Effective Provisioning in Multi-Interface Multi-Channel Wireless Mesh Networks

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Abstract

Effective Provisioning in Multi-Interface Multi-Channel
Wireless Mesh Networks

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Wireless Mesh Network (WMN) is a network communication technology that can provide high coverage and consistency using multihop communication features. Operating various applications in parallel on WMNs implies the need for improvement in the network's performance, where capacity is one of the most significant factors. Multi-Interface Multi-Channel (MIMC) networks, a type of WMN, can increase overall network capacity by using several interfaces and channels simultaneously. However, employing many channels at once poses the problem of selecting suitable channels and interfaces for links while avoiding interference and efficiently utilizing the resources. The majority of MIMC WMN used the same type of wireless technology as their interfaces and a limited number of non-overlapping channels to reduce the likelihood of network interference. This thesis investigates the MIMC WMN provisioning problem by using three widely used wireless technologies: WiFi, Bluetooth, and Zigbee, with all their channels in the 2.4 GHz spectrum. To assess interference among links, we use a conflict graph for all channels of the three technologies. Furthermore, we formulate a joint interference-aware routing, Interface Assignment (IA), and Channel Assignment (CA) scheme using Integer Linear Programming (ILP) for both static and dynamic traffic, aiming to maximize the overall throughput considering bandwidth and latency requirements of requests. We use the Gurobi solver to implement the models and conduct a series of experiments in both cases. The numerical studies demonstrate that using various wireless technologies and properly managing channels leads to improved performance in terms of throughput while preventing interference and transmitting heavy real-time data.

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Contents

Acronyms

AI Artificial Intelligence. 5, 55

AP Access Point. 1, 2, 9, 11

BFS Breadth First Search. 16

CA Channel Assignment. iii, 2–9, 12, 15–18, 42, 53, 54

CLICA Connected Low Interference Channel Assignment. 16

CSMA Carrier Sense Multiple Access. 5

DOCCA Distributed Optimum Congestion control and Channel assignment Algorithm. 17

FBMIS Fuzzy-Based Multi-Interface System. 17

GTS Genetic Tabu Search. 16

HPMI High-Priority Minimum Interference. 16

IA Interface Assignment. iii, 3, 5, 7, 9, 54

ILP Integer Linear Programming. iii, 5, 7, 14, 16, 23, 32, 54

MANET Mobile Ad-hoc Network. 18

MILP Mixed Integer Linear Programming. 5, 16

MIMC Multi-Interface Multi-Channel. iii, 2–12, 14–20, 32, 37, 38, 42, 53–55

MIMO Multiple-Input Multiple-Output. 11

POCs Partially Overlapped Channels. 17

QoS Quality of Service. 2, 17

RF Radio Frequency. 11–13

SISC Single-Interface Single-Channel. 2, 10, 11

SVM Support Vector Machine. 17

TACCA Traffic-demand-Aware Collision-free Channel Assignment. 16

WMN Wireless Mesh Network. iii, 2–12, 15–19, 38, 42, 53, 54

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Chapter 1

Introduction

In this chapter, we provide a short outline of wireless mesh networks, discuss existing potential challenges in such networks, and state our contributions. Section 1.1 presents a general overview of wireless mesh networks, followed by our research project challenge in Section 1.2. Section 1.3 gives a brief description of two relevant primary sources for this work, and finally, our contributions are provided in Section 1.4.

1.1 General Background: MIMC WMN

The increasing usage of mobile devices, social media, and many other technologies produces an astounding amount of data every single day. To manage the transmission of this volume of data from one place to another at any time or location, companies in every industry require a more reliable, stable, cost-effective, and high-speed data transmission infrastructure more than ever. The needs may be met by a network connecting several devices, which also must be prepared to handle the increased traffic.

Wireless networks were developed a long time ago as a low-cost network infrastructure for use within a building or in a limited outdoor space. It enables end users to transport and access real-time information with convenience and mobility by deploying wireless Access

Points (APs) everywhere [3]. However, obtaining consistent coverage might be challenging in some places.

Wireless Mesh Network (WMN), a next-generation wireless network, has grown in popularity over the years because of its advantages over other wireless networks, such as its long-distance coverage capability. Nodes in WMN are typically stationary, and each one contributes to the data distribution, resulting in a multi-hop network [12]. Due to the inter-communication between nodes, even if one of the nodes malfunctions, the other nodes can still connect with one another directly or through a number of intermediary nodes to forward data from the source to the destination [1, 3]. Consequently, it ensures a stable connection over the network. Moreover, WMN can provide professional high-speed, last-mile internet connectivity and the delivery of heterogeneous traffic in a scalable and Quality of Service (QoS)-aware manner [1]. Nevertheless, there are some performance concerns with low throughput and/or high latency, notably in classic WMNs that use Single-Interface Single-Channel (SISC) design [7].

The limited number of wireless channels in SISC WMN is mostly responsible for performance degradation, which results in wireless interference, congestion, and low capacity in the network [12]. To resolve these difficulties, it is possible to equip each node in the network with multiple wireless interface technologies capable of functioning on various frequency channels, referred to as Multi-Interface Multi-Channel (MIMC) wireless mesh network [7]. Therefore, MIMC WMN can handle heavy data flows, minimize congestion, maximize throughput, and boost packet receive ratio by effectively using multiple channels and interfaces in parallel [12, 18]. However, there are a few things to take into account before using a MIMC architecture. The two most significant ones are how to assign channels to interfaces (Channel Assignment-CA) to prevent interference and from which logical link in the network the data packets should be sent (routing) [31].

As a result, a proper CA technique to accomplish optimum channel usage without interference as well as an efficient routing protocol to handle multiple data flows with the best performance are required [12].

1.2 Our Research Project: Provisioning in MIMC WMN

In this thesis, we investigate the provisioning in MIMC WMN along with building a combined interference-aware routing, interface assignment (IA), and channel assignment (CA) algorithm that operates in both static and dynamic modes. This subsection gives a straightforward illustration of the problem.

Input

The physical MIMC WMN is made up of nodes that are located across various geographic regions in a way that preserves network connectivity. Each node contains at most three interfaces supporting three common wireless technologies: Bluetooth, WiFi, and Zigbee. Nodes are classified according to the wireless interface technologies they support. They can communicate with each other over any common wireless interface, based on their physical distance. Each interface has distinctive characteristics, including communication range, data rate, transmission latency, and a distinct set of frequency channels within the 2.4 GHz common spectrum.

The input of the system in terms of traffic instances is slightly different between the static and dynamic scenarios. In the static case, the network receives several requests at once and provisions them in a single time slot. Each request is defined by its attributes, including its source and destination nodes, bandwidth and latency requirements. Whereas, in the dynamic scenario, a large number of new requests continually enter the network, and the model provisions them in various time slots. Each request includes the same characteristics as in the static case, together with its start and end time slots.

Output

Based on the inputs described above, our goal is to build a model to allocate an appropriate channel and interface to links and select the optimal path in order to satisfy requests' needs, with the following objective in each scenario:

- Static scenario: Maximizing the overall network throughput in the system,
- Dynamic scenario: Maximizing overall throughput by giving a higher priority to current ongoing requests over incoming ones,

subject to the following constraints:

- Bandwidth: The bandwidth utilization of a link should be less than its capacity,
- Delay: Requests should be provisioned within the delay range,
- Interference: Channel assignment should be done such that interference is prevented.

1.3 Key Resources

The major focus of our review of the existing literature is on how to assign channels to links and the routing protocols via an optimization-based approach in a MIMC WMN in order to increase overall throughput and minimize interference.

Channel Assignment in MIMC WMN

Exploring the MIMC WMN's advantages leads to a significant increase in network performance. The expectation is mostly based on a careful assignment of channels and interfaces to links. Therefore, channel assignment (CA) is gaining popularity in this area. A variety of strategies have been developed to address the problem based on their underlying methods, as listed out in [2], which are classified into five main groups: graph-based, mathematical formulation or optimization-based, Artificial Intelligence (AI)-based, peer-oriented, and greedy techniques, with a focus on different metrics, i.e., interference (i.e. [16, 24, 23]), capacity or data rate (i.e. [9]), throughput (i.e. [31, 18, 30]), latency (i.e. [17]), and channel diversity, in order to optimize the network's performance.

Since the CA issue is NP-hard, as further confirmed in [25] and [8], few studies have attempted to solve it using mathematical formulation-based techniques. For example, [20] used an ILP approach, where the authors formulated a static joint routing, CA, and IA problem with the aim of reducing network congestion by considering a variety of constraints, i.e., link effective capacity, interference, using only one link per node pair, and number of hops for routing. This motivates us to apply some of these constraints to our static and dynamic problems, with some modifications based on our assumptions. The model also defined a set of possible interfere links based on the communication range and interference range of two links in order to prevent interference. This method, however, was evaluated with a small number of the same technologies (WiFi IEEE 802.11a) as available interfaces and only orthogonal channels, which is more restricted than our work.

To the best of our knowledge, the closest effort to solving our problem in terms of channel diversity is [26]. This work can be considered as the most recent one, where the authors proposed a joint routing and CA scheme as a Mixed Integer Linear Programming (MILP) to achieve collision-free channel assignment using partially overlapped channels in MIMC WMN. To determine the optimal solution, this work considered some constraints like link usage, path length, and traffic flow conservation. They designed a Carrier Sense Multiple Access (CSMA)-aware interference model to avert potential collisions by listening to the broadcasting nodes and then informing devices to transmit data when the channel is free. Therefore, they assumed that links interfere if they are only located in the hidden-terminal position, meaning if they are located within the channel sensing range from a receiver but out of the channel sensing range from the transmitter. Nodes in this architecture are only outfitted with two WiFi IEEE 802.11g interfaces, and an equal amount of traffic enters the network statically. The model can systematically use all channels on the spectrum, resulting in more parallel transmissions and a higher peak throughput compared to using only orthogonal channels, which also inspires us to apply overlapping channels to our CA problem. However, for heavy, concurrent heterogeneous data in static and dynamic scenarios, this might not be applicable.

Routing in MIMC WMN

Developing efficient routing strategies in MIMC wireless mesh networks brings some complexities due to the option of multi-hopping, channel diversity, and the usage of numerous interfaces on each node. As described in [3] and [11], the routing techniques are traditionally grouped into a variety of categories based on their common features, including geographical, geo-casting, hierarchical, multi-path, power-aware, and hybrid routing algorithms.

Taking interface and channel switching cost into account in the route selection, some studies proposed an independent routing protocol, i.e., [32], [19], and [14], taking link interference into account as a leader factor for finding a path. However, in light of the fact that MIMC WMN's CA presents a significant difficulty, in some cases, according to [4], route selection and CA can be formulated as mutually dependent. This concept motivates us to deploy the joint technique in order to find the optimal path and channel assignment in only one step. Therefore, researchers have recently developed integrated routing and channel assignment systems that optimize the route by choosing the interfaces and channels along the path, avoiding congestion, and minimizing interference in the network, for example [26], [25].

1.4 Our Contributions

Following is a list of our key contributions:

1. We design a novel MIMC WMN that accounts for multiple interfaces from three technologies (WiFi, Zigbee, and Bluetooth) and all of their given frequency channels in the same 2.4 GHz spectrum. Employing various technologies provides the chance that if one of the technologies used by nodes (devices) became unavailable, the other technologies could still be used to continue data transmission. To the best of our knowledge, all prior research on the MIMC WMN concentrated on multiple interfaces of the same type of wireless technology with a limited number of channel options.

2. We propose a joint interference-aware routing, interface assignment (IA), and channel assignment (CA) model for provisioning requests, considering their bandwidth and latency requirements.

3. We introduce a conflict graph approach to measure channel interference during routing by integrating channels of three different technologies in the common 2.4 GHz frequency spectrum.

4. We propose two ILP formulations of our problem to solve two use cases: static and dynamic.

5. We conduct a series of experiments in both static and dynamic scenarios and evaluate the performance of our suggested models, which demonstrate that they can achieve great performance in terms of throughput, latency, and interference.

1.5 Organization of Thesis

The thesis is organized as follows: Chapter 1 covers the general background, including MIMC WMN, CA techniques, routing protocols, and a high-level description of the research project on MIMC WMN provisioning. Chapter 2 thoroughly discusses the research problem, presents the proposed static and dynamic formulations of our MIMC WMN architecture, and discusses the obtained results. Chapter 3 concludes the research and presents possible future work.

Chapter 2

Effective Provisioning in Multi-Channel Multi-Interface Wireless Mesh Networks

The chapter will be submitted shortly to an international peer-reviewed journal, titled "Effective Provisioning in Multi-Channel Multi-Interface Wireless Mesh Networks".

2.1 Abstract

Multi-Interface Multi-Channel (MIMC) has increasingly been deployed in Wireless Mesh Networks (WMNs) to improve radio performance in dense environments, such as healthcare centers, auditoriums, or hotel meeting rooms. MIMC allows wireless nodes to select simultaneously available orthogonal channels of multiple radio interfaces, thus increasing throughput and reducing interference. However, assigning appropriate channels to communication links is a challenging problem with respect to available capacity and the wireless coverage range of different technologies. In this study, we design a MIMC WMN in which each access point (AP) can be equipped with three types of technologies, namely WiFi, Zigbee, and Bluetooth. Then, we mathematically formulate a joint routing, interface assignment (IA), and channel assignment (CA) problem in both static and dynamic manners

aimed at maximizing the overall throughput. Our proposed models find a route for each request and, for each link along that route, allocate an appropriate non-conflict channel of one available interface, considering the bandwidth and delay requirements of requests. We use the Gurobi optimization solver to solve the problem. Our extensive experiments demonstrate that both models achieve high overall throughput by providing the option of using all channels in the spectrum while considering interference prevention, which means the proposed models are practical solutions to design and manage MIMC WMNs.

2.2 Introduction

Today's digital world produces a large volume of data. This amount of data is generated each day by media platforms, financial institutions, healthcare centers, e-commerce sites, and many other online communications and activities and must be transferred at high speed in real-time. Different communication technologies can be used to transfer data, i.e., wireless networks or wired networks, which increase the network's efficiency, making them suitable infrastructure to handle large-scale data transmission.

Over the last decade, Wireless Mesh Networks (WMNs) have emerged as an efficient deployment model for wireless networks that complements or substitutes the public wireless network in dense areas. WMNs can serve as omnipresent communication and allow devices to communicate at high speeds across long distances. The wireless backbone of the WMNs is made up of a number of stationary wireless mesh routers (nodes). These routers can route data packets from/to the other routers, defined as multi-hop transmissions, while maintaining a steady connection over the network [3, 1].

In a classic multi-hop wireless mesh network called Single-Interface Single-Channel (SISC), most wireless mesh nodes are provided with a single interface (radio) that communicates across a common channel. In this infrastructure, end-to-end data flow is substantially impacted by both nearby simultaneous flows and nearby hops of the same flow.

According to [7] and [12], the SISC WMNs can also suffer from capacity degradation, high latency, multi-path interference, and congestion due to their design, which reduces the network's performance.

Several researchers have contributed to increasing the performance of WMNs, depending on what and how they want to enhance it. For example, they have focused on building optimal routes, reducing end-to-end delay, maximizing data flow, using channel assignment techniques, preventing interference and congestion, and so on. They used different methods, such as relocating stations, making use of intelligent antennas, Multiple-Input Multiple-Output (MIMO) technology, Multi-Interface Multi-Channel (MIMC) structure, multiplexing, efficient routing, control of traffic, delay management, energy efficiency, and some other techniques to boost network performance [7, 14, 11]. Among these methods, as described in [11], MIMC structure has the highest production level in terms of performance (almost 2-3 times).

A well-optimized wireless mesh network is known as MIMC WMN, in which nodes may be equipped with multiple wireless interfaces as a result of the ongoing trend of lower hardware costs. Employing one or many interfaces across non-overlapping Radio Frequency (RF) channels allows several devices to communicate at the same time [31], which increases the network's performance and therefore alleviates the issues associated with SISC WMNs. In some previous works, different fixed, non-overlapping channels were assigned to adjacent access points (APs), thereby minimizing interference between them, while other APs located far enough away could swap between the remaining channels.

Although a lot of attention has been paid to the MIMC technique recently, challenges still remain. For instance, certain modern wireless interfaces may switch from one channel to another; however, the switching latency may rise and lead to a larger end-to-end delay [7, 14, 31]. Likewise, coexisting multiple wireless technologies on a device requires additional management efforts in terms of resource sharing, spectrum efficiency, concurrent data transfer, and so on, according to [11]. Furthermore, because mesh routers have a limited number of interfaces and accessible orthogonal channels, several connections in the network are forced to operate on the same channel, resulting in substantial transmission interference. Consequently, for the purpose of boosting network performance, multiple aspects such as interface and channel availability, interference prevention, traffic demands, latency, link capacity, data size, data order, and data priority [31] should be considered at the same time in the network.

Therefore, an efficient channel assignment (CA) strategy that assigns a free, non-overlapping channel to each technology on a node is required in order to minimize interference in the network. To this end, we first need to understand how the current applied wireless technologies on routers are structured. The three most commonly used technologies in the MIMC WMNs are Bluetooth (IEEE 802.15.1), WiFi (IEEE 802.11), and Zigbee (IEEE 802.15.4). The key distinctions between these technologies are shown in Figure 1 in terms of standards, speed, network topology, frequency spectrum, and communication range.

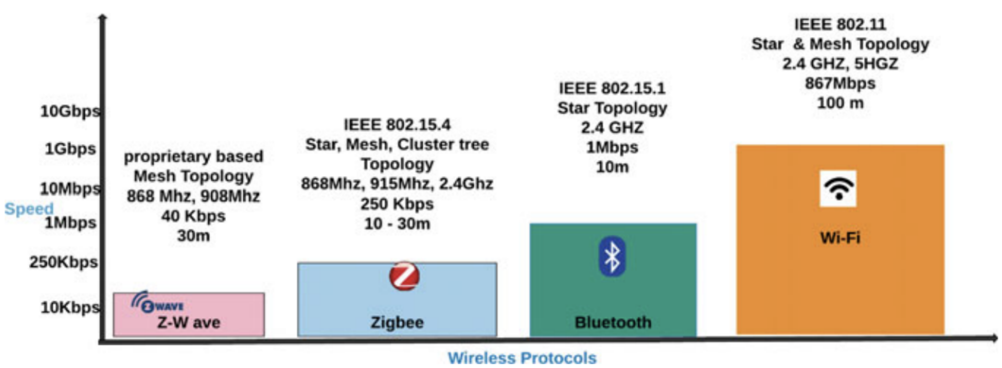


Figure 1: Comparison of wireless technologies [21]

The majority of wireless technologies often share the same RF band. In particular, the ubiquitous 802.11 WiFi standard, Bluetooth, and Zigbee all share the same chunk of 2.4 GHz radio spectrum. Because they share a common spectrum, intra-/inter-interference can occur, causing competition among technologies to access frequency channels simultaneously. Each of the three aforementioned technologies provides a set of RF channels at 2.4 GHz that are different in terms of numbers and channel bandwidth [15]:

- Bluetooth uses 79 RF channels with 1 MHz bandwidth,
  $C^B = \{1, ..., 79\}$.
- Zigbee uses 16 RF channels with 2 MHz bandwidth,
  $C^Z = \{1, ..., 16\}$.
- WiFi uses 14 RF channels with 22 MHz bandwidth,
  $C^W = \{1, ..., 14\}$.

As seen in Figure 2, Bluetooth employs the narrowest band, whereas WiFi uses the broadest band. The result is that each WiFi channel has intra-overlap with four consecutive WiFi channels, but Zigbee and Bluetooth have no intra-overlap among their channels. Likewise, each WiFi channel has an inter-overlap with four consecutive Zigbee channels as well as twenty-two Bluetooth channels, causing an interference problem between these two technologies. Subsequently, each Zigbee channel has a conflict with only two Bluetooth channels in the shared spectrum. Using conflicting channels at the same time over adjacent links in the network will generate interference.

A conflict graph is a mechanism for assigning channels to decrease interference. The conflict graph in [23], [19], [16], [18], [30], [24] is an undirected graph that depicts the possibility of mesh routers' interference. Each vertex in the conflict graph is mapped to an edge in their connectivity graph. If and only if two vertices are in the interference range of one another, there is an edge connecting them in their conflict graph. Using such a graph, suitable channels are assigned to each interface, causing interference prevention in the network and finally increasing the performance.

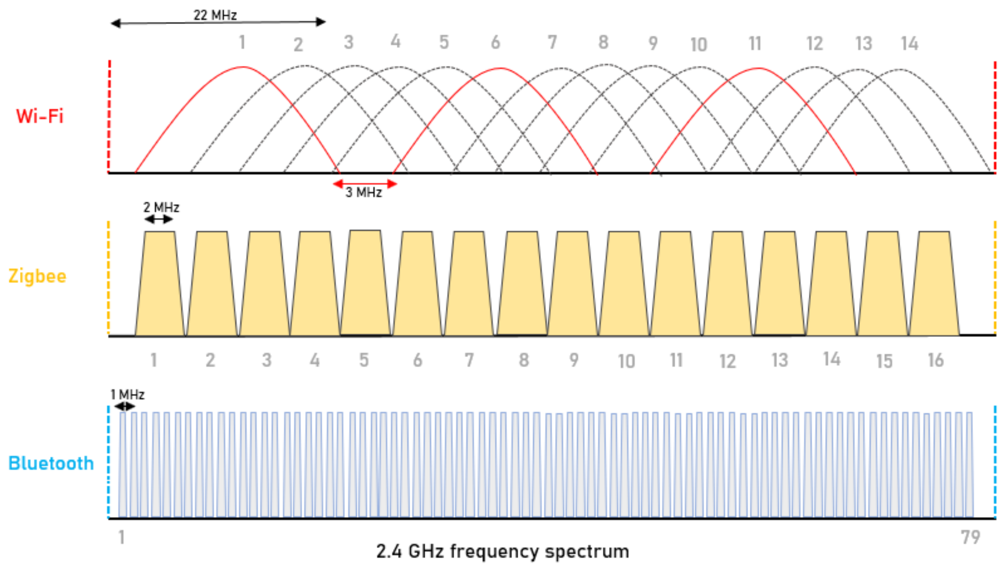


Figure 2: Frequency channels of WiFi, Bluetooth, and Zigbee on shared 2.4 GHz band

The contributions of our paper are described as follows: First, we propose a new model that takes into account multi-radio of three technologies (WiFi, Zigbee, and Bluetooth) and all their provided channels in the same 2.4 GHz spectrum for the MIMC wireless mesh network, unlike previous works that consider only multi-radio of the same technology with a small number of channels. Second, we propose a joint interference-aware routing, interface assignment, and channel assignment model for provisioning requests while satisfying the bandwidth and delay requirements. Third, to prevent interference, we generalize the definition of the conflict graph in order to integrate the channels of three different technologies, i.e., if two channels intersect in the 2.4 GHz frequency spectrum, a connection exists between their corresponding nodes in the conflict graph. Finally, we mathematically formulate the problem and propose both static and dynamic Integer Linear Programming (ILP) models to address it subject to constraints on link capacity, link delay, and interference, etc.

The rest of this paper is structured as follows: We discuss the related work in Section 2.3 and introduce a formal problem statement for the provisioning in multi-interface, multi-channel wireless mesh networks in Section 2.4. Then, the static and dynamic ILP models are formulated in Section 2.5 and Section 2.6, respectively. This is followed by numerical experiments and results for both models in Section 2.7. Finally, conclusions and future works are drawn in Section 2.8.

2.3 Literature Review

With the advent of MIMC WMNs, an extensive improvement has been accomplished in network execution through simultaneous transmissions over various channels utilizing multiple interfaces. Several research projects have been undertaken on different aspects of MIMC WMNs, such as routing algorithms, interference minimization, network capacity utilization, low-latency models, congestion investigation, and especially interface and channel assignment strategies. [2] and [4] performed a comprehensive analysis of MIMC WMNs in terms of designing issues, different objectives, and existing CA schemes, categorising them and discussing the benefits and drawbacks of each CA strategy.

Technically, channel assignment and interface switching can be classified into three categories [4]: static, dynamic, and hybrid. In a static strategy [29], a fixed channel is assigned to each interface for a long interval, but in a dynamic approach [20], the interfaces can swap from one channel to another at any time. The static and dynamic models can be combined in the hybrid method, e.g., in [14], [19], and [27], such that a common channel is assigned to each node's fixed interface for use as a receiving interface in communication with other nodes, while other interfaces are swapped among the remaining channels based on traffic demands.

On the other hand, the number of accessible interfaces on routers can decide the number of available channels in the network, which results in network density, topology, and the price of network design. All prior attempts have employed multiple interfaces using IEEE 802.11-based MAC protocols to increase channel usage. Additionally, the number of interfaces available in routers is often smaller than the total number of available channels, as seen in the works of [14, 24, 29, 32]. Therefore, the number of channels assigned to links starting from a node is limited to the number of interfaces on that node. Although the throughput increases along with the number of interfaces, increasing the number of interfaces further is not desirable since channel contention will be a performance barrier.

To the best of our knowledge, various studies on channel assignment techniques have concentrated on a particular approach. For instance, Zhanmao et al. [31], Marina et al. [18], and Zahng et al. [30], investigated CA strategy in the contexts of maximizing concurrent data flow via a heuristic greedy strategy, traffic independent framework via greedy polynominal-time heuristic channel assignment called Connected Low Interference Channel Assignment (CLICA), and effectively using available channels through the Genetic Tabu Search (GTS) algorithm, respectively.

Several other studies focused on interference minimization in MIMC WMNs along with CA, such as [23], [19], [16], [24], [32], [8], [25], and [26]. They used different mechanisms for determining channels used for communication. For instance, a multi-radio conflict graph is employed to model interference between nodes, and Breadth First Search (BFS) is used to intelligently distribute channels, according to [23]. Mirzaie and Sedaghat [19] developed a centralized controller to designate an appropriate static channel for an interface and to route traffic based on the remaining non-interfered channels between links. Le et al. [16] established a High-Priority Minimum Interference (HPMI) system to assign channels to links based on their priority, and to create links if nodes were within communication range. Some other interference-aware CA techniques, according to [32], [8], and [24] are respectively: a Viterbi algorithm to allocate interfaces on a node along the shortest path; a distributed heuristic CA with an ILP; and a centralized tabu-based approach with a distributed greedy CA algorithm. Tian and Yoshihiro [25] created a Traffic-demand-Aware Collision-free Channel Assignment (TACCA) algorithm using Mixed Integer Linear Programming (MILP) to improve network utility. Additionally, they introduced an interference model with Partially Overlapped Channels (POCs) to increase parallel transmissions in the network [26]. Their results show that POCs can efficiently improve spatial reuse in WMNs. They achieved a higher number of simultaneous transmissions than when using only three orthogonal channels, by systematically using all channels to avoid interference.

Some studies in MIMC WMN compared one standard technology to another with the intention of determining whether interference exists. For example, authors in [28] analyzed the impact of IEEE 802.15.4 and IEEE 802.11b on each other in the 2.4 GHz band and proposed a detailed analytical model to improve the coexistence channel problem. Similarly, [6] examined the impact of various standards (Bluetooth, Zigbee, and WiFi) on one another in small environments and proposed a heuristic paradigm to address multi-radio interference issues.

In the context of congestion management in the network, Mohsenian-Rad and Wong [20] proposed a joint linear optimization model for CA to minimize congestion. Their model assigned available channels to links among routes by considering the capacity of each link to prevent bottlenecks. Similarly, David et al. [9] studied a Distributed Optimum Congestion control and Channel assignment Algorithm (DOCCA) strategy that passed on information to the previous node if congestion was observed. The node then adapts to the level of congestion to reduce traffic in the network.

Other challenges with MIMC WMNs are end-to-end latency and service quality. To reduce end-to-end latency in multi-hop WMNs, Lim and Ko [17] presented a priority-based data transmission technique for multi-interface devices. Their strategy gives urgent data packets top priority. They employed Support Vector Machine (SVM) supervised learning approach to forecast the delivery time for each new packet. As a result, the technique prevents the delay of crucial communications. In [13], authors presented a Fuzzy-Based Multi-Interface System (FBMIS) to enhance the Quality of Service (QoS) in wireless cellular networks while using fewer network resources. Their model uses two interfaces on each node: Mobile Ad-hoc Network (MANET), and cellular. Its inputs included network reliability, angle, and distance, which were fuzzyfied by a fuzzy logic controller. The output decision value is then utilized to choose the interface.

In this paper, we propose a model that takes into account many factors that have a direct impact on network performance, i.e., routing, channel assignment, interface assignment, and interference prevention. Unlike prior work, we outfitted the network's routers with various types of technologies in order to broaden our model. To this end, we propose both static and dynamic joint routing, interface allocation, and channel allocation models for a MIMC wireless mesh network that take the demanded delay and bandwidth into account for each request. Our goal is to maximize the overall network throughput and, at the same time, avoid interference while assigning channels to routes, provide precedence to previously approved requests to fulfil delayed demand, and prevent network congestion by considering link capacity.

2.4 Problem Statement

MIMC WMNs are gaining popularity as a way to boost network throughput by combining several interfaces. In this field, there are still some intriguing research challenges to tackle. The paucity of non-overlapping channels and the limited number of interfaces per node in MIMC WMNs may cause interference, which in turn affects the network's capacity, delay, and potential throughput. A proper CA scheme is required since interference is influenced by how channels are tied to interfaces. To increase network performance, we propose novel static and dynamic joint interference-aware routing, interface assignment, and CA models for MIMC WMN provisioning with three wireless technologies.

Static

Our static solution addresses the problem of multiple requests in a single time slot. Each request has four components: the source and destination nodes, bandwidth and latency requirements. The model determines the optimal route for each request based on the specifications provided, assigns a non-overlapping channel and an accessible interface to the edges of the path, and transmits all data from a certain source to a specific destination.

Dynamic

Our dynamic model is time-slotted, in which each request can span multiple consecutive slots. The network constantly receives a bunch of new incoming requests. Each request includes starting and ending time slots in addition to the four elements in the static model (source node, destination node, demanded bandwidth, demanded delay). Requests may have a varied life span, meaning different start and end times. Similar to the static model, the dynamic model chooses a single optimal route and assigns free-interference channels and interfaces to edges. However, it transmits the most partial data of each request at each time and attempts to complete it before its end time by giving all currently active requests a higher priority than any new incoming ones.

In the rest of this section, we comprehensively outline certain key prerequisites of our proposed MIMC WMN topology, network graph modeling, network traffic description, and concept of a conflict graph before describing in detail our static and dynamic models.

2.4.1 MIMC WMN

We propose a MIMC WMN comprised of stationary network nodes (fixed in their positions) of the same kind (all routers). The nodes are classified based on the technologies they support. In practice, there is more Bluetooth technology available than WiFi, as well as more WiFi technology used on nodes than Zigbee. In our topology, the first group contains all three technologies (Bluetooth, WiFi, and Zigbee); the second one has the two cheapest technologies (Bluetooth and WiFi); and the last group is equipped with only Bluetooth cards. Each type of supported technology on the node has a single interface card and unique properties such as maximum communication range, maximum capacity, and a distinct set of frequency channels in the 2.4 GHz spectrum; see Table 1.

Table 1: Comparison of three technologies: Bluetooth, WiFi, Zigbee in 2.4 GHz spectrum [15, Tab. 1]

Standard	**Bluetooth**	**WiFi**	**Zigbee**
IEEE Specification	802.15.1	802.11 a/b/g	802.15.4
Max. data rate	1 Mb/s	54 Mb/s	250 Kb/s
Max. communication coverage	10 m	100 m	100 m
Number of RF channels	79	14	16
Channel bandwidth	1 MHz	22 MHz	2 MHz

2.4.2 Network Graph

We design a MIMC wireless mesh network environment, which is represented by $G = (V, E)$, where V denotes the set of router nodes and E the set of edges, i.e., undirected links. Two nodes $v, v' \in V$ are connected by an edge $e = \{v, v'\} \in E$ if both nodes are equipped with the same technology and are within the communication range of that technology. Let I be the set of used technologies, indexed by i. We have three groups of nodes based on their provided technologies. Therefore, multiple edges may exist between two nodes. Each group of nodes requires an adequate number of nodes so that, in all probability, every node can link to any other node through a route, which does not have to be a direct connection.

An example of our proposed network G is represented in Figure 3. The example includes 11 nodes in total, each of which belongs to one of the aforementioned groups in terms of the technology provided on it. For example, nodes V_7, V_8, V_9, and V_{10} (nodes of group #3) have only a Bluetooth card and there is maximum one undirected link between them if they are within the Bluetooth communication range. Nodes of groups #1 and #2 are capable of having multiple links among themselves as they supported with different technologies on them, e.g. nodes V_1 and V_{11} are connected through three links. In addition, there are certain nodes that share a common technology but are far beyond the communication range of that technology; in this situation, they could not establish a logical link with one another over that technology, e.g., nodes V_1 and V_3 over Zigbee and WiFi. However, all the nodes in the network are connected through at least one route, which leads to consistent network communication.

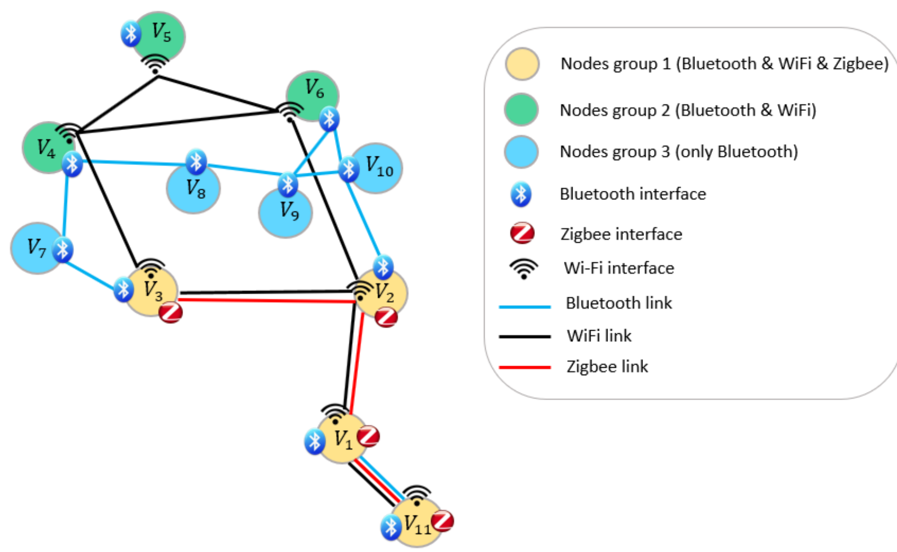


Figure 3: Sample the proposed MIMC WMN with 11 nodes in total, each equipped with different technologies

2.4.3 Network Traffic

The two proposed models are request-based, meaning many requests may have the same source and destination pair nodes. In the static model, all requests pass through the network at once. However, in the dynamic model, the start time and remaining bandwidth determine whether a request can be served at a given time slot.

2.4.4 Conflict Graph

Each wireless technology has a variable number of frequency channels on a given spectrum. For instance, Bluetooth, WiFi, and Zigbee provide 79, 14, and 16 frequency channels in the 2.4 GHz spectrum, respectively; see Table 1. Some channels of these technologies may overlap with each other and cause interference in the network; see Figure 2.

Due to channel overlapping when multiple technologies share a common frequency spectrum, data transmission and network performance may be impacted. We propose a conflict graph $G^{\text{C}} = (C, L^{\text{C}})$ to prevent interference in our models, where C is the set of nodes, each of which is associated with a particular channel in wireless technology:

$$C = C^{\text{B}} \cup C^{\text{W}} \cup C^{\text{Z}},$$

where $C^{\text{B}}, C^{\text{W}}, C^{\text{Z}}$, respectively, are the sets of all available channels of Bluetooth, WiFi, and Zigbee technology in the shared frequency spectrum.
L^{C} is the set of links, with each link associated with a pair of conflicting channels, i.e., a pair of two channels sharing some spectrum:

$$L^{\text{C}} = L^{\text{WW}} \cup L^{\text{WB}} \cup L^{\text{WZ}} \cup L^{\text{ZB}},$$

where each subset is defined as,

- L^{WW}: Set of WiFi channels conflicting with each other,
- L^{WB}: Set of WiFi channels conflicting with Bluetooth channels,
- L^{WZ}: Set of WiFi channels conflicting with Zigbee channels,
- L^{ZB}: Set of Zigbee channels conflicting with Bluetooth channels.

Figures 4 and 5 depict our proposed conflict graph G^{C} and its corresponding matrix, respectively. They specify intra- and inter-interference channels in the 2.4 GHz band. Figure

4 contains 109 nodes overall for the three employed technologies, and its links are based on channel overlapping in the shared spectrum.

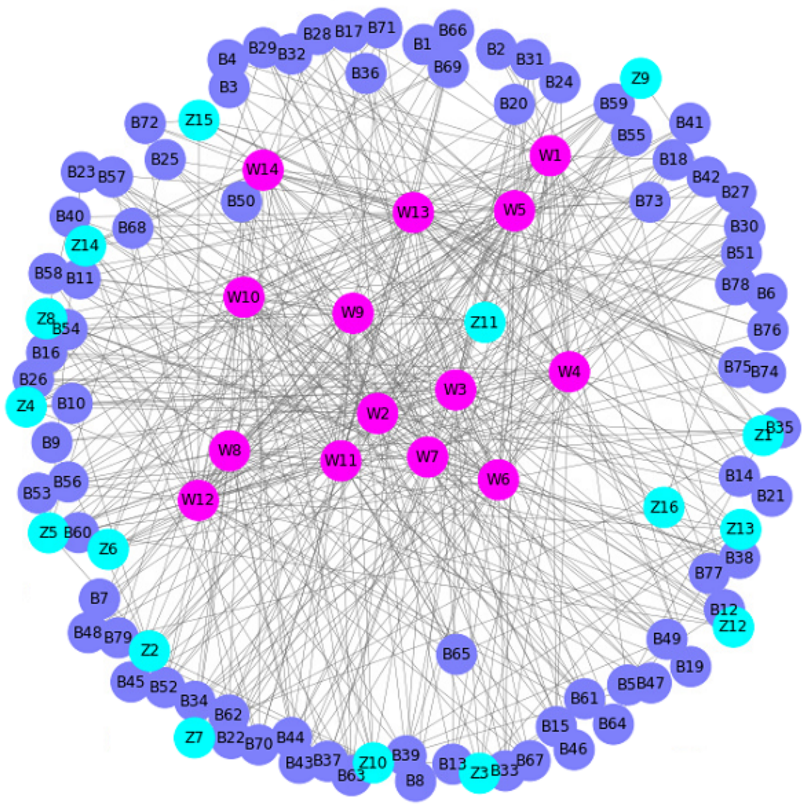


Figure 4: Channel conflict graph (G^c) made of all channels of three technologies (Bluetooth, WiFi, and Zigbee) in 2.4 GHz spectrum

2.5 Static Model

For our static problem, we provide an interference-aware ILP formulation with the aim of maximizing network throughput. The model does the joint routing, channel, and interface assignment by considering the traffic's latency and bandwidth demands. We first discuss the presumptions, notations, and variables utilized in our model before defining it with constraints.

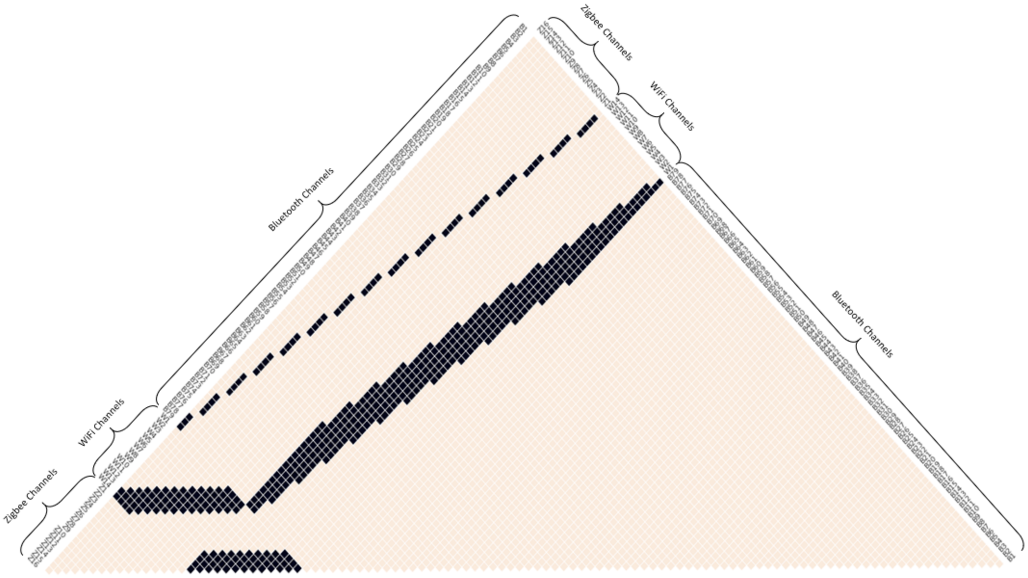


Figure 5: Matrix of (G^{c}); pink pixels: non-overlapping channels, black pixels: overlapping channels

2.5.1 Assumptions

In order to solve our static model, we make the following hypothesis:

- The model is designed for routing over a single path,
- Delay is constant on every edge (i.e., independent of the number of transmitted packets) but varies with the technology,
- The packet size used to calculate transmission delay is independent of the technology.

2.5.2 Notation

All the notations of the proposed static model are listed in Table 2.

2.5.3 Decision Variables

There are four sets of binary variables in the static model:

Table 2: Notations

Notation	Definition
I	Set of all available technologies: $I = \{\text{B}, \text{W}, \text{Z}\}$ $I_e \subset I_v \subset I$ I_e = Set of corresponding technologies on each edge I_v = Set of corresponding technologies on each node
$d_i^{\max}$	Max. transmission range (m) of technology $i \in I$
V	Set of nodes in network G with the corresponding technologies on each node: $V = \{v \equiv v_i : i \in I_v\}$
$\omega(v)$	Set of adjacent links of node $v \in V$
E	Set of edges in network G with the corresponding technologies on each edge: $$E = \{e \equiv e^i_{vv'} : d_{vv'} \leq d_i^{\max}; v, v' \in V, i \in I_e\}$$ $d_{vv'}$ = Length of edge $e = \{v, v'\}$
CAP_e	Capacity/bit rate of edge $e \in E$ over corresponding technology $i \in I_e$ (kbps)
δ_e	Delay of edge e = Transmission + Queuing Delays Transmission Delay = $\frac{\text{S}*8}{\text{CAP}_e*1024} * 1000$ (ms) Queuing Delay = δ_q (ms) Packet size of data = S (bytes)
C	Overall set of frequency channels for all technologies of I: $C = \bigcup_{i \in I} C_i$
$\varphi_{cc'}$	= 1 if channels c and c' are overlapping (there is a link between them in conflict graph G^{C}), = 0 otherwise.
E^{TCL}	Union set of all triangle cycle links in network G: $E^{\text{TCL}} = \bigcup_{tcl \in \text{triangle}} tcl$; $E^{\text{TCL}} \subset E$
R BW_r δ_r SRC_r DST_r	Set of requests; $r \in R$ Requested bandwidth for request r Requested end-to-end delay for request r Source node of request r Destination node of request r

- x_{ec}: Edge channel allocation variable

$$x_{ec} = \begin{cases} 1 & \text{if channel } c \text{ of assigned technology} \\ & \text{to edge } e \text{ is used on that edge,} \\ 0 & \text{otherwise,} \end{cases}$$

for $c \in C_i, i \in I_e, e \in E$.

- y_{rv}: Node routing variable

$$y_{rv} = \begin{cases} 1 & \text{if node } v \text{ is used in routing request } r, \\ 0 & \text{otherwise,} \end{cases}$$

for $r \in R, v \in V$.

- a_{re}: Edge routing variable

$$a_{re} = \begin{cases} 1 & \text{if request } r \text{ is routed via edge } e, \\ 0 & \text{otherwise,} \end{cases}$$

for $r \in R, e \in E$.

- z_r: Granting variable

$$z_r = \begin{cases} 1 & \text{if request } r \text{ is granted,} \\ 0 & \text{otherwise,} \end{cases}$$

for $r \in R$.

2.5.4 Objective

The intention of the static model is to maximize the overall network throughput,

$$\text{OBJ} = \max \sum_{r \in R} \text{BW}_r z_r. \tag{1}$$

2.5.5 Constraints

The following are the applied constraints to solve the static problem linearly:

Single channel per edge:

For a given link and its corresponding technology, we can use at most one channel,

$$\sum_{c \in C_i} x_{ec} \leq 1, \qquad i \in I_e, e \in E. \tag{2}$$

Link usage for routing:

If a channel of associated technology for a particular link is assigned to the edge, it means that the edge is utilizing it for routing,

$$a_{re} \leq \sum_{c \in C_i} x_{ec}, \qquad i \in I_e, e \in E, r \in R. \tag{3}$$

Net flow conservation for a single route:

Net flow conservation is necessary to identify a single path for each request at each node encountered in the network. It leads to particular cases for the source and destination nodes, where it must equal 1 if an outgoing and an incoming route are selected, respectively (i.e., the request is granted). Otherwise, flow conservation must be enforced for all the other nodes,

$$\sum_{e \in \omega(v) \cap E} \sum_{i \in I_e} a_{re} = \begin{cases} z_r & \text{if } v \in \{\mathrm{SRC}_r, \mathrm{DST}_r\}, \\ 2y_{rv} & \text{otherwise,} \\ & \text{i.e., } v \notin \{\mathrm{SRC}_r, \mathrm{DST}_r\} \end{cases}$$
$$v \in V, r \in R. \tag{4}$$

Net flow conservation for multiple routes:

We need to introduce as many a_{re} variables as the number of paths we want to allow,

$$\sum_{e\in\omega(v)\cap E}\sum_{i\in I_e} a_{re} = \begin{cases} z_{r_1}+z_{r_2}+z_{r_3}+... & \text{if } v\in\{\text{SRC}_r,\text{DST}_r\} \\ 2(y_{r_1v}+y_{r_2v}+y_{r_3v}+...) & \text{otherwise,} \\ & \text{i.e., } v\notin\{\text{SRC}_r,\text{DST}_r\} \\ z_{r_1}\geq z_{r_2}\geq z_{r_3}\geq ... & \\ y_{r_1v}\geq y_{r_2v}\geq y_{r_3v}\geq ... & \end{cases}$$

$$v\in V, r\in R. \tag{5}$$

Note that constraint (5) does not apply in our model since we assume a single route for each request. In contrast, it will be utilized instead of constraint (4) if we consider multi-paths to fulfil a certain request.

Single technology among two nodes per request:

For a given node pair $\{v,v'\}$, there may be as many edges as the number of corresponding technologies linking the two nodes. However, for a given request, we can use only one common technology between them,

$$\sum_{e\in E:e=\{v,v'\}}\sum_{i\in I_e} a_{re}\leq 1, \qquad v,v'\in V, r\in R. \tag{6}$$

Due to our model's underlying premise that there should be a single route or none for every request depending on its granting value, a restriction like (6) is not required. However, it will be necessary if we take into account multiple routes to satisfy a certain demand.

Node usage for routing:

The status of a given request granted or not determines whether or not a given node is utilized to route that request,

$$y_{rv} \leq z_r, \qquad v \in V, r \in R. \tag{7}$$

Bandwidth requirement:

For a given edge and its corresponding technology, the total transmitted data of those requests passing via that edge should not exceed the edge's capacity,

$$\sum_{r \in R} \mathrm{BW}_r a_{re} \leq \mathrm{CAP}_e, \quad i \in I_e, e \in E. \tag{8}$$

Note that the capacity constraint is technology dependent. It implies that every technology offers a unique capacity. It is also worth mentioning that, in our static model, we grant all or nothing of each request's traffic.

Delay requirement:

For a given request, the total delay of the traversed links from source to destination, corresponding to the technology used on them, should not exceed the request's demanded delay,

$$\sum_{e \in E} \sum_{i \in I_e} \delta_e a_{re} \leq \delta_r, \qquad r \in R. \tag{9}$$

Interference:

Two edges e and e' originating from the same node may generate interference with each other if both are used and the following conditions are satisfied (see Figure 6 for an illustration):

- Both edges belong to one of the triangle cycles (i.e., a cycle with three edges) in the network. In other words, there is a third used edge, e'', which connects the two endpoints of the initial two edges.

- At least two out of the three following conditions are satisfied:

  $c_e \cap c_{e'} \neq \emptyset,$

  $c_e \cap c_{e''} \neq \emptyset,$

  $c_{e'} \cap c_{e''} \neq \emptyset,$

where $c_e, c_{e'}, c_{e''}$ are nodes in the conflict graph G^{C} and each edge of the triangle (e, e', e'') can be associated with any of the three technologies (not necessarily the same).

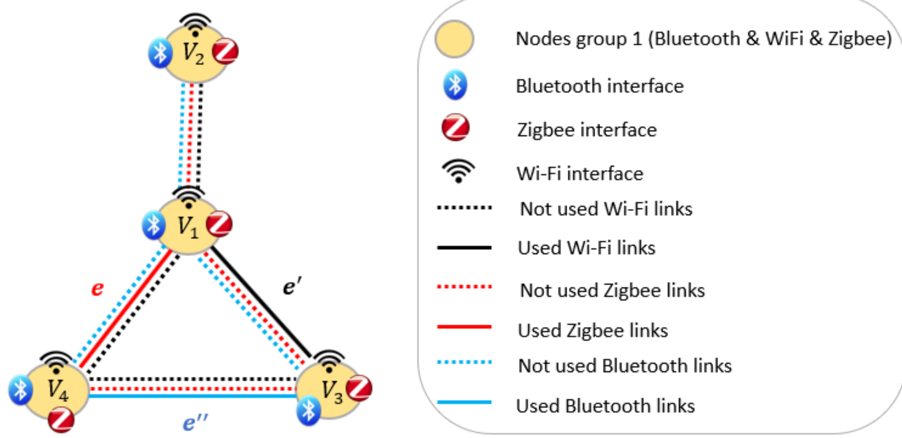


Figure 6: Link interference while there is an active triangle links in the network

For any triangle of set E^{TCL} in the network, if the channels allocated to the triangle's edges conflict with each other based on their connection in conflict graph G^{C}, the model does not permit those channels to be used over those edges simultaneously in order to prevent interference in the network. Therefore, the interference constraint is as follows:

$$
\begin{aligned}
x_{ec} + x_{e'c'} + x_{e''c''} &\leq 3 - (\varphi_{cc'} + \varphi_{cc''} + \varphi_{c'c''}) + \varphi_{cc'}\varphi_{c'c''} + \varphi_{cc'}\varphi_{cc''} + \varphi_{c'c''}\varphi_{cc''} \\
x_{ec} + x_{e'c'} &\leq 2 - \varphi_{cc'} \\
x_{ec} + x_{e''c''} &\leq 2 - \varphi_{cc''} \\
x_{e'c'} + x_{e''c''} &\leq 2 - \varphi_{c'c''}
\end{aligned} \tag{10}
$$

For:

$c \in C_i, c' \in C_j, c'' \in C_k, i \in I_e, j \in I_{e'}, k \in I_{e''}, \{e, e', e''\} \in tcl, tcl \in E^{\text{TCL}} \subset E.$

Proof of all cases:

- If none of the three channels on triangle links conflict with each other, then all three links can be used simultaneously.

- If all three channels on triangle links conflict with each other, then at most one of those three links can be used.

- If only two of the channels on triangle links conflict with each other, then two out of three links can be used simultaneously. Taking into account this condition, only one of those two channels can be on, and the other one should be off.

- If one of the channels on triangle links has a conflict with both of the other two channels, then two out of three links can be used simultaneously. Therefore, only those two links not using the common conflict channel can be used.

Subtour elimination:

In the context of the search for a route for a given request, a subtour is a loop that may or may not be connected to the request's route between its source and its destination. By implementing constraint (4), we prevent loops from involving the source and the destination nodes. We could eliminate them using the well-known subtour elimination constraints (see, e.g., [22]), but there are an exponential number of them, i.e., as many as the number of subsets of nodes in our network. However, if some subtours are generated, it is because their used bandwidth does not prevent other requests from being granted. Therefore, they are not an issue in our problem and can be easily removed with a post-processing test; this is the solution we adopted.

2.6 Dynamic Model

In contrast to the static scenario where all requests are known in advance, in this section we consider a dynamic scenario where requests are not known in advance and can enter or exit the network at various times, just as in the real world. For the dynamic scenario, we propose an interference-aware ILP formulation with the objective of maximizing throughput while taking the priority of ongoing requests into account. Dynamic traffic instances comprise their start and end time slots, both source and destination nodes, and their required latency and capacity. Based on their start time, they enter the network in multiple time slots. At each time slot, the model tries to convey data as quickly as possible and finds a single optimal route for each request. To handle an incoming set of requests, the model runs a preprocessing phase at the beginning of each time slot, which accepts only ongoing requests with remaining bandwidth from the previous time slot and new incoming requests that start at the current time. The model uses all notations, variables, and some assumptions defined in the static model. To solve the problem, though, explicit presumptions, notations, parameters, and restrictions must be in place.

2.6.1 Assumptions

We make some suppositions in our proposed dynamic model for the MIMC wireless mesh network to address the joint routing, interface, and channel allocation issue. The presumptions are as per the following:

1. The model is written for a given time slot, but to simplify the notations, we ignore the time slot index,

2. At the beginning of each time slot, all network resources are available and free in all nodes,

3. We assume that the bandwidth of each request is a positive integer ($\text{BW}_r \in \mathbb{Z}^+$).

2.6.2 Notations

Table 3 contains all the additional notations of the dynamic model, besides all the notations in the static model in Table 2.

Table 3: Extra Notations of Dynamic Model

Notations	Definitions
t^{CURRENT}	Current time slot
t_r^{START}	Start time of request r, i.e., it is the time that request r comes into the network
t_r^{END}	End time of request r, i.e., transferring all data of request r should be completed by this time; $t_r^{\text{END}} = t_r^{\text{DURATION}} - t_r^{\text{START}}$ t_r^{DURATION} = Duration time of requests r, that follows geometric distribution
t_r^{SERVE}	Serving time of request r, i.e., the time that request r start being provision
REMAINING_r	Maximum number of time slots left for a given request r before the deadline; $\text{REMAINING}_r \geq 1$; $\text{REMAINING}_r = t_r^{\text{END}} - t^{\text{CURRENT}} + 1$
AGE_r	Age of given request r, which determines precedence for granting the request; $\text{AGE}_r = \frac{t^{\text{CURRENT}} - t_r^{\text{SERVE}} + 1}{\text{REMAINING}_r}$
$\text{BW}_r^{\text{BEFORE}}$	Total transferred bandwidth for a given request r from its serving time slot till the current time slot
$\overline{\text{BW}}_r$	Current upper bound of bandwidth/ residual bandwidth for request r; $\overline{\text{BW}}_r = \text{BW}_r - \text{BW}_r^{\text{BEFORE}}$
$R^{\text{remaining}}$	Set of requests whose either have not yet been fully granted (has some remaining bandwidth for transmission) or their start time equals to the current time ($t_r^{\text{START}} = t^{\text{CURRENT}}$)
R^{active}	Set of ongoing requests which they already started and have a serve time
M	Big-M to make the priority's fundamental achievable solution readable in the objective
d^{SLOT}	Length (duration) of the time slot

2.6.3 Parameters

The following definitions apply to parameters used in the dynamic model:

- $\text{BW}_{re}^{\text{CURRENT}}$ = Amount of bandwidth for request r to be transferred during the current time slot over a certain edge $e \in E$; $\text{BW}_{re}^{\text{CURRENT}} \in \mathbb{Z}^{+}$.

2.6.4 Request Screening

Preprocessing involves searching for requests that remain eligible ($R^{\text{remaining}}$) before each scheduling round (i.e., time slot). At the current time slot (t^{CURRENT}), if one of the following conditions applies, a given request r becomes or remains eligible:

- The request's start time equals the current time slot,
- The request's residual bandwidth must be smaller than $\text{REMAINING}_r \times \max(\text{CAP}_e)$. Otherwise, the request is deleted, meaning it is interrupted because we cannot fulfil its requirements.

2.6.5 Objective

The dynamic model aims to maximize overall throughput by giving a higher priority to requests that have already begun to be delivered. The model prevents transmitting requests that could not complete their packet transfer within the allotted period (i.e., the number of remaining slots). The AGE_r parameter indicates the request's priority.

$$\text{OBJ} = \max\left(\sum_{r\in R^{\text{remaining}}}\sum_{e\in\omega(\text{SRC}_r)} \text{BW}_{re}^{\text{CURRENT}} + \text{M}\sum_{r\in R^{\text{active}}} \text{AGE}_r z_r\right). \tag{11}$$

2.6.6 Constraints

While determining the optimum path over various time frames, we employed some restrictions in our dynamic model to assign the appropriate interface and channel to each edge. Some of the restrictions are identical to those in our static model (constraints (2), (3), (6), (7), and (10)). Additional limitations to solve our dynamic problem linearly are as follows:

Bandwidth requirement:

Partial data packets from a request ($\text{BW}_{re}^{\text{CURRENT}}$) will be sent to the supplied destination during each time slot, based on the request's priority and current total network traffic. The model should ensure that we do not transmit more data than are required, i.e., $\text{BW}_{re}^{\text{CURRENT}}$ must be fewer than the total data to be sent,

$$\text{BW}_{re}^{\text{CURRENT}} \leq \overline{\text{BW}}_r a_{re}, \qquad r \in R^{\text{remaining}}, e \in E. \tag{12}$$

The total transmitted data of those requests that travel over a given edge should not exceed the edge capacity of the technology used,

$$\sum_{r \in R^{\text{remaining}}} \text{BW}_{re}^{\text{CURRENT}} \leq \text{CAP}_e, \qquad i \in I_e, e \in E. \tag{13}$$

Delay requirement:

According to our hypothesis, the edge's latency remains constant but varies depending on the technology, meaning that the sum of the traversed edges' delays from source to destination nodes determines the entire delay used by a request. However, the delay requirement for a request is not the same for subsequent time slots. In other words, the utilized delay from prior time slots should be subtracted from the required delay at each time slot. Therefore, only the remaining delay will be taken into account for the request's delay requirement

(δ_r) in the consecutive slots,

$$\sum_{e \in E} \sum_{i \in I_e} \delta_e a_{re} \leq \delta_r - (d^{\text{SLOT}}(t^{\text{CURRENT}} - t_r^{\text{SERVE}})), \qquad r \in R. \tag{14}$$

Net flow conservation for single route:

This identifies a single optimal path such that, for source and destination nodes, if a request was previously granted, it should continue to be granted. Otherwise, it might/might not be granted. It must be enforced for the other nodes,

$$\sum_{e \in \omega(v) \cap E} \sum_{i \in I_e} a_{re} = \begin{cases} 1 & \text{if } v \in \{\text{SRC}_r, \text{DST}_r\} \text{ and } r \text{ was} \\ & \text{granted in previous time slot,} \\ z_r & \text{if } v \in \{\text{SRC}_r, \text{DST}_r\} \text{ and } r \text{ was not} \\ & \text{granted in previous time slot,} \\ 2y_{rv} & \text{otherwise,} \\ & \text{i.e., } v \notin \{\text{SRC}_r, \text{DST}_r\} \end{cases}$$
$$v \in V, r \in R^{\text{remaining}}. \tag{15}$$

2.7 Experiments and Results

We now report on the performance of the two models presented in Sections 2.5 and 2.6 on various data instances. We first describe the data instances in Section 2.7.1. The network topology construction is then explained in Section 2.7.2. Finally, in Sections 2.7.3 and 2.7.4, respectively, we discuss the traffic cases for static and dynamic. We next discuss the performance of the static model in Section 2.7.5 and then of the dynamic case in Section 2.7.6.

The experiments conducted in this work have been done on a computer with 32 GB of RAM and an Intel(R) Xeon(R), 3.60 GHz. The implementation of both mathematical models has been performed using the Gurobi optimizer (version 9.1.2) [10] with Python.

2.7.1 Data Instances

We generated one MIMC wireless mesh network instance and several traffic instances, so that each data instance is made of the mesh network instance and one specific traffic instance. The network instance is characterized by its set of nodes, as well as by their location in a given area and the number of available technologies for each node. Illustration is given in Figure 7 (some nodes have been slightly moved in order to avoid node overlapping in the figure). Each traffic instance is defined by its set of requests. For the static model, each request is characterized by its source node, destination node, maximum latency, and bandwidth requirement. For the dynamic model, in addition to the characteristics of the static model, each request is also given a starting and maximum ending time. All the numerical values for the input parameters are summarized in Table 4.

2.7.2 Network topology construction

The challenge in designing a MIMC wireless mesh network topology is to make sure that nodes can communicate among themselves, thus guaranteeing the connectivity of the overall network so that any two nodes can always communicate. We build a network with an overall number of 70 nodes. See Table 4 for the details of how many nodes we use with each combination of technologies. The selection of the locations of the nodes is done as follows: We start with a random selection for the location of nodes in group #1, i.e., with all three technologies. Whenever we generate the location of an additional node, we make sure it can be connected to at least one of the previously generated nodes, considering their communication range. We proceed in the same way with the generation of the locations

Table 4: Input Parameters

Parameters	**Values**
Area	$300 \times 300 \quad (m^2)$
Type of technology	WiFi / Bluetooth / Zigbee
Number of nodes in group #1 with all three technologies: Bluetooth, WiFi, Zigbee	20 (Static / Dynamic)
Number of nodes in group #2 with only two technologies: Bluetooth, WiFi	10 (Static / Dynamic)
Number of nodes in group #3 with a single technology: Bluetooth	40 (Static / Dynamic)
Number of Channels per Technology (see Table 1 for the overall number of RF channels)	14 (WiFi) 79 (Bluetooth) 16 (Zigbee)
Communication range per technology (Maximum communication coverage in Table 1)	100 m (WiFi) 10 m (Bluetooth) 100 m (Zigbee)
Maximum data rate per technology (Maximum bit rate in Table 1)	54,000 kbps (WiFi) 1,000 kbps (Bluetooth) 250 kbps (Zigbee)
Packet size (S)	1500 (Bytes)
Queuing delay (δ_q)	15 (ms)
Duration of each time slot (d^{SLOT})	90 (ms)
Big M optimization parameter (M)	1,000
Latest start time for a request ($t^{\text{L–START}}$) (Used only in dynamic case)	10
Latest end time for a request ($t^{\text{L–END}}$) (Used only in dynamic case)	15

of the nodes in groups #2 and #3, using the shortest range technology, in order to ensure that each node added can communicate with the nodes already generated. The last step is to define the set of links connecting the nodes. Each node pair can have multiple links connecting them, depending on their distance and their supported technologies. For instance, three links (one WiFi link, one Bluetooth link, and one Zigbee link) will connect two nodes from group #1 that are separated by less than 10 metres.

The resulting MIMC WMN topology associated with the parameters in Table 4 is depicted in Figure 7. We use that topology for the evaluation of both static and dynamic models. We use Python's NetworkX library to create the MIMC wireless mesh network instance, i.e., a set of nodes and links.

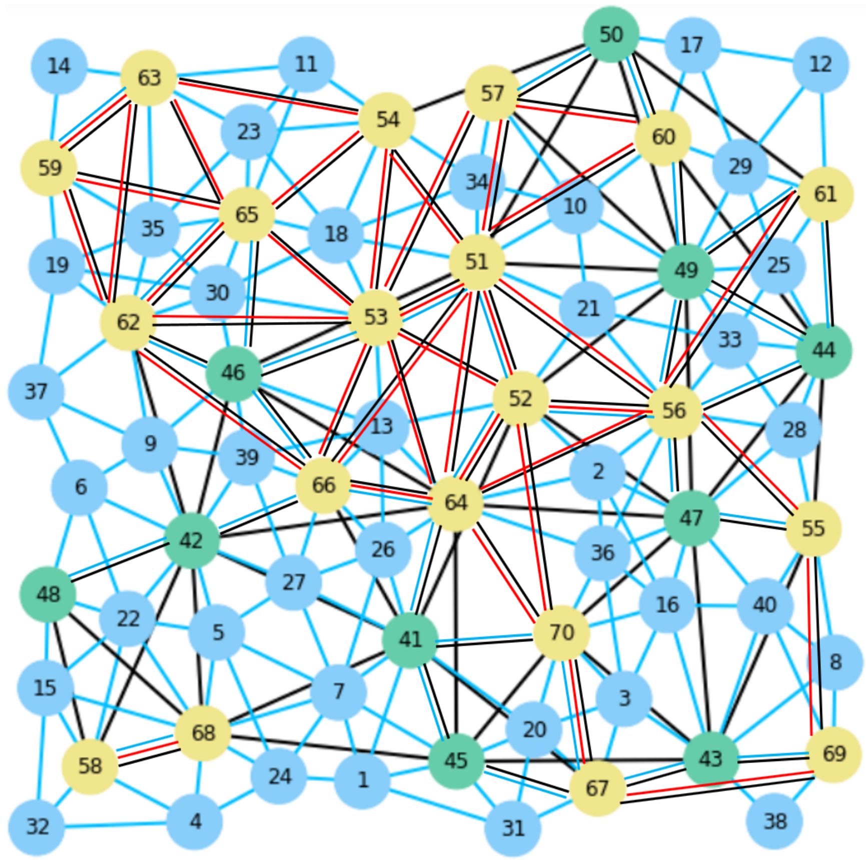


Figure 7: MIMC wireless mesh network topology; yellow nodes: group #1, green nodes: group #2, blue nodes: group #3; red lines: Zigbee links, black lines: WiFi links, blue lines: Bluetooth links

2.7.3 Static traffic instances

We generated 15 incremental traffic instances, each comprising multiple requests with different bandwidth requirements. Each instance of traffic is built on the previous one, i.e., with the addition of a given number of requests. To generate the dataset, for each traffic instance, we take into account a uniform distribution of the different traffic types, as described in Table 5. It is worth mentioning that a uniform or non-uniform distribution of traffic makes no difference in our model. This is because the traffic type only influences the delay requirement and not the bandwidth requirement, as we base our models on the idea that each request is a collection of some requests of the same traffic type, and a path selection can be made regardless of the traffic type as long as the delay requirement is satisfied. Each request is first defined by its source (SRC_r) and destination (DST_r) nodes. The bandwidth requirement of each request (BW_r) is randomly generated in an interval defined as follows. The upper bound is the data rate of the slowest common technology within source and destination nodes and its lower bound is the lowest data rate (bandwidth) of the selected traffic class in Table 5. The delay required for a request (δ_r) varies from one type of traffic to another. In our experiments, we set it to the maximum delay (upper bound) of the assigned traffic class specified in Table 5.

Table 5: QoS metrics for different data types in network [5]

Traffic class	Maximum Delay (ms)	Bandwidth
Web Browsing	400	<30.5 Kbps
SMTP, FTP, Telnet	250	<1 Kbps
Audio/Video Broadcasting	150	28.8 Kbps - 1.5 Mbps
Interactive Audio/Video on Demand	150	28.8 Kbps - 1.5 Mbps
Audio/Video Conferencing	150	8 Kbps - 2 Mbps
Audio-graphics Conferencing	150	9.6 Kbps - 19.6 Kbps
Video-Phony	100	80 Kbps - 2 Mbps
VoIP	100	8 Kbps - 80 Kbps

Bandwidth distribution:

In this work, we evaluate the model for six runs. The bandwidth distribution of the requests for the average of six runs is shown in Figure 8. As can be seen, the number of generated requests in each traffic instance for all ranges is increasing. In addition, we attempted to generate more requests within the range of 0–250 Kbps that could be used by all three technologies. We generate fewer requests in two other ranges, which can be used by Bluetooth or WiFi.

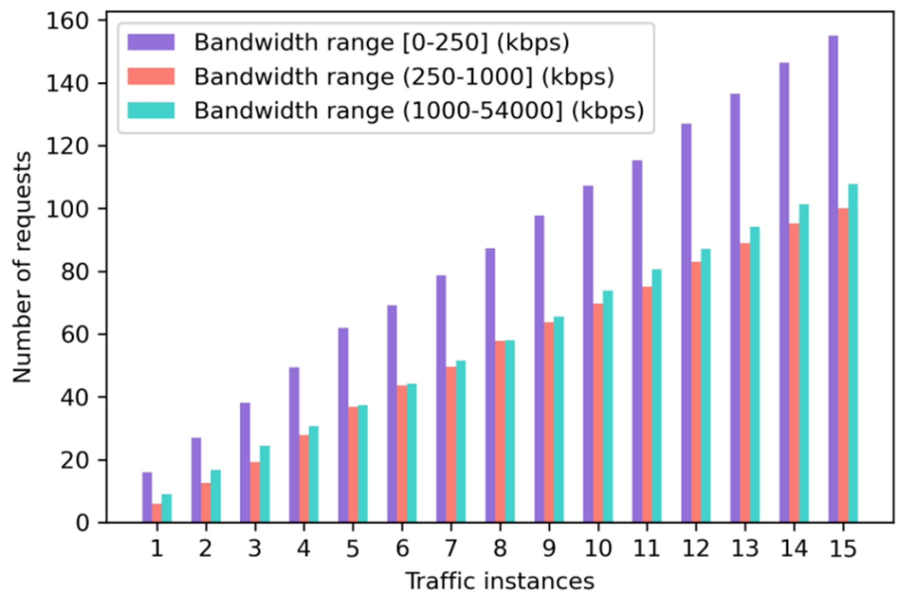


Figure 8: Static - Bandwidth distribution comparison

2.7.4 Dynamic traffic instances

We generated a traffic instance of multiple requests, such that the traffic type, source node, destination node, and delay and bandwidth requirements of each request are constructed using a similar approach as the traffic instance generation of the static model. We defined $t^{\text{L\_START}}$ and $t^{\text{L\_END}}$ (specified in Table 5) as the latest time slots that may be assigned as the start time of a request (t_r^{START}) and the end of the experiment, respectively. To give requests a chance to be finished before the latest end time slot ($t^{\text{L\_END}} = 15$), we set the latest start time of requests as $t^{\text{L\_START}} = 10$. We established the duration time using a geometric distribution with a probability value of $p = 1/3$, which gives an average duration of around 2-3 ms. The duration is used to determine the request's end time (t_r^{END}), ensuring that it does not exceed the $t^{\text{L\_END}}$.

It is worth mentioning that, in both static and dynamic models, we presume that each traffic comprises a collection of small amounts of traffic since all the varied traffic's data types (Table 5) are much smaller than the technologies' capacity or data rate (Table 4).

2.7.5 Results - Static case

To evaluate the performance of our proposed static model, we conducted the experiment six times, each with fifteen traffic instances, and finally got the average results (i.e., throughput ratio, percentage of granted bandwidth, resource utilization, and delay). In each experiment, for the first traffic instance, we created a set of requests with a total bandwidth of around 30 Kbps. Then, we built a new batch of requests with a total load of about 30 Kbps and added them on top of the previous batch to generate the next traffic instance. This process is successively repeated to generate all the following traffic instances. Our suggested static model attempts to address the joint CA and routing problem by inserting each traffic instance at once into the designed MIMC WMN. The following describes the results of our static model's experiments.

Throughput ratio

The throughput ratio per provided total load is shown in Figure 9. We observe that the throughput ratio is over 99% on average across all the traffic instances. Despite the total load increase, fewer requests were accepted because of their bandwidth or latency requirements, which resulted in a decrease in the throughput ratio. However, the decrease is moderately small, indicating that the model looks for a high objective (throughput) by granting more requests.

Percentage of granted bandwidth going through each technology

Figure 10 shows the proportion of the granted bandwidth going through each technology, considering the overall provided load. It reveals that the model prefers to transmit data first through WiFi, followed by Bluetooth, but less through Zigbee technology, which is consistent with real-world preferences. It means that almost all the requests have at least one WiFi link in their path, due to the geographical distance and WiFi's bandwidth capacity.

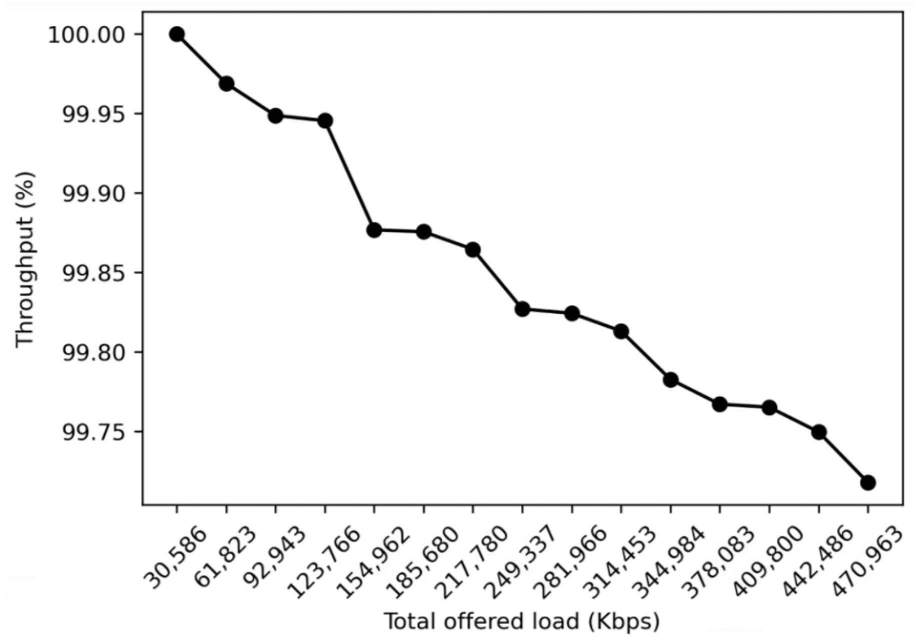


Figure 9: Static - Throughput ratio per offered load

The intention to utilize less Zigbee technology to grant requests could be because it offers a lower data rate compared to WiFi and Bluetooth.

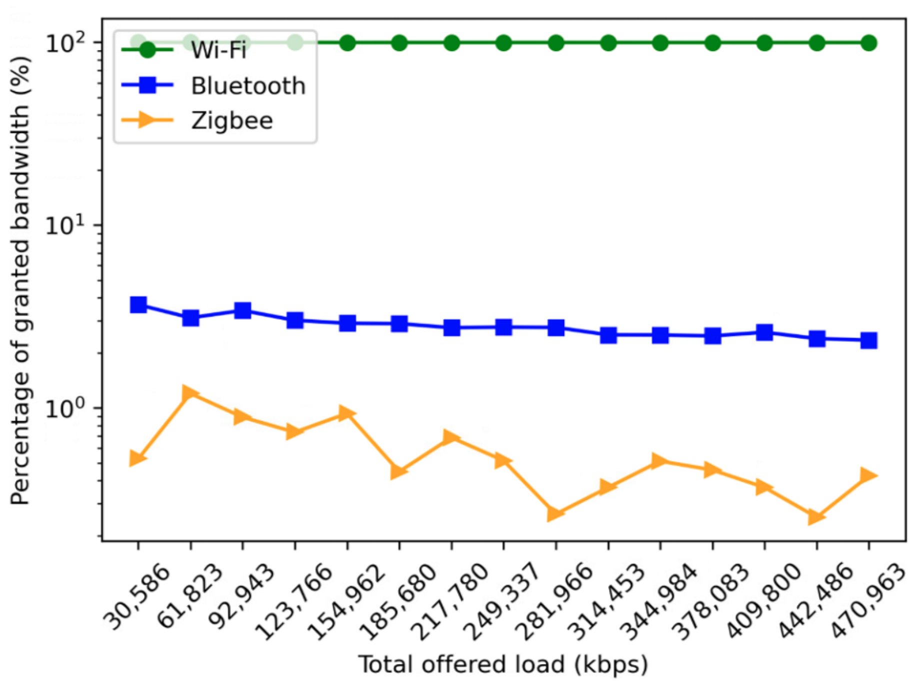


Figure 10: Static - Proportion of the granted bandwidth per technology

Resource utilization ratio

Figure 11 illustrates the resource (bandwidth) utilization ratio of each technology. The model requires more resources for provisioning the requests as the total offered load increases. The maximum resource utilization of the three technologies is less than 40%. This is first because our formulation takes into account all frequency channels of the shared spectrum for the three technologies, which results in a high initial resource availability, and second because of the offered load. In addition, WiFi utilization is lower than Bluetooth and Zigbee when the offered load is small, but as the network's offered load increases, we see more WiFi resources being utilized than Zigbee, with Bluetooth having the highest utilization ratio. One explanation could be that as WiFi's total resource availability in the network is substantially greater than Bluetooth's and Zigbee's, with a lower offered load, the utilization of WiFi can be lower than that of Bluetooth and Zigbee. When the load increases, more WiFi starts to be used in comparison to Zigbee, and its utilization becomes greater.

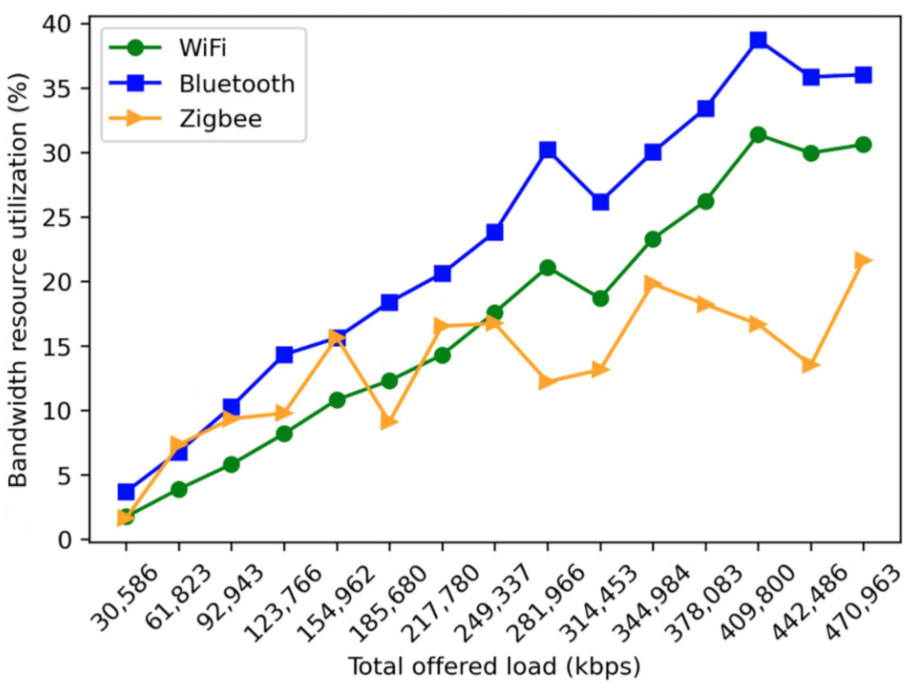


Figure 11: Static - Resource utilization ratio per technology

Delay

For each request, the required delay fits into one of four categories: 400, 250, 150, or 100 milliseconds. Figure 12 depicts the number of requests within each different delay range for the four delay categories. We see that, on average, more than 50% of requests are granted by our model with a delay less than 100 ms, and none of the requests are granted with a delay greater than 200 ms. This is a positive feature of our model, as it finds paths with small delays. Furthermore, for requests with less delay restriction, i.e., requests with a required delay of 400 ms, we are even sure they will be served with less than 50% of their required delay. We note that there is no request for the delay range of 0 to 10. It is because each link in our network has a minimum latency of more than 10 ms. Only a few requests are routed in a 20-30 delay range. This is because only a few paths have a delay in that range.

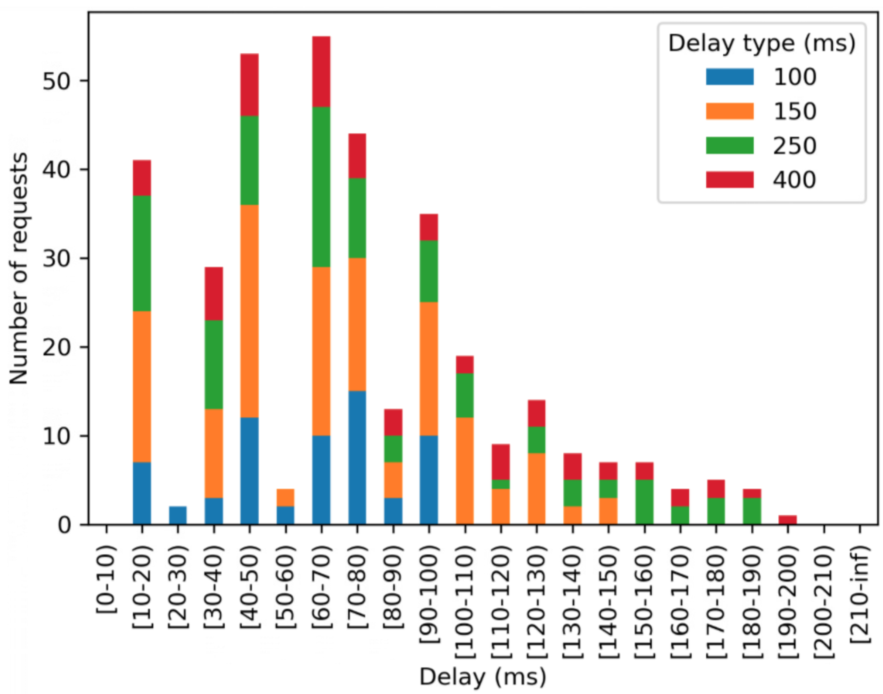


Figure 12: Static - Delay analysis

2.7.6 Results - Dynamic case

To demonstrate the effectiveness of our suggested dynamic model, we carried out the experiments six times by increasing the load. In each experiment, a dynamic traffic instance is made up of numerous requests that simultaneously entered the network at various time slots. At the beginning of each time slot, only the requests whose start time is equal to the current time slot (i.e., new coming requests) as well as those that have remaining data to transfer (i.e., ongoing requests) go through the network. The model allocates appropriate and interference-aware channels and interfaces to edges with the goal of maximizing the overall network throughput. In order to transfer as much data as possible, the model determines the best path for each request while taking its bandwidth and latency needs into account and preventing interference. In the following, we discuss the results of our dynamic model's experiments.

Throughput ratio

Figure 13 analyzes the overall provided load and throughput ratio for six dynamic traffic instances. As we can see, even with a large amount of data (around 8.5 GB), our model still achieves a high overall throughput of over 98%, demonstrating that it is able to transport large amounts of data concurrently. The throughput ratio trend exhibits two phases. The first phase is where the ratio is almost 100%, characterizing the availability of the resources. The second phase is where the ratio decreases due to some request rejection, which may be caused by the fact that the remaining capacity of links is not enough to handle the leftover requests, the path's delay does not satisfy the delay requirement of the request, or the request's life span is already over.

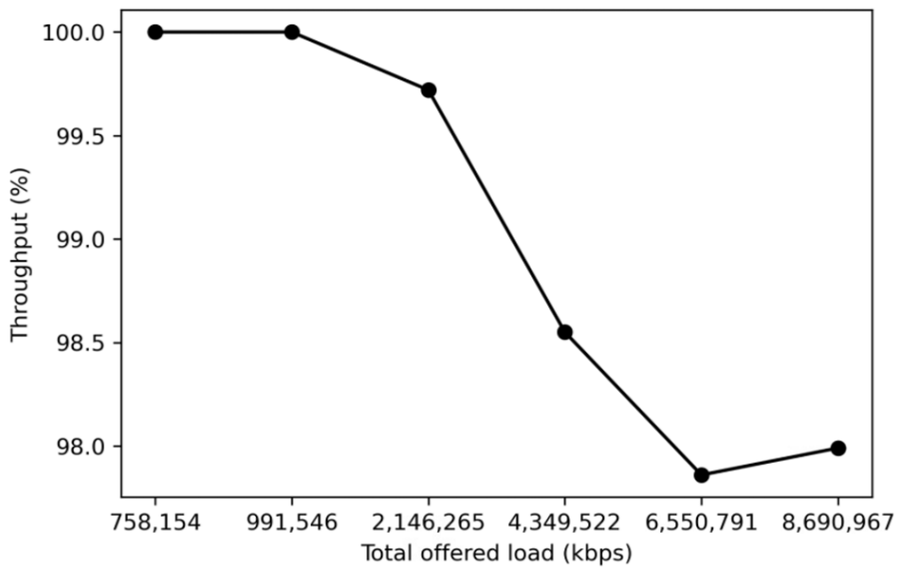


Figure 13: Dynamic - Throughput ratio per offered load

Percentage of granted bandwidth going through each technology

In order to analyze how each technology is used in the granting process, taking the overall given load into account, Figure 14 shows the percentage of granted bandwidth passed via each technology for the six traffic instances. As a path can be made of links of different technologies, this figure indicates that about 100% of the granted bandwidth will go through WiFi, meaning that almost all the paths include a WiFi link. We can also observe that around 10% of the granted bandwidth will have a Bluetooth link in its path, whereas only 1% will have a Zigbee link. This demonstrates that the model favours WiFi transmission first, followed by Bluetooth transmission, and finally Zigbee technology, which is similar to the behaviour of the static model.

Resource utilization ratio

The proportion of resource (bandwidth) utilization for the three technologies is depicted in Figure 15. Due to the high availability of resources, the bandwidth utilization for all three technologies is less than 60%. We observe that, when the load is small, the model tends

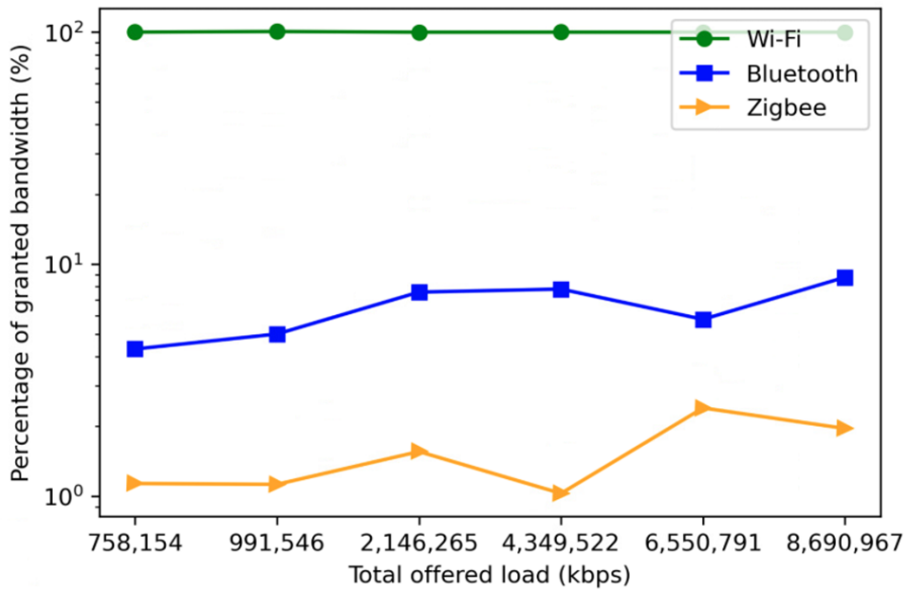


Figure 14: Dynamic - Proportion of the granted bandwidth per technology

to favour WiFi. However, raising the provided load also encourages the employment of Bluetooth and Zigbee technologies, which can be due to the WiFi resources limitation on a specific link, interference avoidance, geographic distance between the hops, or type of nodes.

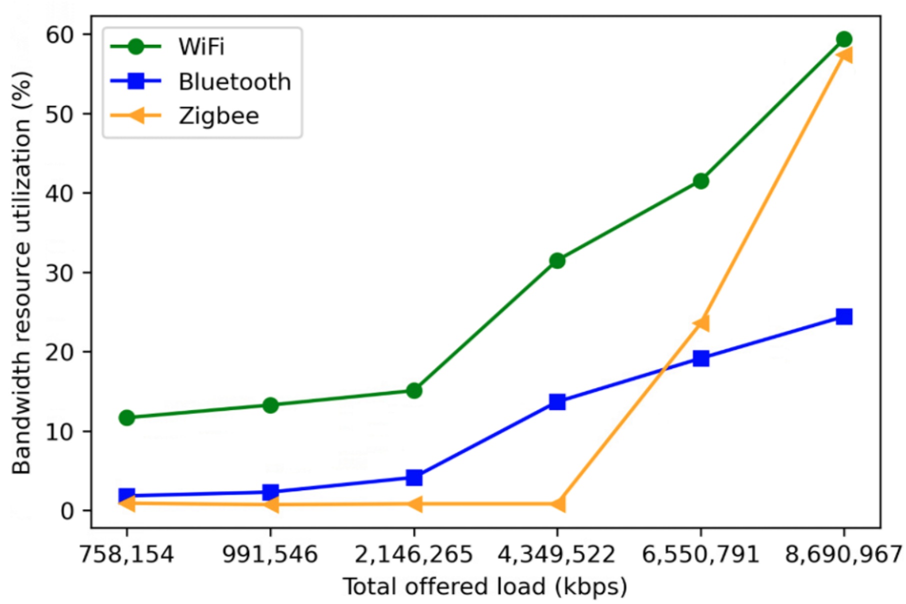


Figure 15: Dynamic - Resource utilization ratio per technology

Delay

Figure 16 represents the delay used to grant the requests based on their delay type. The majority of the requests are granted for less than 80 ms. Traffic types with a lower delay requirement, like web browsing or SMTP, FTP, and Telnet represented with delay types in red and green, respectively, can be granted with more than 150 ms, with no request granted with more than 210 ms. This shows that our model tries to grant the requests with the least possible delay. We observe that for the delay range 0–10, there is no request. It is because the minimum delay of each link in our network is over 10 ms. Moreover, the reason we see few requests in some delay range, e.g., 20–30, is because only a few paths in the network have a delay in that range.

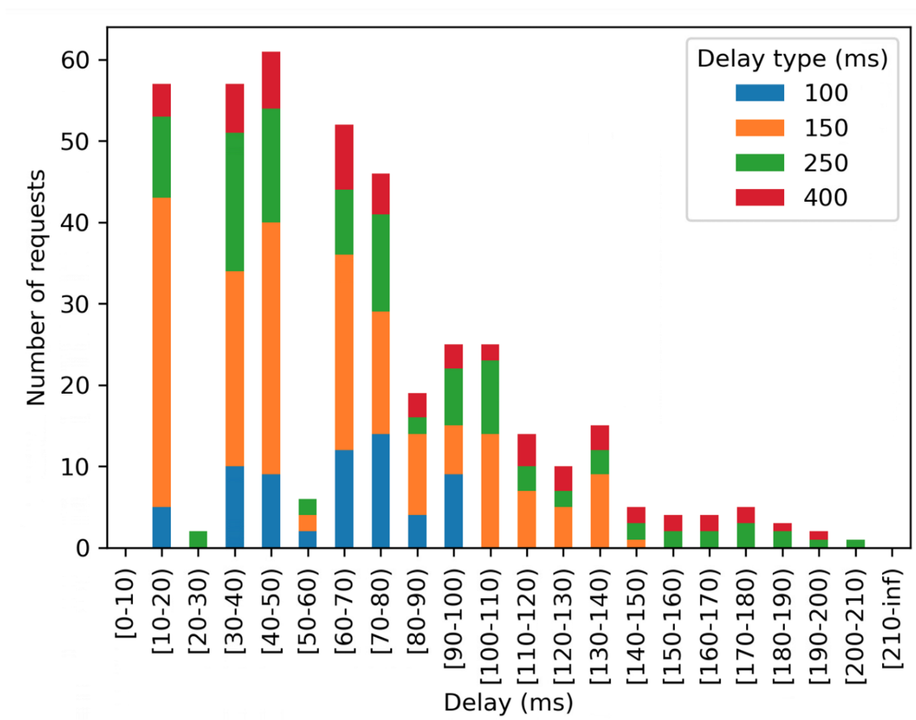
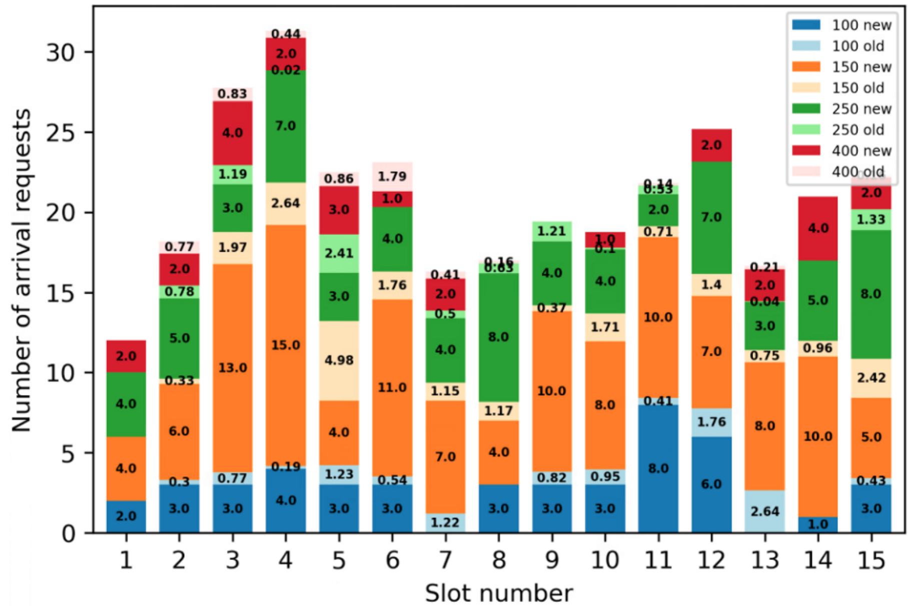


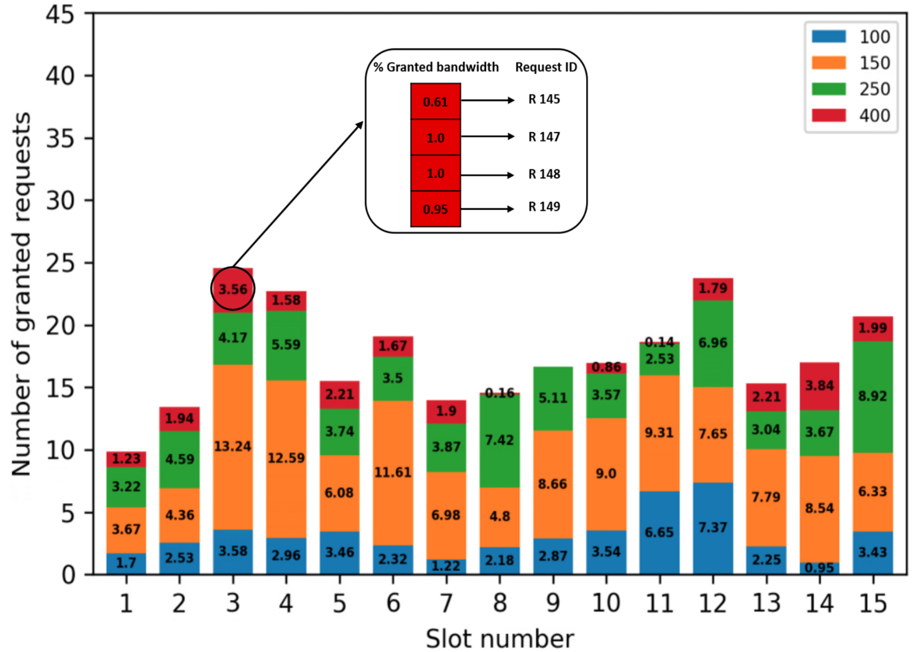
Figure 16: Dynamic - Delay analysis

Requests arriving and dynamic assignment

Figures 17a and 17b show the number of requests entering the network and their dynamic assignment through time slots based on the type of delay requirement. The terms "new" and "old," respectively, in Figure 17a explicitly denote the number of new incoming requests and ongoing requests. The values on the bars in Figures 17a and 17b represent the number of requests for each type of delay during a specific time slot. The decimal part exists when some requests are not fully granted in a slot, and it represents the proportion of the request that needs to be granted (Figure 17a) and that has been granted (Figure 17b) looking at its granted bandwidth versus its total bandwidth. We can see that, in general, the model fully grants requests with a more restrictive delay requirement (i.e., requests with a delay of "100" ms) earlier than those with a less restrictive delay requirement (i.e., requests with a delay of "400" ms) when we have requests with various delay types entering the network at the same time. However, in rare circumstances, the opposite can occur. For instance, for time slots $8, 11$, and 13, the model completely grants requests with delays of 400 ms (shown in red), while some requests with delays of 100 ms (shown in blue) are still not totally granted. In these rare circumstances, we observe that the 400 ms requests that are fully granted are ongoing requests; thus, the reason might be because the model gives ongoing requests a higher priority than the new incoming requests, taking their age into account. Furthermore, based on the provisioning of the dynamic model, which fully grants a request in multiple time slots, the model transfers the amount of bandwidth that could not be transmitted at each time slot to the subsequent time slot. However, in some time slots, such as time 4, and for some requests, we can see that the entire proportion of bandwidth that was not granted in the previous time slot did not transfer to the new time slot (for example, only 0.44 of a "400 old" request from time slot 3 arrives at time 4 out of 1.27 (i.e., 4.83 - 4.56) requests). This is due to the duration of those requests in time slot 3, as some of them are rejected because they have reached their end time.



(a)



(b)

Figure 17: Dynamic - Requests arriving and granting dynamicity

Channel interference

In Figure 18, the matrix shows whether or not the channels of the three different technologies (WiFi, Bluetooth, and Zigbee) in the same 2.4 GHz spectrum overlap in black and pink pixels, respectively. Blue and red are the utilized channels in a certain time slot; if two used channels overlap, the border pixel is red and is in the black area; otherwise, the border pixel is blue and is in the pink region. While the model tries to use non-overlapping channels, represented by blue cells, we also notice some red cells, which represent channels that overlap. Thus, we conducted more investigation. In order to do that, we examine all requests that used those overlapping channels within that particular time slot and determine their physical distance based on their geographical positions in the network. As expected, we discover that those requests are sufficiently far from one another, meaning that even though the assigned channels on them were basically overlapping in the 2.4 GHz spectrum, they were out of interference range of each other. Therefore, in such a scenario, those channels can still be used without causing interference. Furthermore, some of the channels in each technology are not utilized, and this is because some nodes may be located beyond the Bluetooth communication range (over 10 meters), and WiFi technology is preferred over Zigbee because it offers a higher data rate, allowing models to operate at higher throughput levels overall.

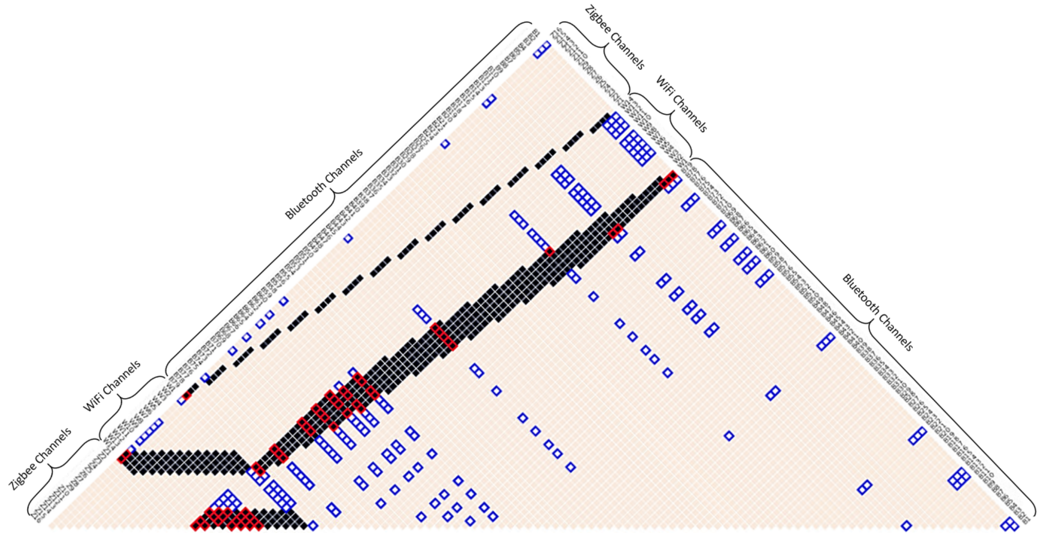


Figure 18: Dynamic - Interference Channels

2.8 Conclusion

In this study, we build up a MIMC WMN with three wireless technologies and propose static and dynamic models for the joint CA and routing problem. The methods identify a single route for each request in a specified set, with the goal of maximizing the network throughput while taking into account the bandwidth and delay requirements of requests. The results of the numerical experiments have shown the efficiency of the models, with a throughput ratio of over 99% and 98% in static and dynamic, respectively. Our models further consider how to mitigate interference considering channel overlap of provided technologies in the same spectrum while doing channel assignment among the paths. However, there are still some open issues needing further investigation, such as how to quantify the performance by increasing the number of interfaces on nodes in order to provide more capacity in the network, using multi-path protocols for routing to provide a higher opportunity for concurrent data transmission, or investigating whether AI-based approaches can be beneficial in solving the problem.

Acknowledgment

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Chapter 3

Conclusions and Future Works

In this chapter, we provide a conclusion to our work and provide some recommendations for future studies in this area. We investigate the problem of joint routing, CA, and IA for provisioning in MIMC WMN; the proposed models and results are detailed in chapter 2 of the thesis.

3.1 Conclusions

In this thesis, we propose ILP models to solve static and dynamic joint routing, CA, and IA on the MIMC wireless mesh network. We employ Bluetooth, WiFi, and Zigbee technologies as available interfaces and their respective 2.4 GHz channel sets to build the MIMC WMN. The models identify a single path for each request and assign suitable non-conflict channels and interfaces to links with the aim of maximizing overall throughput while taking into account the requested latency and bandwidth. Furthermore, the models use a conflict graph constructed from channels of provided technologies operating in the same spectrum to avoid network interference during channel assignment. Through numerical experiments, we prove the models' effectiveness. The proposed static model gives a throughput ratio of over 99%, with a higher preference to use WiFi technology followed by Bluetooth and

Zigbee for data transmission and a maximum resource usage of less than 40% for all three technologies. Requests, in the static model, have an average chance of being granted greater than 50% with a delay ratio under 50% of their delay requirements, which illustrates the capability of the model to grant requests with less delay. In the dynamic setting experiments, the obtained throughput ratio was over 98%. On average, the model splits requests that couldn't be fully granted in one time slot into mostly two time slots, which corresponds to the average duration of the requests based on the geometric distribution parameter we set. The interference analysis proves the dynamic model's ability to prevent interference by using mostly non-conflict channels. However, conflicting channels might be used if the corresponding links are beyond their interference range, which does not generate interference.

3.2 Future Works

Future research can extend the current work in several directions, e.g., including:

- Investigating the MIMC wireless mesh networks' performance by expanding the number of interfaces on nodes
- Employing multi-path routing approaches instead of single-path to provision requests
- Investigating whether AI-based approaches can be beneficial in solving the problem

Bibliography

[1] I. Akyildiz and X. Wang. A survey on wireless mesh networks. *IEEE Communications Magazine*, 43(9):S23–S30, 2005.

[2] A. B. M. Alim Al Islam, M. J. Islam, N. Nurain, and V. Raghunathan. Channel assignment techniques for multi-radio wireless mesh networks: A survey. *IEEE Communications Surveys Tutorials*, 18(2):988–1017, 2016.

[3] E. Alotaibi and B. Mukherjee. A survey on routing algorithms for wireless ad-hoc and mesh networks. *Computer networks*, 56(2):940–965, 2012.

[4] A. Alzubir, A. Yousif, and A. Abuobieda. State of the art, channel assignment multi-radio multi-channel in wireless mesh network. *International Journal of Computer Applications*, 37(4):14–20, 2012.

[5] A. S. Arsalaan, H. Nguyen, A. Coyle, and M. Fida. Quality of information with minimum requirements for emergency communications. *Ad Hoc Networks*, 111:102331, 2021.

[6] A. Baid, S. Mathur, I. Seskar, S. Paul, A. Das, and D. Raychaudhuri. Spectrum mri: Towards diagnosis of multi-radio interference in the unlicensed band. In *2011 IEEE Wireless Communications and Networking Conference*, pages 534–539, 2011.

[7] D. Benyamina, A. Hafid, and M. Gendreau. Wireless mesh networks design—a survey. *IEEE Communications surveys & tutorials*, 14(2):299–310, 2011.

[8] H. Cheng, N. Xiong, G. Chen, and X. Zhuang. Channel assignment with topology preservation for multi-radio wireless mesh networks. *JOURNAL OF COMMUNICATIONS*, 5(1):63, 2010.

[9] D. J. David, V. Jegathesan, and T. J. Jebaseeli. Distributed optimal congestion control and channel assignment in wireless mesh networks. *Telkomnika*, 19(2):414–420, 2021.

[10] Gurobi Optimization, LLC. Gurobi Optimizer Reference Manual, 2022.

[11] S. Harkusha and M. Yevdokymenko. *The Development of Routing Flow Model in IEEE 802.11 Multi-radio Multi-channel Mesh Networks, Shown as a Konig Graph*, volume 5, pages 513–528. Springer, Cham, 2021.

[12] N. Kaur and J. S. Saini. Performance enhancement of 802.11 based wireless mesh network by using multi- radio multi-channel. In *2013 International Conference on Green Computing, Communication and Conservation of Energy (ICGCE)*, pages 71–76, 2013.

[13] E. Kulla, G. Mino, S. Sakamoto, M. Ikeda, S. Caballé, and L. Barolli. Fbmis: A fuzzy-based multi-interface system for cellular and ad hoc networks. In *2014 IEEE 28th International Conference on Advanced Information Networking and Applications*, pages 180–185, 2014.

[14] P. Kyasanur and N. Vaidya. Routing and interface assignment in multi-channel multi-interface wireless networks. In *IEEE Wireless Communications and Networking Conference, 2005*, volume 4, pages 2051–2056 Vol. 4, 2005.

[15] J.-S. Lee, Y.-W. Su, and C.-C. Shen. A comparative study of wireless protocols: Bluetooth, uwb, zigbee, and wi-fi. In *IECON 2007 - 33rd Annual Conference of the IEEE Industrial Electronics Society*, pages 46–51, 2007.

[16] G. Li, C. Hu, T. Peng, X. Zhou, and Y. Xu. High-priority minimum-interference channel assignment in multi-radio multi-channel wireless networks. In *Proceedings of the 2nd International Conference on Telecommunications and Communication Engineering*, pages 314–318, 2018.

[17] S.-H. Lim and Y.-B. Ko. Intellectual priority-based low latency data delivery scheme for multi-interface and multi-channel devices in multi-hop wireless mesh networks. In *2020 IEEE International Conference on Big Data and Smart Computing (BigComp)*, pages 417–419, 2020.

[18] M. K. Marina, S. R. Das, and A. P. Subramanian. A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks. *Computer networks*, 54(2):241–256, 2010.

[19] S. Mirzaie and S. Sedaghat. Joint channel assignment and routing in software defined wireless mesh networks. In *2017 Iranian Conference on Electrical Engineering (ICEE)*, pages 1515–1519. IEEE, 2017.

[20] A. Mohsenian-Rad and V. Wong. Joint logical topology design, interface assignment, channel allocation, and routing for multi-channel wireless mesh networks. *IEEE Transactions on Wireless Communications*, 6(12):4432 – 4440, December 2007.

[21] G. Naidu and J. Kumar. Wireless protocols: Wi-Fi SON, Bluetooth, ZigBee, Z-Wave, and Wi-Fi. In *Innovations in Electronics and Communication Engineering*. Springer Singapore, 2019.

[22] G. Nemhauser and L. Wolsey. *Integer and Combinatorial Optimization*. Wiley, 1999, reprint of the 1988 edition.

[23] K. N. Ramachandran, E. M. Belding-Royer, K. C. Almeroth, and M. M. Buddhikot. Interference-aware channel assignment in multi-radio wireless mesh networks. In *Infocom*, volume 6, pages 1–12, 2006.

[24] A. P. Subramanian, H. Gupta, S. R. Das, and J. Cao. Minimum interference channel assignment in multiradio wireless mesh networks. *IEEE Transactions on Mobile Computing*, 7(12):1459–1473, 2008.

[25] Y. Tian and T. Yoshihiro. Traffic-demand-aware collision-free channel assignment for multi-channel multi-radio wireless mesh networks. *IEEE Access*, 8:120712–120723, 2020.

[26] Y. Tian and T. Yoshihiro. Collision-free channel assignment with overlapped channels in multi-radio multi-channel wireless mesh networks. In *International Conference on Mobile and Ubiquitous Systems: Computing, Networking, and Services*, pages 681–692. Springer, 2021.

[27] A. Tripathi. An efficient hybrid channel assignment protocol for a multi interface wireless mesh network. *International Journal of Research, Science, Technology & Management*, 10:2455 – 2240, February 2018.

[28] N. L. UK. Co-existence of IEEE 802.15.4 at 2.4 GHz-application note. `https://www.nxp.com/docs/en/application-note/JN-AN-1079.pdf`, Nov. 2013.

[29] C. Xin. A layered graph interface assignment algorithm for multi-channel wireless networks. In *Proceedings of 15th International Conference on Computer Communications and Networks*, pages 469–474, 2006.

[30] L. Zhang, X. Wang, and C. Liu. Channel assignment in multi-radio multi-channel wireless mesh network by topology approach. In *2009 WRI International Conference on Communications and Mobile Computing*, volume 2, pages 358–362, 2009.

[31] C. Zhanmao, H. Qisong, and C. Wu. Maximize concurrent data flows in multi-radio multi-channel wireless mesh networks. *Computer Science and Information Systems*, 17(3):759 – 777, 2020.

[32] Y. Zhou. *An Efficient Routing and Interface Assignment Algorithm for Multi-Channel Multi-Interface (MCMI) Ad Hoc Networks*, pages 131–142. Springer International Publishing, Jan. 2018.