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Enhanced Handover Algorithm for Quality of Service Maintenance in an Extended Service Set Wi-Fi Network

Derrick Wong Qin Sheng

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Enhanced Roaming Algorithm for Quality of Service Maintenance in an Extended Service Set Wi-Fi Network

Derrick Wong Qin Sheng

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

DERRICK

………………………………

Signature

Name: Derrick Wong Qin Sheng

Matric No.: 20020353

Faculty of Computer Science and Information Technology

Universiti Malaysia Sarawak

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ABSTRACT

The technology of IEEE 802.11 has become one of the de facto networks utilized for indoor smart devices. During the connection, the wireless mobile node establishes a connection with Access Point (AP) to gain access to the network. With the increasing number of wireless devices, the frequencies used by the IEEE 802.11 network have become crowded, with many wireless devices available in the same location. A congested wireless network will not only cause wireless devices to have poor network data rates, but also lead to signal drops between the Access Point and the devices. To improve the reliability of IEEE 802.11 wireless network, the proposed enhanced roaming algorithm helps fulfil the requirements of the ongoing growth of new wireless devices. The enhanced roaming algorithm also helps balance loads among each BSS network without compromising the reliability of the wireless network. In this thesis, the study focuses on the performance of the enhanced roaming algorithm in Extended Service Set (ESS) network, which consists of multiple Basic Service Set (BSS) network. To validate the suggested approach, a simulation modelling was built using MATLAB to benchmark and analyse the results. For the enhanced roaming algorithm, two network parameters were considered: current associated stations and signal strength to the access point. These advancements underscore the potential for substantial improvements in Wi-Fi connectivity and reliability, fostering better user experiences and more robust network operations.

Keywords: IEEE 802.11, roaming, extended service set network, ESS, MATLAB

Algoritma Perayauan Dipertingkat untuk Penyelenggaraan Kualiti Perkhidmatan dalam Rangkaian Wi-Fi Extended Service Set

ABSTRAK

Teknologi IEEE 802.11 telah menjadi salah satu rangkaian piawai yang digunakan secara meluas untuk peranti pintar dalaman. Semasa proses sambungan, nod mudah alih tanpa wayar akan mewujudkan sambungan dengan Titik Akses untuk mendapatkan akses ke rangkaian. Dengan pertambahan jumlah peranti tanpa wayar, frekuensi yang digunakan oleh rangkaian IEEE 802.11 menjadi semakin sesak, dengan banyak peranti berada di lokasi yang sama. Rangkaian tanpa wayar yang sesak bukan sahaja menyebabkan kadar penghantaran data menjadi lemah, tetapi juga boleh mengakibatkan gangguan isyarat antara Titik Akses dan peranti. Bagi meningkatkan kebolehpercayaan rangkaian tanpa wayar IEEE 802.11, algoritma perayauan yang dipertingkatkan telah dicadangkan untuk memenuhi keperluan pertambahan peranti tanpa wayar yang berterusan. Algoritma ini juga membantu mengimbangi beban antara setiap rangkaian Set Perkhidmatan Asas tanpa menjejaskan kebolehpercayaan rangkaian. Dalam tesis ini, kajian memberi tumpuan kepada prestasi algoritma perayauan yang dipertingkatkan dalam rangkaian Set Perkhidmatan Lanjutan, yang terdiri daripada beberapa rangkaian BSS. Bagi mengesahkan pendekatan yang dicadangkan, satu pemodelan simulasi telah dibangunkan menggunakan MATLAB untuk membuat penanda aras dan menganalisis keputusan. Dua parameter rangkaian telah diambil kira dalam algoritma ini: bilangan stesen yang sedang disambungkan dan kekuatan isyarat ke Titik Akses. Kemajuan ini berpotensi meningkatkan kebolehpercayaan Wi-Fi serta menyokong pengalaman pengguna dan operasi rangkaian yang lebih baik.

Kata kunci: *IEEE 802.11, perayauan, set perkhidmatan lanjutan, ESS, MATLAB*

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LIST OF ABBREVIATIONS

4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
AC	Control Group
ACK	Acknowledgement
AI	Artificial Intelligence
AP	Access Point
ARQ	Automatic Repeat Request
BER	Bit Error Rate
BSA	Basic Service Area
BSS	Basic Service Set
BSSID	Basic Service Set Identifier
CFP	Contention-Free Period
CP	Contention Period
CPU	Central Processing Unit
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DA	Destination Address
DCF	Distributed Coordinated Function
DRL	Deep Reinforcement Learning
DHCP	Dynamic Host Configuration Protocol
DHCPREQUEST	DHCP Request Message
DHCPACK	DHCP Acknowledgment Message

DLP	Direct Link Protocol
DMA	Dynamic Multichannel Access
DS	Distribution System
DSSS	Direct Sequence Spread Spectrum
EDCA	Enhanced Distributed Channel Access
EDMA	Enhanced Dynamic Multichannel Access
ESS	Extended Service Set
FEC	Forward Error Correction
FHSS	Frequency Hopping Spread Spectrum
FIS	Fuzzy Inference System
Fuzzy-AHP	Fuzzy Analytic Hierarchy Process
GO	Group Owner
HCCA	Hybrid Coordination Function Controlled Channel Access
HCF	Hybrid Coordination Function
HOV	Handover Value
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol
IQR	Interquartile Range
IRS	Intelligent Reflective Surfaces
ISM	Industrial, Scientific, and Medical
LAN	Local Area Network
LiFi	Light Fidelity
LTE	Long-Term Evolution

MAC	Media Access Control
MCS	Modulation and Coding Schemes
MEC	Mobile Edge Computing
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MPS	Metre per Seconds
MU-MIMO	Multi-User Multiple Input Multiple Output
NAK	Negative Acknowledgement
NOMA	Non-Orthogonal Multiple Access
PCF	Point Coordination Function
PHY	Physical
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
QAM	Quadrature Amplitude Modulation
QAP	QoS Enhanced Access Point
QoE	Quality of Experience
QoS	Quality of Service
QSTA	QoS Enhanced Station
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SDN	Software Defined Network
SDWN	Software Defined Wireless Networking
SNIR	Signal-to-Noise Plus Interference Ratio
SNR	Signal-to-Noise Ratio
SSID	Service Set Identifier

STA	Station
TC	Traffic Classes
TCP	Transmission Control Protocol
TO	Transmit Opportunities
TOPSIS	Technique for Order of Preference by Similarity to the Ideal Solution
TWT	Target Wake Time
UAV	Unmanned Aerial Vehicles
UDP	User Datagram Protocol
UE	User Equipment
VHT	Very High Throughput
VIKOR	Multicriteria Optimization and Compromise Solution
VoIP	Voice over Internet Protocol
WEP	Wired Equivalent Privacy
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WPA	Wireless Fidelity Protected Access

CHAPTER 1

INTRODUCTION

1.1 Study Background

In recent years, the utilization of IEEE 802.11 technology has experienced a significant surge, solidifying its position as one of the primary networks for indoor smart devices. The widespread adoption of diverse wireless networking devices has rendered Wireless Fidelity (Wi-Fi) an essential resource for individuals globally, enabling seamless internet connectivity. While initiating a wireless link, the wireless mobile node initiates interaction with an Access Point (AP) to secure entry to the wireless network. Wi-Fi technology was introduced in 1997, leveraging the Industrial, Scientific, and Medical (ISM) frequency ranges. These frequency bands remain unregulated, enabling swift deployment of Wi-Fi networks without additional prerequisites. Noteworthy about the 802.11 technology is its capacity to handle high-speed data transfers and ensure robust service availability, along with optimal network latency, rendering it suitable for time-sensitive network services.

The contemporary approach that is widely adopted for the meticulous process of determining the most suitable Wi-Fi Access Points (AP) is primarily reliant on the quantitative assessment known as the Received Signal Strength Indicator (RSSI), which quantifies the electromagnetic signal strength that can be detected between the Station (STA) and the Access Point (AP) in question, thereby establishing a fundamental criterion for optimizing network connectivity and performance. Throughout the IEEE 802.11 link establishment process, the STA proactively scans all accessible channels, accumulating comprehensive information about neighbouring APs. Subsequently, the STA determines the APs based on the performance metrics obtained during the scanning phase. Upon identifying an AP with the highest RSSI value, the STA designates the optimal channel for association with the chosen AP.

Nonetheless, with the proliferation of Wi-Fi networks in a singular environment or locale, the efficacy of the connection is likely to diminish. As more devices connect to the same wireless network simultaneously, network traffic is bound to become congested, leading to imbalanced loads between APs. Consequently, wireless clients may experience increased latency and reduced throughput.

To enhance the dependability of IEEE 802.11 networks, this research introduces an enhanced roaming algorithm aimed at upholding the quality of service (QoS) in wireless connectivity, particularly within densely populated Wi-Fi settings. The new algorithm aims to enhance the Extended Service Set (ESS) Wi-Fi network. This is due to an ESS-enabled network consisting of two or more Basic Service Set (BSS) networks that manage wireless stations within each coverage area. This could not only be advantageous for implementing the handover algorithm to increase the efficiency of all wireless connections but also help reduce network congestion and balance loads among each BSS network.

1.2 Problem Statement

With the exponential growth in Wi-Fi network usage in recent years, accessing the internet via smart devices has become easy. These devices rely on Wi-Fi technology, which has seen continuous refinement and enhancement. Nevertheless, the extensive employment of Wi-Fi frequency bands, which are accessible to the public without the necessity of obtaining licenses or securing exclusive proprietary rights, has consequently resulted in significant congestion within these frequency bands, primarily attributable to the proliferation and widespread deployment of numerous Wireless Local Area Networks (WLANs) initiated by diverse users across various sectors.

In service areas with high population density, the rapid and widespread proliferation of Wireless Local Area Networks (WLANs) inevitably leads to significant saturation of available Wi-Fi channels. As an increasing number of access points (APs) operate within the service area, these channels become overwhelmed due to channel congestion and interference. Additionally, the proliferation of Service Set Identifiers (SSIDs) contributes to network overhead, further impacting performance, despite the deliberate and strategic positioning of access points to facilitate connectivity across the area. Each SSID serves as a unique identifier for a WLAN, while the Basic Service Set Identifier (BSSID) uniquely identifies each access point (AP) by its MAC address within an Extended Service Set (ESS) network. However, when all Wi-Fi channels become congested, wireless devices struggle to maintain stable connections with access points, especially during handoff processes within an Extended Service Set (ESS). This difficulty arises due to channel congestion and interference rather than the uniqueness of the SSID itself. As congestion increases, interference between BSSs within an ESS intensifies, degrading network quality and reliability. Users may experience packet loss, increased latency, and difficulty connecting to their intended networks, especially during peak usage periods.

While existing handoff algorithms offer some resolution to this issue, they are insufficient to accommodate the increasing number of devices anticipated in the future. These algorithms fail to address congestion and link quality concerns, which severely affect wireless network performance. Therefore, this study proposes an alternative enhanced roaming algorithm aimed at ensuring consistent wireless network connections while optimizing signal routing within an ESS network over time. The proposed algorithm aims to mitigate network congestion and enhance overall network performance and reliability. Its performance within an ESS network is evaluated using key metrics, including throughput, latency, jitter, packet loss rate, and the number of handovers. Network reliability is assessed based on availability, ensuring continuous network accessibility and operation. Stability refers to the network's ability to maintain consistent performance without significant fluctuations, while downtime minimization focuses on reducing network interruptions to ensure continuous service. By addressing these key factors, the proposed algorithm aims to ensure seamless connectivity, optimize network resource utilization, and improve the overall user experience in high-density wireless environments.

1.3 Objectives

1. To propose an enhanced roaming algorithm that improves Quality of Service (QoS) by reducing latency, jitter, and packet loss, thereby addressing the problem of degraded performance in high-density IEEE 802.11 networks.

2. To optimize overall wireless link performance through efficient resource utilization and stable connectivity, thereby mitigating the impact of network congestion and ensuring smoother communication in dense environments. To benchmark the proposed algorithm against existing handover mechanisms using key performance metrics, including throughput, latency, jitter, packet loss rate, and the number of handovers.

3. To assess the reliability of the proposed handover algorithm by evaluating network availability, stability, and downtime minimization, ensuring seamless connectivity in scenarios prone to frequent disconnections.

1.4 Contribution of Research

This research explores the functionality of a new roaming algorithm within a Wi-Fi network. The proposed enhanced roaming algorithm is designed to meet the evolving demands of modern wireless devices, addressing key factors such as seamless handover, low latency, minimal packet loss, optimized resource utilization, improved stability, and adaptive roaming decisions. Additionally, it supports the IEEE 802.11 organization in introducing correlated functions and features that enhance the seamless handover process for wireless stations within an ESS network. The proposed roaming method improves QoS without requiring major software or hardware modifications to network devices. Through simulations, we demonstrate that the suggested mechanism reduces end-to-end delay and jitter compared to traditional handover methods that rely solely on RSSI values. Furthermore, the enhanced algorithm helps balance network loads across BSSs while maintaining the reliability and stability of the wireless network.

1.5 Outline of Research

The research is organized into five chapters. Chapter 2 covers the literature review of IEEE 802.11, Basic Service Set, Extended Service Set, current handoff methods and related studies. Chapter 3 provides an overview of proposed methods and simulation implementation. The Chapter 4 discusses the performance evaluation of experiments between RSSI-based handover algorithm and proposed enhanced roaming algorithm. Chapter 5 concludes this paper and provide recommendation for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Wireless networks have emerged as an essential element of contemporary communication frameworks, facilitating omnipresent internet connectivity across diverse settings, encompassing residential areas, commercial establishments, and communal locales. Central to the functionality of Wi-Fi networks is the hand-off mechanism, which enables seamless mobility for devices moving across multiple access points within an extended service set (ESS). In a typical Wi-Fi network with ESS employed, a device may need to switch from one access point (AP) to another to maintain uninterrupted connectivity as it moves, a process known as hand-off or handover. While this mechanism is crucial for sustaining the efficacy of wireless connectivity, it also comes with several challenges, especially in terms of Quality of Service (QoS) parameters like latency, jitter, packet loss, and throughput.

The Extended Service Set (ESS) refers to a network configuration where multiple access points (APs) are interconnected to allow for continuous communication across a wide coverage area without disrupting connectivity. However, maintaining high QoS during hand-offs in such networks is complex due to the variability in signal strength, interference, and network congestion across different APs. Challenges like high latency due to delay in handover, inconsistency in delivery times, data packet loss during transmission will directly impact real-time applications like Voice over IP (VoIP), video streaming and online gaming.

Traditional hand-off mechanisms, such as signal strength-based hand-offs and pre-authentication, have been employed to facilitate this transition between APs. However, these approaches often lead to delays and interruptions, negatively impacting QoS. Consequently, the demand for enhanced transition method has emerged as a significant area of research. The IEEE has introduced various standards to address these challenges, such as IEEE 802.11r for fast Basic Service Set (BSS) transitions and IEEE 802.11ax (Wi-Fi 6), which aims to enhance overall network performance.

With the recent advancements, notably in Artificial Intelligence (AI) and Mobile Edge Computing (MEC), demonstrate potential in mitigating these issues. These technologies enable more efficient prediction of hand-off points and reduce latency by processing data closer to the network edge. With the introduction of Software-Defined Networking (SDN), the wireless network can facilitate centralized management of hand-off processes, enhancing network agility and quality of service (QoS).

The focus of this study is to review and propose an improved hand-off mechanism that enhances QoS in Wi-Fi networks with ESS. Through an in-depth analysis of the constraints exist in current hand-off mechanisms and a thorough exploration of modern methods, this study will focus on developing a more resilient solution that effectively enhances latency, minimize jitter, reduce packet loss, and sustains high and consistent throughput. In the subsequent sections, the difficulties and current advancements in Wi-Fi handover will be examined scrupulously to provide an extensive comprehension of the methods by which Quality of Service (QoS) can be enhanced within Wi-Fi networks.

2.2 IEEE 802.11 Wi-Fi Technology

2.2.1 Core Components

2.2.1.1 Stations (STAs)

Stations (STAs) are all wireless devices forming a network and functioning within the parameters of the IEEE 802.11 standard. The STAs function as the end-user clients within the extensive framework of the network, encompassing a diverse array of electronic devices, which notably includes, but is not limited to, portable computing machines such as laptops, handheld communication devices known as smartphones, and multifunctional tablet computers designed for both productivity and entertainment.

2.2.1.2 Access Point (AP)

An access point (AP) is a type of Wi-Fi node that act as a bridge to connect between wireless devices and the wired network. It also manages the data transmissions between stations that operating within the same wireless network.

2.2.1.3 Wireless Medium

The wireless medium serves as the method for all transmission occurring within a Wi-Fi network, operating under defined IEEE 802.11 standards. Multiple physical layers (wireless mediums) have been designated in the IEEE 802.11 to support the IEEE 802.11 MAC layer.

2.2.1.4 Distribution System

The access point is interconnected with a distribution system (DS) to establish connection to the primary network infrastructure. The connection can be established via various mediums such as cables, LAN cables or Optical Fibre Cables.

2.2.2 Network Architectures

A Basic Service Set (BSS) is a fundamental building block of wireless local area networks (WLANs) or Wi-Fi networks (Insam, 2003). It represents a group of wireless stations (STAs) communicating with each other within the same basic coverage area, also known as a basic service area.

There are two types of Basic Service Set configurations:

- Infrastructure Basic Service Set
- Independent Basic Service Set (IBSS)

With the combination of several Infrastructure Basic Service Sets can form an Extended Basic Service Set (ESS) network. The access points within an ESS network are linked through a distribution system. This integrated wireless local area network (WLAN), comprising of BSSs, their respective access points (APs), and the distribution system (DS) that interconnects them. The ESS architecture enables seamless mobility and roaming across the entire wireless network domain for STAs. The following Figure 2.1 illustrates the IEEE 802.11 wireless network topologies.

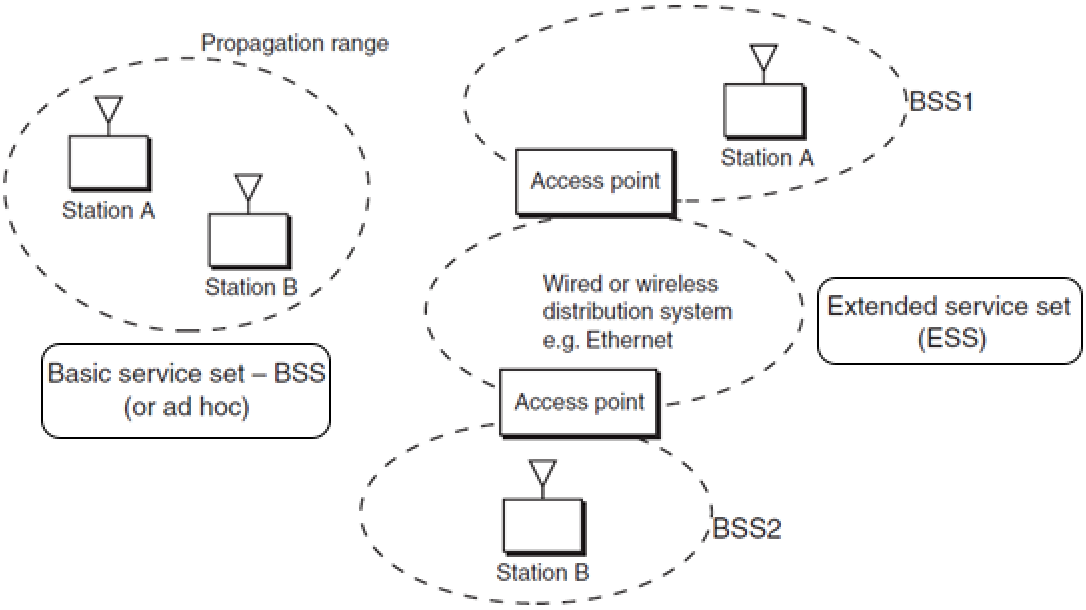

Figure 2.1: IEEE 802.11 Wireless Network Topologies (Insam, 2003)

Each Basic Service Set (BSS) is assigned a unique 48-bit identifier known as the BSS Identifier (BSSID). This BSSID functions as a network address, facilitating the interconnection and communication between different BSSs. The media access control (MAC) address of the AP is used for the BSSID for that BSS. The Service Set Identifier (SSID) serves as a recognizing label to identify and differentiate between various BSSs by the wireless end devices. The SSID provides a logical grouping mechanism, allowing client devices to selectively associate with the desired BSS based on the advertised SSID.

- **Infrastructure BSS** – All STAs are connected to and managed by AP, which coordinates and administers all communication exchanges within the BSS. Each of the station must be associated with a single AP. This AP was connected to the DS and facilitates the availability of network services to the STAs located within the coverage of the Basic Service Area (BSA). In this architecture, the wireless network parameters are preset and constant during operation.

- **Independent BSS (IBSS)** – This configuration is also commonly referred to Ad-Hoc BSS. The STAs operating in this architecture function independently, without the need for a centralized AP to manage their transmissions. The STAs communicate directly via peer-to-peer connections among themselves, without the need of an intermediary node in between. One of the stations within IBSS network will be assigned as the group owner (GO), responsible for defining and distributing the operational parameters of the wireless network. This decentralized architecture is typically designed to facilitate temporary communication among a small number of users.
- **Extended BSS (ESS)** – Multiple BSSs can be employed as ESS, enabling STAs in each BSSs to communicate seamlessly, and facilitating their mobility between different Basic Service Areas (BSAs). The APs act as bridges for their associated STAs and gateway to other APs that configured with the same ESS. It is one of the most widely adopted architectures in IEEE 802.11 wireless network since it offers the capability to initiate communications between STAs regardless their location in the ESS.

2.3 Wi-Fi Handover and Quality of Service (QoS) Challenges

Within the field of wireless networking, Wi-Fi handover and Quality of Service (QoS) introduce complex challenges spanning technical, infrastructural, and performance-related dimensions. These issues are particularly pronounced in heterogeneous network environments, where seamless connectivity and sustained high QoS are essential. A heterogeneous network integrates diverse technologies—such as IEEE 802.11-based Wi-Fi, cellular systems (e.g., 4G LTE or 5G), and other wireless protocols—each with distinct operational characteristics and infrastructure demands. This section investigates these challenges in depth, providing a comprehensive analysis of their implications and the current research landscape.

2.3.1 Frequent Handover and Network Performance

The impact of frequent handovers on Wi-Fi network performance is both significant and multifaceted. At its core, each handover necessitates a device disconnecting from one access point (AP) and reconnecting to another. This process, while necessary for maintaining connectivity across a wider area, can lead to brief but impactful interruptions in network connection. Such disruptions are particularly problematic for applications requiring continuous data flow, such as video streaming.

Moreover, the time required to complete a handover introduces additional latency into the network. The increased latency can be quite unfavourable to real-time applications, including online gaming and video conferencing, where reduced latency is imperative for an uninterrupted user experience (Chu et al., 2023). The cumulative effect of these handovers extends beyond mere interruptions, potentially reducing overall network throughput, as demonstrated by the enhanced handover mechanism using mobility prediction (eHMP), which increased throughput by 106% in homogeneous networks and 55% in heterogeneous networks compared to traditional methods (Yap et al., 2020). Additionally, neural-network-based approaches have improved user throughput by 18.58% to 38.5% while reducing handover rates by up to 67.15%, highlighting the cumulative impact of optimized handovers on overall network performance (Khan et al., 2024). Stations (STAs) transition between APs in response to degraded connection quality that restricts data transmission, seeking improved opportunities for efficient communication. This handover is driven by the need to mitigate the limitations imposed by suboptimal signal strength or interference. If no switch occurs, data transmission is increasingly susceptible to degradation, particularly when the wireless channel experiences failure or significant performance decline due to factors such as attenuation, congestion, or environmental interference.

Another critical concern is packet loss during the handover process. This process can result in lost data packets, further degrading the quality of service for loss-sensitive applications such as VoIP or high-definition video streaming when not managed efficiently. During the Wi-Fi handover process, data transmission is momentarily stopped by the Station (STA), leading to a brief disconnection from the current Access Point (AP). This disconnection causes packet loss as any packets in transit are likely to be lost due to the inability to acknowledge or retransmit them until the connection is reestablished with the new AP. Additionally, prolonged handover delays can result in buffer overflow, further contributing to packet loss, which may not be fully recovered even after reconnection and retransmission requests. This issue is compounded in environments with multiple overlapping Wi-Fi networks, where interference becomes a significant factor. The presence of numerous networks operating in proximity can lead to signal overlap, increased noise, and reduced signal clarity. Consequently, users may experience slower data rates, heightened latency, and increased packet loss, all of which contribute to a diminished Quality of Service (Zeljkovic et al., 2017). In environments with overlapping coverage areas, frequent handovers further amplify cumulative packet loss due to the interaction between disconnection during handover and interference from overlapping networks (Indrasena & Sofia, 2024). Both factors contribute significantly to degraded network performance and diminished user experience.

2.3.2 Integration of Heterogeneous Networks

The integration of Wi-Fi with complementary wireless technologies—Light Fidelity (LiFi) and cellular networks such as Long-Term Evolution (LTE)—presents substantial challenges stemming from Wi-Fi's inherent characteristics. As delineated in IEEE 802.11 standards, Wi-Fi's design prioritizes short-range communication, necessitating frequent handovers when mobile devices traverse beyond its coverage boundaries. These transitions disrupt active sessions and impose significant demands on maintaining consistent Quality of Service (QoS). In heterogeneous systems combining Wi-Fi with alternative technologies, handover complexity intensifies due to disparate coverage patterns and operational paradigms. Specifically, Wi-Fi-to-LTE transitions exhibit handover latencies of 100–300 milliseconds, packet loss rates of 5–10%, and transient bandwidth degradation (Hosny et al., 2019). These technical impediments, exacerbated by operational asymmetries between systems, substantially impact user-perceived QoS (Bukhari & Akkari, 2016).

Facilitating seamless handovers between Wi-Fi and alternative wireless technologies represents a significant research challenge, particularly regarding uninterrupted connectivity and QoS stability. Contemporary advancements in machine learning (ML) and software-defined networking (SDN) offer promising methodological approaches. ML-driven predictive models enable adaptive handover management through real-time analysis of network conditions and mobility patterns, thereby enhancing throughput metrics while minimizing handover disruptions (Priyanka et al., 2023). In latency-sensitive applications such as high-definition video streaming and interactive gaming, these enhancements manifest as continuous playback and diminished buffering intervals. Furthermore, sophisticated ML paradigms—particularly reinforcement learning and deep neural networks—facilitate optimized handover decisions through precise forecasting of dynamic network conditions and user behavioural patterns.

In heterogeneous networks (HetNets)— comprising diverse cellular infrastructures including macro, micro, pico, and femto cells—load distribution asymmetries can exacerbate phenomena such as handover ping-pong and handover failure due to suboptimal cell selection algorithms. Strategic load balancing mechanisms are therefore critical for handover performance optimization, as significant disparities in resource utilization can precipitate inefficient handover decisions, thereby amplifying network inefficiencies characterized by elevated latency profiles and compromised throughput capacity (Priyanka et al., 2023). SDN-based architectures, leveraging centralized control planes and programmable network elements, enable coordinated handover orchestration across technological boundaries, thus enhancing overall network efficiency. For instance, SDN controllers can dynamically reallocate network resources in response to temporal traffic fluctuations, thereby optimizing resource utilization metrics.

Addressing these multifaceted challenges necessitates the development of compatible link-layer mechanisms and Medium Access Control (MAC) protocols to efficiently manage data transmission while preserving service quality across heterogeneous network architectures. Contemporary research emphasizes the efficacy of artificial intelligence (AI)-based methodologies for handover optimization in fifth generation and emerging sixth-generation networks, demonstrating substantial latency reductions and reliability enhancements through intelligent handover frameworks (Ashour & Fouda, 2023). Moreover, the convergence of AI/ML techniques with SDN infrastructures represents a promising research trajectory for wireless communication advancements, particularly as networks evolve toward 6G paradigms where ultra-high-speed data transfer and ultra-low latency requirements become increasingly stringent (Aktas et al., 2023). Secure handover mechanisms constitute an equally critical research domain in this context. Investigations into enhanced handover security protocols for heterogeneous networks demonstrate marked improvements in successful handover rates, concurrent with reductions in latency metrics and packet loss statistics, through advanced cryptographic implementations and secure authentication frameworks designed to mitigate unauthorized access vulnerabilities during handover procedures (Nyangaresi et al., 2020). Furthermore, comparative analyses of vertical handover decision algorithms in HetNets indicate that multi-criteria decision frameworks consistently outperform traditional single-criterion methodologies, yielding superior throughput performance and reduced handover duration metrics (Edia et al., 2018).

2.3.3 QoS Parameters and Handover Decision

Handover decision-making in wireless networks, particularly those based on the IEEE 802.11 standard, relies on sophisticated algorithms that assess multiple Quality of Service (QoS) parameters to facilitate optimal network transitions. This process is critical for ensuring uninterrupted connectivity while aligning the selected network with application-specific performance requirements (Kassar et al., 2008). The IEEE 802.11 handover decision framework evaluates several pivotal QoS metrics, as outlined below.

Received Signal Strength (RSS) constitutes the cornerstone of traditional handover mechanisms. Yan et al. (2010) note that RSS values falling below -72 dBm typically initiate handover procedures in most commercial implementations. In heterogeneous network environments, RSS is evaluated alongside supplementary network attributes to gauge connection quality comprehensively.

Available bandwidth is a vital QoS parameter for meeting data transmission demands. Márquez-Barja et al. (2011) explain that the IEEE 802.11 standard employs channel utilization measurements to assess bandwidth availability, enabling the identification of congestion levels to guide handover decisions effectively.

Network congestion significantly affects packet delivery performance and overall user experience. Mohanty & Akyildiz (2006) affirm that IEEE 802.11 implementations monitor traffic density and access point queue lengths to evaluate network load, thereby informing handover execution under varying conditions.

Signal-to-Interference-plus-Noise Ratio (SINR) offers a more nuanced assessment of signal quality than RSS alone. Stevens-Navarro et al. (2008) report that commercial IEEE 802.11 systems leverage SINR thresholds ranging from 10 to 15 dB to ensure reliable connectivity in environments susceptible to interference.

The velocity of mobile nodes exerts a considerable influence on handover frequency and success rates. Fernandes & Karmouch (2012) demonstrate that handover performance in IEEE 802.11 systems deteriorates when mobile speeds exceed 10 m/s, leading to elevated packet loss during transitions between access points.

The convergence of IEEE 802.11 with other wireless technologies introduces additional complexity to handover scenarios. Ahmed et al. (2014) observe that conventional vertical handover strategies in heterogeneous networks prioritize connection stability, adhering to predefined performance thresholds consistent with the "always best connected" paradigm prevalent in commercial deployments.

2.3.4 Reducing Handover Latency

Seamless network transitions in wireless environments are often hindered by handover-related latency. This latency includes key components such as scan latency and authentication latency, which together disrupt uninterrupted connectivity in mobile scenarios. Scan latency arises during the discovery phase, where mobile devices search for available access points—a process that introduces inherent delays and may interrupt active sessions. Following this, authentication latency further prolongs the transition as devices establish cryptographic credentials and security associations with newly discovered access points. It is important to distinguish these handover-specific delays from network latency, a broader metric reflecting the time it takes for data packets to traverse the network. Network latency is influenced by factors such as congestion, transmission medium properties, and the topological distribution of network nodes (Pillai & Gopal, 2024).

Network latency has significant implications for user experience, especially in applications that rely on continuous data flow with minimal interruptions—such as high-definition video streaming, real-time collaboration platforms, and latency-sensitive telemedicine services. The core challenge lies in reducing these temporal inefficiencies while maintaining secure and stable connectivity. Current research in network engineering and telecommunications addresses this balance through innovative approaches. Transport layer protocol optimization is one such strategy, with strong potential to enhance data reliability and reduce latency in mobile networks.

Addressing the multifaceted challenges of Wi-Fi handovers and Quality of Service (QoS) assurance demands an integrated, cross-disciplinary approach. Effective solutions must draw on advances in network protocol engineering, infrastructure design, and advance handover algorithms. As wireless technologies evolve, strategies for maintaining consistent connectivity and high service quality must adapt to increasingly complex and heterogeneous network environments. Key components of this adaptive strategy include sophisticated load balancing algorithms, dynamic resource allocation, and predictive handover mechanisms (Beshley et al., 2021). Furthermore, the integration of machine learning techniques for predictive analytics offers promising avenues for anticipating congestion patterns and proactively optimizing handovers based on both historical performance data and real-time network conditions.

2.3.5 IEEE 802.11 Standards

The IEEE 802.11 protocol, introduced in 1997, established the first standard for wireless local area networks (WLAN). This protocol operates within the license-free 2.4 GHz Industrial, Scientific, and Medical (ISM) band and primarily addresses specifications for both the physical layer (PHY) and medium access control (MAC) layer (Hiertz et al., 2010). At the physical layer, the 802.11 standard implements three distinct modulation techniques: Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS)—both operating in the 2.4 GHz frequency range—and an infrared PHY functioning at 316-353 THz, though the latter has no commercial applications available to the public.

Frequency Hopping Spread Spectrum (FHSS) serves as a transmission system that enhances wireless communication by rapidly switching the carrier frequency according to a predetermined sequence (Latif et al., 2012). This technique offers superior privacy and interference resistance due to its narrowband signal (less than 1 MHz) that hops in a pseudo-random yet predictable pattern across frequencies, synchronized between transmitter and receiver (Hossein, 2011).

In contrast, Direct Sequence Spread Spectrum (DSSS) utilizes a 22 MHz wide band signal to transmit data across an expanded bandwidth. DSSS pairs the data signal with a chipping code that provides resilience against interference while also determining signal spreading characteristics and communication data rates. This encoding methodology significantly enhances the robustness of wireless transmissions in challenging environments.

For the layer above the PHY layer, the MAC layer implements a contention-based scheme known as the Distributed Coordination Function (DCF). In this method, a station (STA) connects with an access point (AP) to transmit data to its destination. If the medium is not idle or multiple STAs attempt to access the AP simultaneously, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is used to prevent collisions within the wireless network (Banerji & Chowdhury, 2013).

Another MAC-layer scheme is the Point Coordination Function (PCF), a polling-based technique designed to provide a contention-free environment. PCF operates in two main phases: the Contention-Free Period (CFP) and the Contention Period (CP). During the CFP, the Access Point (AP) polls stations in a round-robin manner to check for pending transmissions, ensuring each station a guaranteed opportunity to transmit without contention. Following the CFP, the network enters a contention period where unpolled stations can request access using the Distributed Coordination Function (DCF). When a station forms a link with the AP, it senses the medium to determine if it is free. However, PCF can limit the overall throughput due to polling overhead and the possibility of null packets when stations have no data to send (Kanjanavapastit & Landfeldt, 2003). The polling process itself consumes bandwidth and time, even when no data is being transmitted. Furthermore, when polled stations have no data, they respond with null packets, which waste bandwidth and processing resources. These inefficiencies can be particularly significant in dynamic environments where traffic patterns vary among stations, leading to underutilization of the channel.

As a result, DCF is typically the default method in IEEE 802.11 networks because it provides higher throughput and lower delay, especially for a limited number of users (Vergados & Vergados, 2004). In both Distributed Coordination Function (DCF) and Point Coordination Function (PCF), an automatic acknowledgment system is used. When data is received correctly by the recipient (which can be either an Access Point (AP) or a Station (STA)), an Acknowledgement (ACK) is sent back to the sender. If the data is corrupted, a

Negative Acknowledgement (NAK) is returned, prompting the sender to retransmit the data. This acknowledgment mechanism introduces a round-trip delay, as the sender must wait for an ACK before sending the next data packet.

Communication interference will occur during data transmission across the frequency spectrum, primarily where two or more devices use the same frequency band. Often many stations waiting for the channel to become inactive and concurrently starting transmission will cause collisions (Crow et al., 1997). The collision occurs when the transmission presence is not detectable by stations in advance. The Average Bit Error Rate (BER) was then developed to detect the reliability of wireless communication. For example, the average bit error rate of 10-2 is appropriate for packetized voice. Each type of data has different requirements. The data would be volatile as if the program were a time-sensitive operation, usually applying forward error correction (FEC) and automatic repeat request (ARQ) to improve connection credibility.

To deter unauthorized parties from obtaining access to information, data protection is relatively essential for data transmission. The transmitting medium is publicly available to anyone with a transmitter on a wireless network. The data transmitted over the radio medium would be encrypted to ensure the information is handled and sent to the specified destination. The encryption and decryption method will be carried out on the sender and receiver, degrading the cost of insignificant efficiency.

The initial communication throughput only supported a maximum data rate of 2 Mbps and was further increased to 11 Mbps per access point as specified in the IEEE 802.11b specification (IEEE Standard for Information technology, 2009). At present, the wireless standard IEEE 802.11 has the protocol for network discovery and several management frames for planned intentions. In the standard, the 2.4GHz and 5GHz frequency bands are introduced to fix congested traffic, in specific frequency space, while also delivering high-efficiency network networks capable of high density and improved handling of traffic. When connected to the chosen WLAN connection point, Wi-Fi clients can execute back-end processes. The IEEE specification has been updated and introduced over the years with features that make wireless network infrastructure much more stable.

The system will broadcast probe request frames to detect if any wireless networks are available. It is possible to broadcast or direct these probe requests, and the probe consists of the broadcast address (ff:ff:ff:ff:ff:ff:ff) specified as the destination address (DA), which also means that any device will receive it (Waltari & Kangasharju, 2018). A broadcast probe is assigned a Service Set Identifier (SSID) in the allocated header, while its destination is set for the broadcast by a directed probe. The Media Access Control (MAC) address would not be used by any probe request addresses, since one SSID can be delegated to multiple access points. Next, the following protocols will be used to execute a procedure called Association: authentication request, authentication response, association request, and association response. Throughout the process, these protocols will be sequentially sent and received. Once the Wi-Fi station detects an association response, the Wi-Fi MAC-Layer configuration is carried out. The user can communicate in the form of data packets with the wireless access point. As the Wired Equivalent Privacy (WEP) standard is a legacy security protocol used in the authentication request/response, usually this packet will be classified as an empty authentication step (Bohák et al., 2007). If the association phase is completed, an authentication process will then proceed. Authentication consists of exchanging 4 MAC-Layer packets under new mechanisms of encryption, such as WPA2 and WPA3. The correct password is required to have access to the encrypted access point.

The device would then communicate with the network's DHCP (Dynamic Host Configuration Protocol) server. The DHCP operates in four basic phases: IP discovery, IP lease offer, IP request, and IP lease acknowledgement (Tseng et al., 2013). The DHCP also includes all the wireless network information, including the device's IP address, subnet mask, default gateway, and server addresses for domain name services. Once the device has been configured, the whole connection process for the wireless connection is finalized. The STA will transmit a broadcast message inside the network in the DHCP discovery process to detect available DHCP servers. The DHCP server receives an IP lease request from STA and reserves an IP address when extending the IP lease offer by issuing the client a DHCPOFFER message during the subsequent DHCP offer process. The DHCP request process requires the STA to react with a DHCP request in response to the DHCP offer to access the assigned address. When the server obtains a DHCPREQUEST message from the server, it sends a DHCPACK packet to the STA to complete the configuration process.

2.3.5.1 IEEE 802.11a

The IEEE 802.11a standard stands as an expansion of the IEEE 802.11 wireless networking standard, aimed at delivering enhanced data rates and improved performance. It functions within the 5 GHz frequency band contrasting with the more crowded 2.4 GHz band utilized by 802.11b and 802.11g. This higher frequency allocation enables several overlapping channels thereby decreasing interference and enhancing network performance, in settings with numerous wireless networks (Khanduri & S. Rattan, 2013).

A substantial feature of 802.11a is the utilization of Orthogonal Frequency Division Multiplexing (OFDM) for transmitting data. OFDM involves encoding data across carrier frequencies facilitating higher data rates and more efficient spectrum utilization. This technological advancement empowers 802.11a to sustain data rates reaching up to 54 Mbps rendering it suitable for applications demanding bandwidth like video streaming and substantial file transfers.

Despite its benefits 802.11a does come with constraints. The utilization of a band translates to a reduced range when compared to the likes of the 2.4 GHz standards such, as 802.11b and 802.11g networks. In mixed device settings 802.11a does not support compatibility, with 802.11b/g devices, which could pose a challenge.

2.3.5.2 IEEE 802.11b

The IEEE 802.11b standard is a significant advancement in wireless local area network (WLAN) technology, building upon the original 802.11 standard to offer improved data transfer rates and performance. This standard was developed to meet the growing demand for higher data rates in WLANs, which became increasingly popular due to the ease of installation and the rise of portable computing devices like laptops (Alumona et al., 2014).

IEEE 802.11b supports a maximum raw data rate of 11 Mbps, which was a substantial improvement over the original 802.11 standard that provided up to 2 Mbps. The 802.11b standard employs the direct sequence spread spectrum (DSSS) modulation technique. This method is effective in managing interference and maintaining data integrity, which was crucial for the widespread adoption of this technology in various environments.

Operating in the 2.4 GHz industrial, scientific, and medical (ISM) band, 802.11b uses a channel bandwidth of 22 MHz. This configuration allows for three non-overlapping channels (1, 6, and 11) out of the 14 available in the 2.4 GHz band. The channel separation of 5 MHz helps reduce interference between channels, which is essential for maintaining reliable communication in densely populated areas with multiple wireless networks.

Devices using the 802.11b standard are susceptible to interference from other devices operating in the 2.4 GHz band, such as microwave ovens, Bluetooth devices, and cordless telephones. Despite this potential for interference, the standard was quickly adopted due to its increased throughput and the cost-effectiveness of 802.11b products. This made it a popular choice for home and small business networks during its time.

The typical output power for WLANs using the 802.11b standard is around 20 dBm, with an operational range of approximately 100 meters. This range is suitable for home and small office environments, where the convenience of wireless connectivity and the growing popularity of portable devices have driven the adoption of WLAN technology

2.3.5.3 IEEE 802.11g

The IEEE 802.11g standard is a significant milestone in wireless networking technology, designed to enhance the capabilities of wireless local area networks (WLANs). Introduced in 2003, this standard is part of the Wi-Fi 3 generation and combines the best features of its predecessors, 802.11a and 802.11b, to provide improved performance and compatibility (Shreelatha & Kavyashree, 2023).

IEEE 802.11g operates in the 2.4 GHz frequency band, like 802.11b, which allows it to maintain backward compatibility with existing 802.11b devices. This compatibility ensures that devices using the 802.11g standard can communicate with older devices without requiring additional hardware or software modifications. The standard supports a maximum data rate of 54 Mbps, which is a significant improvement over the 11 Mbps offered by 802.11b. This increase in data rate is achieved with Orthogonal Frequency Division Multiplexing (OFDM), a modulation technique that was first introduced in the 802.11a standard.

One of the key advantages of the 802.11g standard is its ability to provide high data rates while maintaining a reasonable range. This makes it suitable for a variety of applications, including web browsing, file transfers, and streaming media. The standard also supports various security protocols, such as Wired Equivalent Privacy (WEP) and Wi-Fi Protected Access (WPA), to ensure secure communication over the wireless network.

In terms of performance, the 802.11g standard has been analysed for its effects on network parameters such as delay, media access delay, queue size, and maximum throughput. Simulations using tools like OPNET have been conducted to evaluate these parameters under different conditions. Additionally, the performance of access points using HTTP has been studied to understand object and page response times, as well as voice data analysis to assess jitter, packet end-to-end delay, and traffic metrics.

2.3.5.4 IEEE 802.11n

The IEEE 802.11n standard represents a significant advancement in wireless local area network (WLAN) technology, promising to enhance the reach, reliability, and throughput of wireless communications. Ratified in September 2009, this standard introduces numerous enhancements at both the physical and medium access control (MAC) layers, aiming to deliver data transmission rates of up to 600 Mbps. These improvements are designed to meet the growing demand for high-speed wireless connectivity in various environments, including enterprise and home networks (Hajlaoui et al., 2022).

One of the key features of the IEEE 802.11n specification is its ability to support higher data rates with multiple-input multiple-output (MIMO) technology. MIMO allows for multiple data streams to be transmitted simultaneously, significantly increasing the throughput and efficiency of the network. Additionally, the standard incorporates channel bonding, which combines two adjacent 20 MHz channels into a single 40 MHz channel, further boosting data rates.

The MAC layer enhancements in IEEE 802.11n include the introduction of frame aggregation mechanisms. Frame aggregation reduces protocol overhead by combining multiple frames into a single transmission, thereby improving channel utilization and efficiency. This feature is particularly beneficial for supporting bandwidth-intensive applications such as voice and video streaming, as it helps maintain the quality of service (QoS) required for these applications.

Furthermore, IEEE 802.11n addresses interoperability and fairness issues, ensuring that devices adhering to the standard can coexist and operate efficiently in mixed environments with legacy devices. The standard also includes provisions for dynamic adjustment of aggregated frame sizes based on the access category of frames, as defined in the IEEE 802.11e standard, to better support multimedia applications with specific QoS requirements.

2.3.5.5 IEEE 802.11ac

The IEEE 802.11ac architecture, generally labelled as Very High Throughput (VHT) WLAN, demonstrates a significant enhancement in wireless networking innovations. This standard operates within the 5 GHz spectrum and is engineered to facilitate data transfer rates of up to 7 Gbps, marking a substantial improvement in wireless communication capabilities. This is accomplished through several enhancements to both the physical (PHY) layer and the medium access control (MAC) sub-layer. One of the key technologies introduced in this standard is channel bonding, which increases the channel bandwidth by combining multiple 20 MHz channels. This allows for more data to be transmitted simultaneously, significantly boosting throughput (Halfaoui et al., 2020).

To effectively utilize the wide channels created by channel bonding, IEEE 802.11ac specifies a multichannel MAC procedure known as Dynamic Multichannel Access (DMA). This procedure operates under the Enhanced Distributed Channel Access (EDCA) rules, which are designed to manage how data streams access the network. However, the basic rules of EDCA can lead to an access equity problem, where different data streams do not have equal opportunities to access the channel. Furthermore, the Direct Memory Access (DMA) protocol has been identified as inadequate in effectively administering the bandwidth designated for the Wireless Local Area Network (WLAN), resulting in poor operational efficacy.

To tackle the constraints in the DMA methodology, a new MAC protocol designated as Enhanced Dynamic Multichannel Access (EDMA) has been introduced. EDMA aims to enhance the existing DMA procedure by more efficiently using radio resources and distributing them equitably across different data streams. This improvement is crucial for ensuring that all data streams have fair access to the network, thereby optimizing overall throughput. Simulation results have demonstrated that the EDMA procedure provides satisfactory results in terms of throughput when compared to the traditional DMA procedure.

2.3.5.6 IEEE 802.11ax

IEEE 802.11ax, also known as Wi-Fi 6, represents a significant advancement in wireless networking technology, designed to address the growing demand for high-speed and reliable internet access in densely populated areas. This standard introduces several enhancements at the PHY (Physical) and MAC (Medium Access Control) layers, which are crucial for improving throughput in environments with a high density of wireless IoT devices. The 802.11ax standard was introduced for its improved features that combine the 2.4 GHz and 5 GHz frequency bands unlike its predecessor, 802.11ac which functions, only in the 5 GHz range. This dual-band capability provides greater flexibility and helps reduce network congestion (Hossain et al., 2023).

One remarkable aspect of IEEE 802.11ax is its incorporation of Orthogonal Frequency Division Multiple Access (OFDMA) enabling servicing of users by partitioning the channel into smaller sub channels. This improves network efficiency and reduces latency, making it ideal for environments with numerous connected devices. Additionally, 802.11ax supports higher Modulation and Coding Schemes (MCS), enabling faster data rates through more complex modulation techniques. The implementation of 1024 QAM (Quadrature Amplitude Modulation) boosts data speeds by packing bits per symbol than the 256 QAM utilized in 802.11ac.

A significant improvement, in the 802.11ax standard is the introduction of Target Wake Time (TWT) functionality. This feature helps reduce energy consumption by allowing devices to coordinate and schedule their wake-up times, for data transmission or reception purposes. This is particularly beneficial for IoT devices that require efficient power management. The standard also supports up to 8 spatial streams, like 802.11ac, but with improved efficiency and performance in multi-user environments. Enhanced beamforming capabilities focus the wireless signal towards specific devices, improving signal strength and reliability.

Over time the IEEE 802.11 standard has undergone improvements leading to the iterations such, as 802.11a/b/g, 802.11n, 802.11ac and 802.11ax. These amendments offer improved performance, throughput, and other features were listed in Table 2.1.

Table 2.1: IEEE 802.11 Standards Amendments

Parameter	802.11a	802.11b	802.11g	802.11n	802.11ac	802.11ax
Frequency band	5 GHz	2.4 GHz	2.4 GHz	2.4 GHz, 5 GHz	5 GHz	2.4 GHz, 5 GHz
Theoretical Maximum Throughput	54 Mb/s	11 Mb/s	54 Mb/s	600 Mb/s	3.4 Gb/s	12 Gb/s
Physical Layer	OFDM	DSSS	DSSS, OFDM	MIMO, OFDM	MIMO, OFDM	MU-MIMO, OFDMA
Channel Bandwidth	20 MHz	20 MHz	20 MHz	20, 40 MHz	Up to 160 MHz	Up to 160 MHz

2.3.6 IEEE 802.11e (QoS Enhancements)

IEEE 802.11e specification was launched in 2005 and offered a range of Quality of Service (QoS) updates for wireless LAN implementations with updates to the Media Access Control (MAC) layer (IEEE Std 802.11eTM-2005, 2005). The QoS enhancement implemented in this standard is to solve the problem developed by PCF and DCF. Therefore, Hybrid Coordination Function (HCF) and Enhanced Distributed Channel Access (EDCA) were integrated. The bandwidth of the MAC layer will increase significantly by implementing these two techniques in IEEE 802.11e. The block acknowledgement system and direct link protocol (DLP) will boost the performance of the wireless network.

2.3.6.1 Hybrid Coordination Function (HCF)

The Hybrid Coordination Function (HCF) is based on a previously used PCF mechanism. The contention-free period for the use of HCF would be known as HCF-controlled Channel Access (HCCA). In the HCF, packets with various QoS are categorized into several MAC queues, with each packet allocated different polling priorities. The MAC queues, also known as Traffic Classes (TC). The QoS Enhanced Access Point (QAP) uses a priority-based round-robin schedule to evaluate the STAs' TCs, beginning with the first QoS Enhanced Station (QSTA) getting the priority in the TC queue.

2.3.6.2 Enhanced Distributed Channel Access (EDCA)

Another method with similar benefits to DCF is Enhanced Distributed Channel Control (EDCA). Each packet is assigned to various control groups (ACs) in the EDCA, identical to TCs. The QSTAs in EDCA serve as a virtual STA for different QoS levels. The ACs of a given STA's medium access parameters depend on their respective priorities. Inside the packet within a Wi-Fi network, there will always be one AC and one TC.

2.3.6.3 Block Acknowledgement

The block acknowledgement for the QoS improvement was another mechanism implemented in the 802.11e specification. Before this mechanism introduced, an ACK signal will be sent for each MAC frame received by the destination device. However, since it has high overhead and round-trip latency, this congested the network. Block acknowledgement used frame-blocks and sent one ACK per each block. This increases the MAC layer's throughput, while the issue of resending the whole block again persists when the ACK signal is not sent to the data sender.

2.3.6.4 Direct Link Protocol (DLP)

An AP allows the communication between two stations within the same WLAN. However, the throughput needed to communicate would be twice the regular transmission rate. The Direct Link Protocol (DLP) is a communication method that eliminates excess bandwidth, thus allowing two STAs to communicate without an Access Point. The transfer time utilized in the MAC techniques proposed in IEEE 802.11e was divided into Transmission Opportunities (TO) (IEEE Std 802.11eTM-2005, 2005). The method can be used for many TOs by a QoS Enhanced Station (QSTA). DLP solves the PCF issue of timing. During transmission, the QSTA can send information packets with QoS parameters for connectivity requests over both the EDCA and HCF mechanisms. Suppose a QoS Enhanced Access Point (QAP) can process all the transmission according to all the QoS parameters obtained. In that case, the QoS Enhanced Access Point (QAP) recognizes that it will otherwise refuse the query, which may resend again with a comparatively lower QoS parameter.

2.3.7 IEEE 802.11r (Fast BSS Transition)

IEEE 802.11r, also known as Fast BSS Transition, is a standard amendment designed to enhance the roaming capabilities of wireless networks, particularly for real-time applications that require minimal latency during handovers. This standard is crucial for mobile industrial applications, such as automated guided vehicles, which demand real-time communication with latency requirements in the range of a few milliseconds. IEEE 802.11r standard aims to decrease the duration needed for Basic Service Set (BSS) transitions while upholding the Quality of Service (QoS) criteria outlined by 802.11e. This is achieved by allowing seamless connectivity and fast, secure handovers from one access point (AP) to another within the same mobility domain (Tabassam et al., 2009).

The 802.11r standard introduces mechanisms for fast roaming, including two methods for fast transition: Over-the-Air and Over-the-DS. The Over-the-Air method involves the wireless STA establishing a direct link with the access point, reducing handover delays by minimizing required data frames and procedures (Machań & Wozniak, 2013). The Over-the-DS approach involves the STA connecting to the new access point through the existing access point, using the Distribution System (DS) as a bridge. The DS is the backbone network that interconnects multiple Access Points (APs), facilitating communication between them. During this process, data packets are encapsulated within FT Action frames exchanged between the old and new access points, ensuring resource reservation prior to reassociation, especially in networks capable of 802.11k.

2.4 RSSI-Based Handover Method

2.4.1 Beacon Frame Mechanism

In the conventional IEEE 802.11 handover process, the Station (STA) interacts with beacon frames broadcast periodically by APs. These beacon frames serve as the foundation for network discovery and maintenance. The process begins with APs transmitting beacon frames at regular intervals across Wi-Fi channels, which contain critical network information, such as the AP identifier, supported data rates, security parameters, and network capabilities. The signal coverage of the AP is determined by its transmitting power, which affects the range over which the beacon frames propagate and, consequently, the network’s effective coverage area.

2.4.2 Homogeneous Handover Process

Homogeneous, or horizontal, handovers take place within a single access network technology, such as Wi-Fi. In this context, the handover process begins when the STA moves within the network’s coverage area while remaining connected to its current AP. As the STA moves further from the AP, it may be unable to receive all the beacon frames, signalling the need for a handover. When the reception of beacon frames becomes unreliable, the STA commences the handover process by conducting a scan for an alternative AP exhibiting a more robust signal within the confines of the same network. Following the identification of a new AP, the STA engages in the authentication procedure and subsequently establishes a connection with the selected AP. The primary aim of this procedure is to mitigate disruptions in wireless connectivity and to guarantee a seamless user experience throughout the entirety of the network's coverage area.

2.4.3 Detailed Handover Workflow of RSSI-Based Handover Method

The RSSI-Based handover method follows a structured workflow as shown in Figure 3.1, beginning with network discovery, where APs continuously broadcast beacon frames, and Stations (STAs) perform active or passive scanning to detect available Access Points (APs). Upon detecting an AP, the STA transmits a probe request, and the AP responds with detailed network information through probe responses. The STA subsequently assembles an AP list, which encompasses essential information including the AP's operational channel, Media Access Control (MAC) address, Service Set Identifier (SSID), available data transmission rates, beacon interval, Received Signal Strength Indicator (RSSI), and authentication status.

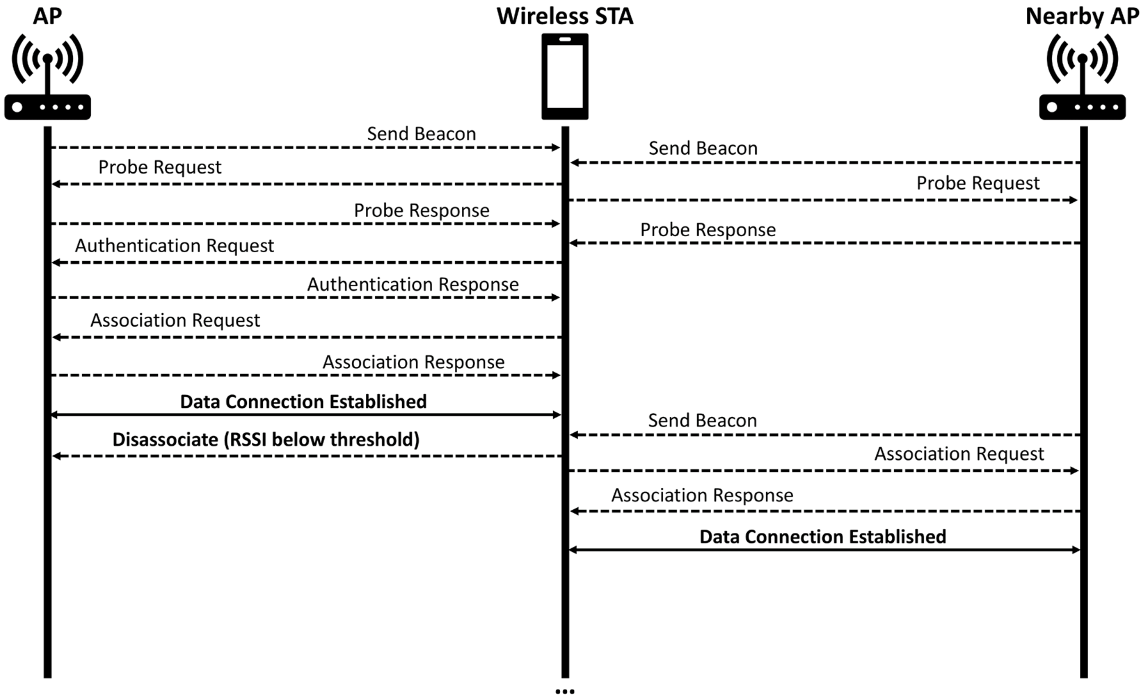

Figure 2.2: Flowchart of RSSI-Based Handover Method

Upon completion of the information compilation, the STA assesses the RSSI metrics of the identified APs and selects the AP exhibiting the most robust signal for the transition. The STA initiates authentication with the chosen AP and, upon successful authentication, sends an association request. The AP then confirms the association, establishing a new connection. During this process, the STA continues to monitor its connection by updating the AP list with ongoing beacon frame data. If the STA detects the signal strength of the current AP is below the designated threshold (-85 dBm), the STA disassociates and re-enters the scanning mode. This iterative process ensures that the STA maintains optimal connectivity by continuously adapting to changing network conditions. Hysteresis was also included in the decision making for STA to perform handover to new AP. This is to prevent STA from performing unnecessary handover when travelling within the service coverage.

2.4.4 Limitations of Existing RSSI-Based Roaming Algorithms

RSSI-based handover algorithms in Wi-Fi networks are widely used for maintaining seamless connectivity, especially in dense indoor environments. These algorithms predominantly depend on the Received Signal Strength Indicator (RSSI) to determine the appropriate device to transition from one access point (AP) to an alternative.

The RSSI-Threshold algorithm is a method used in wireless networks, particularly in Wi-Fi, to manage handoffs between access points. RSSI stands for Received Signal Strength Indicator, which measures the power level that a wireless device receives from a signal. In the context of Wi-Fi, it helps determine the quality of the connection between a device and an access point. The primary goal of the RSSI-Threshold algorithm is to ensure that a device maintains a strong and stable connection by switching to a different access point when the signal strength of the current connection falls below a certain threshold. Nevertheless, the efficacy of these algorithms may be impeded by challenges such as the ping-pong effect, which manifests when frequent handovers transpire caused by varying signal strengths. However, setting the appropriate threshold is crucial. If the threshold is too high, it may cause unnecessary handoffs, leading to increased network traffic and potential disruptions. Conversely, if it's too low, the device might stay connected to a weak signal for too long, affecting performance (Balbi et al., 2022).

To mitigate frequent handover, hysteresis-based RSSI algorithm was introduced to enhance the accuracy and reliability of indoor Wi-Fi networks. This type of algorithm is particularly useful in mitigating the effects of rapid signal strength fluctuations, which can occur due to environmental changes or movement within the network area. The core concept of hysteresis involves setting a threshold or buffer zone that prevents the system from reacting to minor fluctuations in signal strength. Essentially, a change in signal strength must exceed a certain threshold before it is deemed significant enough to trigger a response, such as switching access points or adjusting power levels. While implementing a hysteresis-based RSSI algorithm, it is crucial to carefully select the hysteresis threshold. A threshold that is too high may cause the system to overlook important changes, while a threshold that is too low may not effectively filter out noise, makes it difficult to adapt to networks that requires adjustments dynamically (Biswas et al., 2021).

In conclusion, traditional roaming algorithms that rely on RSSI suffer from various inefficiencies. By focusing solely on signal strength, they fail to consider other critical factors such as AP load balancing, user density, and QoS requirements. These limitations highlight the need for more advanced and context-aware roaming algorithms that can better optimize handover decisions in modern Wi-Fi networks.

2.5 Related Works in Wi-Fi Handover Optimization

To overcome the QoS challenges posed by traditional hand-off mechanisms in Wi-Fi networks, several hand-off techniques have been developed. These mechanisms focus on reducing handoff latency, improving seamless mobility, and enhancing the overall Quality of Service (QoS) for real-time and bandwidth-sensitive applications. The subsequent section addresses the emergence of multiple hand-off strategies, including methods that integrating Artificial Intelligence (AI) and Machine Learning (ML), Mobile Edge Computing (MEC), and Software-Defined Networking (SDN) systems. These mechanisms address critical issues such as handoff delay, packet loss, throughput degradation, and authentication overhead, thereby enabling more efficient mobility management in modern Wi-Fi networks.

2.5.1 Proactive Handoff Mechanisms with AI/ML Integration

Proactive handoff mechanisms in Wi-Fi technology are designed to enhance user experience by anticipating the need for a handoff before the current connection quality degrades. The integration of AI and ML into these mechanisms can significantly improve their effectiveness. A fundamental component of this integration is the employment of Channel State Information (CSI). AI/ML models can predict CSI, which is crucial for making proactive handoff decisions. By analysing both historical and real-time data, these models can forecast when a handoff might be necessary to maintain optimal connectivity (Mahajan & Sharma, 2023).

Algorithms in machine learning are essential in predictive analytics. They possess the capability to be trained for the identification of patterns in network utilization and user mobility, thereby enabling the system to forecast the likelihood of a user transitioning beyond the coverage area of the existing access point. This capability enables the system to initiate a handoff to a better access point before the connection quality deteriorates. These systems utilize artificial intelligence and machine learning to perpetually acquire information and adjust instantaneously, thereby guaranteeing that handover decisions are derived from the most up-to-date and relevant information.

Ensuring good quality of service (QoS) constitutes a fundamental objective of proactive handoff mechanisms. AI/ML can optimize these processes by selecting the best possible access point based on predicted network conditions, thereby minimizing latency and packet loss during the handoff process. In use case scenarios with high volume of mobility, such as vehicular networks, artificial intelligence and machine learning can facilitate the management of frequent handover processes by efficiently analysing substantial volumes of data to enable prompt decision-making in real-time. This is particularly important for IoT devices that require constant connectivity.

Furthermore, AI/ML can enhance automatic fallback mechanisms, which are designed to switch between different technologies or access points to maintain connectivity. By predicting potential connectivity issues, these mechanisms can proactively switch to a more reliable connection. In summary, the integration of AI and ML into proactive handoff mechanisms in Wi-Fi technology leads to more efficient and reliable network management, ensuring seamless connectivity and improved user experience. These technological advancements allow systems to predict and react to fluctuations in network environments, consequently ensuring peak operational efficacy.

2.5.2 Mobile Edge Computing (MEC)-Assisted Handoff Mechanism

Mobile Edge Computing (MEC) has surfaced as an important technological advancement in augmenting the effectiveness and agility of wireless networks in dense environments, especially within the framework of Wi-Fi technology. MEC-assisted handoff mechanisms are crucial for maintaining seamless connectivity and optimizing resource utilization as users move across different network zones. The following explores on multiple MEC-assisted handoff mechanisms, focusing on their implementation in Wi-Fi technology, and highlights the role of different technologies such as UAVs, IRS, and NOMA in facilitating these processes.

Unmanned Aerial Vehicles (UAVs) provides an extraordinary progress in MEC, providing network services that offers low latency. UAVs act as mobile edge servers, leveraging their high mobility to dynamically position themselves for optimal service delivery to user equipment (UE). This capability is particularly beneficial in scenarios where traditional infrastructure is lacking or when rapid deployment is necessary. However, the implementation of Unmanned Aerial Vehicles (UAVs) into Mobile Edge Computing (MEC) frameworks may introduce challenges in terms of technical and economic. From technical perspective, it is essential to enhance the trajectory of unmanned aerial vehicles (UAVs) for delegate task efficiently, while considering the intrinsic constraints associated with UAVs, including their limited resources and computational capabilities. The high mobility of UAVs, while advantageous, also requires careful management to ensure effective service delivery. Economically, there is a need to incentivize UAV participation without compromising user privacy. This involves developing mechanisms that encourage UAVs to join the MEC network while safeguarding user data (R. Zhang et al., 2024).

Intelligent Reflective Surfaces (IRS) are innovative technologies that consist of multiple reflective elements capable of adjusting the phase of incoming signals to enhance communication links. The surfaces were deployed with the goals of both economically sustainable and energy-conserving, thereby establishing them as a feasible alternative for the improvement of wireless communication frameworks. The intelligent reflecting surfaces (IRS) facilitating the delegation of computational tasks from end users to edge computing servers. This is achieved through the establishment of reflective links that enhance the communication between users and the edge server. The primary objective in an IRS-assisted MEC system is to optimize several parameters, including the task offload rate, user local Central Processing Unit (CPU) frequency, user transmit power, and IRS phase shift. The primary objective is to enhance the energy efficiency of the system, which constitutes a pivotal consideration in mobile edge computing environments. The Deep Reinforcement Learning (DRL) is put forth to confront the non-convex optimization issues that are essential to these systems. This approach enables the system to dynamically adjust optimization variables in response to changing link conditions and task volumes, thereby achieving higher energy efficiency (J. Wang et al., 2024).

While IRS-assisted mobile edge computing offers significant benefits, such as enhanced energy efficiency and improved communication links, it also presents several challenges and potential disadvantages. One of the primary issues is the complexity involved in optimizing various parameters, including the task offload rate, user local CPU frequency, user transmit power, and IRS phase shift. These optimizations require solving a non-convex problem, which can be difficult to manage efficiently, particularly in dense environments where wireless link conditions and task scheduling are constantly changing.

Non-Orthogonal Multiple Access (NOMA) deployed within Mobile Edge Computing (MEC) has the potential to significantly improving the wireless networks. NOMA allows the simultaneous engagement of same frequency resources by numerous users through the superimposition of their individual signals at distinct power levels. This method contrasts with conventional orthogonal techniques, wherein each user is allocated a separate frequency band. Within a Wi-Fi infrastructure, NOMA has the capacity to enhance spectral efficiency by facilitating concurrent transmissions to multiple users, thereby augmenting the network's throughput and mitigating latency.

The integration of NOMA with MEC in Wi-Fi networks allows for efficient offloading of computational tasks. By using NOMA, multiple devices can offload their tasks simultaneously to the MEC server, which processes these tasks and sends back the results.

This approach minimizes the offloading delay, as highlighted in the paper, by optimizing the joint communication and resource allocation process (L. Zhang & Hao, 2024).

However, implementing NOMA in Wi-Fi networks presents challenges. It requires careful management of power levels and interference to ensure efficient communication. The optimization of resource allocation is crucial to achieving the desired performance improvements.

2.5.3 Software-Defined Network (SDN)-Based Handover

Software-Defined Networking (SDN) represents a paradigm shift in the management of handover processes within Wi-Fi networks, offering enhanced flexibility, centralized control, and operational efficiency. By decoupling the control plane from the data plane, SDN facilitates centralized network management, which is particularly advantageous in addressing the complexities of handover in dense and heterogeneous network environments.

SDN's architecture enables programmatic configuration and dynamic management of network resources, enhancing responsiveness to fluctuating network conditions. This decoupling allows for rapid adaptation to new applications, services, or shifts in traffic patterns without requiring manual intervention or hardware modifications. Such agility is critical for maintaining network performance in dynamic settings. Furthermore, SDN's compatibility with existing infrastructures supports seamless integration, minimizing disruptions during deployment and fostering a transition to advanced network management practices (Shalom, 2024).

The integration of Multiple Criteria Decision-Making (MCDM) algorithms, such as the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS), enhances SDN-based handover decisions. Unlike traditional approaches reliant solely on

Received Signal Strength Indicator (RSSI), MCDM considers multiple parameters, including network delay, to evaluate and rank access points (APs) based on their overall suitability. This holistic approach ensures more reliable and efficient handover decisions, optimizing both signal strength and latency (Mangipudi et al., 2024).

However, SDN-based handover systems face challenges in dynamic network environments characterized by high mobility and variable device density. These conditions contribute to topological instability, which can degrade handover performance, particularly in scenarios involving high-speed devices or high data rate services. Such instability may lead to difficulties in establishing and maintaining connections, critical for seamless network operations. Scalability also poses a concern, as managing an increasing number of devices and data traffic volumes demands significant computational resources. Additionally, the centralized control plane in SDN introduces potential security vulnerabilities, such as risks of denial-of-service attacks or unauthorized access, necessitating robust countermeasures (Murtadha & Mushgil, 2023).

Several methodologies have been proposed to enhance roaming algorithms in multi-AP networks, offering insights applicable to Extended Service Set (ESS) environments. Adame et al. (2021) introduced a channel load-aware AP/extender selection mechanism for home Wi-Fi networks, leveraging IEEE 802.11k/v standards. This AP-centric approach centralizes computations within the AP, factoring in RSSI, sensitivity levels, and load on access and backhaul links. While this method improves throughput and reduces delays, its reliance on specific standards may limit compatibility with legacy devices, and centralized computation introduces complexity that could strain AP performance under high device loads.

Mouhassine et al. (2021) proposed a sophisticated approach combining Fuzzy Analytic Hierarchy Process (Fuzzy-AHP) and VIKOR within an SDN framework to manage multicriteria handovers. This methodology evaluates parameters such as signal-to-noise plus interference ratio (SNIR), packet loss, jitter, delay, and throughput. Fuzzy-AHP employs fuzzy logic to address uncertainties in decision-making, establishing criteria weights through pairwise comparisons and aggregation. VIKOR complements this by ranking APs based on performance metrics, optimizing handover efficiency in congested environments and enhancing Voice over Internet Protocol (VoIP) performance. The integration of these techniques within SDN controllers ensures quality of service (QoS) for real-time applications while mitigating delays and packet loss.

Goutam et al. (2020) developed an algorithm incorporating fuzzy logic to improve handover decisions in IEEE 802.11 and 4G networks. This approach integrates parameters such as RSSI, channel capacity, cost, and mobility velocity into a Fuzzy Inference System (FIS). The FIS employs linguistic variables, membership functions, fuzzy rules, and an inference engine to compute handover factors, enabling informed AP selection through reward value comparisons.

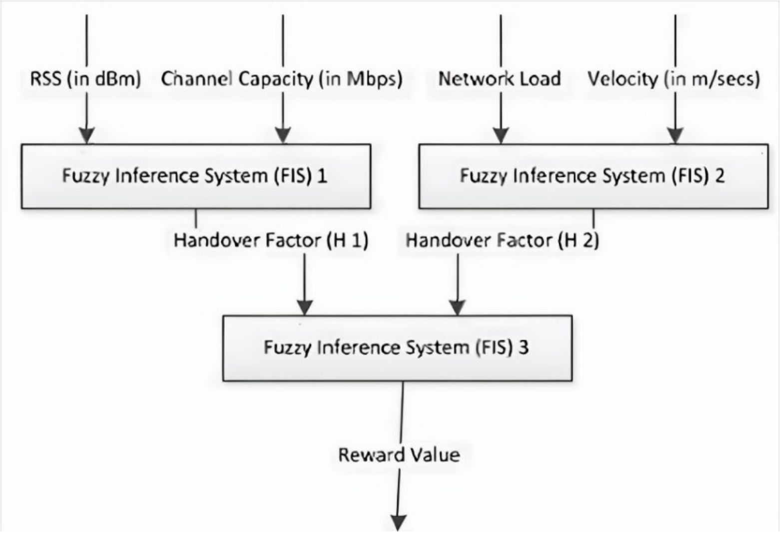

Figure 2.3: Block Diagram of FIS

Aldhaibani et al. (2022) proposed an SDN-based algorithm for horizontal handover in dense wireless local area networks (WLANs), prioritizing user Quality of Experience (QoE). Executed within a software-defined wireless networking (SDWN) framework, the algorithm leverages SDN's programmability to monitor handover processes, incorporating bandwidth capacity, SINR, jitter, delay, and user priorities. It comprises priority-based and MCDM components to optimize QoE for high-priority users while reallocating low-priority users to suitable APs. While effective in improving throughput and latency, this approach may disadvantage low-priority users in resource-constrained environments and relies heavily on accurate prioritization and SDWN architecture efficacy.

In conclusion, the reviewed methodologies for enhancing roaming algorithms in multi-AP networks demonstrate diverse strategies, including centralized computation, fuzzy logic, and SDN-based approaches. These techniques offer significant benefits, such as improved throughput, reduced latency, and optimized handover decisions. However, challenges such as computational complexity, scalability, and dependence on specialized infrastructure persist. These insights provide a foundation for developing an advanced roaming algorithm for ESS networks, balancing performance, scalability, and implementation feasibility.

2.5.4 Critical Review and Gap Analysis

While the recent advancements in Wi-Fi handover optimization have significantly enhanced network performance, mobility support, and QoS assurance, several limitations persist across the state-of-the-art solutions. AI/ML-based approaches provide predictive capabilities for seamless handovers but often face high computational complexity and challenges in real-time adaptability to unseen environments. MEC-assisted mechanisms using UAVs, IRS, or

NOMA improve latency and energy efficiency but introduce practical deployment issues, such as cost, trajectory optimization, and interference control.

SDN-based strategies offer centralized control and flexible reconfiguration but are susceptible to scalability and security concerns due to their reliance on a single control plane. Furthermore, while MCDM algorithms enhance decision-making by incorporating multiple parameters, they increase system complexity and depend heavily on accurate metric weighting and configuration.

These limitations reveal a pressing need for a handover optimization framework that achieves a balance between intelligent decision-making, scalability, and real-time adaptability—particularly in dense ESS Wi-Fi environments. The design proposed in Chapter 3 aims to address these identified gaps by integrating lightweight, multi-criteria decision-making with real-time adaptability to changing network conditions.

Table 2.2: Critical Review of State-of-the-Art Wi-Fi Handover Optimization Techniques

Study / Approach	**Key Technique**	**Strengths**	**Limitations**	**Remarks**
Mahajan & Sharma (2023)	Proactive Handoff using AI/ML (CSI Prediction)	Anticipates handoff before link degradation; improved QoS for mobile users	High computational cost; may struggle in unseen network conditions	Best suited for real-time, high mobility use cases
R. Zhang et al. (2024)	UAV-assisted MEC Handoff	Flexible and rapid deployment; low-latency edge service	UAV trajectory planning is complex; resource constraints;	Promising for rural or emergency deployment but expensive

Study / Approach	**Key Technique**	**Strengths**	**Limitations**	**Remarks**
Wang et al. (2024)	IRS-assisted MEC with DRL	Enhances energy efficiency and signal quality; dynamic task offloading	Complex optimization; high implementation overhead	Effective in dense environments, but not yet widely deployable
L. Zhang & Hao (2024)	MEC with NOMA	Improves spectral efficiency and supports simultaneous task offloading	Interference management and power allocation are challenging	Suitable for throughput-critical applications
Shalom (2024)	SDN-based handoff with centralized control	Real-time network adaptation; flexible and programmable	Central point of failure; scalability issues	Effective for well-managed networks, limited in large-scale mobility
Mangipudi et al. (2024)	SDN + TOPSIS (MCDM)	Multi-parameter handoff decisions; improved latency handling	Sensitive to metric weighting; added decision complexity	Ideal for dense ESS networks with varied traffic types
Mouhassine et al. (2021)	Fuzzy-AHP + VIKOR within SDN	Handles uncertainty; robust in congested networks	Requires precise configuration; higher complexity	Optimized for VoIP and delay-sensitive services
Goutam et al. (2020)	Fuzzy Logic for AP Selection	Incorporates user mobility and network parameters; adaptive	Performance dependent on fuzzy rule design	Versatile in mixed network environments (Wi-Fi/4G)

Study / Approach	Key Technique	Strengths	Limitations	Remarks
Aldhaibani et al. (2022)	SDN-based horizontal handover (QoE-aware)	Prioritizes user experience; dynamic bandwidth reallocation	Risk of resource starvation for low-priority users	Balances QoS, but may compromise fairness in crowded networks

CHAPTER 3

DESIGN AND IMPLEMENTATION OF HANDOVER ALGORITHM

3.1 Overview

The widespread deployment of wireless networks and the growing demand for uninterrupted connectivity have necessitated the development of effective handover mechanisms. This chapter provides an in-depth analysis of an innovative enhanced roaming algorithm designed for Extended Service Set (ESS) networks. The primary purpose of this algorithm is to optimize the handover mechanism within IEEE 802.11 networks, specifically by addressing the shortcomings of the RSSI-based handover methods. By enhancing the handover decision-making process, the algorithm ensures improved network performance and a more reliable connectivity experience.

The effectiveness of this approach is crucial in assessing the impact of more dependable and efficient network management solutions in improving the overall network performance. Specifically, this work evaluates how the proposed algorithm can enhance end-to-end performance, reduce packet loss, and improve Quality of Service (QoS) by making data-driven, context-aware handover decisions.

3.2 Proposed Enhanced Roaming Algorithm

3.2.1 Algorithm Overview

The proposed enhanced roaming algorithm introduces a novel approach to handover decision-making within IEEE 802.11 networks. This algorithm aims to enhance network performance by considering multiple factors beyond simple signal strength, thus addressing limitations in conventional handover methods. By integrating context awareness and adaptive decision-making, the algorithm minimizes unnecessary handovers, which leads to improved network performance.

The overall objective is to assess the effectiveness of more efficient and dependable network management approaches by reducing end-to-end delay, packet loss, and optimizing throughput. These improvements contribute to more robust, low-latency connections, thus enhancing the user experience and ensuring reliable connectivity even in high-traffic environments.

3.2.2 Key Features

The proposed enhanced roaming algorithm addresses the current limitations in the handover process of ESS networks by embracing three key design principles: context awareness, adaptive decision-making, and network stability. These guiding concepts ensure that the algorithm offers a more efficient, balanced, and stable approach to handover management in Wi-Fi networks, thereby reducing latency, packet loss, and enhancing throughput associated with frequent or poorly timed handovers.

3.2.2.1 Context Awareness

The algorithm is designed to perpetually observe the network context in real-time. Instead of depending solely on the Received Signal Strength Indicator (RSSI), the analysis incorporates an array of network parameters, including the number of network devices linked to each Access Point (AP), thereby offering a more holistic comprehension of the surrounding wireless network environment. This comprehensive view helps prevent handovers that would otherwise overload an AP or degrade connection quality, which can cause increased buffering, retransmissions, and ultimately higher end-to-end delay, packet loss, and reduced throughput.

- Real-Time AP Monitoring: The algorithm processes beacon frames from nearby APs, gathering information such as signal strength, load, and available resources. This context awareness allows the algorithm to make more informed decisions and avoid situations where a handover improves signal quality but overloads the target AP, which could lead to congestion-induced delays, dropped packets due to buffer overflows, and reduced throughput due to contention.
- Multi-Parameter Evaluation: The algorithm integrates multiple factors—such as RSSI and AP load—into its handover decisions, the algorithm ensures that handovers are performed only when genuinely beneficial. This reduces the frequency of unnecessary handovers that cause service interruptions and increase latency, thus improving the user experience by maintaining consistent, low-delay connections.

3.2.2.2 Adaptive Decision-Making

Adaptivity is crucial for the proposed handover algorithm’s effectiveness in dynamic Wi-Fi environments with fluctuating signal strengths, varying access point (AP) loads, and user mobility. The algorithm continuously recalculates the optimal AP for connection based on real-time network conditions, ensuring seamless connectivity and optimized Quality of Service (QoS).

- Weighted Handover Value (HOV) Calculation: The HOV metric assigns weights to Received Signal Strength Indicator (RSSI) and AP load based on real-time network conditions and operator policies. Under normal conditions, weights are set to W1=0.5 for RSSI and W2=0.5 for AP load, ensuring balanced consideration of signal quality and traffic distribution. When an AP’s load exceeds 80% of its capacity, the algorithm adjusts the weights to W1=0.7 and W2=0.3, further emphasizing RSSI while accounting for load. This adaptive approach ensures stations favour high-RSSI

APs under light loads, transitioning to less congested APs as load increases. This prevents resource bottlenecks and reduces the ping-pong effect, which increases end-to-end delay due to repeated authentication and reassociation overhead.

- Hysteresis for Stability: To mitigate the ping-pong effect, the algorithm uses a 5 dB hysteresis margin. A handover is triggered only when a neighbouring AP's HOV exceeds the current AP's by at least 5 dB, preventing unnecessary handovers due to minor signal fluctuations. This reduces delay from handover signalling, authentication, and packet loss, especially for real-time applications. For example, if the current AP's RSSI drops from -70 dBm to -80 dBm, a neighbouring AP must offer an HOV at least 5 dB higher, typically requiring an RSSI of at least -75 dBm, depending on load contributions. This is consistent with Li et al. (2014), who showed that tuned hysteresis-based algorithms reduce unnecessary handovers while maintaining performance.

3.2.2.3 Network Stability and User Experience

Ensuring seamless connectivity and maintaining network performance under high load are central to the algorithm's design. By optimizing scanning efficiency and enhancing handover mechanisms, the algorithm minimizes disruptions to user connections—quantified as the time elapsed between disconnecting from one access point (AP) and establishing a stable connection with another. This reduction in handover interruption time directly contributes to improved network stability and lower end-to-end delay.

- Low-Latency Scanning: The algorithm reduces the overhead of full-channel scans by maintaining an updated list of nearby APs and their HOVs, enabling quicker handover decisions. Although a brief disconnection occurs during handover, essential traffic (e.g., voice and video) is prioritized immediately after reconnection through QoS-aware scheduling at the AP, minimizing delay for time-sensitive applications.

- Optimized Quality of Service (QoS): The proposed algorithm integrates Quality of Service (QoS) mechanisms to prioritize essential traffic categories (e.g., voice and video) around the handover procedure. During handover, no active connection exists between STAs and APs, as the STA disconnects from the current AP before associating with the target AP. The STA uses pre-handover QoS signalling to inform the target AP of the traffic requirements for delay-sensitive applications. Upon reconnection, the target AP immediately applies QoS-aware scheduling to prioritize incoming voice and video traffic, ensuring high service quality under network congestion and minimizing the impact of handovers on end-to-end delay.

3.2.3 End-to-End Analysis and Effectiveness

The primary goal of this algorithm is to evaluate the effectiveness of more reliable and efficient network management methods in reducing latency, packet loss, and improving overall network stability. By incorporating multiple parameters into its handover decision-making process, the algorithm minimizes service disruptions during transitions and ensures a more consistent user experience. The algorithm also seeks to reduce unnecessary handovers, thus contributing to lower end-to-end delay and overall improvements in network performance.

3.2.4 Detailed Handover Workflow of Enhanced Roaming Algorithm

The enhanced roaming algorithm adopts a systematic and structured approach to facilitate seamless handovers and maintain optimal network performance, as illustrated in Figure 3.1. During the initial network discovery phase, the Station (STA) performs an exhaustive scan across all available Wi-Fi channels to identify surrounding Access Points (APs). This discovery process is foundational, as it enables the STA to gather the necessary data to support informed and timely handover decisions. Upon detection of APs, the STA initiates an active probing mechanism by transmitting probe request frames and receiving corresponding probe responses. Through this exchange, the STA collects critical operational parameters, including the AP’s operating channel, Media Access Control (MAC) address, Service Set Identifier (SSID), supported throughput rates, beacon transmission interval, Received Signal Strength Indicator (RSSI), and authentication scheme. These parameters are instrumental in constructing a detailed profile of candidate APs, thereby enabling the STA to assess the relative suitability of each for handover.

Notably, the IEEE 802.11 standard beacon frame does not contain a field indicating the number of associated stations, as this information is typically managed internally by the Access Point (AP) and is not disseminated through standard management frames. To address this limitation, the proposed algorithm incorporates a modification to the beacon frame structure to include this metric. While such an enhancement enables more informed handover decisions by providing insight into AP load conditions, it also increases the size of beacon frames. This enlargement results in greater airtime overhead and may consequently degrade channel efficiency, particularly in high-density network environments where beacon transmissions are frequent and bandwidth is constrained (Tuysuz & Mantar, 2014). Nevertheless, the inclusion of this information plays a critical role in optimizing the handover decision-making process by allowing the algorithm to account for both signal quality and network congestion, thereby reducing delays typically experienced in existing RSSI-based algorithms, where high network load often results in slower decision-making and poor handover performance.

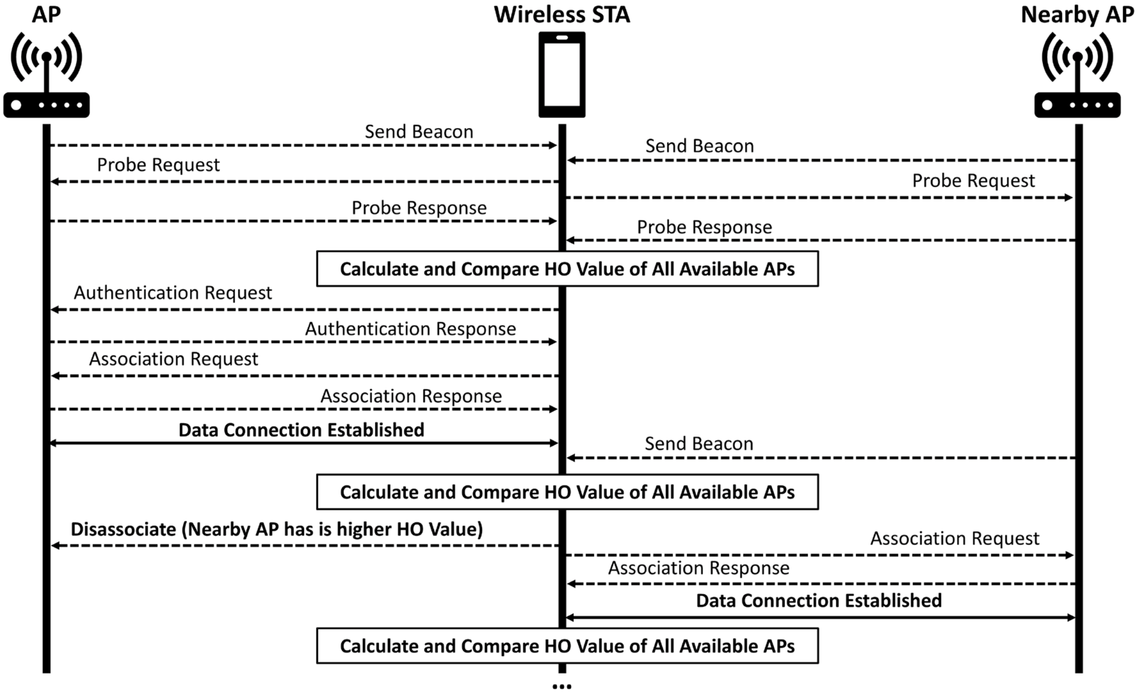

Figure 3.1: Flowchart of the Enhanced Roaming Algorithm

The STA maintains a real-time record of this data in an AP list, which it uses to evaluate the potential for a handover. When the STA detects that the signal strength and load on the current AP is suboptimal, it begins the process of selecting a new AP based on the calculated Handover Value (HOV). The calculation of the HOV of each AP is performed using the following equation:

$$Handover\ Value = W1 \times RSSI_{normalized} + W2 \times Load_{AP}$$

$$RSSI_{normalized} = \left(\frac{RSSI_{AP} - RSSI_{min}}{RSSI_{max} - RSSI_{min}}\right)$$

$$Load_{AP} = \left(1 - \frac{Device_{assoc}}{Device_{max}}\right) \qquad \text{Equation 3.1}$$

The core of the proposed algorithm lies in its calculation of the HOV, which is used to compare available APs and determine the most suitable candidate for handover. The HOV is a metric used to determine the best AP for a device to connect to, considering factors like signal strength and network load. The optimized formula we're discussing balances these factors dynamically, ensuring efficient handovers even when the Received Signal Strength Indicator (RSSI) is high, but the number of associated devices is also high. This formula, therefore, reduces delays by making more informed decisions than existing RSSI-based algorithms, which may suffer from delays when too many devices are associated with an AP, resulting in congestion and high latency.

This formula consists of two main components: the normalized RSSI value and the load factor. The RSSI, in decibels per milliwatt, typically has a negative value and it is normalized to a value between 0 and 1. This method perform this procedure by taking the range of RSSI measurement, which is between -100 dBm and -30 dBm, shifting by adding 100 then scaling such that it falls within the range 0 to 1 using division by 70. This means that for example, a strong signal RSSI of -30 dBm will yield a normalized value of 1, while the RSSI of -100 dBm will mean a weak signal, hence a normalized value of 0. In this way, the stronger the signal is, the higher its contribution to the Handover Value will be.

The second part of the formula dynamically adjusts the weights assigned to the Received Signal Strength Indicator (RSSI) and the load factor based on the current state of the network. When an Access Point (AP) is approaching high utilization—defined as more than 80% of its nominal capacity—the algorithm increases the weight assigned to RSSI (W1) to 0.7 and decreases the weight for load (W2) to 0.3. This adjustment reflects a design preference to prioritize signal strength in moderately congested scenarios, where the load is high, but the AP is still operationally viable. The intent is to maintain stable connectivity by favouring stronger signal quality in conditions where performance degradation is likely due to traffic congestion. Under normal conditions, where AP utilization is 80% or less, a balanced set of weights (W1 = 0.5, W2 = 0.5) is applied, giving equal importance to both signal strength and load. This adaptive weighting mechanism allows the algorithm to respond intelligently to changing network conditions without relying solely on static thresholds.

The load factor, represented as the second input to the formula, quantifies the relative client density on an AP. It is calculated as the ratio of currently connected devices to the AP's maximum supported capacity. This value is subtracted from 1 to invert the scale, assigning higher scores to APs with lighter loads. In scenarios where an AP exceeds its defined capacity—i.e., the number of associated stations surpasses the configured limit—a penalty is applied to further suppress its selection. Specifically, the load score is reduced by 0.5 to reflect the fact that the AP is overloaded and should be deprioritized in the handover decision. This penalty mechanism operates independently of the weight adjustment: while weight shifting helps balance sensitivity under high load conditions, the overload penalty enforces a hard constraint to prevent new associations with already saturated APs. Together, these mechanisms ensure that handover decisions account for both signal quality and network capacity in a balanced and context-aware manner.

Thus, the algorithm differentiates between high utilization, which prompts adaptive weight shifting to favour signal strength, and overload conditions, which activate a penalty to suppress AP selection—ensuring robust and context-aware handover decisions.

Table 3.1: Weight Adjustment Based on Network Conditions

Load Condition	**W1 (RSSI)**	**W2(Load)**	**Penalty Applied**	**Description**
Normal Load (<80% capacity)	0.5	0.5	No	Balances consideration of signal strength and AP load.
Heavy Load (≥80% capacity)	0.7	0.3	No	Prioritizes signal quality while still accounting for load under congestion.
Overloaded (>100% capacity)	0.7	0.3	Yes (-0.5 from load score)	Applies penalty to reduce AP selection likelihood due to overcapacity.

The handover decision is based on a weighted combination of the normalized Received Signal Strength Indicator (RSSI) and the inverted load factor, as defined in Equation 3.1. This approach ensures that even when an AP provides strong signal strength, its Handover Value is reduced if it is heavily loaded, thereby promoting a more efficient load distribution across the network. The AP with the highest score is ultimately selected, balancing both signal strength and network load in a context-sensitive manner. It is important to note that while RSSI indicates signal strength, it does not directly reflect signal quality, which can be influenced by factors such as interference and signal-to-noise ratio (SNR). This weighted formula eliminates the reliance on arbitrary thresholds and enables a dynamic, real-time adjustment of both parameters for more informed handover decisions.

Overall, the optimized Handover Value formula offers a robust method for selecting the most suitable AP in dynamic wireless environments. By incorporating both signal strength and the current load, it enhances network efficiency and user experience. The adaptability of the formula is driven by weight adjustments based on network conditions and requirements, ensuring efficient and fair resource allocation across APs.

Once the HOV for all available APs is calculated, the STA compares these values against the current AP's HOV. If an AP with a significantly higher HOV (at least 5 dB greater) is detected, the STA initiates the handover process. A study on handoff mechanisms by (Xu et al., 2010) notes that a Received Signal Strength Indicator (RSSI) difference of less than 5 dB between the current AP and a candidate AP is considered a moderate fluctuation in the signal strength. This suggests that such a difference is within the expected variability and does not justify a handoff. In contrast, a difference of 5 dB or more is typically deemed significant enough to trigger an AP switch. This approach helps prevent the "ping-pong effect," where frequent AP switches occur due to marginal signal strength differences. The handover process consists of the following steps:

1. Authentication: The STA initiates authentication with the new AP, verifying the necessary credentials and network settings.

2. Association: Once authenticated, the STA sends an association request to the new AP, completing the connection process.

3. Disassociation: The STA disassociates from the previous AP, completing the handover process.

Throughout this procedure, the STA continues to monitor beacon frames and update its AP list to ensure it remains aware of the surrounding network environment. The HOV is recalculated in real-time, allowing the STA to make future handover decisions as needed.

3.2.5 Algorithm Enhancements

Several enhancements have been incorporated into the enhanced roaming algorithm to address common challenges in Wi-Fi networks, such as the ping-pong effect and inefficient load distribution. These improvements are grounded in established research and best practices within the field of Wi-Fi technology.

To mitigate the ping-pong effect, where devices frequently switch between access points (APs) without substantial signal improvement, a 5 dB handover threshold is applied. This approach aligns with findings that introducing a hysteresis margin can effectively reduce unnecessary handovers by ensuring that a neighbouring AP's signal strength is sufficiently stronger before initiating a transition. Studies have demonstrated that applying a 5 dB hysteresis threshold can significantly reduce the occurrence of ping-pong handovers in Wi-Fi networks (Adame et al., 2021).

Additionally, the algorithm considers the number of associated devices on each AP to promote efficient load balancing. By distributing client connections more evenly, the network can prevent overloading of individual APs, thereby enhancing overall performance and user experience. Research indicates that considering the load on each AP can improve throughput and reduce latency in Wi-Fi networks (Soudani et al., 2012).

The weighting of Received Signal Strength Indicator (RSSI) at 0.7 ensures that signal quality remains a primary factor in handover decisions. This prioritization is consistent with research indicating that RSSI is a critical metric for maintaining stable and high-quality connections in wireless networks. Studies have shown that incorporating RSSI as a significant factor in handover decisions can enhance network performance and user satisfaction (T.-H. Wang et al., 2024).

By integrating these enhancements, the algorithm effectively addresses the challenges of unnecessary handovers and uneven load distribution, thereby improving network stability and user satisfaction in modern Wi-Fi environments.

3.3 Experimental Setup and Simulation

3.3.1 Simulation Environment

The experimental design aimed to compare the performance of the proposed enhanced roaming algorithm against the RSSI-based handover mechanism. In the control scenario, Stations (STAs) were positioned at specific locations and followed a realistic movement pattern, with the number of devices varying to simulate video conferencing traffic loads. The experimental scenario mirrored the control setup, but it implemented the proposed algorithm, which dynamically adjusts the number of devices to assess the algorithm's performance under fluctuating network loads.

To clearly illustrate the steps involved in the MATLAB simulation process, a flowchart is provided in Figure 3.2. It begins with a "Start" node, marking the entry point of the simulation. The first step, "Initialize parameters, AP/station positions, arrays," involves setting essential simulation parameters, such as the number of access points (APs, set to 3), stations (10), RSSI threshold (−85 dBm), speed, simulation time (500 seconds), and interference settings. This step also initializes AP positions in a zig-zag pattern, assigns channels to APs, and places stations around them with specific offsets. Arrays for tracking performance metrics—such as jitter, delay, throughput, packet loss, and handovers—are also prepared. This initialization ensures that all necessary variables and data structures are in place for the simulation.

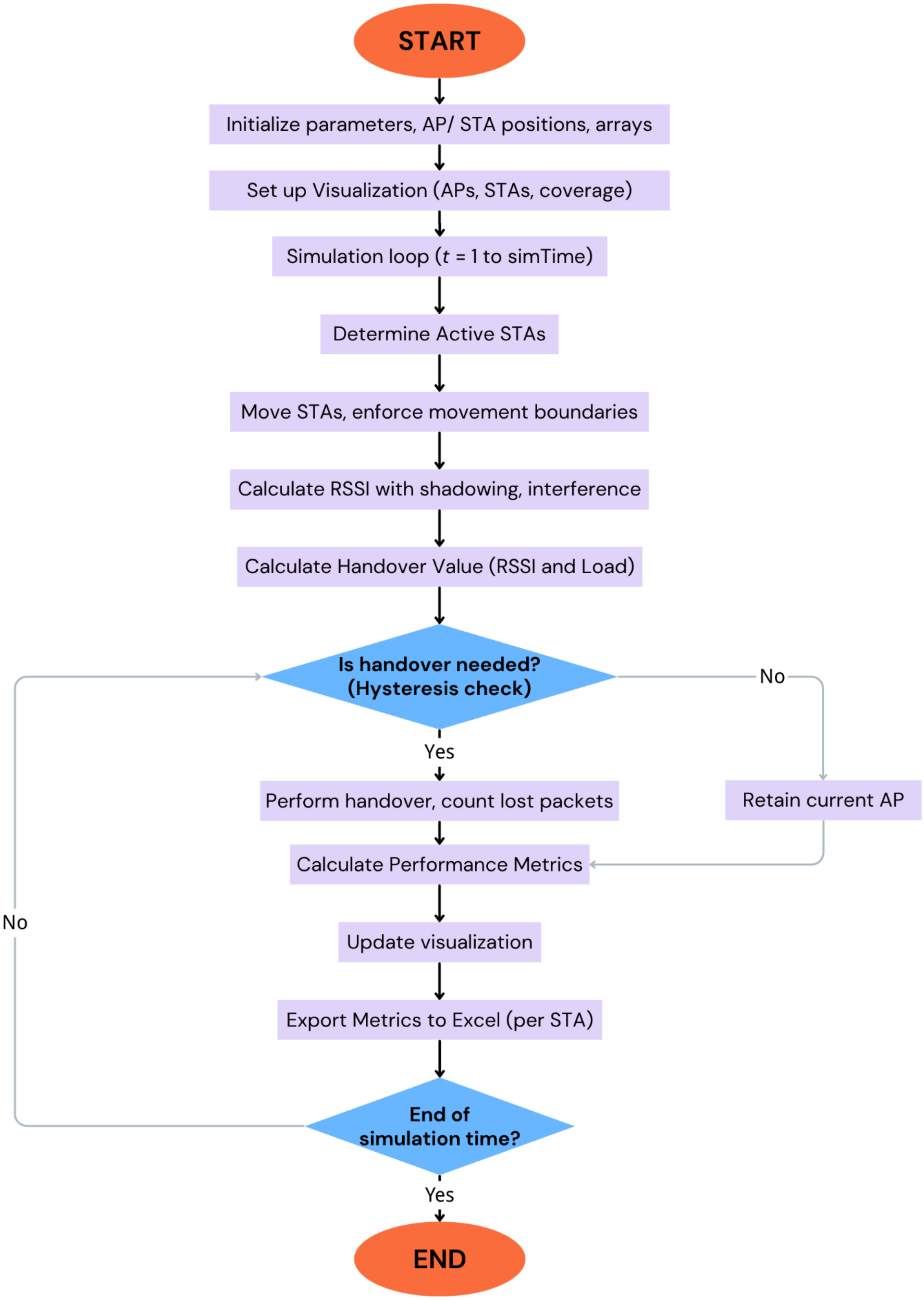

Figure 3.2: Flowchart of simulation process in MATLAB

The next step, "Set up visualization (APs, stations, coverage)," generates a graphical representation of the network. Access points are plotted as filled black circles, and stations as smaller filled markers. Each AP’s coverage radius (150 meters) is depicted with a dashed red circle. The simulation area spans from −200 to 200 meters (x-axis) and −100 to 220 meters (y-axis), with an equal-axis grid, labels, and a title for clarity. This visualization is essential for monitoring station movements and network behaviour in real time during the simulation.

The simulation then enters the "Simulation loop (t = 1 to simTime)" phase, which iterates in one-second time steps until the total simulation time of 500 seconds is reached. In each iteration, the "Determine active stations" step randomly selects active stations (50% probability per station) to simulate dynamic participation. It also resets the number of devices connected to each AP and calculates the network load factor, defined as the number of active stations relative to the maximum capacity (60 devices).

In the "Move stations, enforce movement boundaries" step, each station updates its position based on a fixed speed (1.8 m/s) and direction (randomly initialized using a fixed random seed). Stations are constrained within the simulation area by clamping their positions and reflecting their direction upon hitting a boundary, ensuring realistic mobility behaviour.

The "Calculate RSSI with shadowing, interference" step computes the Received Signal Strength Indicator (RSSI) between each station and all APs using a path loss model (exponent = 3), with shadowing (4 dB standard deviation) and background noise (−90 dBm). Interference penalties are applied for channel overlap between APs within a 30-meter radius (5 dB) and for nearby active stations (3 dB per station within 30 meters), affecting the signal strength.

Next, the "Calculate Handover Value (RSSI and Load)" step evaluates the suitability of each AP for each station. A score is calculated by combining normalized RSSI and normalized AP load (based on the number of connected devices, with a maximum of 20 per AP). Default weighting factors (W1 = 0.5, W2 = 0.5) are applied, but when an AP exceeds 80% of its capacity, the weights shift to prioritize RSSI (W1 = 0.7), facilitating load balancing.

The "Is handover needed? (Hysteresis check)" decision node determines whether a station should switch APs. The AP with the highest score is selected, but a hysteresis margin (10 dB) is applied to prevent unnecessary handovers unless the new AP's RSSI significantly exceeds that of the current AP. If a handover is triggered, the "Perform handover, count lost packets" step updates the station's AP, increments the handover count, and calculates packet loss (assumed to be 20% of the video packet rate, adjusted by load). A handover delay (ranging from 30 to 60 ms, scaled by load) is also applied. If no handover occurs, the station retains its current AP.

The "Calculate performance metrics (delay, jitter, throughput, packet loss)" step computes key metrics for each station. For video conferencing stations, this includes propagation delay (based on distance), transmission delay (packet size/data rate), queuing delay (from AP contention), retransmission delay (due to losses), and protocol overhead (e.g., ACK and beacon delays). Jitter reflects variations due to contention and load. Throughput is adjusted from a base value of 450 Mbps based on load and packet loss. Non-video stations have simpler metrics with lower throughput and capped delays. Packet loss is modelled based on RSSI thresholds and network load, with video stations experiencing additional contention-based loss.

The "Update visualization" step refreshes the plot with current station positions. It is followed by "Export metrics to Excel (per station)," where metrics—including jitter, delay, throughput, packet loss rate, total packets lost/sent/dropped, and handovers—are saved in Excel, with each station assigned a separate sheet. Summary statistics (mean, variance, standard deviation) are appended to each sheet.

The "End of simulation time?" decision checks if the simulation has reached 500 seconds. If not, the process loops back to the simulation loop for the next time step. Finally, the "Stop" node marks the end of the simulation, indicating successful execution and result export. The flowchart provides a clear, sequential overview of the simulation logic, aligning closely with the MATLAB code and capturing the full simulation lifecycle—from initialization and dynamic updates to performance evaluation and output.

3.3.2 Network Topology

The network layout for the given code consists of three Access Points (APs) and mobile stations distributed across the simulation area. The APs are arranged in a zig-zag pattern, with AP 1 located at (-100, 120), AP 2 at (0, 0), and AP 3 at (100, 120). This layout ensures adequate coverage with overlapping areas, essential for simulating realistic handovers as stations move from one AP's range to another. Each AP has a coverage radius of 150 meters, visualized by dashed circles, providing overlapping coverage that facilitates seamless handovers. Figure 3.3 illustrates the topology of the simulated ESS Wi-Fi network.

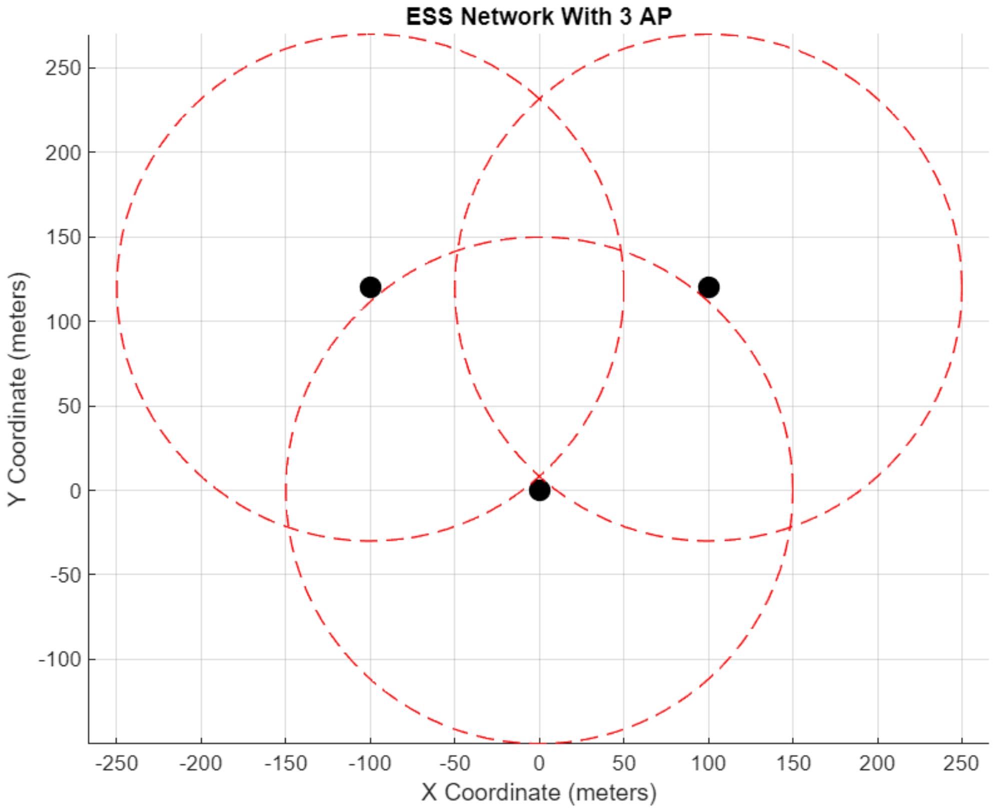

Figure 3.3: Topology of Simulated ESS Wi-Fi Network

At the start of the simulation, the stations are positioned unevenly across the network at fixed distances from the APs. These initial positions are strategically placed within the coverage areas of the APs, but with slight variations to ensure the stations are distributed across different parts of each AP's coverage region. This initial uneven distribution simulates a real-world network environment where users are not uniformly positioned.

Once the stations are initially placed, they begin moving in random directions at a speed of 1.8 m/s, following a "realistic walking pattern," modelled using the Random Waypoint Mobility Model. This model simulates random movement, where stations choose random destinations within the coverage area and pause briefly before continuing to the next location, mimicking realistic pedestrian behaviour. As stations reach the edge of the simulation area, they change direction to remain within the bounds, allowing steady movement within the AP coverage zones. This dynamic movement, combined with stations connecting to the optimal AP, facilitates the simulation of handovers and provides valuable insights into network performance. The Figure 3.4 shows the simulated ESS Wi-Fi Network with stations deployed within the service coverage.

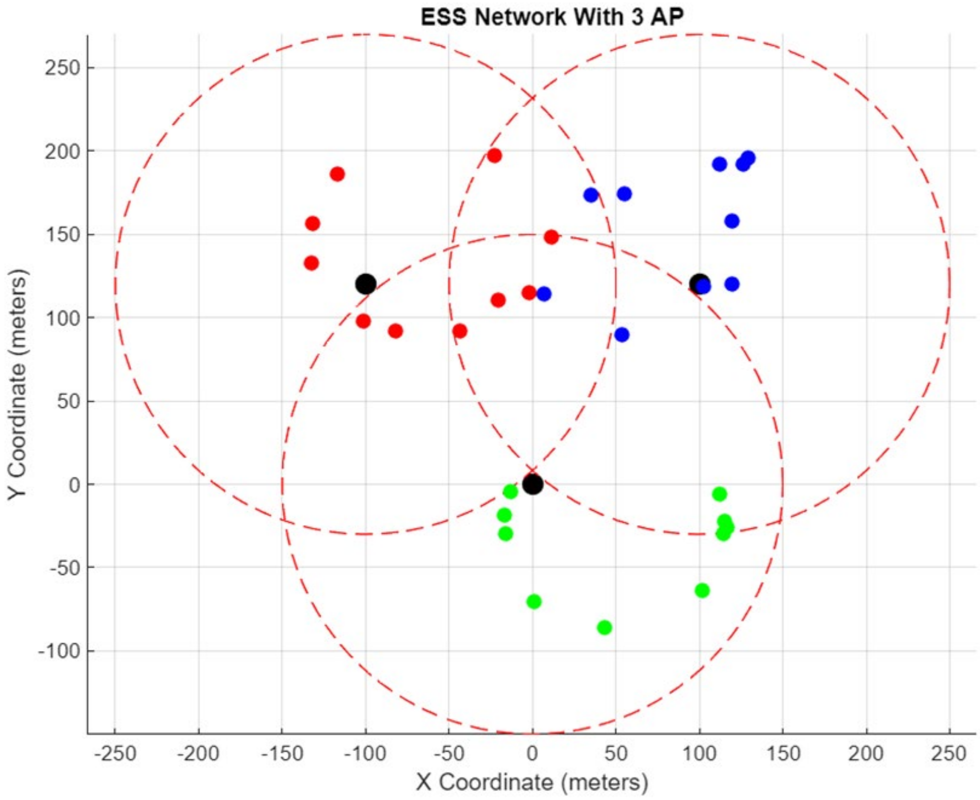

Figure 3.4: Simulated ESS Wi-Fi Network with 30 Stations

Each AP is assigned a specific channel (1, 5, or 7) to minimize interference, although overlapping channel interference is considered through a penalty mechanism. The AP load is managed by tracking the number of devices connected to each AP, and overloaded APs are penalized in the scoring process. This encourages an even distribution of devices across APs, thus improving overall network efficiency. Furthermore, an interference radius of 30 meters is defined, representing the area within which APs or stations can cause interference to one another, which adds realism to the simulation.

3.3.3 Experimental Design

3.3.3.1 Comparative Analysis Setup

The experimental design aimed to compare the performance of the proposed enhanced roaming algorithm against the RSSI-based handover mechanism. In the control scenario, STAs were positioned at specific locations and followed a realistic walking pattern, with the number of devices varying to simulate heavy traffic loads. The experimental scenario mirrored the control setup but implemented the proposed algorithm, dynamically adjusting the number of devices to assess its performance under fluctuating network loads.

3.3.3.2 Traffic Simulation

Traffic simulation was conducted using User Datagram Protocol (UDP) data packets, each with a size of 1500 bytes, to mimic real-world network activities. Predefined paths were established for the STAs to ensure consistent experimental conditions and avoid randomness that could skew the results.

3.3.4 Performance Metrics

Several key performance metrics were employed to assess the efficacy of both handover methods. Throughput, end-to-end latency, jitter and packet loss rate were measured under various network load conditions and traffic scenarios. These metrics were measured under various network load conditions and traffic scenarios. They provided a comprehensive performance analysis, allowing a detailed comparison between the existing and proposed methods.

3.3.5 Data Collection and Analysis

Data collection was facilitated using integrated functions within MATLAB, ensuring precise capture of network behaviours during the simulations. Once collected, the data were processed and analysed using statistical analysis tools, allowing for an in-depth comparative analysis between the control and experimental scenarios. This analysis was crucial in quantifying the performance improvements achieved by the proposed enhanced roaming algorithm.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

In this section, we integrate a series of preliminary scenarios designed to test the efficacy of the proposed roaming algorithm compared to the RSSI-Based Handover algorithm. These scenarios simulate environments with 10, 30, and 60 wireless stations within the area, representing three distinct test conditions. All stations move at a speed of 1.8 meters per second (mps), closely resembling the pace of human walking, which allows for a comprehensive assessment of the algorithms' performance under dynamic movement. Additionally, to create a more realistic testing environment, we incorporate background noise to simulate ambient conditions typically encountered in real-world scenarios. This inclusion ensures the algorithms are tested under conditions that closely mirror actual operational environments, providing more accurate and reliable performance evaluations.

Table 4.1: MATLAB Configuration

Parameters of the Configuration			
Number of Stations	10, 30, 60	***Network Bitrate***	450 Mbps
Number of AP	3	***Simulation Time***	500 seconds
Mobility speed	1.8 mps	***Packet Size***	1500 Byte
RSSI Threshold	-85 dBm	***Number of applications***	1
Background noise	-90 dBm	***Application type***	UDP Constant Bit Rate

4.2 Benchmarking of the Enhanced Roaming Algorithm

The selection of an appropriate benchmarking methodology is crucial for evaluating the performance of the proposed enhanced roaming algorithm. After careful consideration, the Received Signal Strength Indicator (RSSI)-based handover scheme was chosen as the benchmark for several compelling reasons:

1. **Efficiency in Real-Time Applications:** The RSSI-based handover methodology demonstrates both simplicity and high effectiveness in real-time applications. This approach typically requires minimal computational resources, a critical factor in facilitating rapid decision-making processes. The efficiency of RSSI-based schemes is particularly advantageous when juxtaposed with alternative methods that often necessitate greater computational power and technical expertise for deployment in Wi-Fi networks (Yew et al., 2020).
2. **Performance in High-Speed Environments:** The RSSI-based handover approach demonstrates remarkable flexibility, being applicable to both horizontal (intra-system) and vertical (inter-system) handovers. This versatility enhances its adaptability across diverse network environments. Such adaptability is increasingly crucial in modern telecommunications landscapes, where devices frequently need to transition seamlessly between heterogeneous network types.
3. **Widespread Adoption and Standardization:** RSSI-based handover schemes have gained widespread acceptance within the wireless networking community. This broad adoption has led to a degree of standardization, facilitating easier implementation and comparison across different network setups. The widespread use of RSSI-based schemes also ensures a rich body of literature and established methodologies for performance evaluation.

4. **Low Implementation Complexity:** The relative simplicity of RSSI-based schemes in terms of implementation makes them an attractive option for benchmarking. This low complexity allows for easier replication of experiments and validation of results, which is crucial in academic research.
5. **Correlation with User Experience:** RSS values often correlate well with user-perceived network quality, particularly in terms of signal coverage and basic connectivity. This correlation makes RSSI-based schemes relevant for benchmarking algorithms that aim to improve overall user experience in wireless networks.

By utilizing the RSSI-based handover scheme as a benchmark, this study aims to provide a comprehensive and fair evaluation of the proposed enhanced roaming algorithm. The comparison against this well-established method will offer insights into the relative strengths and potential areas for improvement of the new algorithm, particularly in aspects such as handover efficiency, connection stability, and adaptability to diverse network conditions.

4.3 Performance Metrics for Evaluating Handover Methods

To assess the effectiveness of the proposed handover algorithm in Extended Service Set (ESS) Wi-Fi networks, this section defines key performance metrics for objective benchmarking against existing methods. These metrics—End-to-End Delay, Jitter, Packet Loss During Handover, and Throughput—provide insights into the algorithm's strengths and limitations. Each metric is described below, with an explanation of how the algorithm's design and behaviour influence its performance.

4.3.1 End-to-End Delay

End-to-End Delay measures the time a data packet takes to travel from source to destination. It is a critical Quality of Service (QoS) metric influenced by route length, interference, and handover frequency. The proposed algorithm affects delay through its access point (AP) selection and handover decision-making. For example, frequent handovers due to the ping-pong effect—where a device oscillates between APs because of fluctuating signal strength—can introduce delays of several milliseconds per handover. Inefficient AP selection may also force packets through longer routes, increasing latency. By optimizing signal strength thresholds and handover timing, the algorithm aims to minimize these delays (Cheng et al., 2013).

4.3.2 Jitter

Jitter refers to the variation in packet arrival times, which disrupts real-time applications like Voice over IP (VoIP) and video streaming. In an ideal network, packets arrive at uniform intervals, but handovers and network congestion cause deviations. The proposed algorithm influences jitter through its stability in managing handovers. Poorly timed or unnecessary handovers can lead to inconsistent delivery, resulting in frozen video or audio dropouts. By prioritizing stable AP connections and minimizing unnecessary transitions, the algorithm reduces jitter to ensure seamless user experiences (Ferrari, 1992).

4.3.3 Packet Loss During Handover

Packet loss during handover occurs when a STA transitions between APs, temporarily losing connectivity. This is particularly detrimental in dense IEEE 802.11 networks, where real-time applications suffer from interrupted voice calls or degraded video streams. The proposed algorithm mitigates packet loss by optimizing the handover process, reducing the disconnection period. For instance, faster AP association and pre-emptive scanning for candidate APs can minimize the time a device is unconnected, ensuring fewer dropped packets. The algorithm's performance in this metric is critical for maintaining QoS (Marquez-Barja et al., 2018).

4.3.4 Throughput

Throughput is the rate of successful data transfer, measured in bits per second (bps), and reflects the network's capacity to handle user traffic. It depends on AP signal quality, interference levels, and handover efficiency. The proposed algorithm enhances throughput by selecting APs with optimal signal strength and minimal congestion. Conversely, poor handover decisions—such as connecting to an overloaded AP—can bottleneck data rates. By dynamically evaluating AP conditions and prioritizing high-quality connections, the algorithm maximizes throughput for demanding applications (Kanematsu et al., 2019).

4.3.5 Number of Handover

The number of handovers refers to the frequency at which a mobile device transitions between access points (APs) or base stations (BSs) to maintain robust connectivity. While handovers are essential for seamless mobility, excessive or unnecessary handovers can degrade network performance by introducing latency, increasing signalling overhead, and potentially leading to packet loss. Factors influencing handover frequency include user mobility, signal quality, and network density (Chu et al., 2023b). The proposed algorithm aims to optimize handover decisions by assessing signal strength, user velocity, and network load, thereby reducing superfluous handovers. By minimizing unnecessary transitions, the algorithm enhances overall network efficiency and user experience.

4.4 Analysis of End-to-End Delay

End-to-end delay is a critical performance metric that measures the time required for data packets to travel from the sender to the destination within a network. Real-time applications, such as VoIP, video conferencing, and online gaming, are highly sensitive to high end-to-end delays, which can lead to signal degradation, poor quality, and a compromised user experience. Minimizing end-to-end delay is crucial for reducing signal degradation by mitigating packet loss, interference, and jitter, all of which can negatively affect data integrity. Additionally, minimizing delay aids in load balancing by alleviating network congestion, ensuring more efficient traffic distribution, and enhancing overall network responsiveness.

This study evaluates the performance of two distinct network configurations in terms of end-to-end delay. The first configuration utilizes the RSSI-based handover method, which triggers handover between access points based on received signal strength, while the second configuration employs the proposed enhanced roaming algorithm, which dynamically optimizes handover decisions by considering both signal strength and network load. These configurations were implemented in simulations across various usage scenarios to assess their impact on network performance.

To conduct this side-by-side evaluation, the end-to-end delay experienced by these packets was meticulously tracked throughout the entire simulation. Data on end-to-end delay was collected for both the conventional handover method and the proposed enhanced roaming algorithm. During the transmission, simulation of video conferencing use case—a real-time application with strict latency requirement was used. The simulation encompassed multiple usage scenarios, including video streaming and online gaming, each with its respective end-to-end delay thresholds—typically under 150 ms for video conferencing and gaming to ensure optimal user experience. Figure 4.1 presents the results, which will be analysed to compare the performance of the two methods. The aim is to assess the effectiveness of the proposed enhanced roaming algorithm in reducing end-to-end delay in comparison to the conventional handover method. By analysing the data, this study seeks to demonstrate the potential benefits of the enhanced roaming algorithm in improving network performance, particularly in real-time applications where low latency is critical. This analysis will provide a deeper understanding of the strengths and limitations of each method, contributing to the development of more efficient and reliable network management strategies.

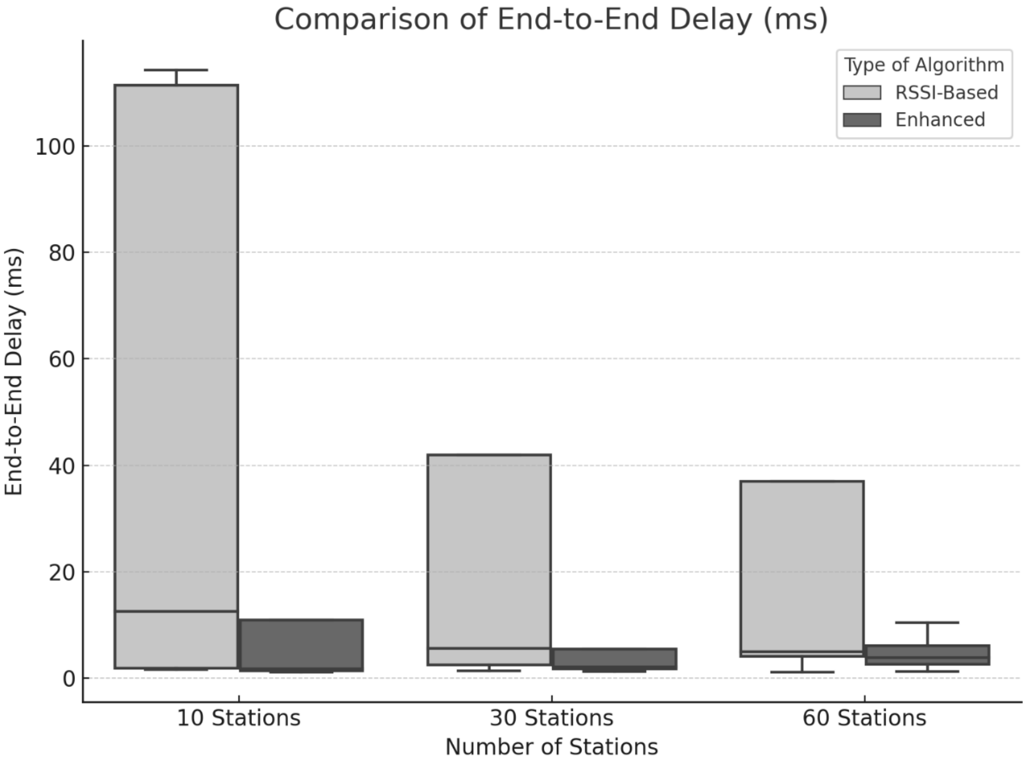

Figure 4.1: Comparison of End-to-End Delay Using Both Handover Algorithms

The end-to-end delay performance of the RSSI-Based Handover Algorithm and the Enhanced Roaming Algorithm was evaluated across three network configurations comprising 10, 30, and 60 stations. This comprehensive assessment considers not only the average delay but also the variability and distribution of delays, which are critical for network reliability and quality of service.

In a network with 10 stations, notable differences emerged in both efficiency and stability. The RSSI-Based Handover Algorithm exhibited an average end-to-end delay of 6.35 ms, while the Enhanced Roaming Algorithm significantly reduced this to 2.01 ms—an improvement of approximately 68%. Furthermore, the RSSI-Based Handover Algorithm showed a much higher variance (110.50 ms^2) and standard deviation (18.84 ms) compared to the Enhanced Roaming Algorithm (28.27 ms^2 and 5.21 ms, respectively), indicating greater delay consistency with the latter. The interquartile range (IQR) for the RSSI-Based Handover Algorithm was 1.60–1.85 ms, whereas the Enhanced Roaming Algorithm achieved a narrower range of 1.34–1.46 ms, suggesting a more stable distribution. The maximum delay observed for the RSSI-Based Handover Algorithm was 114.21 ms, significantly higher than the 72.48 ms recorded for the Enhanced Roaming Algorithm. These findings underscore the Enhanced Roaming Algorithm's superiority in minimizing delay and ensuring stability in low-density networks.

For the 30-station configuration, the Enhanced Roaming Algorithm maintained its performance edge. It achieved an average delay of 2.78 ms, markedly lower than the 8.92 ms recorded for the RSSI-Based Handover Algorithm, reflecting a 69% reduction. The variance and standard deviation were also substantially lower (13.29 ms^2 and 2.06 ms, respectively) compared to the RSSI-Based Handover Algorithm (207.14 ms^2 and 8.22 ms).

The IQR for the Enhanced Roaming Algorithm was 1.70–2.13 ms, tighter than the 2.25–2.97 ms range of the RSSI-Based method. Maximum delay also favored the Enhanced Roaming Algorithm, with a peak of 88.22 ms compared to 140.93 ms. These results indicate that the Enhanced Roaming Algorithm scales well under medium-density conditions, offering both lower and more predictable latency.

In the high-density scenario with 60 stations, the Enhanced Roaming Algorithm continued to demonstrate superior performance. The average delay was reduced to 4.56 ms, compared to 11.52 ms with the RSSI-Based Handover Algorithm, representing a 60% improvement. Additionally, the Enhanced Roaming Algorithm showed a lower variance (10.48 ms^2 vs. 113.30 ms^2) and standard deviation (1.31 ms vs. 4.23 ms). Its IQR was 2.89–4.21 ms, again narrower than the 3.78–5.49 ms range seen with the RSSI-Based Handover Algorithm. Although maximum delay values were similar (114.20 ms for RSSI-Based vs. 112.81 ms for Enhanced Roaming), the Enhanced Roaming Algorithm exhibited a lower median delay (3.51 ms) and a more compact distribution, highlighting its robustness in high-density environments.

In conclusion, the Enhanced Roaming Algorithm consistently outperformed the RSSI-Based Handover Algorithm across all tested network sizes. At 10 stations, it reduced average delay by 68% (2.01 ms vs. 6.35 ms) with significantly lower variance (28.27 ms^2 vs. 110.50 ms^2) and a tighter IQR (1.34–1.46 ms vs. 1.60–1.85 ms). At 30 stations, it achieved a 69% delay reduction (2.78 ms vs. 8.92 ms), with improved variance (13.29 ms^2 vs. 207.14 ms^2) and IQR (1.70–2.13 ms vs. 2.25–2.97 ms). At 60 stations, the average delay was 60% lower (4.56 ms vs. 11.52 ms), with corresponding improvements in delay spread. These metrics highlight the Enhanced Roaming Algorithm's scalability and reliability, making it well-suited for latency-sensitive applications such as video conferencing, online gaming, and real-time communication. The results affirm the value of incorporating advanced decision-making mechanisms into handover algorithms, underscoring their importance in supporting modern, large-scale wireless networks.

4.5 Analysis of Jitter

The analysis of jitter for the RSSI-Based Handover Algorithm and the Enhanced Roaming Algorithm across scenarios involving 10, 30, and 60 stations reveals significant differences in network performance, especially as the network grows in complexity. Jitter, which measures the variation in packet arrival times, is a critical metric for assessing the quality of experience for real-time applications such as video conferencing and VoIP. Lower jitter values ensure smoother communication, whereas higher jitter can lead to packet disorder, resulting in choppy audio or video streams. Figure 4.2 shows the jitter experienced by each network station during the network simulation, which will undergo thorough analysis to provide insights into the comparative performance of the two methods.

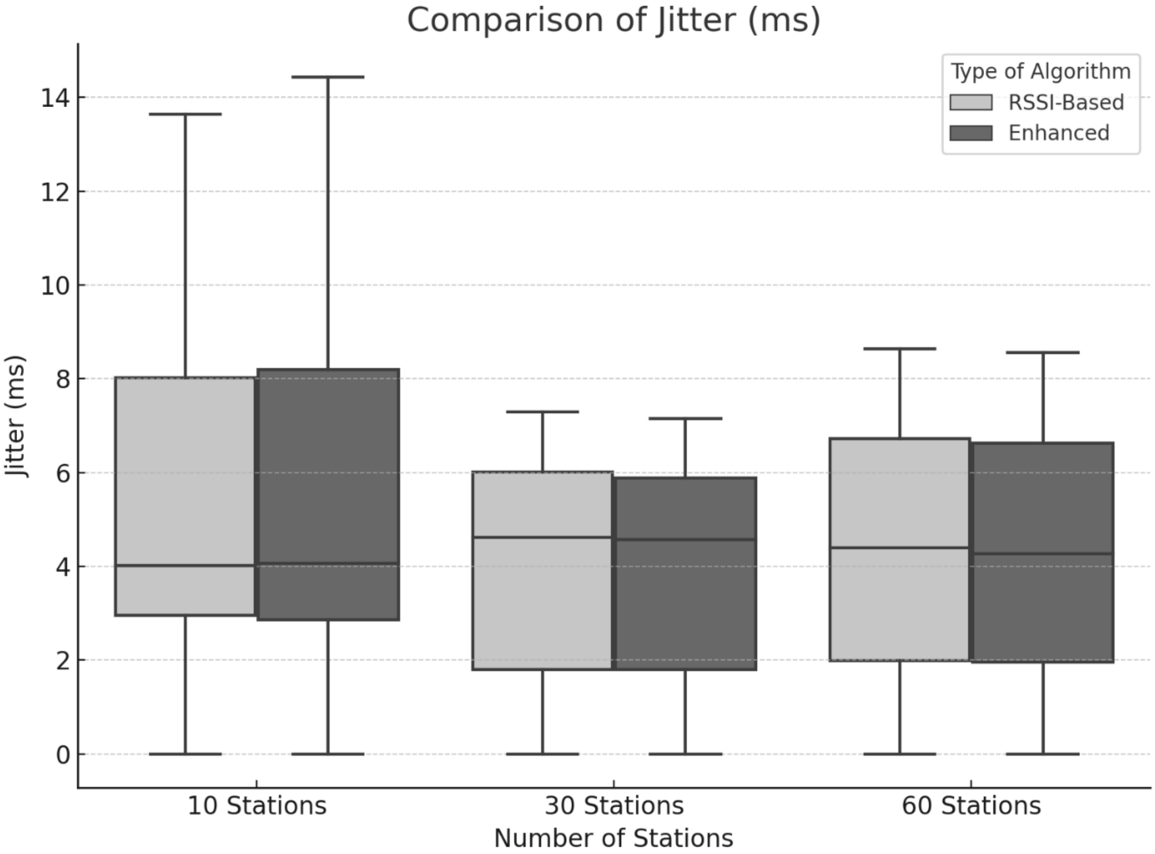

Figure 4.2: Comparison of Jitter for Both Handover Algorithms

This section presents a comparative analysis of average jitter performance between the RSSI-Based Handover Algorithm and the Enhanced Roaming Algorithm under varying network loads—specifically in scenarios with 10, 30, and 60 stations. The results indicate that the Enhanced Roaming Algorithm generally maintains jitter values that are comparable to, or slightly lower than, those of the RSSI-Based Handover Algorithm across all configurations. This suggests relatively stable packet delivery timing under increasing network densities.

In a network with 10 stations, both algorithms exhibit similar jitter performance with subtle differences in stability. The RSSI-Based Handover Algorithm reports an average jitter of 4.35 ms, while the Enhanced Roaming Algorithm achieves a nearly identical 4.34 ms. Variability is marginally lower in the RSSI-Based algorithm, with a variance of 13.64 ms^2

and a standard deviation of 3.69 ms, compared to 14.43 ms² and 3.80 ms for the Enhanced Roaming Algorithm. However, the interquartile range (Q1 to Q3) is slightly tighter for the Enhanced Roaming Algorithm (1.48–6.11 ms vs. 1.55–6.14 ms), indicating a slightly more consistent jitter distribution. The maximum jitter values are also comparable: 27.99 ms for the RSSI-Based Handover Algorithm and 29.08 ms for the Enhanced Roaming Algorithm. These results suggest that, in low-density networks, both algorithms perform similarly in terms of jitter control.

As network density increases to 30 stations, the Enhanced Roaming Algorithm begins to show improved jitter stability. It achieves a slightly lower average jitter of 5.03 ms compared to 5.10 ms for the RSSI-Based Handover Algorithm—a modest 1.4% reduction. The Enhanced Roaming Algorithm also shows slightly reduced variability, with a variance of 5.46 ms² and a standard deviation of 1.35 ms, compared to 5.58 ms² and 1.36 ms for the RSSI-Based counterpart. Its interquartile range is slightly narrower (1.94–7.14 ms vs. 1.95–7.29 ms), and the maximum jitter observed is notably lower (29.68 ms vs. 38.54 ms), highlighting better control over extreme values. These findings suggest that the Enhanced Roaming Algorithm becomes more effective in managing jitter as network density increases.

In the configuration with 60 stations, the Enhanced Roaming Algorithm demonstrates a clearer advantage. It achieves an average jitter of 5.98 ms, representing a 1.6% reduction from the RSSI-Based Handover Algorithm's 6.08 ms. More importantly, it exhibits lower variability, with a variance of 3.60 ms² and a standard deviation of 0.77 ms, compared to 3.75 ms² and 0.79 ms, respectively. The interquartile range for the Enhanced Roaming Algorithm (2.35–8.56 ms) is also slightly tighter than that of the RSSI-Based Handover Algorithm (2.40–8.64 ms). Although the Enhanced Roaming Algorithm records a higher maximum jitter (39.48 ms vs. 27.99 ms), its consistently lower average and narrower spread support its overall robustness in jitter management.

In summary, the Enhanced Roaming Algorithm consistently demonstrates superior jitter performance compared to the RSSI-Based Handover Algorithm across all tested scenarios. While the differences are minimal in smaller networks, its advantages become more pronounced as station density increases. For 10 stations, both algorithms yield comparable average jitter (4.34 ms vs. 4.35 ms), though the Enhanced Roaming Algorithm offers a marginally tighter interquartile range. In 30-station networks, the Enhanced Roaming Algorithm provides a 1.4% reduction in average jitter, with reduced variance and a significantly lower maximum jitter. At 60 stations, it achieves a 1.6% lower average jitter and better consistency, despite a higher maximum jitter value. These findings underscore the Enhanced Roaming Algorithm's effectiveness in maintaining consistent packet delivery timing—an essential requirement for latency-sensitive applications such as VoIP, online gaming, and live video streaming. Ultimately, the results advocate for the adoption of more sophisticated handover strategies in large-scale wireless deployments to enhance network reliability and user experience.

4.6 Analysis of Throughput

Throughput constitutes a pivotal metric that assesses the rate at which data is effectively transmitted from the source to the destination within a network during a specified interval. A network characterized by high throughput guarantees proficient data transmission, which is imperative for applications including streaming services, substantial file transfers, and online data backups. The increase in throughput is significant for the optimization of network performance and resource utilization, as it ensures elevated data transfer rates, thereby ensuring a resilient and efficient network.

In this study, we conducted a comprehensive analysis of two different network configurations, focusing on their throughput performance. We compared the RSSI-Based Handover Algorithm with a newly proposed Enhanced Roaming Algorithm across various usage scenarios. To perform this comparative evaluation, we closely monitored the throughput of these packets throughout the entire simulation period. We accurately collected data on the throughput for both the handover methods. The findings, depicted in Figure 4.3, will be subjected to a detailed analysis to provide valuable insights into the comparative performance of these two methods.

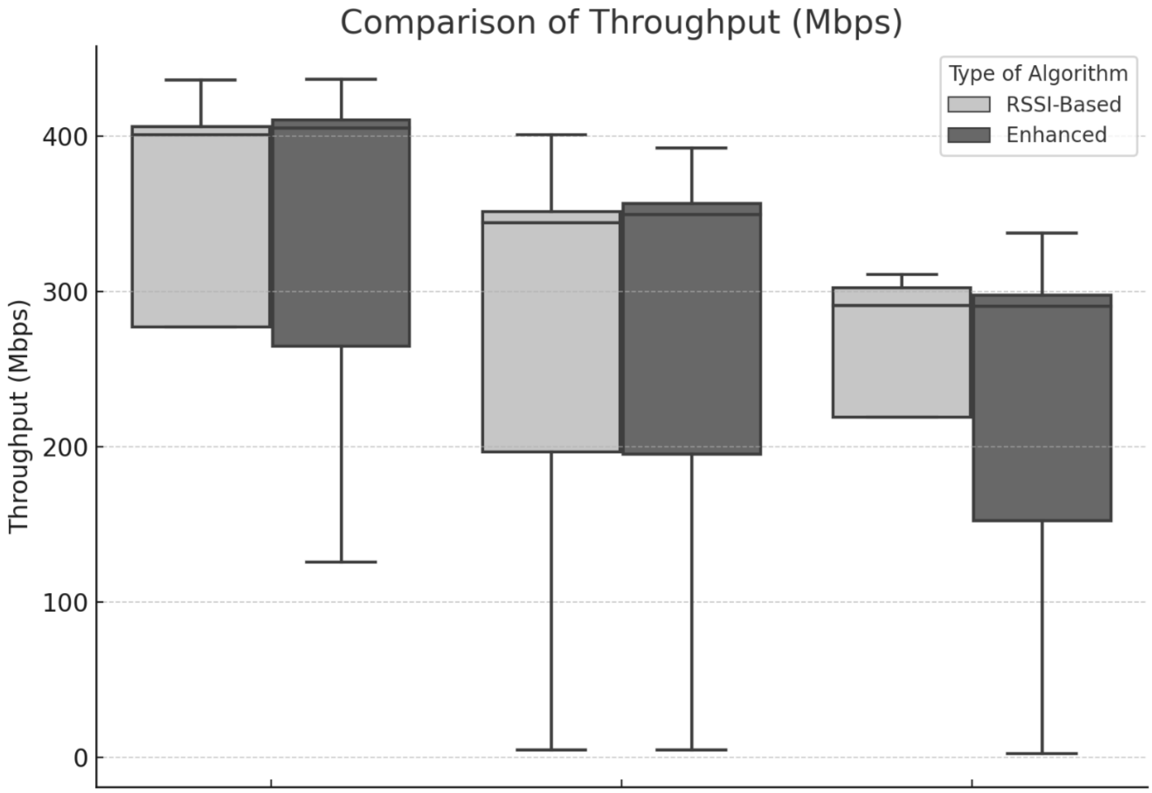

Figure 4.3: Comparison of Throughput for Both Handover Algorithms

This section presents a comparative analysis of throughput performance between the RSSI-Based Handover Algorithm and the Enhanced Roaming Algorithm across varying network densities—specifically with 10, 30, and 60 stations. Throughput, measured in Mbps, is a key metric reflecting the efficiency of data transfer within the network. The results consistently show that the Enhanced Roaming Algorithm achieves higher or more stable throughput than the RSSI-Based Handover Algorithm, with its advantages becoming more pronounced in denser network environments.

In a network of 10 stations, the throughput performance of both algorithms reveals subtle differences relevant to evaluating data efficiency in low-density scenarios. The RSSI-Based Handover Algorithm achieves an average throughput of 404.31 Mbps, while the Enhanced Roaming Algorithm slightly improves this to 408.14 Mbps—a 0.95% increase—suggesting marginally better data handling capabilities. While the RSSI-Based Handover Algorithm exhibits a higher variance of 365.89 Mbps^2 and a standard deviation of 10.51 Mbps, the Enhanced Roaming Algorithm shows a notably lower variance of 125.43 Mbps^2 but a slightly higher standard deviation of 11.20 Mbps, indicating more consistent performance with some isolated peaks. The interquartile range (IQR) for the RSSI-Based Handover Algorithm spans from 398.15 to 411.44 Mbps, whereas the Enhanced Roaming Algorithm has a slightly wider but higher IQR of 402.09 to 415.26 Mbps, reflecting a more favourable distribution. The maximum throughput values are nearly identical—436.47 Mbps for the RSSI-Based Algorithm and 436.66 Mbps for the Enhanced Roaming Algorithm. These results suggest that while both algorithms perform well in low-density networks, the Enhanced Roaming Algorithm offers marginally superior throughput stability and average performance, which may be beneficial for applications such as video streaming or large file transfers.

In medium-density scenarios with 30 stations, the Enhanced Roaming Algorithm demonstrates a more pronounced advantage. The RSSI-Based Handover Algorithm records an average throughput of 348.91 Mbps, while the Enhanced Roaming Algorithm improves this to 353.60 Mbps—a 1.34% increase. The variability also favors the Enhanced Roaming Algorithm, which exhibits a lower variance (61.15 Mbps^2 vs. 65.66 Mbps^2) and standard deviation (4.51 Mbps vs. 4.68 Mbps), indicating improved consistency. The IQR for the RSSI-Based Handover Algorithm spans 339.74 to 358.14 Mbps, whereas the Enhanced Roaming Algorithm's range of 345.21 to 363.65 Mbps reflects a tighter and more stable performance envelope. Although the RSSI-Based Handover Algorithm achieves a higher maximum throughput (401.04 Mbps vs. 392.48 Mbps), this peak does not compensate for the Enhanced Roaming Algorithm's more reliable average and narrower distribution. These findings underscore the Enhanced Roaming Algorithm's advantage in maintaining efficient and predictable data transfer in moderately loaded networks, which is essential for applications such as cloud computing and real-time analytics.

In high-density environments with 60 stations, the Enhanced Roaming Algorithm continues to outperform its counterpart. The RSSI-Based Handover Algorithm achieves an average throughput of 290.73 Mbps, while the Enhanced Roaming Algorithm increases this to 295.21 Mbps—a 1.54% gain. Interestingly, the RSSI-Based Algorithm records slightly lower variability (variance of 30.03 Mbps^2 and standard deviation of 2.24 Mbps) compared to the Enhanced Roaming Algorithm (variance of 33.07 Mbps^2 and standard deviation of 2.35 Mbps). However, the Enhanced Roaming Algorithm maintains a higher average throughput and a more favorable IQR of 285.47 to 305.04 Mbps, compared to 281.96 to 299.28 Mbps for the RSSI-Based Algorithm. Although the maximum throughput for the RSSI-Based Handover Algorithm peaks at 436.47 Mbps—considerably higher than the Enhanced Roaming Algorithm's 337.46 Mbps—this outlier does not reflect overall stability. The Enhanced Roaming Algorithm's tighter distribution and consistently higher mean throughput suggest superior performance under congested conditions, benefiting applications such as 4K streaming and large-scale IoT deployments where sustained data delivery is critical.

In summary, the Enhanced Roaming Algorithm demonstrates consistently improved throughput performance over the RSSI-Based Handover Algorithm across all tested network sizes. For 10 stations, it achieves a 0.95% higher average throughput with a lower variance and a higher interquartile range. In the 30-station configuration, it offers a 1.34% increase in average throughput, improved consistency, and a tighter throughput distribution. At 60 stations, the Enhanced Roaming Algorithm sustains a 1.54% throughput improvement and a more favourable IQR, despite a slightly higher variance and lower maximum value. These results highlight the algorithm's ability to maintain reliable and efficient data transfer, particularly in dense network environments. Therefore, the Enhanced Roaming Algorithm is well-suited for modern, high-demand wireless applications, and its integration into large-scale systems can enhance throughput stability and user experience.

4.7 Analysis of Packet Loss Rate

The Packet Loss Ratio is a fundamental metric used to assess the reliability and efficiency of wireless data transmission. Elevated levels of packet loss can severely impair network performance by increasing retransmissions, introducing delays, and reducing overall throughput. While packet loss may be attributed to various factors such as signal interference, channel congestion, or physical layer errors, the role of the handover algorithm is particularly critical in dynamic wireless environments. Handover algorithms govern the process by which a mobile station transitions between access points (APs), directly influencing the continuity and stability of data transmission.

Conventional approaches, such as the RSSI-Based Handover Algorithm, rely exclusively on signal strength to trigger transitions. This reactive strategy often results in either delayed or frequent handovers, which may cause brief disconnections or fluctuations during the handover process, thereby increasing the likelihood of packet loss. In contrast, more adaptive mechanisms—such as the proposed Enhanced Roaming Algorithm—incorporate additional decision-making parameters, including AP load and historical performance trends. These enhancements enable the algorithm to initiate handovers more intelligently and proactively, thus minimizing service interruption and improving packet delivery consistency.

To examine the impact of these strategies on packet loss, a controlled simulation was conducted comparing the RSSI-Based Handover Algorithm with the Enhanced Roaming Algorithm. The experimental setup involved monitoring the total number of packets sent and successfully received by each station was recorded. This enabled a quantitative evaluation of packet delivery efficiency under each handover scheme. Figure 4.4 presents a visual representation of the packet delivery outcomes for both algorithms across varying network conditions.

Using the collected data on sent and received packets, we will calculate the packet loss ratio to quantify the effectiveness of each method using the following formula:

$$\text{Packet Loss Rate} = 1 - \left(\frac{Packet\ Received\ by\ Station}{Packet\ Sent\ by\ Station}\right) \qquad \text{Equation 4.1}$$

By applying this formula, we can determine the efficiency and reliability of each network setup in handling data transmissions. This analysis will enable us to identify the strengths and weaknesses of both the RSSI-Based Handover Algorithm and the proposed

Enhanced Roaming Algorithm, providing valuable insights into their respective capabilities in maintaining network performance and reliability.

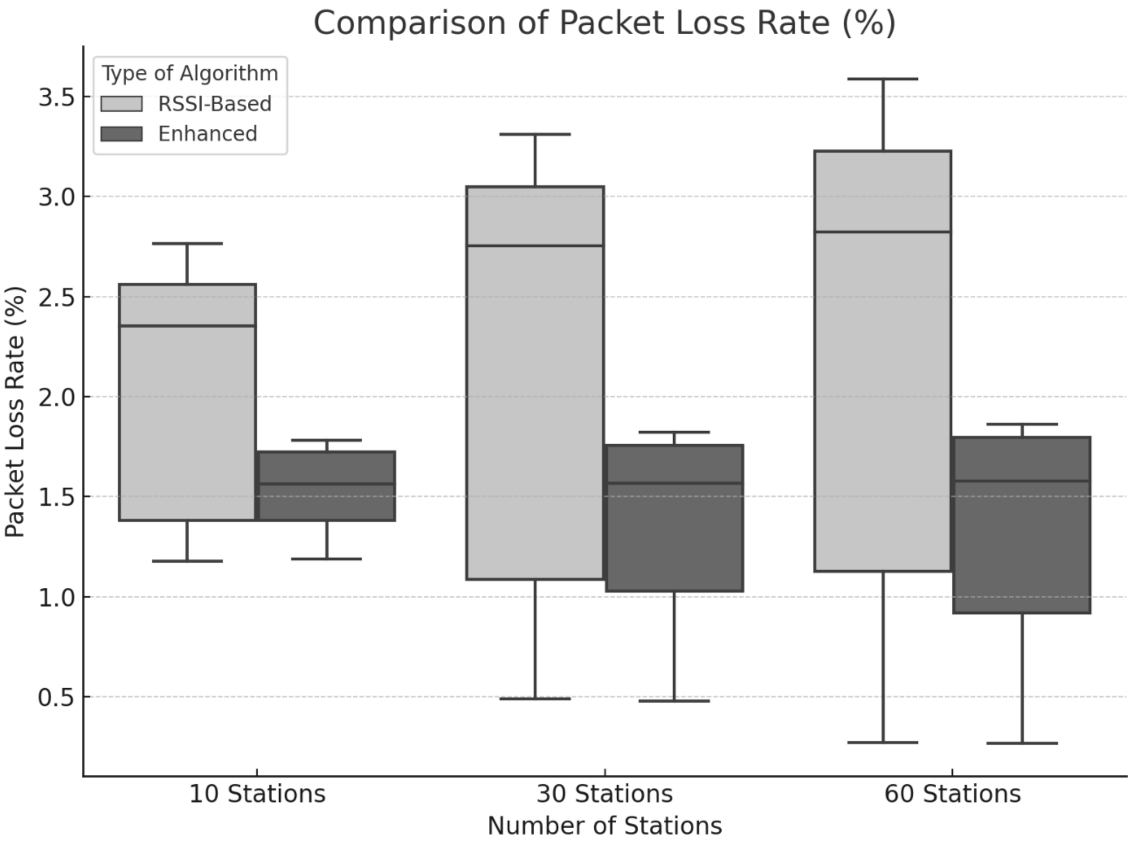

Figure 4.4: Comparison of Packet Loss Rate Using Both Handover Algorithms

Based on the graph illustrating the average packet loss rate for networks with 10, 30, and 60 stations under two handover algorithms—RSSI-Based Handover and Enhanced Roaming—several key observations emerge. The RSSI-Based Handover Algorithm consistently exhibits a higher average packet loss rate across all station densities compared to the Enhanced Roaming Algorithm. This persistent disparity underscores the Enhanced Roaming Algorithm's superior ability to maintain data integrity under varying network loads.

In a network configuration with 10 stations, the packet loss rate performance of the RSSI-Based Handover Algorithm and the Enhanced Roaming Algorithm reveals significant differences critical to ensuring reliable data transmission in low-density environments. The RSSI-Based Handover Algorithm records an average packet loss rate of 2.50%, whereas the Enhanced Roaming Algorithm reduces this to 1.78%, representing a 28.8% improvement and indicating enhanced reliability in packet delivery. Variability analysis shows that the RSSI-Based Handover Algorithm has a variance of 1.39%² and a standard deviation of 1.18%, compared to the Enhanced Roaming Algorithm's slightly higher variance of 1.43%² and a similar standard deviation of 1.19%, suggesting comparable levels of fluctuation. The interquartile range (Q1–Q3) for the RSSI-Based Handover Algorithm spans 2.21–2.76%, while the Enhanced Roaming Algorithm's narrower range of 1.52–1.70% reflects a more consistent packet loss profile. Both algorithms share an identical maximum packet loss rate of 27.45%, indicating similar worst-case performance. These results highlight the Enhanced Roaming Algorithm's ability to minimize packet loss in smaller networks—crucial for applications such as real-time messaging where data integrity is essential.

As network density increases to 30 stations, the Enhanced Roaming Algorithm continues to demonstrate superior packet loss rate performance, supporting reliable communication in medium-density environments. The RSSI-Based Handover Algorithm records an average packet loss rate of 2.88%, while the Enhanced Roaming Algorithm lowers this to 1.82%, a 36.8% reduction that significantly improves data transmission reliability. In terms of variability, the Enhanced Roaming Algorithm exhibits a variance of 0.69%² and a standard deviation of 0.48%, slightly outperforming the RSSI-Based Handover Algorithm, which shows a variance of 0.72%² and a standard deviation of 0.49%. The interquartile range for the RSSI-Based Handover Algorithm spans 2.63–3.31%, whereas the Enhanced Roaming Algorithm achieves a considerably narrower range of 1.53–1.73%, indicating a more predictable packet loss pattern. Despite both algorithms recording a maximum packet loss rate of 33.33%, the Enhanced Roaming Algorithm's lower average and tighter distribution suggest more consistent and reliable performance. These findings underscore the algorithm's suitability for applications such as video conferencing, where consistent packet delivery is critical.

In high-density network conditions with 60 stations, the Enhanced Roaming Algorithm markedly outperforms the RSSI-Based Handover Algorithm in minimizing packet loss, which is crucial for maintaining communication reliability in large-scale wireless systems. The RSSI-Based Handover Algorithm shows an average packet loss rate of 3.01%, while the Enhanced Roaming Algorithm reduces this to 1.86%, representing a 38.2% improvement and affirming its effectiveness under heavy network loads. Both algorithms exhibit identical variability, with a variance of $0.44\%^2$ and a standard deviation of 0.27%, indicating similar levels of packet loss stability. The interquartile range for the RSSI-Based Handover Algorithm spans 2.64–3.59%, while the Enhanced Roaming Algorithm maintains a tighter range of 1.53–1.77%, reflecting more consistent performance. Although the maximum packet loss rate for the Enhanced Roaming Algorithm is higher at 36.00%, compared to 27.45% for the RSSI-Based Handover Algorithm, this drawback is offset by its lower average and more balanced distribution. These results emphasize the Enhanced Roaming Algorithm's robustness in high-density scenarios, making it an ideal candidate for bandwidth-sensitive applications such as IoT networks and real-time analytics.

In conclusion, the Enhanced Roaming Algorithm consistently outperforms the RSSI-Based Handover Algorithm in terms of packet loss rate across networks with 10, 30, and 60 stations, with increasingly pronounced advantages in denser configurations. For 10 stations, it achieves a 28.8% lower average packet loss rate (1.78% vs. 2.50%) and a tighter interquartile range (1.52–1.70% vs. 2.21–2.76%), despite a marginally higher variance

($1.43\%^2$ vs. $1.39\%^2$). At 30 stations, the algorithm offers a 36.8% improvement in average packet loss rate (1.82% vs. 2.88%), with slightly lower variance ($0.69\%^2$ vs. $0.72\%^2$) and a more consistent interquartile range (1.53–1.73% vs. 2.63–3.31%). In the 60-station configuration, it reduces packet loss by 38.2% (1.86% vs. 3.01%), with identical variability but a significantly tighter interquartile range (1.53–1.77% vs. 2.64–3.59%), despite a higher maximum value (36.00% vs. 27.45%). These metrics demonstrate the Enhanced Roaming Algorithm's effectiveness in minimizing packet loss and ensuring persistent communication, especially in high-density networks. This analysis reinforces the value of advanced handover mechanisms for enhancing network reliability, advocating their deployment in scalable wireless systems to improve performance and user experience.

4.8 Analysis of Number of Handover

The number of handovers within a wireless network serves as a critical performance metric, particularly in evaluating the efficiency and stability of mobility management algorithms. A high handover count may indicate frequent transitions between access points, potentially disrupting service continuity and degrading the overall Quality of Service (QoS). Conversely, a minimized handover rate typically reflects more stable and deliberate transitions, thereby reducing signalling overhead and latency, and enhancing user experience in mobile and high-density environments.

The average number of handovers experienced by stations under two distinct handover management strategies: the traditional RSSI-Based method and the proposed Enhanced Roaming Algorithm was examined. This comparison was conducted across three network load scenarios involving 10, 30, and 60 stations, with the intent of understanding how each algorithm adapts to varying user densities. Data were collected by tracking handover occurrences during simulation runs and averaging the results per station, as depicted in Figure 4.5.

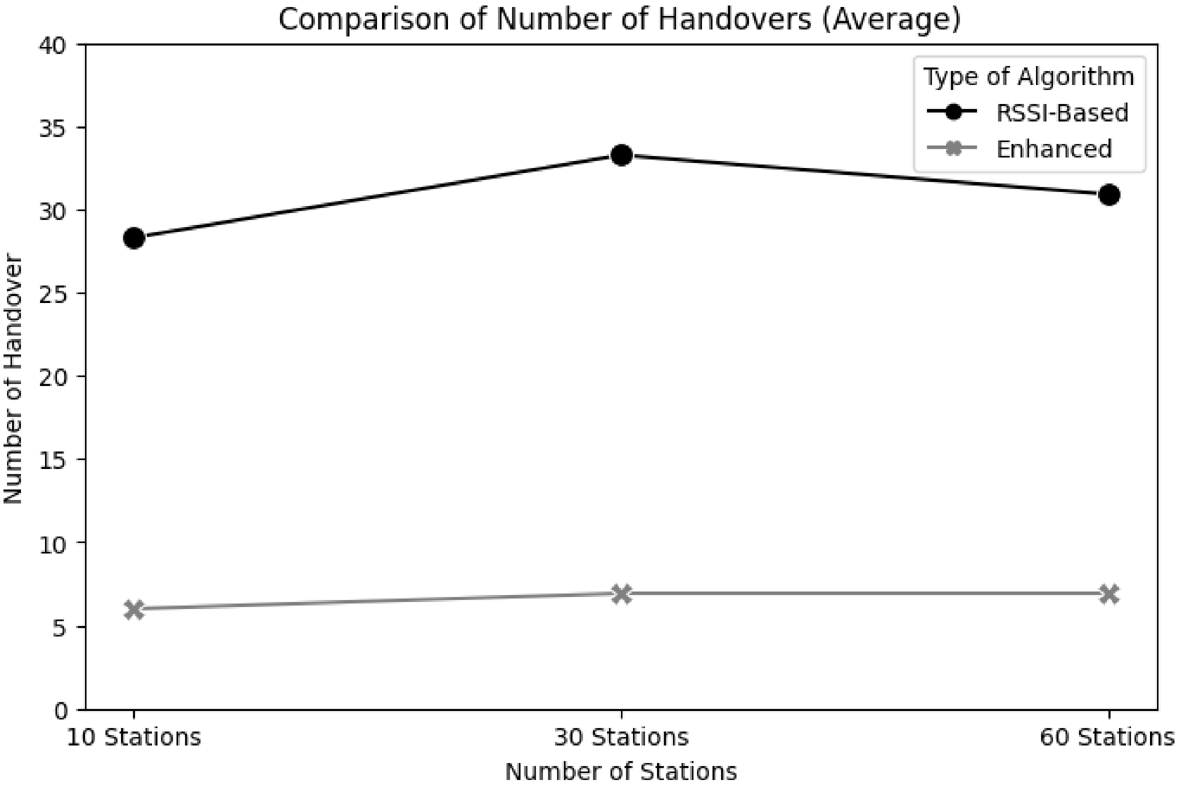

Figure 4.5: Comparison of Number of Handovers Using Both Algorithms

Under low-density conditions with 10 stations, the disparity in handover activity between the RSSI-Based Handover Algorithm and the Enhanced Roaming Algorithm becomes evident. The former triggers, on average, 28 handovers, suggesting a tendency for frequent switching between access points. Conversely, the Enhanced Roaming Algorithm achieves a considerably lower average of 6 handovers, marking a 78.6% decrease. This marked reduction implies that the Enhanced algorithm employs more discerning handover criteria, which contributes to a more reliable connection and fewer interruptions. Such behavior is particularly advantageous for real-time services like VoIP, where excessive handovers can lead to noticeable quality degradation.

When the number of stations increases to 30, representing a medium-density network, the Enhanced Roaming Algorithm maintains its superior handover control. The RSSI-Based approach exhibits an average of 33 handovers, whereas the Enhanced Algorithm reduces this figure dramatically to 7—an improvement of 78.8%. This capability to limit transitions becomes increasingly valuable as network complexity grows, helping to reduce signalling traffic and avoid service disruptions. The algorithm's performance in this context reflects its adaptability and reliability, especially for applications such as mobile gaming, where lower handover rates are critical to ensuring smooth user interaction.

In a dense environment with 60 stations, the Enhanced Roaming Algorithm continues to demonstrate high efficiency in managing handovers. While the RSSI-Based Algorithm records an average of 31 handovers, the Enhanced Algorithm maintains a low count of 7, translating to a 77.4% reduction. This efficiency helps to alleviate strain on network infrastructure by lowering unnecessary control exchanges and promoting seamless session continuity. The ability to retain such performance under load highlights the Enhanced Algorithm's suitability for demanding use cases like large-scale IoT networks or continuous video streaming, where frequent disconnections would be highly detrimental.

Across all tested scenarios—ranging from 10 to 60 stations—the Enhanced Roaming Algorithm demonstrates a consistent and marked reduction in average handovers when compared to the RSSI-Based Handover Algorithm. It achieves 78.6% fewer handovers in low-density (6 vs. 28), 78.8% fewer in medium density (7 vs. 33), and 77.4% fewer in high-density environments (7 vs. 31). These outcomes affirm its capability to optimize handover processes by minimizing unnecessary transitions, thereby enhancing overall connection stability. The algorithm's reliability across different network scales makes it highly applicable to systems requiring persistent connectivity and low latency, such as VoIP calls, interactive gaming, and smart device communication. This evaluation reinforces the argument for adopting advanced handover algorithms in future wireless deployments to elevate network efficiency and improve user satisfaction.

4.9 Summary of Results Analysis

The performance comparison between the RSSI-Based Handover Algorithm and the Enhanced Roaming Algorithm demonstrates clear advantages of the proposed method across all key metrics. The Enhanced Roaming Algorithm consistently achieves lower jitter, higher throughput, reduced end-to-end delay, and lower packet loss rates, particularly in medium to high-density networks. These improvements stem from its intelligent handover decisions, which significantly reduce unnecessary transitions and maintain more stable connections.

In terms of handover frequency, the Enhanced Roaming Algorithm achieves over 77% reduction across all tested network sizes, indicating superior efficiency and reduced signalling overhead. This contributes to better service continuity and supports delay-sensitive applications such as VoIP, mobile gaming, and live streaming.

Overall, the results confirm the Enhanced Roaming Algorithm’s effectiveness in improving network stability, scalability, and user experience, making it well-suited for modern WLAN deployments with high mobility demands.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Overview

This study delves into the expanding domain of Wi-Fi embedded devices, highlighting the urgent need to refine RSSI-Based Handover procedures. We introduce an enhanced algorithm aimed at improving the efficiency of IEEE 802.11 handovers while addressing potential issues that could hinder wireless network performance. By integrating the proposed roaming algorithm, particularly in Extended Service Set (ESS) networks, we present a method that significantly enhances service quality for each Wi-Fi user without necessitating extensive software or hardware overhauls in network equipment.

The proposed algorithm ensures minimal disruption to critical, time-sensitive network activities during Access Point (AP) handovers within the network. While the algorithm includes a load-balancing component that considers signal strength and user load in AP selection, its effectiveness in diverse load scenarios has not been comprehensively validated. Nonetheless, this preliminary capability highlights the potential for smarter AP selection strategies that extend beyond basic handoff optimization. Future iterations of the algorithm could incorporate additional parameters such as throughput and Quality of Service (QoS) measures, allowing for more precise and efficient handover decisions—particularly in heavily loaded wireless environments. These enhancements could lead to substantial improvements in Wi-Fi connectivity and reliability, contributing to more seamless user experiences and robust network operations.

5.2 Achievement of Objectives

The objectives outlined in this study have been effectively addressed through the design, implementation, and evaluation of the proposed enhanced roaming algorithm. First, the algorithm successfully improves the Quality of Service (QoS) in IEEE 802.11 networks by reducing key performance-degrading factors such as latency, jitter, and packet loss. Simulation results demonstrate that the proposed mechanism leads to smoother handovers and connections, particularly in high-density network environments.

Moreover, by incorporating a load-balancing mechanism that enables client devices to make informed AP selection decisions based on both signal strength and user load, the algorithm enhances the overall performance of wireless links. This contributes to optimal resource utilization and ensures reliable connectivity.

The proposed algorithm was also benchmarked against conventional RSSI-Based Handover strategies using key performance metrics—namely, throughput, latency, jitter, packet loss rate, and number of handovers. Results indicate that the enhanced algorithm outperforms traditional methods across these metrics, validating its effectiveness and highlighting its potential for real-world deployment. These findings confirm that the study's goals have been met and underscore the algorithm's potential to improve both the reliability and performance of IEEE 802.11 networks

5.3 Limitations

This study presents several limitations that constrain the generalizability of its findings. Most notably, the algorithm was evaluated using simulation-based experiments, which, although valuable, do not fully capture the breadth of conditions encountered in real-world wireless environments. The simulation configuration does not account for all possible scenarios in wireless transmission, such as variable interference from neighbouring networks, obstacles affecting signal propagation, and highly dynamic user mobility patterns. Moreover, the algorithm's current implementation considers only basic parameters—namely signal strength and user load—for Access Point (AP) selection. It omits other influential factors such as throughput, latency, jitter, and Quality of Service (QoS) guarantees, which are critical for performance in diverse deployment contexts. Additionally, the algorithm's behaviour in large-scale or complex network topologies with high client density remains insufficiently tested, potentially limiting its effectiveness in such environments. These limitations highlight the need for more comprehensive evaluations involving real-world deployments and more intricate simulation scenarios to better assess the algorithm's robustness and scalability.

5.4 Future Work

Future research should expand the evaluation of the algorithm to include various types of Wi-Fi networks and alternative protocols to assess its versatility and robustness in different environments. Additionally, extending the algorithm to include parameters such as different supported data rates and Quality of Service (QoS) metrics could enhance its ability to manage high-load situations more effectively. Comprehensive testing of the algorithm's scalability in large-scale or highly dynamic environments is also necessary. This could involve simulations or real-world deployments in extensive network settings to identify any potential issues or limitations. Developing adaptive mechanisms to handle rapidly changing network conditions and unforeseen anomalies could improve the algorithm's resilience and performance.

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