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Overall Power Optimization of Thread Mesh Wireless Networks

by

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ABSTRACT

This research investigates power optimization in Thread mesh wireless networks, focusing on transmission power as a key parameter. With the increasing prevalence of IoT applications, such as MOOD-Sense, the need for energy-efficient solutions is paramount. We compare the effectiveness of two algorithmic approaches, Monte Carlo (MC) and Genetic Algorithm (GA), in optimizing transmission power to reduce overall power consumption. Our study incorporates two locations, using various network modes and devices. Results demonstrate that GA consistently outperforms MC in optimizing power consumption, leading to a more energy-efficient network. GA effectively minimizes energy usage by adjusting transmission power based on distance without compromising network performance. In addition to MOOD-Sense, our findings have implications for other IoT applications, promoting more sustainable and energy-efficient implementations. Our research highlights the importance of responsible and sustainable innovation, emphasizing ethical aspects, reliable services, professional skills, and applied research for system design. The findings contribute to the development of energy-efficient IoT networks, supporting the integrating of devices and systems with minimal environmental impact. This study serves as a foundation for further exploration into power optimization techniques and the expansion of sustainable IoT ecosystems.

Keywords: Thread network, Parameter optimization, Power optimization.

DECLARATION

I hereby certify that this report constitutes my own product, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions or writings of another.

I declare that the report describes original work that has not previously been presented for the award of any other degree of any institution.

Signed,

Md Mazedul Islam Khan

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Chapter 1

Rationale

1.1 Introduction

The research project, titled "Overall Power Optimization for Thread-Based Wireless Network," is a child project within the broader MOOD-Sense initiative. The MOOD-Sense project employs IoT devices to detect and predict challenging behavior in dementia patients. The project aims to develop an early warning system combining sensors, artificial intelligence, and wireless communication to provide feedback for healthcare professionals and improve patient care and safety [1].

This child project focuses on optimizing the energy efficiency and performance of the wireless Thread network protocol utilized by different wireless sensors and various MOOD-Sense projects. By examining network parameters such as transmission power, correct device types, path loss, positions, RSSI Downlink, RSSI Uplink, and more, this project aims to determine the optimal configuration of these parameters.

This child project forms a Thread network and employs an algorithmic approach to optimize network parameters using the appropriate hardware. The goal is to investigate how the transmission power parameter helps reduce the overall power consumption in an algorithmic approach while maintaining reliable communication between devices. Additionally, the project explores the integration of Thread with other wireless technologies, such as Bluetooth Low Energy, to enable connections between non-Thread-enabled devices.

1.2 Problem Definition

The growing reliance on wireless networks and IoT devices has intensified the need for energy-efficient communication protocols like Thread. Optimizing the energy efficiency and performance of the wireless Thread network protocol is essential for successfully operating various wireless sensors and applications. The challenge lies in determining the optimal configuration of network parameters, like transmission power and device types, to minimize power consumption without compromising reliability. Thread devices consume more power in mesh networks due to their high transmission frequency, leading to frequent battery replacement and reduced device availability. Furthermore, limited compatibility with existing devices can constrain Thread network protocol's functionality and reliability. Addressing these challenges is essential for realizing the full potential of Thread-based wireless communication in a wide range of fields.

1.3 Goals and Objectives

The main objective of this research project is optimizing power efficiency for the Thread network protocol, applicable in projects like MOOD-Sense. The research focuses on addressing power consumption and compatibility challenges, with the following goals:

1. Examine the impact of transmission power optimization on Thread devices' power consumption.
2. Apply algorithms like Monte Carlo and Genetic Algorithm for optimizing network parameters and determining efficient configurations.
3. Evaluate optimized Thread network performance in various environments, comparing it to maximum power mode.
4. Investigate integration with other wireless technologies, ensuring seamless communication with non-Thread devices.
5. Suggest future research directions and improvements for Thread network optimization, including device positioning, path loss, and broader application scope.

1.4 Main Research Question

- How can parameter optimization be applied to develop a power-optimized Thread mesh wireless network?

1.5 Sub-Research Questions

1. How does transmission power optimization affect Thread devices' power consumption?
2. How can algorithms like Monte Carlo Method and Genetic Algorithm be applied to optimize network parameters and determine efficient configurations?
3. How does optimized Thread network performance compare to maximum power mode in various environments?
4. How can Thread be integrated with other wireless technologies to ensure seamless communication with non-Thread devices?
5. What are the future research directions and improvements for Thread network optimization, including device positioning, path loss, and broader application scope?

1.6 Present Situation

The MOOD-Sense research project had initially planned to use three wireless communication technologies, namely BLE, ZigBee, and WiFi, for the entire network communication. However, there has been no active implementation of any network protocol, and different subprojects are being carried out in parallel. These subprojects involve various aspects of the MOOD-Sense framework, such as the registration of dementia patient behavior and monitoring of the environmental context. However, the lack of a central network communication protocol has resulted in all the devices from different projects being separate, hindering data sharing and integration. The current state of the MOOD-Sense project can be visualized in the diagram, which shows the separate subprojects and devices without any active network implementation. The proposal to use a Thread mesh wireless network was introduced to address these issues due to its mesh nature, low cost, reliability, and remote management capabilities, making it an ideal candidate to connect BLE, ZigBee, and WiFi in a central place. The Thread mesh network protocol will enable seamless connectivity, interoperability, and communication among all devices in the MOOD-Sense framework.

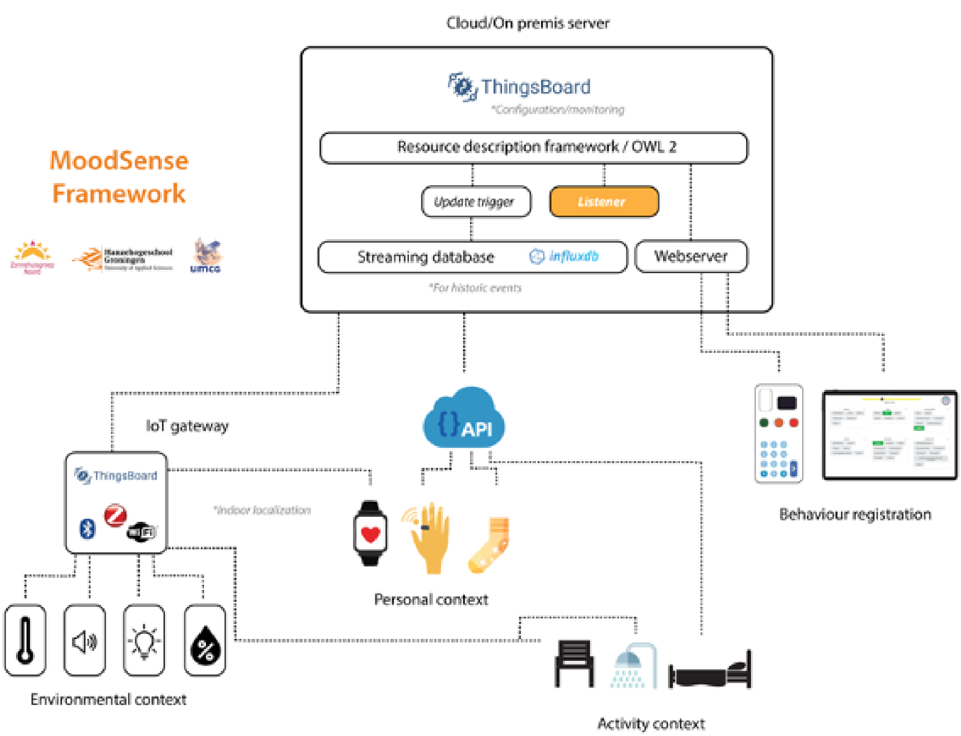

Figure 1.1: Current state of the MOOD-Sense project

1.7 Desired Outcome

The desired outcomes of the current project aim to optimize the energy efficiency and performance of the wireless Thread network protocol while considering ethical aspects, reliable services, professional skills, applied research, and sustainability. The objective is to implement a Thread mesh network for seamless communication and to optimize power consumption through parameter optimization techniques, specifically transmission power. By comparing algorithmic approaches like Monte Carlo Method and Genetic Algorithm, the project seeks to identify the best method for achieving maximum power reduction while adhering to responsible research practices. Ultimately, the project aims to develop recommendations and strategies applicable to other MOOD-Sense projects, emphasizing ethical aspects, professional skills and applied research in developing and implementing energy-efficient wireless networks.

Chapter 2

Situational & Theoretical Analysis

2.1 Thread Wireless Network

Thread wireless network, introduced in 2014, is an open standard designed for secure, low-power, and cost-effective IPv6 communication in connected home and commercial applications. Thread offers simple installation, self-configuring, dynamic optimization, and self-healing capabilities, utilizing a low-power wireless mesh network topology, which ensures scalability and reliability [2]. Its low power consumption makes it ideal for smart home devices running on batteries and supports long-range communication. Thread uses IPv6 security features and Backbone Border Routers to prevent unauthorized access and extend the network range. It's an application-layer agnostic solution, allowing multiple layers to share the network and providing flexibility in application choices. Refer to the OSI model diagram for a clearer understanding of Thread's structure and functionality [3].

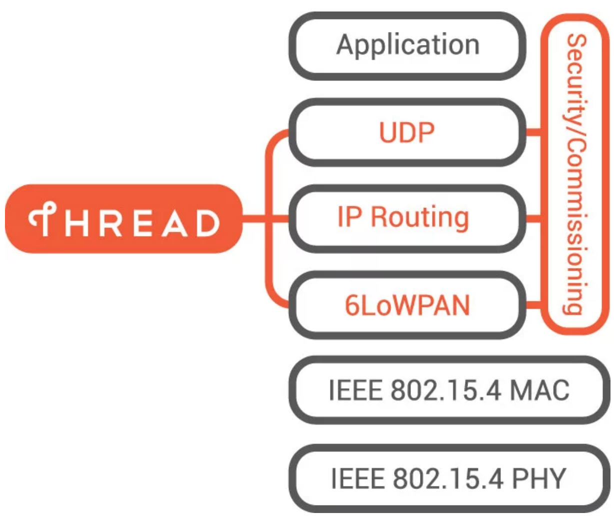

Figure 2.1: Thread OSI model [3].

2.1.1 Topology

The network topology of a Thread Network depends on the number of Routers in the network. A single Router forms a basic star topology, while multiple Routers create a mesh topology, increasing reliability and redundancy. Refer to the network topology image for a visual representation of a Thread Network's basic topology, showing Routers and various device types forming a mesh network [3].

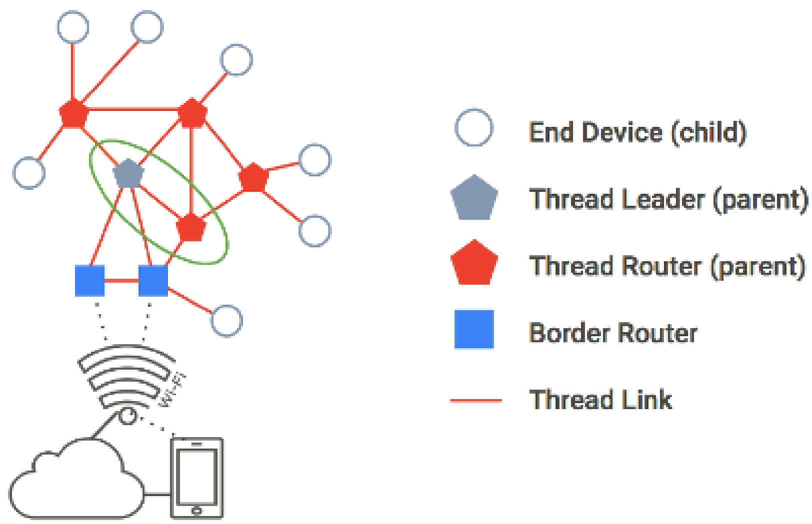

Figure 2.2: Thread Network topology [3].

2.1.2 CoAP

CoAP (Constrained Application Protocol) is a lightweight protocol for IoT communication between constrained devices and networks, such as Thread. It enables peer-to-peer communication over IPv6 mesh networks and benefits low-power devices with limited memory. CoAP operates over UDP and offers Confirmable (CON) and Non-confirmable (NON) message types, providing flexibility in application requirements. While the maximum message size should be small enough to fit into a single packet to avoid IP fragmentation, which can increase power consumption, CoAP measurements typically focus on cases without fragmentation [4].

2.1.3 6LoWPAN

6LoWPAN, a protocol used by Thread devices, enables IPv6 packet transmission over IEEE 802.15.4 networks. It features header compression to minimize packet size, conserving energy and bandwidth. The mesh header improves link-layer forwarding efficiency and supports end-to-end fragmentation. Thread devices use MLE messages for node and router discovery, eliminating the need for IPv6 neighbor discovery and simplifying network operations [3].

2.1.4 IEEE 802.15.4

Thread Specification uses IEEE 802.15.4 PHY and MAC layers for link layer communication. Operating at 250 kbps in the 2.4 GHz band ensures reliable message transmission among Thread Devices. The CSMA-CA mechanism allows multiple devices to share the bandwidth while link-layer acknowledgments, retries, and security features maintain reliable and secure communication. The Thread Specification leverages the well-established IEEE 802.15.4 protocol for dependable end-to-end communication [3].

2.1.5 ICMP

ICMPv6 (Internet Control Message Protocol version 6) is integral to the IPv6 protocol suite, providing error reporting and diagnostic functions. Thread devices support ICMPv6 messages and error reporting, communicating network conditions and issues to other devices. In addition to error reporting, devices also support using echo request (ping) and echo reply messages, which are used for testing network connectivity and diagnosing network problems. With the support of ICMPv6, Thread devices can communicate and troubleshoot network issues more efficiently and streamline [3].

2.1.6 No Single Point of Failure

Thread Network is designed to operate without any single point of failure, ensuring reliable communication between devices. Devices with specific functions can be replaced automatically without disrupting communication. For instance, Sleepy End Devices automatically select another parent if their current parent is unavailable. Individual devices may lack backup capabilities in specific topologies, but the Thread Network operates autonomously to minimize the impact on users. The Leader role is dynamically elected, and if a Leader fails, another router takes its place, ensuring no single point of failure. Thus, Thread Network delivers reliable, seamless communication without depending on a single device [5].

2.1.7 Power Consumption

Total power consumption in Thread nodes depends on node type, radioactivity, base consumption, and application activity. Factors like functional requirements, network traffic, protocols, commissioning and maintenance logic, and environmental conditions impact radioactivity. Data transmission varies with applications sending frequent small packets or infrequent large packets, and the energy consumption is influenced by payload size. As packet size increases, transmission time and energy consumption also increase. Considering overhead added by network layers besides the actual data size is vital [6].

2.2 Parameter Optimization

Parameter optimization in wireless networks, including Thread mesh networks, balances performance and resource consumption to achieve robust and reliable networks [7]. Fundamental techniques include adjusting transmission power, duty cycling, data rate selection, network topology and routing optimization, efficient retransmission strategies, adaptive power control, channel hopping, network scheduling, parent selection, and load balancing. These methods improve power efficiency, performance, energy consumption, battery life, and network reliability. Optimization is an iterative process that employs algorithms, simulation tools, and real-world testing to find the ideal combination of parameter values, meet performance criteria, and efficiently utilize resources [8].

2.2.1 Transmission Power

Transmission power in Thread mesh wireless networks is vital for performance, coverage, connectivity, and power consumption. Thread operates in the 2.4 GHz ISM band based on the IEEE 802.15.4 standard, with transmission power varying due to hardware capabilities and regional regulations [9]. Balancing energy efficiency and network performance ensures reliable communication and minimal power consumption. Techniques for optimizing transmission power include minimum transmission power, adaptive transmission power control, and power control based on link quality, distance, traffic load, application requirements, and node energy. Additionally, multi-objective optimization and control protocols, such as Transmit Power Control, can be employed. These strategies improve energy efficiency, reduce interference, and enhance network performance.

2.3 Algorithm

2.3.1 Monte Carlo Method

The Monte Carlo method is a computational technique that uses random sampling to obtain numerical results, often applied in mathematical modeling, simulation, and optimization problems across various fields such as physics, engineering, finance, and computer science.

The Monte Carlo method consists of the following steps:

1. **Define the problem:** Identify the problem and input parameters to consider.
2. **Generate random samples:** Produce many random samples for input parameters using random number generators or Latin hypercube sampling methods.
3. **Run simulations:** Use each set of input parameters to simulate the problem, which could be a mathematical model or physical experiment.
4. **Analyze the results:** Examine the simulation results to determine the system's statistical properties, including mean, variance, and standard deviation.

5. **Refine the model:** Utilize the results to refine the model or adjust input parameters by selecting a subset of input parameters producing desirable outcomes or adjusting parameters based on statistical analysis.
6. **Repeat:** Continue the process until a satisfactory level of accuracy is achieved.

The following Monte Carlo simulation diagram shows random inputs generated and evaluated for desired results. If successful, the simulation ends; otherwise, new random inputs are developed and evaluated. This method is a powerful tool for complex problems and has widespread applications [10].

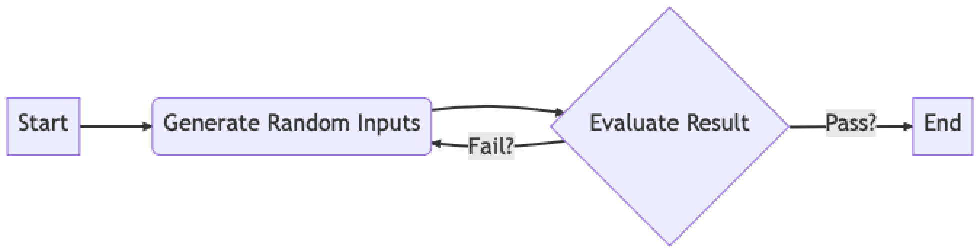

Figure 2.3: Monte Carlo Simulation diagram.

2.3.2 Genetic Algorithm

Inspired by natural selection, genetic algorithms are optimization algorithms used for complex problems where traditional methods may be inefficient. They create a population of potential solutions, evaluate them based on a fitness function, and employ selection, crossover, and mutation operations to generate new solutions. Although they handle large search spaces and find global optima, limitations include random sampling, longer computation times, and potential convergence issues. Nevertheless, they are versatile engineering, finance, and machine learning tools.

The Genetic Algorithm (GA) workflow includes the following:

1. **Initialization:** Generating a random population of potential solutions.
2. **Selection:** Choosing the fittest individuals for the next generation.
3. **Crossover:** Combining pairs of selected chromosomes to create offspring.
4. **Mutation:** Introducing small random changes to offspring bit strings.
5. **Evaluation:** Determining fitness values using a fitness function.
6. **Termination:** Stopping the algorithm when a criterion is met.

By iterating through these steps, the GA searches the solution space, converging on an optimal or near-optimal solution. A flowchart illustrates the GA's basic process, from initialization to the final solution, upon meeting a termination condition [11].

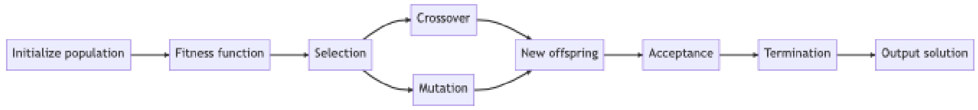

Figure 2.4: Genetic Algorithm flowchart.

2.4 Euclidean Distance Matrix

The Euclidean distance matrix represents the straight-line distances between pairs of devices in a two-dimensional Thread network, affecting parameters like signal strength, connectivity, and energy consumption. By calculating this matrix, the research project can optimize the network using different algorithms while accounting for spatial relationships between devices.

The Euclidean distance between devices i and j with coordinates $(x1, y1)$ and $(x2, y2)$ is calculated as follows:

$$distance\,(i, j) = \sqrt{(x^2 - x^1)^2 + (y^2 - y^1)^2} \tag{2.1}$$

This calculation helps account for spatial constraints and device placements, ensuring Monte Carlo random input generation considers these factors for a more efficient and optimized Thread network [12].

2.5 RSSI Calculation

Received Signal Strength Indicator (RSSI) is a vital metric in wireless systems like Thread networks, representing the received signal's power level and providing information about the wireless link quality. Antenna gains significantly influence signal strength, affecting overall performance [13].

The RSSI calculation, including transmit and receive antenna gains, is:

$$RSSI = P_t + G_t + G_r - L_p \tag{2.2}$$

Where $RSSI$ represents the Received Signal Strength Indicator (dBm), P_t is the transmission power (dBm), G_t is the transmit antenna gain (dBi), G_r is receive antenna gain (dBi), and L_p is path loss (dB) [14].

Thread devices typically have an RSSI sensitivity of -100 dBm. This formula applies to uplink and downlink connections, offering a more accurate signal strength representation and aiding in network performance optimization and energy consumption [9].

2.6 General Path Loss Model

Wireless communication systems are crucial in modern life, and understanding radio wave behavior is essential for optimizing their performance. Path loss models predict received signal strength and account for gains and losses in wireless channels. This research analyzes four key path loss models and their applications in wireless communication systems.

2.6.1 Free-Space Propagation Model

The free-space propagation model is used for predicting the received signal strength in line-of-sight (LOS) environments, where there are no obstacles between the transmitter and receiver. It is often adopted for satellite communication systems. The Friis equation 2.3 describes the received power at distance d, considering non-isotropic antennas with transmit gain G_t and receive gain G_r [15]:

$$P_r\left(d\right) = \frac{P_t G_t G_r \lambda^2}{\left(4\pi\right)^2 d^2 L} \tag{2.3}$$

Where P_t represents the transmit power $(watts)$, d is the distance between transmitter and receiver in $meters$, λ is the wavelength of radiation (m), G_t is transmit gain, G_r receive gain, and L is the system loss factor independent of the propagation environment. The free-space path loss $PL_F\left(d\right)$ can be directly derived without any system loss from 2.3:

$$PL_F\left(d\right)\left[dB\right] = 10log\left(\frac{P_t}{P_r}\right) = -10log\left(\frac{G_t G_r \lambda^2}{\left(4\pi\right)^2 d^2}\right) \tag{2.4}$$

Without antenna gains (i.e., $G_t = G_r = 1$), 2.4 is reduced to:

$$PL_F\left(d\right)\left[dB\right] = 10log\left(\frac{P_t}{P_r}\right) = 20log\left(\frac{4\pi d}{\lambda}\right) \tag{2.5}$$

2.6.2 Log-Distance Path Loss Model

The log-distance path loss model is a more generalized approach, accounting for the varying path loss exponent n depending on the environment. The path loss at distance d is given by 2.6, where d_0 is the reference distance at which the path loss inherits the characteristics of free-space loss [15]:

$$PL_{LD}\left(d\right)\left[dB\right] = PL_F\left(d_0\right) + 10nlog\left(\frac{d}{d_0}\right) \tag{2.6}$$

Where d_0 is a reference distance and n corresponds to free space which tends to change as shown in the table following table.

Table 2.1: Path Loss Exponent.

Environment	**Path Loss Exponent** (n)
Free space	2
Urban area cellular radio	2.7 - 3.5
Shadowed urban cellular radio	3 - 5
In building line-of-sight	1.6 - 1.8
Obstructed in building	4 - 6
Obstructed in factories	2 - 3

The path loss exponent (n) varies based on the environment, as shown in Table 2.1, and helps to adjust the log-distance path loss model for more accurate predictions. Lower values represent environments with fewer obstructions, such as free space, while higher values indicate more complex environments with buildings or other obstacles.

2.6.3 Log-Normal Shadowing Model

The log-normal shadowing model considers the random nature of shadowing effects, making it more suitable for realistic situations. The model is given by 2.7, where X_σ is a Gaussian random variable with a zero mean and a standard deviation of σ:

$$PL\left(d\right)\left[dB\right] = \overline{PL}\left(d\right) + X_\sigma = PL_F\left(d_0\right) + 10nlog\left(\frac{d}{d_0}\right) + X_\sigma \tag{2.7}$$

In other words, this particular model allows the receiver at the same distance d to have a different path loss, which varies with the random shadowing effect X_σ [15].

2.7 Literature Research

2.7.1 Thread Network Power Consumption

Thread network power consumption research has been limited but offers promising results. One study by Nordic Semiconductor demonstrates that the battery life of a Thread node is heavily dependent on the network configuration. For example, a node with an idle current of $3\mu A$ and a transmit current of $17mA$ can last up to 10 years in a network with a low data rate of $250kbps$ and a small number of packets per day. However, in a network with a high data rate of $1Mbps$ and many packets per day, the same node would only last for a few months [6].

In a different style, a white paper research by Thread Group provides noteworthy results on the power consumption and optimization of Thread networks. The study analyses the benefits of using a low-power wireless protocol like Thread to optimize energy consumption in Internet of Things (IoT) applications. The results of the study showed that the Thread protocol could achieve a standby power consumption of less than $3mW$, with typical transmit and receive power consumption ranging between $15mW$ and $20mW$. The study also demonstrated that devices on a Thread network could achieve up to 10 years of battery life when transmitting once per minute, making Thread a strong candidate for low-power IoT applications [16].

Another research effort, conducted by Eva Azoidou at KTH Royal Institute of Technology, analyzed the power consumption of Thread end devices, routers, and coordinators. The study demonstrated that enabling power management features could reduce power consumption by up to 70% in sleep mode. Additionally, two power optimization techniques, dynamic power management and dynamic voltage and frequency scaling, were evaluated, with the latter having a greater impact, reducing consumption by up to 35%. The research also emphasized that power consumption is influenced by transmission power level, data rate, and routing topology and suggested that implementing optimization techniques could reduce power consumption by up to 70% [17].

In summary, although the literature on Thread power optimization is limited, the results from existing studies suggest that the protocol has significant potential for reducing energy consumption in low-power wireless networking applications. More research is needed to fully understand and optimize the power consumption of Thread networks in large-scale deployments.

2.8 Algorithm

2.8.1 Monte Carlo Method

The Monte Carlo method (MCM) is a robust, efficient, flexible, and scalable tool used across various fields, including science, finance, and engineering. Research by Kroese emphasizes MCM's popularity and its applications in areas like industrial engineering, operations research, physical processes, random graphs, finance, biology, medicine, and computer science. The authors highlight MCM's simplicity, strength in randomness, and theoretical justification [10].

In contrast, William Oberle's technical note from the US Army Research Laboratory discusses the number of iterations required for accurate estimation and the accuracy or error in estimating of the probability distribution's mean. The research emphasizes the relationship between these topics through the central limit theorem and provides methods for estimating the number of iterations and confidence intervals. The study also highlights the importance of caution when dealing with small sample sizes or non-normal distributions [18].

Overall, MCM has significantly influenced quantitative problem-solving across numerous research fields, becoming an indispensable tool for understanding complex systems.

2.8.2 Genetic Algorithm

Genetic Algorithm (GA) is a heuristic optimization algorithm that handles non-linear, non-convex, and intermittent problems. It is widely applied in various engineering and scientific applications.

One study employs GA to optimize wireless sensor networks (WSNs) for precision agriculture applications. The research determines active sensors, cluster heads, and signal ranges while considering network connectivity, energy conservation, and application requirements. Results indicate that GA-generated designs outperform random deployments regarding connectivity and energy consumption [19].

In another research, Norouzi and Zaim explores the potential of GA in optimizing the operational stages of WSNs. The authors discuss node placement, network coverage, clustering, data aggregation, and routing. Simulations demonstrate that GA-based approaches outperform existing protocols, suggesting that GA can optimize WSNs in military, medical, and commercial applications [20].

Lastly, a research survey explores GA applications, insights, and future directions in wireless networking. It addresses key challenges such as parameter selection, enhancing theoretical understanding, and developing efficient multi-objective GAs. The survey emphasizes the need for further research to address open issues and explore new applications in wireless networking [21].

In summary, GA is a powerful tool for optimizing parameters in various applications. However, its computational complexity increases with the number of parameters, making it challenging to apply to large-scale problems.

2.9 Hardware Analysis

2.9.1 nRF52840 DK

The nRF52840 DK by Nordic Semiconductor is a versatile IoT and wireless connectivity development kit featuring a 32-bit ARM Cortex-M4F processor, $1MB$ flash memory, and $256KB$ RAM. The kit supports protocols like Bluetooth 5, Mesh, Thread, and Zigbee. The kit includes an onboard debugger, external antenna, sensors, and peripherals. Compatible with software tools like nRF5 SDK, nRF Connect SDK, and Zephyr RTOS, it offers multiple SoC support, Bluetooth 5.3 multiprotocol radio, Arduino Rev3 shield compatibility, onboard programming/debugging, direct USB interface, external memory support, integrated antennas, SWF RF connector, user-programmable buttons and LEDs, and various power supply options, making it ideal for low-power, high-performance wireless applications [22].

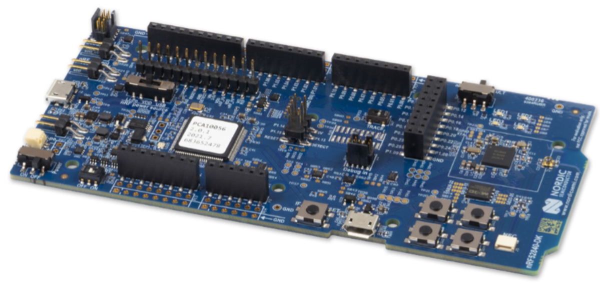

Figure 2.5: Nordic Semiconductor nRF52840 DK [22].

2.9.2 nRF52840 Dongle

The nRF52840 Dongle by Nordic Semiconductor is a compact, cost-effective platform for wireless application development, offering multiprotocol radio, Bluetooth 5.2 readiness, IEEE 802.15.4 radio, Thread, and Zigbee support. Featuring an Arm Cortex-M4 processor, DSP instruction set, and enhanced security through the Arm CryptoCell CC310 cryptographic accelerator, the dongle includes 15 accessible GPIOs, a direct USB interface, and an integrated 2.4 GHz PCB antenna. It also has one user-programmable button, one user-programmable RGB LED, and one additional programmable LED. The device operates between 1.7 and 5.5 V, powered via USB or external sources [23].

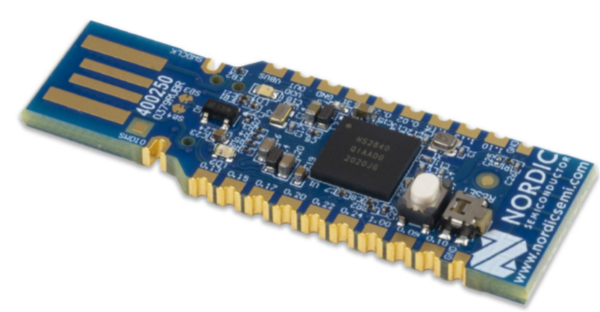

Figure 2.6: Nordic Semiconductor nRF52840 Dongle [23].

2.9.3 Power Profiler Kit II

The nRF Power Profiler Kit II (nRF PPK II) is a precise power profiler for optimizing power consumption in embedded systems using Nordic Semiconductor's nRF5x and nRF91 Series devices. It provides high accuracy with a resolution of up to 140 nA and a dynamic range of 100 mA to 1 A, allowing developers to correlate power consumption with code execution, measure real-time power consumption, and optimize battery life. Key features include a wide current measurement range, source and ampere meter modes, a programmable regulator, a high sampling rate of up to 100 kbps, compatibility with all Nordic DKs and custom boards, and support for nRF Connect for Desktop's

Power Profiler app. The nRF PPK II is ideal for engineers seeking a comprehensive, flexible, and user-friendly power profiling tool [24].

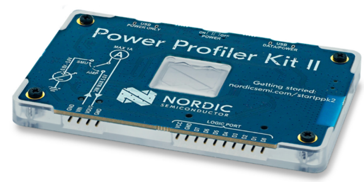

Figure 2.7: Nordic Semiconductor nRF Power Profiler Kit II [24].

2.9.4 Raspberry Pi

The Raspberry Pi 4 is a popular, low-cost single-board computer with versatile capabilities. It can function as a Thread border router when paired with an nRF DK or Dongle that supports Thread. Thread is a low-power, wireless mesh networking protocol designed for IoT devices. The nRF DK or Dongle is the Thread radio, enabling communication between the Raspberry Pi and Thread-enabled devices. This combination offers an affordable, easy-to-use, and versatile solution for building a Thread border router. The Raspberry Pi 4's general-purpose computing capabilities allow it to host various applications for managing and monitoring the network [25].

Figure 2.8: Raspberry Pi 4 [26].

Chapter 3

Conceptual Model

3.1 Introduction

Thread mesh wireless networks have gained popularity recently due to their low-power and short-range capabilities, making them ideal for IoT applications. However, optimizing the power consumption in these networks remains a challenge. This chapter presents a conceptual model for overall power optimization in Thread mesh wireless networks by algorithmizing parameters. The following image incorporates a representative network image, illustrating the key components of a Thread mesh network.

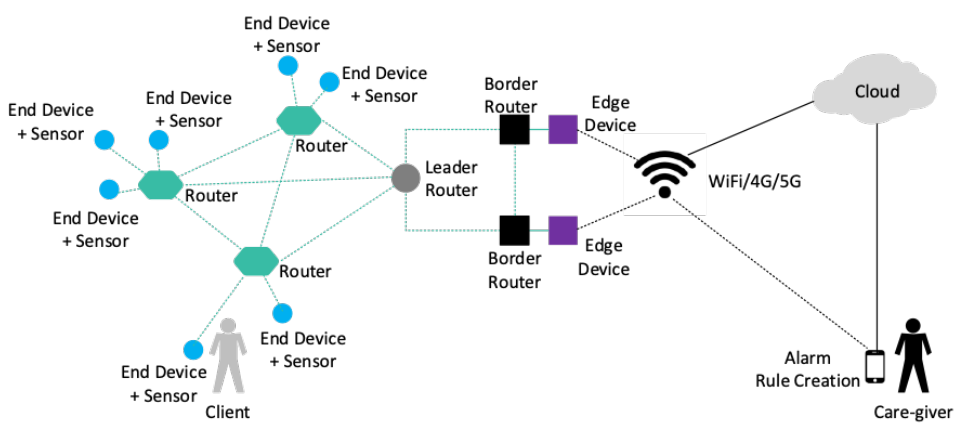

Figure 3.1: A representative Thread mesh network.

3.2 Network Components and Structure

The representative network image for a Thread mesh wireless network includes:

1. **2 Border Routers:** Gateways to external networks, ensuring redundancy and no single point of failure.

2. **3 Routers:** Relay messages within the network, with one selected as the leader for managing configurations and operations.
3. **(Sleepy) End Devices (SEED):** Low-power devices connected to router parents, conserving energy when not in use, and allowing integration with various devices.
4. **2 Edge Devices:** Connected to border routers, serving as bridges or coordinators for external network communication.
5. **Wi-Fi or Internet Cloud Service:** Enables interaction with other networks and devices, with mobile devices connected for user control and monitoring.

3.3 Power Optimization Approach

Several factors contribute to the power consumption in Thread mesh networks, including transmission power, node density, routing algorithms, and network topology. This conceptual model focuses on transmission power optimization, as it plays a significant role in determining the overall power consumption in the network.

3.3.1 Monte Carlo Method for Initial Network Nodes Build and Optimization Values

Monte Carlo Method is a powerful statistical technique for modeling complex systems with random variables. In the Thread mesh wireless networks context, Monte Carlo simulation can generate initial network node builds based on different mathematical constraints with varying node densities, positions, and transmission power levels. These initial builds can then be used as input for the Genetic Algorithm optimization process.

3.3.2 Genetic Algorithm for Power Optimization

The conceptual model integrates Genetic Algorithm, inspired by natural selection, with Monte Carlo simulation to optimize transmission power levels in Thread mesh wireless networks. Monte Carlo simulation generates initial network node builds with varying densities, positions, and power levels, while GA iteratively evaluates, combines, and mutates these builds to find the optimal settings. The fitness function assesses power efficiency and network performance, considering factors like distance and path loss, enabling the model to explore various configurations and converge to a globally optimal solution.

3.4 Conclusion

The proposed conceptual model presents an integrated approach to power optimization in Thread mesh wireless networks, utilizing Genetic Algorithm and Monte Carlo Method to optimize transmission power and initial network node build. By optimizing these critical factors, the model aims to enhance the performance and energy efficiency of the network, ensuring a more sustainable and reliable IoT communication infrastructure.

Chapter 4

Research design

The research design section outlines the procedures to accomplish the objectives and enhance the understanding of the subject matter. It presents the methodology as a series of interconnected steps, each crucial for tackling research questions and achieving goals. The following sections further elaborate on these steps and their significance to the research.

4.1 Simulate Thread Networks using OTNS and Codelab with Docker

The research used OpenThread Network Simulator (OTNS) and Codelab with Docker to simulate Thread networks under different conditions. OTNS is a powerful tool for creating, visualizing, and analyzing virtual Thread networks, while Codelab offers hands-on tutorials for simulating Thread networks in a Docker container environment. This setup allowed accurate emulation of real-world Thread network behavior and efficient execution of numerous simulations. The combination of these tools facilitated a deeper understanding of Thread network principles and mechanisms, enabling the analysis of various configurations and their impact on performance metrics like latency, throughput, and energy consumption, thus paving the way for a more informed optimization process.

4.2 Mathematical Constraints for Building a Thread Network

The objective of the mathematical model is to build a Thread network that adheres to specific mathematical constraints, ensuring a well-functioning network with the required device types, sensitivity, and received signal strength intensity (RSSI). The following mathematical model is designed for this purpose:

$$Min \sum_{i=1}^{M} P_t^i \tag{4.1}$$

Subjects to:

$$\begin{aligned} RSSI_{ED}^{j} &> EDSensitivity, j \in 1, \cdots, N \\ -20dbBm \leq P_t^j &\leq 8dBm \\ N_{REED} &= n_{Router} + n_{Leader} \end{aligned} \tag{4.2}$$

$$\begin{aligned} RSSI_{Router}^{k} &> RouterSensitivity, k \in 1, \cdots, O \\ -20dBm \leq P_t^k &\leq 8dBm \end{aligned} \tag{4.3}$$

$$\begin{aligned} RSSI_{BD}^{L} &> BDSensitivity, L \in 1, \cdots, P \\ -20dBm \leq P_t^L &\leq 8dBm \\ Sensitivity &= -100dBm \\ SEED &\in 0, 1 \\ n_{Leader} &= 1 \\ n_{Router} + n_{Leader} &\geq 3 \\ n_{BR} &= 2 \end{aligned} \tag{4.4}$$

Where P_t represents the Transmit Power of each one of the M devices, $RSSI$ is the Received Signal Strength Intensity, ED is End Device, $REED$ is Router Eligible End Devices, N_{REED} is the number of the REEDs, n_{Router} is the number of the routers, n_{Leader} is number of the leaders, N is amount of end devices, O is the number of Routers, P is the number of Border Routers, $SEED$ is Sleepy End Devices, and $Sensitivity$ is $-100dBm$ with IEEE 802.15.4 [22].

The model seeks to minimize the transmitted power of each device while ensuring adequate signal strength, proper device type distribution, and network resilience. By complying with these constraints, the Thread network can be effectively optimized for both performance and energy consumption.

The constraints of the model are as follows:

- To establish a link between the sensors and the End Devices (EDs), the Received Signal Strength Intensity (RSSI) of each ED must be approximately above the sensitivity of each ED. This ensures a stable connection between the devices.
- The maximum transmission power of each End Device is limited to $8dBm$ to minimize energy consumption while maintaining effective communication.
- The number of Router Eligible End Devices (REEDs) must be equal to the number of Routers + the Leader because, if a Router is lost, a connected REED must become

a Router to replace the "Dead Router" and maintain network resilience.

- To establish a connection between the EDs and routers, the RSSI of each Router must be approximately above the Sensitivity of each Router. This guarantees a stable link between the devices and the Routers.
- The maximum transmission power of each Router is also limited to $8dBm$, conserving energy while maintaining efficient communication.
- To establish a connection between the Routers and Border Routers, the RSSI of each Border Router must be approximately above the sensitivity of each Border Router, ensuring a reliable link between the network components.
- The maximum transmission power of each Border Router is also set to $8dBm$, optimizing energy consumption while maintaining effective communication within the network.

4.3 Monte Carlo Method for Initial Buildup

Monte Carlo Method is utilized to build the initial Thread network, considering various factors such as the distance between devices, the total number of devices, device types, device positions, and transmission power. The Monte Carlo method comprises several steps, each with its distinct processes.

These steps are separated and explained in detail as follows:

4.3.1 Step 1: Start

The Monte Carlo method is initiated to optimize the Thread network, considering the key parameters influencing the network's performance and energy efficiency.

These parameters are outlined in the table below:

Table 4.1: Parameters influencing Monte Carlo Method.

Parameter	**Description**
Number of Devices	The total number of devices (8 for this research)
Device Types	The type of each device (Unallocated, SEED, REED, Router, Leader, and Border Router)
Device Positions	The position of each device, randomly generated from 1 to 8
Transmission Power	The transmission power of each device, randomly generated between -20 dBm to 8 dBm with 4 steps difference
F_c	Carrier frequency for RSSI calculation using genral path loss model - 2.4 GHz

Continued on next page

Table 4.1: Parameters influencing Monte Carlo Method. (Continued)

Parameter	**Description**
D_0	Reference distance followed by F_c - 0.25 m
d	Distance between two devices (Figure 4.4 and 4.5)
n	Path loss exponent - 5.0
σ	Variance of the shadowing component - 3.0 dB
G_t	Transmit antenna gain - 0.0 dB
G_r	Receive antenna gain - 0.0 dB

4.3.2 Step 2: Generate Random Numbers

Based on the factors mentioned at the start, MCM generates a vector X of length equal to $2n$, where n is the number of places where network elements can be allocated. Network elements include all device types and sensors.

The vector is represented as:

$$\begin{aligned} X = [x_1, x_2, x_3, \cdots x_n, p_1, p_2, p_3, \cdots, p_n] \\ for\ x_n \in 0, 1, 2, 3, 4, 5 \\ transmission\ power\ p_n \in -20 : 4 : 8\ dBm \end{aligned} \tag{4.5}$$

Where 0 represents no element allocated, 1 is allocate a SEED, 2 is allocate a REED, 3 is allocate a Router, 4 is allocate the Leader, and 5 is allocate a Border Router.

4.3.3 Step 3: Evaluate Results

The objective function aims to build a Thread network using the minimized power value of the entire system without violating the constraints specified in the mathematical formulation. If a constraint is violated, a penalty should be added to the objective function, which is weighted according to the importance of the constraint.

The objective function with penalty values can be written as:

$$Min \sum_{i=1}^{M} P_t^i + penal_1 + penal_2 + penal_3 \ldots + penal_{nr} \tag{4.6}$$

Where $penal_1$ represents penalty for violating the first restriction, $penal_2$ is penalty for violating the second restriction, and $penal_{nr}$ is the penalty for violating the last restriction.

A solution is viable only if all constraints are satisfied without penalties. To ensure this, the mathematical model requirements are verified at each step. If a step fails to meet the requirements, the MCM generates new random inputs and re-evaluates the network until a constraint-compliant solution is found. This iterative process guarantees a Thread network that meets performance and energy optimization criteria.

4.3.4 Step 4: End

The MCM converges on an optimal solution that satisfies necessary constraints, providing outputs such as device types, transmission power, and location. It also offers information on constraint violations, including the penalty, network power consumption, and RSSI sensitivity violations—these outputs aid in understanding the optimization process and refining the network design.

4.4 Genetic Algorithm for Transmission Power Optimization

GA optimizes the Thread network's transmission power to reduce energy consumption while maintaining wireless communication quality. MCM-generated configuration is the starting point for GA.

Key steps and parameters for GA:

Table 4.2: Parameters influencing Genetic Algorithm.

Parameter	**Description**
Population Size	The number of individuals in the population - (100)
Population	The initial population consisting of transmission power, device types, and device positions
Max Iteration	The maximum number of iterations - (100)
Maximum Transmission Power	The minimum transmission power - -20 (dBm)
Minimum Transmission Power	The maximum transmission power - 8 (dBm)
Mutation Rate	The probability of mutation - 0.1
Selection Method	The method used for selecting individuals - Tournament
Mutation Method	The method used for mutating individuals - Random

In this table, the "Population" row represents the output from the Monte Carlo simulation, which is a list of transmission power, device types, and device positions.

The GA process includes the following steps:

1. Initialization: Generate the initial population using MCM output.
2. Selection: Choose best individuals based on fitness using the "sorted" method.

3. Crossover: Produce offspring by crossing over selected individuals' genes.
4. Mutation: Introduce random changes to transmission power using the "swap" method.
5. Evaluation: Calculate fitness by assessing transmission power and RSSI penalty.
6. Termination: Iterate until reaching the maximum number of iterations.

The output is a list of optimized transmission power values for each device, along with device types, positions, and penalty values. The solution minimizes transmission power while meeting connectivity constraints.

4.5 Prototype Development

This section details the steps taken to build the prototype that applied the output from Monte Carlo and GA to validate the results. We followed the Monte Carlo output to construct the network by selecting the appropriate device types. Our setup consisted of 8 devices: 2 Border Routers, 3 Routers (with one of them automatically elected as a leader), and 3 Router Eligible Devices (REEDs). The prototype was designed to closely resemble the conceptual model presented earlier in the figure, with the only slight difference being using REEDs instead of sensors as the end devices.

An image is provided below to illustrate the Thread network topology that we have constructed.

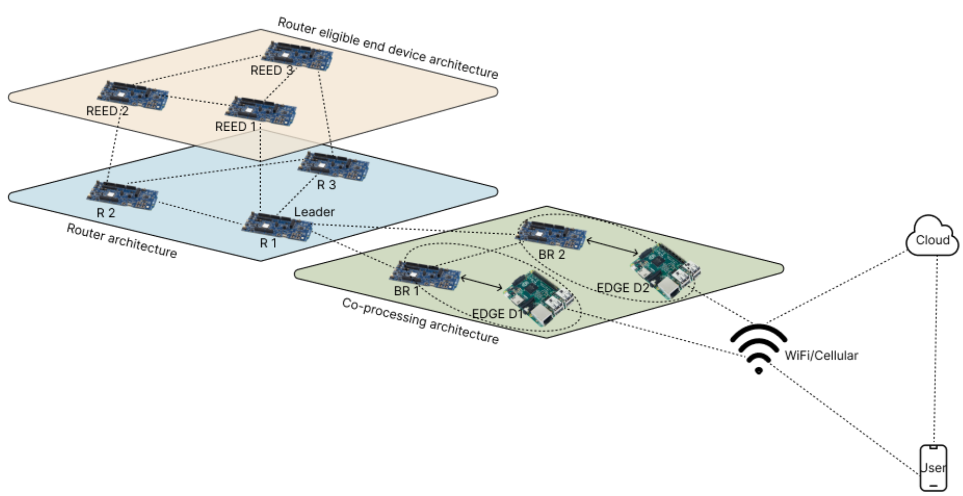

Figure 4.1: Thread network prototye topology.

4.5.1 Software Implementation

The nRF-provided Thread Client and Server setup, supporting multiprotocol communication, allowed concurrent communication with Thread and BLE devices. This simplified the process of connecting non-Thread devices to the network. The setup was customized to forward data from Client nodes to the Server using CoAP, validating data transfer within the network. The setup supported both Unicast and Multicast communication out-of-the-box, making it valuable for research purposes.

4.5.2 Construction Process

To construct the prototype, we followed these steps:

1. Assigned device roles based on the output from Monte Carlo and GA, ensuring an optimal configuration for the network.
2. Flashed each router with the Thread Server setup and each REED with the Thread Client setup. In this configuration, routers acted as servers, while REEDs acted as clients. Communication between devices was bidirectional, with the clients having BLE enabled for multiprotocol support.
3. Flashed the Border Router nodes with the Coprocessor setup provided by nRF. To enable the Raspberry Pi to act as an Edge device, we implemented the OpenThread Radio Coprocessor (RCP) architecture.
4. Turned on the devices one by one, noting that the first device activated in the network is most likely to become the leader, although leadership can change during the network's lifetime.
5. Validated all the nodes by running multicast messages using Thread ICMP service. The ICMP service allowed us to send echo requests (ping) to devices, activating their Thread antennas. This allowed us to test the Thread connection, and devices could also reply.
6. Validated the multiprotocol support connection by running a data flow from the ESP32 UWB devices to the REEDs, which then forwarded the data to the routers. This step ensured seamless communication between non-Thread devices and the Thread network.
7. Monitored the network for stability and performance, adjusting settings to maintain optimal operation.

Following these steps, we successfully constructed the prototype to apply the optimized settings obtained from the Monte Carlo simulation and the Genetic Algorithm. The following figure presents a real-world Thread network prototype setup. The image provides a clear view of the nRF52840-based Thread nodes, Raspberry Pi as the Edge device, and the Border Router setup with the Dongle. It also showcases the Development Kits used for Routers and REEDs.

In the next section, we will discuss the multiprotocol support in more detail, addressing the connection of non-Thread devices with the Thread network.

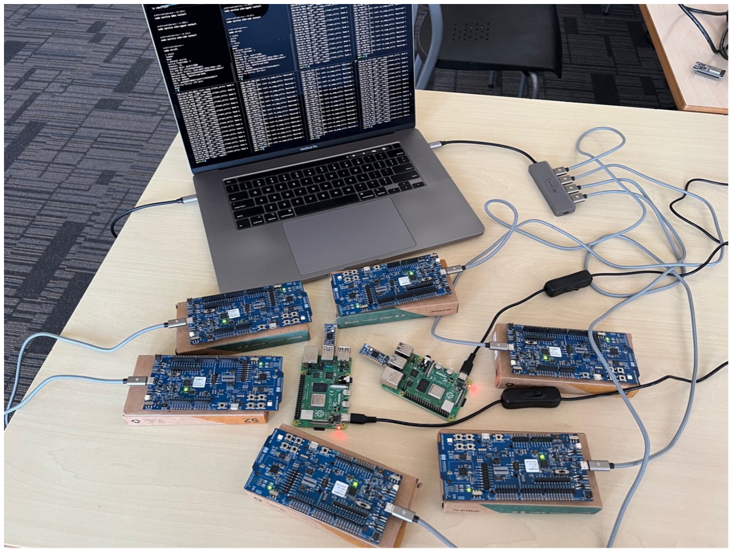

Figure 4.2: Thread network prototype setup in the lab.

4.5.3 Multiprotocol Support

The nRF52840 hardware's multiprotocol support, enabled by the MPSL library, allows integration of non-Thread devices like ESP32 UWB devices. MPSL provides services for multiprotocol apps and facilitates transmission timeslot negotiation. SoftDevice Controller ensures MPSL support as a Bluetooth LE Controller implementation. The dynamic solution enables the simultaneous operation of multiple radio protocols, requiring only radio peripheral reinitialization when switching between protocols [27].

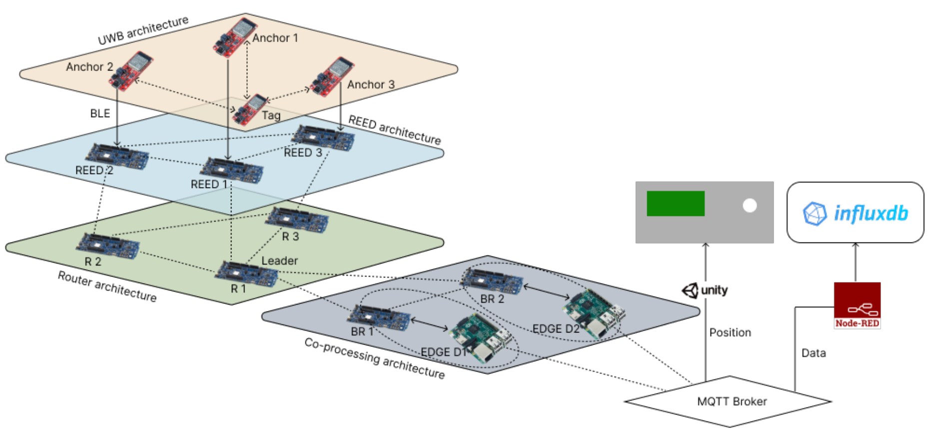

Figure 4.3: Multiprotocol support architecture.

Figure 4.3 shows ESP32 UWB devices connected via BLE to the Thread network, enabled by nRF52840 SoC's multiprotocol support. ESP32 UWB devices bridge non-Thread devices and the Thread network, connecting to REEDs via BLE. This integration highlights network adaptability to various devices. Multiprotocol support expands the device range that can interact with the Thread network, which is crucial in real-world scenarios. Integration of ESP32 UWB devices is possible due to nRF52840 SoC's concurrent support for BLE and Thread. Integrating diverse devices showcases the potential for real-world implementation, particularly in MOOD-Sense applications.

4.6 Data Collection

This section will discuss the data collection process for our research, which was conducted in two locations. These locations offered different spaces and distances for the devices, critical factors for our study. We will provide detailed explanations of the locations and distances and an overview of the data collection setup.

4.6.1 Locations

The prototype was set up in two locations: a TechHub Assen lab and a home hallway. These two locations provided different spaces and distances for the devices, which is essential for the research. The lab is small within TechHub Assen, while the home hallway offers a slightly larger space for the devices to operate. By utilizing two different locations, we collected data from diverse environments and better understood our system's performance.

4.6.2 Distances

We considered various distances between devices in our research. The following Euclidean distance matrices represent the distances between devices at each location:

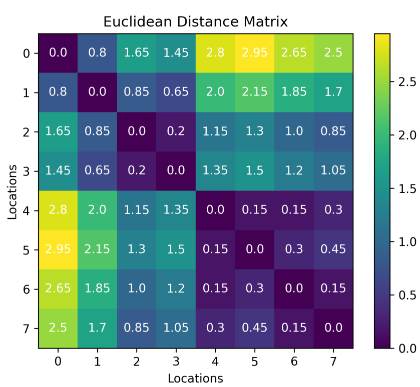

Figure 4.4: Distance matrix for lab.

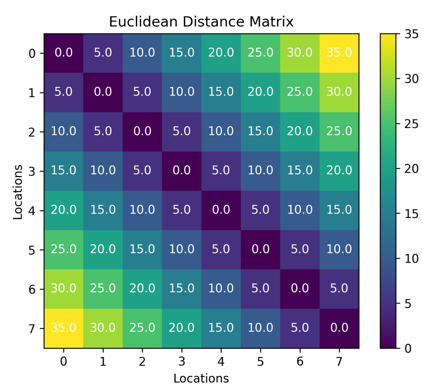

Figure 4.5: Distance matrix for home.

These distances played a crucial role in our data collection, allowing us to analyze the impact of distance on our system's performance.

4.6.3 Data Collection Methodology

The data collection process utilized various modes, time periods, and data types to analyze system performance, as detailed below:

1. **Modes:** Two modes were employed: *Maximum* and *Optimized*. Maximum mode operated at $8dBm$, while Optimized mode used Monte Carlo Method and Genetic Algorithm outputs for transmission power.
2. **Time Periods:** 60 *seconds* was selected for the *Lab* location and 300 *seconds* for the *Home* location, capturing a larger data set for each location.
3. **Data Types:** Data was collected with *No Sensor* connected and with Thread *ICMP Ping*, measuring power consumption under different conditions.

Data was collected using the nRF Power Profiler Kit II at $100,000$ samples per second. More extended time periods or higher ping rates would have resulted in excessive data, complicating the analysis process.

A table illustrating the data collection process is provided.

Table 4.3: Data collection methodology.

Location	**Mode**	**Time Period**	**Data Type**	**Ping Frequency**	**Input Voltage**
Lab	Maximum	60 *seconds*	No Sensor	0	3.588 V
			ICMP Ping	50	
	Optimized		No Sensor	0	
			Ping	50	
Home	Maximum	300 *seconds*	No Sensor	0	
			ICMP Ping	290	
	Optimized		No Sensor	0	
			ICMP Ping	290	

4.6.4 Device Setup

This section discusses preparing various device types and modes for data collection.

Source Meter Mode for Routers and REEDs

For Routers and REEDs, we used the nRF PPK2 in Source Meter mode to measure the current flow and deliver power to the devices. Each device operated at an input voltage of 3.588V. The Source Meter mode allowed us to accurately measure the current flowing through the devices during the data collection.

Figure 4.6 displays current measurement using the nRF PPK2 from the nRF 52840 DK and Figure 4.7 shows the current measurement in Source Meter mode using the Power

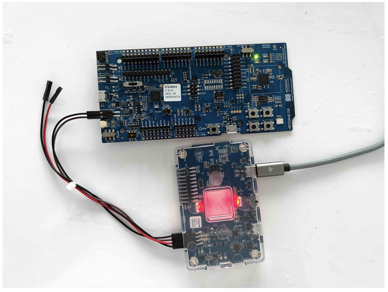

Figure 4.6: PPK2 connected to a Router.

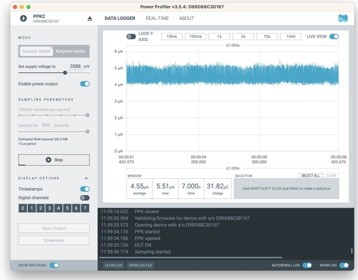

Figure 4.7: PPK2 Software in Source Meter mode.

Profiler software.

Ampere Meter Mode for Border Routers

Since the USB connection cannot be used with Source Meter mode, and the Border Routers require a connection from the Edge device (Raspberry Pi) to the nRF device to run the RCP (Radio Coprocessor), we used the nRF PPK2 in Ampere Meter mode to measure the current flow for the Border Routers.

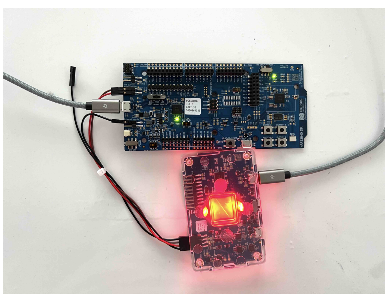

Figure 4.8: PPK2 connected to a Border Router.

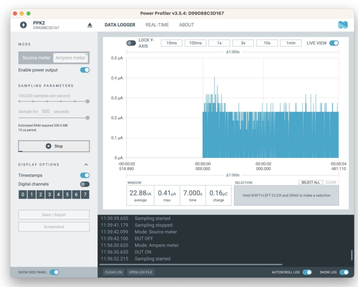

Figure 4.9: PPK2 Software in Ampere Meter mode.

Figure 4.8 displays current measurement using the nRF PPK2 from the nRF 52840 DK and Figure 4.9 shows the current measurement in Ampere Meter mode using the Power Profiler software.

To accurately measure the current from Border Routers during data collection, the SB40 bridge connection from the SoC was cut so that the current flowed through the PPK2 only and not through the USB. This modification enabled precise current flow measurements.

The prototype, built using specific hardware, was optimized using Monte Carlo simulations and Genetic Algorithms for the transmission power of a Thread network. This provided valuable insights into network performance under various conditions and was a basis for further analysis and validation.

Chapter 5

Research Results

This section examines prototype testing results, comparing Thread network performance in various modes and locations to assess the effectiveness of the Monte Carlo Method and Genetic Algorithm optimization in enhancing energy efficiency.

5.1 Algorithm Output

This subsection investigates the output from Monte Carlo and Genetic Algorithm simulations, which are crucial in determining transmission power settings for the Thread network.

5.1.1 Monte Carlo Method

The parameters table 4.1 provides insights into network performance based on transmission power values derived from the Monte Carlo Method. These parameters greatly influence results, making the table essential for comprehending the context of the generated output. Since the research was conducted in two distinct locations, it is necessary to showcase the Monte Carlo Method outputs separately for each location.

Location: Lab

This section presents the Monte Carlo Method output for the Lab location. The table below shows a few network configuration rows generated by the method, with thousands in total. Space limitations restrict the display to the last rows. The final row represents the correct configuration without penalty, meeting the mathematical model for appropriate device types and initial transmission powers.

Table 5.1: Monte Carlo Method output from Lab.

Device Type	txpower	Total txpower	Penalty	RSSI Penalty	Entire Power
3, 5, 2, 5, 1, 5, 0, 0	-20, 0, 0, -8, 0, -12, 0, -20	-60	3000	0	2940
3, 4, 1, 3, 0, 4, 1, 3	-16, -8, -4, -20, 0, -12, -4, -20	-84	3000	0	2916
3, 4, 4, 1, 2, 4, 4, 2	4, -12, -20, -4, -8, -12, -20, -8	-80	3000	0	2920
2, 0, 1, 2, 0, 0, 1, 1	-12, 4, -8, -8, -20, 0, -8, -20	-72	4000	0	3928
2, 5, 3, 3, 5, 2, 2, 4	-8, 8, 0, -16, 0, -8, -20, 8	36	0	0	36

Additionally, Monte Carlo Method generates a comprehensive table with details on each device in the network configuration, including individual distances, path loss, RSSI for downlink and uplink, and sensitivity penalties. Due to its size, we present only the first five rows of the correct configuration output. Examining these selected outputs offers insights into network performance and efficiency in each environment, keeping the focus on the primary research objectives.

Table 5.2: Device specific output from Monte Carlo Method for Lab.

Current Device	Next Device	Distance	Path Loss	RSSI Down-link	RSSI Uplink	Sensitivity Penalty
5	5	0.00	2.08	7.91	-0.08	0
5	4	0.15	-0.02	10.02	10.02	0
5	3	1.50	-9.06	-19.06	11.06	0
5	3	1.50	-12.55	22.55	-1.44	0
5	2	2.30	-9.85	19.85	3.85	0

Location: Home

Similarly, this section focuses on the Monte Carlo Method output for the Home location. The table below displays several rows of the network configuration data from the

Monte Carlo Method for the home location. The last row in the table represents the correct configuration that has no penalty and satisfies the mathematical model.

Table 5.3: Monte Carlo Method output from Home.

Device Type	**txpower**	**Total txpower**	**Penalty**	**RSSI Penalty**	**Entire Power**
2, 0, 2, 2, 5, 5, 1, 1	-12, -8, 8, -4, 0, 8, -20, -12	-40	3000	0	2960
4, 1, 1, 4, 0, 5, 1, 0	-12, 4, 0, -8, 8, 8, -12, -20	-32	4000	0	3968
0, 2, 5, 2, 4, 2, 5, 4	-20, -4, -12, -12, -4, -8, -20, -4	-84	3000	0	2916
1, 2, 0, 2, 1, 2, 0, 1	-8, -8, -16, -16, -12, -8, -16, 4	-80	4000	0	3920
2, 3, 5, 2, 2, 3, 4, 5	8, 8, -20, -8, -4, -16, 4, -16	-44	0	0	-44

Moreover, the following table represents some of the comprehensive data for specific devices. By analyzing this table, we can understand the inter-device relationships and the factors impacting the overall performance of the wireless communication network at the home location. This detailed information is valuable in identifying potential areas for improvement and optimization.

Table 5.4: Device specific output from Monte Carlo Method for Home.

Current Device	**Next Device**	**Distance**	**Path Loss**	**RSSI Down-link**	**RSSI Uplink**	**Sensitivity Penalty**
5	5	0.00	34.99	-52.99	-48.99	0
5	4	5.00	32.08	-50.08	-26.08	0
5	3	10.00	14.02	-32.02	-4.02	0
5	3	10.00	28.33	-46.33	-42.33	0
5	2	15.00	23.05	-41.05	-13.05	0

A comparison between the lab and home locations reveals some key differences. With its smaller room size, the lab location experiences lower path loss and RSSI values, attributed to more efficient signal transmission. In contrast, the home location exhibits higher path loss and RSSI values due to the increased distance between devices. By analyzing these outputs, we can better understand the impact of various environments and distances on network performance, allowing for informed optimization decisions for different applications.

5.2 Genetic Algorithm

This section highlights the Genetic Algorithm output and key parameters affecting the results. The parameters in table 4.2 are crucial as they significantly influence outcomes. The GA algorithm was applied in lab and home settings, with outputs presented separately for comparison and analysis under different environmental conditions. This approach provides insight into the GA algorithm's performance and adaptability in optimizing wireless communication networks across various scenarios.

Location: Lab

This section examines the Genetic Algorithm output for the lab location, highlighting transmission power results. These findings reveal the GA's effectiveness in optimizing power consumption in a lab environment.

Transmission Power The power optimization plot demonstrates the effectiveness of the GA in optimizing the transmission power for the devices in the lab. Initially, the maximum transmission power was 56, optimized to the lowest value of -160. This significant reduction in power consumption is expected due to the proximity of the devices in the lab setting, indicating that using the lowest transmission power for each device is the most efficient strategy under these conditions.

Network Configuration The network configuration data obtained from the GA provides information on the list of transmission power, total transmission power, and the maximum transmission power determined by the algorithm. By analyzing these values, we can better understand the factors contributing to an efficient and effective wireless communication network in the lab environment.

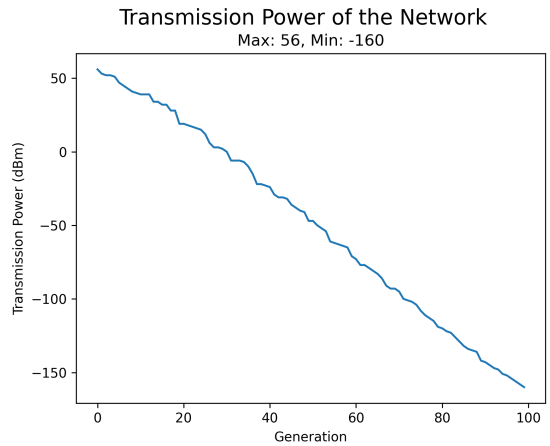

Figure 5.1: Genetic Algorithm transmission power optimization for lab location.

Table 5.5: Genetic Algorithm output for lab location.

Transmission Power (dBm)	**Total** (dBm)	**Maximum** (dBm)
-20, -20, -20, -20, -20, -20, -20, -20	-160	56

Location: Home

This section examines the Genetic Algorithm output for the home location, highlighting transmission power. This finding reveals the GA's effectiveness in optimizing power consumption in a home environment.

Transmission Power The power optimization plot demonstrates the effectiveness of the GA in optimizing the transmission power for the devices in the home. Initially, the maximum transmission power was 56, optimized to a significantly lower value of -149. This notable reduction in power consumption can be attributed to the GA's ability to adapt the transmission power according to the specific requirements of the home environment, where distances between devices can vary significantly compared to a lab setting.

Network Configuration Similarly, the network configuration differs from the one observed in the lab setting, highlighting the unique requirements of each environment. In the home location, the devices have a different distribution of transmission power levels to optimize power consumption and maintain efficient communication in the presence of various obstacles and more considerable distances between devices. By adjusting the transmission power according to the specific conditions of the home environment, the GA can find a practical solution that balances power consumption and network performance.

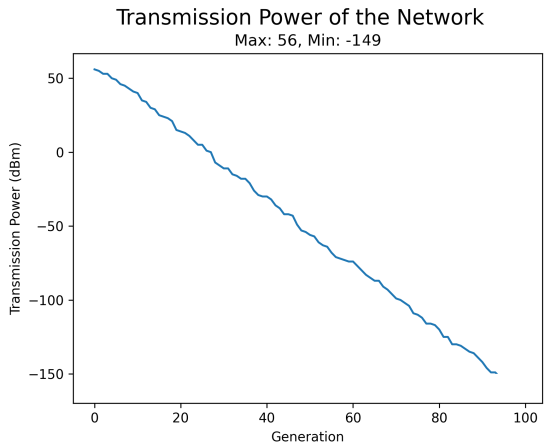

Figure 5.2: Genetic Algorithm transmission power optimization for home location.

Table 5.6: Genetic Algorithm output for home location.

Transmission Power (dBm)	**Total** (dBm)	**Maximum** (dBm)
-20, -19, -20, -19, -18, -18, -16, -19	-149	56

Large Random Distance

In this section, the performance of the GA algorithm, when applied to a considerable distance scenario, is explored. The significant distance output has yet to be tested on the physical prototype due to resource constraints and the impracticality of implementing such a large-scale test. In this scenario, the distance between each device is set to 500 meters apart from one.

Transmission Power When observing the transmission power plot for this considerable distance scenario, we find that the GA algorithm can significantly optimize the transmission power from an initial value of 38,877 down to -68 dBm. This impressive optimization result highlights the capability of the GA algorithm to effectively adjust the transmission power even in situations with considerable distances between devices.

Network Configuration In the network configuration for the large distance scenario, the transmission power for each device is no longer set to closer to the lowest value, resulting in a total transmission power of -68 and a maximum value of 38,877. The results from this test demonstrate the potential of the GA algorithm to optimize transmission power over large distances, making it a valuable tool for optimizing wireless communication networks in various environments.

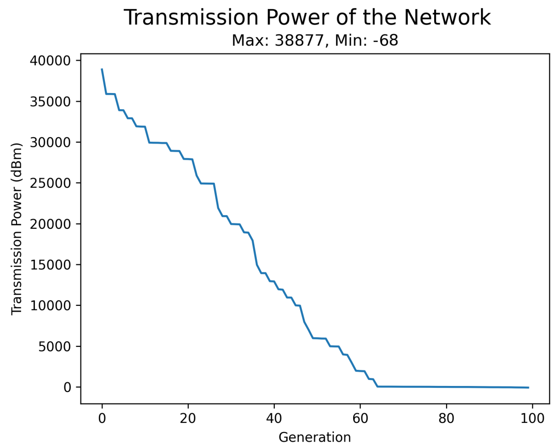

Figure 5.3: Genetic Algorithm transmission power optimization for large random distance scenario.

Table 5.7: Genetic Algorithm output for large random distance scenario.

Transmission Power (dBm)	**Total** (dBm)	**Maximum** (dBm)
-17, -8, -5, 7, -13, -11, -9, -12	-68	38,877

5.2.1 Comparison Overview

In conclusion, the GA and Monte Carlo algorithms were applied to various scenarios, including large distances, home environments, and laboratory settings, to optimize transmission power in wireless communication networks. However, the GA algorithm stands out for its exceptional ability to optimize transmission power across all scenarios.

In the large distance scenario, the GA algorithm optimized transmission power from a maximum of 38,877 to a minimum of -68, showcasing its remarkable performance in tackling large-scale challenges. In the home and lab environments, the GA algorithm effectively adapted to the specific requirements of these scenarios, optimizing transmission power to -149 and -160, respectively.

While the Monte Carlo algorithm also demonstrated its capacity to optimize transmission power in home and lab settings, the GA algorithm consistently outperformed Monte Carlo in optimizing transmission power across all considered environments.

5.3 Current Consumption Analysis

This section will analyze the current consumption for individual devices in the wireless communication network. We will examine the maximum and optimized current consumption across Lab and Home locations, considering scenarios with and without sensor data and utilizing Monte Carlo Method and Genetic Algorithm optimization.

5.3.1 Maximum Current Consumption

This section investigates the power consumption profiles of devices operating at their highest transmission power setting of 8 dBm, regardless of location and type. This analysis provides a baseline for understanding power consumption limits and identifying potential optimization areas.

Location: Lab

This section examines the current consumption at the lab location, a small research room with efficient signal transmission. We discuss the impact of this confined environment on network performance and optimizations, considering the unique characteristics of the lab setting.

Mode: No Sensor The following plot and table present an overview of the network's current consumption in No Sensor mode, where devices do not send any pings to their radios, resulting in lower power consumption.

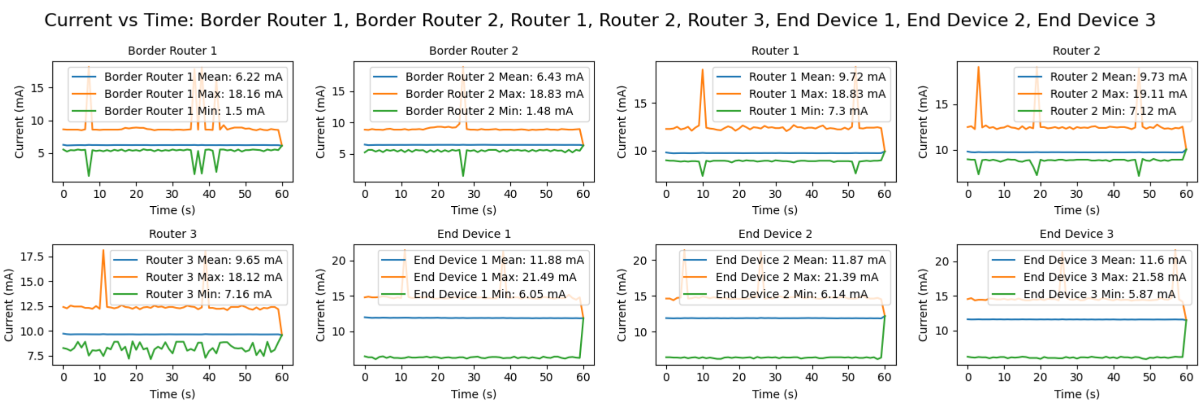

Figure 5.4: Current consumption overview from individual devices in Lab location, No Sensor mode.

Table 5.8: Current consumption overview from individual devices in Lab location, No Sensor mode.

Device	**Input xpower** (dBm)	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1			6.22	18.16	1.5
Border Router 2			6.43	18.83	1.48
Router 1			9.72	18.83	7.3
Router 2			9.73	19.11	7.12
Router 3	8	0	9.65	18.12	7.16
End device 1			11.88	21.49	6.05
End device 2			11.87	21.39	6.14
End device 3			11.6	21.58	5.87

Mode: Ping The following plot and table provide an overview of the current consumption across the entire network in Ping mode, where devices actively send pings to their radios at regular intervals. This increased communication leads to higher power consumption.

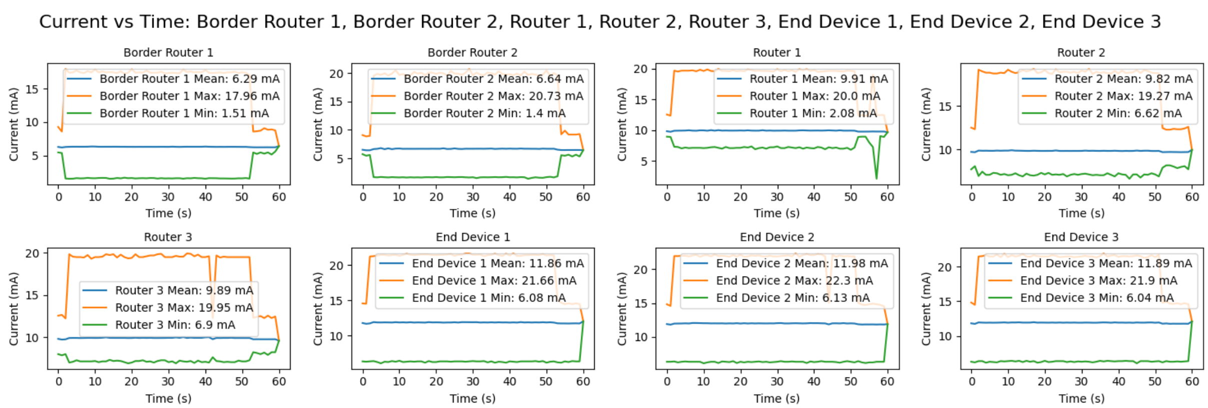

Figure 5.5: Current consumption overview from individual devices in Lab location, Ping mode.

Table 5.9: Current consumption overview from individual devices in Lab location, Ping mode.

Device	**Input txpower** (dBm)	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1			6.29	17.96	1.51
Border Router 2			6.64	20.73	1.4
Router 1			9.91	20.0	2.08
Router 2			9.82	19.27	6.62
Router 3	8	50	9.89	19.95	6.9
End device 1			11.86	21.66	6.08
End device 2			11.98	22.3	6.13
End device 3			11.89	21.9	6.04

Mode: Ultra-Wide Band In addition to No Sensor and Ping modes, another mode involves receiving data from an Ultra-Wide Band (UWB) network formed with ESP32 UWB devices shown in the research design section. The plot and table below showcase the current consumption in UWB mode, where devices utilize wide bandwidth for communication, resulting in higher power consumption across the network.

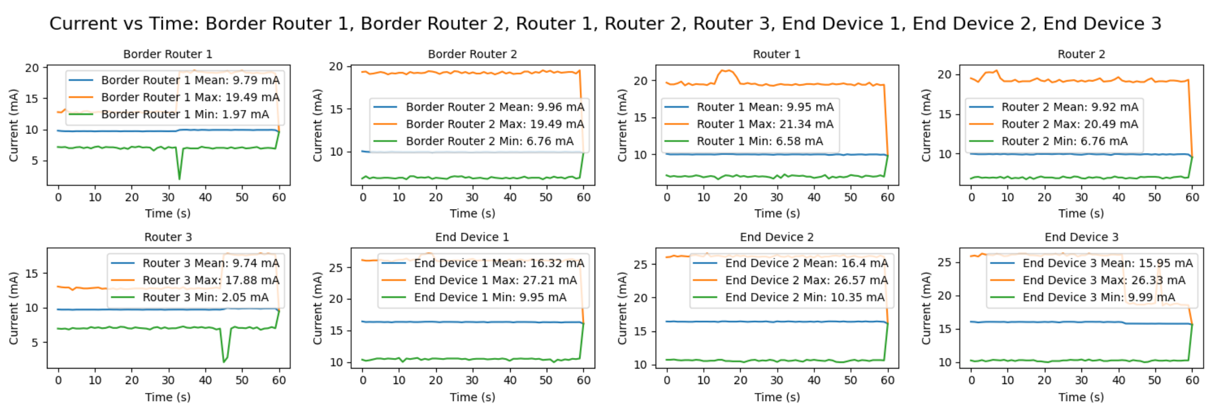

Figure 5.6: Current consumption overview from individual devices in Lab location, UWB mode.

Table 5.10: Current consumption overview from individual devices in Lab location, UWB mode.

Device	**Input txpower** (dBm)	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1	8	5 per second (average)	9.79	19.49	1.97
Border Router 2			9.96	19.49	6.76
Router 1			9.95	21.34	6.58
Router 2			9.92	20.49	6.76
Router 3			9.74	17.88	2.05
End device 1			16.32	27.21	9.95
End device 2			16.4	26.57	10.35
End device 3			15.95	26.33	9.99

Comparison: No Sensor vs. Ping vs. UWB The following plots compare the current consumption of the network in No Sensor, Ping, and Ultra-Wide Band (UWB) modes, highlighting the differences in power usage among the various communication methods.

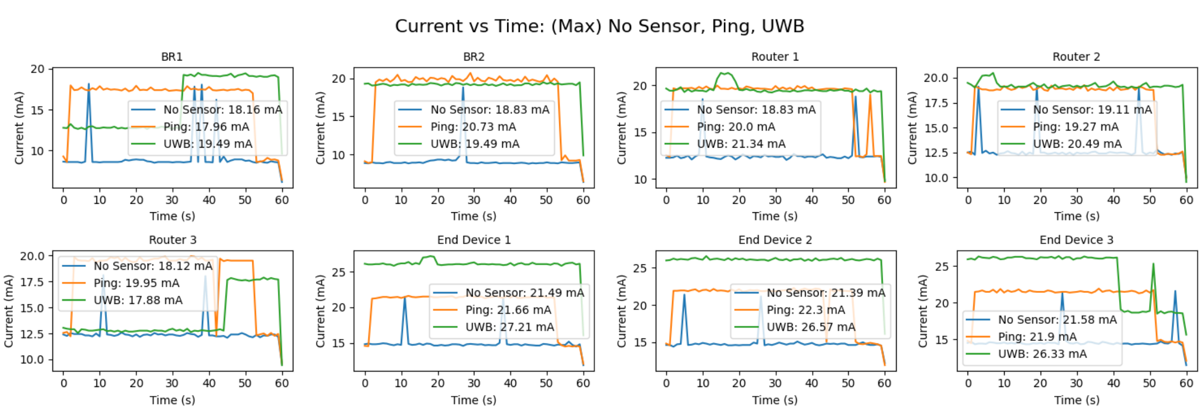

Figure 5.7: Mean Current Consumption Comparison in Lab location, No Sensor vs. Ping vs. UWB modes.

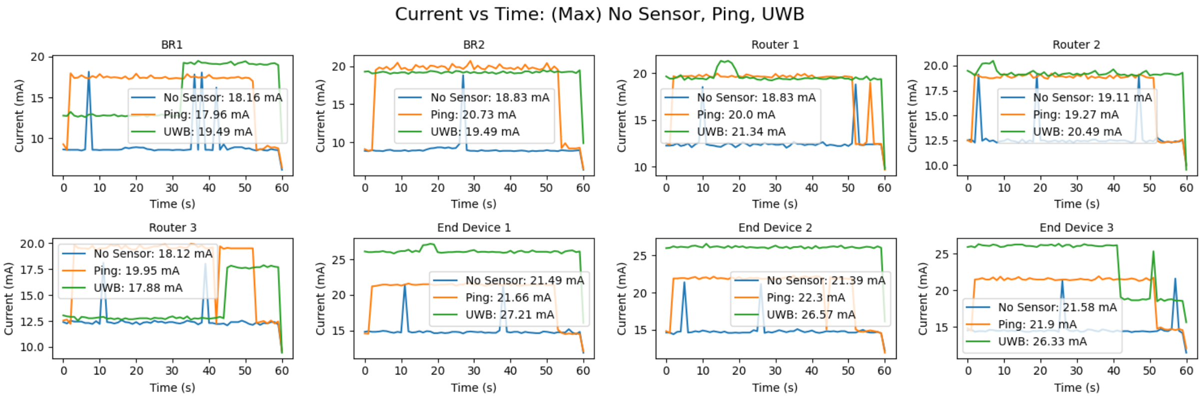

Figure 5.8: Maximum Current Consumption Comparison in Lab location, No Sensor vs. Ping vs. UWB modes.

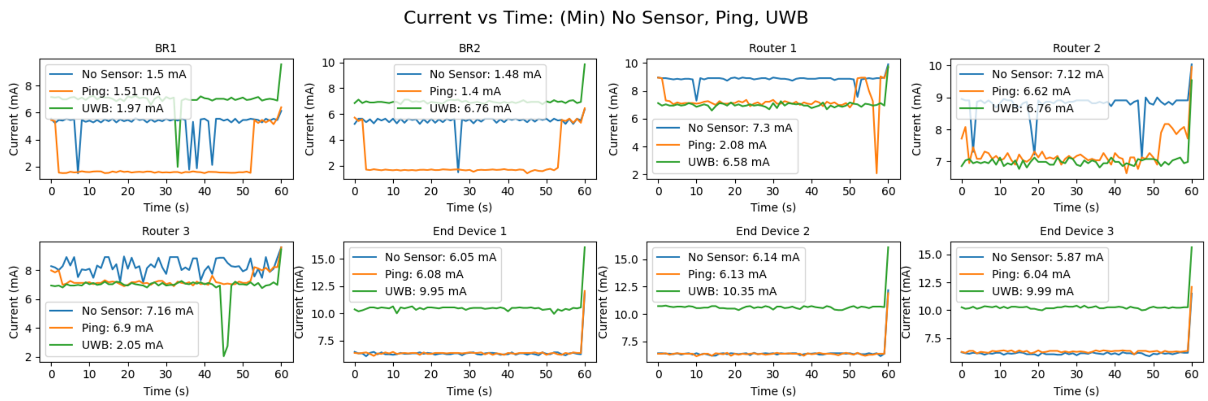

Figure 5.9: Minimum Current Consumption Comparison in Lab location, No Sensor vs. Ping vs. UWB modes.

All the Figures above comprehensively compare current consumption measurements across devices operating in three modes: No Sensor, Ping, and UWB. Each device was set to a maximum transmission power of 8 dBm. In the No Sensor and Ping modes, 50 pings were sent over a 60-second duration, while in the UWB mode, 5 pings were sent each second for the entire 60-second period, resulting in a significantly higher number of pings.

As expected, due to the lack of radioactivity, the No Sensor mode demonstrates the lowest mean current consumption for all device types. Border Routers range from 6.22 to 6.43 mA, Routers from 9.65 to 9.73 mA, and End devices from 11.6 to 11.88 mA. The Ping mode shows a slight increase in mean current consumption for all devices, attributed to the radio usage for transmitting pings. In contrast, the UWB mode reveals a more pronounced change, particularly for End devices, which experience a significant jump to between 15.95 and 16.4 mA due to the increased radioactivity and higher frequency of pings.

The maximum and minimum current consumption values also vary among the different modes. The higher number of pings in the UWB mode contributes to the increased current consumption, especially for End devices. This observation highlights the impact of communication frequency and radioactivity on power requirements.

Location: Home

This section focuses on the home location, which features a more significant distance between devices than the lab setting. The accompanying plot and table illustrate the impact of this increased distance on the network's current consumption.

Mode: No Sensor The following plot and table display the current consumption of devices in No Sensor mode at the home location, demonstrating the impact of reduced radio communication on power usage in this setting.

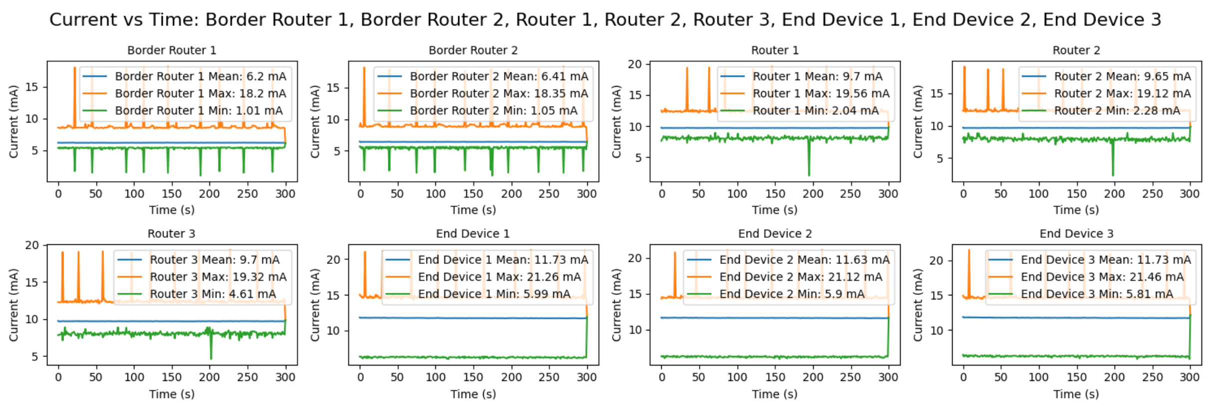

Figure 5.10: Current consumption overview from individual devices in Home location, No Sensor mode.

Table 5.11: Current consumption overview from individual devices in Home location, No Sensor mode.

Device	**Input txpower** (dBm)	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1			6.62	18.2	1.01
Border Router 2			6.41	18.35	1.05
Router 1			9.7	19.56	2.04

Continued on next page

8 dBm 0

Table 5.11: Current consumption overview from individual devices in Home location, No Sensor mode. (Continued)

Device	**Input txpower** (dBm)	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Router 2			9.65	19.12	2.28
Router 3			9.7	19.32	4.61
End device 1			11.73	21.26	5.99
End device 2			11.63	21.12	5.9
End device 3			11.73	21.46	5.81

Comparison: Lab No Sensor vs Home No Sensor In this section, a comparison is made between two different locations, considering the first 60 seconds of data from the Home location out of 300 seconds.

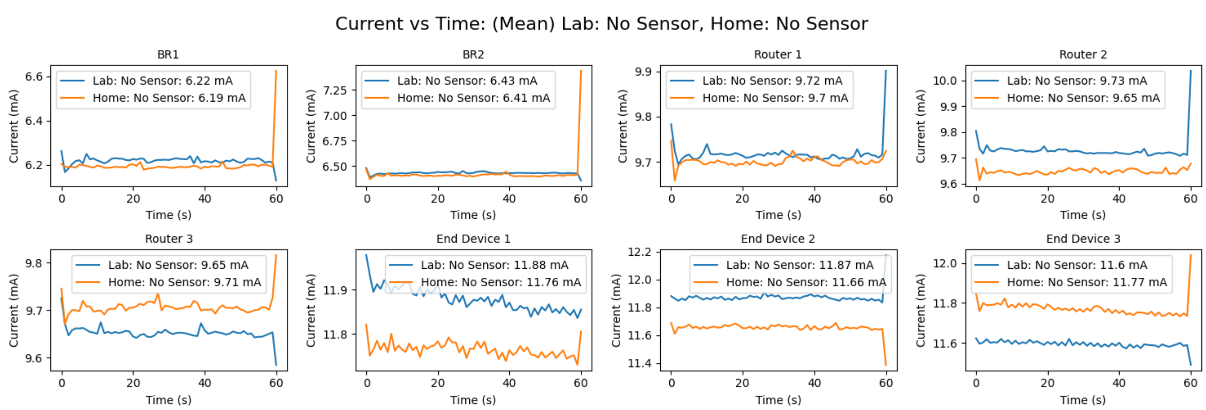

Figure 5.11: Mean Current Consumption Comparison in Home location, No Sensor mode vs. Lab location, No Sensor mode.

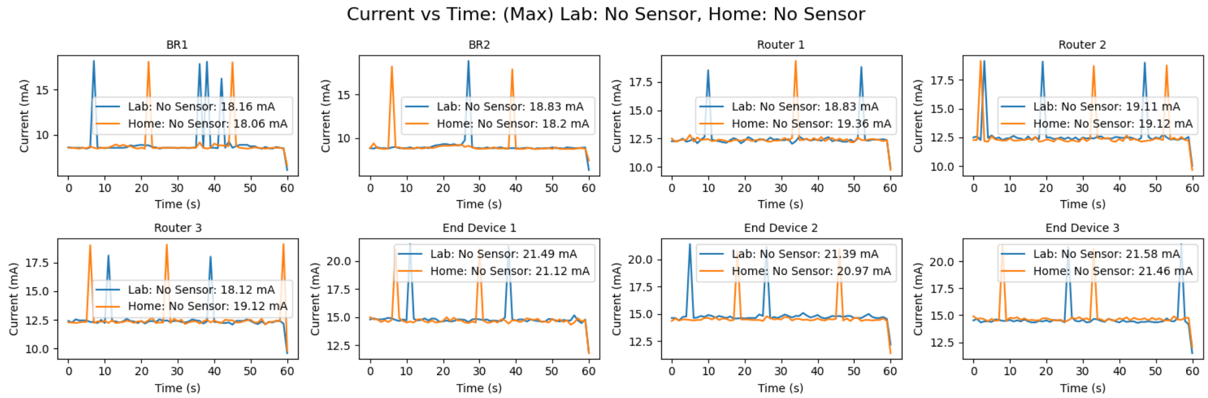

Figure 5.12: Maximum Current Consumption Comparison in Home location, No Sensor mode vs. Lab location, No Sensor mode.

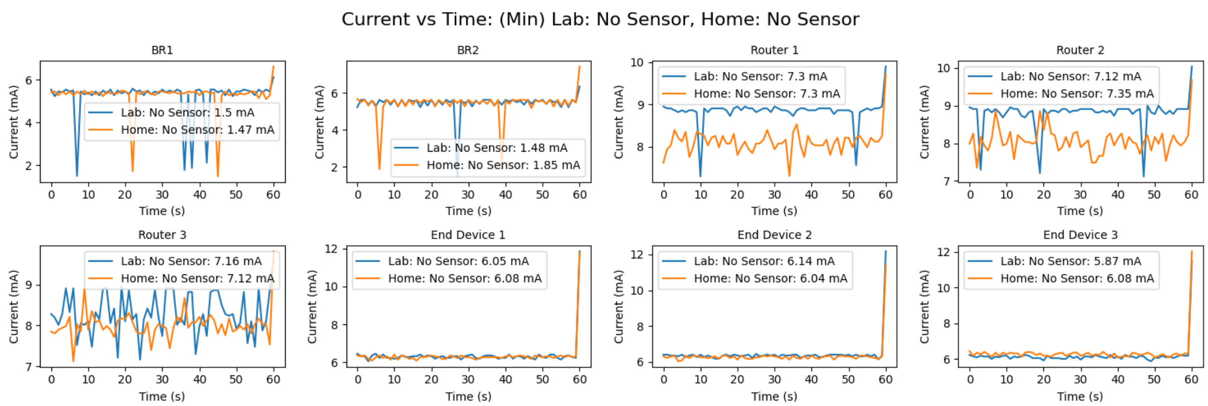

Figure 5.13: Minimum Current Consumption Comparison in Home location, No Sensor mode vs. Lab location, No Sensor mode.

The accompanying graphs compare the No Sensor modes in two locations for current consumption in terms of mean, maximum, and minimum values. The results reveal that the power consumption is generally similar between Lab and Home environments, with slight variations among the devices. Border Routers 1 and 2 show marginally higher mean values in the Home environment, while Routers 1, 2, and 3 and End Devices 1, 2, and 3 exhibit minimal differences between the two domains.

Mode: Ping The following plot and table display the current consumption data for devices operating in Ping mode within the Home environment, providing insights into the power usage while actively sending pings.

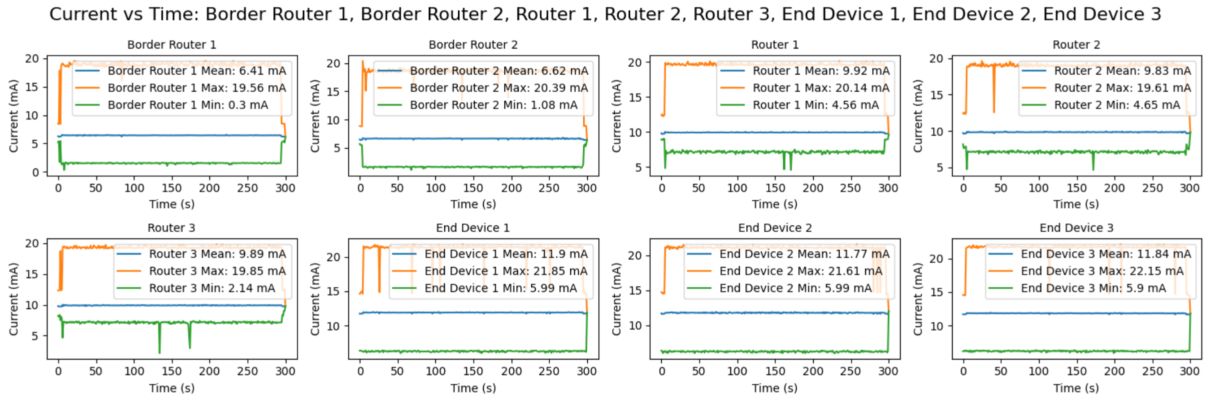

Figure 5.14: Current consumption overview from individual devices in Home location, Ping mode.

Table 5.12: Current consumption overview from individual devices in Lab location.

Device	**Input txpower** (dBm)	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1	8	290	6.41	19.56	0.3
Border Router 2			6.62	20.39	1.08
Router 1			9.92	20.14	4.56
Router 2			9.83	19.61	4.65
Router 3			9.89	19.85	2.14
End device 1			11.9	21.85	5.99
End device 2			11.77	21.61	5.99
End device 3			11.84	22.15	5.99

Comparison: Home No Sensor vs. Home Ping The following plots showcase a comparison between No Sensor and Ping modes in the Home environment, providing an overview of the differences in current consumption when devices operate passively without sending pings and when actively sending pings in the network.

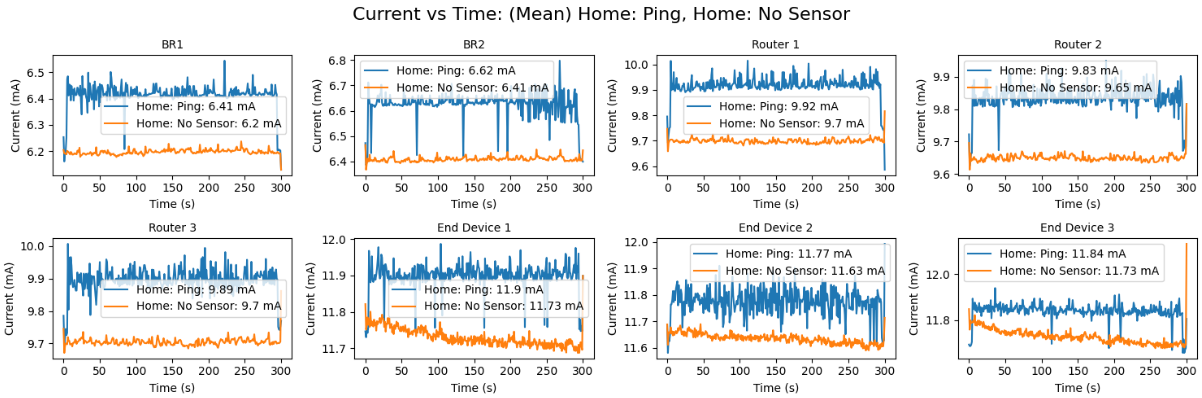

Figure 5.15: Mean Current Consumption Comparison in Home location, No Sensor mode vs. Home location, Ping mode.

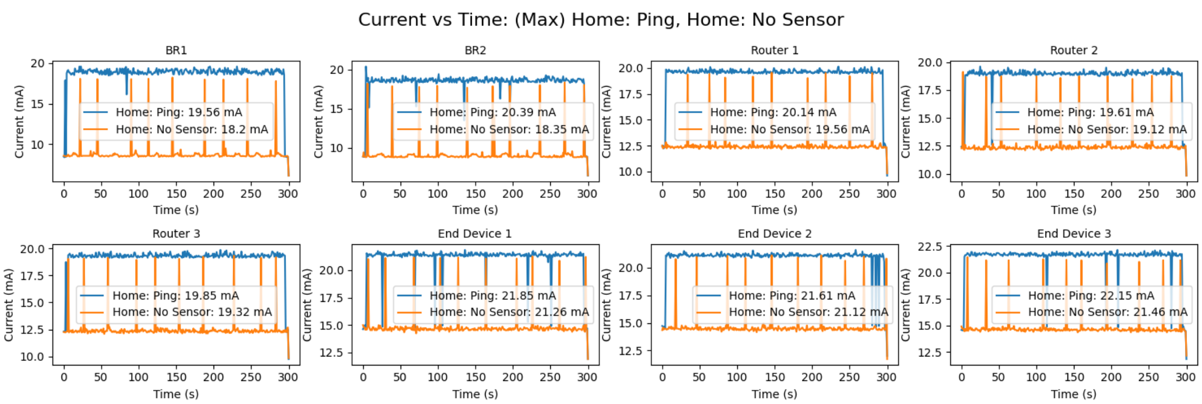

Figure 5.16: Maximum Current Consumption Comparison in Home location, No Sensor mode vs. Home location, Ping mode.

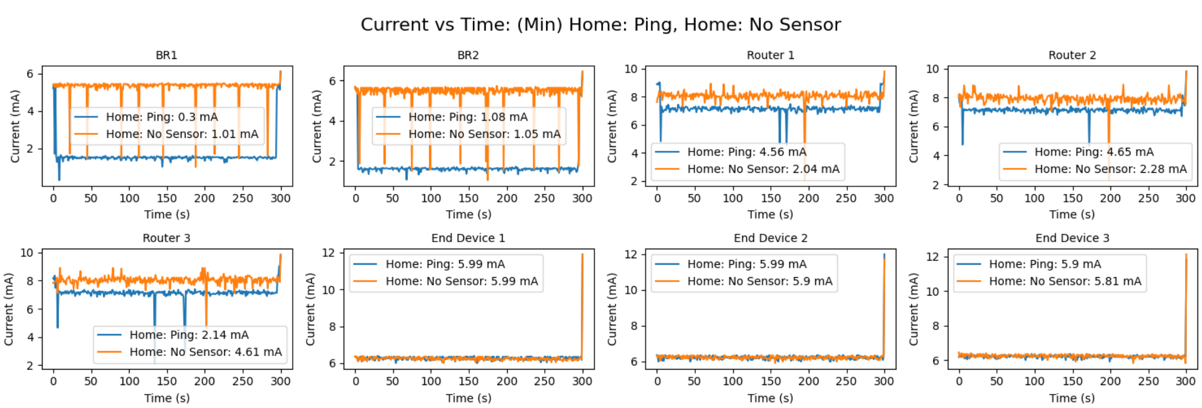

Figure 5.17: Minimum Current Consumption Comparison in Home location, No Sensor mode vs. Home location, Ping mode.

The comparison of the Home location's No Sensor and Ping modes highlights the differences in current consumption for each device in the network. The Ping mode generally has slightly higher mean current consumption for most devices, except for the border routers. The maximum and minimum current consumption values also vary between the two modes.

Comparison: Lab Ping vs. Home Ping The following plots compare different location's Ping modes, illustrating the differences in current consumption for other devices when actively sending pings in the network. Only the first 60 seconds of data from the Home Ping mode is considered to ensure a fair comparison.

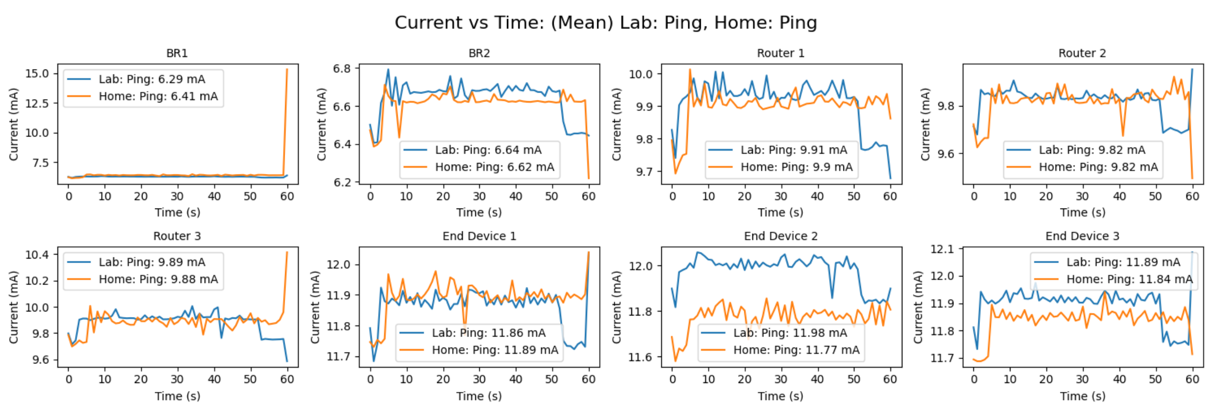

Figure 5.18: Mean Current Consumption Comparison in Lab location, Ping mode vs. Home location, Ping mode.

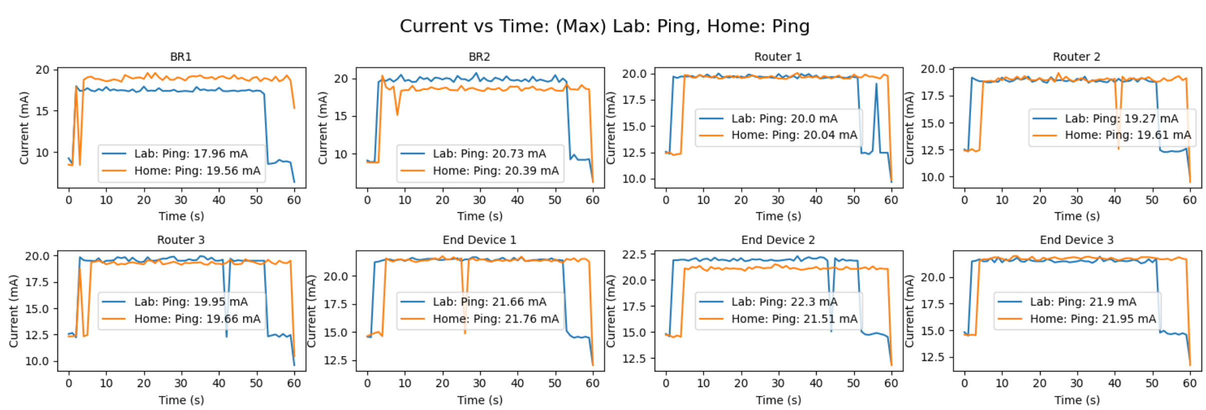

Figure 5.19: Maximum Current Consumption Comparison in Lab location, Ping mode vs. Home location, Ping mode.

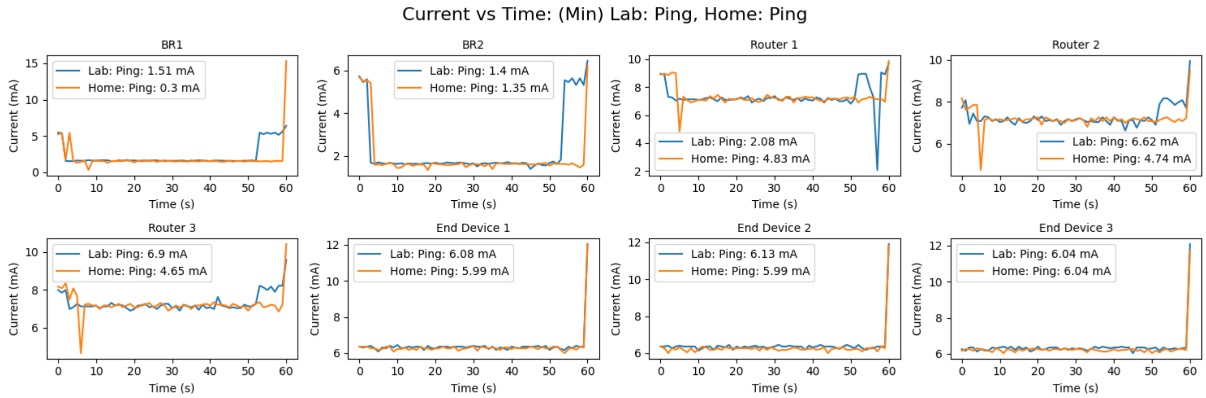

Figure 5.20: Minimum Current Consumption Comparison in Lab location, Ping mode vs. Home location, Ping mode.

The graphs compare power consumption between Lab and Home locations in Ping mode. The Lab location, being a smaller room, has lower distances between devices, resulting in a more efficient power consumption profile. On the other hand, the Home location has more considerable distances between devices, contributing to slightly higher current consumption in mean values for some devices. Maximum and minimum values also display minor variations between the Lab and Home environments, underscoring the impact of environmental factors and distances on power consumption.

5.3.2 Optimized Current Consumption

In this section, we explore the effects of applying Monte Carlo (MC) and Genetic Algorithm (GA) techniques to optimize transmission power for each device. This approach aims to minimize power consumption while maintaining reliable communication across the network, showcasing the benefits of implementing such optimization algorithms.

Location: Lab

Data and power consumption patterns are explored in this location when MC and GA algorithms are applied for transmission power optimization. This examination highlights the potential for improved power management within a confined space, emphasizing the importance of energy-efficient communication in such environments.

Mode: No Sensor This analysis focuses on idle device mode when devices aren't actively sending pings. By applying MC and GA algorithms for transmission power optimization, the goal is to evaluate the impact of these methods on reducing power consumption.

Monte Carlo Method The following plot and table showcase the Monte Carlo Method (MCM) optimized mode, which aims to meet mathematical constraints and deliver the correct network configuration with initial transmission power values.

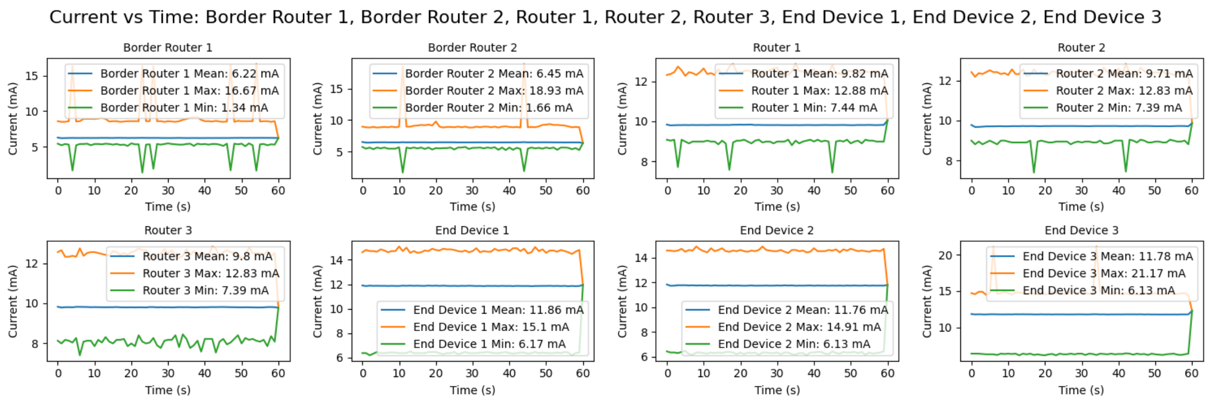

Figure 5.21: Overview of Current Consumption in Lab location, No Sensor mode, MCM optimized mode.

Table 5.13: Current Consumption in Lab location, No Sensor mode, MCM optimized mode.

Device	**Input txpower** (dBm)	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1	-8	0	6.22	16.67	1.34
Border Router 2	8		6.45	18.93	1.66
Router 1	-16		9.82	12.88	7.44
Router 2	0		9.71	12.83	7.39
Router 3	0		9.8	12.83	7.39
End device 1	-8		11.86	15.1	6.17
End device 2	-20		11.76	14.91	6.13
End device 3	8		11.78	21.17	6.13

Comparison: Maximum Lab No Sensor vs Optimized Lab No Sensor MCM

The following plots provide a comparison highlighting the differences in power consumption when applying optimization techniques to reduce energy usage in a lab setting without sensor data transmission.

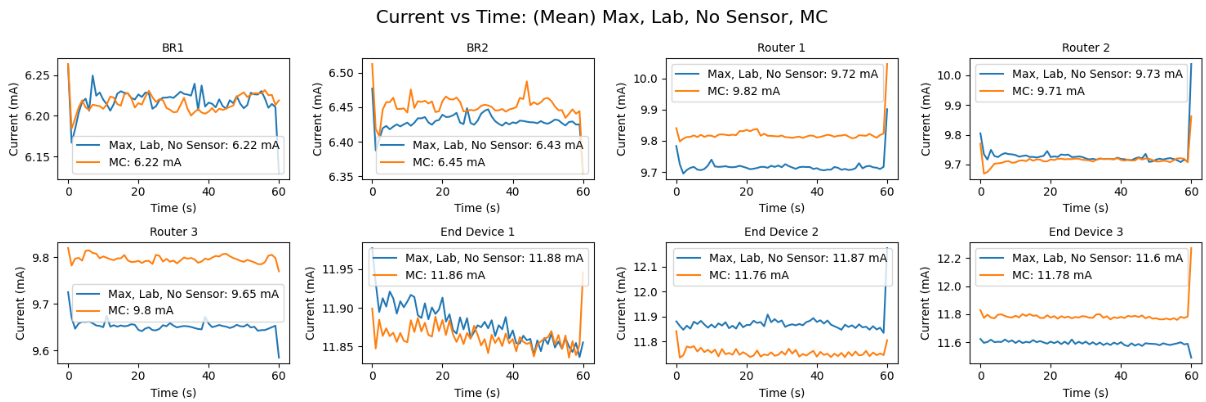

Figure 5.22: Mean Current Consumption Comparison in Lab location, No Sensor mode vs. Lab location, No Sensor mode, MCM optimized mode.

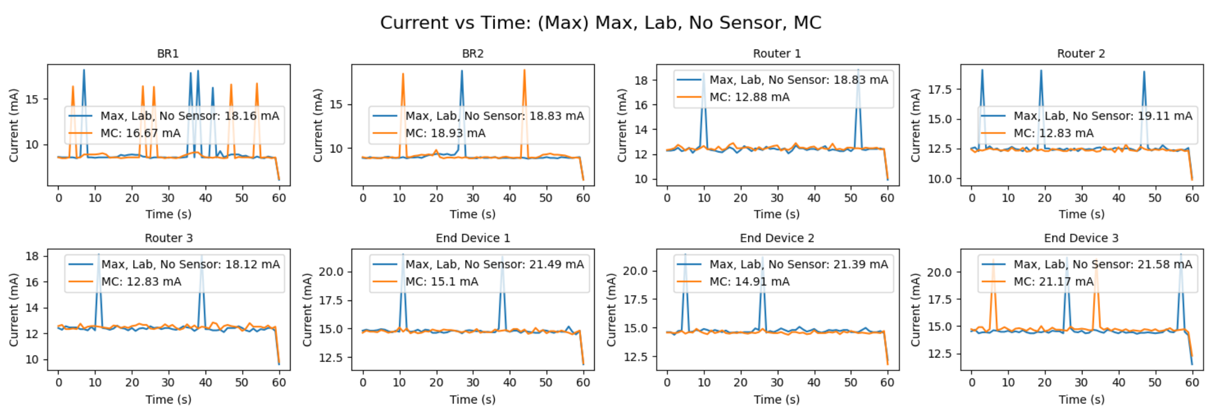

Figure 5.23: Maximum Current Consumption Comparison in Lab location, No Sensor mode vs. Lab location, No Sensor mode, MCM optimized mode.

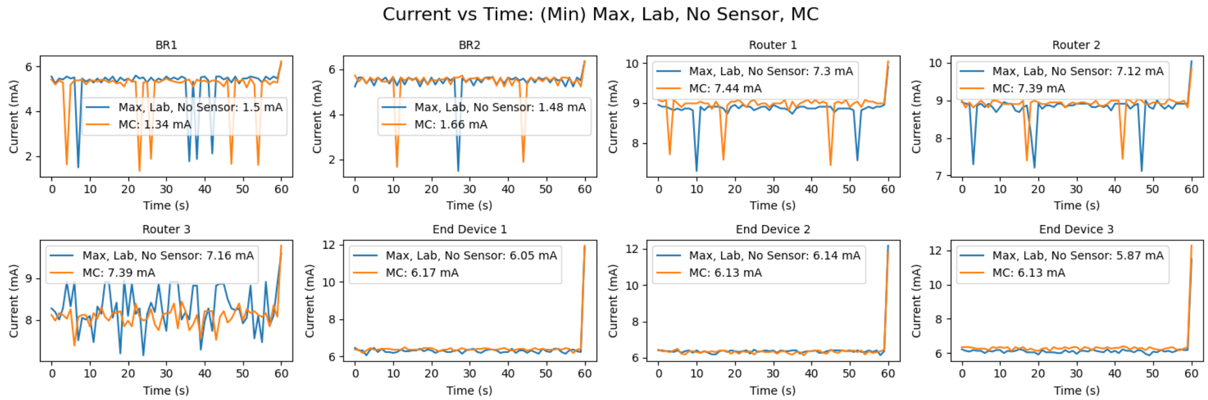

Figure 5.24: Minimum Current Consumption Comparison in Lab location, No Sensor mode vs. Lab location, No Sensor mode, MCM optimized mode.

The comparison graphs show the Optimized mode improved current consumption, particularly for End devices and Routers with reduced transmission power. For instance, Router 1 has a maximum current consumption of 12.88 mA in the optimized mode compared to 18.83 mA in the maximum mode. Similarly, End device 2 shows a maximum current consumption of 14.91 mA in the optimized mode compared to 21.39 mA in the maximum mode.

Genetic Algorithm The following plot and table showcase the power consumption results utilizing Genetic Algorithm (GA) that aims to reduce transmission power by satisfying mathematical constraints.

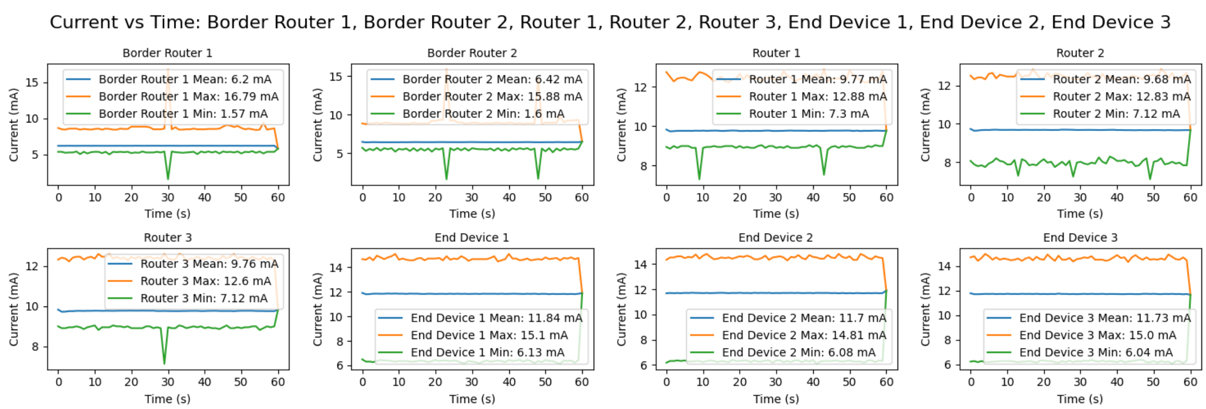

Figure 5.25: Overview of Current Consumption in Lab location, No Sensor mode, GA optimized mode.

Table 5.14: Current Consumption in Lab location, No Sensor mode, GA optimized mode.

Device	**Input txpower** (dBm)	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1			6.2	16.79	1.57
Border Router 2			6.42	15.88	1.6
Router 1			9.77	12.88	7.3
Router 2			9.68	12.83	7.12
Router 3	-20	0	9.76	12.6	7.12
End device 1			11.84	15.1	6.13
End device 2			11.7	14.81	6.08
End device 3			11.73	15.0	6.04

Comparison: Optimized Lab No Sensor MCM vs Optimized Lab GA This section compares MC and GA optimization approaches, showcasing their differences in power consumption through the following plots and table, highlighting the efficiency of each optimization technique.

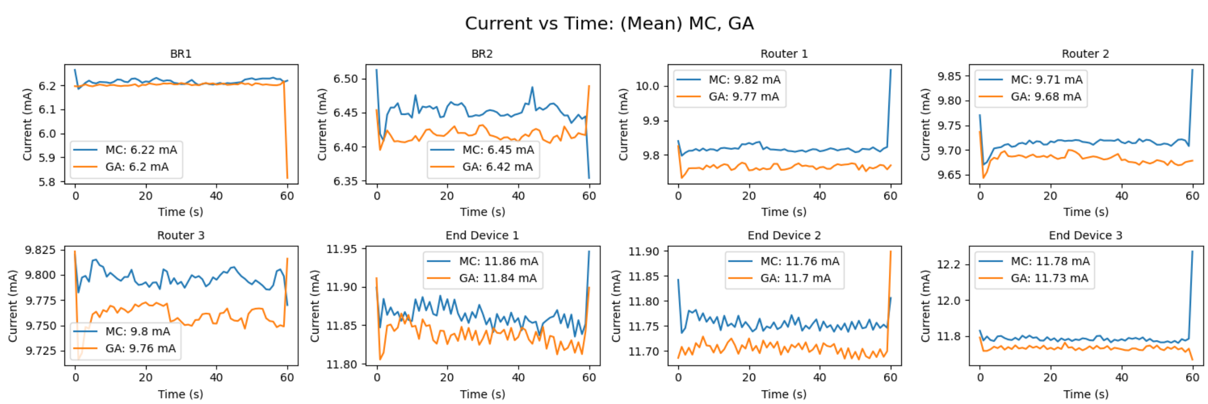

Figure 5.26: Mean Current Consumption Comparison in Lab location, No Sensor mode, MCM optimized mode vs. Lab location, No Sensor mode, GA optimized mode.

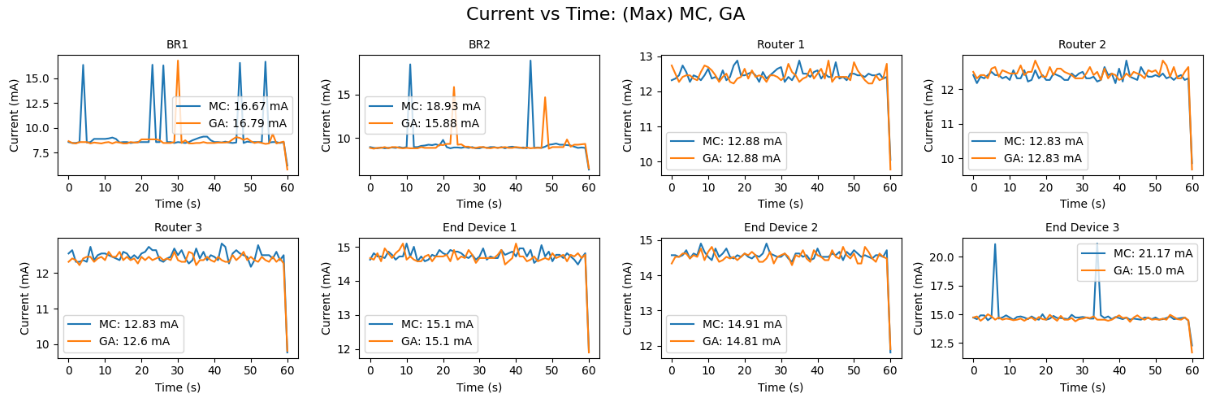

Figure 5.27: Maximum Current Consumption Comparison in Lab location, No Sensor mode, MCM optimized mode vs. Lab location, No Sensor mode, GA optimized mode.

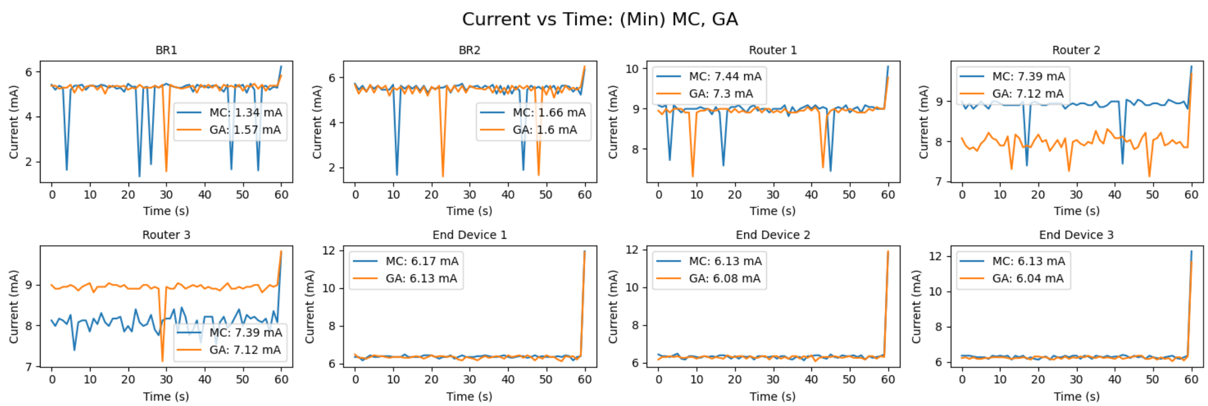

Figure 5.28: Minimum Current Consumption Comparison in Lab location, No Sensor mode, MCM optimized mode vs. Lab location, No Sensor mode, GA optimized mode.

The graphs' comparison of MCM and GA modes highlights differences in current consumption across devices. Generally, GA mode shows the slightly lower mean, maximum, and minimum current consumption levels for most devices than MCM mode. With GA consistently used for all devices, the GA optimization approach may offer marginally better energy efficiency.

Comparison: Maximum Lab No Sensor vs Optimized Lab No Sensor GA This section compares the Maximum mode with the Optimized mode, showcasing the total transmission power optimization achieved through the Genetic Algorithm, reducing current consumption while maintaining network performance.

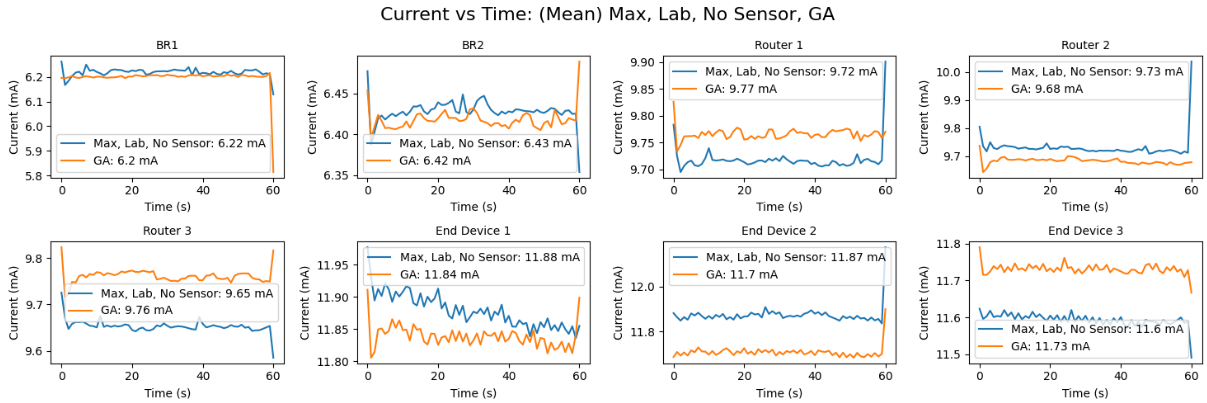

Figure 5.29: Mean Current Consumption Comparison in Lab location, No Sensor mode vs. Lab location, No Sensor mode, GA optimized mode.

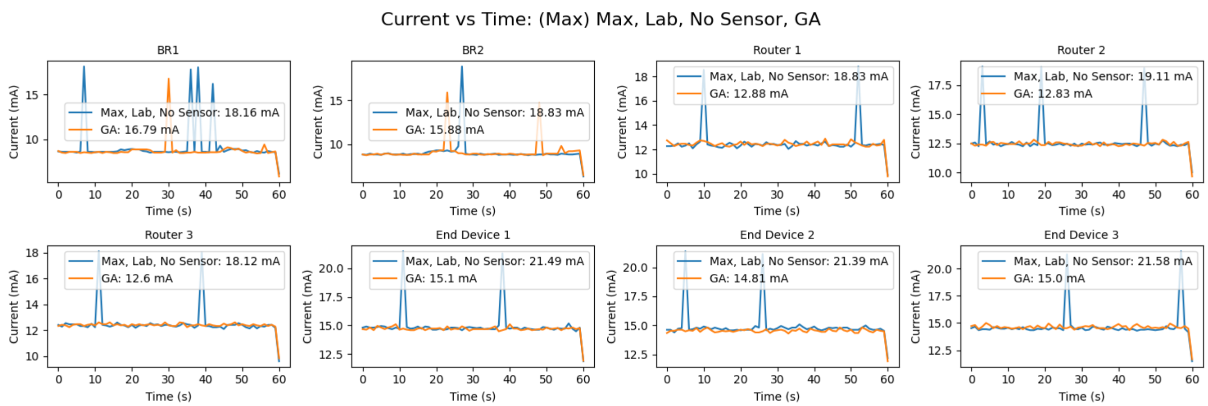

Figure 5.30: Maximum Current Consumption Comparison in Lab location, No Sensor mode vs. Lab location, No Sensor mode, GA optimized mode.

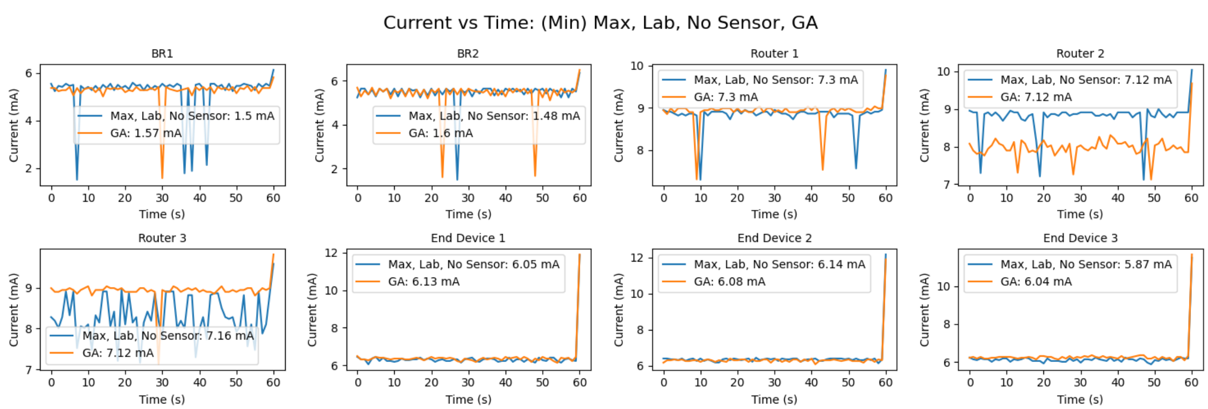

Figure 5.31: Minimum Current Consumption Comparison in Lab location, No Sensor mode vs. Lab location, No Sensor mode, GA optimized mode.

The comparison graphs for Maximum and Optimized modes reveal significant differences in current consumption. The Optimized GA mode generally exhibits lower maximum, minimum, and mean current consumption for most devices. This is likely due to varying transmission power settings determined by the Genetic Algorithm.

Mode: Ping In the Ping mode, devices transmit data at varying intervals, with the ping frequency ranging from 50 in 60 seconds to 290 in 300 seconds, depending on the location. This analysis focuses on the active device mode when devices send pings.

Monte Carlo Method The following plot and table illustrate the impact of this optimization technique on current consumption in the Monte Carlo Method (MCM), aiming to improve energy efficiency during active communication.

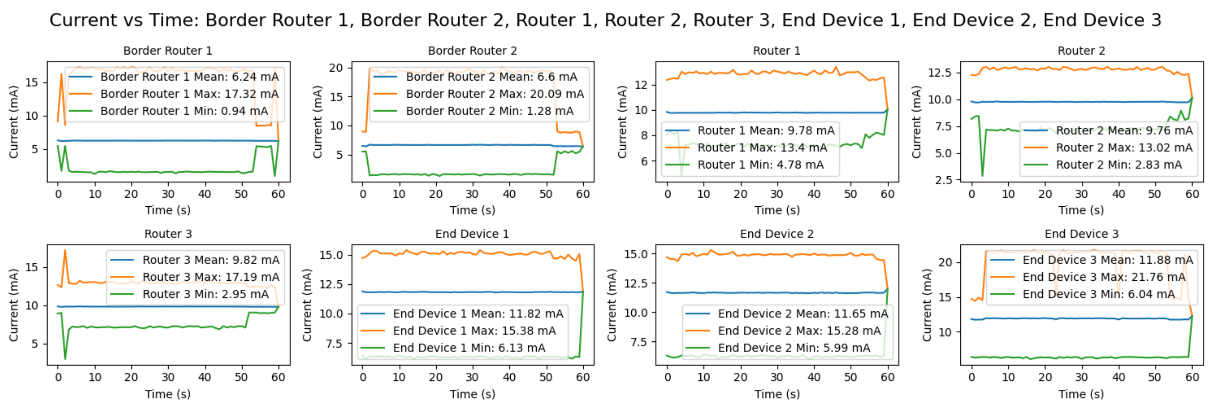

Figure 5.32: Overview of Current Consumption in Lab location, Ping mode, MCM optimized mode.

Table 5.15: Current consumption overview from individual devices.

Device	**Input txpower** (dBm)	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1	-8		6.24	17.32	0.94
Border Router 2	8		6.6	20.09	1.28
Router 1	-16		9.78	13.4	4.78
Router 2	0		9.76	13.02	2.83
Router 3	0	50	9.82	17.19	2.95

Continued on next page

Table 5.15: Current consumption overview from individual devices. (Continued)

Device	**Input txpower** (dBm)	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
End device 1	-8		11.82	15.38	6.13
End device 2	-20		11.65	15.28	5.99
End device 3	8		11.88	21.76	6.04

Comparison: Maximum Lab Ping vs Optimized Lab Ping MCM The following plots provide a comparison analysis between Maximum and Optimized MCM modes to evaluate the power consumption differences and potential improvements in energy efficiency.

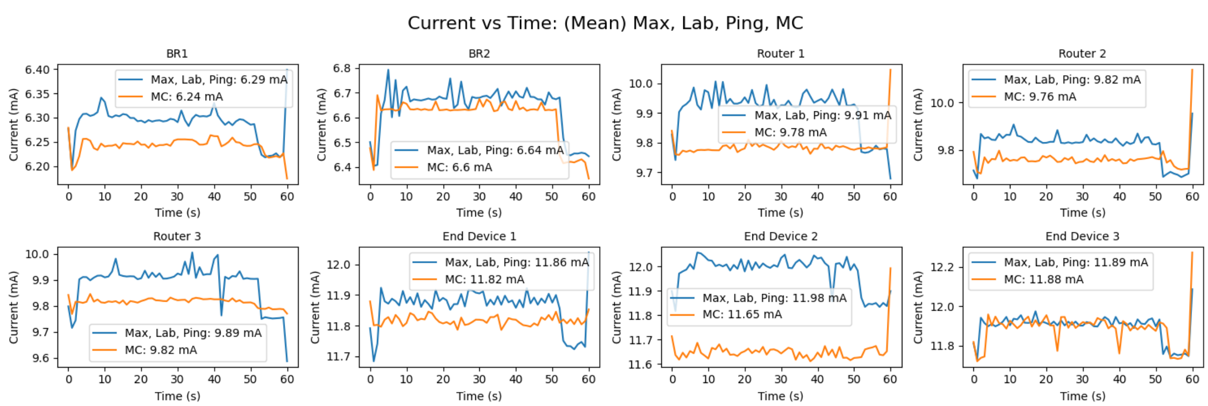

Figure 5.33: Mean Current Consumption Comparison in Lab location, Ping mode, MCM optimized mode vs. Lab location, Ping mode, MCM optimized mode.

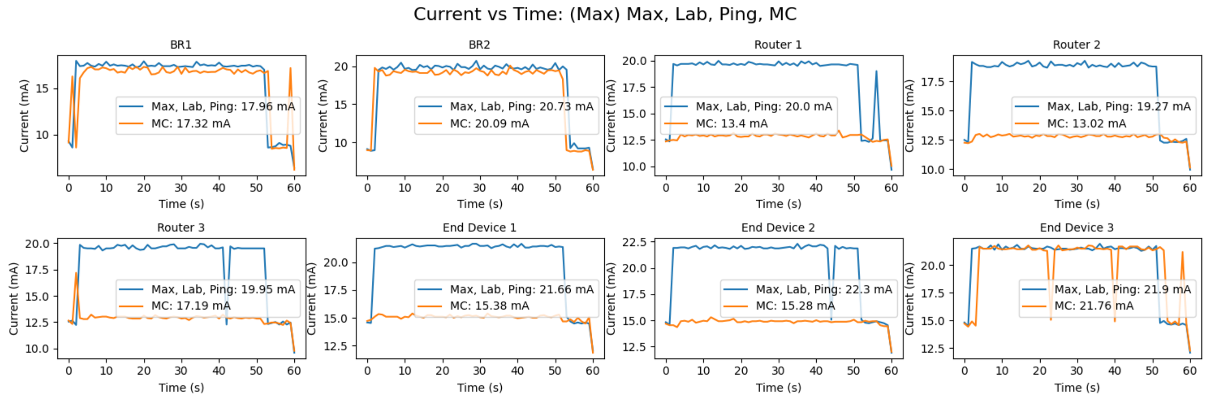

Figure 5.34: Maximum Current Consumption Comparison in Lab location, Ping mode, MCM optimized mode vs. Lab location, Ping mode, MCM optimized mode.

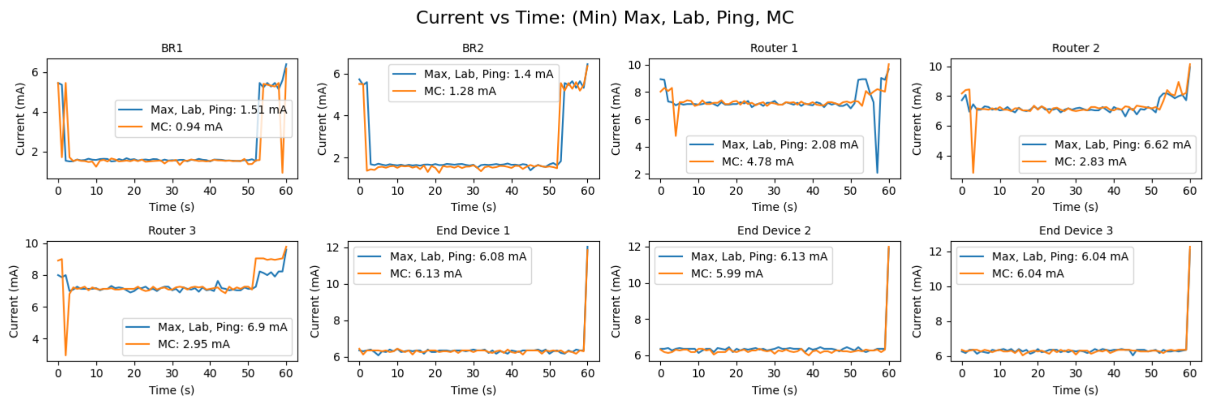

Figure 5.35: Minimum Current Consumption Comparison in Lab location, Ping mode, MCM optimized mode vs. Lab location, Ping mode, MCM optimized mode.

The comparison graphs present the optimized mode demonstrating lower mean current consumption values for several devices, particularly in the case of Router 1, Router 2, and End device 2. The maximum current consumption values are also notably lower in the optimized mode for some devices, highlighting the benefits of power optimization in improving the overall network performance and energy efficiency.

Genetic Algorithm The following plot and table showcase the differences in current consumption resulting from using a Genetic Algorithm (GA), which aims to reduce power consumption and improve overall energy efficiency.

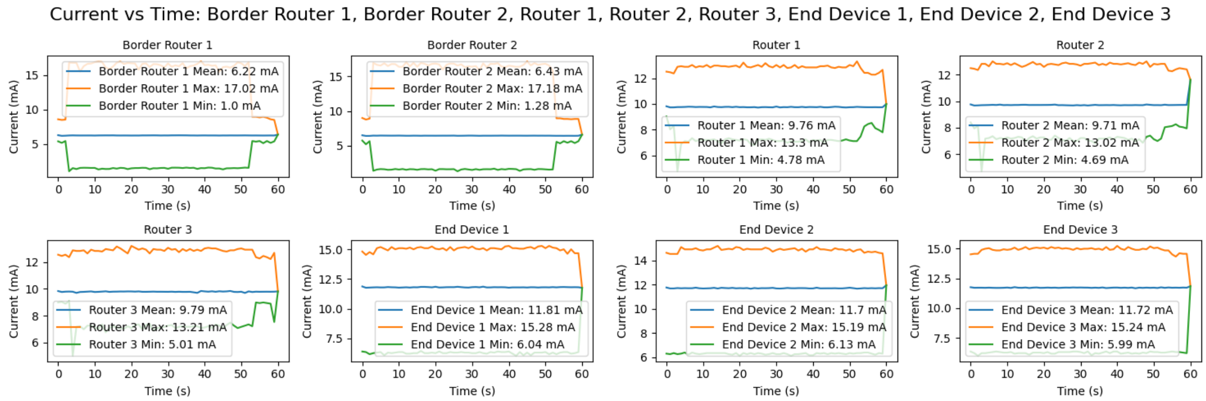

Figure 5.36: Overview of Current Consumption in Lab location, Ping mode, GA optimized mode.

Table 5.16: Overview of Current Consumption in Lab location, Ping mode, GA optimized mode.

<table>
<tr><th>Device</th><th>Input txpower (dBm)</th><th>Total Ping</th><th>Mean (mA)</th><th>Max (mA)</th><th>Min (mA)</th></tr>
<tr><td>Border Router 1</td><td rowspan="8">-20</td><td rowspan="8">50</td><td>6.22</td><td>17.02</td><td>1.0</td></tr>
<tr><td>Border Router 2</td><td>6.43</td><td>17.18</td><td>1.28</td></tr>
<tr><td>Router 1</td><td>9.76</td><td>13.3</td><td>4.78</td></tr>
<tr><td>Router 2</td><td>9.71</td><td>13.02</td><td>4.69</td></tr>
<tr><td>Router 3</td><td>9.79</td><td>13.21</td><td>5.01</td></tr>
<tr><td>End device 1</td><td>11.81</td><td>15.28</td><td>6.04</td></tr>
<tr><td>End device 2</td><td>11.7</td><td>15.19</td><td>6.13</td></tr>
<tr><td>End device 3</td><td>11.72</td><td>15.24</td><td>5.99</td></tr>
</table>

Comparison: Optimized Lab Ping MCM vs Optimized Lab Ping GA The following comparison plots represent the differences in current consumption between the MCM and GA modes from the exact location, showcasing the impact of the Monte Carlo Method and Genetic Algorithm optimization approaches.

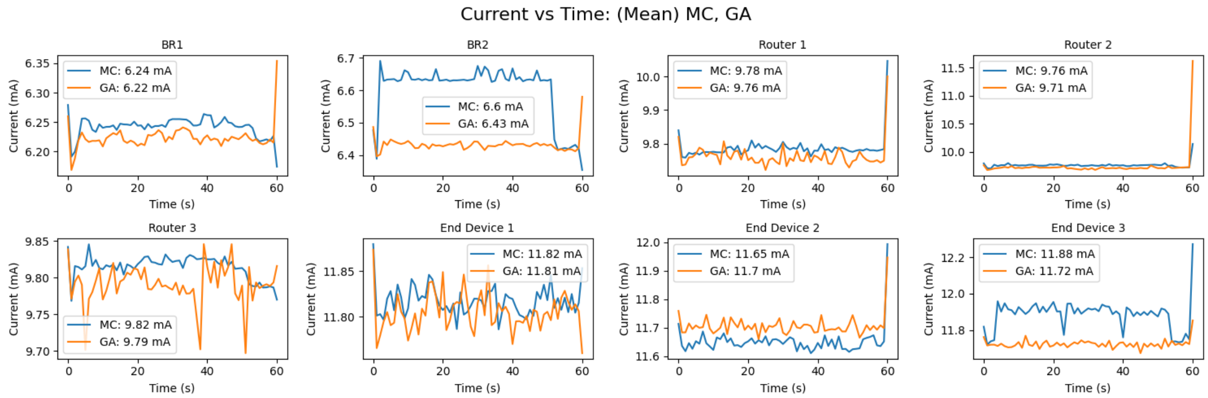

Figure 5.37: Mean Current Consumption Comparison in Lab location, Ping mode, MCM optimized mode vs. Lab location, Ping mode, GA optimized mode.

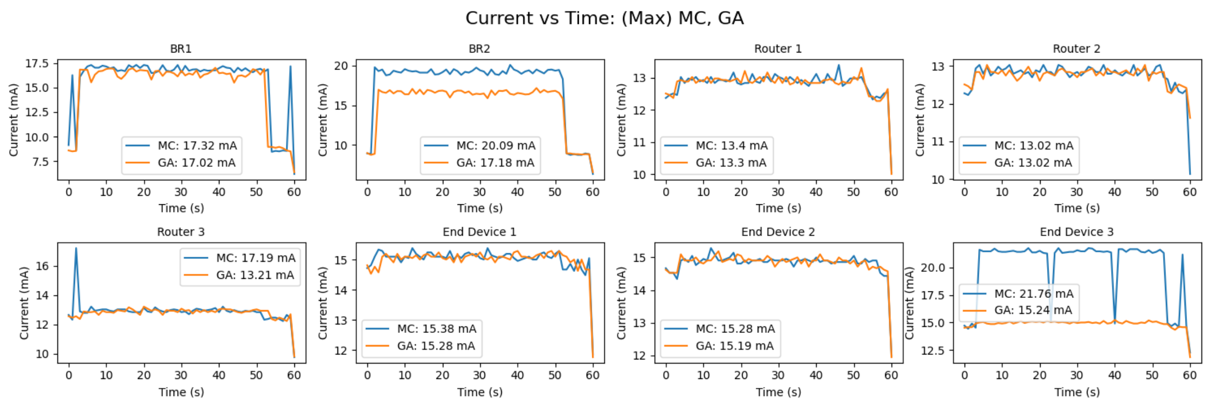

Figure 5.38: Maximum Current Consumption Comparison in Lab location, Ping mode, MCM optimized mode vs. Lab location, Ping mode, GA optimized mode.

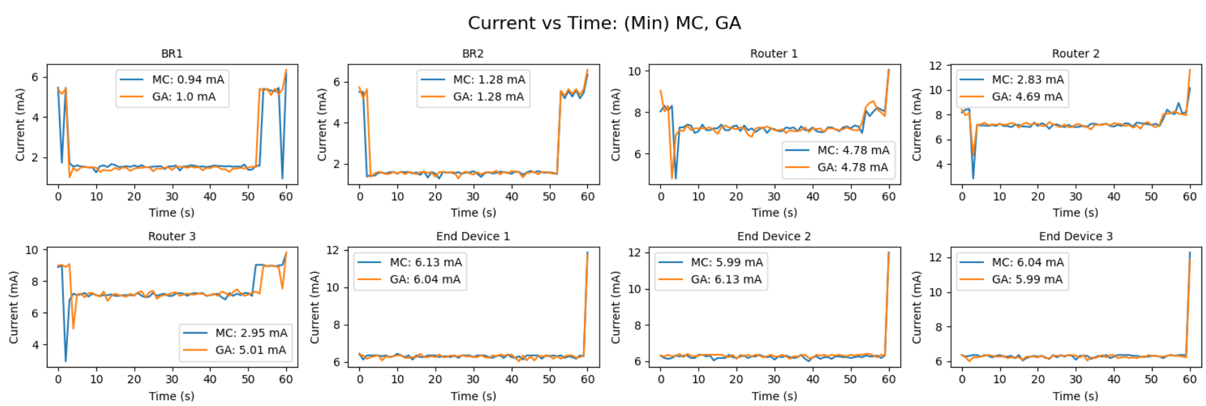

Figure 5.39: Minimum Current Consumption Comparison in Lab location, Ping mode, MCM optimized mode vs. Lab location, Ping mode, GA optimized mode.

The graphs comparing Optimized Lab Ping MC and GA modes reveal differences in device performance under these optimization methods. Generally, Optimized Lab Ping GA mode yields slightly lower mean current consumption for most devices and reduced maximum current consumption for some devices, while minimum Current consumption results vary. The GA mode consistently uses -20 dBm transmission power, while the MCM mode varies. This difference may influence current consumption patterns.

Location: Home

This section examines the more considerable device distances and 300 seconds of data compared to the lab's 60 seconds. The accompanying plot and table reveal the impact of these factors on the network's current consumption.

Mode: No Sensor This section showcases the current consumption in No Sensor mode, where devices are idle and not actively sending pings. The data highlights the impact of the increased distance between devices on power consumption in this mode.

Monte Carlo Method The following plot and table provide an overview of the current consumption for each device in the network, showcasing the impact of the Monte Carlo Method (MCM) on power usage.

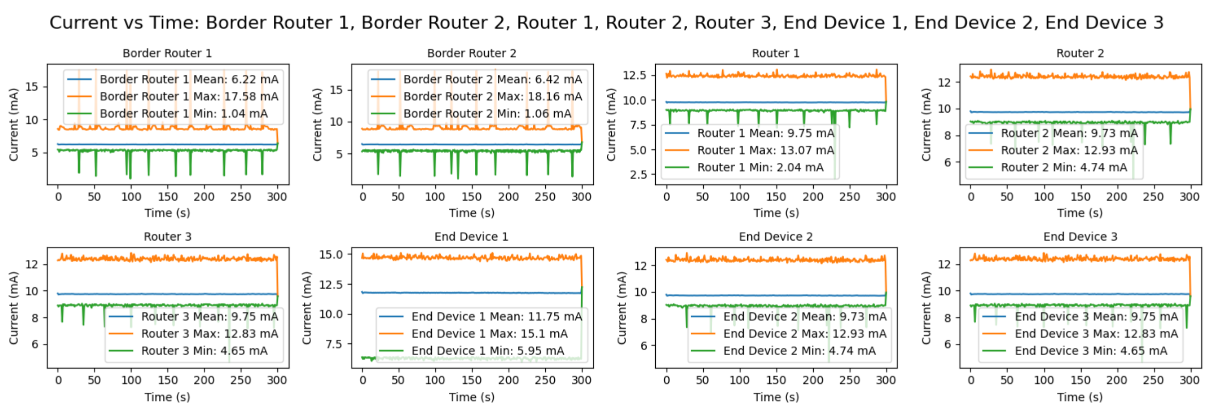

Figure 5.40: Overview of Current Consumption in Home location, No Sensor mode, MCM optimized mode.

Table 5.17: Overview of Current Consumption in Home location, No Sensor mode, MCM optimized mode.

Device	**Input txpower**	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1	8		6.22	17.58	1.04
Border Router 2	8		6.42	18.16	1.06
Router 1	-8		9.75	13.07	2.04
Router 2	-20		9.73	12.93	4.74
Router 3	-4	0	9.75	12.83	4.65
End device 1	-16		11.75	15.1	5.95
End device 2	4		9.73	12.93	4.74
End device 3	-16		9.75	12.83	4.65

Comparison: Home - Maximum No Sensor vs Optimized No Sensor MCM The following comparison graphs depict the differences between Maximum and Optimized No Sensor MCM modes in the home environment, focusing on each device's varying transmission power settings.

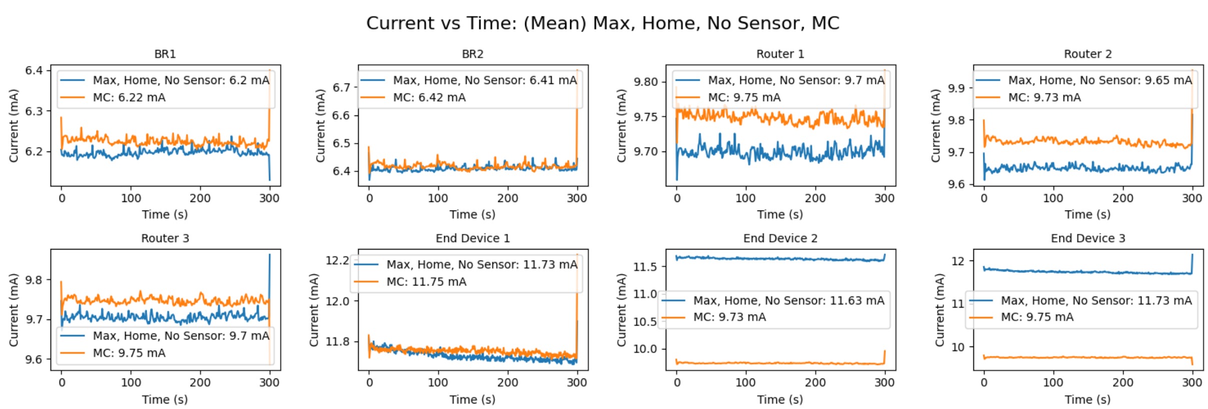

Figure 5.41: Mean Current Consumption Comparison in Home location, No Sensor mode, MCM optimized mode vs. Home location, No Sensor mode, Maximum mode.

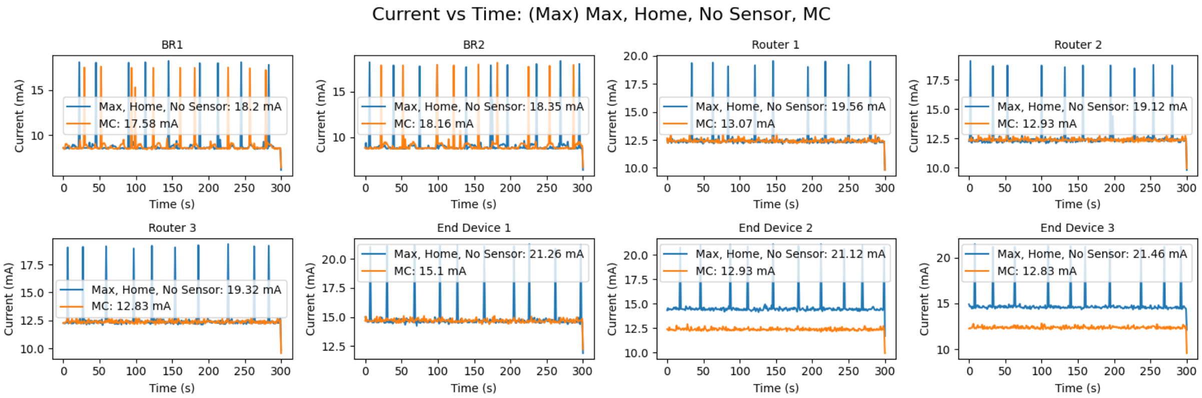

Figure 5.42: Maximum Current Consumption Comparison in Home location, No Sensor mode, MCM optimized mode vs. Home location, No Sensor mode, Maximum mode.

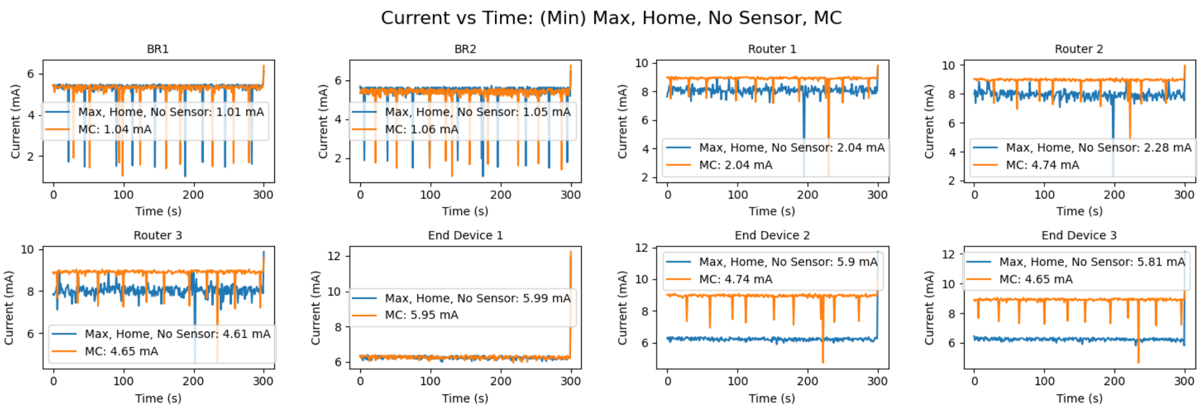

Figure 5.43: Minimum Current Consumption Comparison in Home location, No Sensor mode, MCM optimized mode vs. Home location, No Sensor mode, Maximum mode.

The comparison graphs reveal differences in current consumption between Maximum and Optimized MCM modes. Border Routers 1 and 2 show slightly higher mean current values in Maximum mode, while Routers 1, 2, and 3 exhibits marginally lower values. End Devices 1, 2, and 3 have higher mean current values in the Maximum mode. Overall, the Maximum mode has slightly increased current consumption compared to the Optimized MCM mode, but the differences are insignificant.

Genetic Algorithm The following plot and table present the current consumption overview of each device in the network, utilizing Genetic Algorithm (GA) optimized transmission power settings.

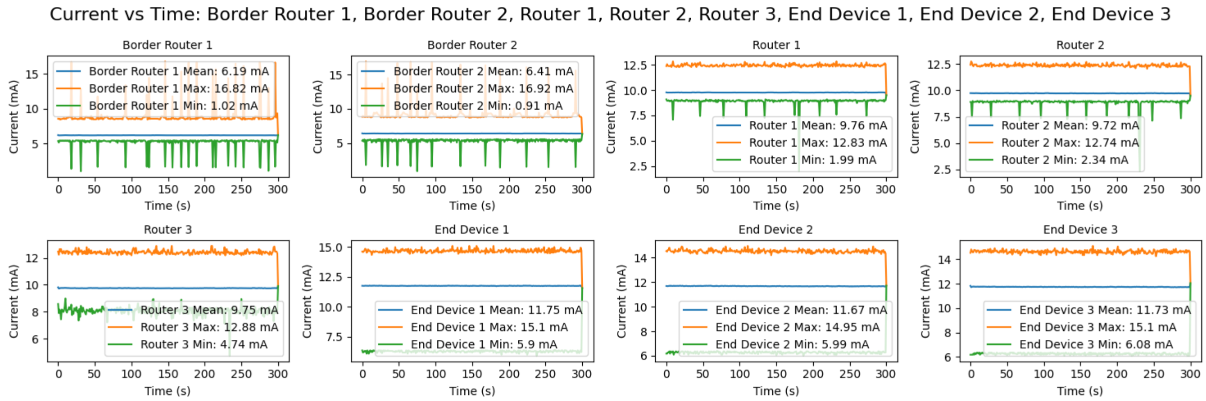

Figure 5.44: Overview of Current Consumption in Home location, No Sensor mode, GA optimized mode.

Table 5.18: Overview of Current Consumption in Home location, No Sensor mode, GA optimized mode.

Device	**Input txpower**	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1	-20		6.19	16.82	1.02
Border Router 2	-19		6.41	16.92	0.91
Router 1	-19		9.76	12.83	1.99
Router 2	-20		9.72	12.74	2.34
Router 3	-18	0	9.75	12.88	4.74
End device 1	-18		11.75	15.1	5.9
End device 2	-16		11.67	14.95	5.99
End device 3	-19		11.73	15.1	6.08

Comparison: Optimized Home No Sensor: MCM vs GA The following comparison graphs showcase the differences in current consumption between the Monte Carlo Method (MCM) and Genetic Algorithm (GA) optimization techniques for the No Sensor mode.

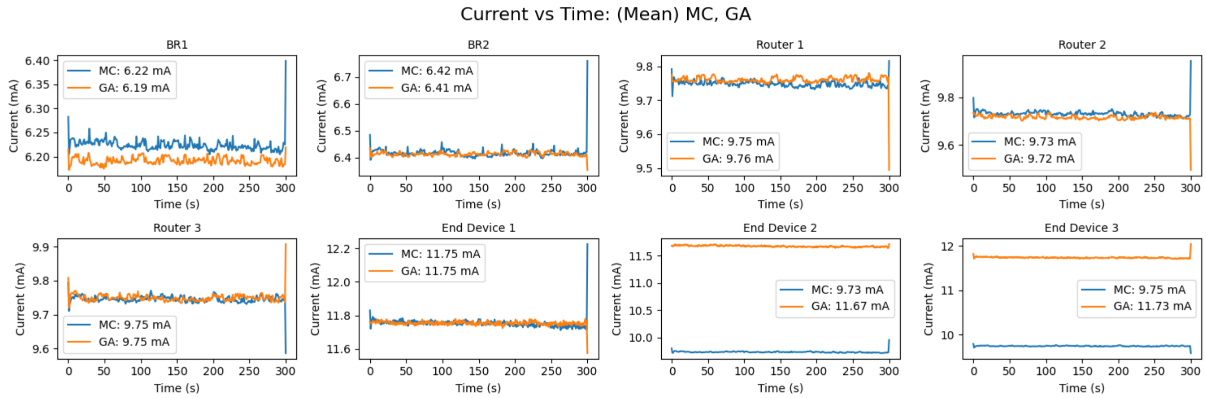

Figure 5.45: Mean Current Consumption Comparison in Home location, No Sensor mode, GA optimized mode vs. Home location, No Sensor mode, MCM optimized mode.

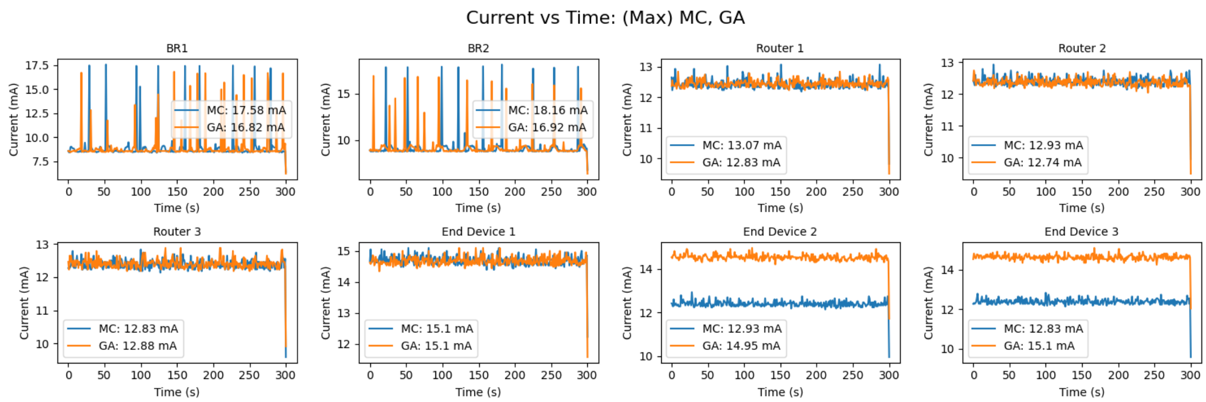

Figure 5.46: Maximum Current Consumption Comparison in Home location, No Sensor mode, GA optimized mode vs. Home location, No Sensor mode, MCM optimized mode.

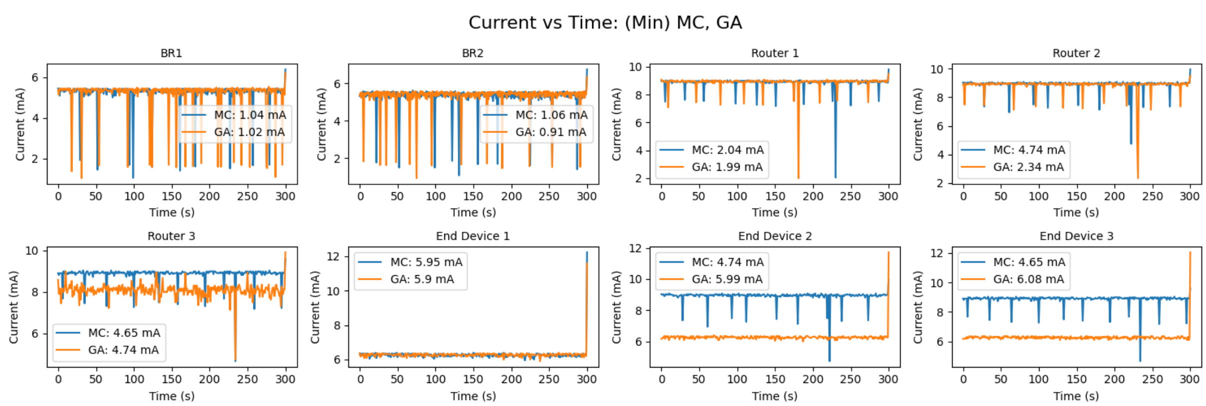

Figure 5.47: Minimum Current Consumption Comparison in Home location, No Sensor mode, GA optimized mode vs. Home location, No Sensor mode, MCM optimized mode.

The comparison graphs depict the differences in input transmission power, mean current, maximum current, and minimum current for each device in the MCM and GA modes. Border Routers and Routers have slightly lower mean current values in GA mode, while End Devices show similar values across both modes. The current consumption between MC and GA modes is similar, with minor device variations.

Mode: Ping This section presents the current consumption in ping mode, aiming to evaluate the performance of devices in the network while the radio is active.

Monte Carlo Method The plot and table showcase the current consumption overview for each device in the network, highlighting the impact of the Monte Carlo optimization method.

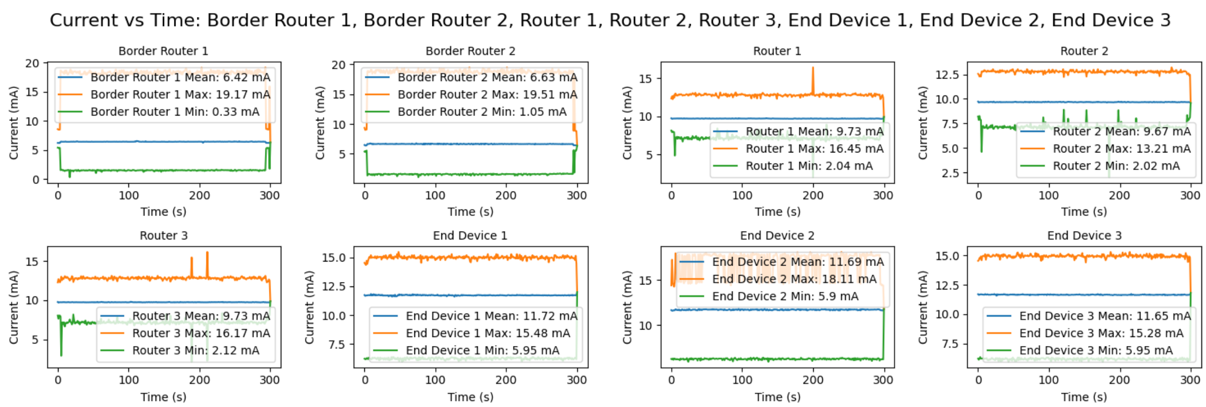

Figure 5.48: Overview of Current Consumption in Home location, Ping mode, MCM optimized mode.

Table 5.19: Overview of Current Consumption in Home location, Ping mode, MCM optimized mode.

Device	**Input txpower**	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1	8		6.42	19.17	0.33
Border Router 2	8		6.63	19.51	1.05
Router 1	-8		9.73	16.45	2.04
Router 2	-20		9.67	13.21	2.02
Router 3	-4	290	9.73	16.17	2.12

Continued on next page

Table 5.19: Overview of Current Consumption in Home location, Ping mode, MCM optimized mode. (Continued)

Device	**Input txpower**	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
End device 1	-16		11.72	15.48	5.95
End device 2	4		11.69	18.11	5.9
End device 3	-16		11.65	15.28	5.95

Comparison: Optimized Ping MCM - Lab vs Home The following comparison graphs showcase the differences in current consumption between the two locations using the Monte Carlo Method (MCM) optimization.

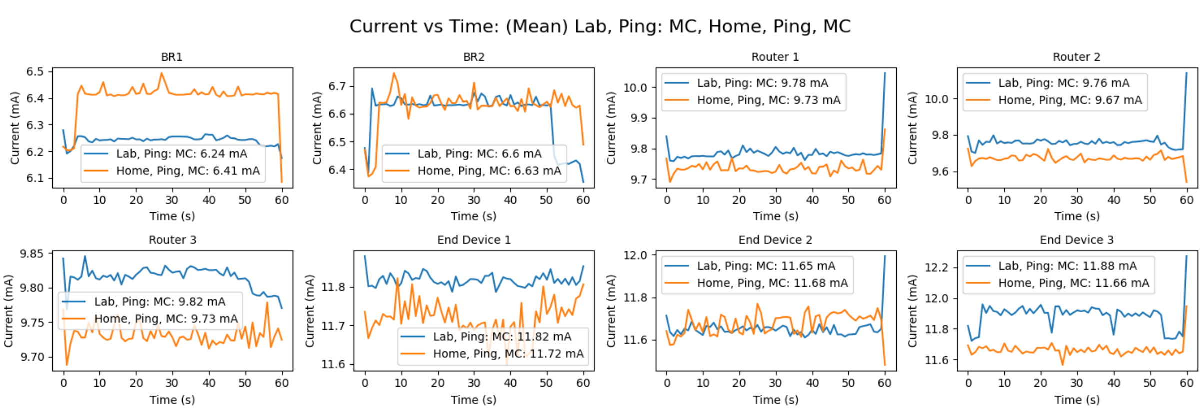

Figure 5.49: Mean Current Consumption Comparison in Home location, Ping mode, MCM optimized mode vs. Lab location, Ping mode, MCM optimized mode.

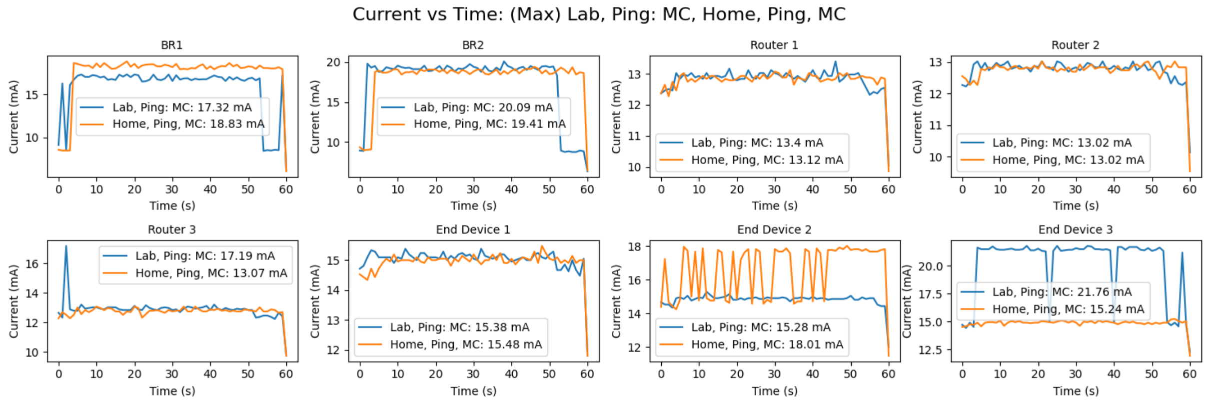

Figure 5.50: Maximum Current Consumption Comparison in Home location, Ping mode, MCM optimized mode vs. Lab location, Ping mode, MCM optimized mode.

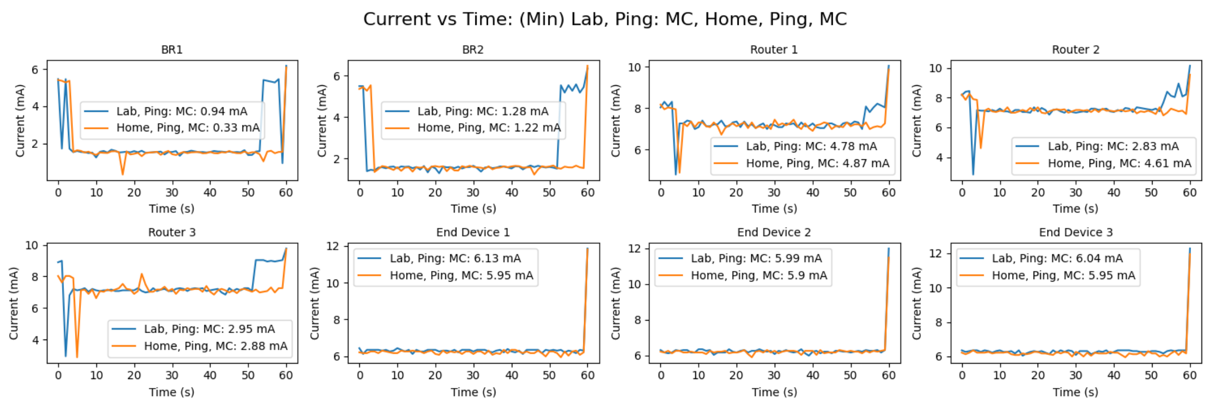

Figure 5.51: Minimum Current Consumption Comparison in Home location, Ping mode, MCM optimized mode vs. Lab location, Ping mode, MCM optimized mode.

Considering that the Home environment has a greater distance between devices than the Lab environment, the data comparison shows that the MCM modes demonstrate robust performance in both settings. Despite the increased distance in the Home environment, the mean current values for Routers and End Devices are reasonably close to those observed in the Lab environment. This indicates that the MCM mode effectively adjusts to various scenarios with different distances between devices and maintains consistent performance levels.

Comparison: Maximum Home Ping vs Optimized Home Ping MCM The following comparison graphs showcase the differences in current consumption between the Maximum and Optimized Monte Carlo Methods (MCM) for optimization while the radio is active.

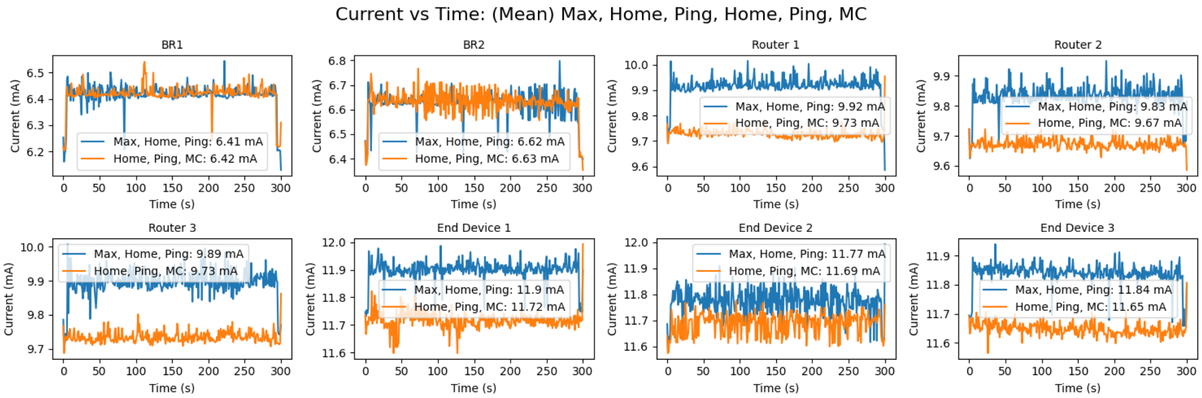

Figure 5.52: Mean Current Consumption Comparison in Home location, Ping mode, Maximum MCM optimized mode vs. Home location, Ping mode, MCM optimized mode.

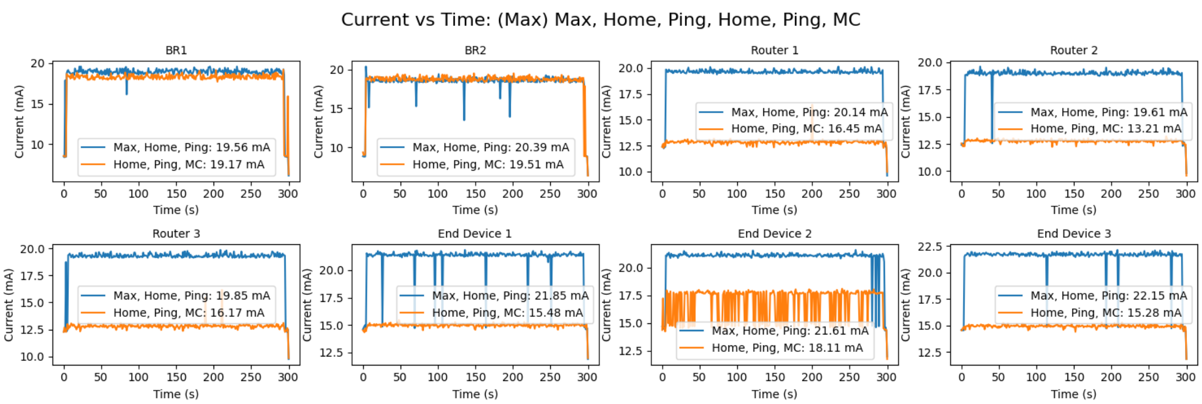

Figure 5.53: Maximum Current Consumption Comparison in Home location, Ping mode, Maximum MCM optimized mode vs. Home location, Ping mode, MCM optimized mode.

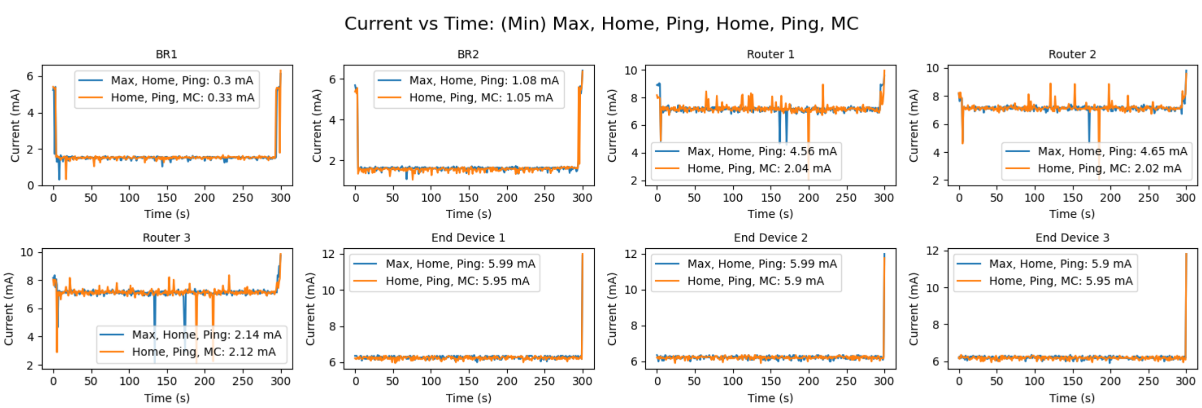

Figure 5.54: Minimum Current Consumption Comparison in Home location, Ping mode, Maximum MCM optimized mode vs. Home location, Ping mode, MCM optimized mode.

The comparison graphs present the Optimized MCM mode demonstrates lower mean current values for Routers and End Devices when compared to the Maximum mode. Notably, the maximum current values for devices in the Maximum mode are consistently higher than those in the Optimized mode. The reduced mean and maximum current values in the Optimized mode indicate better energy efficiency and overall performance than in the Maximum mode.

Genetic Algorithm The following plot and table illustrate the impact of current consumption for each device in the network when using GA optimization for transmission power settings while the radio is active.

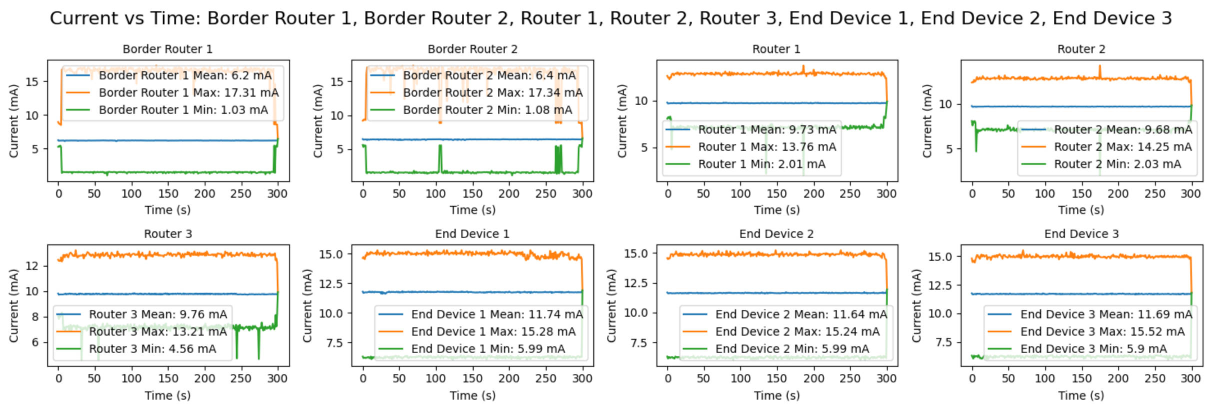

Figure 5.55: Overview of Current Consumption in Home location, Ping mode, GA optimized mode.

Table 5.20: Overview of Current Consumption in Home location, Ping mode, GA optimized mode.

Device	**Input txpower**	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
Border Router 1	-20	290	6.2	17.31	1.03
Border Router 2	-19		6.4	17.34	1.08
Router 1	-19		9.73	13.76	2.01
Router 2	-20		9.68	14.25	2.03
Router 3	-18		9.76	13.21	4.56
End device 1	-18		11.74	15.28	5.99

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Table 5.20: Overview of Current Consumption in Home location, Ping mode, GA optimized mode. (Continued)

Device	**Input txpower**	**Total Ping**	**Mean** (mA)	**Max** (mA)	**Min** (mA)
End device 2	-16		11.64	15.24	5.99
End device 3	-19		11.69	15.52	5.9

Comparison: Optimized Home Ping – MCM vs GA The following comparison graphs showcase the differences in current consumption between the MCM and GA optimization methods in a home setting with devices in ping mode.

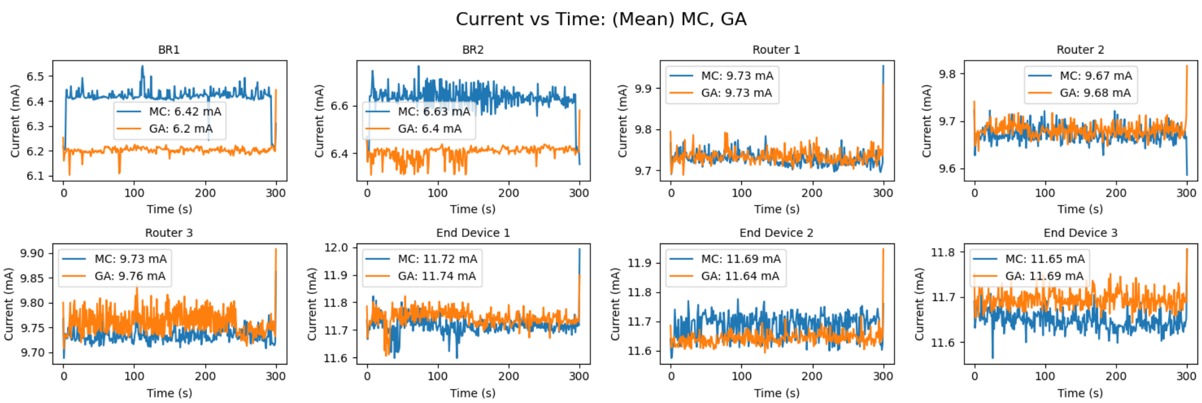

Figure 5.56: Mean Current Consumption Comparison in Home location, Ping mode, MCM optimized mode vs. Home location, Ping mode, GA optimized mode.

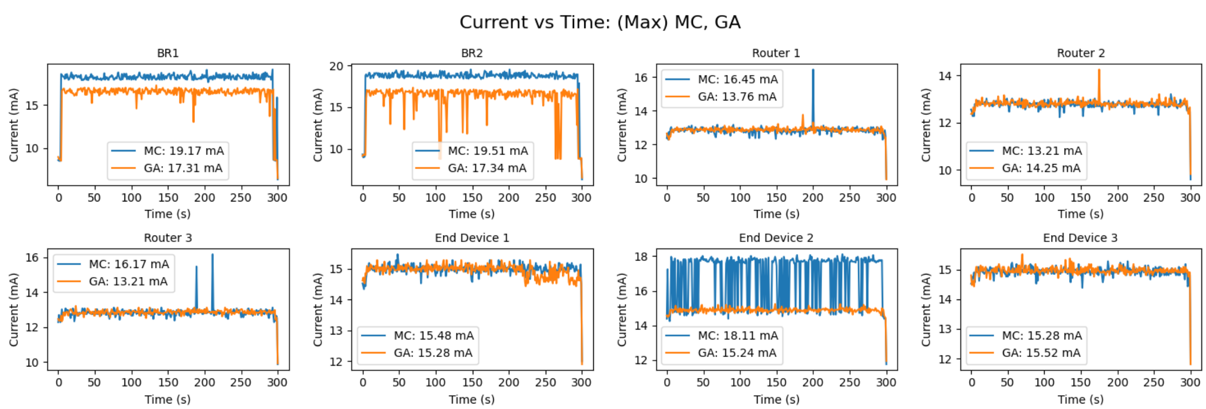

Figure 5.57: Maximum Current Consumption Comparison in Home location, Ping mode, MCM optimized mode vs. Home location, Ping mode, GA optimized mode.

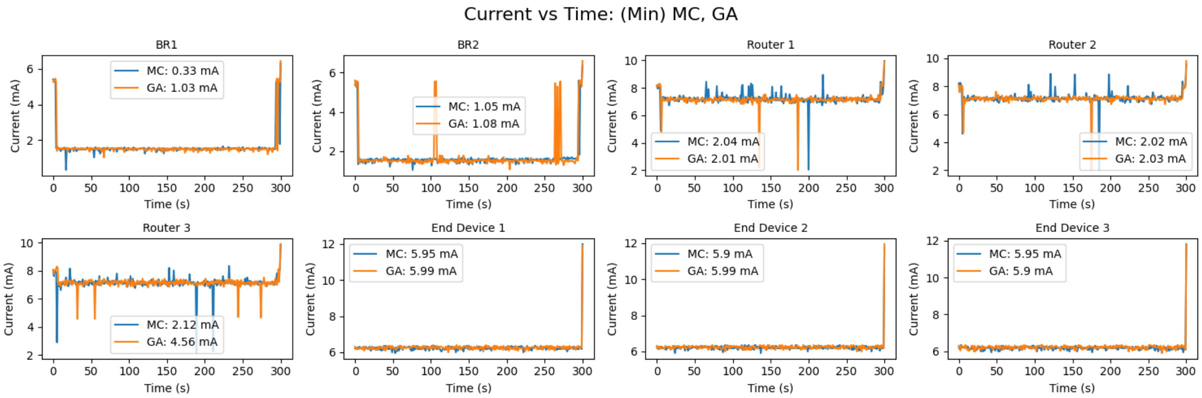

Figure 5.58: Minimum Current Consumption Comparison in Home location, Ping mode, MCM optimized mode vs. Home location, Ping mode, GA optimized mode.

The comparison graphs display differences between Optimized Home Ping MC and GA modes for various devices. Border routers generally have a higher mean and maximum current values in MC mode. Routers show similar mean current values in both modes but higher maximum current values in MC mode for Router 1 and 3. End devices exhibit relatively similar mean current values across both modes, with only End Device 2 having a higher maximum current value in MC mode. Minimum current values show minimal differences between MC and GA modes for all device types.

Comparison: Home Ping - Maximum vs Optimized GA The following comparison graphs display the differences between Maximum and Optimized GA modes for various devices in the Home setting while the radio is active.

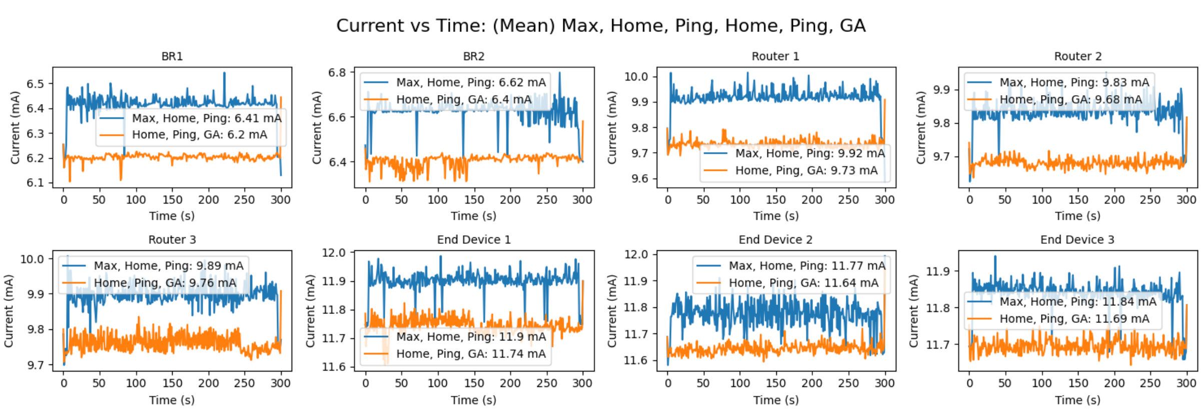

Figure 5.59: Mean Current Consumption Comparison in Home location, Ping mode, Maximum MCM optimized mode vs. Home location, Ping mode, GA optimized mode.

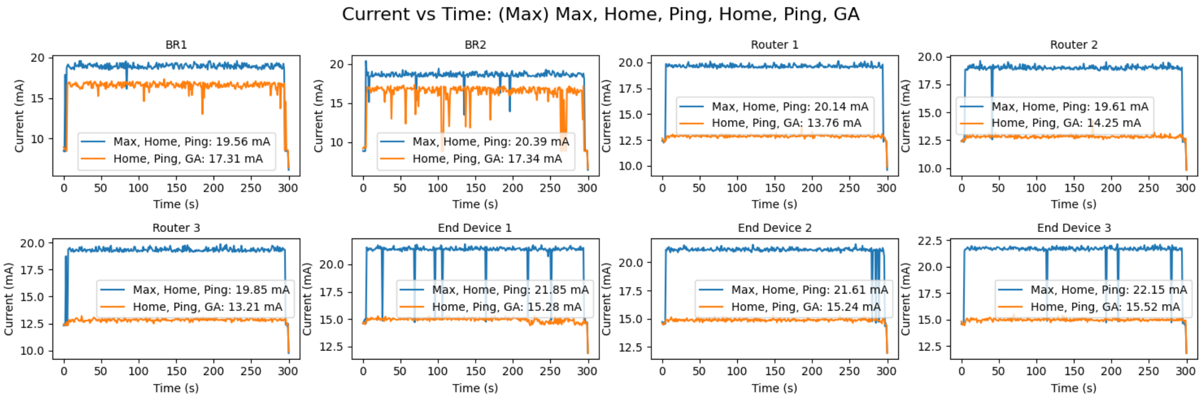

Figure 5.60: Maximum Current Consumption Comparison in Home location, Ping mode, Maximum MCM optimized mode vs. Home location, Ping mode, GA optimized mode.

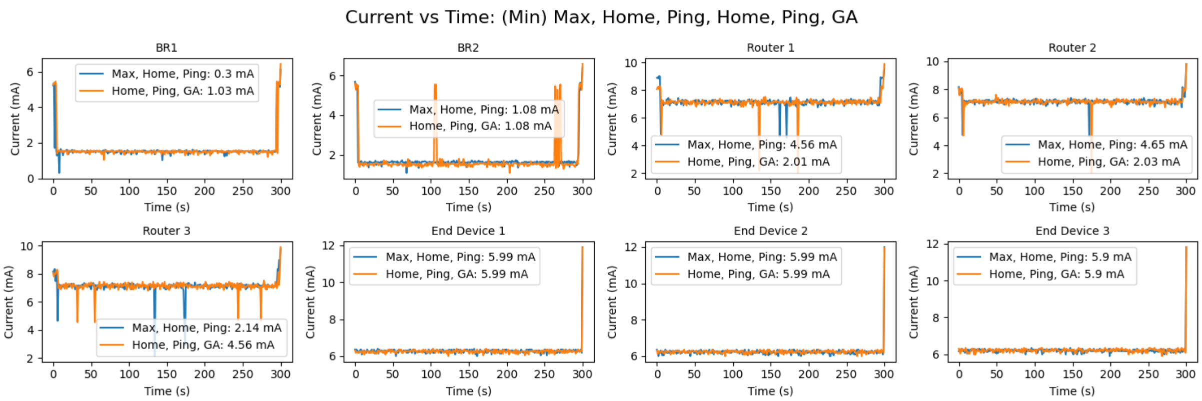

Figure 5.61: Minimum Current Consumption Comparison in Home location, Ping mode, Maximum MCM optimized mode vs. Home location, Ping mode, GA optimized mode.

The graphs compare Maximum and Optimized GA modes for various devices. Border Routers and Routers exhibit higher mean and maximum current values in Maximum mode, with some differences in minimum current values. End devices show marginally higher mean current values in Maximum mode, with noticeably higher maximum current values. Minimum current values for End Devices are similar in both modes, with only minor variations between Maximum and Optimized GA modes.

5.3.3 Concluding Remarks

The analysis of current measurements for different modes and devices highlights the importance of considering various methods for comparing performance. The findings consistently show that the Genetic Algorithm (GA) outperforms other modes in optimization by setting the lowest transmission power for each device, resulting in a more energy-efficient and eco-friendly network configuration.

To further understand the overall efficiency of each network mode, a new section with a bar chart comparing power consumption across modes rather than individual devices is suggested. This comparison will help identify trends and guide well-informed decisions when selecting the most suitable mode for specific applications and scenarios. By considering these comparisons and the inherent advantages of GA mode, which consistently offers the best results due to its optimization of transmission power, stakeholders can optimize their networks for peak performance and minimal energy consumption.

5.3.4 Power Comparison on Different Network Modes

This section presents a bar chart comparing power consumption across various network modes, providing a broader perspective on overall efficiency. Analyzing power consumption helps understand energy efficiency and supports informed decisions when choosing the best mode for specific applications or scenarios. The bar chart visualizes power differences between modes, making it easier to identify patterns and trends less evident when comparing individual devices.

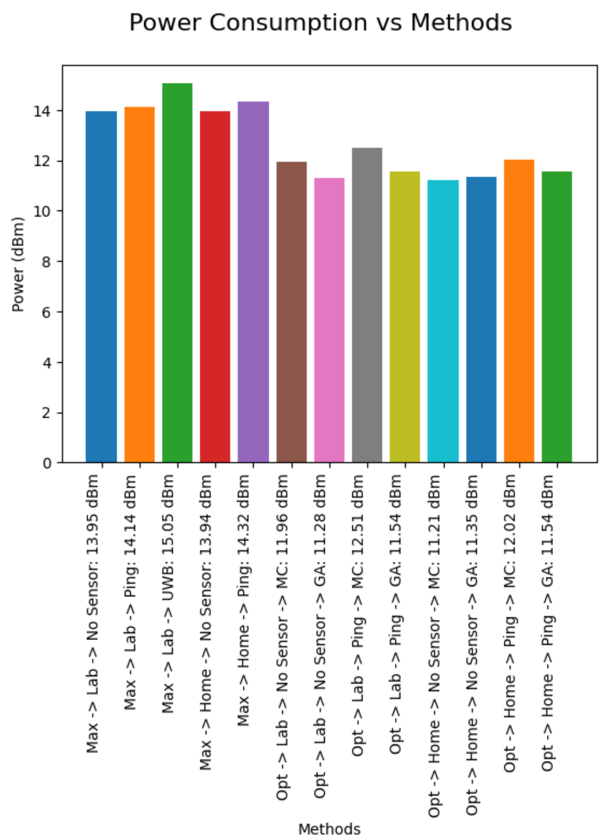

Figure 5.62: Power Comparison on Different Network Modes

Table 5.21: Power Comparison on Different Network Modes.

<table>
<tr><th>Method</th><th>Location</th><th>Type</th><th>Mode</th><th>Input txpower (dBm)</th><th>Power Consumption (dBm)</th></tr>
<tr><td rowspan="5">Maximum</td><td rowspan="3">Lab</td><td>No Sensor</td><td colspan="2" rowspan="5">8</td><td>13.95</td></tr>
<tr><td>Ping</td><td>14.14</td></tr>
<tr><td>UWB</td><td>15.05</td></tr>
<tr><td rowspan="2">Home</td><td>No Sensor</td><td>13.94</td></tr>
<tr><td>Ping</td><td>14.32</td></tr>
<tr><td rowspan="8">Optimized</td><td rowspan="4">Lab</td><td rowspan="2">No Sensor</td><td>MCM</td><td>-8, 8, -16, 0, 0, -8, -20, 8</td><td>11.96</td></tr>
<tr><td>GA</td><td>-20</td><td>11.28</td></tr>
<tr><td rowspan="2">Ping</td><td>MCM</td><td>-8, 8, -16, 0, 0, -8, -20, 8</td><td>12.51</td></tr>
<tr><td>GA</td><td>-20</td><td>11.54</td></tr>
<tr><td rowspan="4">Home</td><td rowspan="2">No Sensor</td><td>MCM</td><td>8, 8, -8, -20, 4, -16, 4, -16</td><td>11.21</td></tr>
<tr><td>GA</td><td>-20, -19, -19, -20, -18, -18, -16, -19</td><td>11.35</td></tr>
<tr><td rowspan="2">Ping</td><td>MCM</td><td>8, 8, -8, -20, 4, -16, 4, -16</td><td>12.02</td></tr>
<tr><td>GA</td><td>-20, -19, -19, -20, -18, -18, -16, -19</td><td>11.54</td></tr>
</table>

The data table compares the power consumption of various network modes in the lab and home environments, emphasizing the effectiveness of the Genetic Algorithm (GA) optimization approach. GA optimization consistently demonstrates better results in reduced power consumption across different types, modes, and locations. In Lab and home environments, GA optimization outperforms MC optimization for No Sensor mode (11.28 dBm in Lab, 11.35 dBm in Home) and Ping mode (11.54 dBm in Lab and Home).

Here's a table summarizing the total power saved when comparing Maximum mode with MCM and GA-optimized modes:

Table 5.22: Total Power Saved When Comparing Maximum Mode with MCM and GA-Optimized Modes.

<table>
<tr><th>Location</th><th>Mode</th><th>MCM</th><th>GA</th></tr>
<tr><td rowspan="2">Lab</td><td>No Sensor</td><td>14.26%</td><td>19.14%</td></tr>
<tr><td>Ping</td><td>11.53%</td><td>18.39%</td></tr>
</table>

Continued on next page

Table 5.22: Total Power Saved When Comparing Maximum Mode with MCM and GA-Optimized Modes. (Continued)

Location	**Mode**	**MCM**	**GA**
Home	No Sensor	19.51%	18.58%
	Ping	16.08%	19.40%

The table demonstrates that both MCM and GA-optimized modes show significant power savings compared to the Maximum mode. The GA-optimized mode consistently outperforms the MCM-optimized mode in terms of power savings. The total power saved when comparing Maximum mode with MCM and GA optimized modes ranges from 11.5% to 19.6%, highlighting the effectiveness of optimization approaches, especially GA optimization, in reducing power consumption in Thread mesh wireless networks.

The Genetic Algorithm (GA) optimization consistently demonstrates reduced power consumption across various types, modes, and locations, outperforming the MCM optimization in both Lab and Home environments. This analysis reveals GA optimization's effectiveness in lowering power consumption in Thread mesh wireless networks by optimizing transmission power. This research establishes a solid foundation for future exploration and enhancements in power optimization using algorithmic approaches.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

In conclusion, this research on power optimization in Thread mesh wireless networks using transmission power as a parameter has shown the effectiveness of algorithmic approaches, particularly Genetic Algorithm (GA), in reducing power consumption. This enhances the performance of MOOD-Sense initiatives and other IoT applications while contributing to sustainable and energy-efficient IoT network implementation.

By considering ethical aspects, sustainability, and reliable services, this study adheres to responsible research and innovation principles. The methodology, leveraging professional skills and applied research, enables the development of an optimized system design adaptable for various applications beyond MOOD-Sense. Additionally, these findings can promote energy-conserving, environmentally friendly, and sustainable IoT devices and network integration.

As IoT technology continues to expand and evolve, researchers, engineers, and industry professionals must develop and implement energy-efficient solutions. This research demonstrates that optimizing transmission power using algorithmic approaches can significantly reduce power consumption in Thread mesh wireless networks, paving the way for a more sustainable and efficient IoT ecosystem.

6.2 Recommendations

Considering the conclusions from this research, several recommendations for future work are proposed to further enhance power optimization in Thread mesh wireless networks and other communication systems. These suggestions aim to build on the foundation laid by this research and contribute to the ongoing development of wireless networking technologies.

1. **Dynamic Transmission Power Algorithms:** Develop algorithms to adjust transmission power dynamically based on the distance between devices, ensuring optimal power usage.

2. **In-depth Transmission Power Plot Exploration:** Investigate the transmission power plot in greater detail to identify potential improvements and optimization opportunities.
3. **Path Loss Modeling Improvement:** Seek ways to enhance path loss modeling and estimation, improving the accuracy of transmission power optimization techniques.
4. **Expansion of Network Parameters:** Broaden the research scope to include other network parameters impacting power consumption and overall network performance.
5. **Application to Other Wireless Communication Networks and Devices:** Examine the application of optimization techniques to other wireless networks and devices for widespread energy savings and performance improvement.

Implementing these recommendations can help future research advance the optimization of Thread mesh wireless networks and other communication systems, ultimately leading to more efficient wireless networking solutions.

Chapter 7

List of Definitions and Abbreviations

Here is a list of abbreviations used throughout the research, along with their short definitions:

1. **IoT** - Internet of Things: A network of interconnected devices and sensors that communicate and share data over the internet.
2. **MCU** - Microcontroller Unit: A small, integrated computer on a single chip, used for embedded systems and control applications.
3. **UWB** - Ultra-Wideband: A radio technology that uses a wide frequency range for high data rate, short-range communication.
4. **MCM** - Monte Carlo Method: A computational method that uses random sampling to solve complex problems and estimate results.
5. **GA** - Genetic Algorithm: A search heuristic inspired by natural selection and genetics, used to optimize complex problems.
6. **mA** - milliampere: A unit of electric current equal to one-thousandth of an ampere.
7. **uA** - microampere: A unit of electric current equal to one-millionth of an ampere.
8. **dBm** - decibel-milliwatts: A unit of power level used to express the ratio of power in decibels relative to 1 milliwatt.
9. **RF** - Radio Frequency: Electromagnetic wave frequencies used for wireless communication.
10. **dB** - decibel: A unit of measurement used to express the ratio of two values in a logarithmic scale.

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Appendix

You are encouraged to put in appendices in your final report. In an appendix you can include things such as large tables or background information. Anything that is useful to know for the reader, but prevents the reader to read your main text in a fluent manner. Each appendix should have a number and a self-explanatory title.