateway**	**Two Gateways**	**Four Gateways**
FCEE	37815	39168	40587
AODV	43824	41447	42602

Interestingly, the standard deviation values for the drop count in both protocols and across different gateway configurations are equal to the drop count values. This implies that the drop count remains consistent and does not exhibit significant variation or dispersion within each category. The uniformity in drop count indicates a stable network performance regarding packet loss. Analyzing the PDR values alongside the drop count and standard deviation provides deeper insights into the effectiveness of each gateway configuration. By correlating the PDR with the standard deviation, we can assess the impact of gateway configurations on network reliability and stability.

The Equation 6.14, using to calculate the standard deviation σ:

$$\sigma = \sqrt{\left[\frac{\sum(xi - \mu)^2}{\ldots} N\right]} \tag{6.14}$$

Where:

Σ represents the sum

x_i represents each individual data point

μ represents the mean (average) of the data points

N represents the total number of data points

This study demonstrates that the drop count exhibits a consistent pattern across various gateway configurations in the FCEE and AODV protocols. Nevertheless, it is imperative to thoroughly assess the influence of gateway configuration on network performance by examining the PDR values in conjunction with the drop count. Moreover, using standard deviation is a significant asset for network administrators and researchers. Through monitoring and analyzing performance metrics, such as drop count, anomalies can be identified, potential network issues can be detected, and informed decisions can be made for network optimization and troubleshooting.

In summary, it is crucial to examine additional performance metrics, such as packet drop rate, and conduct further research on the correlation between gateway configuration and network stability, despite the consistent performance observed within each gateway configuration as indicated by the standard deviation for drop count in this study. The utilization of standard deviation offers significant insights into the dispersion of data, enabling network administrators to evaluate network performance and make informed decisions to enhance the efficiency and reliability of the mesh network.

As shown in Table 6.4, the proposed work considers analyzing the packet drop count's minimum, maximum, median, mean, and sum values. FCEE performs better than AODV in terms of packet drop account. FCEE has a lower minimum and maximum, indicating a reduced occurrence of packet drops compared to AODV. The median and mean values for FCEE are also lower than those for AODV, indicating better overall performance in minimizing packet drops.

The standard deviation is a statistical measure that quantifies the degree of variability in the count of packet drops. By comparing the standard deviations of AODV and FCEE, we can evaluate the level of consistency in their performance. A low standard deviation implies a higher degree of consistency and reliability in performance. However, in the case of a high standard deviation, it signifies a greater degree of variability in the counts of dropped packets. The relative standard deviations of both protocols exhibit similarity, indicating a consistent variation in their respective means.

Table 6.4: Statistics for Packet Drop Rate.

Statistic	**AODV**	**FCEE**
Minimum	41447	37815
Maximum	43824	40587
Median	42602	39168
Mean	799.78	931.33
Standard Deviation	1188.7	1386.1
SUM	127873	117570
Relative SD	67.28413	67.18942

The statistical analysis presents in Figure 6.14, is paramount in comprehending the efficacy of routing protocols, specifically regarding the quantification of packet drop occurrences. Through the analysis of various metrics, including minimum, maximum, median, mean, and standard deviation, valuable insights can be obtained regarding the efficacy and dependability of the protocols. This analysis compares the AODV and FCEE routing protocols, focusing on their respective capabilities in mitigating packet drops. The strengths and weaknesses of each protocol will be examined in this context.

Efficiency analysis, specifically in terms of packet drop count, is vital for evaluating the effectiveness of routing protocols. Minimizing packet drops is essential for ensuring reliable and uninterrupted data transmission. By assessing the efficiency metrics of AODV and FCEE, it can determine which protocol better handles packet delivery, reducing the occurrence of dropped packets and improving overall network performance.

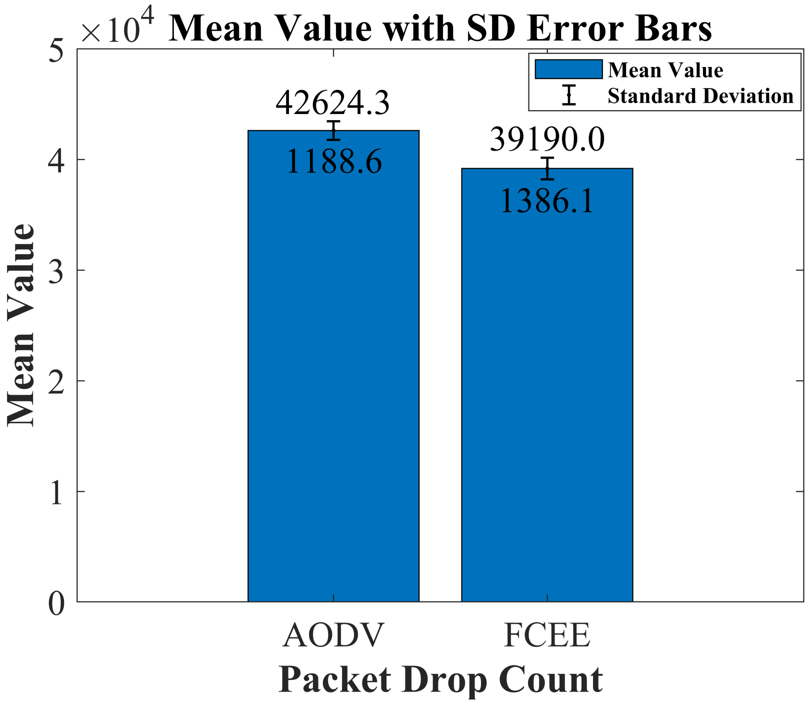


Figure 6.14: Comparative Statistical Analysis of Packet Drop Rate.

The in-depth statistical analysis of the AODV and FCEE routing protocols in mesh networks underscores the superior efficacy of FCEE across various performance metrics. As delineated in Appendix 7.4, FCEE consistently outperforms its counterpart, AODV, and other alternative routing protocols. This empirical evidence solidifies the claim that FCEE is adept at enhancing the overall network performance, making it a preferred choice for mesh network configurations.

6.5.4 Evaluating FCEE Protocol Efficacy in Mesh Networks

The simulation studies conducted, as detailed in Appendices 7.4, 7.4, and 7.4 offer a detailed comparative analysis of the FCEE routing protocol's efficacy relative to established protocols such as standard AODV, DSR, AODV and Intelligent Routing AODV (IRAODV) (Anand and Sasikala, 2019), Enhanced-Ant-AODV (Sarkar, Choudhury, and Majumder, 2021), Stable-AODV (STAB-AODV) (Pandey and Singh, 2022), and Signal Strength-Based Ad-Hoc On-Demand Distance Vector (SSAODV) (Manjhi and Patel, 2012) within the field of wireless mesh networks.

The FCEE protocol exhibits a marked superiority regarding throughput, achieving an average of 352 Kbps. This figure significantly surpasses the throughput rates of AODV (39 Kbps), IRAODV (90 Kbps), STAB-AODV (67.98 Kbps), SSAODV (66.16 Kbps), Enhanced-Ant-AODV (123 Kbps), and

DSR (122 Kbps). Such an enhanced throughput capability of FCEE is mainly ascribable to its refined routing mechanism, which optimizes link connectivity and extends route durations.

In the context of energy efficiency, FCEE demonstrates a notable advantage over AODV and IRAODV. It records an average energy expenditure of merely 14 joules, in contrast to the 40 and 90 joules consumed by IRAODV and AODV, respectively. This reduced energy requirement of FCEE is pivotal for network longevity, particularly in environments where nodes rely on battery power. The Packet Delivery Ratio (PDR) of FCEE, standing at 98%, also stands out. This is substantially higher than the PDRs of AODV (35%), IRAODV (68%), STAB-AODV (62.36%), and SSAODV (62%). Such a high PDR underscores FCEE's reliability in packet transmission from source to destination, bolstering overall network efficiency.

FCEE's performance in terms of end-to-end delay is also commendable, with a minimal delay of 13 ms. This is considerably lower than the delays observed in AODV (39 ms), IRAODV (55 ms), STAB-AODV (0.076 seconds), SSAODV (0.076 seconds), Enhanced-Ant-AODV (31 ms), and DSR (50 ms). This efficiency in packet transmission is vital for applications requiring real-time data exchange. Furthermore, FCEE's energy consumption is significantly lower than AODV and IRAODV, enhancing its suitability for battery-dependent network nodes. However, specific consumption figures are not detailed in the referenced materials. Additionally, the Normalized Routing Load (NRL) for FCEE is calculated at 5.93, which is considerably lower than the NRLs for STAB-AODV (585.54) and SSAODV (627.42).

After presenting the essential data of Comparisons that highlight the superior performance of the FCEE protocol in wireless mesh networks, it becomes imperative to delve into the underlying mechanisms that facilitate this enhanced functionality. Understanding these mechanisms corroborates the observed results and provides insight into the innovative design principles that set the FCEE protocol apart.

This **thesis** also examines the key strategies employed by the FCEE protocol that effectively mitigate network congestion and efficiently manage energy consumption, therefore underscoring its robustness and suitability for diverse network scenarios.

The FCEE routing protocol plays an essential role in enhancing the efficiency of mesh networks by simultaneously mitigating congestion and reducing energy consumption through a series of integrated strategies:

- **Adaptive Routing:** FCEE dynamically adjusts routing decisions based on real-time network conditions, rerouting data packets through less congested paths. This adaptive routing, coupled with flow control, regulates the data transmission rate, preventing network overload, bottlenecks, and consequent packet loss and delays.
- **Energy Efficient Routing:** The protocol employs energy-efficient routing algorithms that select paths with lower energy costs, such as routes involving nodes with higher residual energy or, as discussed earlier. This approach reduces the overall energy consumption of the network.
- **Normalized Routing Overhead:** By minimizing the Normalized Routing Overhead required for route discovery and maintenance, FCEE conserves energy across the network. Furthermore, the protocol can implement adaptive duty cycling, allowing nodes to alternate among active and sleep modes based on network demand, reducing energy consumption during low traffic periods.
- **Intelligent Packet Forwarding and QoS Awareness:** FCEE may include intelligent packet forwarding to avoid redundant transmissions, ensuring packets take the most efficient routes. It also incorporates QoS awareness, prioritizing critical data, and optimizing energy usage for different transmissions.
- **Scalability and Feedback Mechanisms:** The protocol's design is scalable, adapting to varying sizes and densities of mesh networks, which is crucial for managing congestion and maintaining energy efficiency in expanding networks. Additionally, FCEE might use feedback mechanisms, where nodes communicate their status (energy levels) to inform routing decisions, avoiding congested nodes or paths. By integrating these features, FCEE effectively manages and mitigates congestion and significantly reduces energy consumption in mesh networks. This dual functionality is especially vital in scenarios where nodes are battery-powered or located in remote areas with limited energy resources, contributing to a more sustainable and efficient network operation.

Further results are detailed in Appendices 7.4, 7.4, and 7.4 where, across a range of tested scenarios, the FCEE protocol consistently outperforms other protocols in key performance metrics, including throughput, delay minimization, packet delivery, and energy efficiency. This consistent superiority underscores the FCEE protocol's potential as an advanced routing solution for wireless mesh networks.

6.6 Summary

Chapter 6, thoroughly examines the simulation outcomes of the FCEE protocol. The FCEE has been compared to the routing mechanisms of various protocols, including AODV, IRAODV, STAB-AODV, SSAODV, and Enhanced-Ant-AODV.

The NS-2.35 simulation tool played a pivotal role in this study, facilitating the analysis and assessment of the performance of the modified AODV routing algorithm, which leverages the FCEE metric.

Key metrics such as PDR, PLR, and NRL were meticulously analyzed. The PDF metric, in particular, was highlighted for its significance in assessing the mesh network's quality of service (QoS). A high PDF value indicates efficient routing, low packet loss, and reliable communication, whereas a low value suggests potential network inefficiencies. The chapter further delves into detailed results and discussions for scenarios such as Scenario A, B, and C. For instance, Scenario A provides a comprehensive analysis of the simulation outcomes, specifically focusing on the performance of the FCEE protocol and the Intelligent Routing protocol for IRAODV regarding network throughput.

In conclusion, Chapter 6, is a testament to the transformative potential of the FCEE metric in enhancing routing protocols, offering valuable insights and findings that can steer future research endeavors in mesh networks.

7

Main Contribution and Conclusion

Contents

7.1 Overview

This chapter concludes the thesis and offers a summary of the findings and the research limitations. It also provides some recommendations for the future. Specifically addressing how this thesis aims to enhance the AODV Routing protocol to support the growing connectivity demands of IoT devices within wireless mesh networks, the research identifies future directions and guidelines for advancing AODV protocols through a complex systematic literature review. This thesis on improving routing protocols in wireless mesh networks is essential for several reasons.

The increasing presence of IoT devices has amplified the demand for enhanced wireless mesh networks. These networks are crucial in supporting the growing connectivity needs of various devices and applications. The AODV protocol plays a central role in improving efficiency and reliability in these networks. However, there is scope for improvement in AODV, as evidenced by developing protocols like the Fuzzy Control Energy Efficient (FCEE) protocol, which aims to boost network performance.

Energy efficiency is another critical aspect, especially in environments where power resources are scarce. The FCEE protocol addresses this by focusing on individual nodes' energy usage and broadcast, helping conserve energy across the network. As these networks expand in size, the challenge of scalability becomes more notable. Effective routing solutions capable of efficiently handling increased data and a growing number of devices are necessary. Additionally, ensuring a high quality of service is essential, especially given the diverse range of applications running on these networks. Implementing fuzzy logic in routing protocols is a step forward in this direction, allowing for more effective management of network resources. This approach ensures that the network can maintain smooth operations across various applications, adapting to the dynamic demands of wireless connectivity. The FCEE protocol addresses these challenges effectively, as demonstrated by the results, marking a significant advancement in this field. Enhancing a routing algorithm is necessary to address specific characteristics of wireless mesh networks, such as scalability, reliability, and energy efficiency, as shown in Figure 7.1, where the hop count metric does not consider the variability of the wireless link quality.

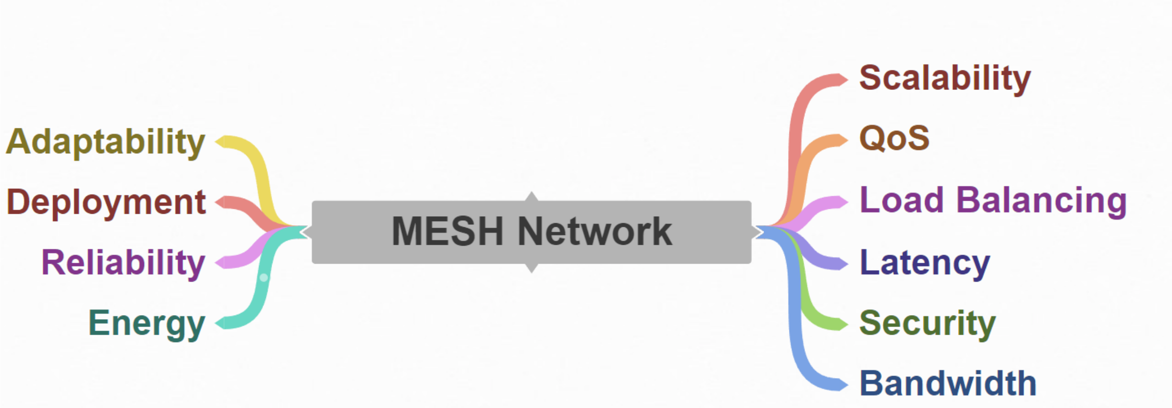


Figure 7.1: Characteristics of a MESH Network.

In the results and discussion, a detailed analysis of selected scenarios assesses the Fuzzy Control Energy Efficient (FCEE) protocol (Alameri, Komarkova, and Al-Hadhrami, 2023), (Alameri, Komarkova, Al-Hadhrami, and Alkaraawi, 2023) & (Alameri, Komarkova, Al-Hadhrami, and Hussein, 2023), emphasizing statistical methods to ensure the robustness and adaptability of routing protocols in dynamic network environments. The research peaks in a concluding chapter that summarizes the findings and charts a course for future inquiries, laying a solid foundation for further development of AODV routing mechanisms.

Chapter 1, establishes the dissertation's framework, highlighting the challenges of wireless mesh networks and the imperative for sophisticated routing solutions.

Chapter 2, outlines the aim, research objectives, methods, tools, and associated scholarly work.

Chapter 3, provides a methodical review of AODV extensions via the PRISMA framework, ensuring scholarly rigor. It commences with identifying relevant studies, followed by a stringent literature selection process. This chapter systematically studies prior findings and relevant literature, encompassing mesh network methodologies. It concludes by discussing the limitations and prospects of employing fuzzy logic in routing protocols, suggesting expansive possibilities for future research.

Chapter 4, This chapter unveils the innovative FCEE protocol, a groundbreaking approach that integrates fuzzy logic with the AODV protocol. The core of this chapter lies in precisely outlining the architecture and design principles of the FCEE protocol. A pivotal aspect of this protocol is the application of fuzzy logic, which has been demonstrated to significantly boost network adaptability and performance, marking a notable advancement in the field. Furthermore, this chapter also presented the concept of the memory channel, a novel proposal in this research, detailing its design and potential implications in enhancing network efficiency.

Chapter 5, compares the FCEE protocol's performance with other protocols across different scenarios using simulation, especially with the NS-2 simulator. It also addresses the roles of mobile nodes and traffic models within these networks.

Chapter 6, presents a thorough analysis and discussion of simulation results, highlighting the enhanced performance of the FCEE protocol. It includes statistical analysis to affirm the reliability and flexibility of routing protocols, reinforcing the FCEE protocol's efficacy.

Overall, the FCEE (Alameri, Komarkova, and Al-Hadhrami, 2023) & (Alameri, Komarkova, Al-Hadhrami, and Alkaraawi, 2023), protocol demonstrates significant improvements over several routing protocols such as: AODV, DSR, AODV and Intelligent Routing AODV (IRAODV) (Anand and Sasikala, 2019), Enhanced-Ant-AODV (Sarkar, Choudhury, and Majumder, 2021), Stable-AODV (STAB-AODV) (Pandey and Singh, 2022), and Signal Strength-Based Ad-Hoc On-Demand Distance Vector (SSAODV) (Manjhi and Patel, 2012): in critical metrics such as throughput, packet delivery ratio (PDR), E-2-E delay, energy consumption, remaining energy, normalized routing load, goodput, nodes survived, and Packet Delivery Fraction (PDF). It proves more effective in data handling and energy conservation, with lower latency and enhanced link stability, particularly evident in specified scenarios, demonstrating its substantial superiority over AODV and other routing protocols.

Having outlined the innovative design of the FCEE protocol, the focus now shifts to its experimental evaluation under various network scenarios.

The shortest path metric pertains to identifying a path connecting a source-destination pair without considering the efficiency of the path. The selection of a low-quality wireless link due to a lack of awareness regarding its nature may lead to a decline in network performance.

Fuzzy logic offers an adaptive routing approach capable of dealing with uncertainties and making decisions based on imprecise input values. It mimics human decision-making by evaluating multiple factors such as bandwidth, delay, and reliability. This approach provides a robust solution to network challenges. This approach stands out for its reduced overhead, as it leans on local decision-making, which can decrease the need for frequent route updates. Furthermore, fuzzy logic is scalable and designed to manage increased network complexity, and its flexibility ensures that it can be modified to accommodate new routing criteria when needed.

The FCEE protocol, an enhancement of the AODV protocol, integrates fuzzy logic into the routing mechanism. The FCEE protocol, based on two critical parameters – the remaining energy of nodes and the memory channel–makes more informed routing decisions. Unlike traditional metrics, it considers nodes' energy and broadcast history to optimize route selection. This helps avoid congested or low-energy nodes, enhancing the network's overall performance.

The NS-2 simulator analyzed randomly generated network topologies across various scenarios. This study evaluates the performance of the path selection rule using the FCEE compared to the standard path selection rule of the AODV protocol and other routing protocols such as AODV and Intelligent Routing AODV (IRAODV), Enhanced-Ant-AODV, Stable-AODV (STAB-AODV), and Signal Strength-Based Ad-Hoc On-Demand Distance Vector (SSAODV). The evaluation considers factors such as node densities, node speed, network size, traffic types, simulation time, different versions of AODV routing protocols, and the number of gateway nodes. The number of nodes was 60 and 100 based on the comparison rules. This study generated 500 network topologies for each scenario, the number of nodes randomly distributed across the network.

The new path selection mechanism aims to avoid congested nodes that tend to packet loss, therefore minimizing the impact on throughput. Avoiding routing through congested nodes improves load distribution across the network, significantly increasing the overall network throughput and the other QoS network performance. The modified routing algorithm based on the AODV and Fuzzy logic has been shown to outperform the AODV and the other routing protocols in WMNs.

7.2 Main Contributions

The contributions of this PhD thesis are multiple. This thesis comprehensively reviews and analyzes the Ad hoc On-Demand Distance Vector (AODV) routing discovery mechanics in Wireless Mesh Networks (WMNs). This thesis also proposed modifications to the AODV routing discovery mechanics, which were rigorously analyzed and disseminated in peer-reviewed academic journals.

This thesis makes multiple contributions, summarized as follows:

1. **Evaluation, Review & Analysis:** A comprehensive examination of AODV routing in Wireless Mesh Networks (WMNs) is presented, focusing on evaluating performance metrics, scalability, network efficiency, and reliability. These studies provide in-depth insights into the adaptability and effectiveness of the AODV protocol under various network scenarios. The results of this contribution have been presented and published in conferences, as detailed in (Alameri and Komarkova, 2019), (Alameri and Komarkova, 2021), (Alameri, Komarkova, and Ramadhan, 2021), & (Alameri, Hubálovskỳ, and Komarkova, 2021).
2. **PRISMA Framework:** Employing a systematic and reliable review methodology, this study comprehensively analyzes the latest improvements and extensions in AODV routing. The results presented advancements in AODV's performance and application and have been published in a journal paper (Alameri, Komarkova, Al-Hadhrami, and Lotfi, 2022), and at a conference (Alameri, Komarkova, and Al-Hadhrami, 2023).
3. **FCEE Protocol:** The Innovation FCEE protocol represents a novel integration of AODV routing with fuzzy logic and energy efficiency rules, marking a significant advancement in network protocol design. This innovative approach optimizes network routing decisions based on dynamic, real-time parameters, effectively enhancing network operations' efficiency and longevity. The impactful results of this innovative work have been published through a publication in a journal paper (Alameri, Komarkova, and Al-Hadhrami, 2023), and a presentation at a notable conference (Alameri, Komarkova, Al-Hadhrami, and Alkaraawi, 2023).
4. **Memory Channel:** Proposing a short-memory model for decision-making, this contribution offers a practical approach to improving the FCEE procedures. The effectiveness of this model in enhancing decision accuracy is detailed. The results are published in a journal paper (Alameri, Komarkova, and Al-Hadhrami, 2023), and presented in a conference paper (Alameri, Komarkova, Al-Hadhrami, and Alkaraawi, 2023).
5. **Pareto Traffic Model Integration:** Enhancing performance analysis for various traffic conditions, this study offers in-depth insights and methods. The detailed outcomes are meticulously outlined and available in Appendix C, where they are presented clearly.
6. **Performance Evaluation:** Demonstrating FCEE's superiority in key metrics over traditional methods as shown in those chapters and the publications related to them, Chapter 6, Appendix A, Appendix B & Appendix C, (Alameri and Komarkova, 2022), (Alameri, Komarkova, and Al-Hadhrami, 2023) & (Alameri, Komarkova, Al-Hadhrami, and Alkaraawi, 2023)& (Alameri, Komarkova, Al-Hadhrami, and Hussein, 2023).

7.3 Conclusions

In a world where the demand for robust WMNs is ever-increasing, this thesis has been conducted to meticulously evaluate and enhance mesh routing protocols. This thesis is anchored by a series of objectives beginning with the holistic assessment of current protocols, underpinned by a deep dive into the AODV protocol's performance, and culminating in the pioneering development of the FCEE Routing Protocol. Each phase of this thesis has been methodically crafted to augment network efficiency, effectively address node congestion issues, and guarantee scalability for the networks of tomorrow.

This study comprehensively evaluated existing mesh routing protocols under various scenarios, such as mobility, network size, and temporal dynamics, to identify the most adaptable protocol for enhanced network performance. This was followed by a systematic and in-depth analysis of the AODV protocol, utilizing the PRISMA framework to uncover its limitations and strengths within mesh networks.

Building on these insights, the study innovated the FCEE Routing Protocol, which integrates fuzzy logic with AODV, leading to notable improvements in routing efficiency. Further advancements were made by proposing and implementing new routing metrics and path selection strategies. These strategies were specifically designed to improve throughput and overall quality of service, with a focus on reducing congestion in network nodes.

The technique of FCEE aims to mitigate congestion, energy consumption, and other QoS in mesh networks and improve the performance of AODV. The study's main findings indicate that incorporating fuzzy logic into the routing protocol can enhance network performance and optimize the use of network resources.

Finally, the study applied robust statistical methods and systematic analysis to validate the FCEE protocol's scalability and effectiveness in large mesh network environments, thereby validating its potential as a significant contribution to the field.

The FCEE protocol has been successfully designed and implemented, fulfilling the thesis's objectives outlined in section 2, effectively completing all the specified goals.

7.4 Future Work Directions

This study compares six routing protocols which are standard AODV, Intelligent Routing AODV (IRAODV), Enhanced-Ant-AODV, Stable-AODV (STAB-AODV), Dynamic Source Routing (DSR), and Signal Strength-Based Ad-Hoc On-Demand Distance Vector (SSAODV) in a WMN environment using the FCEE approach. Additionally, other research issues have been identified that could be investigated to enhance the reliability and effectiveness of the FCEE path selection rule.

- An in-depth exploration of the FCEE approach, which together integrates AODV with fuzzy logic, highlights its dynamic behavior in mesh networks. Preliminary studies, delineated in Appendices 7.4, 7.4, and 7.4, shed light on the settling time of the enhanced AODV routing protocol. This FCEE modified AODV algorithm takes intervals of 150, 200, and 300 seconds to achieve steady-state, signalling the establishment of stable transmission paths. The algorithm is credited with its native capability to adapt dynamically to shifts in network conditions. Such settling time durations are shaped by many determinants, encompassing network topology, load attributes, and initial setups. These findings show that the FCEE network's throughput settling time is adept and responsive to any topological shifts within the network.
- The routing of network traffic plays a pivotal role in determining the efficiency and reliability of a wireless mesh network (WMN). While in-depth analysis has been meticulously conducted for scenario E 5.4.3. Extending the evaluation by assessing the enhanced AODV protocol's performance, including the FCEE approach, in real-world traffic scenarios is essential. Such scenarios should extend packet sizes, transmission rates, and varied packet types. Undertaking this broader assessment will provide a comprehensive understanding of the protocol's adaptability and efficiency. Furthermore, it would be careful to explore integrating other traffic models, notably the Poisson model, to ensure a robust and comprehensive evaluation.
- Investigate use of different transmit power ranges, such as 500m and 750m, for the AODV protocol in a mesh network is significant for several reasons such as:
  - **Coverage Area:** Different transmit power levels determine the coverage area of a node. A higher transmit power, such as 750m, would allow a node to cover a larger area, potentially reaching more distant nodes directly, while a lower power, like 500m, would limit its reach.
  - **Network Connectivity:** The transmit power influences how densely or sparsely the network is connected. A higher power can lead to denser connectivity, potentially reducing the hops required for data transmission.

  - **Energy Consumption:** Nodes, especially those running on batteries, consume more energy when transmitting at higher power levels. Balancing energy consumption with network performance is crucial in many scenarios. Energy consumption is significant because FCEE is based on energy efficiency.
  - **Adaptive Mechanisms:** In dynamic environments, nodes might need to adjust their transmit power based on network conditions. For instance, increasing the transmit power might help maintain network connectivity in case of node failures.

In wireless mesh network research, the transmission power selection is a pivotal factor significantly influencing the network's performance and characteristics. This aspect of network design has been the focus of various studies, as evidenced by the work of (Alameri, Komarkova, and Al-Hadhrami, 2023) & (Alameri, Komarkova, Al-Hadhrami, and Alkaraawi, 2023), who employed a transmission power of 250 meters in their evaluations and simulations. This choice aligns with the methodologies adopted by other researchers in the field, such as (Anand and Sasikala, 2019), (Sarkar, Choudhury, and Majumder, 2021), & (Pandey and Singh, 2022).

The strategic variation of transmission power within a mesh network is not merely a technical consideration but a critical tool for network optimization. By adjusting the transmission power, network designers can tailor the network to meet specific operational requirements. These include maximizing coverage area, essential for ensuring network accessibility over extensive geographical regions. Conversely, minimizing power consumption is crucial for networks relying on battery-powered or energy-harvesting nodes, directly impacting the network's sustainability and maintenance costs.

Furthermore, adjusting transmission power plays a significant role in managing and mitigating signal interference. In densely populated network environments, reducing transmission power can decrease signal overlap and interference, thereby enhancing the overall signal quality and reliability of the network. On the other hand, increasing transmission power can enhance network robustness and reliability, particularly in scenarios where nodes are sparsely distributed, or physical obstructions may impede signal propagation.

In conclusion, the judicious management of transmission power in mesh networks emerges as a fundamental aspect of network design. It offers a versatile approach to balance and optimize various performance metrics, such as coverage, energy efficiency, interference management, and network reliability. As such, it remains a critical area of investigation and innovation in developing efficient and effective wireless mesh networking solutions.

List of Publications

Publications Derived from This Thesis

While conducting the research for this thesis, several key findings about the research questions under investigation were rigorously analyzed and disseminated. These results have been presented at esteemed international conferences and published in peer-reviewed academic journals, as detailed below:

Refereed Journal Papers:

- **[J1]** **Ibrahim Alameri**, and Jitka Komarkova, "Performance and statistical analysis of ant colony route in mobile ad-hoc networks," International Journal of Electrical and Computer Engineering, Vol. 12, No. 3, pp. 2818-2828, 2022. (Scopus CS=3.8, Q2)
- **[J2]** **Ibrahim Alameri**, Jitka Komarkova, Tawfik Al-Hadhrami, and Ahmad Lotfi, "Systematic review on modification to the ad-hoc on-demand distance vector routing discovery mechanics," PeerJ Computer Science, PeerJ, vol. 8, 2022. (WoS IF=3.800, Scopus CS=4.2, Q1)
- **[J3]** **Ibrahim Alameri**, Jitka Komarkova, and Tawfik Al-Hadhrami, "Fuzzy-based Optimization of AODV Routing for Efficient Route in Wireless Mesh Networks," PeerJ Computer Science, PeerJ, vol. 8, 2023. (WoS IF=3.800, Scopus CS=4.2, Q1)

Refereed Conference Papers:

- **[C1]** **Ibrahim Alameri**, and Jitka Komárková, "Comparative Study and Analysis of Wireless Mobile Adhoc Networks Routing Protocols," International Masaryk conference for Ph.D. Students and Young Researchers, 2019.
- **[C2]** **Ibrahim Alameri**, and Jitka Komárková, "Network Routing Issues in Global Geographic Information System," The 20th International Scientific Conference Globalization and its Socio-Economic Consequences, pp.10, 2021. (WoS)
- **[C3]** **Ibrahim Alameri**, Jitka Komárková, and Mustafa K. Ramadhan, "Conceptual analysis of single and multiple path routing in MANET network," Information and Digital Technologies, pp. 235-244, 2021. (IEEE, Scopus).
- **[C4]** **Ibrahim Alameri**, Stepan Hubalovsky, Jitka Komarkova, and Mustafa K. Ramadhan, "Evaluation of impact of mobility, network size and time on performance of adaptive routing protocols," Information and Digital Technologies, pp. 245-253, 2021. (IEEE, Scopus).

- [**C5**] **Ibrahim Alameri**, Jitka Komarkova, and Tawfik Al-Hadhrami, "Fuzzy Logic-Based Congestion Control in AODV Mesh Networks," International Conference on Electrical, Computer, Communications and Mechatronics Engineering, 2023. (IEEE, Scopus).

Book Chapters:

- [**B1**] **Ibrahim Alameri**, Jitka Komarkova, and Tawfik Al-Hadhrami. "A Survey of Mobile Ad-Hoc Networks Based on Fuzzy Logic." on Data Engineering and Communications Technologies series - Advances on Intelligent Computing and Data Science, Springer Nature, 2023. (WoS, Scopus).
- [**B2**] **Ibrahim Alameri**, Jitka Komarkova, Tawfik Al-Hadhrami, and Raghad I. Hussein. "The Influence of Node Speed on MANET Routing Protocol Performance." on Data Engineering and Communications Technologies series - Advances on Intelligent Computing and Data Science, Springer, 2023. (WoS, Scopus).

Other Publications: Other publications that are not part of this dissertation.

- [**O1**] Haider AlKaraawi, Mohammed Dhahir, **Ibrahim Alameri**, "Development modeling methods of analysis and synthesis of fingerprint deformations images," International Journal of Electrical and Computer Engineering, Vol. 10, No. 6, pp. 6053-6060, 2020. (Scopus CS= 3.8, Q2)
- [**O2**] Kadum Ahmed, Muneer Mansoor, Naseer Al-Imareen, and **Ibrahim Alameri**, "Evaluation of Eteaching Implementation in Iraqi Universities," Third Congress on Intelligent Systems, Springer, pp 735–748, 2023. (WoS, Scopus)
- [**O3**] Aymen Adil, Naseer Al-Imareen, **Ibrahim Alameri**, and Fatimah ihsan abdulsahib, "Improved Hybrid Model to Text Detection by Using k-means and mser-swt with CNN," International Conference on Electrical, Computer, Communications and Mechatronics Engineering, IEEE, 2023. (IEEE, Scopus)

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Appendix A

Scenario C 5.4.3, Detailed Results in Appendix A

Throughput	PDR
E-2-E Delay	Node Survived

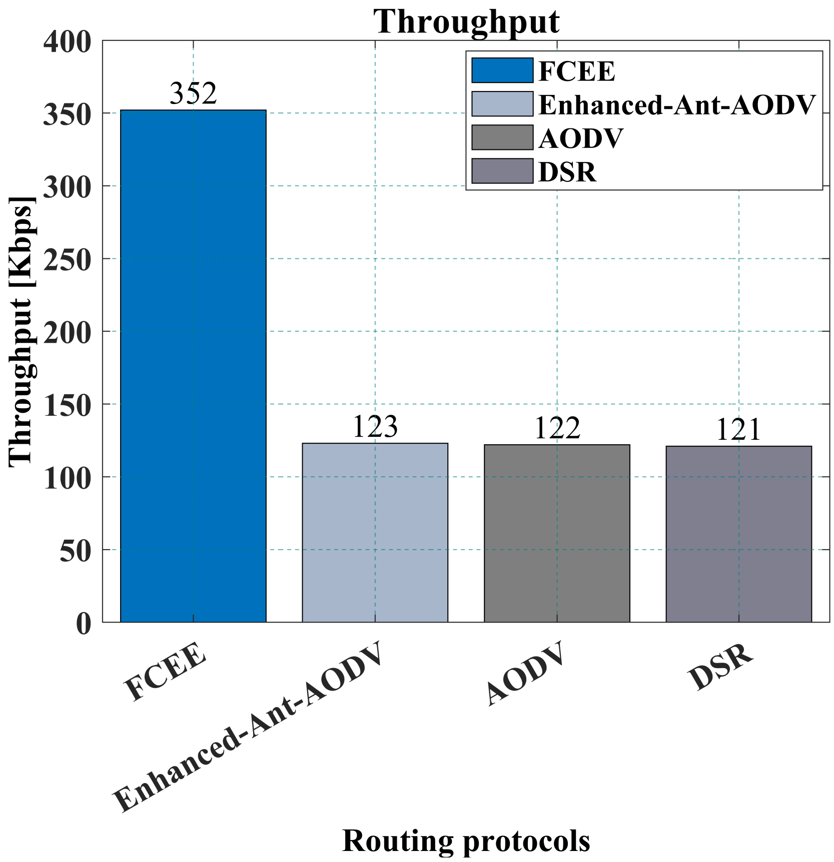

Figure 2: Throughput Of Scenario **C**.

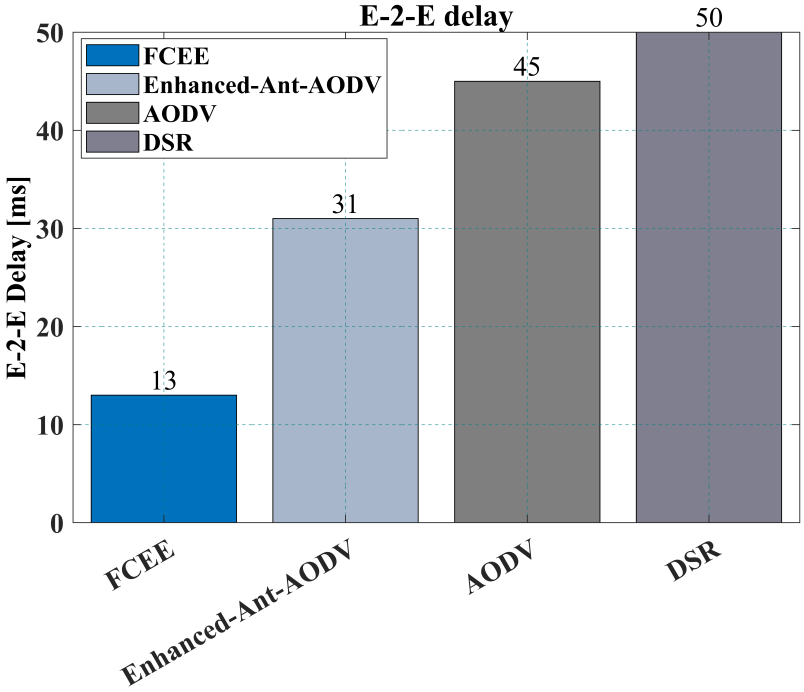

Figure 3: PDR of Scenario **C**.

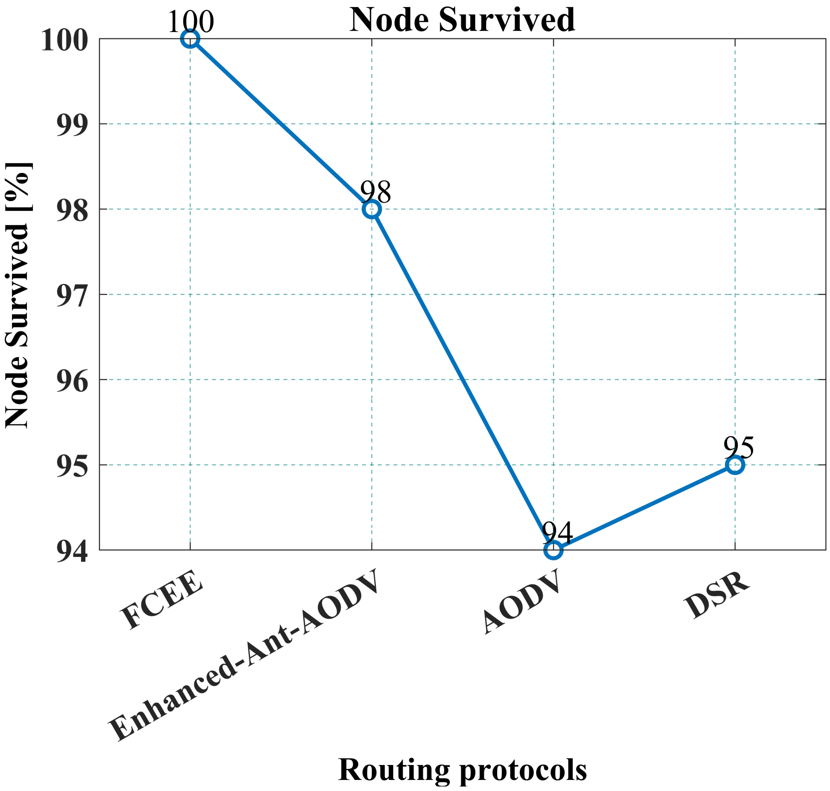

Figure 4: E-2-E Delay of Scenario **C**.

Gateway Influence Detailed Results in Appendix A 5.4.3

1 Gateway	2 Gateway
4 Gateway	

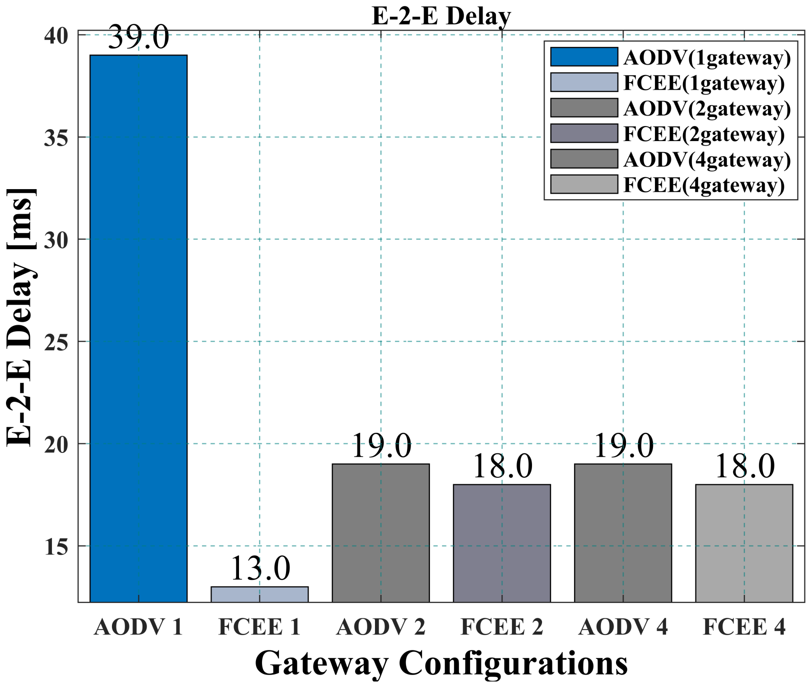

Figure 5: E-2-E Delay Across a Different Gateway.

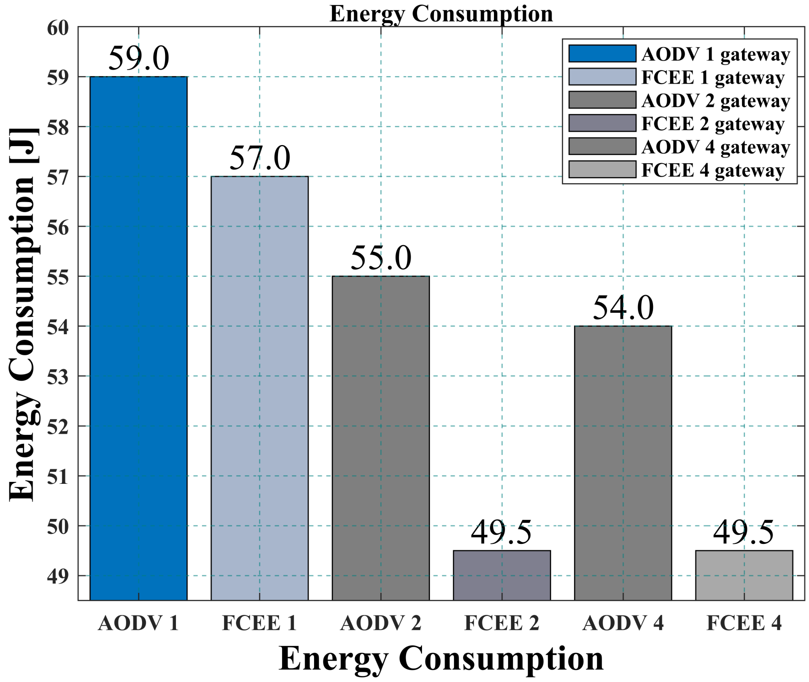

Figure 6: Energy Consumption Across Different Gateway .

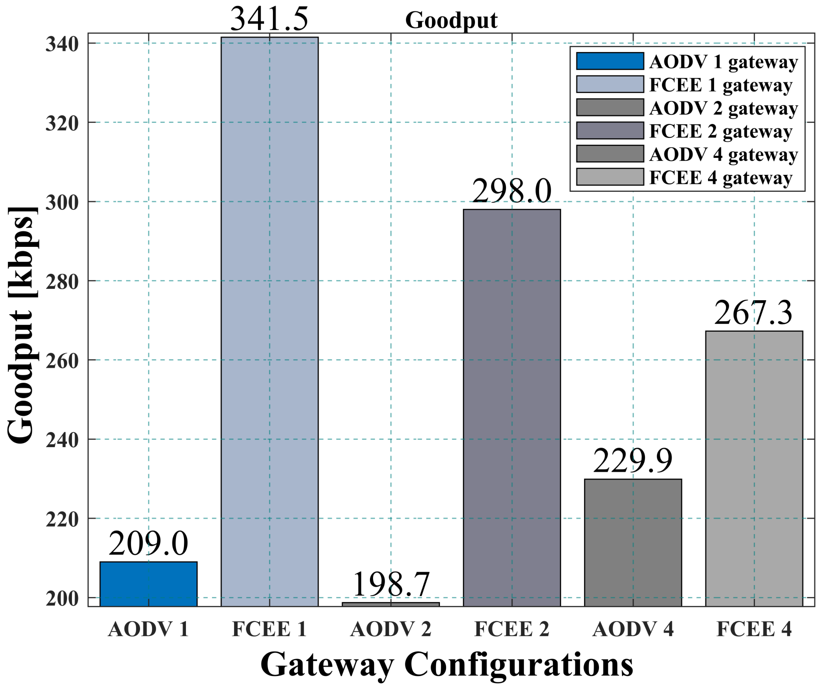

Figure 7: Goodput Across a Different Gateway .

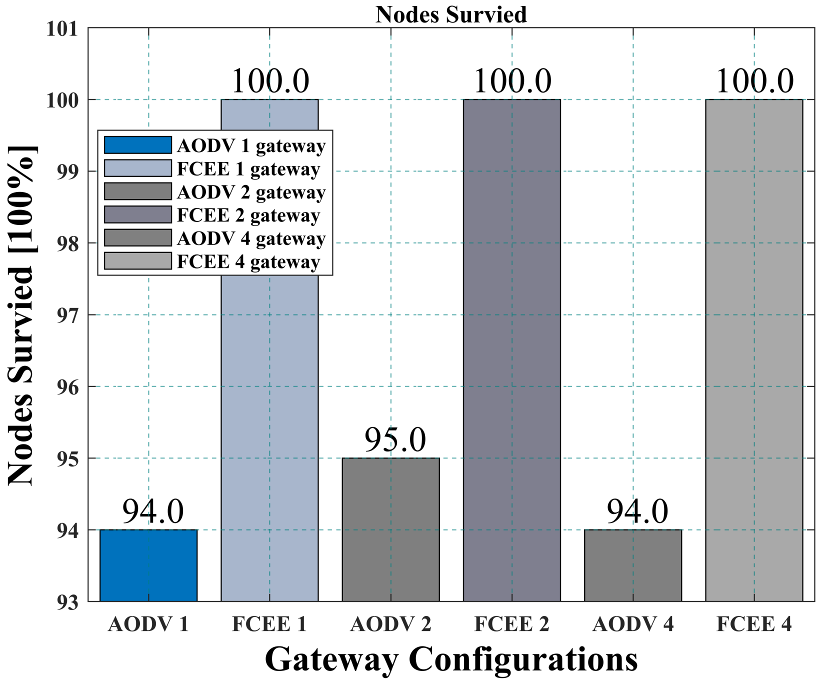

Figure 8: Nodes Survived Across a Different Gateway.

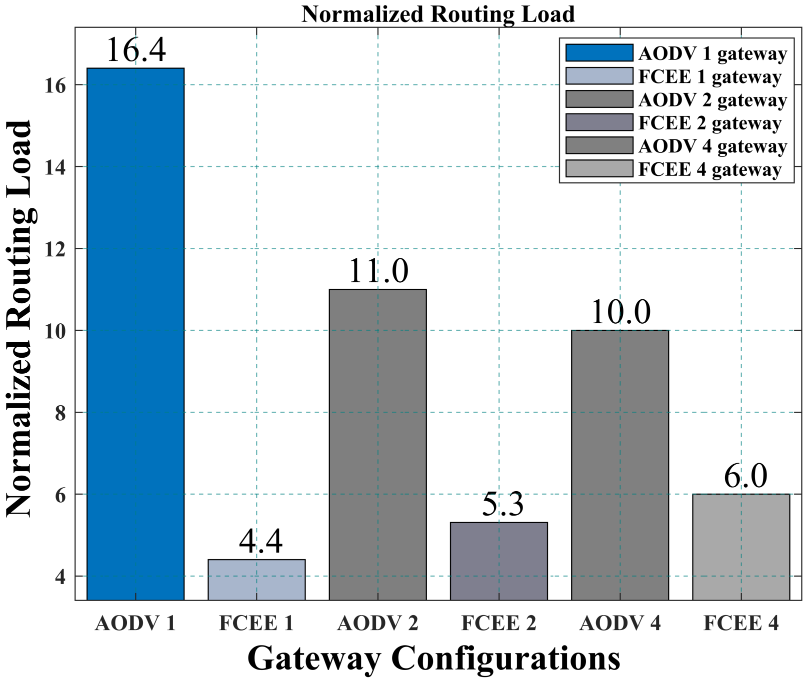

Figure 9: NRL Across Different Gateway.

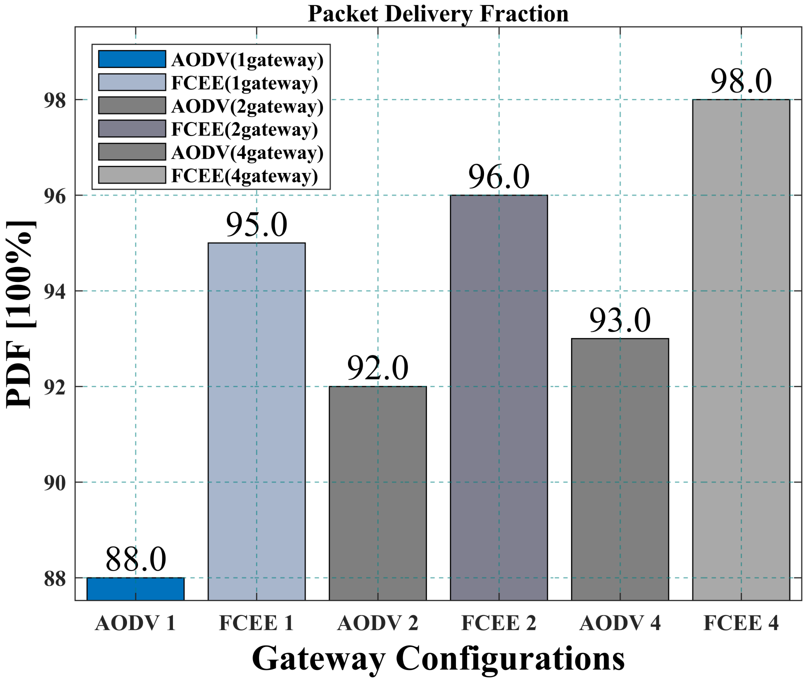

Figure 10: PDF Across a Different Gateway.

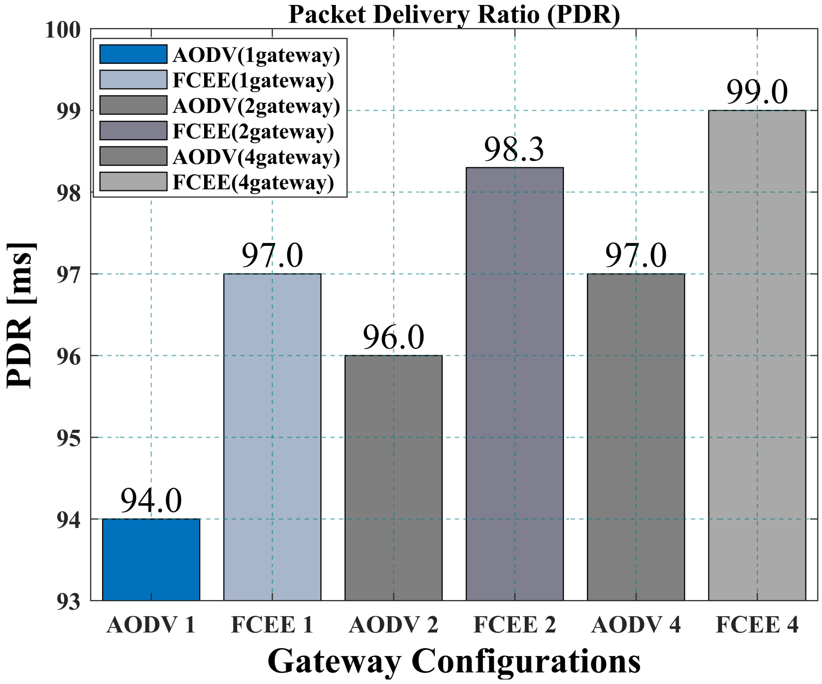

Figure 11: PDR Across a Different Gateway .

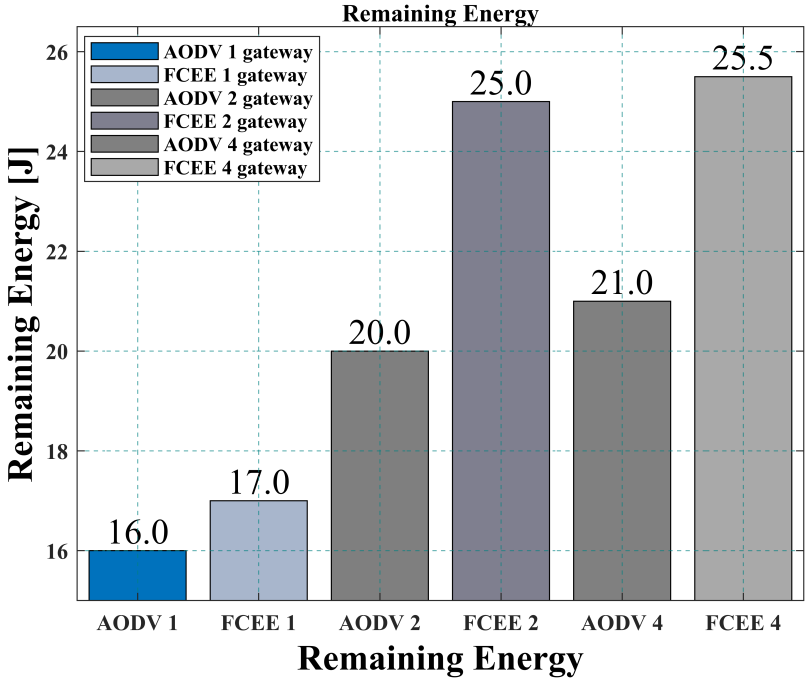

Figure 12: Remaining Energy Across a Different Gateway.

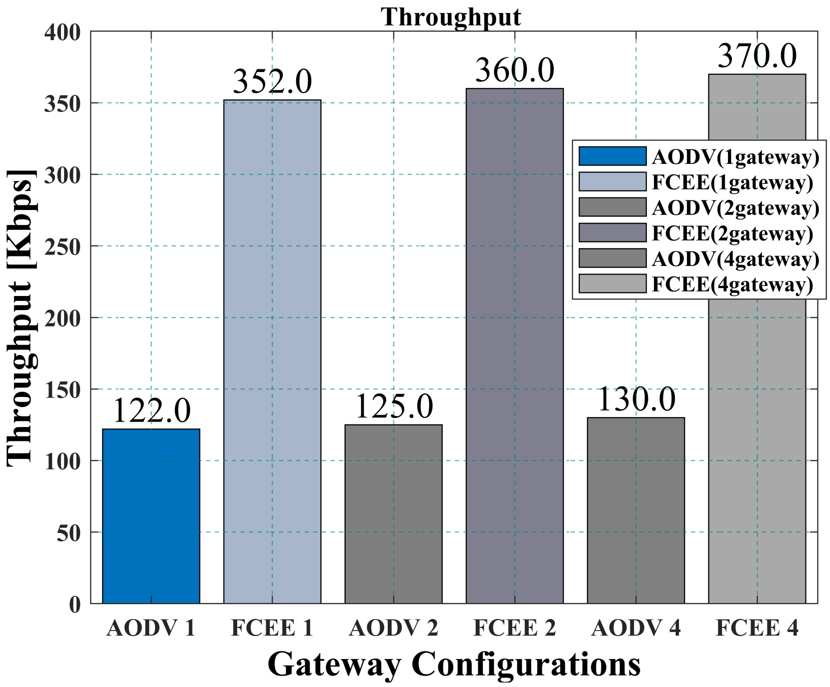

Figure 13: Throughput Across a Different Gateway.

Appendix B

Statistical Analysis Results in Appendix B

Mean	Median
Standard Deviation (SD)	Relative SD

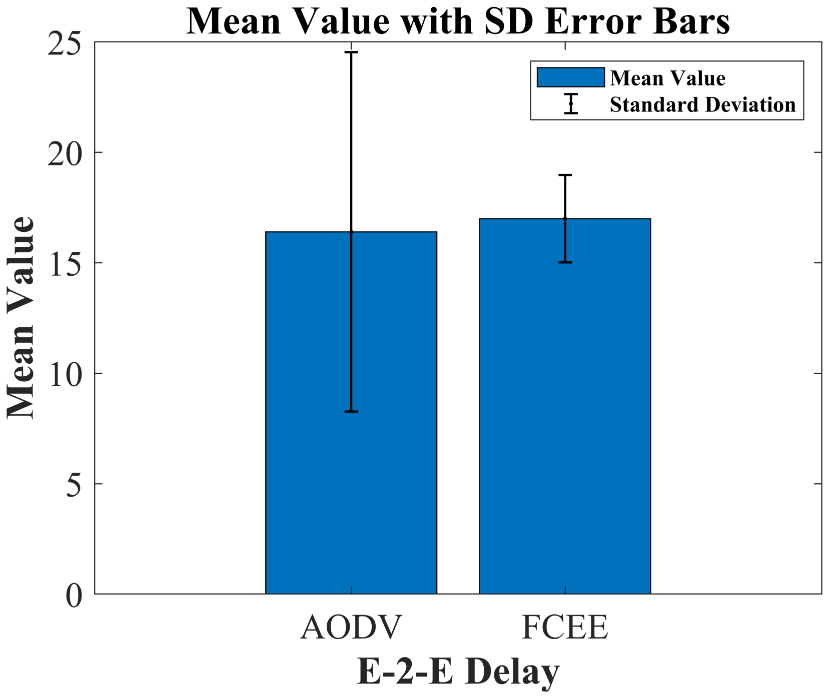

Figure 14: Comparative Statistical Analysis of E-2-E Delay .

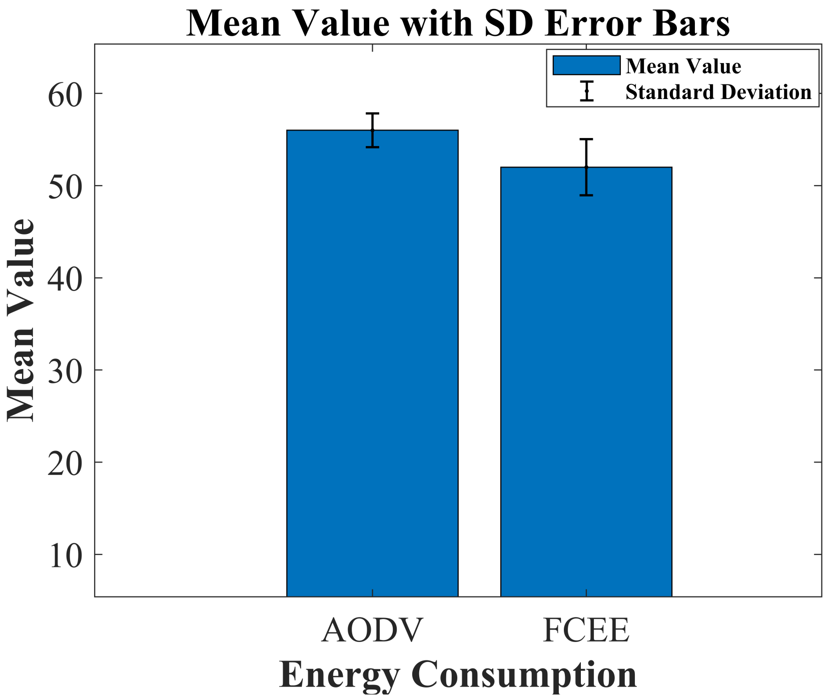

Figure 15: Comparative Statistical Analysis of Energy Consumption.

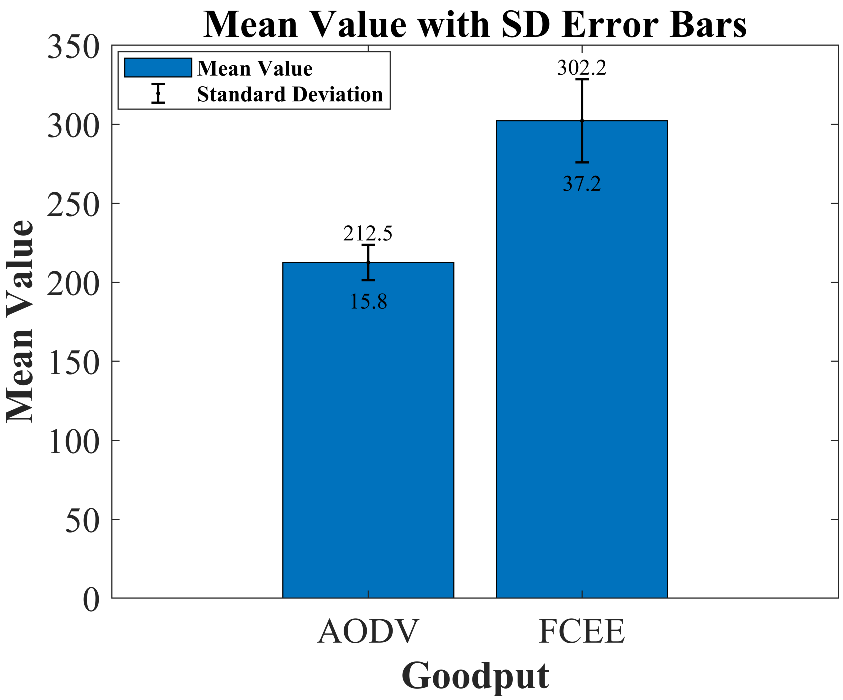

Figure 16: Comparative Statistical Analysis of Goodput.

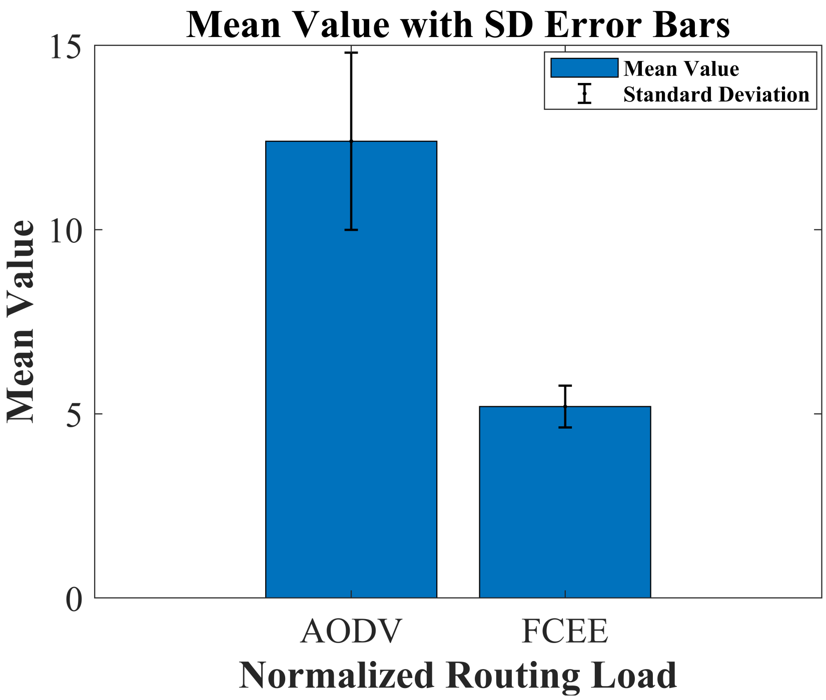

Figure 17: Comparative Statistical Analysis of NRL.

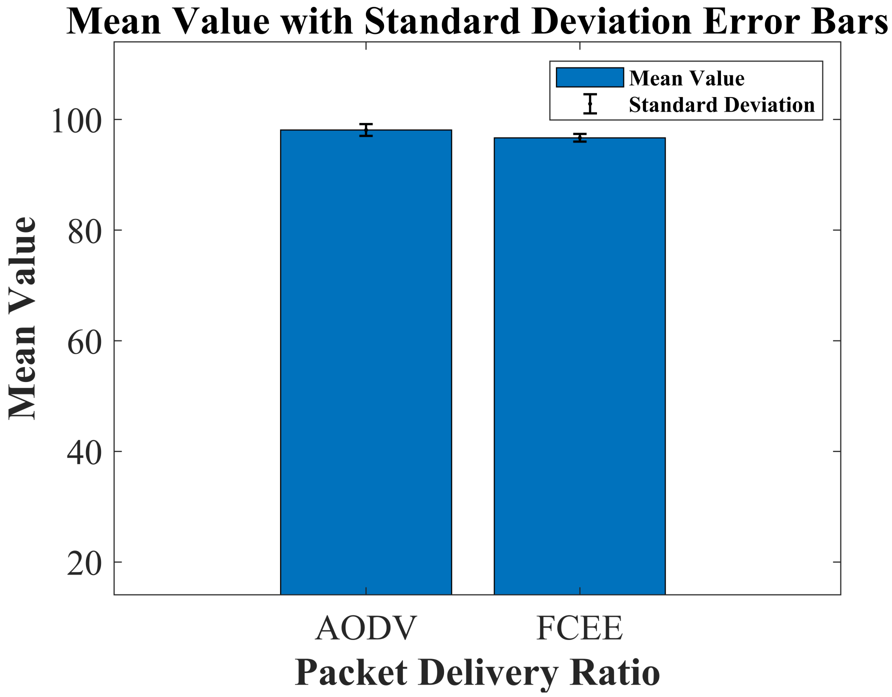

Figure 18: Comparative Statistical Analysis of PDR.

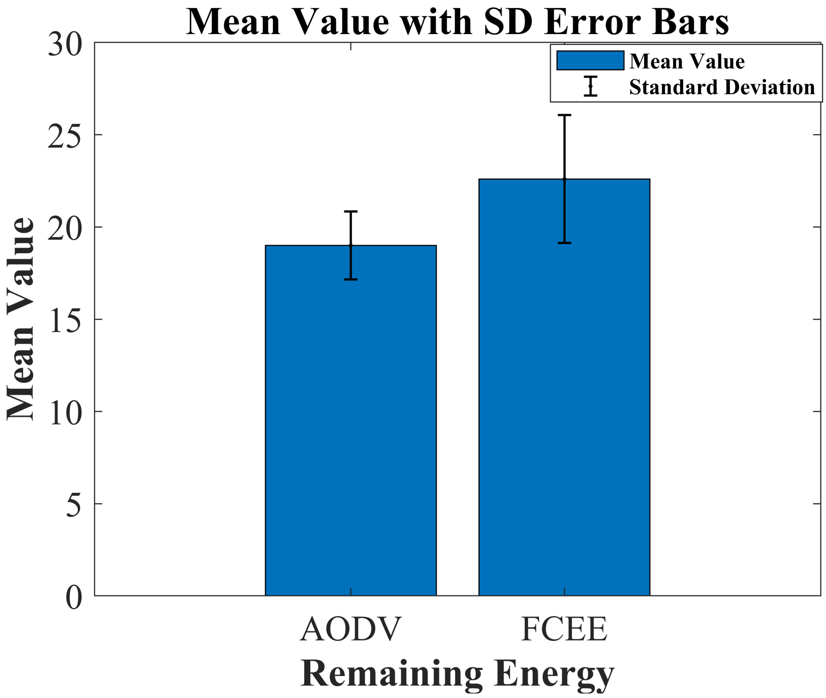

Figure 19: Comparative Statistical Analysis of Remaining Energy.

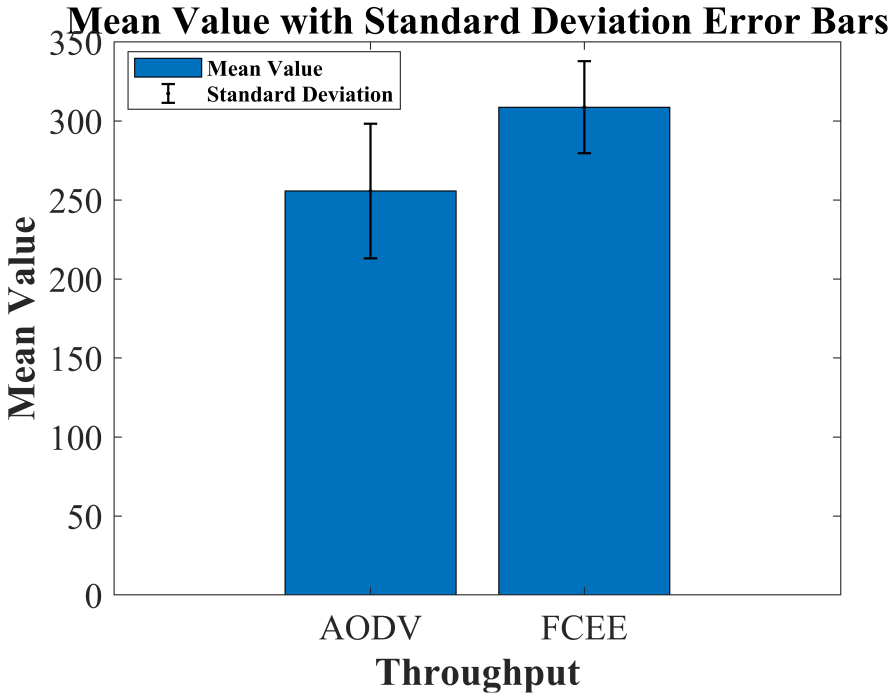

Figure 20: Comparative Statistical Analysis of Throughput.

Appendix C

Traffic Models Analysis Results in Appendix C

Traffic Models	FCEE & AODV
CBR	Pareto

Table 1: Simulation parameters of CBR and Pareto.

Parameter	**Value/Type**
Channel type	Wireless channel
Node Number	31
Simulation Network Size	1000 m X 1000 m
Time	180 s
Routing Protocols	FCEE & AODV
Mobility model	Random Waypoint
Propagation model	Propagation/Free Space
Agent type	UDP
Application Protocol	CBR & Pareto
Network protocol	IPv4
Node Speed	10 (m/sec)

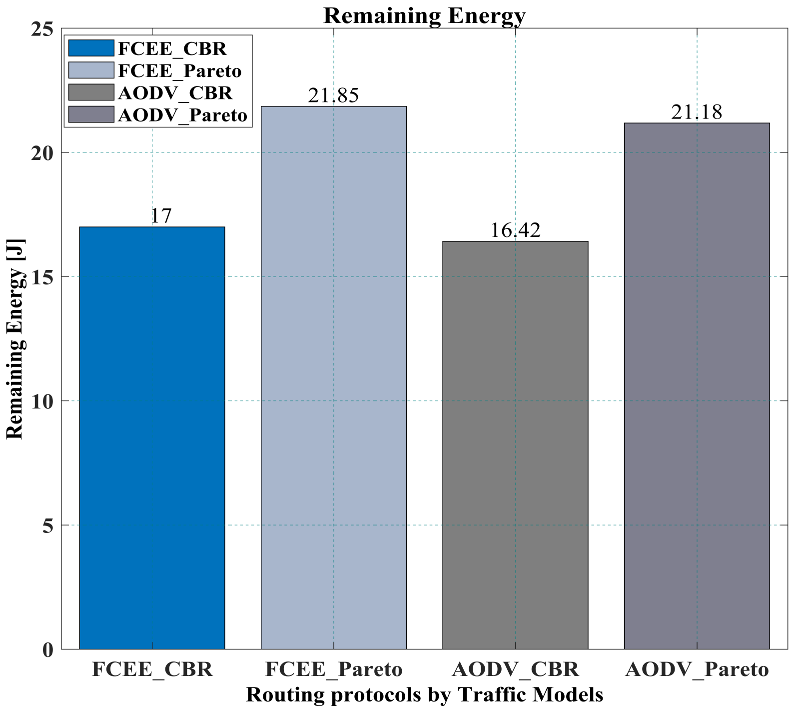

Figure 21: Remaining Energy .

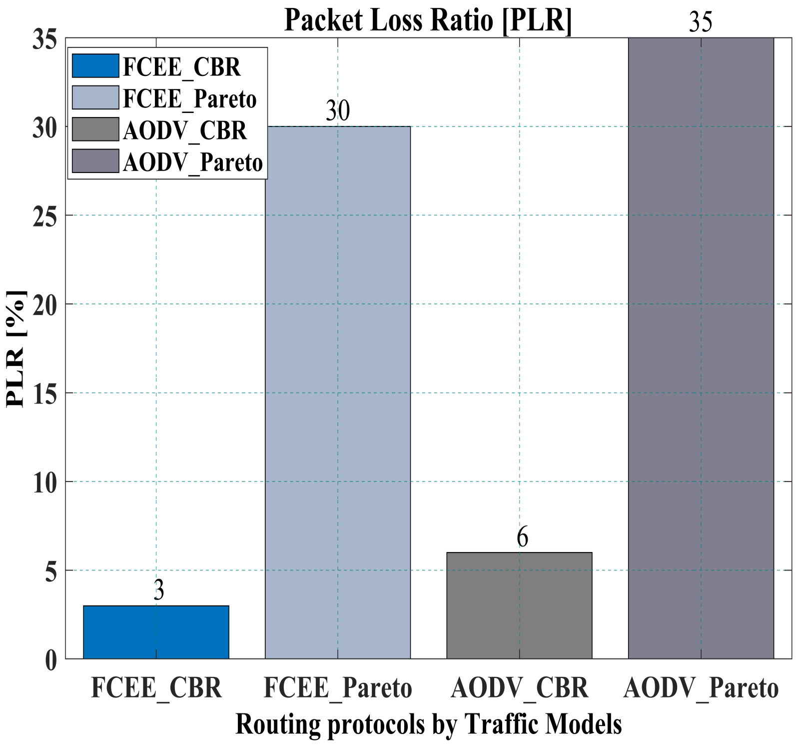

Figure 22: Packet Loss Ratio.

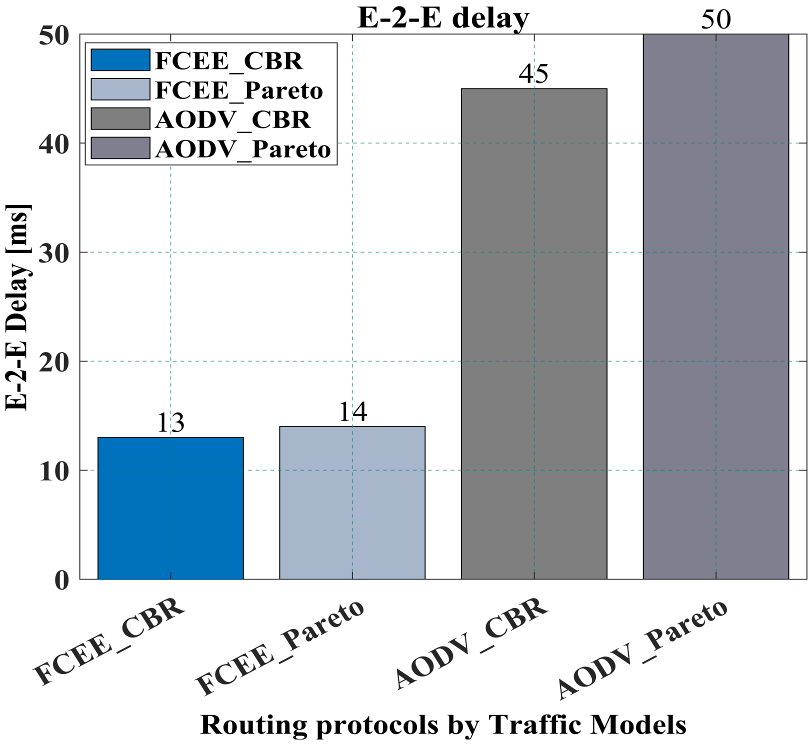

Figure 23: E-2-E Delay .

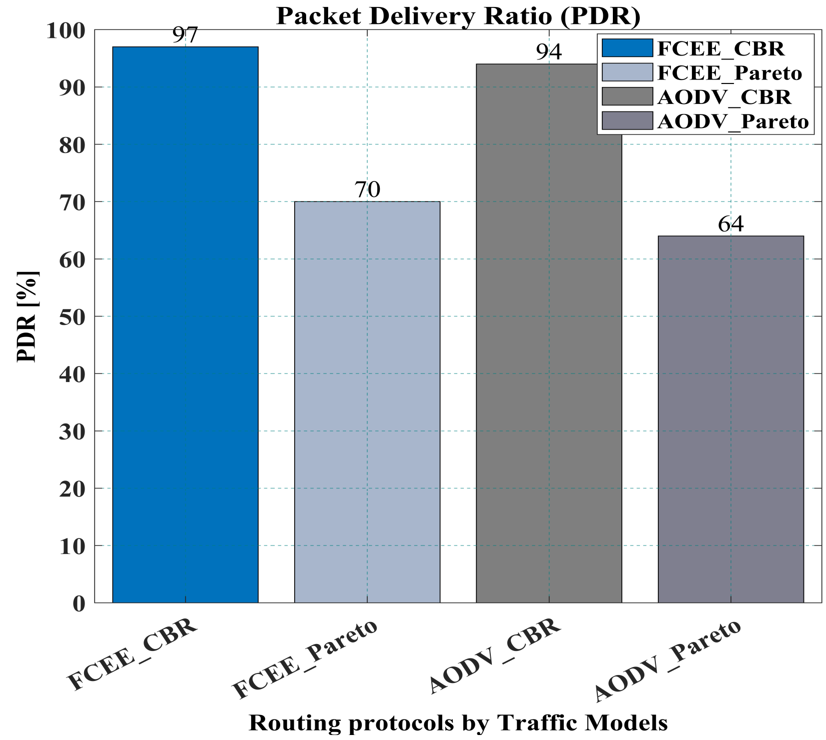

Figure 24: Packet Delivery Ratio .

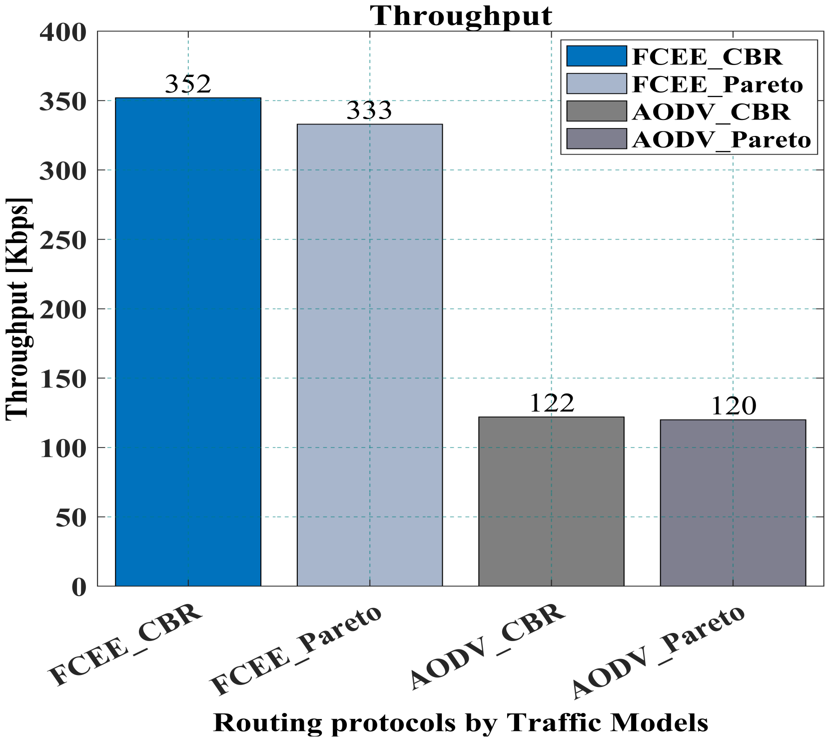

Figure 25: Throughput .

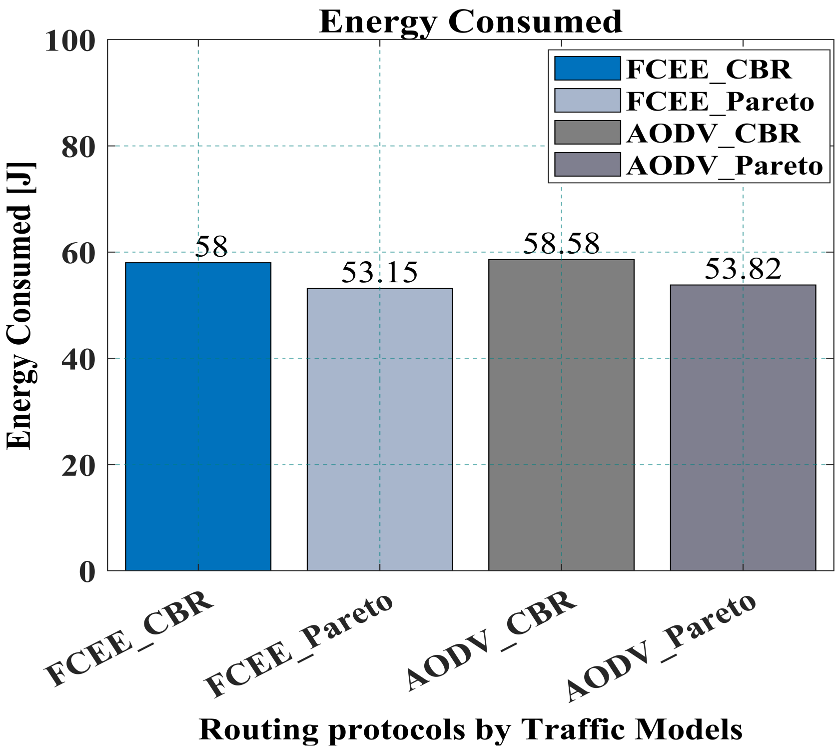

Figure 26: Energy Consumed .

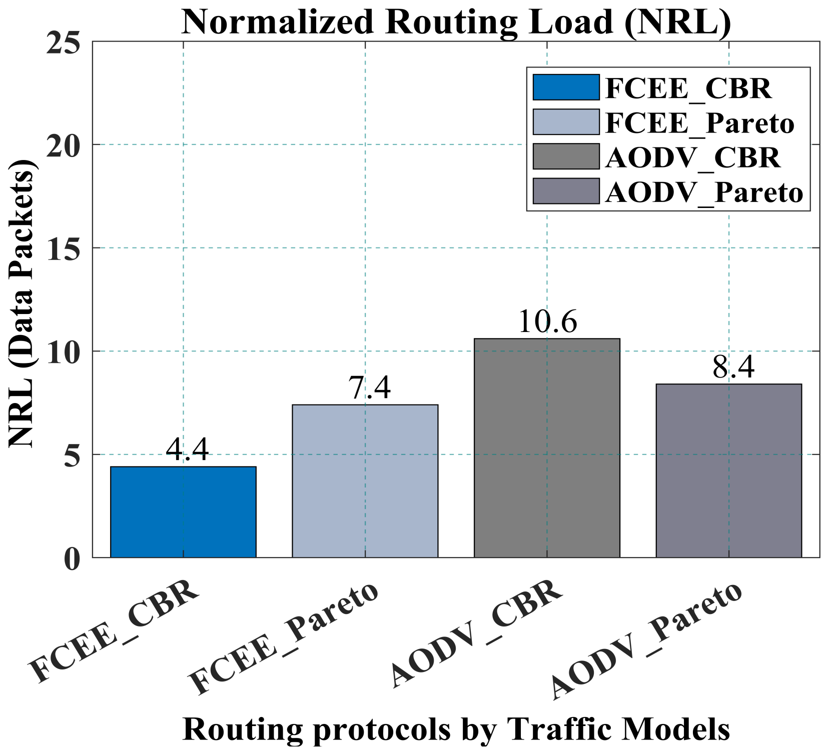

Figure 27: Normalized Routing Load .

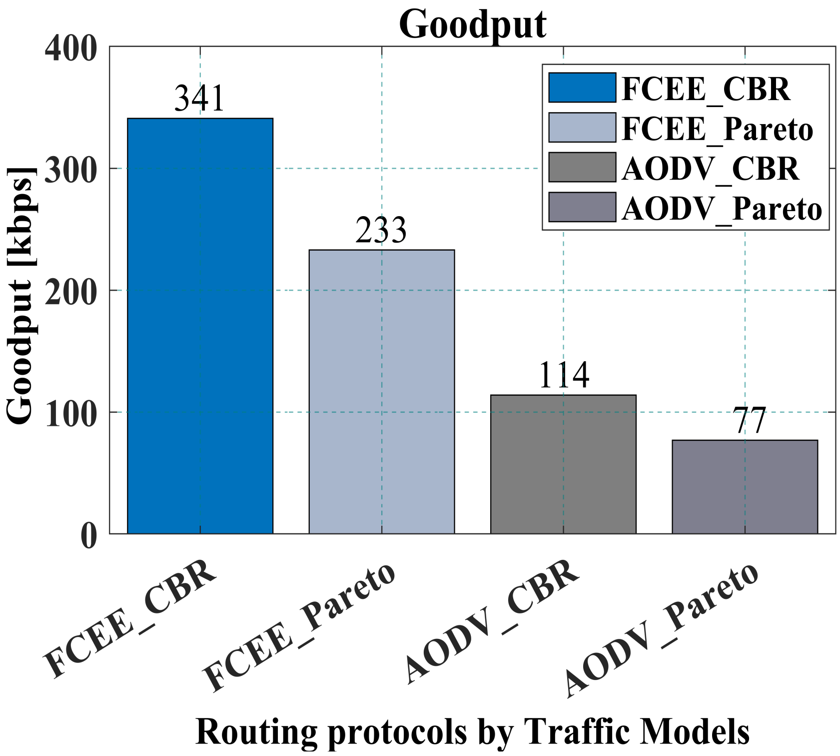

Figure 28: Goodput .

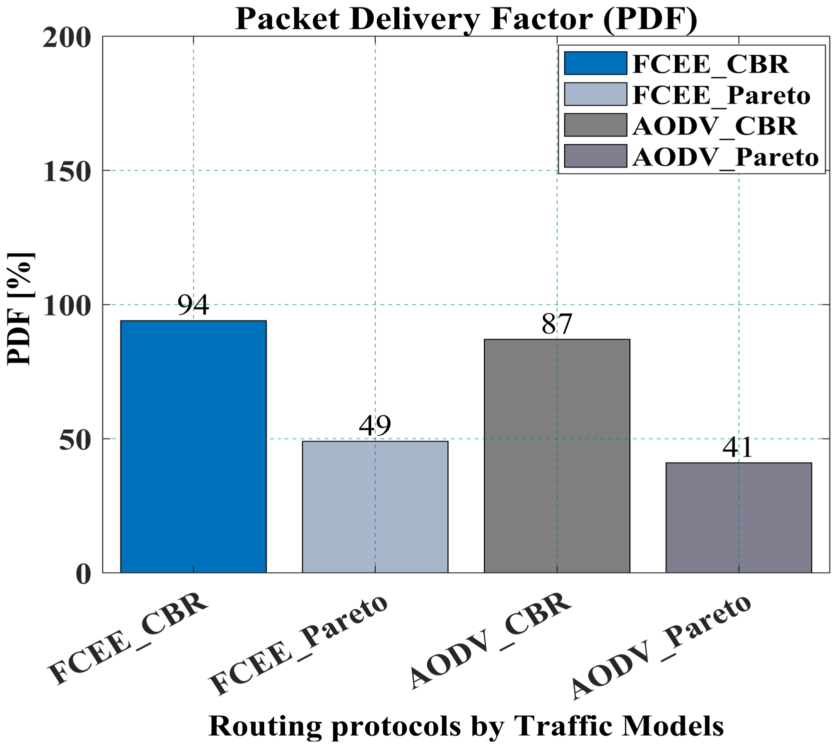

Figure 29: Packet Delivery Factor.

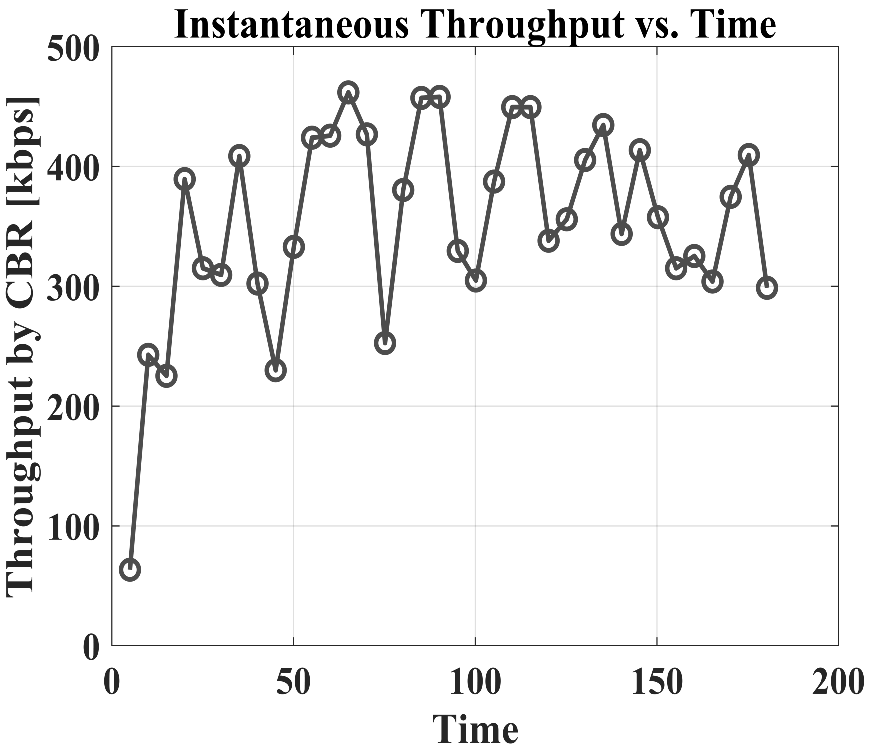

Figure 30: Instantaneous Throughput vs. Time Based on **CBR**.

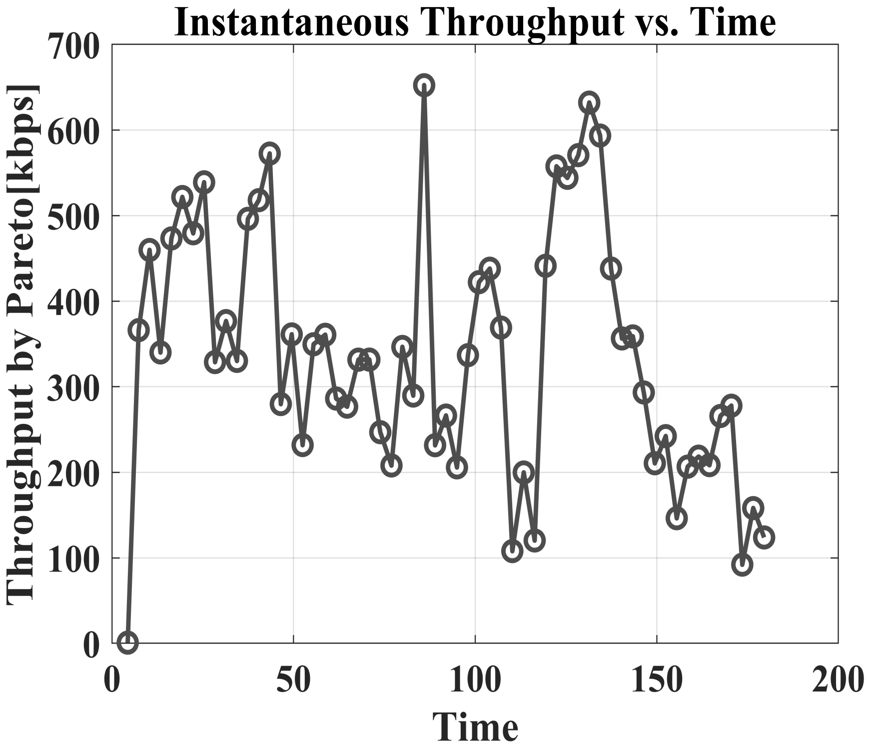

Figure 31: Instantaneous Throughput vs. Time Based on **Pareto**.

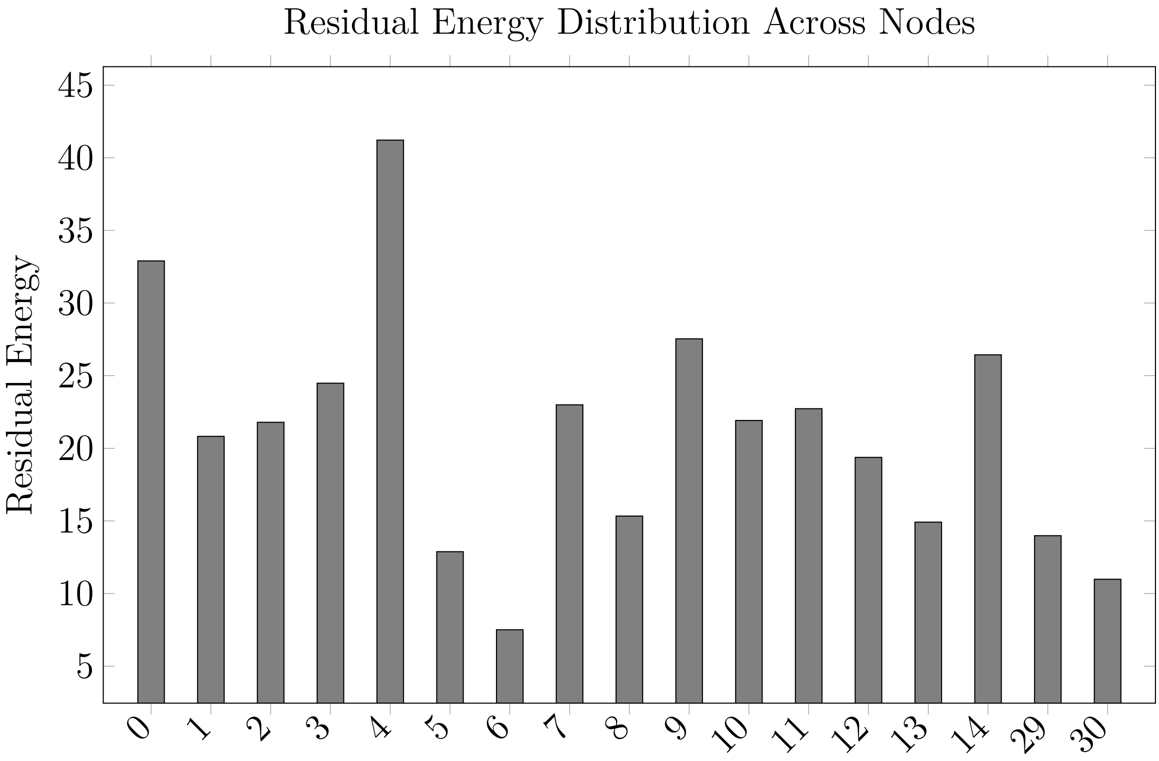

Figure 32: Node Residual Energy Distribution (Avg. 21.89) on FCEE Pareto.

Table 2: Energy Consumption of the Nodes Based on FCEE Pareto.

Node	Initial Energy	Final Energy	Consumed Energy
0	75	32.90	42.10
1	75	20.82	54.18
2	75	21.79	53.21
3	75	24.48	50.52
4	75	41.22	33.78
5	75	12.88	62.12
6	75	7.51	67.49
7	75	22.99	52.01
8	75	15.33	59.67
9	75	27.54	47.46
10	75	21.91	53.09
11	75	22.73	52.27
12	75	19.37	55.63
13	75	14.92	60.08
14	75	26.44	48.56
⋮	⋮	⋮	⋮
29	75	13.98	61.02
30	75	10.98	64.02
⋮	⋮	⋮	⋮

Table 3: Instantaneous Throughput Based on FCEE Pareto.

Time	**Throughput [kbps]**
4.33761	0.981202
7.35461	366.139
10.3555	459.765
13.363	340.085
16.3685	473.256
19.3725	521.63
22.373	479.307
25.3759	538.838
28.3765	328.827
31.4065	376.662
34.4111	330.186
37.4277	496.186
⋮	⋮
49.4926	361.111
52.4948	231.866
55.509	349.599
58.7292	360.674
61.7307	286.171
64.7464	276.749
67.862	331.615
70.8747	331.682
73.8759	246.877
76.9589	207.994
79.9591	346.471
82.9593	289.698
85.9596	652.283
88.969	231.657
91.9707	266.279
94.989	205.787
98.0089	336.867
101.03	422.148
104.03	437.908
107.121	369.1
110.237	107.949
113.376	199.753
116.385	120.358
119.388	441.294
122.388	557.433
125.393	544.094
128.401	570.627
131.403	631.966
134.406	593.449
137.409	438.088
140.413	356.438
143.415	358.804
146.427	293.286
149.462	210.577
152.47	242.256
155.495	146.374
158.509	206.608
161.515	218.271
164.522	208.391
167.53	265.796
170.54	277.803
173.546	92.1258

Table 4: Instantaneous Throughput Based on FCEE CBR.

Time	**Throughput [kbps]**
5.00364	63.4427
10.0371	242.77
15.0462	225.261
20.0529	389.435
25.0799	315.048
30.1	309.512
35.1	408.678
40.1	302.278
45.1	229.926
50.1	332.922
55.1	424
60.1	425.702
65.1053	461.812
70.1923	426.793
75.1974	252.648
80.2	380.36
85.2	457.197
90.2	458.048
95.2	329.517
100.2	304.832
105.2	387.398
110.2	449.536
115.2	449.536
120.2	338.029
125.2	355.904
⋮	⋮
145.3	413.594
150.3	357.606
155.3	315.046
160.3	325.261
165.3	303.981
170.3	374.63
175.3	409.53
180.304	298.724