# ENHANCING QUALITY OF SERVICE IN MULTI-RADIO MULTI-CHANNEL WIRELESS MESH NETWORKS

By

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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**August 2023**

**Chair : Ts. Abdullah bin Muhammed, PhD**
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Wireless Mesh Networks (WMNs) have rapidly evolved as cost-effective, scalable, and robust communication solutions. Multi-Radio Multi-Channel (MRMC) WMNs, in particular, have gained prominence due to their ability to meet the growing demand for wireless network services. However, they contend with interference, routing, and Quality of Service (QoS) challenges, which impede network performance.

Efficient channel assignment in MRMC WMNs is dominant for ensuring high-quality wireless communication. Inadequate channel assignment can lead to interference, signal degradation, and packet loss. The Priority-based Minimum Interference Channel Assignment (PRIMICA) algorithm is introduced to address this issue. PRIMICA assigns distinct frequency channels to each radio, significantly reducing interference, packet loss, delay and ultimately enhancing QoS. PRIMICA yields impressive results, with efficient channel resource utilization leading to a 55% boost in throughput and a 54% reduction in average End-to-End Delay (EED), particularly benefiting time-sensitive traffic.

Congestion reduction and optimized routing in MRMC WMNs are equally critical. These networks must effectively manage fluctuating communication traffic, signal fading, and interference. The COngestion Reduction Routing Algorithm (CORRA) tackles this challenge by evaluating link quality and interference to find optimal data paths. CORRA minimizes average delay, maximizes network throughput, and ensures QoS even in large network sizes. CORRA consistently achieves a 90% packet delivery ratio, demonstrating its collision-free scheduling, even in more extensive networks.

Load-balancing and fair resource allocation present further challenges in MRMC WMNs. Striking the right balance between coverage, capacity, and interference management requires scalable load-balancing algorithms. The Load-balanced Resource Allocation (LRA) algorithm is proposed to address this challenge. LRA optimizes resource utilization, distributes network traffic evenly, and prevents overloading specific nodes or links, ultimately enhancing QoS and fairness. LRA consistently reduces delays in more extensive networks, optimizing resource utilization and maintaining low delays across various network sizes.

Through extensive simulations, this research validates the effectiveness of the proposed algorithms compared to existing ones. This research utilizes the OmNET++ 4.6 simulator, an open-source tool in C++, to evaluate proposed algorithms effectively. It includes network structures, NED language for topology, and configuration files for tailored experiments. Simulation involves grid topologies and diverse conditions, using the two-ray Rayleigh model for accuracy. Ten experiments enhance statistical robustness, and specific simulation parameters ensure clear, reproducible experimental conditions.

PRIMICA, CORRA, and LRA collectively contribute to improving and supporting MRMC WMNs, addressing core challenges in wireless communication networks. This research highlights the potential of these algorithms as valuable tools for network enhancement in MRMC WMNs, ensuring reliable, efficient, and high-performance data transmission.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**MENINGKATKAN KUALITI PERKHIDMATAN DALAM MULTI-RADIO MULTI-SALURAN RANGKAIAN JEJARING TANPA WAYAR**

Oleh

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Rangkaian Jejaring Tanpa Wayar (WMNs) telah berkembang pesat sebagai penyelesaian komunikasi yang kos efektif, berskala, dan mantap. WMN Multi-Radio Multi-Saluran (MRMC), khususnya, telah mendapat perhatian kerana keupayaan mereka untuk memenuhi permintaan yang semakin meningkat untuk perkhidmatan rangkaian tanpa wayar. Walau bagaimanapun, mereka berhadapan dengan cabaran gangguan, laluan, dan kualiti perkhidmatan (QoS), yang menghalang prestasi rangkaian.

Penguntukkan saluran yang cekap dalam MRMC WMNs adalah dominan untuk memastikan komunikasi tanpa wayar berkualiti tinggi. Penguntukkan saluran yang tidak mencukupi boleh menyebabkan gangguan, kemerosotan isyarat, dan kehilangan paket. Algoritma Penguntukkan Saluran Gangguan Minimum berasaskan Keutamaan (PRIMICA) diperkenalkan untuk menangani masalah ini. PRIMICA menetapkan saluran frekuensi yang berbeza untuk setiap radio, mengurangkan gangguan, kehilangan paket, kelewatan dan akhirnya meningkatkan QoS. PRIMICA menghasilkan keputusan yang mengagumkan, dengan penggunaan sumber saluran yang cekap membawa kepada peningkatan 55% dalam pemprosesan dan pengurangan 54% dalam Purata kelewatan hujung ke hujung (EED), terutamanya memberi manfaat kepada trafik yang sensitif pada masa.

Pengurangan kesesakan dan penghalaan yang dioptimumkan dalam WMN MRMC sama pentingnya. Rangkaian ini mesti menguruskan trafik komunikasi yang berfluktuasi, pudar isyarat, dan gangguan. Algoritma Penghalaan Pengurangan Kesesakan (CORRA) menangani cabaran ini dengan menilai kualiti pautan dan gangguan untuk mencari laluan data yang optimum. CORRA meminimumkan kelewatan purata, memaksimumkan pemprosesan rangkaian, dan memastikan QoS walaupun dalam saiz rangkaian yang besar. CORRA

secara konsisten mencapai nisbah penghantaran paket 90%, menunjukkan penjadualan bebas perlanggaran, walaupun dalam rangkaian yang lebih luas.

Keseimbangan beban dan peruntukan sumber yang adil menimbulkan cabaran lebih lanjut dalam WMN MRMC. Mencapai keseimbangan yang betul antara liputan, kapasiti, dan pengurusan gangguan memerlukan algoritma penyeimbangan beban yang boleh diskalakan. Algoritma Peruntukan Sumber Seimbang Beban (LRA) dicadangkan untuk menangani cabaran ini. LRA mengoptimumkan penggunaan sumber, mengedarkan trafik rangkaian secara merata, dan menghalang beban nod atau pautan tertentu, akhirnya meningkatkan QoS dan keadilan. LRA secara konsisten mengurangkan kelewatan dalam rangkaian yang lebih luas, mengoptimumkan penggunaan sumber dan mengekalkan kelewatan yang rendah di pelbagai saiz rangkaian.

Melalui simulasi yang luas, penyelidikan ini mengesahkan keberkesanan algoritma yang dicadangkan berbanding dengan yang sedia ada. Penyelidikan ini menggunakan simulator OmNET++ 4.6, alat sumber terbuka dalam C++, untuk menilai algoritma-algoritma yang dicadangkan dengan berkesan. Ia termasuk struktur rangkaian, Bahasa NED untuk topologi, dan fail konfigurasi untuk eksperimen yang disesuaikan. Simulasi melibatkan topologi grid dan pelbagai keadaan, menggunakan model Rayleigh dua sinar untuk ketepatan. Sepuluh eksperimen meningkatkan ketahanan statistik, dan parameter simulasi tertentu memastikan keadaan eksperimen yang jelas dan boleh diulang.

PRIMICA, CORRA, dan LRA secara kolektif menyumbang untuk meningkatkan dan menyokong WMN MRMC, menangani cabaran teras dalam rangkaian komunikasi tanpa wayar. Penyelidikan ini menonjolkan potensi algoritma ini sebagai alat berharga untuk peningkatan rangkaian dalam WMN MRMC, memastikan penghantaran data yang boleh dipercayai, cekap, dan berprestasi tinggi.

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Date: 14 March 2024

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| | |
|---|---|
| CBR | Constant Bit-Rate |
| CORRA | COngestion Reduction Routing Algorithm |
| EED | End-to-End Delay |
| FI | Fairness Index |
| GB | gigabyte |
| GHz | gigahertz |
| GW | Gateway |
| IEEE | Institute of Electrical and Electronics Engineers |
| MANETs | Mobile Ad-hoc Networks |
| MC-POCA | Min-interference and Connectivity Partially Overlapped Channels Assignment |
| MC | Mesh Clients |
| MG | Mesh Gateways |
| MR | Mesh Routers |
| MRMC | Multi-Radio Multi-Channel |
| NIC | Network Interface Card |
| OC | Orthogonal Channel |
| OmNET | Operation and Maintenance New Equipment Training |
| OSI | Open System Interconnection |
| PDR | Packet Delivery Ratio |
| PLR | Packet Loss Ratio |
| POC | Partially Overlapped Channel |
| PRIMICA | PRIority-based Minimum Interference Channel Assignment |
| QoS | Quality of Services |
| LRA | Resource Allocation of Load-balancing Algorithm |

| | |
|---|---|
| RAM | Random Access Memory |
| SRMC | Single-Radio Multi-Channel |
| SRSC | Single-Radio Single-Channel |
| TACCA | Traffic-demand-Aware Collision-free Channel Assignment |
| VoIP | Voice over Internet Protocol |
| WMN | Wireless Mesh Networks |
| CORRA | COngestion Reduction Routing Algorithm |
| EED | End-to-End Delay |
| FI | Fairness Index |
| GB | gigabyte |

# CHAPTER 1

# INTRODUCTION

Over the past decade, Wireless Mesh Networks (WMNs) have been intensively studied in various areas, including design, deployment, and protocols. Numerous organisations have adopted Multi-Radio Multi-Channel (MRMC), particularly in rural networks, battlefields, and natural disasters that demand rapid communication network implementation. Mesh nodes in WMNs are composed of mesh gateways (MG), mesh routers (MR), and mesh clients (MC). The MG provides wired Internet access to a small number of MR devices. The MR consists of a network of wireless links that serve as an access point and internet gateway for the MC. The MR is responsible for assembling and transmitting the traffic generated by the MC.

Nonetheless, MR has limited movement. MC may be either mobile or stationary. Typically, only one radio is included, and MR transmits traffic to the appropriate location. In WMNs, numerous sorts of approaches and models are accessible. The classic WMNs adhere to the single-radio single-channel (SRSC) and single-radio multiple-channel (SRMC) wireless network paradigm. Each mesh router is equipped with a single radio, and all nodes share a single channel. However, according to several studies, the SRSC has a low throughput and capacity due to traffic collisions (Liu & Bai, 2012). The performance of SRSC degrades dramatically as the network size increases (Si et al., 2010). SRMC overcomes the shortcomings of SRSC by employing multiple channels for channel negotiation before packet transmission (Aryafar et al., 2008). Still, SRMC may not be suitable for meeting network requirements, such as maintaining fault tolerance or synchronising neighbouring nodes that wish to interact (Si et al., 2010).

The WMNs require a specific function to facilitate adaptability and provide users with command over their resources. In addition, algorithms such as channel assignment and routing will raise the complexity of the WMNs algorithm's architecture (Pióro et al., 2014). Hence, SRSC and SRMC improved, commonly known as MRMC. The research revealed the importance of channel resource modification in enhancing network performance. As shown in previous work (Cidon & Sidi, 1989), the fundamental framework of the channel assignment method for MRMC is based on the minor interference between nodes in WMNs and the optimal utilisation of network resources. The primary advantage of MRMC is that nodes can simultaneously broadcast and receive data by utilising the available channel and assigning a distinct frequency channel to each radio. MRMC is, therefore, a simple model and the optimal topology for WMNs.

This chapter briefly overviews the research's context and highlights its issues and motives. Then, this chapter provides the primary research objectives and the research's scope. This chapter finishes with a summary of the organisation of the thesis.

## 1.1 Research Problem

The proliferation of Wireless Mesh Networks (WMNs) has increased users' peak data rates, improved channel efficiency, and expanded coverage. WMNs offer Quality of Service (QoS) support, reduced packet loss ratio, delay, and interference while maximising network throughput. However, catering to QoS in MRMC WMNs presents significant challenges, demanding the development of efficient channel assignment algorithms to ensure network QoS. Despite existing solutions, an optimal approach to minimising interference and optimising network performance remains elusive.

The domain of MRMC is marked by a persistent challenge arising from its inherently complex nature, characterized by the dynamic interaction of multiple radios and channels. Current solutions predominantly address isolated aspects of this complexity, focusing on singular elements like channel allocation or radio usage without embracing a holistic system-wide approach. This segmented strategy often leads to QoS degradation, underscoring the need for a comprehensive, systemic strategy for efficient traffic prioritization and management. The absence of such a strategy result in heightened packet loss and latency, especially under conditions of high network demand where escalating requirements challenge the network's capacity for data transmission. The varying deployment environments of WMNs, each with unique physical layouts, user densities, and traffic patterns, further amplify this complexity. In addressing these challenges, a profound understanding of the network's architecture is crucial, considering diverse signal strengths, the potential for cross-channel interference, and the evolving nature of network demands.

Identifying a methodology that effectively mitigates interference, adapts to changing network conditions, and enhances performance across diverse scenarios is a paramount area of research in MRMC WMNs. This highlights the urgent need to develop innovative algorithms adept at managing the intricate dynamics of channel assignment in MRMC WMNs, aimed at reducing packet loss, minimizing delay, and improving network throughput, thereby preserving or enhancing the overall QoS.

In addition, inadequate management of these factors can exacerbate network congestion, leading to increased packet loss and delay while reducing overall network throughput. These issues are particularly acute in environments with dense user populations or heavy data traffic, where maintaining optimal network performance is essential for satisfactory service levels. These irregular traffic flows primarily induce high congestion within these networks, coupled with the limited bandwidth for data transmission. Additionally, factors like the overlapping of frequency channels and the simultaneous operation of multiple radios nearby exacerbate this congestion, leading to significant challenges in traffic management.

Fading transmission signals, a common issue in wireless communication, further impede data transmission. This fading is often a consequence of physical obstructions, varying environmental conditions, and the inherent limitations of wireless signal propagation over distances. Interference between wireless links, another critical factor, can be attributed to co-channel and adjacent-channel interference, particularly pronounced in densely populated network environments. Such interference not only disrupts signal clarity but also reduces data transmission efficiency. Moreover, the increasing adoption of on-demand services, which require substantial bandwidth and low latency, amplifies the complexity of ensuring QoS. These services add to the network load, demanding more robust and efficient management of network resources.

Although efforts like multipath routing algorithms and congestion-aware routing protocols have been proposed, the optimal solution to alleviate congestion and guarantee QoS remains elusive. These existing solutions, while beneficial, often do not fully address the multifaceted nature of the problems at hand. The challenge lies in developing a comprehensive strategy that can dynamically adapt to the varying conditions of network traffic, signal quality, and user demand, thus ensuring minimal interference and reliable QoS in MRMC WMNs.

Also, achieving efficient load-balancing while ensuring fairness and optimal resource allocation poses a considerable challenge in MRMC WMNs. Various strategies have been explored, such as considering channel diversity and separating load levels. However, the challenge in implementing these strategies often lies in the inherent disparities in network resource distribution and usage patterns. Certain nodes or channels in the network are often burdened with a disproportionately high traffic volume, while others remain underutilized. This imbalance can arise from various factors, including but not limited to the geographical distribution of nodes, the varying capacities of different channels, and the uneven distribution of users and devices across the network.

There is unfairness in load-balancing primarily from these skewed resource allocation policies, where certain nodes or channels are consistently overburdened, leading to network bottlenecks and reduced service quality for certain users or areas. This situation is further exacerbated by static load-balancing approaches that fail to adapt to the dynamic changes in network traffic and user demands, thereby failing to redistribute loads effectively as the network conditions evolve.

A comprehensive approach that simultaneously addresses load-balancing, fairness, and network throughput is lacking. Such an approach would require a deep understanding of the network's topology and traffic patterns and the incorporation of adaptive algorithms capable of continuously monitoring and responding to changes in network usage. This would ensure a more equitable distribution of network resources, thereby alleviating bottlenecks, enhancing overall network performance, and achieving the dual goals of efficient load-balancing and fairness. The development of a holistic load-balancing algorithm, which evenly distributes network resources while maintaining high throughput, is therefore paramount.

Overall, this research addresses the challenges of MRMC WMNs. The primary focus areas are effective channel assignment, congestion reduction through routing optimization, and load-balancing for fair resource allocation. This thesis aims to solve these enduring challenges in MRMC WMNs, enhancing these networks' overall efficiency and reliability.

## 1.2 Research Objectives

The primary aim of this study is to develop multi-radio multi-channel (MRMC) algorithms specifically for wireless mesh networks (WMNs). These algorithms are intended to minimize interference, reduce network congestion, and optimize network capacity utilization. The research is structured around three key objectives to realise this goal, each addressing a specific aspect of the network's performance challenges.

The first objective focuses on the development of a Priority-based Minimum Interference Channel Assignment algorithm for MRMC WMNs by allocating each radio at a node on a different channel based on channel status to minimise delay and packet loss without sacrificing network throughput.

The second objective involves proposing a Congestion Reduction Routing Algorithm for MRMC WMNs to reduce congestion by effectively finding the optimal path by evaluating link quality as well as minimising interference for packet transmission to maximise network throughput.

Lastly, the third objective is to introduce a Load-balanced Resource Allocation algorithm for MRMC WMNs to provide the available radios and channels without wasting network resources by allocating resources optimally and minimising packet loss.

In summary, this research is committed to addressing the challenges of MRMC WMNs through innovative algorithmic solutions. Each proposed algorithm is designed to enhance a particular aspect of the network's performance, be it minimising interference, reducing congestion, or achieving balanced resource allocation. The successful implementation of these algorithms is expected to improve the functionality and reliability of MRMC WMNs significantly.

## 1.3 Research Questions

The WMNs have become a rapidly expanding new technology that provides various services to the telecommunications industry. Traffic and applications like video streaming and VoIP may overwhelm the WMN environment.

Generally, this research aims to design algorithms that can optimise network performance for WMNs. This research is significant in determining the following aspects:

1. How can network capacity be appropriately allocated among routes in MRMC through channel assignment?

2. How can the congestion for packet transmission in MRMC be reduced to maximise the network's performance?

3. How do we accommodate the available resources among nodes in MRMC WMNs?

## 1.4 Research Scope

As depicted in Figure 1.1, the proposed algorithms in this thesis concentrate on the MRMC to optimise network performance for MRMC WMNs. The process of assigning a channel to minimise interference among resources. Then, a routing algorithm is used to manage congestion and load-balancing to accommodate the resources among users.

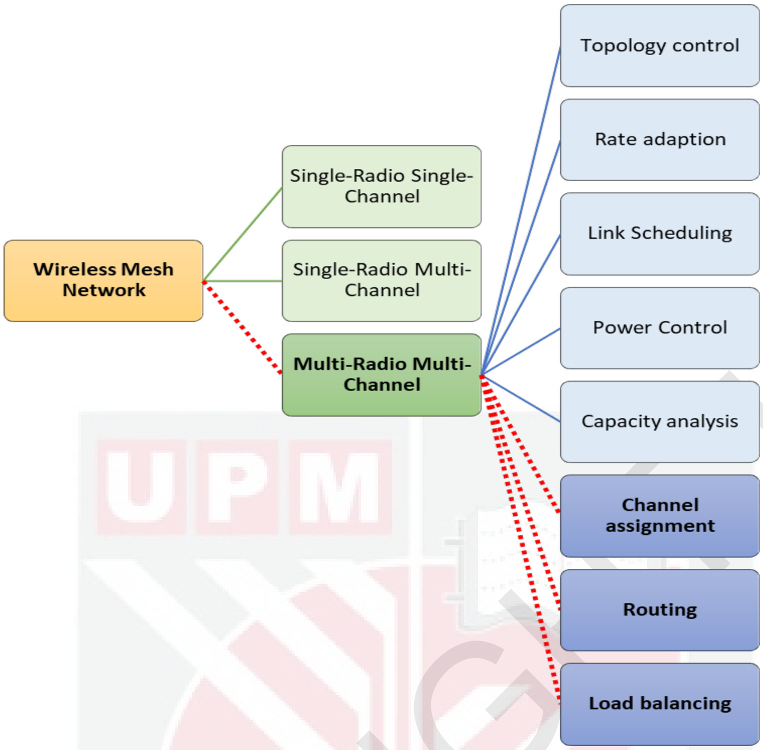


**Figure 1.1 : Research Scope**

## 1.5 Thesis Organisation

This research study presents novel algorithms for MRMC in WMNs. The thesis is structured as follows: Chapter 2 overviews MRMC WMNs, channel assignment, routing algorithm, and load-balancing. It also shows related works that address channel assignment, routing algorithm, and load balancing. The research framework of this thesis and its details—problem formulation, previous and proposed works, simulation environment, measurement metrics, and their simulation validation—are presented in Chapter 3. Chapter 4 presents the design and evaluation of the proposed PRIMICA algorithm for MRMC WMNs. The chapter ended with a performance evaluation of the algorithm compared with the MC-POCA algorithm according to valuable metrics, including network throughput, average end-to-end delay (EED), and packet loss ratio (PLR). Exploring the design and evaluation of CORRA for the MRMC WMNs scheme is presented in Chapter 5. It also presents the performance evaluation of the proposed algorithm. It compares with the TACCA algorithm in terms of QoS performance. Additionally, the simulation results and numerical results have been compared. Chapter 6 covers a proposed LRA that fully utilises the resources. This thesis concludes with Chapter 7, where the conclusion and some promising directions for future research are presented. The structure of the thesis is depicted in Figure 1.2.

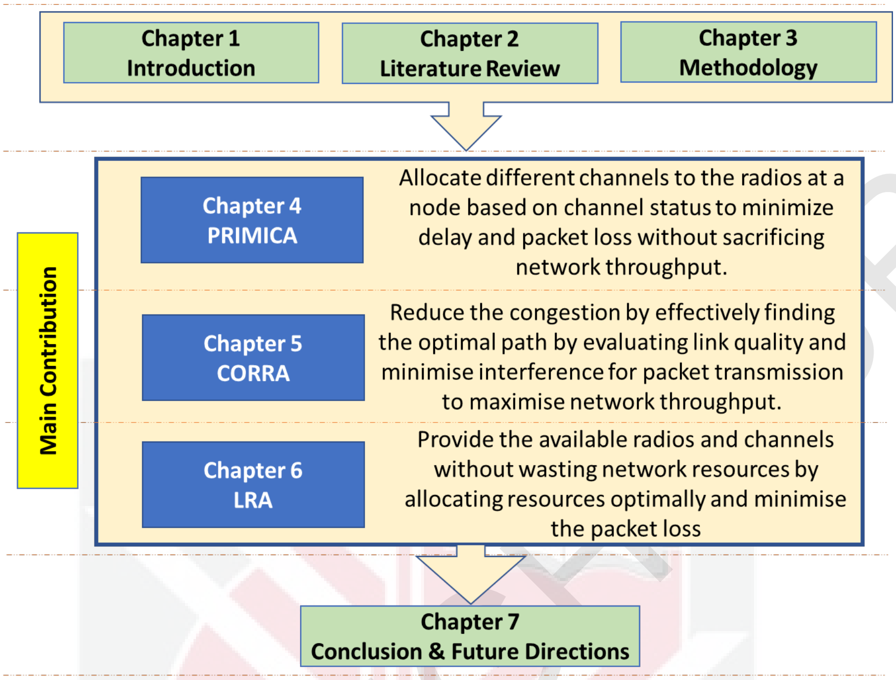


**Figure 1.2 : The Structure of The Thesis**

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