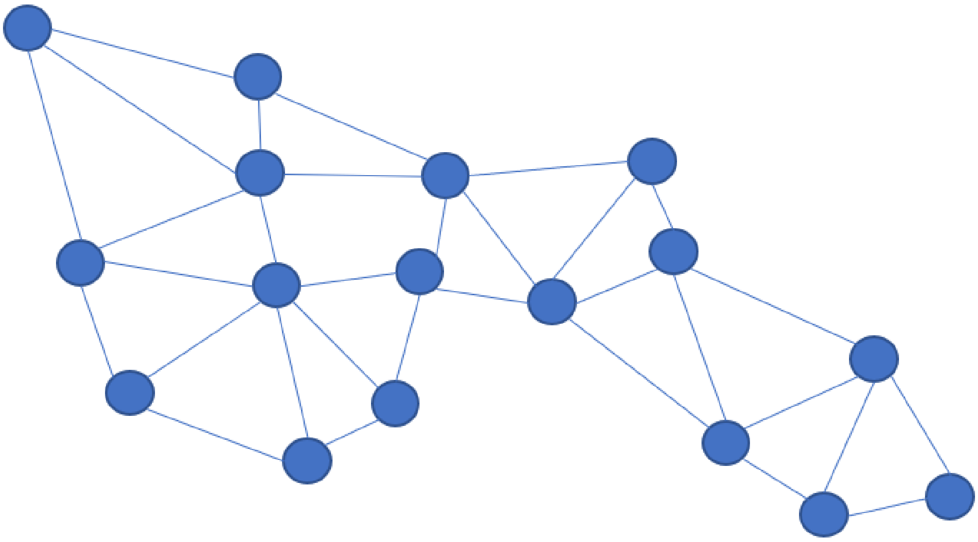
CHALMERS
UNIVERSITY OF TECHNOLOGY



Benefits of adaptivity in time slotted channel hopping systems

Master thesis in Communication Engineering

VAIDYANATHAN KUMAR

DEPARTMENT OF ELECTRICAL ENGINNERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

Master's thesis 2023

Benefits of adaptivity in time slotted channel hopping systems

Vaidyanathan Kumar

Department of Electrical Engineering
Communications Systems group
Chalmers University of Technology
Gothenburg, Sweden 2023

Benefits of adaptivity in time slotted channel hopping systems
Vaidyanathan Kumar

Supervisor: Johannes Arvidsson, LumenRadio AB
Examiner: Tommy Svensson, Department of Electrical Engineering
Chalmers Advisor: Jafar Banar, Department of Electrical Engineering

Master's Thesis 2023
Department of Electrical Engineering
Communications Systems group
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Typeset in LaTeX
Gothenburg, Sweden 2023

VAIDYANATHAN KUMAR
Department of Communications Engineering
Chalmers University of Technology

Abstract

Wireless technology in globally available unlicensed frequency bands, also known as Industrial, Scientific and Medical (ISM) bands, is facing greater challenges due to overcrowding caused by the growing number of wireless devices. The Internet of Things (IoT) expansion across various industries and applications has led to increased congestion, particularly in commercial buildings and industrial settings. In many cases, the congestion has become so severe that wireless solutions are no longer reliable and cannot effectively function. There is a clear need for resilient wireless technology capable of handling congestion, particularly in critical applications.
Wireless Sensor networks (WSNs) are low-power and lossy networks widely used for various applications across various industries on the 2.4 GHz band. Frequency hopping techniques are used to effectively counteract the disturbance and interference. Time Slotted Channel Hopping (TSCH) is a frequency hopping technique used in the Medium Access Control (MAC) layer of low-power lossy networks. Therefore, evaluating the WSNs with TSCH is the main focus of this thesis. Particularly, the application of channel adaptivity used together with TSCH to avoid sources of disturbances is investigated. This possibly mitigates/avoids packet losses and delays in transmissions, improving the overall behavior in an effective way.
The thesis investigates and evaluates the performance of Adaptive frequency hopping. It quantifies the relationship between bandwidth and congestion for static hopping sequences, and how it changes by introducing more informed frequency choices. It evaluates methods of updating hopping sequences, their efficiency, and potential diminishing returns. An implementation of the WiFi behaving as a jammer is made in LumenRadio's in-house simulator MiraSim and from predefined use cases, simulations are run to evaluate the performance of different classes of channel implementations against multiple types of disturbances.
The results show that large mesh networks using adaptive frequency hopping perform better in the presence of multiple jammers. There is a significant increase in the Packet Delivery Rate (PDR), which reduces the latency and power consumption of the nodes by adapting well to good channel conditions and successfully avoiding the channels interfered with by the jammers. There is also a comparison made with other classes of channel utilization to observe how well adaptive frequency hopping performs.

Keywords: Wireless Sensors Networks(WSNs), Time Slotted Channel Hopping(TSCH), Internet of Things(IoT), WiFi, Adaptive Frequency Hopping(AFH)

Acknowledgements

I wish to express my deepest gratitude to my thesis supervisor Johannes Arvidsson to give me the opportunity to work as a MSc thesis student at LumenRadio AB. I thank him for giving valuable suggestions for improvising the report. I would like to express my sincere appreciation to Max Sikström for his guidance throughout the thesis. His insightful ideas and thoughts are greatly appreciated in this project work. Without his constant support and encouragement, the thesis goals would not have been accomplished. I am also equally indebted to Robin Jonsson who helped me with his programming knowledge and skills and constant assistance during tough times. I also thank the Mira Platform team members for their great support throughout the thesis.
I thank my Examiner, Prof. Tommy Svensson, for approving this thesis and Jafar Banar for giving valuable suggestions for improving the report and quickly responding to my queries.
I also wish to acknowledge the support and love of my friends and family, and this project would not have been possible without their support.

Vaidyanathan Kumar, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed :

AFH	Adaptive Frequency hopping
CQI	Channel quality Index
DODAG	Destination Oriented Acyclic Graph
ETX	Estimation number of transmissions
FDMA	Frequency division multiple access
HVAC	Heating, ventilation and Air conditioning
IoT	Internet of Things
IP	Internet Protocol
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
KPI	Key performance indicator
LLN	Low power lossy networks
MTU	Maximum transmission unit
OF	Objective Function
PDR	Packet delivery rate
RPL	Routing protocol for low power and lossy networks
RX	Receiving
TCP	Transmission Control Protocol
TDMA	Time division multiple access
TSCH	Time slotted channel hopping
TX	Transmission
UDP	User Datagram Protocol
WSNs	Wireless Sensor Networks

Contents

List of Figures

List of Tables

1
Introduction

The ecosystem of the Internet of Things (IoT) consists of smart devices that are connected to the Internet and embedded systems equipped with sensors and actuators. These smart devices collect data from their surroundings and perform tasks based on the acquired information. With the advent of this technology, IoT devices have been increasing, driving its inclination in new business areas and many different applications in various industrial domains [2]. The field of sensors, communication and information technology is constantly evolving at a very high pace resulting in the proliferation of Wireless Sensor Networks (WSNs).

1.1 Company Background

LumenRadio AB is a wireless technology company that provides ultra-reliable and ultra-low power device-to-device wireless connectivity for most business-critical applications. They work in different domains, from entertainment lighting control to heavy-duty industrial applications. They offer radio modules and an embedded software solution based on their patented technology "Cognitive Coexistence". LumenRadio has seen a need in various industries for more complex networks at lower cost while maintaining low power consumption and low resource usage.

1.2 Background

Wireless technology in globally free Industrial, Scientific and Medical (ISM) bands is experiencing increasingly tough environments due to congestion, driven by the proliferation of wireless devices. IoT is driving this incline in many different applications and business areas, and increasing congestion can be seen in commercial buildings and industry. Oftentimes, the congestion is so significant that wireless solutions are unreliable to the point of being useless. The demand for robust wireless technology that can handle congestion is clear, specifically in critical applications. Frequency hopping [3] is a technology that aims to mitigate the effects of congestion by constantly moving around in the spectrum avoiding other wireless signals in the air. In a frequency-hopping scheme with many channels, there will eventually be some spectrum left over for communication to take place. However, in very congested environments the ratio of “good” to “bad” channels will be low, and very little of the communication will succeed [4]. Also, robustness to interferences is an increasingly valuable quality in wireless low-power lossy networks. It is particularly true in 2.4 GHz, where many wireless technologies operate, making it crowded.

LumenRadio's wireless technology implements Adaptive Frequency Hopping (AFH) allowing reliable communication. MiraOS is an embedded OS and IPv6 stack, also known as the MiraMesh networking stack which uses AFH. MiraMesh is a routed mesh network that is IPv6 based and operates on a 2.4 GHz frequency band. Its networking architecture is designed to operate on battery-powered devices, providing reliable communication and end-to-end connectivity.

1.3 Aim

The aim of this thesis is to evaluate the performance of Adaptive Frequency Hopping (AFH) in a highly congested radio environment. Different use cases are considered to evaluate the performance of AFH in different scenarios. The evaluations are conducted by identifying relationships between Key Performance Indicators (KPI) including Packet Delivery Rate (PDR), latency and power consumption.

1.4 Scope

This thesis mainly focuses on the efficacy of adaptive frequency hopping in congested environments against multiple types of disturbances. It identifies relationships between different Key Performance Indicators (KPIs) and finds compromises between them. The evaluation is done using technologies from LumenRadio, which limits the scope to evaluating networks using the 2.4 GHz spectrum using a Bluetooth physical layer. Networks are typically 10-100 devices with star or mesh topology. The network technology is focused on extreme reliability, low latency, and low power consumption. The use cases considered in this thesis are based on LumenRadio's industrial real-world use case.

1.5 Outline

The thesis report comprises five chapters: Introduction, Theory, Methods, Results, and Conclusions. The introduction provides a summary of the thesis work, while the theory chapter delves into the fundamentals of Frequency hopping and elaborates on adaptive frequency hopping. It also covers the basics of the MiraOS network stack and WiFi technology. In the methods section, the report outlines the modeling of interference and describes the simulation setup employed. Additionally, this section concludes by specifying the use cases considered in the thesis. The results chapter presents the findings from the simulations and evaluations conducted throughout the thesis. The conclusion and Future work section serves as a conclusion to the report, summarizing the key findings and suggesting areas for improvement in future work.

2

Theory

2.1 MiraMesh Networks

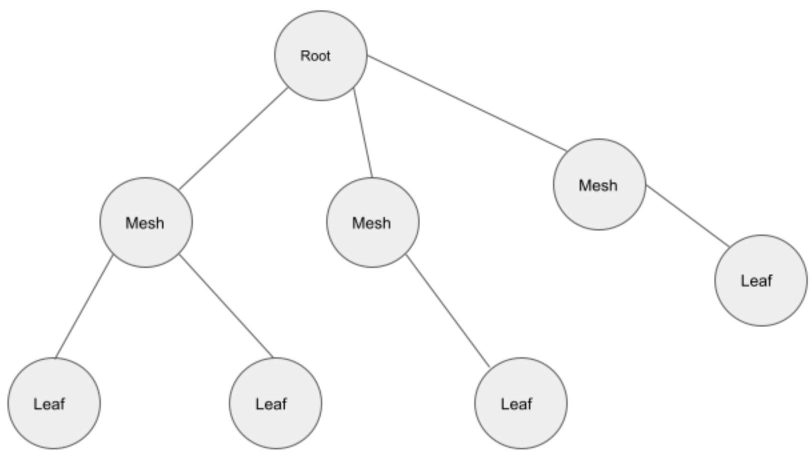


Figure 2.1: An example of the mesh network

MiraMesh networks [5] use the concept of mesh networking. MiraMesh networks are self-organizing, self-healing wireless networks. The nodes in the MiraMesh networks connect to one and only one node. They can dynamically change the connection, and maintain information about all nodes within the hearing range to be able to qualify which node is best. An example of the MiraMesh network is shown in figure 2.1. There are different roles that nodes can play in the MiraMesh networks. They are classified as follows.

Root node:
The root node commonly known as the gateway, is the root of the routing tree. All other nodes in the MiraMesh network are formed around the root node. The root node is the heart of the MiraMesh network which chooses the possible route to

effectively transmit the data from one node to another node in the network.

Mesh node:
The mesh node in the MiraMesh network helps forwarding data to and from the other nodes. Mesh nodes are commonly referred to as routing nodes.

Leaf node:
The leaf node in the MiraMesh network doesn't have the routing capability to route traffic to and from the other nodes.

2.1.1 Nodes Joining Process :

The nodes within the MiraMesh network follow to a specific method when connecting to the network. The process is explained below.

The nodes joining Process comprises three steps. They are Scanning, Associated and Joined. When node is on or starts the stack, it starts scanning for the available network. If it doesn't find any network within 5 minutes, the node will stop scanning for 5 minutes to preserve the battery. If the node finds a network within 5 minutes, the node gets "Associated" with the network and it becomes part of the frequency hopping. In the "Associated" state, the routes are not established and hence cannot send network traffic. When the node is in the "Joined" state, the routes are established to the node and can start sending packets.

2.2 MiraOS Network Stack

MiraOS is an embedded OS that consists of MiraMesh Networking with built-in IPv6 networking. MiraMesh uses Adaptive frequency hopping (AFH) achieving ultra-low energy reliable communication and also ensures resilience towards external disturbances by adapting the network to the environmental conditions. MiraMesh uses 6LoWPAN enabling compatibility to any UDP/IP protocol. 6LoWPAN is responsible for packet fragmentation and compression to be able to send packets lesser than the limited Maximum Transmission Unit (MTU) by the physical layer. MiraOS uses Time Slotted Channel Hopping (TSCH) as the MAC layer.

2.2.1 MiraOS Supported Hardware

MiraOS-supported hardware or MiraOS target platforms are the Nordic Semiconductors nRF52832 [6] and nRF52840[7] along with the NXP MKW41Z. The platform also provides a 2.4GHz BLE or a 2.4GHz dual-mode BLE and IEEE 802.15.4 radio.

2.3 Time Slotted Channel Hopping

Time Slotted Channel Hopping or TSCH is a channel access method used by the Medium Access Control (MAC) layer. It is used mainly by low-power devices to communicate over a wireless link. TSCH not only provides a reliable MAC layer but is also designed for Low power Lossy Networks (LLNs)[8]. TSCH uses time slots and also assigns different channels for different slots. One can infer that TSCH is the combination of Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) [9]. Therefore it uses both time and frequency diversity providing reliable low-power communication over wireless networks.

2.3.1 Basics Of Mira Frequency Hopping

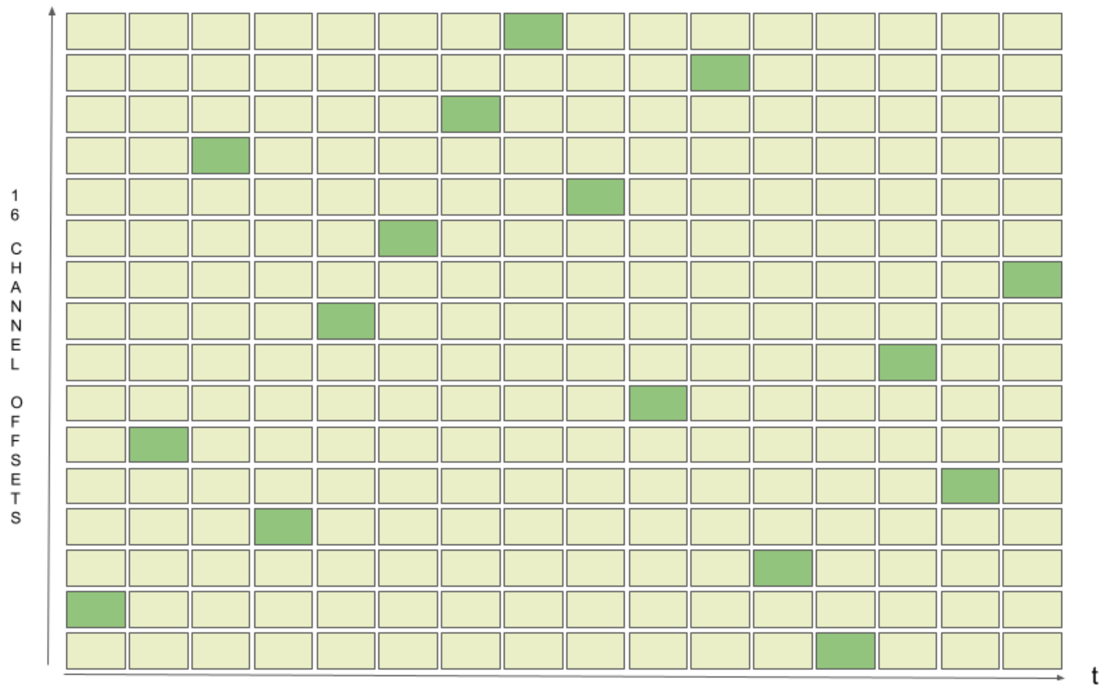


Figure 2.2: The figure represents TSCH where dark green color slots depict that transmissions happen in each channel for every slot.

MiraMesh networks use TSCH to provide reliable communication. Mira uses the 2.4 GHz frequency band. An example of TSCH is shown in figure 2.2. The entire frequency band is split into 16 channel bands each with 1 MHz bandwidth and they are spread out with a 4 MHz interval. In Mira, the duration of each slot is 10 ms. Each slot can be used for sending or receiving the data packets. When sending packets, the slot is considered as TX slot and for receiving packets, it is considered as RX slot. The radio is powered on when the slot operation happens. It also assigns different channels for each slot. This creates a time schedule for each node to either transmit or receive. Therefore, this reduces the time for each node to keep the radio on. Tight synchronization is needed among the nodes due to physical variations of the clocks causing crystals drift.

2.3.2 Adaptive Frequency Hopping

Adaptive Frequency Hopping (AFH), a frequency hopping technique, is the ability of the communication nodes to adapt to the environment by identifying the interferences and continuously changing to good channels to avoid the interferences. In Mira, the frequency hopping sequence using AFH depends on the Channel Quality Index (CQI). The CQI is usually calculated by the mesh nodes and they send the CQI information to the root. The frequency hopping sequence is generated by the root node. The frequency hopping sequence is generated after accumulating the CQI values that are sent by the mesh nodes to the root. The root weighs the importance of each channel based on the accumulated CQI. The channel quality is determined by the ability of each node to have a successful transmission on a particular channel. If a successful transmission occurs, that particular channel is termed as "good" and adds more weightage. If a failed transmission occurs, that particular channel is termed as "bad" and adds less weightage. Based on this, the frequency hopping sequence is generated containing more repetition of the good channels thereby adapting to the environment. The MiraMesh network using AFH continuously changes the channel every time and adapts to better channels if either intentional or unintentional disturbances occur.

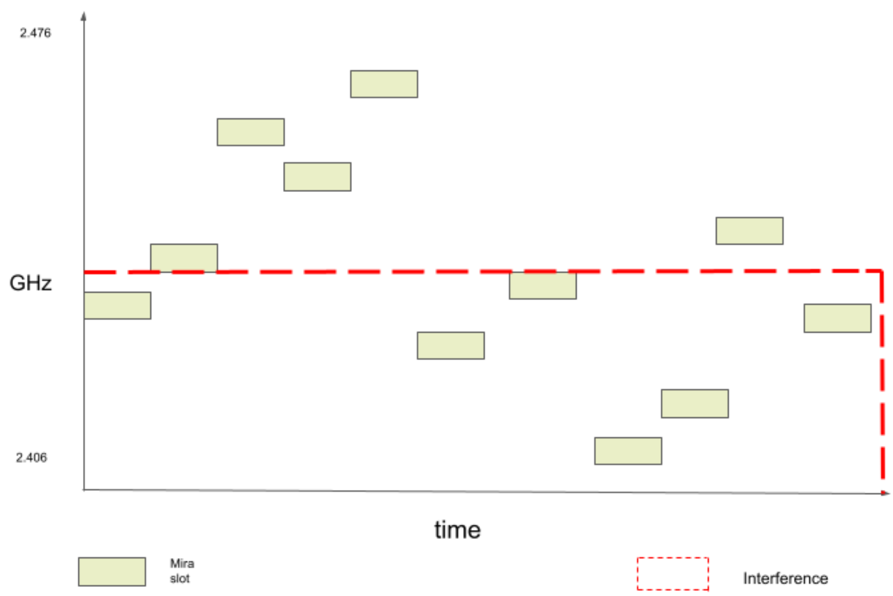


Figure 2.3: Frequency hopping

Figure 2.3 shows that a part of the spectrum is affected due to interference. From

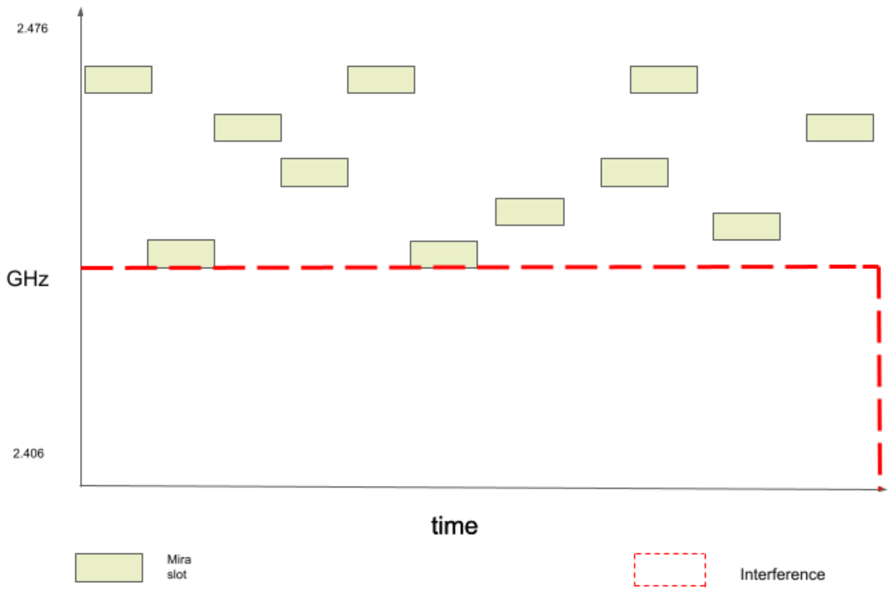


Figure 2.4: Adaptive Frequency hopping

the figure 2.4, it can be seen that the nodes adapt to good channels using AFH and the channels that are interfered are not used.

2.3.3 Network Parameters And Measurement Points

Channel Quality index (CQI) determines the quality of the frequency channel. CQI is a tool used to achieve adaptability. Depending on the values of CQI, the root differentiates the channels into good and bad channels. Generally, the lower the value of CQI, the greater the quality of the channel. Each mesh node in the MiraMesh network sends CQI to the root. CQI for all channels gets reported to the root.

All nodes track the estimated number of transmissions (ETX) per link. ETX influences node parent choice. In general, it is the metric of link quality. In the Mira mesh network, the packet loss of each node depends on the link quality of their parent node. In the Mira mesh network, the maximum number of re-transmissions is 7. If the number of re-transmissions exceeds 7, it results in a packet loss. Increasing the number of re-transmissions also increases the value of ETX. The greater the value of ETX, the poorer the parent link quality of a particular node.

Rates	0	8	10
Time between listening slots(ms)	10	470	1270

Table 2.1: Performance of different rates

Rate determines which slots to execute and also determines how fast a particular slot can be executed. The rate decides how often listening slots are executed. This gives the user of the mesh network to modify the transmission capabilities according to their application needs.

2.4 Routing Protocol For Low-power And Lossy Networks

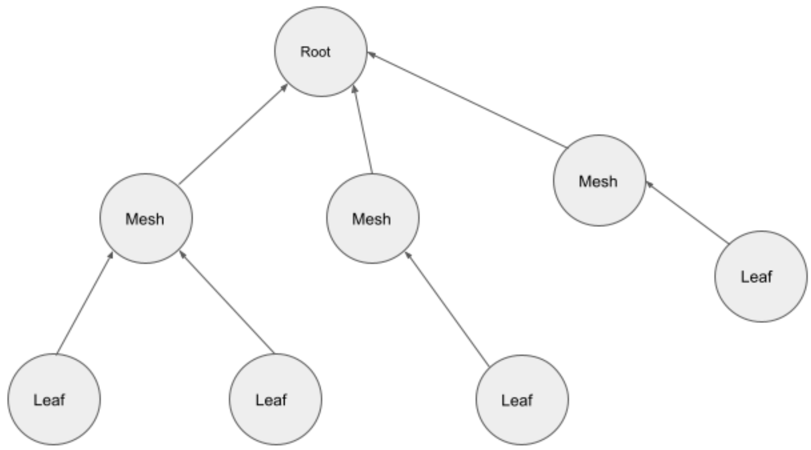


Figure 2.5: Routing of the MiraMesh Network using DODAG

Routing protocol for low power and lossy networks also known as RPL creates a robust and efficient routing for connecting nodes in MiraMesh networks. RPL can handle point-to-point, point-to-multipoint and multipoint-to-point efficient routing structures. RPL is a layer 3 routing protocol and is targeted for low-power networks. It optimizes the sending of packets over the lossy links from the nodes in the network to the root node and vice-versa.
RPL uses Destination Directed Acyclic Graph (DODAG) for maintaining network topology. There is no cyclic path. All paths are oriented and point toward the root. Hence, the packet between any two nodes is routed via the root node.

Figure 2.5 represents an example of routing topology using DODAG. The arrows are pointed toward the root and are also acyclic.
The DODAG uses an objective function (OF) to calculate the rank. All nodes in the MiraMesh network maintain rank. The main purpose of the rank is for the nodes

to choose their desired parent[10].

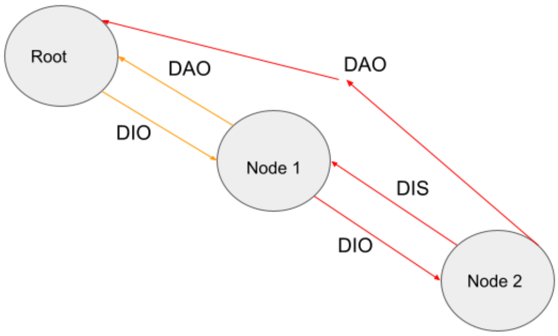


Figure 2.6: Routing of the MiraMesh network with ICMPv6 control messages. Different color describes two different joining times of the mesh nodes. The red link depicts when node 2 joins the existing RPL network.

ICMPv6

ICMPv6 is an integral part of IPv6 and is responsible for providing feedback about the status of the packets that are sent in the mesh networks. RPL relies on ICMPv6 to support the efficient routing of messages throughout the whole mesh network. In short, RPL uses ICMPv6 for the distribution of the control messages to maintain the routes in the network. [11]. The different types of control messages are :

- DODAG Information Solicitation (DIS)
- DODAG Information Oject (DIO)
- Destination Advertisement Object (DAO)
- Destination Advertisement Object Acknowledgement (DO-ACK)

The process of constructing a DODAG starts with the root node sending DIO messages to its neighboring nodes. When a node receives a DIO message, it can respond by sending a DAO message if it wants to join the DODAG. The root or parent node then sends a DOA-ACK message back to the node that sent the DAO message. If a new node wants to join an existing DODAG, it sends a DIS to join the RPL network. The DIS message includes information about path cost and other metrics. If the new node decides to join, it sends a DAO message that is propagated to the root of the DODAG [12]. The routing is also shown in figure 2.6.

2.5 IEEE 802.11 Networks

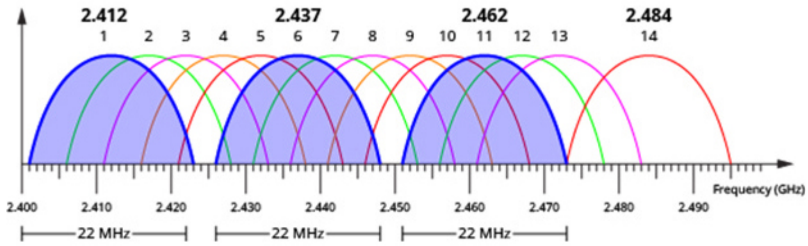


Figure 2.7: WiFi spectrum [1]

IEEE 802.11 networks or commonly known as WiFi networks are widely deployed in home and office environments. WiFi uses both 2.4 GHz and 5 GHz bands to perform an operation for wireless networks. The 2.4 GHz is broken down into 11 sub-channels(1-11) each 22 MHz wide. These sub-channels overlap with each other. Depending on the country, the channel numbers vary. In Europe, 1,6 and 11 channel bands are usually used because these bands don't overlap or interfere with each other (figure 2.7). The base channels are 22 MHz wide which are identified by the center frequency.

Why WiFi ?
MiraMesh networks share the 2.4 GHz ISM license-free band with many other wireless technologies such as IEEE 802.11b/g networks, Bluetooth, Zigbee networks and a few more [13]. MiraMesh networks are mainly vulnerable to interferences introduced by IEEE 802.11 WLANs because MiraMesh networks use low output powers between 3.5 dBm and 20 dBm whereas IEEE 802.11 networks operate at high power limited to 30 dBm in North America and 23 dBm in Europe. Therefore, due to heavy interferences introduced by IEEE 802.11, Mira nodes face difficulties in accessing the channels to transmit large packets. Therefore, this thesis primarily concentrates on examining the behavior of LumenRadio's wireless technology, which employs AFH, when confronted with significant interference such as WiFi. The primary inquiry also centers around the reaction of AFH in the face of such interferences.

3
Methods

This chapter discusses the different implementations that are considered to be used to evaluate the performance of AFH. The implementation is evaluated using simulations for all the test cases that are considered for this thesis.

3.1 Classes Of Channel Utilisation And Disturbance Scenarios

Various categories of channel utilization and disturbance scenarios are taken into account for this thesis. These are explained in detail in the subsequent subsections.

Disturbance Scenarios
In this thesis, various disturbance scenarios have been considered for the simulations: One can imagine many different disturbance scenarios. There are four different aspects to consider when interference interferes with the nodes in the Mira mesh network. They are:
1) The bandwidth of the interference node: To identify which frequencies are blocked. These can be categorized as narrowband or broadband frequencies.
2) The locality of the interference node: To find the coverage of the interference node. These can be understood as which parts of the network are affected.
3) The periodicity/ duty cycle of the interference node - To find out the activity of the disturbance
4) The number of interference present in the network.
The disturbance scenarios include: Single narrowband disturbances that only interfere with one channel. Multiple narrowband disturbances interfere with many channels (but not all). Based on the coverage, these disturbances are divided into disturbances affecting the whole network and affecting only a part of the network. Also in terms of periodicity, it is classified as either always on (100 % duty cycle) or intermittent (variable duty cycle) disturbances.

Classes Of Channel Utilisation
In this thesis, different disturbance scenarios are evaluated with different types of channel utilization. The different classes of channel utilization [14] that are considered are:
1) single channel network
2) TSCH without adaptivity
3) TSCH with adaptivity (or AFH)

3.2 WiFi Interference

The WiFi interference is considered in this thesis as the source of the disturbance. In real-time scenarios, interference due to WiFi over the mesh networks has a greater influence than the other wireless technology that performs in the same frequency spectrum. WiFi operates at high power and wideband transmission with respect to the MiraMesh networks [15]. Hence, this thesis limits modeling the behavior of the WiFi that almost mimics the real-time behavior. The behavior of WiFi with respect to frequency is shown in figure 2.7.
The amount of WiFi traffic in the 2.4 GHz band depends on the user's usage. Different applications contribute to different degrees of channel interferences. Two factors define how WiFi traffic is shaped in the time domain; burst length/burst size and inter-burst separation. Burst length is how many packets are sent in each burst, and inter-burst separation is the time between bursts. High data applications use long bursts and/or low inter-burst separation, which has a high spectrum occupancy making them a stronger source of disturbance. Inversely, low data applications have short bursts with long times in between them, lowering their potency for disturbance. The usage pattern differs for different applications over time depending on the user's needs. But there is also a stable pattern generated by the WiFi Access Points (APs) which are the control signaling on the WiFi channels. The WiFi control signalling is part of the Management Frames which follows IEEE 802.11 a/g network protocol. Control messages in the management frame include WiFi beacons, probe responses from the access points and probe requests from the WiFi clients.

3.3 Simulator Implementation

The simulator is used in this thesis to simulate a network that consists of various nodes. The maximum size of the nodes can vary from 100 to thousands in number. The simulator that is used for this thesis is MiraSim. MiraSim is developed at LumenRadio. It is the in-house simulator. The simulator is entirely developed in Rust [16]. MiraSim simulates only the radio medium and it is event-driven. There are various types of radio mediums that have been implemented in MiraSim. One of them is the ITU Indoor Propagation Radio Model. The ITU radio model is used as a radio medium in this thesis. All the simulations are done using this particular radio medium.
The ITU Indoor Propagation Radio Model computes the path loss of a communication link inside an indoor environment. This model is mainly suitable for indoor environments and approximately calculates the total path loss that each node link experiences [17]. This model is also suitable for all wireless devices that operate in the 2.4 GHz band.
The mathematical formula for this model is defined below

$$L = 20 * \log_{10} f + N * \log_{10} d + P(n) - 28$$

where,

L = The total path loss. Unit: decibel(dB)
f = Frequency of transmission (expressed in MHz)
d = Distance (in metres(m))
N = distance power loss coefficient
p(n) = floor loss penetration factor.

In the MiraSim simulator, all the nodes are connected to the MiraSim controller through a TCP stream connection. The nodes run on the native platform of the system containing the MiraMesh stack. All nodes in the MiraMesh network run independently of each other. They are run asynchronously to each other. For the communication to happen, the controller checks the TX and RX times and checks if the TX time is in the range of the RX node's time slot. Since the nodes are connected to the controller via the TCP connection, the nodes also inform the controller about the start time of the transmissions if it is in the TX slot and also inform the start time of the reception if it's in the RX slot. Based on this, the MiraSim controller matches the TX and RX timestamps for all the nodes. Then, the controller schedules the timestamps for each slot either TX or RX, for all nodes, during the entire simulation period.

3.3.1 Key Performance Indicators

The focus of the thesis is to evaluate the performance of different classes of adaptivity for different disturbance scenarios. Evaluating the KPIs are one way of comparing the performance of any communication system. The main purpose is to identify the relationships between Key Performance Indicators (KPIs) and find compromises and trade-offs between different metrics. The KPIs considered for this thesis are explained in detail.
This thesis will measure performance with three metrics:

Packet Delivery Rate
The packet delivery rate (PDR) defines the percentage of successful transmissions for all the nodes in the network for the entire simulation. The PDR is measured in percent. The PDR is calculated as,

$$PDR(\%) = (\frac{N_r}{N_t}) * 100$$

where,
N_r is the number of received packets
N_t is the number of transmitted packets

Latency
The latency is defined as the measure of delay between the communication link of root and mesh nodes. The latency is measured in milliseconds.

Current Consumption
The current consumption is calculated by sampling the energy used over time. Lu-

menRadio has already created a model of the current consumption of the nRF52840 chip. As a result, the MiraOS uses this current consumption model providing an estimation functionality. The entire evaluation of the current consumption is done only using the simulation and there is no real hardware setup to measure this metric. The current consumption of the entire network and also for each node is calculated and estimated.

3.4 WiFi Implemented As interference Node

Figure 3.1 explains the implementation of both Mira and interference nodes. The Mira nodes are compiled to the native MiraMesh Stack except for the radio layer. The radio layer also called radio medium is simulated in the MiraSim simulator. The interference node which is implemented doesn't contain the MiraMesh Network stack but uses the same radio medium to communicate and therefore creates interference to the Mira nodes in the MiraMesh network. The nodes are connected to the MiraSim simulator through a TCP stream connection. The interference node is implemented the same way as the Mira node. This is done in order for the interference node to be compatible with the MiraSim simulator. Mira node connects to the simulator through a set of predefined commands for TX and RX. Similarly, for the interference node, the commands are created using the same format that is used for the Mira node. These commands are essential as they are responsible for transmitting packets through The TCP connection stream. The functionality of the command includes timestamps of the start time, end time, transmitting power and the current channel used. These commands are used in order to differentiate between the transmission of data packets from the Mira node and the interference node. Figure 3.2 depicts the TCP connection setup. As discussed, different applications that are used over WiFi differ in burst duration and inter-burst separation. These two parameters are considered for modeling the behavior of WiFi as an interference node. More about these are explained in the next section.

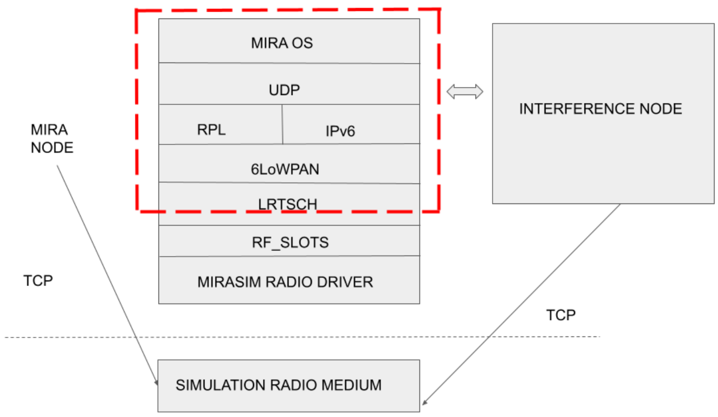


Figure 3.1: Implementation setup of both Mira node and interference node

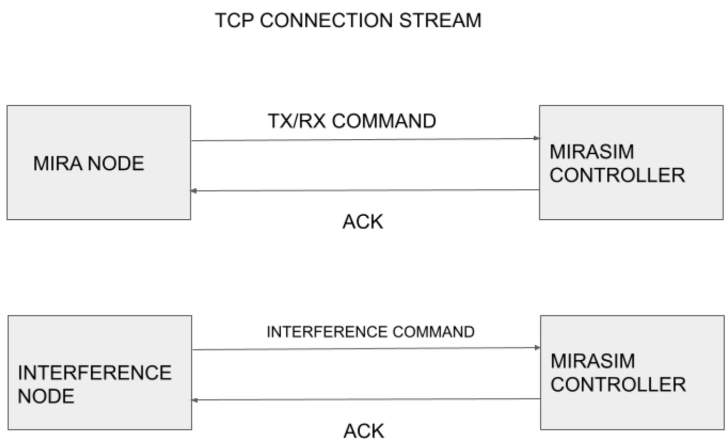


Figure 3.2: TCP connection stream

3.4.1 Distinguishing Channel Traffic

There are different applications that are considered when using WiFi. In the real-time scenario, multiple users use WiFi for different applications. These different applications create different channel traffic. The impact of the channel traffic over a wireless network is determined by many factors based on usage trends/patterns. The different applications that can be considered are file download/file transfer, Web browsing and video streaming over WiFi. For this thesis, the above-mentioned applications are considered.
To empirically determine the inter-burst separation and burst length/burst size for different applications, the values are considered from one of the research papers [18]. In networking, the burst is defined as the continuous sequence of data packets that are being transmitted for a particular duration. This specific duration is also known as burst duration. Normally, the burst size is determined by the maximum amount of traffic allowed to pass through. According to article [19], every WiFi router sets the burst-size limit. In theory, the burst size is calculated as 10 * MTU, where MTU is the Maximum Transmission Unit in bytes. The main motive of this thesis is to model the behavior of WiFi working as interference rather than focus on its exact implementation. Hence, the burst size limit is not considered. Considering the assumption and for simplicity, the burst duration is calculated as the amount of traffic in the network(burst length) over the data rate where, the amount of traffic is in bytes and the data rate is Mb/s.
For different cases, the burst duration has been calculated and recorded in the table 3.1. The table 3.1 considers the data transfers over WiFi for different applications and WiFi beacons. WiFi also transmits beacons every 100ms periodically. This is also taken into account while modeling the behavior of WiFi as an interference node. From the table, each application has a different burst duration. This is because variable amounts of traffic are considered to obtain variations in the behavior rather than having the same type of traffic.

Application type	Inter-burst Separation (ms)	Burst duration(ms)
File download/File transfer	23	600
Streaming video	63	100
Web browsing	146	8
WiFi beacons	100	0.006

Table 3.1: Table shows the variation of burst duration and inter-burst separation for different applications used over WiFi

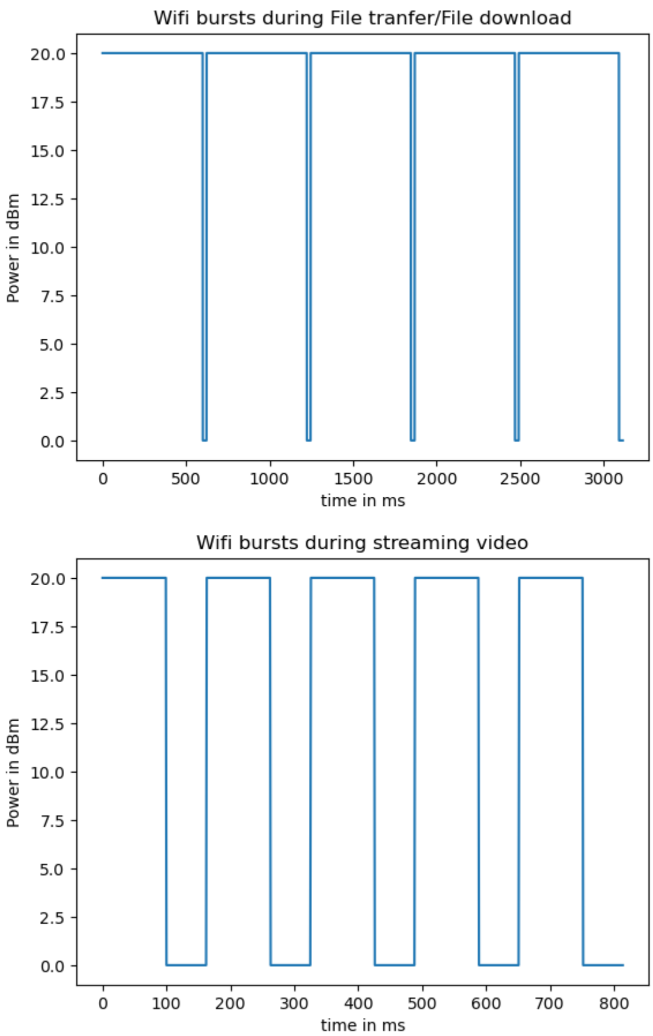


Figure 3.3: WiFi bursts during file transfer and video streaming

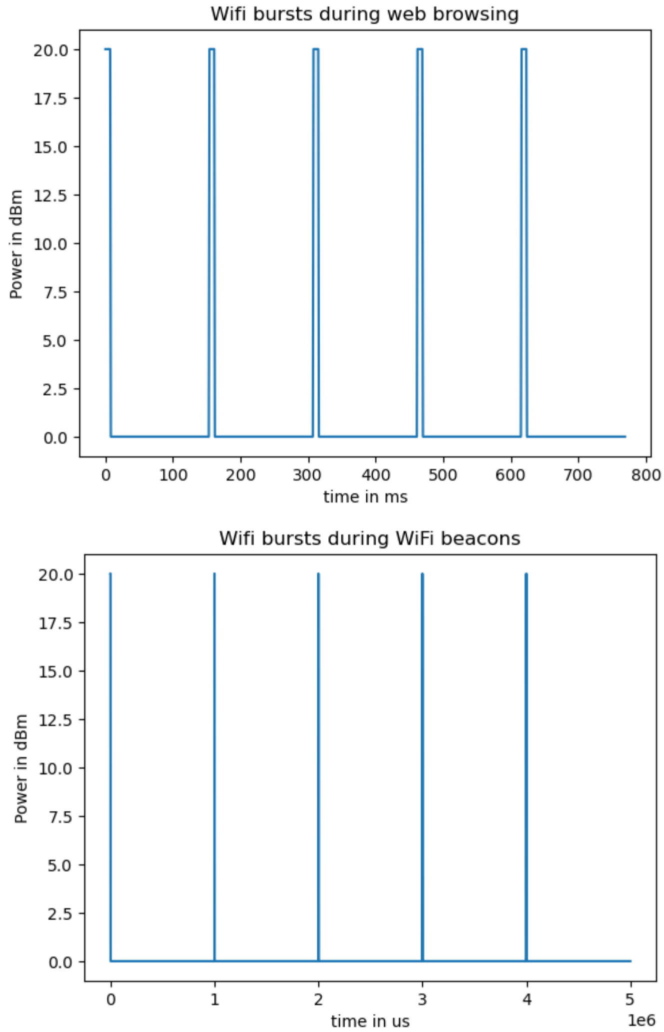


Figure 3.4: WiFi bursts during web browsing and transmission of WiFi beacons

3.5 Simulation Use Cases

For setting up the simulation environment, different parameters need to be set. These parameters need to be set in order to simulate real-world use cases. The use cases for different scenarios are defined below. The parameters for different use cases mainly depend on

- Number of nodes
- Placement of nodes
- The number of concurrent disturbances.
- Duration of the simulation time
- The radio range for the simulation
- KPIs measured for each scenario of the simulation environments

The use cases that are considered in this thesis are based on LumenRadio's industrial real-world case. With the help of these use cases, the simulation is carried out by introducing different types of disturbances with different classes of channel utilization. Two different LumenRadio industrial use cases are considered for this thesis.

3.5.1 Building Automation

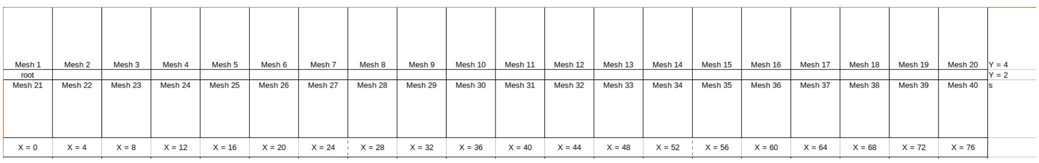


Figure 3.5: Building Automation Topology

Building automation is the automatic centralized control of the building's HVAC (Heating, Ventilation and Air Conditioning)in different locations of the building. The benefits of building automation are it performs the efficient operation of the building systems, consume low energy and reduction of maintenance cost. The need for Building automation is growing and the demand for it is increasing. Using wireless technology in buildings is robust and beneficial since that eliminates the need for cables which reduces the installation cost and can enable new use cases.

Scale
The locality is chosen as the interior corridor of the hotel. The nodes are placed at different locations at different doors, ceilings and windows. The size of the room inside the hotel is 4 m wide and 76 m long.

Topology
There are 40 nodes placed. All the nodes are battery-powered and each node doesn't have a line of sight between each other. There are also many WiFi access points that are chosen and can vary from 1 to 3 WiFi access points. The topology is shown in figure 3.5. In the topology, X donates the x-coordinate and Y depicts the

y-coordinate of the placement of the mesh nodes and root node.

KPIs

In this use case, the primary metrics of concern are latency and current consumption. Given that the nodes operate on batteries, it is crucial to minimize power consumption for prolonged battery life. Moreover, in home automation scenarios, fast communication between nodes is essential, necessitating low latency in the wireless network, particularly for high-critical situations. Additionally, achieving a high PDR is important for ensuring reliability. Therefore, evaluating and considering PDR, latency, and current consumption are vital metrics across various disturbances in wireless networks with different levels of channel utilization.

3.5.2 Condition Monitoring

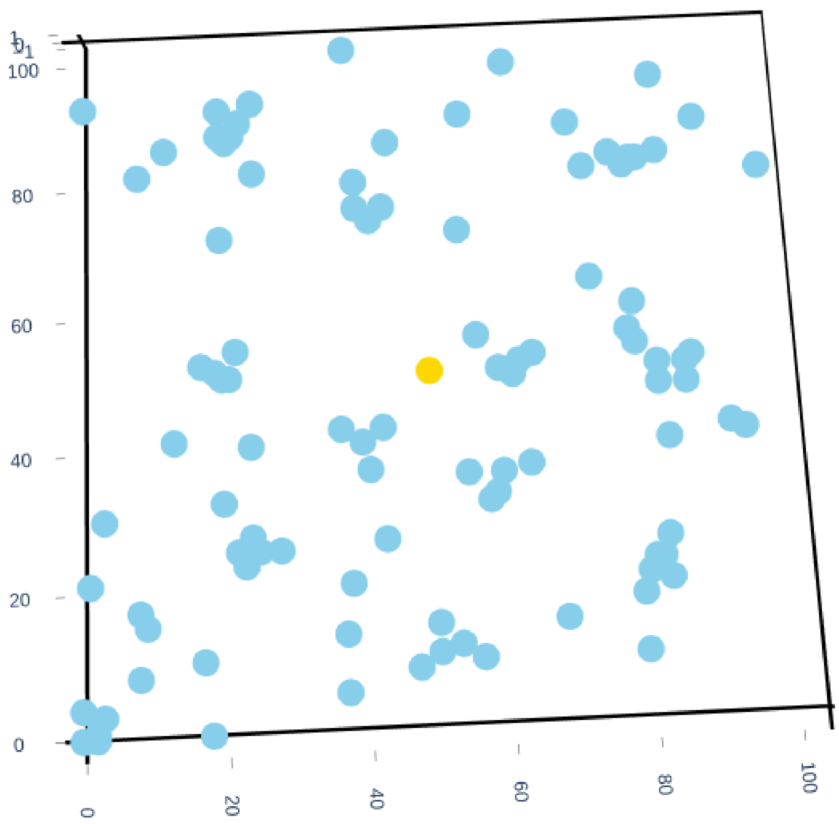


Figure 3.6: Condition Monitoring Topology

Condition monitoring is widely used in the machinery industries to continuously monitor the data from different sensors (namely, temperature sensor, humidity sensor and vibration sensor). This is done to monitor the efficiency of the machinery and therefore needs a timely replacement if found faulty or repaired. By continuously getting the reports from the sensors, it is easy to estimate the lifetime of the machinery. The need for this use case is to improve efficiency and increase the lifetime of industrial machinery. In the industry, there are a number of WiFi access points as there are many people in the industry who use WiFi for different purposes.

Scale

The number of nodes is chosen to be 100 and the number of interference chosen is 4. The number of interferences is chosen such that WiFi uses the entire band of 2.4 GHz. With this setup, the simulation setup is chosen to be 10 hours. From figure 3.6, the blue dots represent the mesh nodes and the yellow dot represents the root node. To also complete the study, the simulation is also done for choosing different numbers of interference to compare the performance.

Topology

The placement of the nodes is in accordance with the defined location set by the LumenRadio test setup. The placement of the nodes is in a 100 by 100-meter square.

KPIs

The simulation for this use case involves the consideration of various KPIs that are selected based on the specific requirements of the use case. Given the continuous transmission of report data from the sensor, measuring network latency becomes crucial to ensure the timely reception of these reports. Additionally, achieving the desired data necessitates evaluating Packet Delivery Rate (PDR) as another important KPI. Given that the sensor nodes operate on batteries, it is vital to measure and calculate current consumption in order to optimize battery usage and extend overall lifetime.

4

Results

In this section, the obtained results from the simulations are examined. The simulations encompass all use cases and encompass various combinations to comprehend the behavior of the MiraMesh networks. Each case is varied with different parameters that are mentioned in section 3.5.
Three distinct sets of simulations are conducted for each use case, each representing a specific topology with a different class of channel utilization. The simulations are executed using three different approaches: a single channel, Static Frequency Hopping Sequence (or TSCH without adaptivity), and Adaptive Frequency Hopping (or TSCH with adaptivity). In each case, KPIs such as PDR, latency and current consumption are calculated. Furthermore, the packet dynamics for each case are visualized through plots that illustrate packet loss, link quality (or ETX), and parent change links. The placement of the interference nodes is also specified for each use case.
At the end of the simulations, the results are stored in the log file. The data stored in the log file are collected and parsed to obtain the necessary KPIs for investigating the differences for different use cases.

Plot Interpretation
The plots in each case depict how the mesh network with different classes of channel utilization reacts to the interferences that are introduced. The way each plot can be interpreted as; each block represents the packet transmitted. The block can vary from dark green to red. This means that the block with dark green has good link quality or low ETX and the red ones have poor link quality or high ETX. The ETX scale is also mentioned in the plot. The blue dotted represents the packet drop or packet loss. The x-axis depicts the time of duration and the y-axis represents the list of mesh nodes in the network. The number on each line represents the parent change(depicted as the node number). The orange stars represent that nodes are "not joined" and the red stars represent that the nodes are "not associated".

4.1 Building Automation

In this scenario, the interference node is placed at the start, middle and end of the mesh network. This is done such that the interference node affects the whole network. It is interesting to observe how MiraMesh networks using adaptive frequency hopping (AFH) react to the interferences. The interference nodes use all the 16 channels used by the Mira nodes. Thus all channels are interfered. But, the level of interferences varies because of different burst duration and inter-burst separations when used over WiFi. Therefore, WiFi uses Mira Channels 1-11 for data transfer and Mira Channels 12-16 for transmitting WiFi beacons.

TSCH With Adaptivity (Adaptive Frequency Hopping)
The figure 4.1 shows the dynamics of packet transmission for each node in the topology. Initially, during the early stages of the simulation, the ETX (Expected Transmission Count) exhibits a high value due to the influence of disturbances caused by WiFi nodes. However, as time progresses, the ETX decreases, indicating an improvement in the link quality between the nodes. This observation signifies the presence of adaptivity within the network, where the nodes adapt to favorable channel conditions, thereby avoiding the disturbances caused by WiFi nodes.

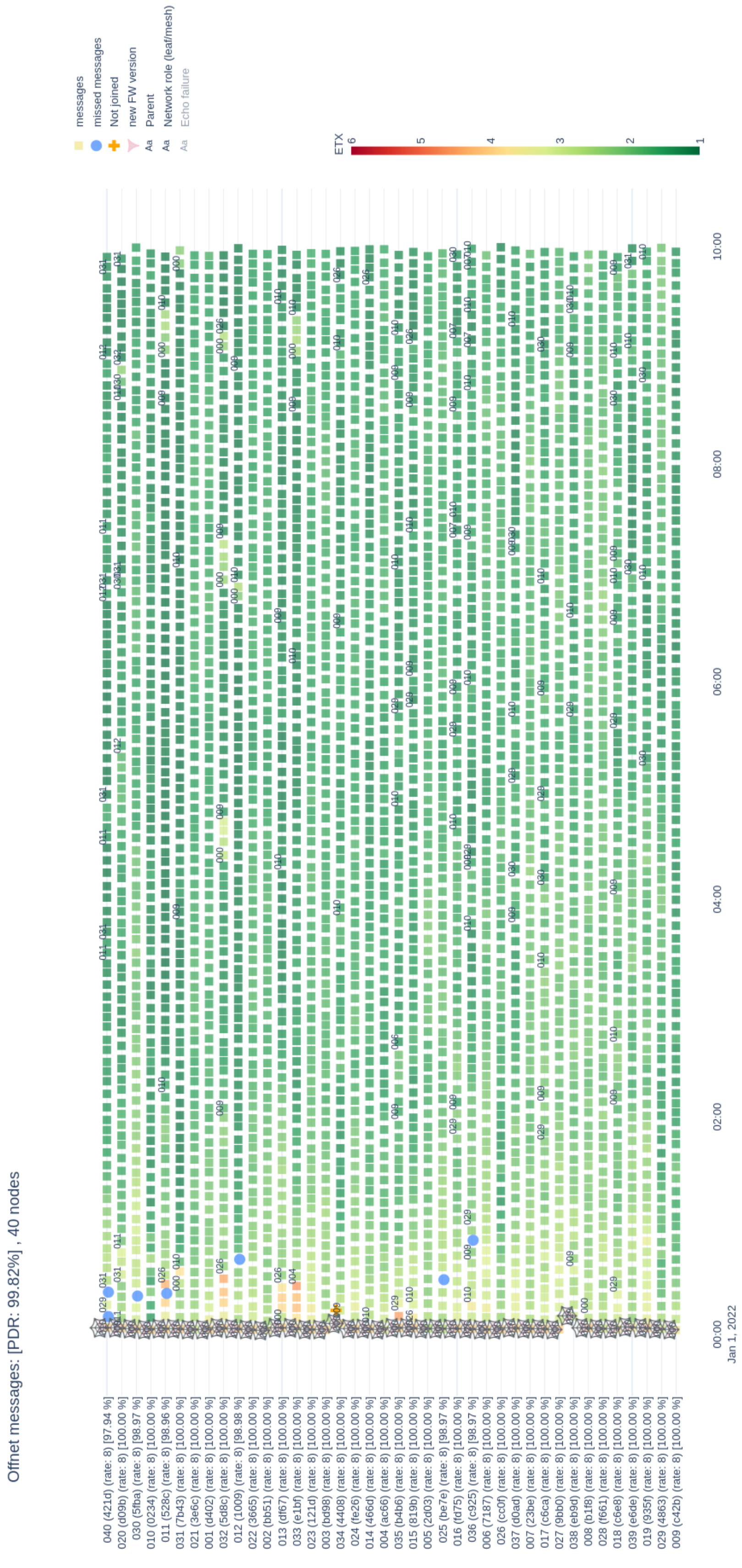


Figure 4.1: Plot depicts the PDR and parent link quality(ETX variation) of each node under Adaptive frequency hopping(AFH)

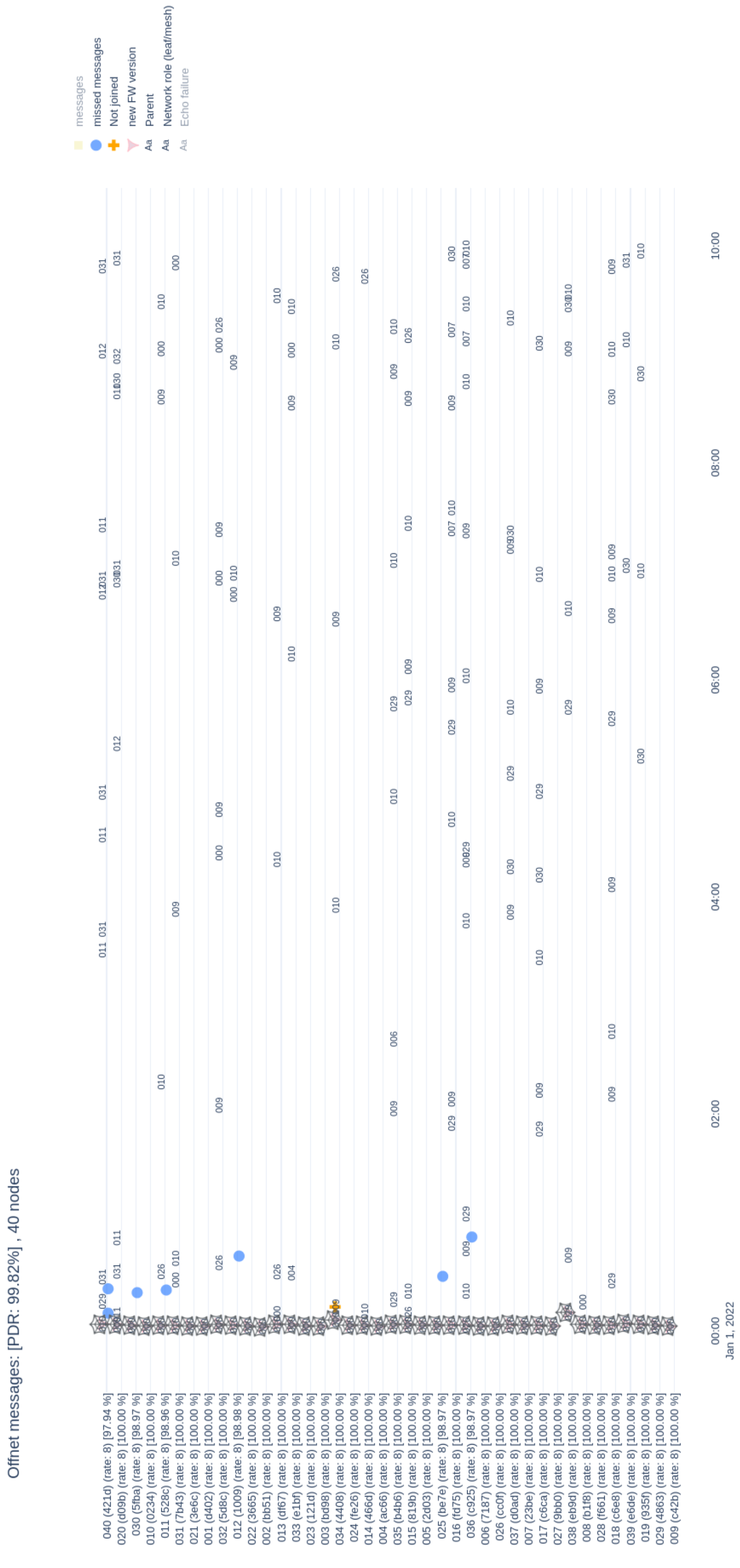


Figure 4.2: Plot shows the Packet loss and parent change of each node under Adaptive frequency hopping(AFH)

Figure 4.2 illustrates that at the start of the simulation, a few packets experience drops due to interference nodes, leading to a decrease in the PDR. However, as time progresses, the Mira nodes adapt to better channels, resulting in improved link quality (as observed in Figure 4.1). Consequently, the link quality enhancement reduces packet loss and subsequently increases the PDR. This demonstrates the adaptive capability of nodes with Adaptive Frequency Hopping (AFH), enabling better performance even in the presence of interference nodes that occupy all available Mira channels.

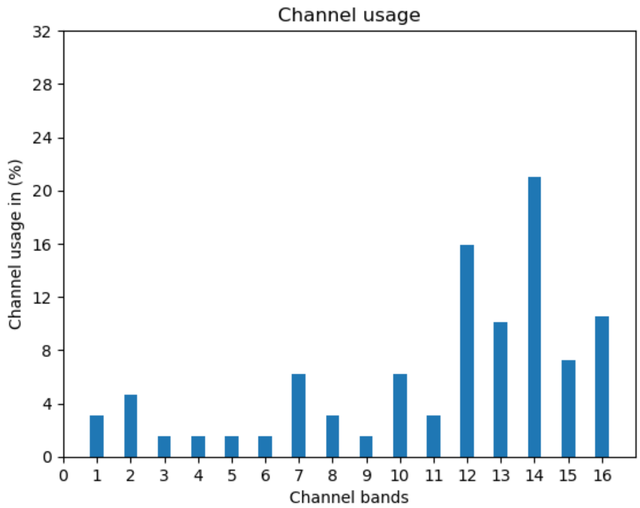


Figure 4.3: Channel usage using Adaptive frequency hopping(AFH) for building automation

The plot 4.3 depicts the channel usage by the Mira nodes when using AFH in the presence of the interference nodes. Despite interference affecting all channels, the level of disturbances caused by interference nodes differs. Specifically, channels 1-11 are utilized for WiFi data transfer, while channels 12-16 are used by WiFi interference nodes for transmitting WiFi beacons. In Section 3.4.1, it was discussed that WiFi beacons transmit periodically every 100ms, with a burst duration of 6 microseconds. Consequently, there are more available slots due to WiFi beacons compared to WiFi data transmissions. To mitigate the impact of interference, Adaptive Frequency Hopping (AFH) strategically selects channels that are least affected by interference while avoiding channels with higher levels of interference. As a result, channel usage increases in channels 12-16 while decreasing in channels 1-11. This dynamic behavior allows good channels to replace bad channels.

TSCH Without Adaptivity
Compared to 4.1, the PDR for this case is reduced (as seen in 4.4). The nodes perform frequency hopping to send packets. It is observed that the ETX value is high throughout the simulation. This shows that the nodes don't adapt to good channels and use the static hopping sequence throughout the simulation. Therefore, PDR is reduced.
In figure 4.5, since there is no adaptivity in the Mira nodes, there is an increase in packet loss throughout the simulation. Also, the parent change is frequent due to poor link quality. Frequent parent change deteriorates the network stability. According to the RPL, for every parent change, the mesh node informs the root node about the parent change and hence the bandwidth usage increases. Hence this leads to inefficient bandwidth usage thus performing worse.
Due to additional usage of bandwidth and poor link quality, the number of retransmissions also increases to successfully transmit the data packets. This increases the current consumption and latency.
The PDR is still high because the Mira nodes use frequency hopping utilizing all 16 channels. Also, due to varied burst duration transmitted by the WiFi interference node, the nodes transmit successfully without packet loss due to inter-burst separation between the WiFi bursts.

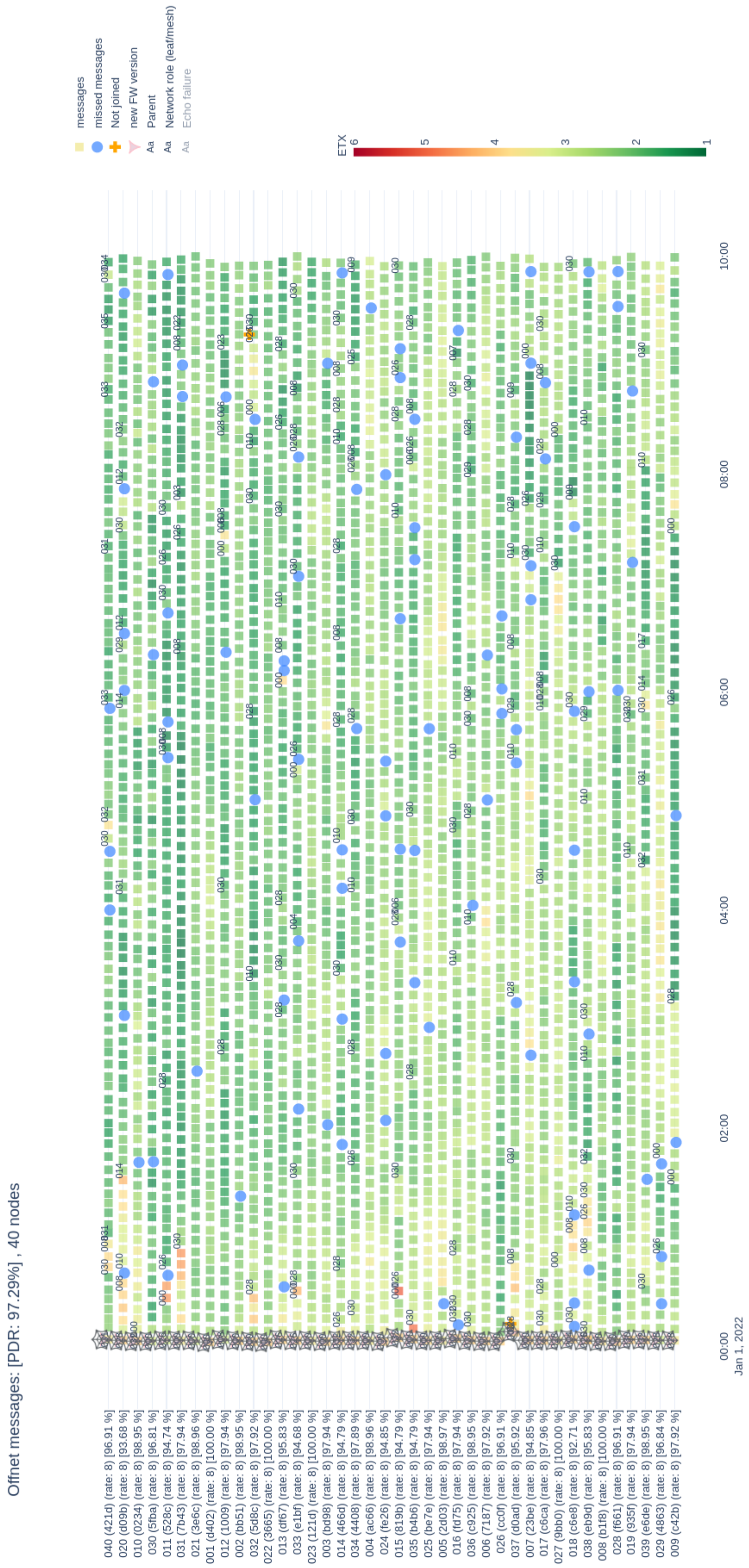


Figure 4.4: Plot depicts the PDR and parent link quality(ETX variation) of each node under TSCH without adaptivity

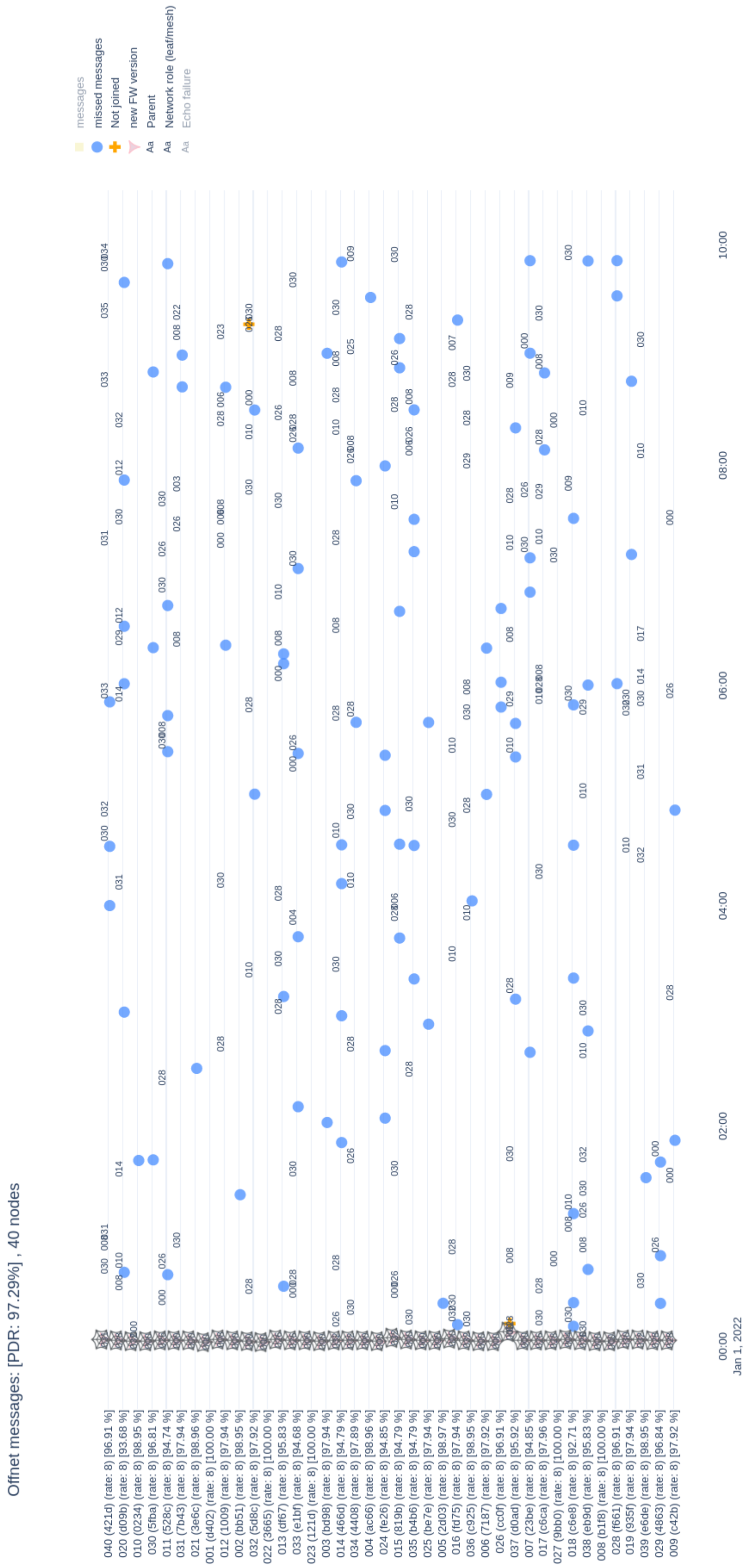


Figure 4.5: Plot shows the Packet loss and parent change of each node under TSCH without adaptivity

Single Channel System

Nodes in the mesh network use only a single channel to communicate. Since all the channels are interfered with by the interference node, nodes in any particular channel will be severely get affected by them. Nodes cannot hop to a different channel and communicate in the same channel for the whole time. Hence, the PDR is significantly reduced (as seen in figure 4.6). With continuous transmission from the interference node, the collision due to it is aggravated leading to network instability. This happens when the transmissions from the Mira nodes exceed 7, the nodes leave the network and desync from the network. This causes an increase in the current consumption and hence nodes become "not associated "with the network (as seen in figure 4.8). This occurrence of instability makes the network perform worst. The packet loss is also increased thereby decreasing the PDR. Due to many re-transmissions of the Mira nodes, the parent link quality decreases (seen in figure 4.7) and the latency is increased.

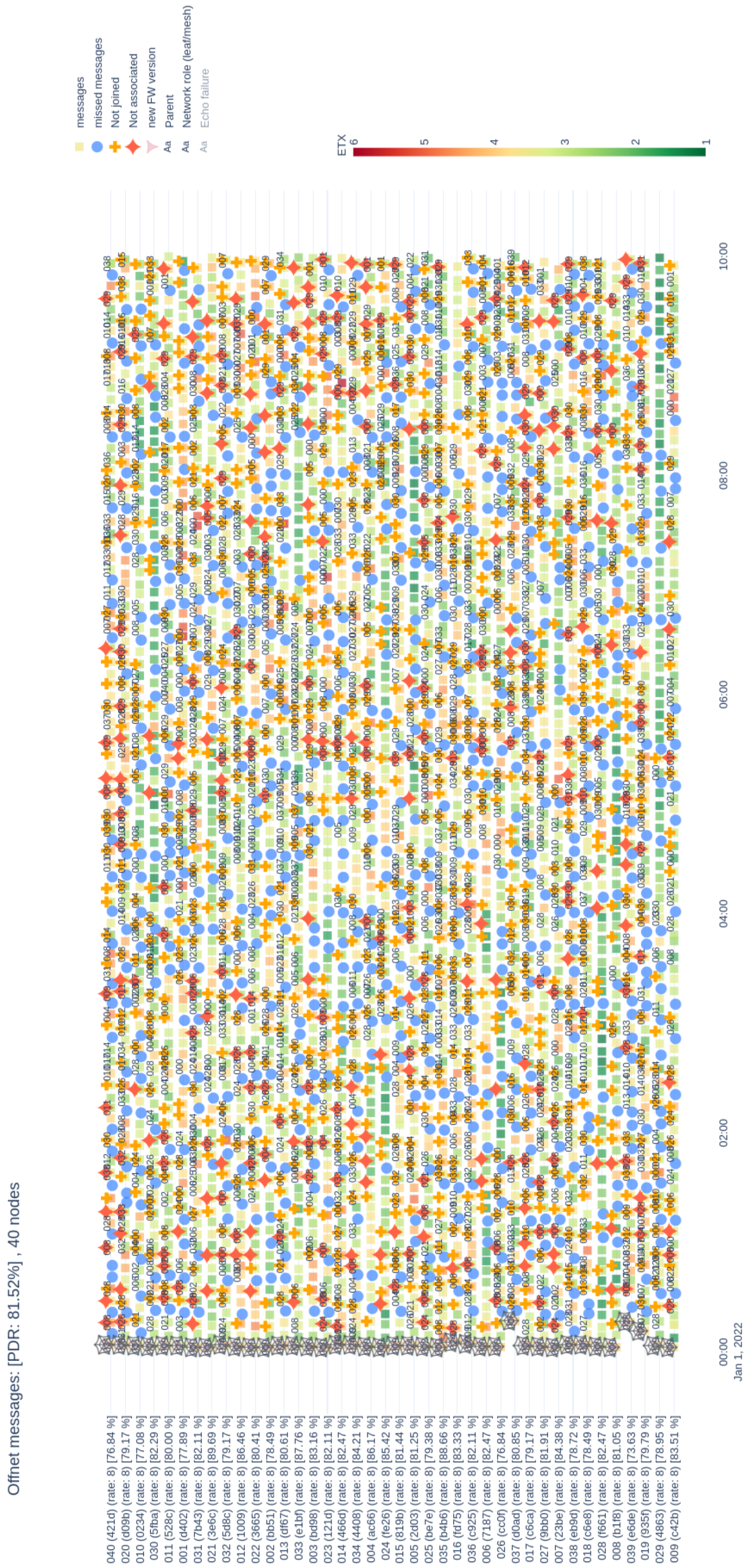


Figure 4.6: Plot depicts each node with single channel

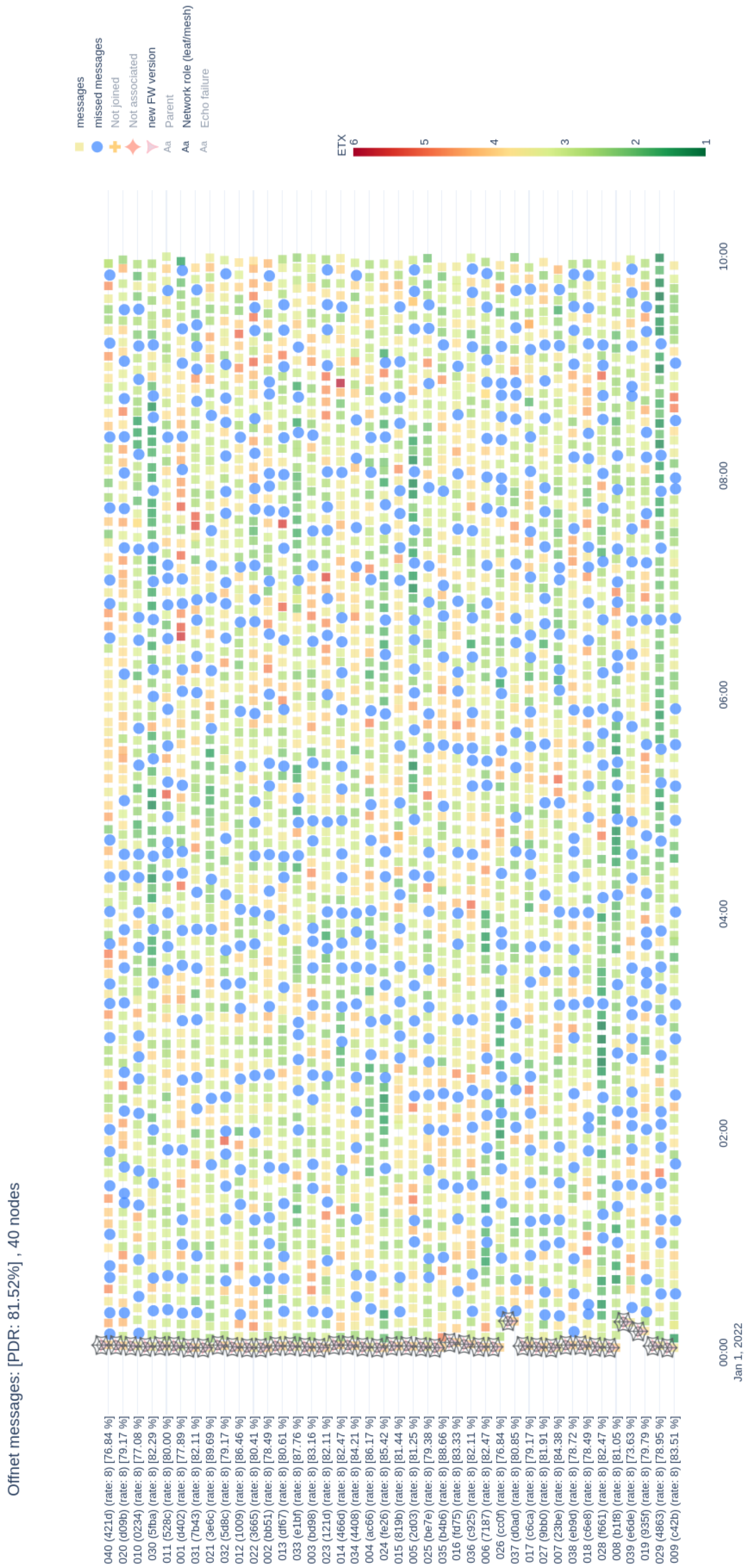


Figure 4.7: Plot depicts the Packet loss and parent link quality(ETX variation) of each node with single channel

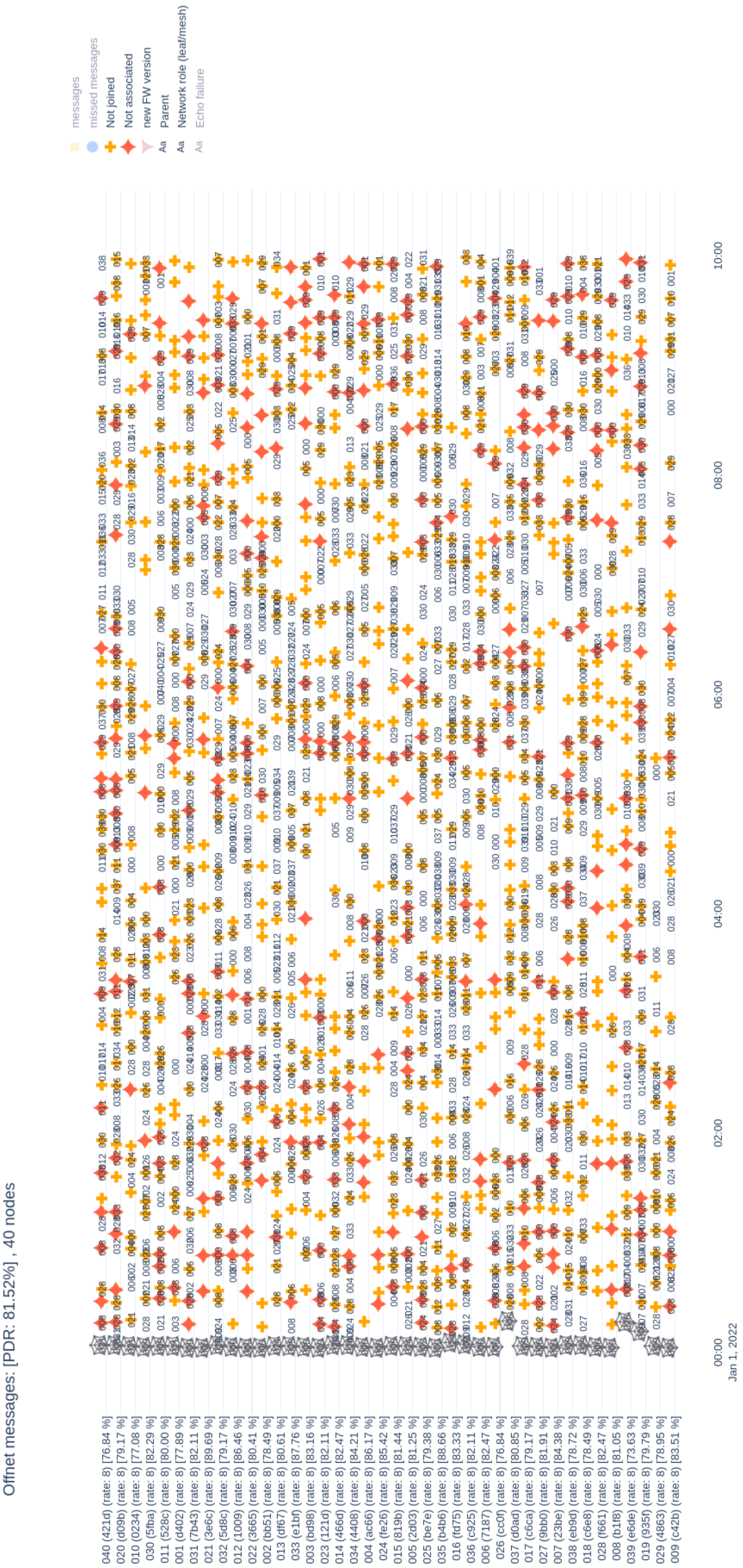


Figure 4.8: Plot depicting the network instability with single channel

4.1.1 Results Of Comparison Of Different Classes Of Channel Utilization

Difference classes of channel utilisation	PDR(%)	Avg Latency(ms)	Avg current usage(μA)	Max current usage (μA)	ETX
TSCH with adaptivity (or AFH)	99.82	672.13	21.54	32.30	1.72
TSCH without adaptivity	97.29	1603.55	25.06	36.13	2.28
Single Channel	81.52	3585.33	351.18	592.91	3.19

Table 4.1: Evaluating different KPIs for different classes of adaptivity in Building Automation

From the above plots and table 4.1, one can observe that Adaptive frequency hopping performs better. In terms of KPIs that are recorded in the above table 4.1, adaptive frequency hopping has high PDR, minimum latency and minimum current consumption. The current consumption is calculated by dividing the total energy by the total simulation time. The current consumption is an important metric to consider for this use case because the nodes are battery-powered. The parent link quality is also good since the ETX for AFH is less. Hence, the adaptive frequency hopping consumes less current and thus performs the best.
The plot 4.9 shows the cumulative distribution of the latency for three different classes of channel utilization. It is observed that nodes using TSCH with adaptivity(or AFH) experience minimal latency between the communication. This is because the nodes use good channels and avoid the channels which have greater influence by the interference node. The nodes communicating using the single channel experience larger latency while communicating under the influence of the interference node. The latency is also an important metric and thus the nodes using adaptive frequency hopping experience less delay due to its adaptable nature.

No. of interferences	PDR	Avg Latency	Avg current usage(μA)	Max current usage(μA)	ETX
1	99.97	547.35	21.55	26.31	1.63
2	99.87	624.84	21.66	32.08	1.63
3	99.82	672.13	21.64	32.30	1.72

Table 4.2: Table shows the variation of PDR, Latency, Current consumption and ETX for increasing number of interferences in the case of Building automation

The above table 4.2 displays the PDR, latency, current consumption and ETX obtained from the simulations. It shows that by adding the interferences in the mesh network using AFH, the differences in the value of each metric is negligible. The performance of the mesh nodes is not degraded by adding the number of interfer-

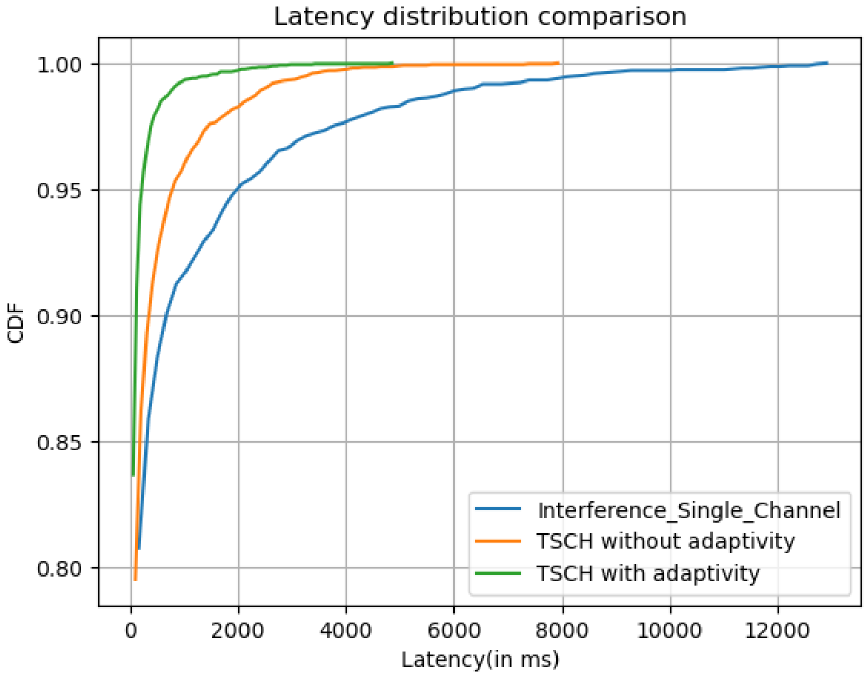


Figure 4.9: CDF distribution of latency for building automation

ences. This shows that the AFH identifies the interferences and hence reacts better. Overall the performance is at its best.

4.2 Condition Monitoring

The topology for this use case is different than the one for building automation. In this case, there is an increase in the number of nodes placement and also they are placed very close to each other. Also, the mesh nodes in this case are run at rate 10 and root nodes at rate 5. Similar to the previous use case, we will investigate the performance of this use case with different classes of channel utilization. Since the area of the topology is increased and also the number of nodes placement has been increased, the number of interferences nodes in this setup is 4. These 4 interference nodes are placed in all 4 corners of the setup. This surrounds all the nodes in the network and thus interference nodes cover the entire region. The interference nodes use all the 16 channels used by the Mira nodes. Thus all channels are interfered. But, the level of interferences varies because of different burst duration when used over WiFi. Therefore, WiFi uses the Mira Channels 1-11 for data transfer and Mira Channels 12-16 for transmitting WiFi beacons. This interference is the same for all the simulations used in the different classes of channel utilization.

The simulations are done for three different cases. The results for these simulations are discussed below

TSCH With Adaptivity (Adaptive Frequency Hopping)

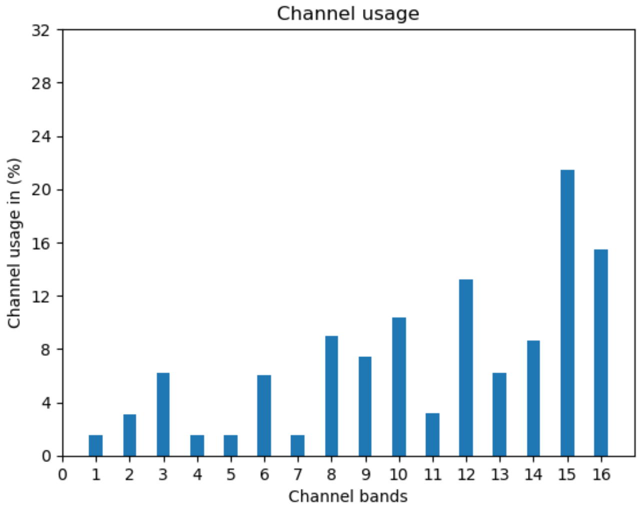


Figure 4.10: Channel usage using adaptive frequency hopping (AFH) for Condition monitoring

The plot 4.11 shows the dynamics of the packet transmission of each mesh node when the interference nodes are introduced. From the plot, we can observe that the ETX is very high at the beginning of the simulation. This is due to the collision of the packets due to adjacent nodes and also due to interference nodes. Since the nodes are placed very close to each other, there are more collisions between packets. Also, the mesh nodes are run at a rate 10. Due to the low rate, the congestion is increased in the network due to less frequent RX slots. But over time the network becomes stable in terms of the parent link quality. The parent link becomes better and this can be seen as the ETX has been significantly reduced. Hence, one can infer that the nodes adapt well making the network stable and communication reliable between the nodes. The adaptivity of the channel usage is also shown in figure 4.10

The next plot 4.12, shows the packet loss and parent change. One can observe that there is significant packet loss in the beginning, which is gradually reduced over time. This shows that the Packet delivery rate increases when hopping over to good channels replacing the bad channels. Despite the congested nodes in the topology, and also a high difference between the rates of mesh and root, there is an increase in the parent change over the entire simulation. According to the RPL, the nodes with higher rate has a top priority in sending the packets to. Since the root operates at a high rate, the mesh nodes try to send packets as much as possible directly to the root while minimizing the number of hops. This compromises the link quality and thus there is a trade-off between the rate and the parent link quality. In the figure 4.11, one can observe there are a few times when the ETX gets high in between and this is because of the reason explained earlier.

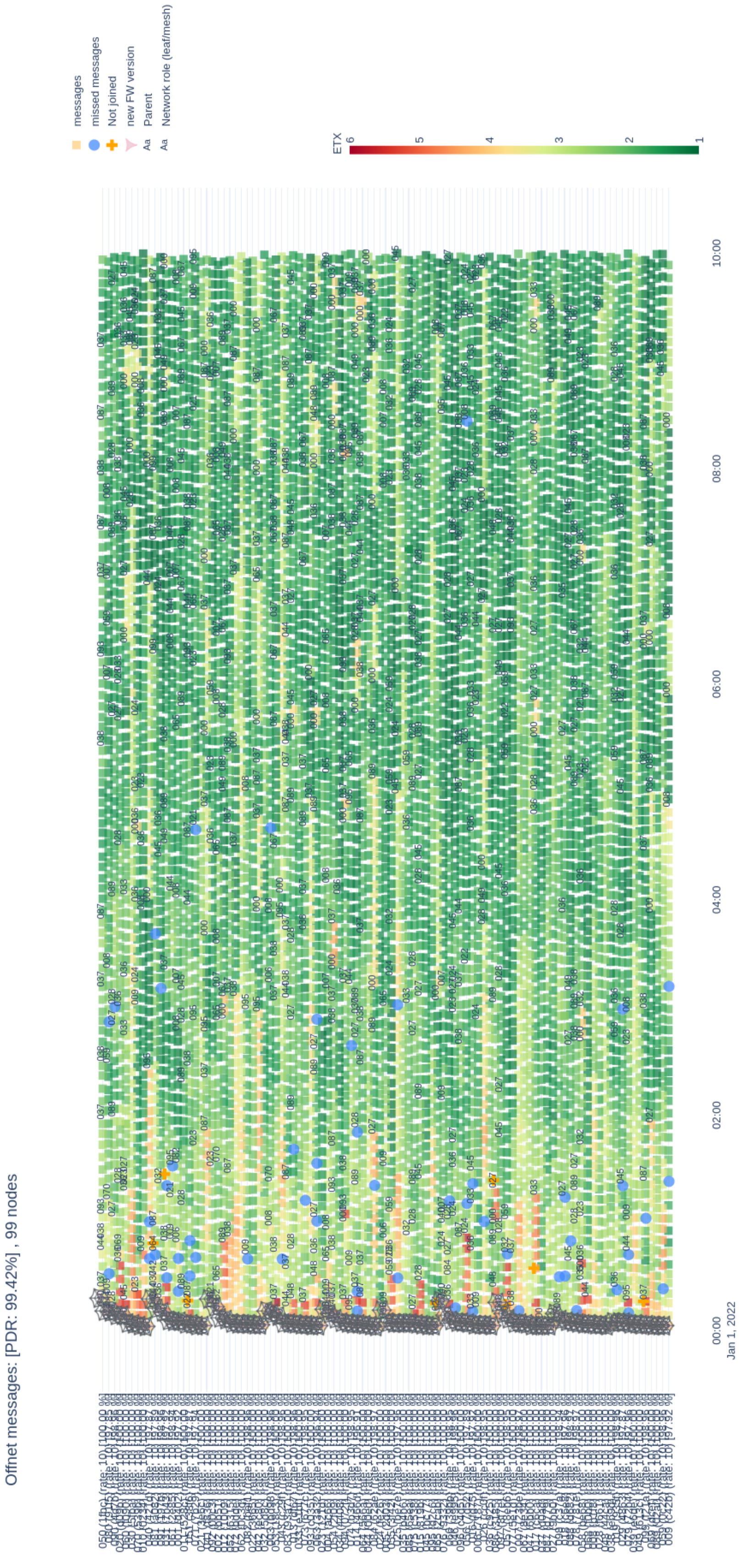


Figure 4.11: PDR and parent link quality(ETX variation) of 100 nodes under Adaptive frequency hopping (AFH).

Figure 4.12: Packet loss and parent change of 100 nodes under Adaptive Frequency hopping(AFH)

TSCH Without Adaptivity
From the plot 4.13, it is observed that the parent link quality is the same throughout the simulation. The ETX is generally high as compared to the ones with the above slots. Although, the nodes can do frequency hopping which improves the packet delivery rate the nodes don't adapt to the channels that are interfered to the least. Thus, the frequency hopping to different channels is static (i.e.) the channel occupancy by each node is the same. Therefore, the PDR is reduced as compared to the above case and the performance is not good as compared to the AFH.

The next plot 4.14, depicts the packet loss and the parent change of the simulations with the static frequency hopping. It is observed that the packet loss is significantly high throughout the simulation and also the parent change is more frequent compared to the above plot 4.12. Hence, nodes with static hopping sequences have high packet loss and frequency parent change leading to more traffic in the network. Due to this, there is a need for additional bandwidth for the mesh nodes to inform the root about its parent change leading to inefficient utilization of bandwidth resources.

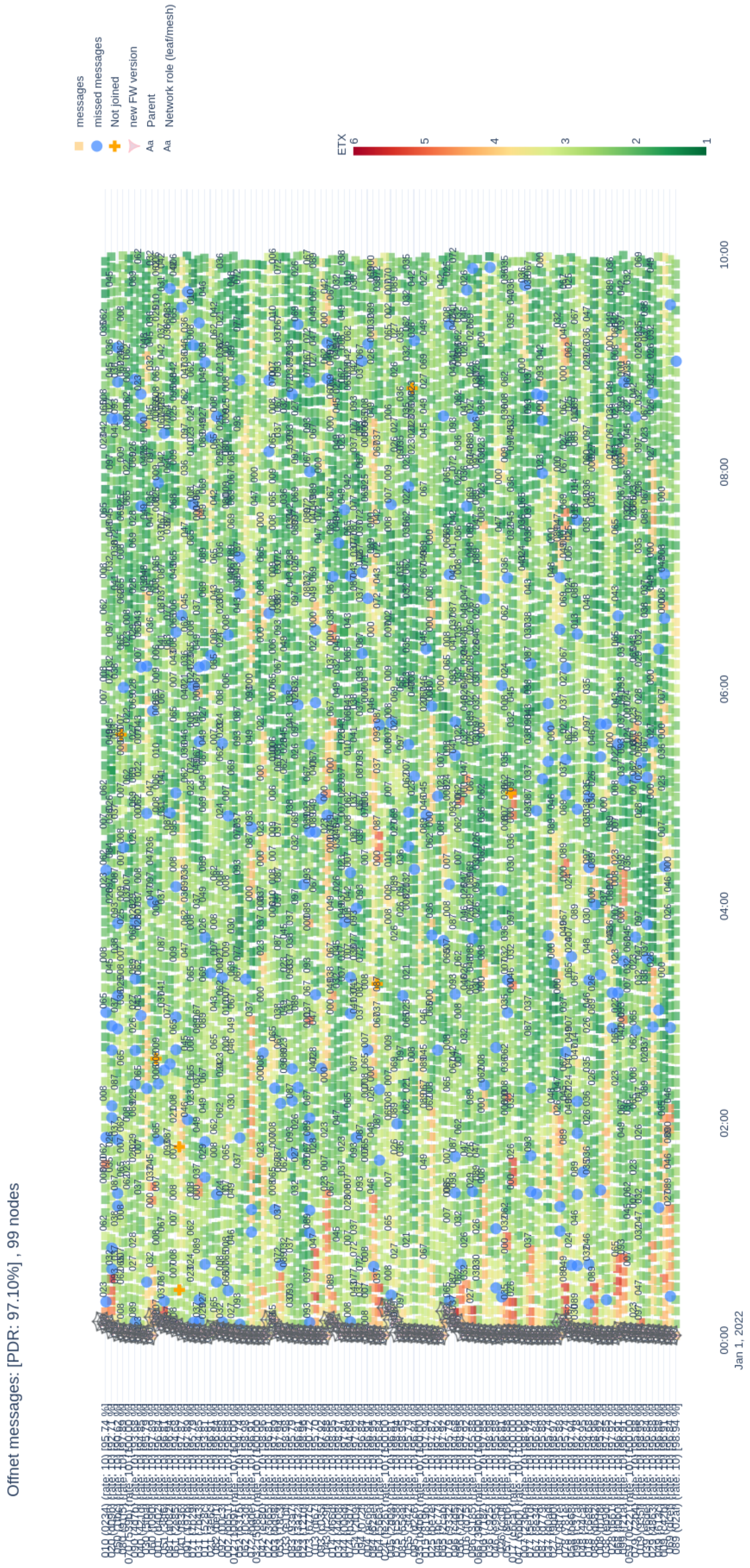


Figure 4.13: PDR and parent link quality(ETX variation) of 100 nodes in TSCH without adaptivity

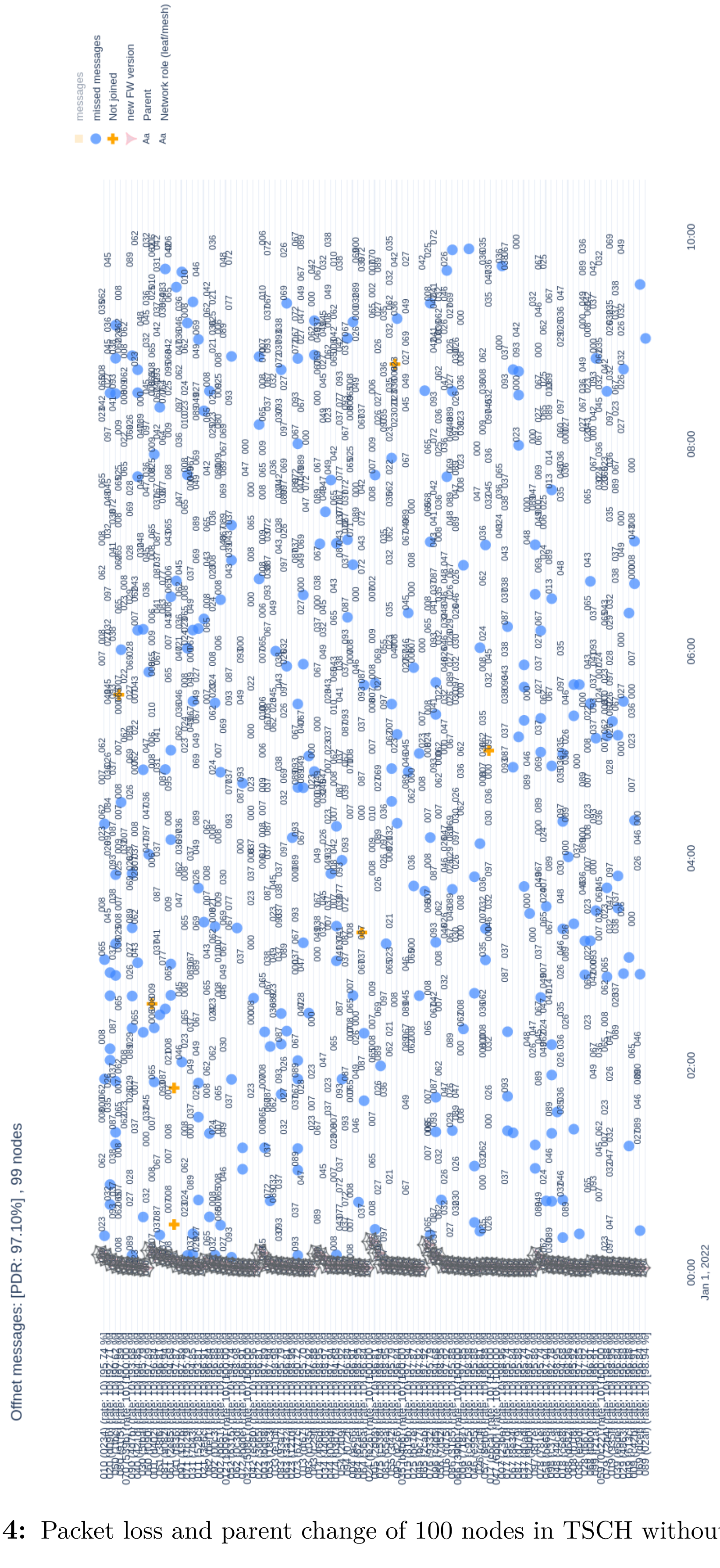


Figure 4.14: Packet loss and parent change of 100 nodes in TSCH without adaptivity

Single Channel System
The nodes in the mesh networks communicate only in a single channel and performance is bad. Since the nodes cannot hop to different frequencies to communicate, there is a huge decrease in the packet delivery rate. The parent link quality is also poor due to many re-transmissions. Therefore, the packet loss is adversely increasing throughout the simulation. Due to continuous re-transmissions, when it exceeds, there is a packet drop. But due to successive collisions and packet drop, the nodes in the network become unstable and hence get removed from the network. Due to this, the network doesn't join the network and always stays in the "not associated" state. Therefore, as expected, the single channel is affected the most due to interferences leading to network instability. The behavior can be seen in the plots 4.15, 4.16 and 4.17. Also comparing the single channel behavior of previous use cases, it is observed that PDR is significantly reduced for this case. This is due to the increase in the placement of nodes increasing traffic and congestion in the network.

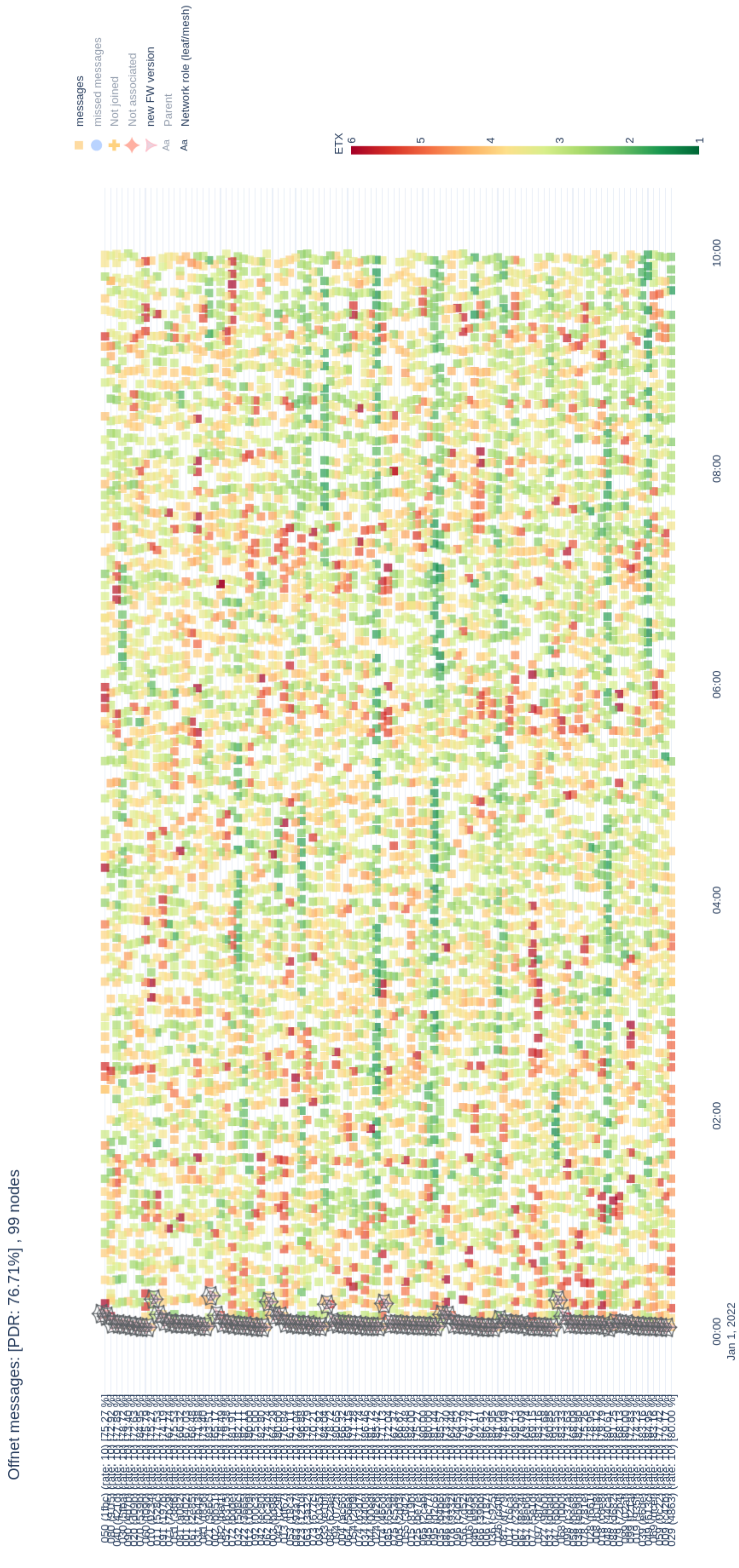


Figure 4.15: PDR and channel quality(ETX variation) of 100 nodes in single channel

Figure 4.16: Packet loss and parent change of 100 nodes in single channel

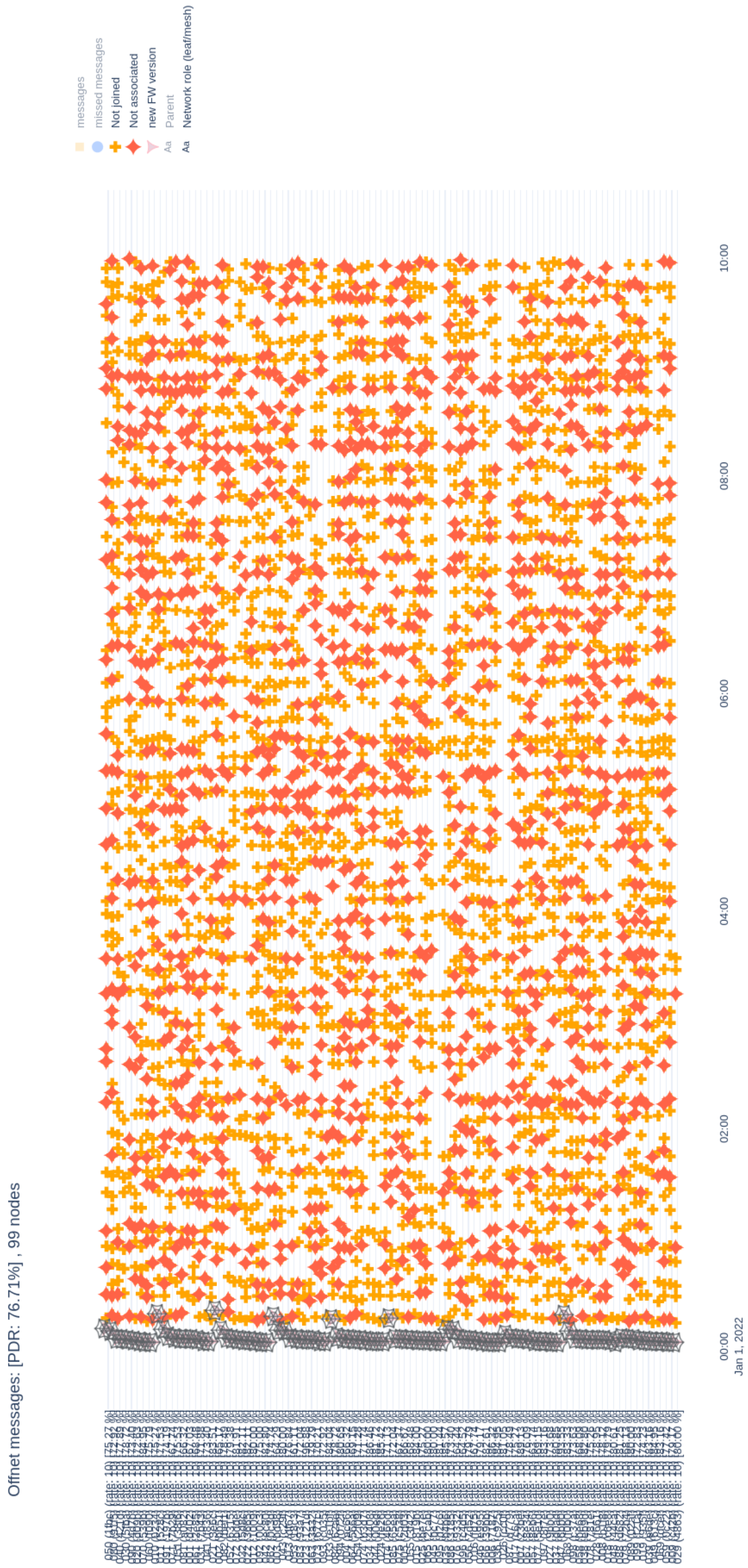


Figure 4.17: Network stability of 100 nodes in single channel

4.2.1 Results Of Comparison Of Different Classes Of Channel Utilisation

Difference classes of channel utilisation	PDR(%)	Avg Latency(ms)	Avg current usage(μA)	Max current usage (μA)	ETX
TSCH with adaptivity (or AFH)	99.42	2045.67	15.13	19.61	2.03
TSCH without adaptivity	97.10	4502.11	28.29	68.62	2.46
Single Channel	76.71	9238.78	689.17	1181.93	3.44

Table 4.3: Evaluating different KPIs for different classes of adaptivity in Conditional Monitoring

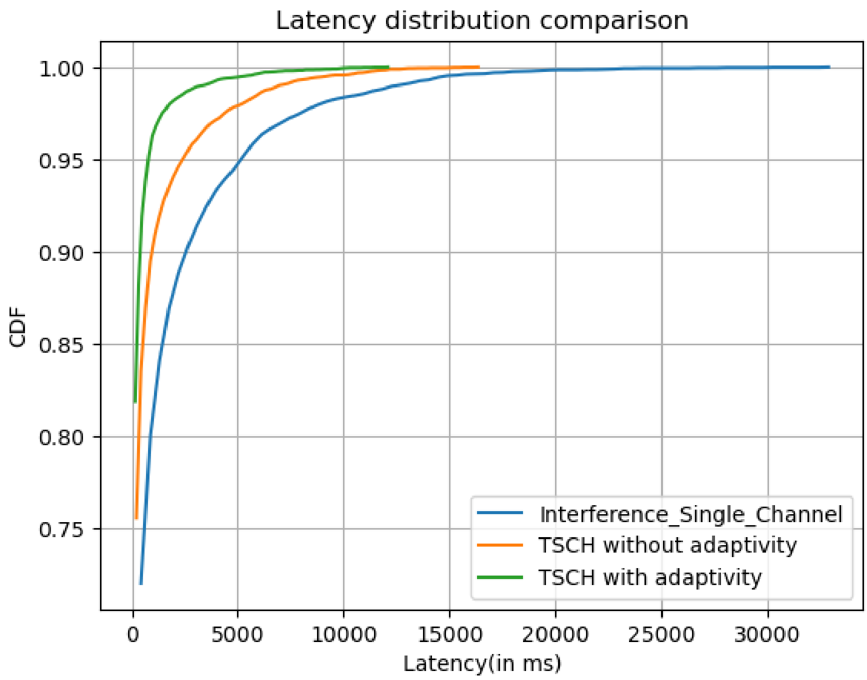


Figure 4.18: CDF distribution of latency for Conditional Monitoring

The plot 4.18 shows the cumulative distribution of the latency for three different classes of channel utilization. It is observed that nodes using TSCH with adaptivity(or AFH) experience minimal latency between the communication. This is because the nodes use good channels and avoid the channels which have greater influence by the interference node. The nodes communicating using the single channel experience larger latency while communicating under the influence of the interference node.

Considering the traffic and also scale of the topology, adaptive frequency hopping (AFH) works really well. In this case, the mesh nodes detect the disturbances well and hence use the channel more often that are less interfered and use the channels less that are interfered the most by the interference nodes. This can be seen from the figure 4.10. Since the mesh nodes adapt well to interferences, the communication is reliable. The packet loss is minimal. Since the ETX is low, the current consumption by the nodes is minimum thereby prolonging the life of batteries. The latency between the communication is also minimal thereby making the PDR close to 100%. Therefore, from the above three classes of channel utilization, Adaptive frequency hopping performs well.

No. of interferences	PDR	Avg Latency	Avg current usage(μA)	Max current usage(μA)	ETX
1	99.75	1689.72	12.54	17.17	1.79
2	99.69	1827.32	12.57	18.04	1.93
3	99.52	1908.43	14.34	19.02	2.04
4	99.42	2045.67	15.13	19.61	2.03

Table 4.4: Table shows the variation of PDR, Latency, Current consumption and ETX for increasing number of interferences in the case of Condition Monitoring

The above table 4.4 displays the PDR, latency, current consumption and ETX obtained from the simulations. It shows a similar behavior as compared to the Building automation use case. Hence, like in the previous use case, Adaptive frequency hopping (AFH) identifies the interference and reacts better.

4.3 Discussions And Evaluations On Performance of AFH

4.3.1 Rate Of Adaptivity

From the results obtained above from the simulations, it can be seen that the mesh networks using AFH perform well by comparing the metrics - PDR, latency, ETX and current consumption.
AFH adapts well to the disturbances introduced by the jammer. It also has the ability to detect the level of interference that affects the channels. But now the interesting question would be how fast the AFH adapts to the disturbances.

From the plot 4.19, it is observed that there are two sets of channels. The y-axis represents the channel percent usage and the x-axis represents the time duration every hour. The time format represents both the date and time every hour. (01-01 represents the date and after that, it represents the time in hours) Their usage percentages over the time for the entire simulation are compared. These two are considered because these two sets of channels have different levels of interference caused by the WiFi interference nodes. As discussed before, channels 1-11 are used for data transfer over WiFi. Channels 12-16 are used by WiFi interference nodes to transmit WiFi beacons periodically. It is known that the burst duration of WiFi

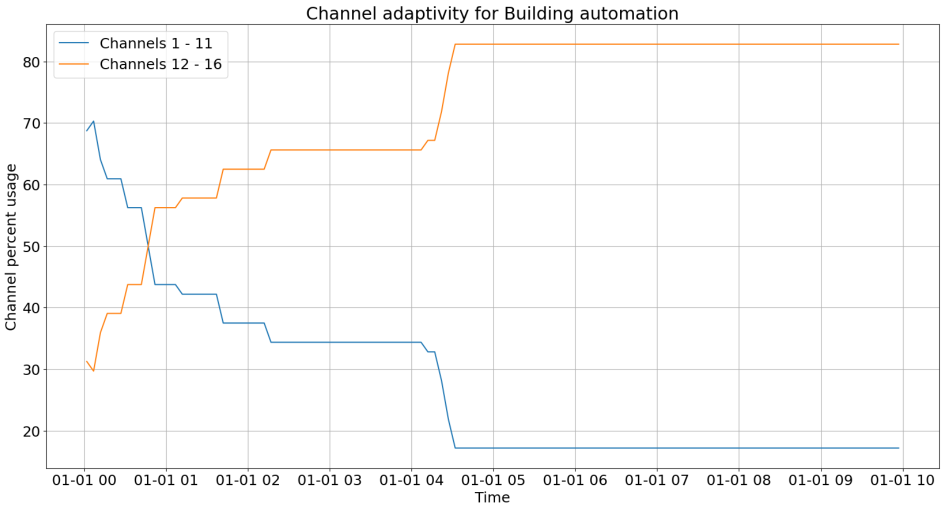


Figure 4.19: Channel adaptivity of the nodes in the Building automation scenario

beacons is very small as compared to the burst duration of data transfers over WiFi. Therefore, channels 1-11 are interfered to a greater level as compared to channels 12-16 by the WiFi interference nodes. Since the AFH successfully detects the disturbances levels in each channel, it is seen that the channel percentage usage of channels 1-11 decreases over time. Also, it is observed that channel usage percentage also increases for channels 12-16 over time. From the plot 4.19, the intersection point of the curves is the point at which where the AFH starts to adapt. It is seen that after some time, the curve gets flattened. This is the point at which the AFH uses only the good channels replacing the bad channel. At this stage, the bad channels are used less than 20 % and the good channel are used more than 80% most of the time. Thus, the above plot is a good way to visualize the channel usage over time (every hour) and also the time taken for all the nodes in the network to completely adapt to the better channels.

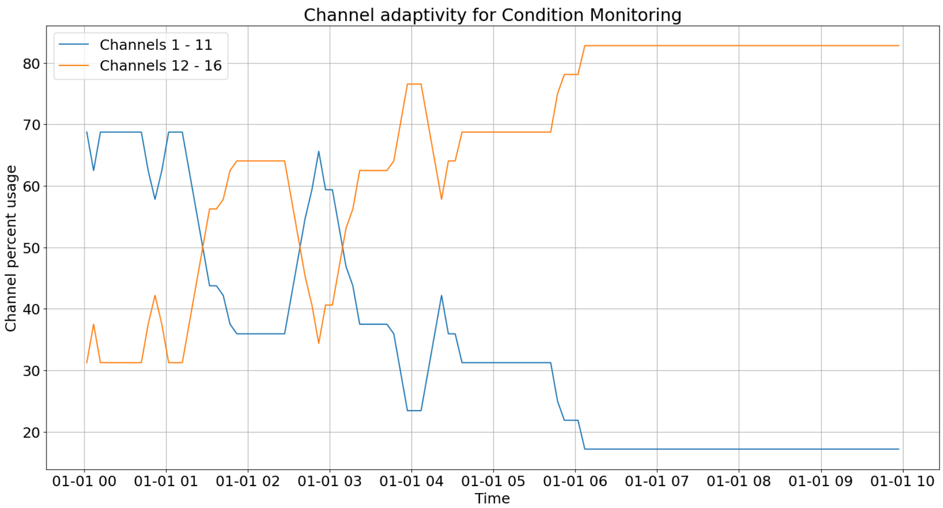


Figure 4.20: Channel adaptivity of the nodes in the condition monitoring scenario

The plot 4.20 depicts the rate of adaptivity of the mesh nodes in Condition monitoring. As the mesh nodes operate at a low rate, the number of listening slots is fewer as compared to the mesh nodes operating at a higher rate. Due to this, the nodes wait for a longer time until the next Rx slot. Also, there are some variations in the channel usage once it starts to adapt. This is because of the congestion of traffic caused by nodes as they are placed close to each other. This causes more collision and hence also delays the rate of adaptivity. There is a delay in the flattening of the curve, reaching the point where only good channels are used as can be seen from the plot. Hence, this case also gives insights into how the rate of nodes in the network affects the rate of adaptivity in AFH.

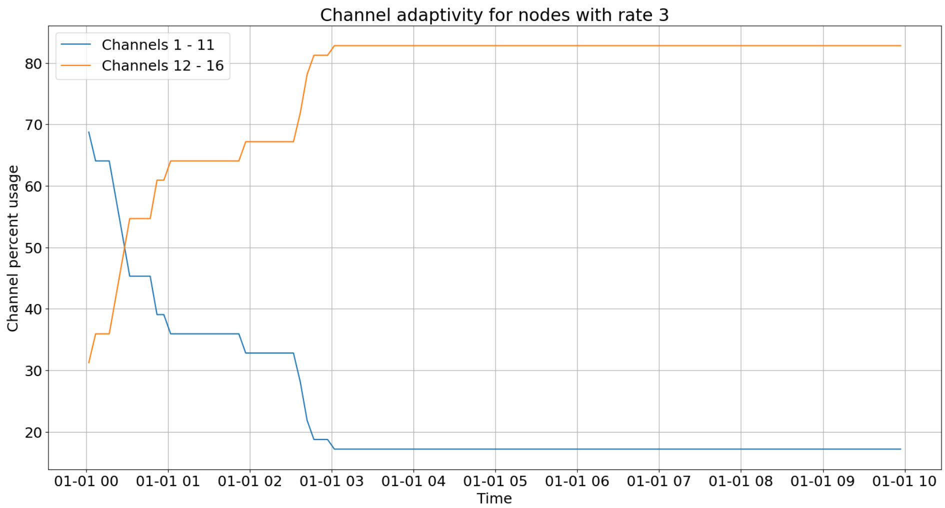


Figure 4.21: Channel adaptivity of the nodes with rate 3

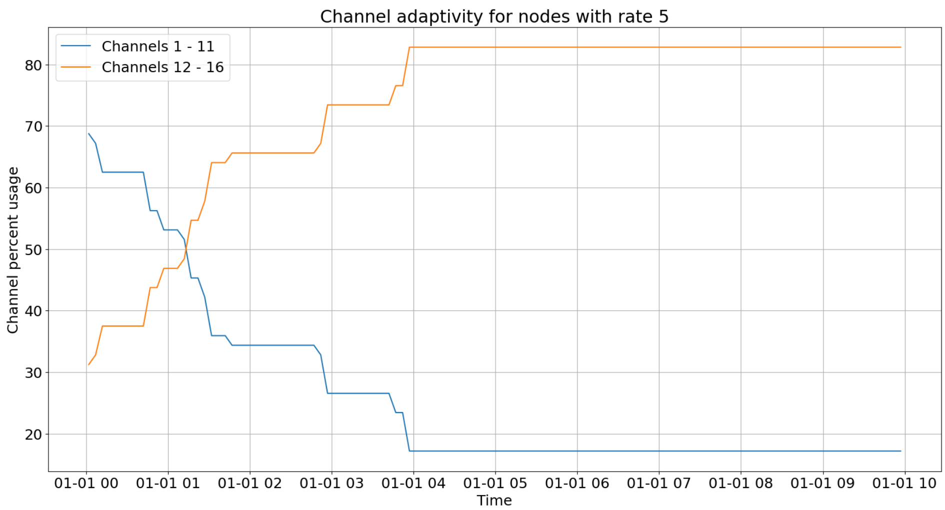


Figure 4.22: Channel adaptivity of the nodes with rate 5

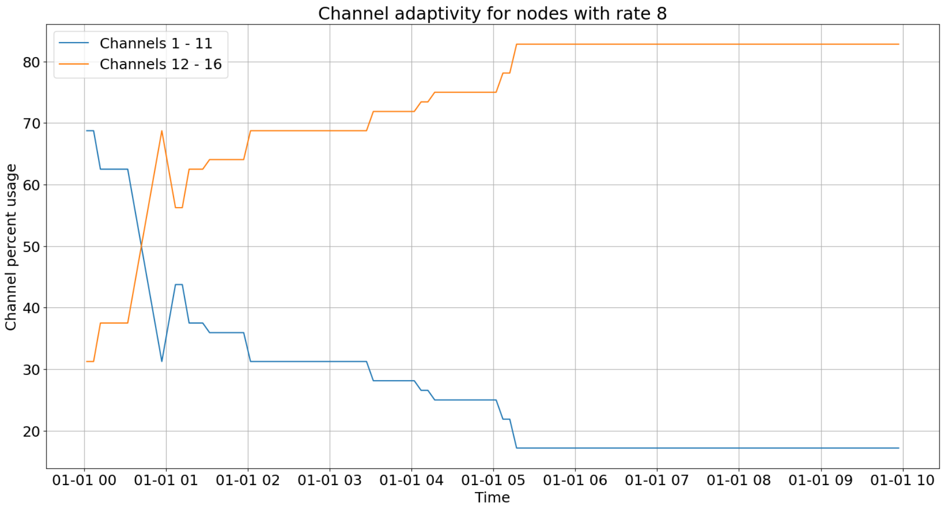


Figure 4.23: Channel adaptivity of the nodes with rate 8

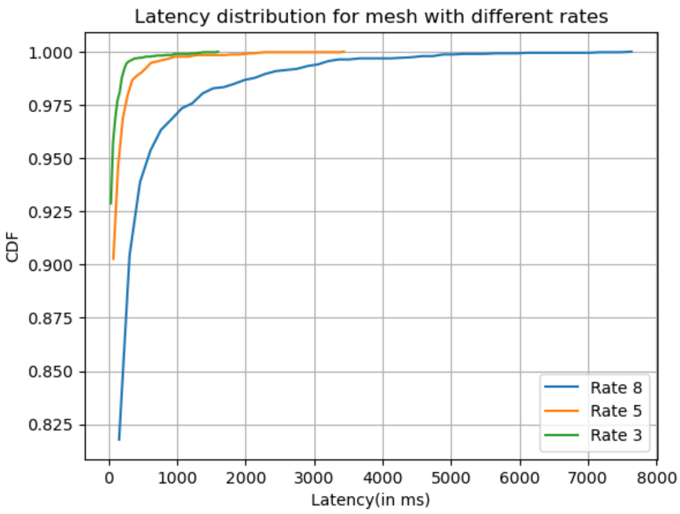


Figure 4.24: CDF distribution of latency for networks with different rates

The plots 4.21, 4.22 and 4.23 depicts the rate of adaptivity when using mesh nodes with different rates for the same use case scenario. It can be observed that the rate of adaptivity increases with increasing the rate of the mesh nodes. The reason behind it is that slow rates have less frequent RX slots. The time between the listening slots increases with increasing value of rates for the mesh nodes. Thus, the mesh nodes waits for its parent's listening slots and then transmit the packet. Hence, increasing the value of rate also increases the waiting time for the nodes to transmit thereby creating more traffic and congestion of the data packets. Due to this effect, the rate of adaptivity also decreases with increasing the value of rate. Also, the latency of the tranmission is also affected by the rates of the mesh nodes (as seen in 4.24). It shows that for nodes with high rates have less latency as compared to the ones with the nodes with lower rates.

These results indicate that nodes operating in the network with AFH at slower rate also has a slower rate of adaptivity. The table 4.5 also gives insights about the met-

Rate	PDR(%)	Latency(ms)	Avg current usage(μA)	Max current usage (μA)
3	99.90	165.16	117.27	132.19
5	99.79	396.52	55.36	67.18
8	99.79	1564.27	21.61	33.876

Table 4.5: Nodes of different rates with adaptive frequency hopping (AFH)

rics latency and current consumption. As the rate of the nodes decreases, the rate of adaptivity decreases and current consumption is also decreased. Thus, in terms of current consumption, the nodes with slower rate consume less current thereby prolonging the battery life since the nodes are battery powered.
For the metric of latency and rate of adaptivity, it is the other way around. As the rate of the nodes increases, the rate of the adaptivity increases and the latency in the network decreases. Therefore, the communication is faster and also network adapts to better channels conditions faster but with increasing current consumption.

4.3.2 Test Result Matrix

	Single narrowband whole network always on	Multiple narrowband whole network always on	Single narrowband local always on
Single channel network	PDR: 13.33% Avg Latency: 35105 ms Max Current: 226.21 uA	PDR: 13.33% Avg Latency:27770 ms Max Current: 252.15 uA	PDR: 99.74% (24 nodes) Avg Latency: 1196.99 ms Max Current: 36.01 uA
TSCH without adaptivity	PDR: 100% Avg Latency: 507.60 ms Max Current: 32.89uA	PDR: 98.80% Avg Latency: 1521.10 ms Max Current: 39.46 uA	PDR: 100% Avg Latency:737.55 ms Max Current: 31.51 uA
TSCH with adaptivity (or AFH)	PDR: 100% Avg Latency: 432.17 ms Max Current: 30.21 uA	PDR: 100% Avg Latency: 863.05 ms Max Current: 31.42 uA	PDR:100 % Avg Latency:627.17 ms Max Current:29.65 uA

	Multiple narrowband local intermittent	Single narrowband local intermittent
Single channel network	PDR:89.45% Avg Latency: 3310.45ms Max Current:579.01 uA	PDR:97.88% Avg Latency: 1371.64 ms Max Current: 419.95 uA
TSCH without adaptivity	PDR: 99.61% Avg Latency: 838.73 ms Max Current: 30.68 uA	PDR:100% Avg Latency: 431.93 ms Max Current: 26.98 uA
TSCH with adaptivity (or AFH)	PDR: 99.95% Avg Latency: 532.92 ms Max Current: 26.22 uA	PDR:100 % Avg Latency: 533.77 ms Max Current: 22.43 uA

	Multiple narrowband local always on	Multiple narrowband whole network intermittent
Single channel network	PDR: 97.83 % (24 nodes) Avg Latency: 6209.46 ms Max Current: 5938.16uA	PDR: 79.69 % Avg Latency: 2651.60 ms Max Current: 384.21 uA
TSCH with adaptivity	PDR: 99.61 % Avg Latency: 1196.02 ms Max Current:32.67 uA	PDR: 99.84 % Avg Latency: 770.09ms Max Current: 31.88 uA
TSCH with adaptivity (or AFH)	PDR: 100% Avg Latency: 578.31 ms Max Current:30.59 uA	PDR:99.97% Avg Latency:571.37 ms Max Current: 29.80 uA

Figure 4.25: Evaluations of different classes of adaptivity for different types of interferences for Building automation

The test result matrix represents the table showing the evaluation of KPIs for each class of channel utilization against different types of disturbances. The KPIs evaluated are PDR, Average latency and maximum current consumption. The test result matrix is obtained for both the use cases:- Building automation and condition monitoring. Figure 4.25 and figure 4.26 represent results for Building automation and condition monitoring respectively.
PDR, Latency and current consumption are evaluated for different scenarios. From figure 4.25, it is observed that AFH performs well in all the scenarios in terms of the KPIs that are calculated. The PDR is always close to 100%, the average latency is very low and also consumes less current(maximum current) as compared to the other

	Single narrowband whole network always on	Multiple narrowband whole network always on	Single narrowband local always on
Single channel network	PDR: 0% Avg Latency: 0 ms Max Current: 0 uA	PDR: 0 % Avg Latency:0 ms Max Current: 0 uA	PDR: 100% (89 nodes) Avg Latency: 935.00 ms Max Current: 18.82 uA
TSCH without adaptivity	PDR: 99.98% Avg Latency: 1426.59 ms Max Current: 35.37uA	PDR: 97.08% Avg Latency: 6443.98 ms Max Current: 26.07 uA	PDR: 100% Avg Latency:625.55 ms Max Current: 15.70 uA
TSCH with adaptivity (or AFH)	PDR: 100% Avg Latency: 1333.51 ms Max Current: 17.32 uA	PDR: 99.83% Avg Latency: 2144.35 ms Max Current: 16.69 uA	PDR:100 % Avg Latency:510.17 ms Max Current:12.80 uA

	Multiple narrowband local intermittent	Single narrowband local intermittent
Single channel network	PDR:86.40% Avg Latency: 2250.78ms Max Current:27.49 uA	PDR:95.68% Avg Latency: 1876.64 ms Max Current: 17.23 uA
TSCH without adaptivity	PDR: 100% Avg Latency: 1730.40 ms Max Current: 18.92 uA	PDR:100% Avg Latency: 416.23 ms Max Current: 14.90 uA
TSCH with adaptivity (or AFH)	PDR: 100% Avg Latency: 519.29 ms Max Current: 13.18 uA	PDR:100 % Avg Latency: 380.50 ms Max Current: 12.77 uA

	Multiple narrowband local always on	Multiple narrowband whole network intermittent
Single channel network	PDR: 100 % (50 nodes) Avg Latency: 805.65 ms Max Current: 17.81 uA	PDR: 78.56 % Avg Latency: 5674.34 ms Max Current: 2257.32 uA
TSCH with adaptivity	PDR: 99.61 % Avg Latency: 798.10 ms Max Current: 15.43 uA	PDR: 99.44 % Avg Latency: 2625.38ms Max Current: 20.44 uA
TSCH with adaptivity (or AFH)	PDR: 100% Avg Latency: 534.91 ms Max Current:13.90 uA	PDR:99.94% Avg Latency:1705.56 ms Max Current: 14.02 uA

Figure 4.26: Evaluations of different classes of adaptivity for different types of interferences for Condition monitoring

two classes of channel utilization. Simulations results in 4.25 give a better picture of how AFH reacts to different types of disturbances introduced in the mesh network. Particularly for all the multiple narrowband disturbances, the PDR is always close to 100 %. This shows the ability of AFH to detect the disturbances well and avoid the bad channels to have end-to-end reliable communication. The same behavior and similar trend can also be seen for the condition monitoring scenario (from figure 4.26).

5

Conclusion and Future Work

5.1 Conclusion

The goal of this Msc thesis was to evaluate the performance of Adaptive frequency hopping in the presence of interference and compare it with single channel and TSCH without adaptivity. The purpose of considering other classes of channel utilization is to observe how well Adaptive frequency hopping performs. To evaluate the Mira mesh network in the presence of interference, support for the interference node had to be implemented in the MiraSim simulator. The considered use cases were considered from LumenRadio's previous knowledge of the industry. Using the available data and information, the behavior of WiFi was modeled as an interference node considering a few assumptions.

From the results obtained, it is observed that AFH performs better as compared to other classes of channel utilization. As a part of this thesis, necessary KPIs were considered and evaluated in different cases and scenarios. It is seen that in both use cases, the AFH performs consistently better. There is improvement in PDR, latency and power consumption. In particular, AFH performs significantly better in Condition Monitoring use case. There is a high difference in the KPIs as compared with the other two classes of adaptivity (as seen in table 4.3). Hence, one can infer that Adaptive frequency hopping works better in congested networks. Furthermore, the performance of AFH is also seen with increasing the number of interferences for both use cases. In both scenarios, adding interference didn't affect the performance much as the differences in the KPIs are negligible. This shows that Adaptive frequency hopping adapts well to interferences, successfully detects the interferences in the channels and mitigates the effect of disturbances in the network.

The rate of adaptivity ("How fast does it adapt") in AFH is also seen. It is observed that the rate of adaptivity increases with an increase in the rate of the nodes in the network. During this observation, the trade-off between latency and power consumption is seen along with the rate of adaptivity. Different levels of disturbances are also simulated with different channel utilization classes to summarize how Mira mesh networks perform in all possible cases. The test result matrix for both the use cases shows that the AFH works better in all the disturbance scenarios. It is also interesting to observe the KPI differences due to adding disturbances. It is evident that the PDR loss of adding disturbance or the power consumption increase of adding disturbance is minimum for Adaptive frequency hopping as compared to

TSCH without adaptivity and single channel network (as seen in A.1 and A.2 for without disturbance comparing with 4.1 and 4.3). Thus, AFH is resilient to disturbances thereby proving it is ultra-reliable and low-power wireless technology.

5.2 Future Work

A lot of improvements can be made to the methods and implementation of the jammer itself. In this thesis, only limited applications over WiFi were considered, but there are also other applications that can be considered for implementation. More measurement datasets for WiFi can be fetched to improvise the implementation of WiFi as a jammer.

There are several investigations that can be conducted to assess the effectiveness of AFH. One approach is to simulate larger networks consisting of more than 100 nodes in order to evaluate AFH performance. To manage the complexity, it is advisable to limit the scenarios for evaluation. Conducting a wider range of simulations would provide a more comprehensive understanding of AFH and allow for the consideration of additional metrics. It would be beneficial to expand the investigations by sending larger packets during the simulations. Furthermore, incorporating leaf nodes with varying rates into the network and conducting simulations would enable further exploration and analysis of AFH. Finally, the evaluations can be done in the test bed and also compare and discuss the results obtained in the simulations and the test bed.

Bibliography

[1] Wifi spectrum. [Online]. Available: https://anritsu.typepad.com/interferencehunting.html

[2] Iot. [Online]. Available: https://www.ericsson.com/en/internet-of-things

[3] U. Javed, D. He, P. Liu, and Y. Yang, "Frequency hopping in ieee 802.15.4 to mitigate ieee 802.11 interference and fading," *Journal of Systems Engineering and Electronics*, vol. 29, pp. 445–455, 06 2018.

[4] S. Zoppi, H. M. Gürsu, M. Vilgelm, and W. Kellerer, "Reliable hopping sequence design for highly interfered wireless sensor networks," in *2017 IEEE International Symposium on Local and Metropolitan Area Networks (LANMAN)*, 2017, pp. 1–7.

[5] Miramesh networks. [Online]. Available: https://docs.lumenrad.io/miraos/2.4.0/description/miramesh.html

[6] nrf52832. [Online]. Available: https://www.nordicsemi.com/Products/nRF52832

[7] nrf52840. [Online]. Available: https://www.nordicsemi.com/Products/nRF52840

[8] G. Cena, C. Demartini, M. Ghazi Vakili, S. Scanzio, A. Valenzano, and C. Zunino, "Evaluating and modeling ieee 802.15.4 tsch resilience against wi-fi interference in new-generation highly-dependable wireless sensor networks," *Ad Hoc Networks*, vol. 106, p. 102199, 05 2020.

[9] Tsch. [Online]. Available: https://en.wikipedia.org/wiki/Time_Slotted_Channel_Hopping#:~:text=Time%20Slotted%20Channel%20Hopping%20or,International%20standard

[10] Rfc 6551 : Routing metrics used for path calculation in low-power and lossy networks. [Online]. Available: https://pike.lysator.liu.se/docs/ietf/rfc/65/rfc6551.xml

[11] Rfc icmpv6. [Online]. Available: https://datatracker.ietf.org/doc/html/rfc4443

[12] E. Hunde, D. Deac, S. Thielemans, M. Carlier, K. Steenhaut, A. Braeken, and V. Dobrota, "Time slotted channel hopping and contikimac for ipv6 multicast-enabled wireless sensor networks," *Sensors*, vol. 5, 03 2021.

[13] R. Musaloiu-Elefteri and A. Terzis, "Minimising the effect of wifi interference in 802.15.4 wireless sensor networks," *IJSNet*, vol. 3, pp. 43–54, 01 2008.

[14] A. Gonga, O. Landsiedel, P. Soldati, and M. Johansson, "Revisiting multi-channel communication to mitigate interference and link dynamics in wireless sensor networks," 05 2012.

[15] M. Petrova, L. Wu, P. Mahonen, and J. Riihijarvi, "Interference measurements on performance degradation between colocated ieee 802.11g/n and ieee 802.15.4

networks," in *Sixth International Conference on Networking (ICN'07)*, 2007, pp. 93–93.
[16] Rust. [Online]. Available: https://doc.rust-lang.org/book/title-page.html
[17] Itu indoor propogation model. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.1238-0-199705-S!!PDF-E.pdf
[18] V. Iyer, F. Hermans, and T. Voigt, "Detecting and avoiding multiple sources of interference in the 2.4 ghz spectrum," vol. 8965, 02 2015, pp. 35–51.
[19] Juniper networks. [Online]. Available: https://www.juniper.net/documentation/us/en/software/junos/routing-policy/topics/concept/policer-mx-m120-m320-burstsize-determining.html

A

Appendix 1

Building automation

	PDR(%)	Latency(ms)	Avg current usage(uA)	Max current usage (uA)	ETX
Adaptive frequency hopping	100	452.92	20.57	30.80	1.58

Table A.1: Evaluating different KPIs for adaptive frequency hopping without disturbance in Building automation

Condition Monitoring

	PDR(%)	Latency(ms)	Avg current usage(uA)	Max current usage (uA)	ETX
Adaptive frequency hopping	100	1211.52	12.45	16.89	1.74

Table A.2: Evaluating different KPIs for adaptive frequency hopping without disturbance in Condition Monitoring

DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

AVANCEZ
1829
CHALMERS
UNIVERSITY OF TECHNOLOGY