A DELAY-TOLERANT NETWORK ARCHITECTURE FOR EDGE COMPUTING WITH APPLICATIONS IN NARROW BAND INTERNET OF THINGS

by

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DECLARATION

I, Waldon Hendricks, declare that the contents of this thesis represent my own unaided work and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore,it represents my own opinions and not necessarily those of the Cape Peninsula University ofTechnology.

Signed **Date 31 July 2024**

ABSTRACT

The increasing use of Internet of Things (IoT) applications had generated significant traffic delays and large amounts of data, impacting the delivery and efficiency of these applications. This necessitated faster response times and minimal delays in packet transmission. Fog devices, responsible for immediate data transmission, computation, and storage, were considered potential solutions to these challenges. However, research into fog and edge computing models was still in the early stages, requiring further exploration to unlock their potential for various IoT applications. This study aimed to determine the most suitable model for building highly available, fault-tolerant networks by designing and evaluating the performance of the CUBIC and BBR algorithms, proposing a novel delay-tolerant network (DTN) architecture for edge and fog computing, specifically designed to run IoT applications. At the heart of this solution was the design and evaluation of two rate-limiting algorithms, CUBIC (Cubic) and BBR (Bottleneck Bandwidth and Round-trip propagation time), on edge network nodes CUBIC is a TCP congestion control algorithm, named for the cubic function it uses to manage network congestion. These algorithms were integrated with bandwidth management techniques within a lightweight Kubernetes (K3s) cluster environment. Specifically, Narrowband Internet of Things (NB-IoT) using the SIM7020E module was employed in a K3s cluster for edge computing. A rate-limiting method with Cilium on a K3s cluster of six nodes acted as a rate limiter for layers 3 and 4 of the of the Open Systems Interconnection (OSI) model, using a bandwidth manager for K3s service pods on the network port to prevent Distributed Denial of Service (DDoS) and Internet Protocol (IP) flooding attacks. Quantitative methods were employed to evaluate the effectiveness of the proposed DTN solution. The evaluation model was designed from the engineering and design process as a research method. Data were collected using Prometheus and Fortio, a load testing tool, within a simulated IP flooding attack environment. Data analysis utilised information and system theories to test and validate the empirical data gathered for fog and edge networks, focusing on delay in fault-tolerant networks. The study made significant contributions across theoretical and practical domains. Theoretically, it introduced a new Delay-Tolerant Network (DTN) architecture specifically designed for Internet of Things (IoT) applications. Practically, it demonstrated the effectiveness of newly designed rate-limiting algorithms in reducing network delays and mitigating potential attacks that could cripple the network and the

application running on it.

Keywords: Narrowband Internet of Things (NB-IoT), Delay-Tolerant Network (DTN), Rate Limiting, Network Security, Kubernetes (K3s)

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DEDICATION

This dissertation is dedicated to my boy, Wyatt Hendricks and my wife Stephia Hendricks. Thank you for allowing me to be a student and your Dad Wyatt and Husband to Stephia. I dedicate this to inspire you to value education and reach for the best in life. To my late Mom, Eleanore Mentoor, Thanks, Mom, for guiding me in spirit and Grandma Katrina Hendricks, I know you are smiling down on me now. Thanks for being the guardian angel in my life.

PUBLICATIONS FROM THIS RESEARCH

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- Hendricks, W. and Kabaso, B., 2023, December. Challenges and Solutions in Integrating Narrowband IoT with Edge Computing: Resource Constraints, Security, Latency, and IDS Deployment. In International Conference on Advanced Computing and Intelligent Technologies (pp. 119-134). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-1961-7_8.
- Hendricks, W., & Kabaso, B. (2024). Evaluating Signal Quality and System Performance in NB-IoT Communications: An Empirical Analysis Using the SIM7020 Module. Journal of Telecommunications and the Digital Economy, 12(2), 115–138. https://doi.org/10.18080/jtde.v12n2.955.

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ABBREVIATIONS AND ACRONYMS

5G	Fifth Generation (mobile networks)
BBR	Bottleneck Bandwidth and Round-trip time
CNI	Container Network Interface
CSV	Comma-Separated Values
CUBIC	CUBIC TCP Congestion Control
DDoS	Distributed Denial of Service
DNS	Domain Name System
HAT	Hardware Attached on Top
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
IDS	Intrusion Detection System
IoT	Internet of Things
IPS	Intrusion Prevention System
JSON	JavaScript Object Notation
K3s	Lightweight Kubernetes
LTE	Long-Term Evolution
NB-IoT	Narrowband Internet of Things
QPS	Queries Per Second

SIM	Subscriber Identity Module
SSH	Secure Shell
SSL	Secure Sockets Layer
TCP	Transmission Control Protocol
TLS	Transport Layer Security
UDP	User Datagram Protocol
UE	User Equipment
YAML	YAML Ain't Markup Language

GLOSSARY

DDoS	A type of cyberattack where multiple compromised systems are used to flood a target with traffic, causing service disruption.
Internet of Things (IoT)	The network of physical objects that contain embedded technology to communicate and interact with their internal states or the external environment.
Load Balancing	The process of distributing network traffic across multiple servers to ensure no single server becomes overwhelmed, improving performance and reliability.
Quality of Service (QoS)	The overall performance of a network service, as seen by the users, especially in terms of the performance factors that affect the quality, such as bandwidth, latency, and error rates.
Rate Limiting	A technique used to control the amount of incoming and outgoing traffic to or from a network, server, or application to prevent abuse or overload.
Shannon Entropy	A measure of uncertainty or randomness in information theory used to quantify the amount of information in a message.
Traffic Filtering	The process of monitoring and controlling the flow of network traffic to protect against unauthorized access and attacks.

CHAPTER 1 INTRODUCTION AND PROJECT OVERVIEW

This dissertation discusses the design of a Narrow-Band IoT Delay-Tolerant Network (NB-IoTDTN) to mitigate DDoS network-based attacks using a rate-limiting algorithm and edge computing. While the concept of rate limiting and edge computing is not new, the unique approach and implementation presented in this dissertation offer novel solutions to the challenges faced by NB-IoT networks. In this chapter, Figure 1-1, sets out the introduction to the research, providing an overview of the chapter.

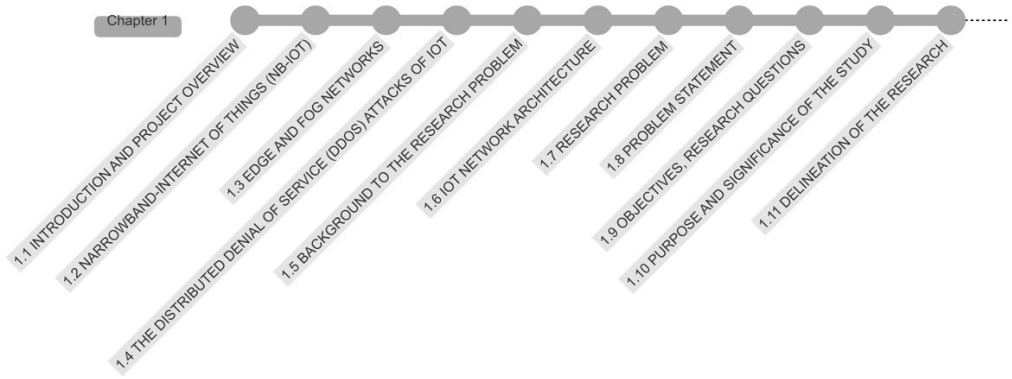

Figure 1-1: Chapter 1 Outline

The Chapter begins with an Introduction and Project Overview, followed by an exploration of the Narrowband-Internet of Things (NB-IoT). It then delves into Edge and Fog Networks and discusses The Distributed Denial of Service (DDoS) Attacks of IoT. The next section provides Background to the Research Problem before detailing the IoT Network Architecture, which includes layers like the Perception Layer, Network Layer, Service Management Layer, Application Layer, and Business Layer.

The discussion then addresses the Research Problem and presents the Problem Statement. Subsequently, it outlines the Objectives and Research Questions, which comprise the Aim of the Study, Main Research Question, and Sub-research Questions. This leads to a section on the Purpose and Significance of the Study. Following this is the Delineation of the Research, which highlights the central focus and key constraints.

1.1 Introduction

IoT technology has dramatically transformed the technological landscape of the 21st century. By connecting billions of devices to the Internet, IoT has enabled unprecedented levels of automation, efficiency, and data-driven decision-making across various industries, including healthcare, manufacturing, agriculture, and smart cities (Latif *et al.,* 2020). The impact of IoT is evidenced by its rapid adoption and integration into everyday life, facilitating smarter environments and enhancing the quality of life (Lampropoulos *et al.,* 2019; Kour *et al.,* 2021).

However, many IoT devices remained unprotected, leaving them vulnerable to notable vulnerabilities and potential threats to the systems they support (Meneghello *et al.,* 2019). The lack of security implementations and weak protections make these devices easy targets for infections and botnet attacks (Opirskyy *et al.,* 2021). Default login credentials and backdoor access further contribute to the security risks associated with IoT devices (Karie *et al.,* 2020). The growing usage of IoT applications raises privacy concerns as well. The diverse nature of IoT and the need for governing policies and standards add to the complexity of securing these devices. Efforts such as the Manufacturer Usage Description (MUD) and blockchain-based solutions have been proposed to address these security challenges (Lear *et al.,* 2019). However, there is still a need for consensus and prioritisation in IoT security to protect devices and data (Rugeles Uribe *et al.*, 2022; Rahman *et al.*, 2023).

Major players in the industry had anticipated such substantial growth. For instance, Cisco Networks predicted that by 2020, around 50 billion intelligent devices would be active and interconnected via the Internet (Mohapatra *et al.*, 2016; Bothra *et al.*, 2023). Significantly, this estimated statistic had surpassed the worldwide human population, emphasising the pervasiveness of these devices.

Furthermore, the swift progression in IoT technology had reached a point where these devices could effortlessly merge and operate in almost any setting, provided there was internet access. This trend of hyper-connectivity was projected to intensify. According to a study by (Bhayo *et al.*, 2021), the subsequent years would see an even sharper incline in these statistics.

The quick progress in Internet of Things (IoT) technology has reached a stage where these

devices can smoothly merge and function in any environment if there is access to the Internet. This fact is apparent when observing the growing number of IoT devices connected to the internet, with the expectation of reaching a staggering 50 billion devices by 2030 (Ozalp *et al.*, 2022). However, this extensive connectivity also brings forth various security challenges. IoT devices, particularly those operating within personal networks with limited operational capacity, remain vulnerable to attacks targeting wireless technologies (Mamdouh *et al.*, 2021).

Furthermore, IoT devices' diverse nature and widespread presence created vulnerabilities that malicious individuals can exploit (Macedo *et al.*, 2019). To tackle these challenges, encryption algorithms, access control mechanisms, and authentication techniques were utilised to safeguard IoT devices and ensure the security of their data (Dangana *et al.*, 2021). Moreover, integrating blockchain technology with Software-Defined Networking (SDN) has emerged as a promising solution to enhance the security and dependability of IoT networks (Meng *et al.*, 2021).

The rapid increase in IoT devices has exposed vulnerabilities in interconnected infrastructures (Rajmohan *et al.,* 2022). In the early months of 2020, cyber adversaries took advantage of the uncertainties surrounding the COVID-19 outbreak and launched sophisticated attacks targeting critical sectors such as healthcare, e-commerce, and educational platforms (Alawida *et al.,* 2022).

These attacks highlighted the potential risks associated with the widespread adoption of IoT technology and the need for robust cybersecurity measures (Mazhar *et al.*, 2023). The vulnerabilities in IoT devices and the lack of global regulations have made it easier for attackers to exploit weaknesses and disrupt essential services. As a result, this recognition started from 2021 and 2022 and has continued addressing security challenges in IoT systems and implementing effective countermeasures to protect against cyber threats (Gaurav *et al.*, 2021; Rugeles Uribe *et al.*, 2022).

According to NETSCOUT's yearly publication, there has been a significant increase in Distributed Denial of Service (DDoS) attacks, with a 126% surge in such attacks and a 31% rise in throughput offensives during the specified time (Shafi *et al.*, 2022; Qureshi *et al.*, 2022). This alarming trend highlighted the growing threat posed by DDoS attacks, which aim to disrupt network communication and overwhelm targeted systems with a flood of service requests from multiple sources (Omolara *et al.*, 2022). The increase in DDoS attacks can be attributed to various factors,

including the transition to remote work and the spread of IoT devices, which provide new opportunities for attackers (Kasinathan *et al.*, 2013). These attacks pose significant challenges for network administrators and cybersecurity experts, as they are difficult to defend against due to their decentralised and complex nature (Gamec *et al.*, 2021). Organisations must implement proactive measures and intelligent defense systems to mitigate the impact of DDoS attacks and ensure the availability and security of their networks.

The core components of IoT, including device chips, sensors, and actuators, face security dilemmas that require immediate rectification. These components have limited computing and storage capacities, making it challenging to implement robust security mechanisms (El-Kady *et al.,* 2023). The use of lightweight technologies is necessary to address these limitations and ensure the security of IoT devices. Additionally, integrating different network technologies in the IoT ecosystem introduces existing and new security problems (Tariq *et al.*, 2023). Therefore, developing effective methods for identifying attacks and threats, such as Intrusion Detection Systems (IDS) and Machine Learning-based approaches, is crucial. Furthermore, architectural considerations play a significant role in implementing security techniques at different levels of the IoT system (Padhy *et al.*, 2023). By understanding these security challenges and implementing appropriate security protocols, IoT can achieve the promised convenience while ensuring authentication, authorization, encryption, anomaly detection and network segmentation (Singh *et al.,* 2023).

1.2 Narrowband-Internet of Things (NB-IoT)

The IoT ecosystem consists of devices that operate within limitations, primarily influenced by their design principles and a strong emphasis on conserving energy. These constraints include limited resources such as energy, memory, communication, and computation power (Popli *et al.*, 2019). The resource limitations in IoT devices make it challenging to implement robust security mechanisms. As a result, IoT devices often have weak security protections or no protection, making them vulnerable to attacks and infections (Nayak & Swapna, 2023). The lack of security implementations in IoT devices led to incidents like the Mirai botnet attack, where hundreds of thousands of compromised IoT devices were launched to launch a massive Distributed Denial-of-Service (DDoS) attack (Ahmed *et al.,* 2019; Kelly *et al.,* 2020). The vulnerabilities in IoT devices, combined with the increasing number of devices connected to the Internet, highlight the urgent

need for improved security measures in the IoT ecosystem (Kamaldeep *et al.*, 2023). Such constrained-resource architecture had not resulted from neglect but rather a conscious decision to ensure durability and peak performance, mainly when the devices were situated where regular recharging or upkeep was challenging (Salva-Garcia *et al.*, 2018).

Low Power Wide Area (LPWA) technology has emerged as a preferred solution for extending the connectivity range of IoT devices while minimising power consumption (Sheng-Tao Chen *et al.,* 2022). This technology enables the seamless connection of IoT devices across large geographical areas, ensuring continuous communication links without incurring significant financial costs. LPWA networks, such as Long Range (LoRa), LoRa Wide Area Network (LoRaWAN) and NB-IoT, offer long-range coverage, low complexity, and reduced deployment costs, making them ideal for IoT applications in various domains (Ksentini & Frangoudis, 2020). These networks provide reliable and efficient communication, allowing IoT devices to transmit data over vast distances without excessive power. The use of LPWA technology has revolutionised the IoT landscape, enabling the deployment of IoT services in remote and challenging environments (Ahmad *et al.*, 2023). LPWA technologies, primarily LoRa and SigFox, have attracted attention. Used often in tandem with WiFi connections, these technologies expanded the communication domain of IoT devices, making them adaptable across diverse scenarios (Chaudhary *et al.*, 2022).

NB-IoT, introduced by the 3rd Generation Partnership Project (3GPP) in its release-13 specifications, is a narrowband IoT technology adaptable to the wireless spectrum used by 4G LTE technology. This adaptability allows NB-IoT to bridge conventional cellular and IoT-specific communications (Lee *et al.*, 2022). The introduction of NB-IoT expands the LPWA technological suite and offers advantages such as comprehensive area network coverage, low power consumption, and low data throughput (Muteba *et al.*, 2021). It is designed to address the needs of massive Machine-Type Communication (MTC). It is expected to play a significant role in the wireless connection of several IoT devices (Savic *et al.*, 2021). Integrating NB-IoT into the existing LTE architecture enables efficient support for many IoT devices with low data rate transmissions and improved coverage (Muteba *et al.*, 2021). This makes NB-IoT a superior choice for LPWA scenarios.

The progression of IoT has been commendable, but there is a need for a more comprehensive research view in terms of security and privacy, especially in the context of NB-IoT (Tembhurne *et*

al., 2024). While much academic work has focused on investigating the possible applications of IoT, the nuanced challenges concerning security and confidentiality in NB-IoT have garnered less focus (Alongi *et al.*, 2022). Jha *et al.* (2021) highlight the importance of addressing security issues in IoT, including confidentiality, integrity, data availability, and protection against unauthorised access and corruption. They emphasised the significance of implementing security measures such as encryption, access control, authentication, and monitoring to ensure IoT systems' safe and efficient operation (More et al., 2023). Additionally, the authors discuss the challenges of resource-constrained devices, inter-fog sharing of resources, near real-time data analysis, security at the gateway level, interoperability between protocols, and the tamper-proof feature of blockchain in the context of IoT security (Farooq *et al.*, 2022; Fischer & Tönjes, 2023).

This neglect became more evident when considering the difficulties in safeguarding the authenticity and privacy of data in transit during security breaches within the NB-IoT framework (Zhan et al., 2021). Jha *et al.* (2021) systematic evaluation highlighted this disparity, emphasising the need for thorough research to understand, predict, and reduce threats that might jeopardise data during security breaches in the NB-IoT environment.

The IoT domain has undergone significant evolution, presenting both academic and industrial sectors with the urgent need to address the emerging security and privacy challenges (Mishra *et al.*, 2023). IoT devices' increasing connectivity and integration have raised concerns regarding data protection and unauthorised access. Additionally, the survey by Sharma *et al.* (2020) emphasised the importance of securing M-IoT networks to safeguard sensitive information and ensure user trust. As discussed in various papers, such as Vaezi *et al.* (2022), the integration of blockchain technology has shown promise in enhancing security and privacy in IoT applications.

Academia and industry must collaborate to develop comprehensive solutions addressing the evolving security and privacy challenges in the IoT domain. Such collaboration fosters innovation and ensures that cutting-edge technologies can be effectively integrated into practical applications. For instance, the establishment of a testbed to support research and experimentation with IoT, edge, and cloud computing technologies exemplifies how industry-academia collaboration can drive advancements in IoT security (Vidal et al., 2023).

1.3 Edge and Fog Networks

The rise of IoT devices at the edge has steered into a new era of data-centric decision-making and automation (Jin *et al.,* 2022). These devices, ranging from household gadgets to industrial sensors, generate a large amount of data that often requires immediate processing for optimal performance. However, this environment also presents challenges (Ksentini & Frangoudis, 2020). The limited resources of edge devices, such as power supply and computing capacity, constrain their deployment and functionality (Lee *et al.*, 2022). Additionally, the security of IoT systems is a significant concern, as these devices are vulnerable to attacks and can be exploited for malicious purposes (Dai *et al.*, 2021). Researchers have proposed various solutions to these challenges, including edge computing, anomaly detection frameworks, and machine learning-based approaches (Li *et al.*, 2021). These advancements aim to enhance IoT networks' security, efficiency, and reliability, paving the way for the widespread adoption of IoT technologies in various domains.

Latency has been a significant concern in applications that require real-time data processing, such as self-driving cars and medical instruments (Shukla et al., 2023). The traditional IoT model, which relies on relaying data to a remote cloud for interpretation, intensifies this issue (Ahmad *et al.*, 2023). The need to transmit data back and forth between the device and the cloud introduces delays that can have severe consequences in time-sensitive applications (Stavrinides & Karatza, 2022). Emerging architectures like fog and edge computing have been proposed to address this problem (Fletcher et al., 2024). These architectures bring computation and storage closer to the edge devices, reducing the latency associated with data transmission to the cloud (Hua *et al.*, 2023).

By migrating computations to external computation systems and storage servers located at the edge, fog and edge computing can ease the computational burden and minimise latency, enabling real-time data processing and analysis (Fazeldehkordi & Grønli, 2022). The IoT framework's extensive connectivity and data interactions have created a challenging environment for ensuring the security of devices, communication channels, and data transportation. With the vast number and variability of devices, guaranteeing security has become a significant challenge (Chatterjee & Ahmed, 2022).

The IoT ecosystem is an attractive target for malicious entities due to its low security measures and high computational power requirements at the device level (Ranaweera *et al.*, 2021).

Organisations that have installed IoT devices have suffered from attacks due to weaknesses in design and vulnerabilities in IoT devices (Tange *et al.*, 2020). It is crucial to provide countermeasures to protect resource-constrained IoT devices against cyber-attacks (Swamy & Kota, 2020). The security measures in IoT networks include lightweight cryptography, hardware security, and intrusion detection and prevention systems (Bhayo *et al.*, 2021). However, there is still a need for novel research and solutions to address the security challenges in the IoT framework (Baniya *et al.,* 2024).

The design of IoT devices to operate on limited power sources like batteries demanded energy efficiency (Zhao *et al.,* 2022). However, higher computational demands for better functionalities resulted in increased energy usage, compromising the lifespan of devices and requiring regular maintenance. This contradicts the fundamental concept of IoT, which aims for devices to be ever-present and unintrusive (Qureshi *et al.*, 2022). The energy consumption of IoT devices, especially during data transmission, is a significant challenge (Kaur & Kumar, 2022). Energy-efficient data transmission schemes and including renewable energy sources through energy harvesting can address this challenge (Farooq *et al.*, 2022). [Additionally, lightweight, energy-efficient security mechanisms are crucial for power-constrained IoT devices (Anand *et al.*, 2020). To ensure sustainable IoT, energy and security sustainability must be considered from the design phase to the end of the device's lifecycle.

Transitioning from a traditional cloud-based IoT framework to an edge computing approach could resolve the obstacles faced in IoT systems (Roopa Devi & Kayethri, 2024). Edge computing allows data processing at the network's edge, closer to the IoT devices, rather than relying solely on cloud servers (Rahman *et al.*, 2023). This reduces latency, improves speed, and enhances the overall performance of the IoT application (Lee *et al.*, 2022). Additionally, edge computing minimises the need for data transmission between the devices and the cloud, thereby reducing the risk of data theft and breaches (Li *et al.*, 2021). By distributing the computing workload among multiple edge nodes, edge computing also improves system resilience and reduces the impact of node failures (Ajayi *et al.*, 2021). Furthermore, integrating blockchain technology with edge computing can enhance IoT systems' security, privacy, and data auditability (Shah *et al.*, 2022). Overall, transitioning to an edge computing approach addressed the limitations of traditional cloud-based IoT frameworks and provided a more efficient and secure IoT environment.

The adoption of edge computing has posed challenges concerning the consolidation of IoT devices and the potential overloading of edge gateways (Lim et al., 2023). These gateways, which serve as intermediaries between devices and the primary cloud, can become bottlenecks, undermining the advantages of edge computing. Furthermore, the dispersion of devices and gateways gives rise to security vulnerabilities, where unauthorised devices could infiltrate the network and its resources, further complicating the cybersecurity landscape (Sutikno & Thalmann, 2022). The extensive utilisation of IoT devices also raises concerns regarding the confidentiality and authenticity of data during communication (Wu *et al.*, 2022). To tackle these challenges, effective resource allocation mechanisms should be implemented in edge computing systems to maximise the utilisation of channels and minimise collisions (Dai *et al.*, 2021). Additionally, the integration of permissioned blockchain technology with edge computing could enhance the security of IoT systems and ensure their trustworthiness (Dantas Silva *et al.*, 2021). In summary, careful consideration and implementation of security measures are of utmost importance to mitigate the risks associated with edge computing and safeguard the integrity of IoT networks.

While the capabilities of IoT on the network's edge were irrefutable, the journey to its smooth and protected incorporation was troubled with obstacles. Navigating this digital age would have required a careful balance between functionality, efficacy, and protection.

1.4 The Distributed Denial of Service (DDoS) attacks of IoT

The evolution of the Internet of Things (IoT) has brought numerous conveniences and opportunities. However, it has also exposed vulnerabilities in the digital realm, as demonstrated by the 2016 Mirai botnet intrusion, commonly known as the Dyn Cyber Attack. During this incident, malicious actors compromised over 400,000 IoT devices, highlighting the extent of the security risks associated with these devices (Benlloch-Caballero *et al.*, 2023). This botnet had been engineered to target vulnerable devices, delivering a staggering 1.1 Terabytes Per Second (Tbps) of traffic aimed at the internet services provider OVH. The attackers took advantage of ports 23 and 223 through brute force access. Once they seized the devices, they initiated a mass of General Routing Encapsulation (GRE) flood attacks, employing Transfer Control Protocol (TCP) and Hypertext Transfer Protocol (HTTP) to weaken the services (Mendez Mena & Yang, 2020).

The report by HP Security revealed that 80% of IoT devices had weak security credentials, while

70% exhibited vulnerabilities during authentication (Shah *et al.*, 2022). This highlights the persistent weaknesses in IoT security and the need for more robust measures to protect these devices (Vaezi *et al.*, 2022). Weak security credentials and authentication vulnerabilities make IoT devices susceptible to attacks and compromise the overall security of IoT networks (Touqeer *et al.*, 2021). These findings emphasise the importance of implementing robust security measures, such as solid authentication protocols and secure credential management, to mitigate the risks associated with IoT devices (Wang *et al.*, 2021). By addressing these vulnerabilities, the security of IoT devices can be significantly enhanced, ensuring the integrity and confidentiality of IoT data and protecting against potential cyberattacks (Mendez Mena & Yang, 2020).

Software-Defined Networks (SDN) have shown promise in enhancing network robustness by providing increased control and flexibility by segmenting the network into three layers (Nandhakumar & Arunkumar, 2023). However, SDN is not immune to Distributed Denial of Service (DDoS) attacks. These attacks can still threaten SDN systems, compromising their performance and availability (Rugeles Uribe *et al.*, 2022). SDN-based IoT networks are vulnerable to DDoS attacks due to the vulnerabilities present in IoT devices. Various techniques have been proposed to mitigate these attacks. These include tracking packets by IP address, using entropy for detection, employing statistical tools like the Sequential Probability Ratio Test (SPRT), implementing strategies like the "Multislot" approach, and utilising users' trust levels. Machine learning algorithms have also been employed for detection and mitigation. These techniques aim to detect and block DDoS attacks in SDN-based IoT networks, improving their security and resilience (Hussein *et al.*, 2022; Mangla *et al.*, 2023; Moura & Hutchison, 2020; Wang *et al.*, 2021).

The challenges of implementing SDN without a hitch and pinpointing malicious packets flowing through the network persisted. SDN brought automation and flexibility to network programming but also introduced security challenges. Centralised control in SDN makes the network more susceptible to mistakes, misuse, and DoS attacks, impacting network survivability (Rahman *et al.*, 2023). Additionally, the migration from a physical to a virtualised environment in SDN raised concerns about a need for more commercial experience in virtualisation and potential unauthorised behaviour exhibited by SDN applications (Rafique *et al.*, 2020). Solutions such as Intrusion Detection System (IDS)-based security mechanisms, blockchain-based SDN, and custom security applications in as SDN have been proposed to address these challenges (Meng *et al.*, 2021). These solutions leverage SDN's programmability, centralised traffic management,

and VLAN ID capabilities to detect and mitigate malicious traffic, protect data during transmission, and ensure trust and authentication between edge nodes and end devices (Eliyan & Di Pietro, 2021).

The Proof of Work (PoW) consensus method is a widely used algorithm in blockchain systems, including Bitcoin. It involves participants solving computationally costly puzzles to add new blocks to the blockchain. PoW ensures the blocks are tamper-proof and prevents malicious participants from corrupting the chain. However, PoW requires significant computational power, making it impractical for resource-constrained IoT networks (Qureshi *et al.*, 2022). In IoT applications with limited computational capabilities, alternative consensus algorithms such as Proof of Stake (PoS) and delegated PoS (DPoS) are more suitable. These algorithms do not require specialised hardware and rely on participants staking their wealth to validate transactions and achieve consensus (Ma & Fan, 2022). Therefore, while PoW is effective in traditional blockchain systems, it could be better for IoT networks due to their unique constraints.

While PoW, PoS, and DPoS provide security and decentralization, they do not inherently address DDoS attacks or Delay-Tolerant Networking (DTN) directly. To mitigate DDoS attacks in IoT networks, implementing rate-limiting algorithms and edge computing can be more effective. Rate limiting helps control the traffic load on the network, preventing overwhelming bursts of malicious traffic typical in DDoS attacks (Nandhini *et al.,* 2023). Edge computing brings computation and data storage closer to the data source, reducing latency and providing real-time processing, which is crucial for delay-tolerant networking (Thondebhavi Shanthakumar *et al.,* 2023). By distributing computational tasks across the edge of the network, the system can better handle disruptions and maintain service availability despite network delays (Saxena *et al.,* 2023).

In summary, while PoW, PoS, and DPoS are essential for achieving consensus in blockchain networks, IoT networks facing DDoS threats and requiring delay tolerance benefit more from rate limiting and edge computing solutions. These approaches enhance network resilience and ensure continuous operation despite attacks or connectivity issues.

The advancement of IoT technology has brought about numerous challenges and tasks that need to be addressed. Chintalapudi (2018) Highlighted that in Table 1-1, one of the most prevalent threats in IoT systems was the DoS attack, which affects all infrastructure tiers. This emphasised

the critical need for solid security strategies. Achieving a developed and secure IoT framework requires continuous efforts, innovative solutions, and collaboration across different sectors (Hua *et al.*, 2023; Omolara *et al.*, 2022; Raj & Shetty, 2022). It was essential to prioritise implementing fortified security measures to protect IoT systems from potential attacks and ensure the privacy and integrity of data. Challenges could be overcome by adopting a proactive approach, and a safer environment for thriving IoT technologies could be created.

Table 1-1: Threats in IoT (Chintalapudi, 2018)

Layer	Main Threats
Application Level	Data leakage
	DDoS Attacks
	Code injection
Transport Level	Routing Attacks
	DDoS Attacks
	Data Transit Attacks
Perception Level	Physical Attacks
	Impersonation
	DDoS Attacks
	Routing Attacks (WSN
	Data Transit Attacks

1.5 Background to the Research Problem

The emergence of the Narrowband Internet of Things (NB-IoT) originated in developing and applying Radio Frequency Identification (RFID) technologies Figure 1-2. Machine-to-machine (M2M) communication created the basis for technologies like the Narrowband Internet of Things (NB-IoT), which connected IoT devices and improved communication. NB-IoT does not prevent long-distance communication at high data rates, so it is suitable for applications such as healthcare monitoring systems. This technology reduces device processing complexity and prolongs battery life, making it highly favourable for remote monitoring scenarios (Muteba *et al.*,

2021)

RFID technology has been widely adopted across various sectors, showcasing its adaptability and versatility, as seen in Figure 1-2. In human-computer interactions, RFID has been integrated into systems for gesture recognition, enabling more intuitive interfaces (Hayyolalam *et al.*, 2022). Incorporating RFID for patient monitoring has significantly enhanced patient safety and streamlined hospital procedures (Dantas Silva *et al.*, 2021). The transportation and logistics sectors have also benefited from RFID, particularly with the implementation of intelligent toll systems. These systems have facilitated smooth vehicular transit and effective toll collection (Moura & Hutchison, 2020).

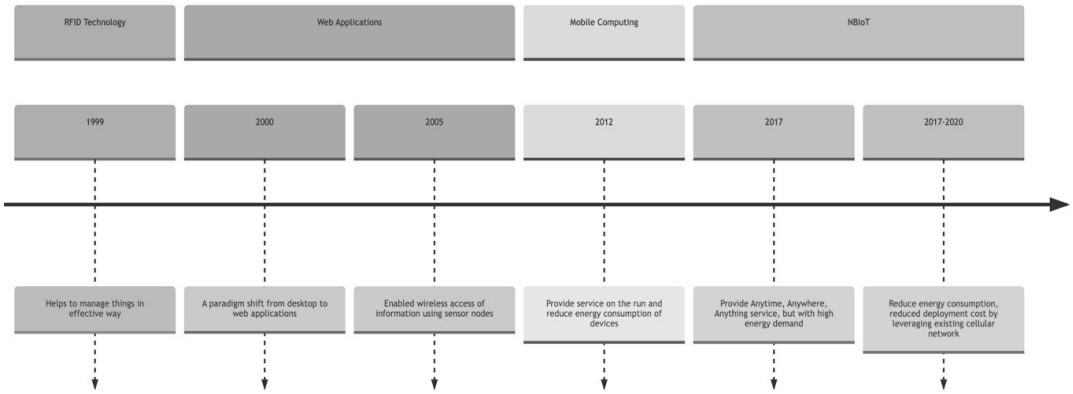

Figure 1-2: Roadmap of NB-IoT (Popli *et al.*, 2019)

1.6 IoT Network Architecture

The Internet of Things (IoT) is structured into several layers, each serving a specific purpose in facilitating data exchange and smooth operations. The architectural design of IoT consists of five primary layers: Perception, Network, Service Management, Application, and Business. The Perception layer collects and processes data from sensors and smart devices (Tariq *et al.*, 2023). The Network layer focuses on data transmission between devices and the IoT cloud platform (Chatterjee & Ahmed, 2022). The Service Management layer handles the management and coordination of IoT services. The application layer connects the network to users, analysing and processing sensor information to provide services based on user needs (Mansour *et al.*, 2023). Finally, the Business layer deals with integrating IoT into business processes and strategies. Each

layer played a crucial role in the overall functionality and success of the IoT framework.

1.6.1 Perception Layer

Positioned as the base layer of the IoT structure, the Perception Layer is tasked with collecting initial data and interfacing it with the physical environment. It keeps sensors and actuators responsible for sensing environmental variations and producing electronic signals corresponding to these changes. Technologies vital to this layer are the Global Positioning System (GPS), wireless sensor networks (WSN), and RFID. The data produced at this stage is relayed to the Network Layer through gateways. It is essential to understand this layer's vulnerabilities, including risks like signal disruption, interference, and falsification (Bilal *et al.,* 2022).

1.6.2 Network Layer

Acting as the primary channel for data relay, the Network Layer is responsible for transferring information from the Perception Layer onwards. This layer utilises network protocols such as Internet Protocol version 6 (IPv6), Internet Protocol version 4 (IPv4), and 6LoWPAN to ensure data movement. Beyond mere transmission, this layer also directs information towards the Service Management layer. Regarding security, challenges such as falsification, DDoS attacks, and bandwidth misrepresentation remain (Elejla *et al.,* 2022).

1.6.3 Service Management Layer

Often labelled the central hub of the IoT application interface, the Service Management Layer interacts with middleware technologies. It processes incoming data and manages the services based on the acquired IP addresses. Managing data and orchestrating information exchanges are vital at this level (Zhang *et al.,* 2020).

1.6.4 Application Layer

The Application Layer delivers services tailored to user-specific needs. This layer addresses user requirements by employing messaging protocols like Message Queuing Telemetry Transport (MQTT) and Constrained Application Protocol (CoAP), ensuring adequate data communication and service provisioning (Gupta & M, 2021).

1.6.5 Business Layer

Located at the pinnacle of the IoT architecture, the Business Layer focuses on advanced data analytics and interpretation. It processes insights derived from the Application Layer. Data confidentiality is crucial due to the strategic decision-making originating from this layer. Guaranteeing user privacy is paramount, especially in scenarios with limited human involvement (Firouzi *et al.,* 2022).

The multilayered architecture of IoT provided a systematic and modular approach to initiating and functioning IoT systems. Each layer in the architecture has unique capabilities that contribute to the system's overall functionality, allowing for the full realisation of IoT's potential.

1.7 Research problem

The rapid growth of the Internet of Things (IoT) has transformed industries and individual experiences. However, this growth has also brought numerous security challenges threatening user privacy, data integrity and service availability (Athira Anil et al., 2023). The security mechanisms currently deployed in IoT environments must be revised and often proprietary, leading to global security mechanisms with known trust anchors (Islam & Aktheruzzaman, 2020; Ayoub *et al.*, 2023). Moreover, the constrained nature of IoT devices limits their ability to implement robust security mechanisms, making it challenging to ensure secure communications and guarantee privacy (Sharma *et al.*, 2021). The massive amounts of sensitive data that pass through IoT networks, coupled with the diverse applications of IoT, increase the risk of security breaches (Savic *et al.*, 2021). To address these challenges, the use of Domain Name System (DNS) and its security extensions and protocols, such as DNSSEC, DNS over Transport-Layer Security (TLS) (DoT), and DNS over HTTP (DoH), could significantly improve the security of IoT communications (Tange *et al.*, 2020). However, adopting these security measures still needs to be more widespread (Macedo *et al.*, 2019).

The Distributed Denial of Service (DDoS) attack is a notorious and impactful threat that leverages network layer protocols to flood targets with malicious packets, consuming the target's bandwidth. In addition to network layer attacks, application layer DDoS attacks focus on depleting the computing resources of target devices. These attacks aim to overwhelm the target's resources by

sending a large volume of legitimate traffic, making it difficult for the device to handle legitimate requests. The attacker can render the device unresponsive or slow by consuming computing resources, such as the Central Processing Unit (CPU) and memory. These application layer attacks pose a significant challenge for defending against DDoS attacks, as they can bypass traditional network-based defenses and require specialised mitigation techniques (Omolara *et al.*, 2022).

The unpredictability of IoT devices from various vendors with unique designs and specifications poses a challenge in developing a one-size-fits-all security solution (Wijethilaka & Liyanage, 2021). With different devices running on different circuitry, using diverse protocols, and using various data processing algorithms, it was challenging to implement robust security mechanisms (Macedo *et al.*, 2019). IoT devices limited computational and storage capacities also restrict the implementation of complex security protocols, requiring lightweight and efficient solutions (Abbood *et al.*, 2020). The lack of standardised protocols and ad hoc network architectures further intensified the security vulnerabilities in IoT ecosystems (Sharma *et al.*, 2020). Furthermore, the large-scale deployment of IoT devices without proper security measures, such as default credentials and lack of timely firmware updates, increased the exposure to attacks. Overall, the heterogeneity of IoT devices and the absence of standardised security frameworks made it challenging to provide comprehensive security solutions for the diverse IoT landscape (Ugwuanyi *et al.*, 2020).

The inherent nature of IoT demands data and command flow across its layered architecture. However, any application traffic within this framework is vulnerable. Threats like DDoS attacks could impede traffic, causing latency and delivery delays. Given these multi-layered issues, there is a pressing need for rigorous academic exploration to engineer a comprehensive security framework for the entire IoT ecosystem (Padhy *et al.*, 2023; Sutikno & Thalmann, 2022; Ozalp *et al.*, 2022; Raj & Shetty, 2022). Researchers have recognised the importance of addressing security concerns in each layer of the IoT architecture, including the physical layer, data layer, network layer, and application layer (Swamy & Kota, 2020).

One proposed approach is an encapsulation-aware traffic filtering mechanism that could efficiently analyse and filter IoT traffic without needing de-encapsulation. This mechanism allows for the classification of packets based on various packet fields and headers, addressing the mobility and

multitenancy requirements of virtualised 5G networks (Benlloch-Caballero *et al.*, 2023). Additionally, machine learning-based DDoS detection techniques are explored, utilising features extracted from IoT network traffic to detect and classify attacks (Lee *et al.*, 2022). Leveraging computational resources at the network's edge is also considered, enabling faster detection and mitigation of IoT-DDoS attacks (Bhardwaj *et al.*, 2018). These innovative strategies aim to bolster NB-IoT networks' resilience against DDoS attacks and ensure their robustness and reliability (Kamaldeep *et al.*, 2023).

1.8 Problem Statement

The increasing potency of Distributed Denial of Service (DDoS) attacks, particularly those targeting network layer protocols, has highlighted a significant vulnerability in Narrowband Internet of Things (NB-IoT) networks. Despite the rapid adoption of NB-IoT for various applications, there remains a gap in the literature concerning effective strategies for enhancing the resilience of these networks against cyber threats.

Current research in IoT security has not fully explored fault-tolerant network designs that leverage the decentralised processing capabilities of emerging technologies like Edge and Fog computing to address this vulnerability.

By integrating Edge computing, it is possible to create a distributed, fault-tolerant architecture that can dynamically counteract security threats. Such an architecture would aim to ensure service persistence and resilience even in the face of challenges, such as changes in external and internal conditions, device mobility, connection loss, and prolonged delays (Welsh & Benkhelifa, 2021).

Edge computing, by reducing latency and improving response times through localized data processing, presents a promising approach to enhance both the security and efficiency of NB-IoT networks (Swamy & Kota, 2020). The proximity of Edge computing resources to IoT devices allows for quicker decision-making and reduced dependency on centralised cloud infrastructures. This approach not only shortens data transfer times but also enables real-time processing, which is crucial for applications requiring low-latency communication, such as connected healthcare systems and industrial IoT environments (Mudassar, Zhai & Lejian 2022).

This research addresses the gap in IoT security by proposing a novel fault-tolerant network design

using Edge computing paradigms. This design seeks to enhance NB-IoT networks' resilience against DDoS attacks, thereby advancing the security and reliability of IoT systems in environments where rapid and secure data processing is critical.

1.9 Aim, Objectives, Research Questions

1.9.1 Aim of the Study

This research aims to design a fault-tolerant architecture to protect Narrowband Internet of Things (NB-IoT) networks against Distributed Denial of Service (DDoS) attacks.

1.9.2 Objectives

From the main aim, several specific objectives emerge, namely:

I. To identify current challenges of low-cost NB-IoT applications.
II. To identify the transmission latency of NB-IoT real-time applications and various parameters.
III. To design a narrow-band IoT delay-tolerant network (NB-IoTDTN) to mitigate DDOS network-based attacks.
IV. To evaluate the reliability and performance of the networking layer of the NB-IoT DTN architecture.

1.9.3 Main Research Question

How can a delay-tolerant narrowband IoT (NB-IoT) network be designed to mitigate Distributed Denial of Service (DDOS) attacks?

1.9.4 Sub-research Questions

I. What are the current delays of low-cost IoT applications on NB-IoT networks?
II. What parameters have impact on reducing the transmission delay of NB-IoT real-time applications??
III. How can a delay-tolerant network architecture be designed for NB-IoT to mitigate DDOS network-based attacks?

IV. How can the reliability and performance of the network layer be improved in the NB-IoT architecture?

This approach provides a comprehensive roadmap to understanding, designing, and enhancing the security infrastructure for NB-IoT networks.

1.10 Purpose and Significance of the Study

In the fast-changing digital world, the Internet of Things (IoT) is a crucial driver of change, leading us towards a future of more excellent connectivity and automation. However, this growth increases risks, especially from Distributed Denial of Service (DDoS) attacks. Tackling these issues is crucial for keeping IoT devices reliable, building trust with users, protecting their data, and moving towards a harmonious digital future. This study aims to explore these themes in a clear and meaningful way.

The aim and significance of this research are explained as follows:

- **Enhanced Security with Efficient Algorithms**: This study tackles the challenge of DDoS attacks on IoT devices, especially those with limited computing power. By using algorithms that require fewer computing resources, the research aims to strengthen these devices against such attacks, ensuring data safety and device reliability, thereby contributing to a more secure IoT environment.
- **Combating Denial of Service Attacks**: Denial of service attacks, particularly those exploiting memory through large packet deliveries, threaten IoT networks. This research focuses on identifying and mitigating the vulnerabilities these attacks target, aiming to lessen their frequency and impact. The goal is to maintain smooth operations and protect the critical services that many sectors rely on.
- **Layered Approach for Diagnosing Faults**: The IoT's layered architecture is used strategically to diagnose and fix faults. By isolating faults in the network layer, targeted solutions can be applied. This method improves the resilience of the IoT ecosystem, ensuring quick recovery from faults and consistent service.
- **Securing Network Layer Packets**: Protecting the valuable information in each network packet is vital. This research addresses the risk of adversaries intercepting these packets

by implementing rate limiting to prevent unauthorised packet inspection. This secures data and enhances data transfer efficiency, improving IoT network performance.

In summary, this study aims to adopt a secure, reliable, and efficient IoT framework, aligning with the vision of an IoT landscape marked by trust, efficiency, and resilience. The research creates a robust IoT environment by tackling these challenges and leveraging the IoT's layered architecture.

1.11 Delineation of the research

1.11.1 Central Focus

This study explores fault-tolerance in networks, specifically emphasising utilising Fog and Edge computing to secure against DDoS attacks in the IoT landscape. The research primarily focuses on the network layer of IoT, which serves as the primary layer for the experimental study and analyses. This allows for an in-depth examination of network-related challenges within the vast IoT framework.

1.11.2 Key Constraints

While IoT encompasses various layers, the research focuses on the network layer. Issues pertinent to other layers, such as perception or application, fall outside the scope of this study. The investigation is confined to in-band mode regarding Narrow-Band IoT (NB-IoT) deployment methods. While NB-IoT can be integrated into multiple modes, the research examines the in-band deployment mode. Recognising the complexity of real-world IoT nodes, the study uses simplified nodes equipped only with essential functionalities. This ensures that the study’s testbed focus is manageable and reproducible.

By defining these boundaries, the research ensures targeted and concentrated exploration within specific areas, promoting thoroughness and accuracy. Readers need to understand these limits to contextualise the findings appropriately. While the insights gained are significant, they should be interpreted within the study's specific focus and constraints.

Although IoT and its security challenges are vast, this research deliberately navigates specific areas. The study aims to uncover deep insights into DDoS threats and the reinforcing capabilities of Fog and Edge computing within the context of the NB-IoT network layer.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Chapter 2 discusses the systematic review that guides the research and the objectives, and it is organised as seen below.

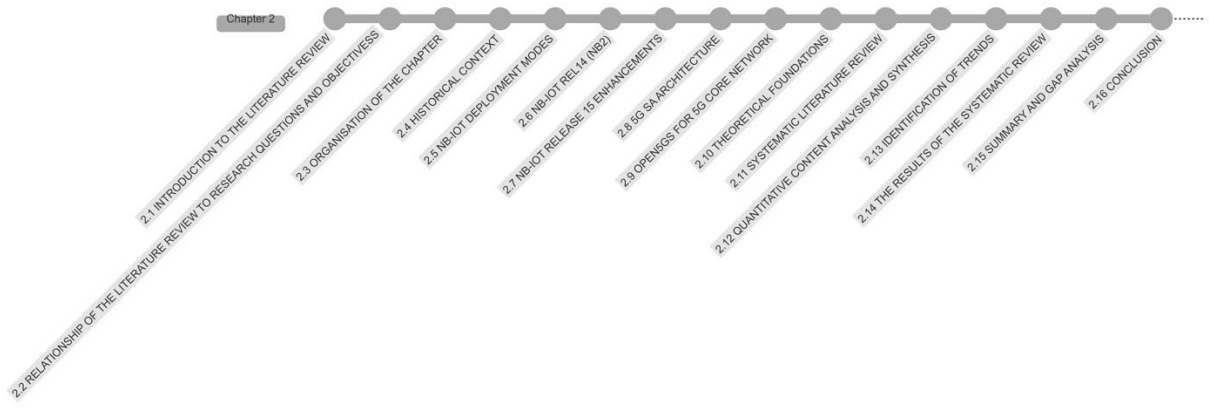

Figure 2-1: Chapter 2 Layout

The Literature Review chapter begins with an Introduction to the Literature Review, which outlines the scope and objectives of the chapter. It examines the Relationship of the Literature Review to Research Questions and Objectives, providing context for the research. The chapter then explains the Organisation of the Chapter and presents a Historical Context of the topics covered.

The review delves into NB-IoT Deployment Modes, detailing the evolution through NB-IoT Rel14 (NB2) and further enhancements with NB-IoT Release 15 Enhancements. It discusses 5G SA Architecture and its role in advancing connectivity, followed by an exploration of Open5GS for 5G Core Network, highlighting its open-source implementation for 5G networks.

The chapter presents Theoretical Foundations relevant to the research, followed by a Systematic Literature Review that synthesises existing studies. It includes Quantitative Content Analysis and Synthesis, leading to an Identification of Trends in the field. The Results of the Systematic Review provide insights into emerging patterns, while the Summary and Gap Analysis discusses key findings and areas where further research is needed. The chapter concludes with a Conclusion

that wraps up the main points discussed.

The literature review serves as a fundamental component of academic research, mapping the knowledge pertinent to fog and edge computing in the context of IoT security. Its primary role is to systematically connect empirical research conducted by previous scholars, forming a continuum of scholarly understanding. This endeavour critically analyses and synthesises existing studies, findings, and theoretical frameworks rather than merely aggregating previous work.

The literature review focuses on designing fault-tolerant networks using fog and edge computing for IoT security. It methodically examines how previous studies approach the intricacies of network design, addressing challenges and proposing solutions within the IoT security paradigm. By reviewing the literature, the study identifies patterns, themes, and gaps in the research, thereby contextualising current understanding within a broader academic landscape.

Central to this review is exploring fog and edge computing dynamics and their role in enhancing IoT network security. It involves critically evaluating the methodologies employed in previous studies, their findings, and the theoretical underpinnings that inform them. This analysis identifies the strengths and limitations of existing approaches, offering insights into areas ripe for further investigation.

The literature review thus acts as a scholarly inquiry into the state of research in IoT security. It highlights vital contributions while noting areas warranting further exploration. Through this rigorous examination, the review aims to contribute to the academic discourse by summarising existing knowledge and setting the stage for future research endeavours in this evolving field.

2.1.1 Purpose of the Literature Review

This study's literature review critically examines and synthesises previous research on fog and edge computing within the framework of IoT security. It goes beyond merely collecting existing studies, aiming to achieve several vital objectives through thorough literature analysis.

Firstly, the review identifies gaps in existing knowledge by mapping out the current research landscape. This process highlights underexplored areas or conflicting viewpoints, revealing further investigation and exploration opportunities. Addressing these gaps ensures that the study tackles

relevant questions and challenges, contributing to filling the identified gaps in the field.

Secondly, the review provides context for the present research. In the rapidly evolving domain of IoT security, understanding the historical progression of ideas, technological advancements, and methodological approaches is essential. This contextual understanding grounds the study in a rich tapestry of scholarly work, ensuring its contributions are both relevant and timely.

Lastly, the review positions the current research within the broader academic dialogue. Understanding how this research intersects with and contributes to ongoing discourse in the field involves aligning the study's objectives and findings with existing theories, debates, and empirical evidence. This situates the research within the continuum of academic scholarship.

Thus, the literature review serves as a foundational pillar for the research, ensuring that the inquiry is deeply rooted in and contributes to the collective intellectual pursuit of the academic community. It acts as a bridge, connecting the study to the vast world of scholarly knowledge and dialogue.

2.1.2 Significance of the Literature Review

The literature review isn't just an academic box to tick; it’s a symbol of the depth and rigour of the research process. It's a cornerstone of scholarly work and a crucial tool that enriches and guides the research journey. Its importance is multifaceted, touching on many aspects of the research endeavour.

Primarily, the literature review helps gather historical and modern perspectives on the topic. It provides a broad view of the subject, showing how thoughts, technologies, and methods have evolved. This big-picture view is essential for placing the current research into the wider field context, ensuring the study is well-grounded in established academic work.

The literature review also acts as a guide, steering the research away from thoroughly explored areas and towards new or emerging topics. This direction is vital to keeping the research original and relevant and ensuring it offers fresh insights or innovative approaches.

Moreover, the literature review lays out a clear and thoughtful path through the complex landscape of academic literature. It showcases the thoroughness and care put into the research, providing

clarity and depth for anyone delving into its contents.

2.2 Relationship of the Literature Review to Research Questions and Objectives

In this scholarly endeavour, the literature review goes beyond the confines of a standard academic assignment. Instead of merely summarising existing studies, it plays a vital role in shaping the research direction. The review is a foundational framework guided by the research questions and objectives.

a) Informing and Refining Research Questions

The literature review is crucial in shaping and refining the research questions. By analysing existing information and identifying gaps in the current understanding of fog and edge computing in IoT security, the review helps develop precise and relevant research questions. It allows the researcher to focus on specific aspects within the broader topic that are ripe for exploration, ensuring that the research questions are both meaningful and valuable.

b) Guiding Research Objectives

The insights obtained from the literature review influence the research objectives. The review guides the study, identifying essential themes and areas that need further research. This thorough understanding of the existing field helps shape the objectives to address gaps and fulfil the academic goal of advancing knowledge and understanding of IoT security.

The literature review lays the groundwork for the research questions and objectives. It ensures that the study is not isolated but makes a well-integrated contribution to the existing body of knowledge. By connecting past research with current inquiries, the review serves as a bridge, setting the stage for meaningful and impactful scholarly work.

2.2.1 Connection to Research Questions to Study Objectives

Connecting the research questions directly to the study's objectives ensures coherence and alignment. Each objective corresponds to a specific research question, allowing for a targeted and systematic approach to the investigation.

Objective i: Identifying Challenges in Low-Cost NB-IoT Applications

- **Related Research Question**: "What are the current delays of low-cost IoT applications on NB-IoT networks?"

This objective focuses on understanding the operational challenges in low-cost NB-IoT applications, particularly delays. The study aims to pinpoint specific hurdles and inefficiencies in NB-IoT by answering this research question.

Objective ii: Assessing Transmission Latency in NB-IoT Real-Time Applications

- Related Research Question: " What parameters have impact on reducing the transmission delay of NB-IoT real-time applications?

This objective aims to identify key parameters that impact transmission latency in real-time applications. The corresponding research question seeks to uncover specific factors that, when measured and optimised, can significantly reduce delays, enhancing network performance.

Objective iii: Designing an NB-IoT Delay-Tolerant Network (NB-IoTDTN) to Mitigate DDoS Attacks

- **Related Research Question:** "How can a delay-tolerant network architecture be designed for NB-IoT to mitigate DDoS network-based attacks?"

This objective is focused on designing a network architecture resilient to DDoS attacks. The research question aligns with this goal by exploring the design aspects of such a network and examining how a delay-tolerant approach can help mitigate cybersecurity threats.

Objective iv: Evaluating the Reliability and Performance of the Networking Layer in NB-IoT

- **Related Research Question:** "How can the reliability and performance of the network layer be improved in the NB-IoT architecture?"

This objective aims to assess and enhance the reliability and performance of the NB-IoT's networking layer. The research question investigates strategies and methodologies to improve these aspects, ensuring a robust and efficient NB-IoT network.

By aligning each research question with a specific objective, the study ensures a focused investigation that systematically addresses each aspect of the overarching aim. This alignment reinforces the relevance of each research question and streamlines the process of data collection, analysis, and interpretation within the context of the study's goals.

2.3 Organisation of the Chapter

This chapter provides a comprehensive literature review that systematically examines the existing research relevant to this study. The chapter begins with an exploration of the foundational concepts and historical evolution of the Internet of Things (IoT) and Narrowband IoT (NB-IoT), highlighting the growing significance of NB-IoT in contemporary technological landscapes (Salva-Garcia et al., 2018; Guo et al., 2019; Macedo et al., 2019). Following this, the chapter addresses the vulnerabilities inherent in IoT systems, particularly focusing on security challenges such as Distributed Denial of Service (DDoS) attacks, which continue to pose significant threats to IoT networks (Bhardwaj et al., 2018; Gaurav et al., 2021).

The discussion then shifts to the roles of Fog and Edge computing in enhancing IoT functionalities. Emphasis is placed on how these paradigms can improve response times and strengthen network security by processing data closer to the source (Dai et al., 2021; Fazeldehkordi & Grønli, 2022). Finally, the chapter reviews various strategies and methodologies currently employed to safeguard IoT networks against security threats, assessing their strengths, limitations, and areas of application (Ahmad et al., 2019; Chatterjee & Ahmed, 2022; Tariq et al., 2023). This structured approach ensures a coherent narrative that situates the research within the broader field of IoT security and highlights the importance of fault-tolerant architectures in addressing these challenges.

Based on the reviewed literature, each theme identified the existing knowledge gaps, highlighting areas that deserve further evaluation. It also defines how the current study seeks to address these gaps. A concise review of the chapter's key insights and findings prepares for the subsequent chapters and a deeper dive into the research methodology and results.

The chapter balances theoretical frameworks, empirical findings, and critical evaluations. Each segment builds upon the previous one, creating a logical progression that enables understanding and aids in understanding knowledge.

The Conceptual framework in chapter four, operates as a guiding lens in the context of literature review, clarifying how past researchers approached similar challenges. By delineating the research into these structured components, it becomes feasible to dissect existing literature based on specific elements of the framework. For instance, studies on Edge and fog computing paradigms can be reviewed under the 'Input' phase, while research focusing on IoT vulnerabilities might be situated under the 'Transformation' phase.

This approach ensures a systematic review of the literature but also aids in identifying gaps in previous studies. Understanding where past researchers concentrated their efforts and where they might have been overlooked or underexplored becomes transparent. Such insights are invaluable, as they steer this research towards areas that can significantly contribute to the existing knowledge.

2.4 Historical Context

The historical context has profoundly shaped the current state of research in the field of the Internet of Things (IoT) and Narrowband IoT (NB-IoT) (Wang *et al.*, 2021). Early scholars and researchers initially explored fundamental concepts of connectivity and postulated initial theories that would pave the way for future technological advancements (Piccialli & Jeon, 2021). These research pioneers provide the rudimentary frameworks that subsequent generations of academics and industry professionals would elaborate on.

As technology progresses, so does the complexity and scope of research. Discoveries in telecommunications and data processing, alongside the proliferation of digital devices, catalysed a paradigm shift in how connectivity was understood and implemented (Koufos *et al.*, 2021). Researchers built upon the early theoretical underpinnings using analytical tools and methodologies (Umunnakwe *et al.*, 2022). This evolution is marked by transitioning from basic wired connections to the intricate wireless networks observed today, encompassing vast arrays of global interconnected devices.

The introduction of NB-IoT further refined the concept of IoT, offering a solution tailored to the burgeoning demand for low-power, wide-area network connectivity (Murtala Zungeru *et al.*, 2020). Research in this area continues to be informed by the historical trajectory of technological innovation and academic inquiry, reflecting a confluence of past insights and contemporary breakthroughs.

This historical context is not merely a backdrop for current research but a critical component that informs its direction. Within this continuum, the present study on NB-IoT and its security against DDoS attacks situates itself, drawing from a rich heritage of inquiry and innovation to address the challenges and opportunities of the modern digital landscape.

2.5 NB-IOT Deployment Modes

Narrowband Internet of Things (NB-IoT), a Low-Power Wide-Area Network (LPWAN) standard, supports IoT applications over cellular networks, emphasising low power consumption and broad coverage. NB-IoT can be deployed in three main modes, as illustrated in Figure 2-2: In-Band, Guard Band, and Standalone.

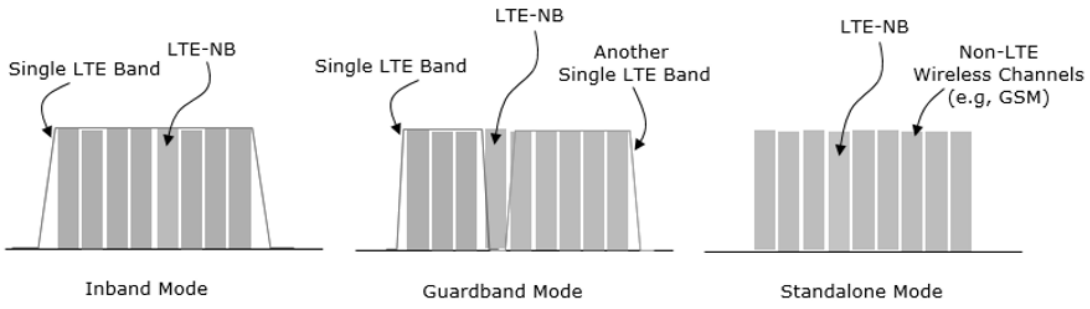

Figure 2-2: The Three Modes of NB-IoT Deployment

I. **In-Band Deployment:** Integrates NB-IoT within existing LTE bands, allowing efficient use of cellular infrastructure without needing additional spectrum. Experimental studies conducted in urban environments yield valuable insights into the deployment scenarios of NB-IoT. These studies indicate that the standalone deployment mode offers optimal performance regarding radio coverage, network capacity, and user experience (Turzhanova *et al.*, 2022).

II. **Guard Band Deployment:** Utilises unused LTE spectrum guard bands, which reduces interference and supports additional IoT connectivity while leveraging existing LTE infrastructure. Studies show that guard-band and in-band modes are viable options. However, certain conditions and applications may prefer one mode over the other. In some network configurations, guard-band mode offers more reliable performance. Additionally, increasing the number of repetitions enhances the performance of the NB-IoT system (Ahmad & Razak, 2019).

III. **Standalone Deployment:** Dedicates a separate spectrum for NB-IoT, independent of LTE, offering improved performance but at a higher cost due to separate infrastructure requirements. Standalone deployment is less common but is used by some providers to offer dedicated IoT services. These strategies highlight the diverse approaches to integrating NB-IoT into existing telecommunications ecosystems, balancing coverage, efficiency, and market needs.

The deployment strategies of key NB-IoT providers indicate a preference for leveraging existing LTE infrastructure through in-band and guard-band deployments, as shown in Table 2-1.

Table 2-1: NB-IoT Deployment Models of Various Providers

Provider	Deployment mode(s)	Focus area
Vodafone	In-Band	Utilises existing LTE network for widespread NB-IoT coverage.
China Mobile	Standalone, In-band	Aims for extensive coverage for a range of IoT applications.
Deutsche Telekom	In-Band, Guard Band	Ensures compatibility and efficiency within its European LTE network.
AT&T	In-Band	Provides comprehensive IoT connectivity options in the US.
Telefonica	In-Band, Guard Band	Enhances IoT offerings without additional spectrum allocations.
China Unicorn	Standalone, In-Band	Focuses on maximizing coverage and service quality in China.
T Mobile	In-Band	Leverages existing network for IoT applications in the US and Europe.
Orange	In-Band, Guard Band	Targets smart city and industrial applications in Europe and Africa.
Telstra	In-Band	Aims for nationwide IoT connectivity in Australia.
Singtel	In-Band	Focuses on smart nation projects and industrial IoT in Singapore.

2.6 NB-IoT Rel14 (NB2)

Figure 2-3 illustrates that in the 1980s, 1G focuses primarily on voice communication and human-to-human interaction. The 1990s brought 2G, introducing data services like messaging and global roaming. Around the 2000s, 3G emerged as an era of telemetry, involving automatic measurement and wireless data transmission from remote sources. With the advent of 4G, the focus has shifted to always being connected, and cloud computing and streaming services have been introduced.

Additionally, advancements such as LTE-M and NB-IoT are mentioned. Looking towards the future, 5G aims to provide enhanced mobile broadband and critical communication while also being associated with the Internet of Things (IoT) era, which is expected to occur around 2025. Each generation is depicted as an ascending step, symbolising progressive improvement and increased capabilities.

The 5G step is highlighted at the top, suggesting a future direction with technologies like LTE-M (Long-Term Evolution for Machines) and NB-IoT (Narrowband Internet of Things), both specifically designed for IoT applications. Therefore, this study focuses on the 5G network.

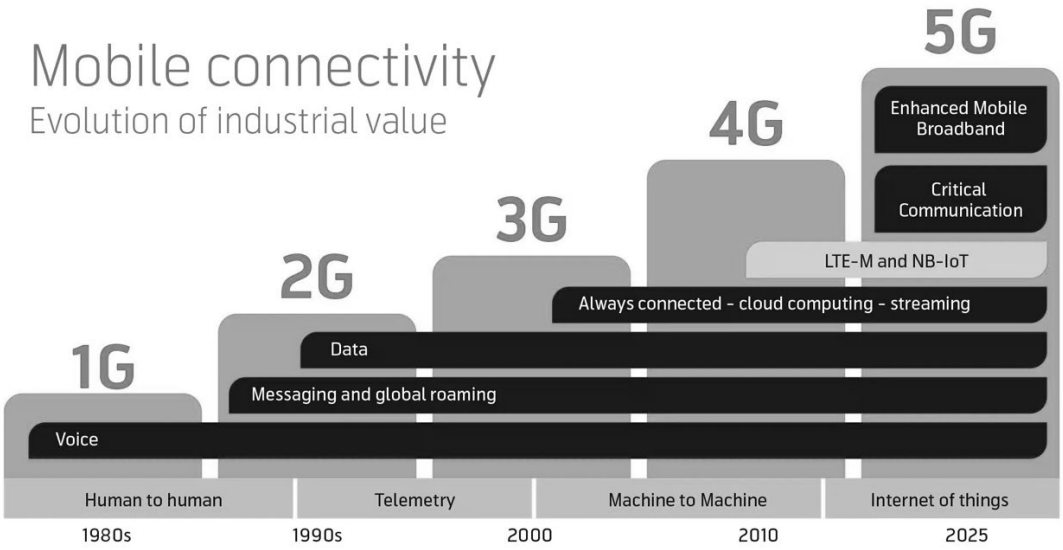

Figure 2-3: Evolution of IOT (Clark-Massera, 2024)

2.7 NB-IoT Release 15 Enhancements

Narrowband Internet of Things (NB-IoT) Release 15 introduces several advancements aimed at optimizing IoT networks for low power consumption, extended coverage, and greater efficiency. Key features include:

I. **Wake-up Signals (WUS)**: This feature reduces power usage by keeping devices in a low-power state until a signal is received, indicating a need to check for paging messages. This enhances battery life by minimizing unnecessary power consumption during idle periods, particularly for devices in Discontinuous Reception (DRX) or enhanced Discontinuous Reception (eDRX) modes (Lingala *et al.,*2022).

II. **Narrowband Physical Random Access Channel (NPRACH) Range Enhancement**: By extending coverage up to 120 kilometers (km), this feature supports communication over greater distances. It uses a new NPRACH format with a 1.25 kHz subcarrier spacing and frequency hopping to improve the reliability of long-range connections compared to the previous 40 km limit (Ravi *et al.,* 2019).

III. **Scheduling Request (SR)**: This feature improves the efficiency of uplink resource requests by allowing devices to signal their needs directly, using methods such as piggybacking Hybrid Automatic Repeat Request (HARQ) acknowledgments. This reduces power and resource overhead.

IV. **Reduced System Acquisition Time**: Devices can now acquire necessary system information more quickly, which shortens connection times and lowers power consumption, contributing to longer battery life. This improvement involves increasing repetitions of System Information Block Type 1 (SIB1-NB) transmissions.

V. **Battery Efficiency Security for low Throughput (BEST)**: This security enhancement provides efficient payload encryption suitable for low-throughput, battery-powered devices. It uses network-based symmetric cryptography based on the 3rd Generation Partnership Project Authentication and Key Agreement (3GPP AKA) protocol, which minimizes battery impact.

These optional enhancements allow for flexible implementation, enabling network operators and device manufacturers to adopt features based on specific deployment needs, thereby improving the overall utility and coverage of NB-IoT networks for diverse IoT applications.

2.8 5G SA Architecture

The New Generation Radio Access Network (NG-RAN), as shown in Figure 2-4, consists of multiple next-generation NodeBs (gNB) connected to the 5G core through an NG interface. This design allows the 5G core to provide several services to the user equipment (UE).

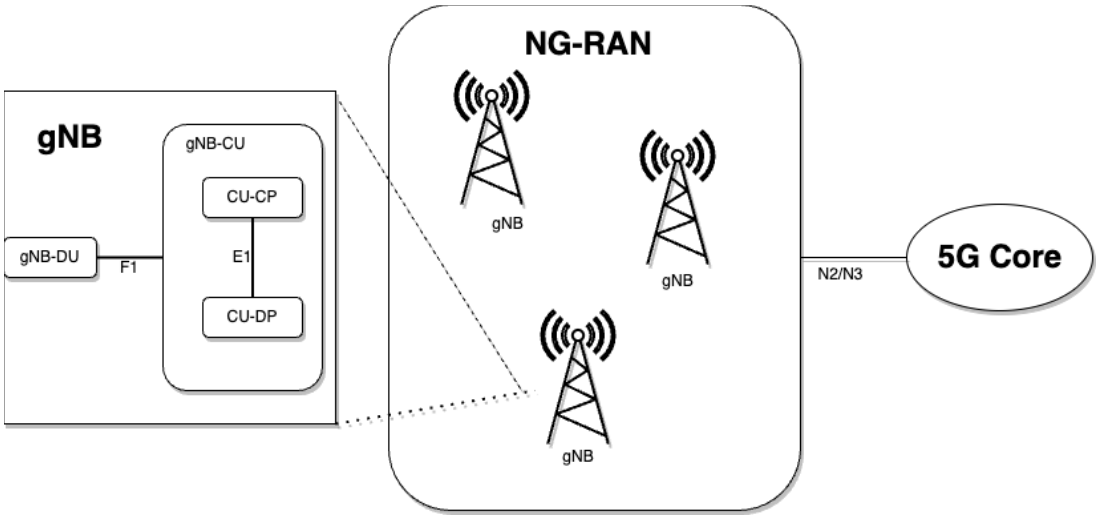

Figure 2-4: NG-RAN Architecture

In a 5G network, base stations known as next-generation NodeBs (gNBs) provide radio access and connectivity for User Equipment (UE), such as NB-IoT modules. The 5G Core manages data and internet connectivity for these devices, linked to the gNBs via the NG interface. Each gNB consists of a Distributed Unit (gNB-DU) for real-time radio signal processing and a Centralized Unit (gNB-CU), which handles both Control Plane (CU-CP) and User Plane (CU-DP) functions. Key interfaces include F1 (between DU and CU), E1 (within gNB-CU), and N2/N3, connecting the Next Generation Radio Access Network (NG-RAN) to the 5G Core for control and user plane interactions, respectively.

2.9 Open5GS for 5G Core Network

Open5GS introduces 5G core functionalities, allowing deployment of 5G services in Narrowband Internet of Things (NB-IoT) environments. It includes modules like the Access and Mobility Management Function (AMF), Session Management Function (SMF), and User Plane Function (UPF), which collectively manage data and connectivity for User Equipment (UE) as shown in Figure 2-4. While Open5GS supports most 5G functionalities, it requires supplementary tools like User Equipment Radio Access Network Simulator (UERANSIM) to fully integrate NB-IoT, enhancing testing and validation of 5G-enabled Internet of Things (IoT) networks (Dolente *et al.,* 2024).

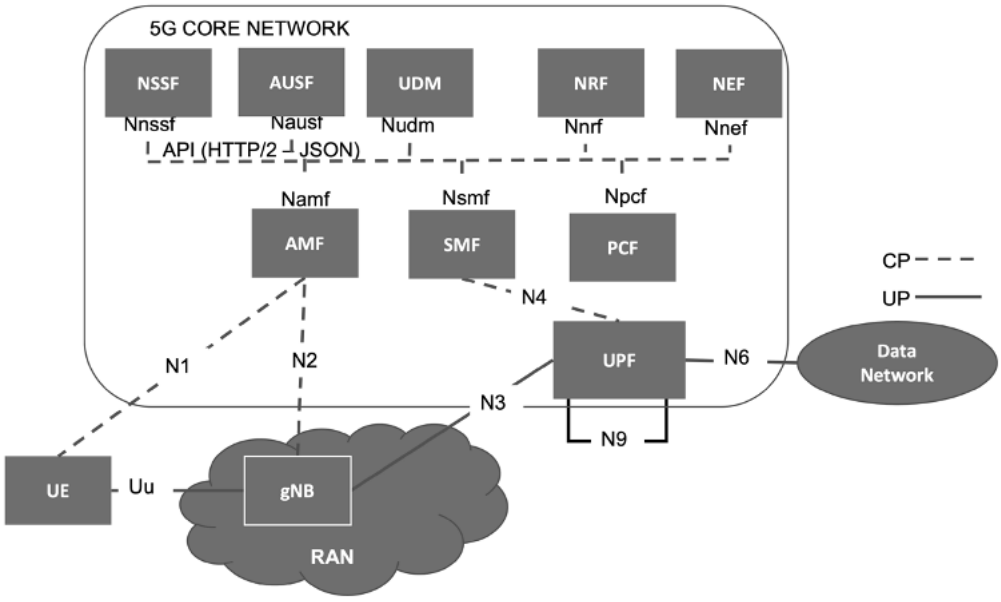

Figure 2-5: 5G System Architecture (Dolente et al., 2024)

2.10 Theoretical Foundations

The theoretical foundations of network communication and its associated vulnerabilities are based on a rich tapestry of established theories and models.

Cybernetics and information theory, for instance, provide fundamental insights into transmitting, controlling, and processing information across networks. These theories establish the conceptual groundwork for interpreting the flow of data and the systematic analysis of communication channels, which are crucial for understanding network vulnerabilities and securing communications (Bordel *et al.*, 2023; Jaafar *et al.*, 2023; Sahraneshin *et al.*, 2023).

Systems theory offers a holistic view, considering the network as an interdependent structure, where altering one component can have cascading effects on the entire system. This perspective is essential for exploring fault tolerance and network strength, especially in designing mechanisms to mitigate security threats like DDoS attacks (Shah, 2019; Zhao *et al.*, 2022; Gupta *et al.*, 2023).

Integrating these diverse theoretical approaches provides a strong foundation for researching and developing secure network architectures. As the field advances, it draws from these multi-layered theoretical foundations, adapting and evolving them to meet the demands of an increasingly connected and complex digital system.

2.10.1 Critical Theories and Models Explored

2.10.1.1 Information Theory

Information Theory is a field of study that provides insights into the quantification and transmission of information. Claude Shannon, a mathematician and electrical engineer, historically proposed it, introducing several fundamental concepts still widely used today. Among these concepts is entropy, which measures the unpredictability or randomness of information (Young, 2022). By applying these concepts, researchers and engineers can better understand and optimise information processing and communication systems.

Information Theory aims to simplify the interaction between different systems by abstracting complex interactions into the process of transferring information. This abstraction leads to a more concise and clear understanding of the problem. Information Theory describes the general laws

governing information transmission and processing. The conveyed message is seen as a mechanism for reducing uncertainty or negative entropy. In other words, the message carries information that increases the amount of knowledge and reduces the level of uncertainty. As seen in equation (5.13), Claude Shannon combined information with probability theory to make information quantifiable. The more random a string is, the higher its calculation of randomness (or rather “entropy”). This calculation is often called an entropy score (Jayasree and Amritha, 2015).

Shannon Entropy formula is given where H(X) is the entropy of a random variable X, and P() n is the number of values, and b is the base of the logarithm, often base 2, reflecting a binary context.

Shannon Entropy plays a fundamental role in understanding data compression in telecommunications, as shown in Figure 2-6. It helps determine the minimum number of bits required to encode symbols based on their occurrence probabilities (Gupta *et al.*, 2023). In cryptography, a system's entropy relates to its unpredictability and security. Higher entropy implies a more secure system, which is more resistant to brute-force attacks.

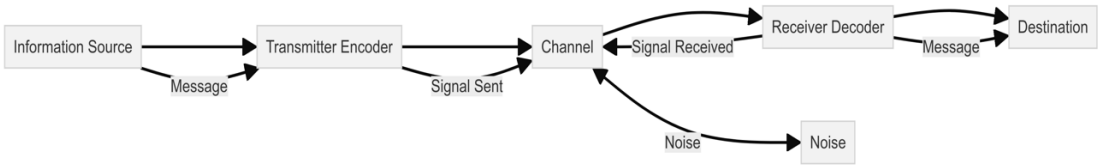

Figure 2-6: Information Theory Model of Communication (Shannon & Weaver, 1964)

These interferences (noise) can significantly impact the accuracy and reliability of received and used information. Regarding the conceptual model, the study applies the conceptual model using the Shannon and Weaver model (Figure 2-6) as a foundational theory for understanding information transmission and its challenges.

Input (I): By examining algorithms and theories that control the behaviour of IoT devices in the network.

Transformation (T): Study how noise and other forms of interference, like network traffic entropy, alter the signals as they transmit through the system.

Narrow Band IoT Delay Tolerant Network (NBIoTDTN): Analyse how the network's delay tolerance affects transmission and use feedback mechanisms to help correct delays and errors.

Data Generation: Analyse metrics for IoT failures, faults, and errors to evaluate the system's output, reliability, and performance. This structured approach ensures a comprehensive understanding of the factors influencing IoT network performance and security.

2.10.1.2 Systems Theory

System Theory deals with the abstraction of objects and focuses on studying them as a whole or system. It uses mathematical models to describe and determine the structure and behaviour of the system. A system comprises several parts that interact and depend on each other. Additionally, the system itself belongs to a more extensive system. This implies that the function of complex objects is far greater than the simple sum of all objects in a causal chain.

Ludwig von Bertalanffy encourages researchers to adopt a dynamic and hierarchical view when examining systems (Bertalanffy, 1967). A system comprises multiple components, whether physical objects or disparate concepts. Its components have relationships, meaning they somehow interact or depend on each other. The nature and structure of these interdependencies can affect the system's behaviour and success. Despite the individual functions of its parts, a system has an overarching purpose or function that arises from interacting with its parts, which cannot be understood by looking at the components in isolation.

The study uses systems theory to apply mathematical models, experiment and analyse the system's behaviour under different scenarios, predict its performance, and identify potential areas for optimisation.

Integrating models to be used based on the conceptual model are:

I. Input (I): Apply differential equations to represent how algorithms and theories influence initial network states and transformations.
II. Transformation (T): Apply differential equations to model how noise and network traffic entropy impact signal transmission.

III. Data Generation and Output (O): Use network models to understand the impact of network structure on these outputs.

2.10.1.3 Cybernetics

According to Norbert Wiener's definition, the communication problem can be regarded as a control problem; that is, the communication problem is the orderly and repeatable control of several dangerous situations (Herring & Kaplan, 2001).

Cybernetics is a theory of self-controlling systems that involves the concept of "feedback" to control the future behaviour of a system based on information about its past performance (Torday, 2023). It is an abstraction of the information transmission process and is relevant in various fields such as physical, mechanical, psychological, social, political, pedagogical, and medical (Huang & Zhang, 2021).

Cybernetics is also used to formalise complex engineering tasks concerning control for groups of mobile robots, where cyber-physical approach and network-centric methods are employed (Manole, 2019). Overall, cybernetics is a multidisciplinary field that studies control systems, information processes, and the circulation of information in various domains.

Cybernetics is an abstraction of the information transmission process. To develop controlled objects, obtaining information, communicating, and acting on them is necessary.

Integrating models to be used based on the conceptual model are:

- NB-IoT Delay-Tolerant Network (NB-IoTDTN): Use Cybernetics to analyse the network's performance and reliability, incorporating feedback mechanisms to optimise delay tolerance and error correction.

Feedback is a fundamental concept of cybernetics. It refers to returning a system's output to the input and changing it somehow, affecting its function. It comprises both negative and positive feedback.

Negative Feedback aims to minimise deviation from a set goal by correcting errors. It is

fundamental in stabilising systems and ensuring consistent performance.

Positive Feedback amplifies deviations, leading to exponential growth or decline in a system's output. It is often associated with system changes, development, or collapse.

The cybernetic strategy incorporates feedback loops, which are critical in the control and adaptation of the network. Negative feedback mechanisms integrate to rectify deviations from the desired performance, thus maintaining system stability. Positive feedback loops are established to reinforce and amplify adaptive responses to dynamic network conditions.

The black box concept allows for a simplified approach to system analysis, focusing on the interactions between input and output variables without delving into the complexities of the internal mechanisms. This abstraction proves beneficial in managing the NB-IoT network's complexity, facilitating enhancements in performance without the need for an intricate understanding of its internal workings.

The uncertainty principle is a crucial aspect of the cybernetic application, acknowledging the inherent unpredictability within the NB-IoT network. This leads to implementing adaptive algorithms and redundant pathways, significantly supporting the network's resilience to disruptions and anomalies.

The cybernetic principles provide a robust framework for developing and refining the NB-IoT network, ensuring it efficiently manages current operational demands and is well-equipped to adapt to future challenges and changes within its ecosystem.

The cybernetic strategy incorporates feedback loops, critical in controlling and adapting the network. Negative feedback mechanisms integrate to rectify deviations from the desired performance, thus maintaining system stability. Positive feedback loops are established to reinforce and amplify adaptive responses to dynamic network conditions.

These theoretical foundations intertwine to inform and shape the research. They offer a broad perspective, enabling a deeper understanding of network communication, its potential pitfalls, and strategies for optimisation and reliability. Adapting these theories and models ensures the research is grounded in established knowledge and offers innovative insights and solutions to

current challenges.

2.11 Systematic Literature Review

The systematic literature review, a cornerstone of Chapter 2, provides a comprehensive and objective assessment of the current state of research relevant to the study's focus. Adopting a rigorous and systematic approach ensures the collection of complete and unbiased data summarising various sources. This section details the methodology employed for this review, offering transparent insight into the process undertaken to collate and analyse the existing literature.

2.11.1 Review Methodology

Clear and focused research questions are articulated to guide the review process before investigating the literature.

RQ1 (Overview of IoT and NB-IoT) What is the historical significance of Narrowband IoT (NB-IoT) in the technological landscape, and how does it relate to the Internet of Things (IoT)?

RQ2 (Security Concerns in IoT) What are IoT systems' primary vulnerabilities and security challenges, focusing on Distributed Denial of Service (DDoS) attacks?

RQ3 (Fog and Edge Computing in IoT) How do Fog and Edge computing paradigms enhance the functionality of IoT and improve security and response times within IoT systems?

RQ4 (Previous Approaches to IoT Security) How effective are current strategies for securing IoT networks, and what are their limitations?

RQ5 (Gap Analysis) What are the IoT security knowledge gaps, and how does the current study address them?

This protocol ensures a comprehensive and objective assessment of the relevant literature, providing a solid foundation for the research study. By systematically addressing these research questions, the systematic literature review aims to:

I. Identify existing knowledge.
II. Highlight significant findings.
III. Pinpoint areas requiring further investigation.

The review procedure follows three distinct steps, namely Step 1 Identification of Database Selection, Step 2 Refinement and Focus of Search Terms and Strategy and Step 3 Application of Inclusion and Exclusion Criteria.

Step 1: Identification of Database Selection

Reputable academic databases are identified for the literature search, ensuring a broad and varied collection of sources. These include MDPI, IEEE Xplore, ScienceDirect, SpringerLink, Wiley, and Google Scholar.

The study uses the “Publish or Perish” software program by Harzing, A.W. (2007) Publish or Perish, available from https://harzing.com/resources/publish-or-perish, which retrieves and analyses academic citations. It engages various data sources to obtain raw citations, then analyses these and presents a range of citation metrics, including the number of papers, total citations, and the h-index.

Step 2 Refinement and Focus of Search Terms and Strategy

Combining keywords and Boolean operators refines and focuses the search. Terms related to the research focus, such as "NB-IoT," "DDoS attacks," "network security," and "Edge and Fog Computing," are used in various combinations to maximise results.

The search uses three different queries or datasets:

- **NB-IoT + Security + DDoS + Edge Computing**: Papers related to Narrowband IoT with a focus on security, particularly DDoS attacks, and the role of Edge Computing.
- **NB-IoT + Security + DDoS**: Papers that discuss Narrowband IoT in the context of security, emphasising DDoS attacks.
- **NB-IoT + Security**: Papers addressing the general security concerns associated with Narrowband IoT.

The “Publish or Perish” software program creates three different queries. The results are saved in Excel and as “.ris” reference manager files for further analysis.

The results contained more detailed information, including:

I. **Authors**: List of authors for each publication.
II. **Title**: Title of the publication.

III. **Year**: Publication year.
IV. **Source**: Source/journal/conference where the paper was published.
V. **Publisher**: Publisher of the paper.
VI. **ArticleURL**: URL to access the full paper.
VII. **CitesURL**: URL pointing to the list of citations.
VIII. **Abstract**: Abstract or a snippet from the paper.
IX. **FullTextURL**: URL to access the full text.

Step 3 Application of Inclusion and Exclusion Criteria

Step 3 entails the application of various inclusion and exclusion criteria.

The Inclusion criteria include:

I. **Relevance to NB-IoT:** The paper must primarily focus on Narrowband IoT (NB-IoT) or its applications.
II. **Security Emphasis:** Given that security is a core aspect of the research, the paper should discuss security challenges, solutions, or methodologies relevant to IoT.
III. **Recent Publications:** To ensure current relevance, prioritise papers published within the last 5-10 years.
IV. **Technological Aspects:** Consider papers discussing technical aspects, such as Edge and Fog computing in the context of NB-IoT.
V. **Peer-reviewed Sources:** Only include peer-reviewed journals, conference papers, or reputable reports to ensure the source's credibility.

The Exclusion criteria include:

I. **Off-topic:** Exclude papers that mention NB-IoT only in passing or as a minor point.
II. **Older Publications:** Exclude publications older than ten years, unless they are seminal works, to focus on current trends and technologies.
III. **Non-technical Aspects:** While societal, economic, or purely theoretical aspects of NB-IoT are important, exclude them if they do not directly relate to the technical focus of the study.

IV. **Low Credibility Sources:** Exclude papers from non-peer-reviewed sources, non-reputable journals, or conferences.

By adhering to these criteria, the literature review ensures a focused and credible analysis, aligning with the study's objectives and providing relevant insights into the current state of research on NB-IoT and IoT security.

2.11.2 Iterations

The meta-analysis literature review strategy followed an iterative design informed by PRISMA guidelines (Moher *et al*., 2009). Figure 2-4 indicates phases which include;

I. Identification.
II. Screening.
III. Eligibility.
IV. Detailed review.
V. Inclusion.

The process linked specific articles to the sub-research questions. Appendix B's Data Extraction Table tabulates the outcome of an iterative meta-analysis strategy.

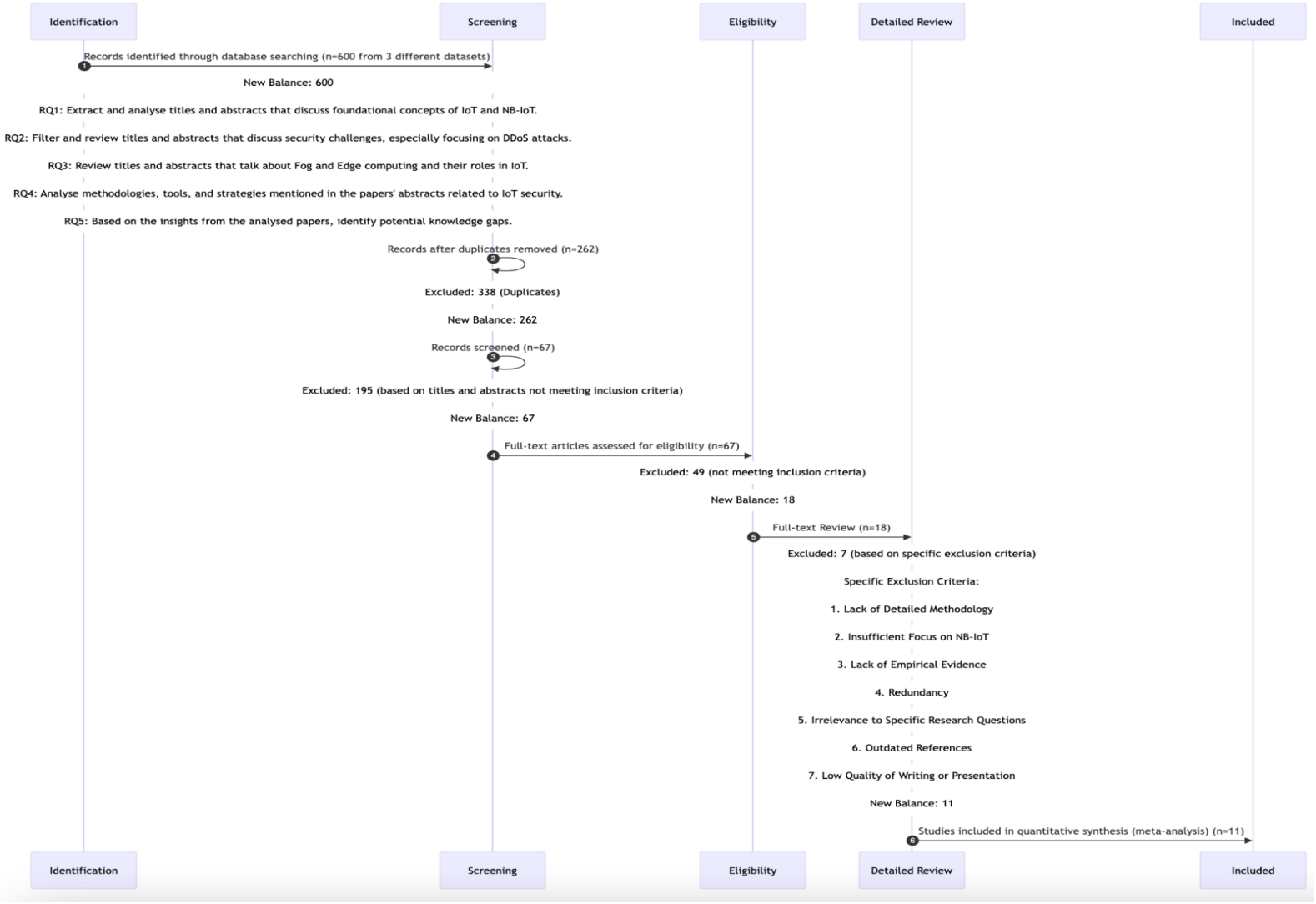

Figure 2-7 An Iterative Meta-Analysis Strategy

2.11.3 Protocol Execution

With the protocol defined, the execution of the literature search occurs systematically.

I. RQ1 (Overview of IoT and NB-IoT) – extract and analyse titles and abstracts that discuss foundational concepts and historical developments of IoT and NB-IoT.
II. RQ2 (Security Concerns in IoT) – filter and review titles and abstracts specifically discussing security challenges, primarily focusing on DDoS attacks.
III. RQ3 (Fog and Edge Computing in IoT) – review titles and abstracts about Fog and Edge computing and their roles in IoT.
IV. RQ4 (Previous Approaches to IoT Security) – analyse the methodologies, tools, and strategies related to IoT security mentioned in the papers' abstracts.
V. RQ5 (Gap Analysis) – identify potential knowledge gaps based on the insights from the analysed papers.

This structured approach ensures the literature review is comprehensive and directly relevant to the research questions. This method allows us to systematically extract valuable information and insights that address NB-IoT and IoT security, providing a solid foundation for the study.

2.11.3.1 Initial Search

An initial purpose-specific sweep of the selected databases using defined search terms occurred, yielding a preliminary list of potential sources based on a selection of search terms, namely:

- A search for articles focusing on NB-IoT and security aspects first applying the search term ("*narrowband iot" OR "nb-iot*") AND ("*security" OR "cybersecurity*").
- A narrowed search to determine specific security threats related to NB-IoT ("*narrowband iot" OR "nb-iot*") AND ("*security" OR "cybersecurity*") AND ("*denial of service attacks*").
- A search introducing edge and fog computing paradigms, modifying the search query ("narrowband iot" OR "nb-iot") AND ("edge computing" OR "fog computing") AND ("security" OR "cybersecurity") AND ("denial of service attacks").

These queries allowed exploration of more articles and narrowed the focus to address specific interests. A screen of abstracts and titles of the identified sources against the inclusion and exclusion criteria, is illustrated earlier as Figure 2-4, indicating a significant reduction of the number

of sources to be considered.

- **Step 1**: This step led to the identification of 600 records through database searching.
- **Step 2A – Exclusion (Duplicates)**: Across all datasets, 338 records were identified as duplicates and excluded.
- **Step 2B – Exclusion (Title and Abstract Screening)**: Out of the remaining records, 195 were excluded based on titles and abstracts that do not meet the inclusion criteria.
- **Step 3A – Exclusion (Full-text Assessment)**: During full-text assessment, 49 records were excluded for not meeting the inclusion criteria.
- **Step 3B – Exclusion (Detailed Review)**: A further 7 records were excluded based on specific exclusion criteria such as lack of detailed methodology, insufficient focus on NB-IoT, lack of empirical evidence, redundancy, irrelevance to specific research questions, outdated references, and low quality of writing or presentation.
- **Step 4A – Eligibility**: eighteen articles remained eligible for the final inclusion.

Tables 2-1 to 2-4 set out the details of the eighteen articles resulting from Steps 1 to Step 4A listed above. Elicited articles are mapped accordingly to research questions RQ1 to RQ4.

Table 2-2: RQ1 Overview of IoT and NB-IoT

#	Title	Authors	Year
1	Distributed dual-layer autonomous closed loops in the Internet of Things	Benlloch-Caballero, Wang and Calero	2023
2	Artificial intelligence for IoMT security: A review	Hernandez-Jaimes, and Martinez-Cruz	2023
3	Cybersecurity for industrial IoT (IIoT): Threats, challenges, and solutions	Mekala, Baig, Anwar and Zeadally	2023
4	Efficient Secure Routing Mechanisms for the LoRaWAN	Hussain and Hanapi	2023
5	Statistical Analysis of Remote Health Monitoring	Ashok and	2023

	Based IoT Security Models & Deployments From a Pragmatic Perspective	Gopikrishnan	

Table 2-3: RQ2 Security Concerns in IoT

#	Title	Authors	Year
6	Artificial intelligence for IoMT security: A review	Hernandez-Jaimes and Martinez-Cruz	2023
7	Abnormal traffic detection method of Internet of things based on deep learning in edge computing environment	Qiu and Wang	2023
8	Edge computing-enabled secure and energy-efficient data transmission for Internet of Things	Lee, Leng, Habeeb and Amanullah	2022
9	Deep reinforcement learning-based computation offloading and resource allocation for mobile edge computing	Ke, Wang, Zhao and Sun	2021

Table 2-4: RQ3 Fog and Edge Computing in IoT

#	Title	Authors	Year
10	Distributed dual-layer autonomous closed loops in the Internet of Things	Benlloch-Caballero, Wang and Calero	2023
11	Artificial intelligence for IoMT security: A review	Hernandez-Jaimes and Martinez-Cruz	2023
12	Cybersecurity for industrial IoT (IIoT): Threats, challenges, and solutions	Mekala, Baig, Anwar and Zeadally	2023
13	Efficient Secure Routing Mechanisms for the LoRaWAN	Hussain and Hanapi	2023
14	Statistical Analysis of Remote Health Monitoring Data Using Edge Computing: A Case Study	Ashok and Gopikrishnan	2023

Table 2-5: RQ4-Previous Approaches to IoT Security

#	Title	Authors	Year
15	A 5G NB-IoT Infrastructure for Secured Demand-Response Management Systems in Smart Grids	Ramana and Priyadarshini	2023
16	Edge–Fog–Cloud Computing Hierarchy for Improving Performance and Security of NB-IoT-Based Health Monitoring Systems	Daraghmi, Daraghmi, Daraghma and Fouchal	2022
17	Denial-of-sleep attack detection in NB-IoT using deep learning	Bani-Yaseen, Tahat and Kastell,	2022
18	Suitability of NB-IoT for indoor industrial environments	Dangana, Ansari, Abbasi and Hussain	2021

Table 2-5 below summarises the outcomes of this iterative process where the final column tabulates the number of articles selected relative to the three datasets. The study examines eleven articles from 2021- 2023 from the inclusion criteria datasets concerning the protocol execution systematic review research questions RQ1-RQ5.

Table 2-6: Number of Articles Meeting Each Dataset's Inclusion and Exclusion Criteria.

#	Dataset	Step 1 Initial Scan	Step 2A Exclusion	Step 2B Exclusion	Step 3A Exclusion	Step 3B Exclusion	Step 4A Eligibility	Step 4B Detailed Reduction	Final Set
1	NB-IoT + Security + DDoS + Edge Computing	200	113	65	12	5	9	1	4
2	NB-IoT + Security + DDoS	200	113	65	20	1	1	1	1
3	NB-IoT + Security	200	112	65	17	1	8	5	6
	Total	**600**	**338**	**195**	**49**	**7**	**18**	**7**	**11**

The iterative process concludes with one final exclusion stage, provided here as Step 4B which is represented as the final column in Table 2-5. This final stage involved a detailed review which led to the exclusion of seven articles as follows:

- **Step 4B – Detailed review**: during a final detailed review, an additional seven articles were excluded leading to a final selection of eleven articles. This reduction comprised:
  - NB-IoT + Security + DDoS + Edge Computing: - excluded 1 record during detailed review.
  - NB-IoT + Security + DDoS – excluded 1 record during detailed review.
  - NB-IoT + Security – excluded 5 records during detailed review.

- **Step 5**: The final set included 11 records that were included in the quantitative synthesis (meta-analysis). Appendix B Data Extraction Table details the final set of articles.

Step 5 entailed a detailed review and the final exclusion of seven articles culminating in the final set of eleven articles. During the detailed review phase, the exclusion of seven additional articles was informed by considering, where applicable, the following specific exclusion criteria:

- Lack of detailed methodology.
- Insufficient focus on NB-IOT.
- Lack of empirical evidence.
- Redundancy.
- Irrelevance to specific research questions.
- Outdated references.
- Low quality of writing or presentation.

This rigorous evaluation ensured that the remaining eleven articles were highly relevant and of high quality. These studies were selected based on contribution to the research questions and included in the quantitative synthesis (meta-analysis).

Figure 2-5 shows that dataset number 1 has the highest number of papers that meet the inclusion criteria. Dataset number 2 has many documents that were excluded based on the requirements. Dataset 3 has a balanced number of included and excluded papers. As shown in Figure 2-5 , the black bars represent the number of papers that met the inclusion criteria, and the grey bars represent the number of papers that met the exclusion criteria.

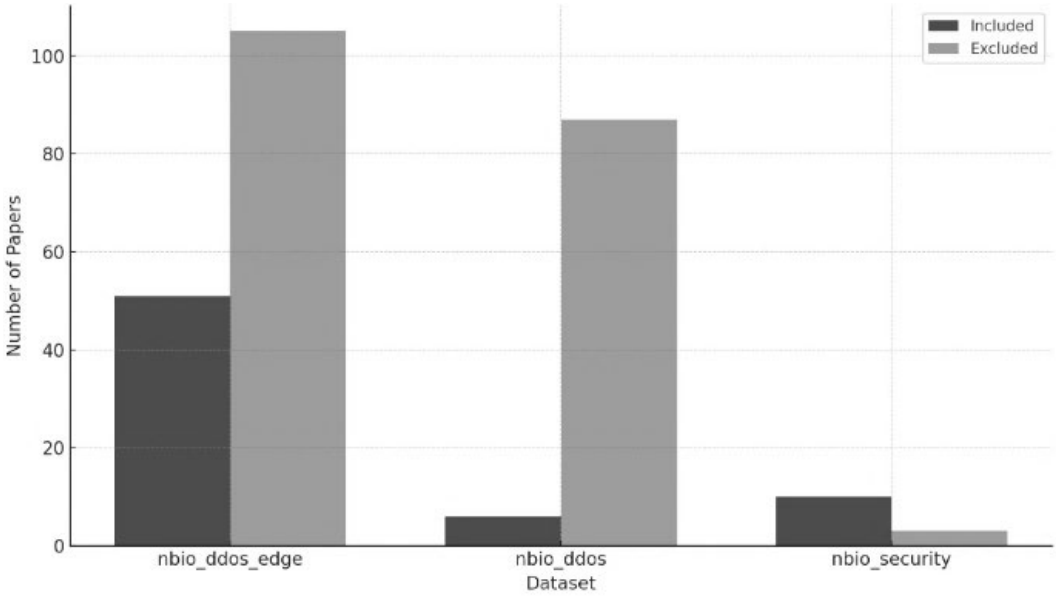

Figure 2-8: Screening Results

2.11.3.2 Full-text Review

The remaining eleven sources undergo a full-text review and are assessed in detail for their relevance and contribution to each research question based on the following criteria.

I. **Relevance to RQ:** Ensure that the paper addresses the research question in depth and is not just indirectly related.
II. **Depth of Analysis:** Ensure that the paper provides detailed insights, experiments, or methodologies contributing to understanding the topic.
III. **Quality of Research:** Ensure the paper follows rigorous research methodologies, has a straightforward research design, and presents valid and reliable results.
IV. **Contribution to the Field:** Ensure that the paper offers novel insights, methods, or findings that advance the state of the art in the domain.

This thorough review ensures that only the most relevant, high-quality sources contribute to the research, providing a robust foundation for addressing the research questions.

2.11.3.3 Data Extraction

Extracted relevant information, such as study methods, main findings, implications, and gaps, from

the finalised sources for analysis formed the foundation for analysis. Once the full-text review was done, the final list of papers materialised based on the following .

I. **Study Methods:** Research design (e.g., experimental, observational, simulation), Data collection methods (e.g., survey, case study, real-world data) Analysis techniques (e.g., statistical methods, machine learning algorithms)
II. **Main Findings:** Key results or observations from the study. Any proposed solutions, algorithms, or methodologies
III. **Implications:** Consequences or significance of the findings. Potential impact on the field or practical applications
IV. **Gaps Identified:** Any limitations of the study areas the authors suggest requiring further research.

2.12 Quantitative Content Analysis and Synthesis

The quantitative synthesis involves a thorough narrative summary of the findings from the selected studies, emphasising their context, methodologies, results, and broader implications. This approach is crucial in systematic review as it allows for a deep understanding of the research landscape, even when quantitative synthesis might not be feasible.

For each study, a detailed examination of the context, addresses specific aspects of technology or problem areas, such as advancements in intelligent grids or security challenges in the Internet of Medical Things (IoMT). Following this, an analysis of each study's methodology supports the understanding of how the research is conducted, the data collection methods used, and how analysis is performed.

To conduct a quantitative content analysis focused on NB-IoT networks, edge computing, and DDoS attack strategies, the study extracts data related to these specific areas from the data extraction in Appendix B, summarising the papers in table format.

The focus includes studies on NB-IoT networks, edge computing, and DDoS attack strategies. Studies that focus on IoT, NB-IoT, edge computing, and cybersecurity. It contains details on the study type, focus, design, consistency of results, data analysis methods, researcher's interpretation, relevance to the research question (RQ), depth of analysis, quality of research, contribution to the field, and other pertinent information.

Valuable insights gained into the research landscape resulted from summarising the studies in a structured tabular format and conducting a detailed quantitative content analysis. This approach scaffolded identification of key trends, challenges, and advancements in NB-IoT networks, edge computing, and DDoS attack strategies, providing a solid foundation for further research and development.

The process incorporated extraction and categorisation of data relevant to NB-IoT networks, edge computing, and DDoS attack strategies from the Appendix B. This involved identifying and coding the data into predefined categories, such as types of DDoS attacks, network performance metrics, and design principles for delay-tolerant networks.

The study focuses on the following key points from each relevant research:

I. **NB-IoT Networks:** Studies focusing on NB-IoT design, implementation, challenges, and advancements.
II. **Performance metrics and design considerations**: For NB-IoT in various applications.
III. **Edge Computing:** Integration of edge computing in IoT systems, focusing on security and efficiency. Challenges and advancements in implementing edge computing in various IoT environments.
IV. **DDoS Attack Strategies:** Studies focusing on DDoS attacks in IoT environments, particularly in NB-IoT and edge computing contexts. Countermeasures, detection techniques, and mitigation strategies for DDoS attacks.

After extraction and categorisation of data, a frequency analysis identified prevalent themes and patterns within each category. Thereafter, the identification of trends and insights, provided a comprehensive overview of the current state and challenges in NB-IoT networks, edge computing, and DDoS attack strategies.

The study focuses on NB-IoT networks, edge computing, and DDoS attack strategies using the relevant data from Appendix B. Five identified entries align with these topics based on the results.

2.12.1 5G and NB-IoT in Smart Grids

A comprehensive 5G NB-IoT design for smart grids focused on secure data transmission and predictive data analysis was developed. It aimed to enhance grid control, market response, and connectivity. The study type was a technological innovation in smart grids. The data analysis method integrated and analysed smart grid data with advanced technologies. The Contribution offered novel insights for advancing intelligent grid technology (Ke *et al.*, 2021; Hernandez-Jaimes *et al.*, 2023; Ramana *et al.*, 2023).

2.12.2 DDoS Protection in 5G/6G IoT Networks

A novel approach to securing 5G and 6G IoT networks against Distributed Denial of Service (DDoS) attacks is discussed and utilised in a distributed dual-layer autonomous closed-loop system. They demonstrated the potential of distributed self-protection systems in enhancing IoT network security. The study type was the development and validation of a DDoS mitigation system.

The main findings were effective real-time detection and mitigation of DDoS attacks in 5G/6G IoT networks. The study's implications showed that cases significantly improved response times and effectiveness compared to standalone systems (Benlloch-Caballero *et al.*, 2023).

2.12.3 AI in 5G Network Security

The study type was research on implementing AI-based anomaly detection systems specifically designed to enhance the security of 5G networks. The data analysis methods used sophisticated AI algorithms to identify unusual patterns or anomalies indicative of potential security threats. The contributions of this approach significantly improved the ability to detect and prevent threats in 5G networks, thereby increasing overall network reliability and user trust (Hernandez-Jaimes *et al.*, 2023).

2.12.4 Edge Computing in IoT Networks

The study explored the integration of edge computing within IoT networks to enhance data processing efficiency. The data analysis methods focused on decentralised data processing methods, where computations were done closer to the data source (at the network's edge) rather than in a centralised cloud-based system. This research's contributions highlight the critical role of edge computing in IoT, particularly in reducing latency and enabling real-time data processing, which is vital for time-sensitive IoT applications (Daraghmi *et al.*, 2022; Lee *et al.*, 2022).

2.12.5 Hybrid Security Model for IoT

The study type was an investigation into the effectiveness of a hybrid security model for IoT networks, particularly in the context of defending against DDoS attacks. The data analysis method analysed security protocols and architectures that combine the strengths of cloud and edge computing to create a more robust defense against cyber-attacks. The contributions of this model demonstrated a novel approach to IoT network security, offering enhanced protection against DDoS attacks. It underscores the potential benefits of integrating cloud and edge computing capabilities for improved security measures in IoT networks (Benlloch-Caballero *et al.*, 2023; Mekala *et al.*, 2023).

2.12.6 Key Themes and Trends

Several key themes and trends emerged, namely:

I. The integration of advanced technologies: There is a significant focus on integrating technologies like 5G, NB-IoT, AI, and edge computing to enhance network efficiency and security (Bani-Yaseen *et al.*, 2022; Ramana *et al.*, 2023).
II. DDoS Attack Mitigation: Innovative approaches, including AI and hybrid models, are being developed for robust DDoS attack mitigation in IoT networks (Bani-Yaseen *et al.*, 2022).
III. Emphasis on Real-Time Processing and Security: Studies highlight the importance of real-time data processing and security, particularly in IoT environments, with a strong focus on reducing latency and improving response times (Ke *et al.*, 2021; Ashok & Gopikrishnan, 2023).

2.12.7 Insights

The convergence of NB-IoT with emerging technologies like 5G and AI was crucial for advancing network performance and security. Edge computing is critical for managing the data demands of IoT networks, offering solutions for efficient processing and reduced latency. Addressing DDoS attacks in IoT networks requires innovative approaches that adapt to the evolving nature of cyber threats, with a trend towards distributed and hybrid models for enhanced defense (Benlloch-Caballero *et al.*, 2023; Ramana *et al.*, 2023).

This analysis provided a comprehensive overview of the current state and challenges in NB-IoT networks, edge computing, and DDoS attack strategies, highlighting the importance of technological integration and innovation.

2.12.8 Coding and Categorising

Coding and categorising involve systematically going through the extracted data and assigning it to predefined categories based on its content.

2.12.8.1 Identification of Categories

Based on the research focus, categories are identified as NB-IoT networks, Edge Computing, and DDoS Attack Strategies.

Subcategories such as network performance, security measures, technological integration, and real-time processing are also identified.

2.12.8.2 Coding the Data

Each relevant article in Appendix B and its information is coded into a category.

For instance, a study discussing the implementation of AI in network security was coded under 'NB-IoT networks' and 'Security Measures'.

2.12.8.3 Sub-Categorising

Subcategories are used to classify the data further within each major category.

Under 'DDoS Attack Strategies', data was sub-categorised into 'Mitigation Techniques', 'Real-time Detection', and 'Hybrid Security Models'.

2.12.8.4 Ensuring Reliability and Validity

The coding process was conducted methodically to ensure consistency and validity of the categorisation. This included revisiting and re-evaluating the categories and the assigned codes as new data was reviewed.

2.12.9 Frequency Analysis

After coding and categorising the data, frequency analysis is performed. This quantitative method identifies patterns and trends by counting the occurrences of each category and subcategory in the dataset.

2.12.9.1 Counting Occurrences

The number of times each category and subcategory appear in the data are counted. This quantified the prevalence of specific themes and topics within the document.

2.12.9.2 Identifying Prevalent Themes

Categories and subcategories with higher frequencies are identified as prevalent themes. For instance, if 'Real-time Detection' in DDoS attack strategies appears frequently, it is marked as a key theme.

2.12.9.3 Comparative Analysis

The frequencies of different categories are compared to understand their relative significance in the study. This helps the study understand which aspects of NB-IoT, edge computing, and DDoS attacks are most emphasised in the studies.

This detailed analysis, shown in Figure 2-6, provides insights into the studies' emphasis and focus areas. It reveals vital trends such as the growing importance of AI in network security, the role of edge computing in inefficient data processing, and innovative strategies in combating DDoS attacks in IoT networks. The researchers can derive meaningful conclusions and insights from the data through this systematic approach.

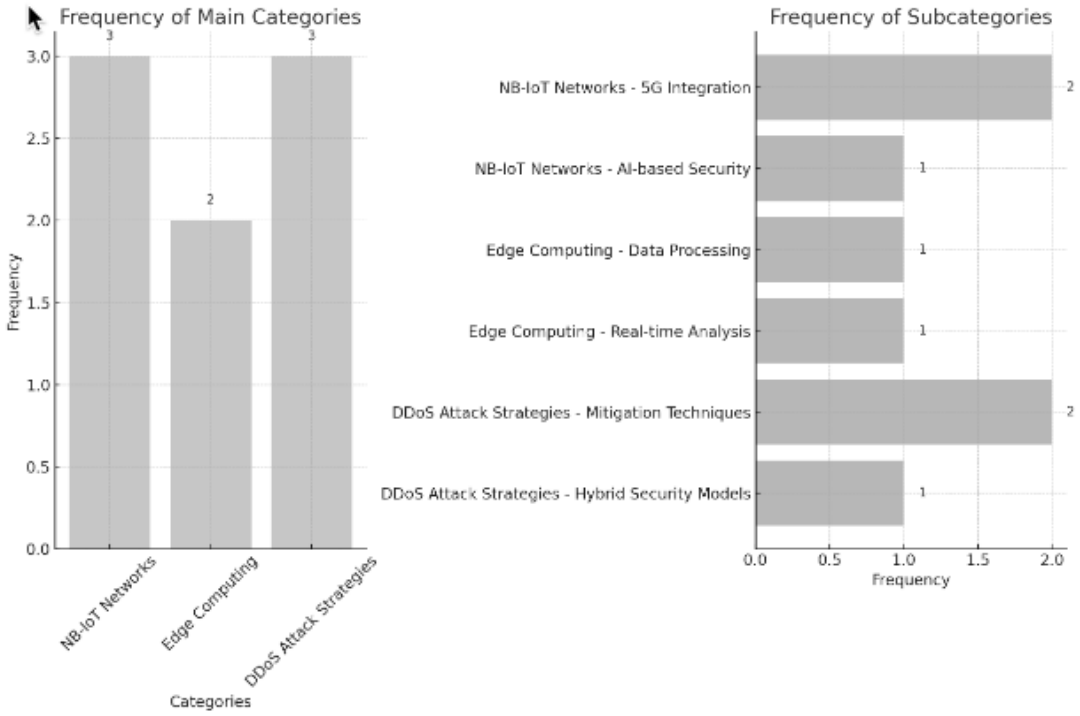

Figure 2-9: Frequency Analysis for Main Categories and Subcategories Related to NB-IoT Networks, Edge Computing, and DDoS Attack Strategies.

2.13 Identification of Trends

2.13.1 Growing Emphasis on 5G and NB-IoT Integration

The repeated mention of 5G technology in NB-IoT networks indicates a trend towards integrating these technologies for enhanced network performance and security. 5G networks offer lower latency, increased system capacity, faster data transmission rates, and energy savings, making them well-suited for IoT applications. The integration of 5G with NB-IoT technologies addresses the connectivity challenges of IoT devices, providing reliable and low-latency connectivity with low power consumption. This integration enables the expansion of telemedicine applications, improves patient monitoring, and enhances the user experience. Additionally, using 5G in IoT networks allows for the implementation of self-managed protection architectures, enhancing security by combining traditional IDS systems with 5G infrastructure information. The combination of 5G and NB-IoT technologies in IoT networks improves network performance and enhances security measures, making it a promising trend in the field (Dangana *et al.*, 2021; Daraghmi *et al.*, 2022; Benlloch-Caballero *et al.*, 2023).

2.13.2 Rising Importance of AI in Network Security

AI's role in enhancing network security, particularly in the 5G and IoT context, is a prominent trend. Integrating AI algorithms, such as machine learning and deep learning, has proven effective in detecting and mitigating security threats in these complex and dynamic environments. AI algorithms can learn and adapt to new attack patterns, making them more effective in detecting zero-day attacks without compromising performance (Benlloch-Caballero *et al.*, 2023). Additionally, Other state-of-the-art technologies like Software-Defined Networking (SDN) and blockchain have been proposed as solutions to strengthen IoT security. SDN enables centralised control and management of network resources, allowing for more efficient security measures (Hernandez-Jaimes *et al.*, 2023). Conversely, blockchain ensures data integrity and confidentiality, enhancing authentication and access control in IoT systems. These advancements in AI-based security solutions signify a shift towards more intelligent and adaptive approaches to network security in the era of 5G and IoT.

2.13.3 Edge Computing as a Key Player in IoT

Edge computing has been highlighted as an essential aspect of IoT networks, particularly for real-time data processing and reducing latency. It enables data from IoT devices to be offloaded to edge servers with lower computational resources and can aggregate and preprocess the data before forwarding it to central servers (Benlloch-Caballero *et al.*, 2023). This shift of computation and storage to the edge improves network performance by reducing communication costs, latency, and energy consumption (Hernandez-Jaimes *et al.*, 2023). Edge computing in IoT architectures can enhance response time, address security challenges, and provide scalability and reliability for IoT applications (Mekala *et al.*, 2023). It also plays a crucial role in enabling immediate action in emergencies and ensuring minimum latency time in the smart healthcare industry (Hussain & Hanapi, 2023). Combining edge computing with other technologies like blockchain and artificial intelligence further enhances the security and intelligence of industrial environments (Ashok & Gopikrishnan, 2023). Multiple studies focus on edge computing, underscoring its growing importance for real-time data processing and latency reduction in IoT networks.

2.13.4 Innovative Approaches to DDoS Attack Mitigation

The entries in the provided contexts indicate a trend towards more sophisticated defense mechanisms in IoT networks to mitigate DDoS attacks. One approach is the use of distributed systems, where the self-protection loop is installed in multiple management layers of the stakeholders involved in the network, creating a distributed dual-layer self-protection loop (Benlloch-Caballero *et al.*, 2023). Another strategy is adopting hybrid security models, which combine techniques such as SDN, NFV, and Cloud-Fog-Edge computing to improve detection performance and efficiency, secure different levels of the IoT architecture, and leverage the advantages of novel paradigms (Hernandez-Jaimes *et al.*, 2023). These hybrid models have shown promising results in detecting attacks at different network layers and securing IoT devices from internal and external cyber-attacks without imposing significant resource consumption overhead (Mekala *et al.*, 2023). Overall, these novel strategies demonstrate the industry's efforts to enhance the security of IoT networks and protect against DDoS attacks (Ashok & Gopikrishnan, 2023; Hussain & Hanapi, 2023).

2.13.5 Interpretation and Insights

This section sets out interpretation and associated insights gleaned from literature sources.

I. **Integration for Enhanced Efficiency and Security**: The convergence of NB-IoT with 5G and AI technologies was about enhancing network capabilities and fortifying security measures against modern cyber threats. This integration was crucial for supporting the complex demands of modern IoT applications, particularly in sectors like smart grids.
II. **Edge Computing's Critical Role**: The studies' emphasis on edge computing revealed its critical role in managing the high data demands of IoT networks. Edge computing addresses bandwidth, latency, and real-time analysis challenges by bringing data processing closer to the source.
III. **Adaptive and Distributed Security Measures**: The trend towards adopting distributed and hybrid models for DDoS attack mitigation reflects the need for more adaptive and resilient security measures in IoT networks.

These approaches are vital in tackling the evolving nature of cyber threats and ensuring robust network security. The analysis revealed significant trends in integrating advanced technologies like 5G, NB-IoT, and AI for network performance and security enhancement, focusing on edge computing for IoT efficiency and innovative strategies for DDoS attack mitigation. These trends and insights, derived from the data in Appendix B, underscore the ongoing evolution and advancement in IoT, NB-IoT networks, and cybersecurity.

2.14 The Results of the Systematic Review

2.14.1 Synthesis of Findings

I. Integration of Technologies (5G, NB-IoT, AI)

Studies by Ramana *et al.* (2023) showcased the potential of integrating 5G and NB-IoT to enhance network performance, particularly in smart grids. Implementing AI in network security suggested a trend toward intelligent, self-learning systems capable of addressing evolving cyber threats(Mekala *et al.*, 2023). However, more practical challenges and scalability issues must be explored when deploying these integrated technologies in diverse real-world environments.

II. Edge Computing in IoT Networks

As highlighted in the study on edge computing in IoT by Lee *et al.* (2022), the focus on edge computing demonstrates its importance in real-time data processing and reducing latency. This is crucial for applications requiring immediate data analysis and response.

The research needs more depth in exploring the potential security vulnerabilities introduced by edge computing and how they can be effectively mitigated.

III. DDoS Attack Mitigation Strategies

Innovative approaches to DDoS attack mitigation, such as distributed systems and hybrid security models, indicate advancements in securing IoT networks against sophisticated cyber-attacks (Bani-Yaseen *et al.*, 2022; Ramana *et al.*, 2023). However, more needs to be understood about the long-term effectiveness of these strategies against rapidly advancing and changing attack methodologies.

2.14.2 Cross-References and Connections

Integrating 5G, NB-IoT, and AI technologies directly correlates with the evolving nature of cyber threats, particularly DDoS attacks. The studies indicated a need for advanced security measures, but they also hint at potential new vulnerabilities that could arise from this integration.

The emphasis on edge computing for efficiency intersects with the need for robust security strategies. This connection highlights a dual focus on performance and security in IoT networks and raises questions about balancing these aspects without compromising.

Different studies might perceive the trade-offs between advanced technology integration and network security differently. While some focus on the benefits of technology convergence, others may emphasise the emerging security risks associated with such integrations.

2.15 Summary and Gap Analysis

2.15.1 Summary of Main Findings and Insights

A significant focus was on integrating technologies like 5G, NB-IoT, and AI to enhance IoT network performance and security. Studies by Ramana *et al.* (2023) illustrated how this integration could

improve efficiency and capabilities, particularly in smart grids and network security.

Edge computing was recognised as a critical component in IoT networks because it reduced latency and processed data in real-time. The research emphasised its importance for IoT applications that required immediate data analysis and response.

Studies on DDoS attack strategies, such as those exploring distributed systems and hybrid security models, indicated an evolution in approaches to mitigate cyber threats in IoT networks. These innovative strategies were crucial in combatting sophisticated cyber-attacks.

The literature revealed an ongoing effort to balance enhanced network efficiency with robust security measures. This balance is pivotal in ensuring the reliability and safety of IoT networks in various applications.

2.15.2 Gaps and Limitations in Existing Research

I. Practical Implementation Challenges

While extensive research is on theoretical models and technological integrations, more studies must address real-world implementation challenges, scalability, and practicality in diverse environments. The current research focuses on developing frameworks and algorithms for IoT systems. Still, there is a need for more practical studies that consider the limitations and constraints of real-world deployments. Additionally, scalability is a significant challenge in IoT networks, and future research should focus on designing architectures and protocols that can quickly adapt and scale to accommodate the growing number of devices. Furthermore, the practicality of IoT solutions in diverse environments, such as smart factories and healthcare systems, must be thoroughly investigated to ensure their effectiveness and security (Ashok & Gopikrishnan, 2023; Benlloch-Caballero *et al.*, 2023; Hernandez-Jaimes *et al.*, 2023; Hussain & Hanapi, 2023; Mekala *et al.*, 2023).

II. Long-Term Effectiveness and Adaptability

The long-term effectiveness of current cybersecurity strategies in the face of rapidly evolving cyber threats is limited and needs further exploration(Benlloch-Caballero *et al.*, 2023). Research on the adaptability of these strategies over time is necessary to ensure their continued effectiveness

(Hernandez-Jaimes *et al.*, 2023). Understanding how these strategies can evolve and adapt to new and emerging threats is essential to protect against cyber-attacks effectively (Mekala *et al.*, 2023). Additionally, evaluation of the performance and effectiveness of these strategies should be ongoing to identify any gaps or weaknesses that may arise over time (Hussain & Hanapi, 2023). By researching the long-term effectiveness and adaptability of current cybersecurity strategies, the enhancement of the understanding of protecting against evolving cyber threats is achieved (Ashok & Gopikrishnan, 2023).

III. Security Risks in Edge Computing

Despite the advantages of edge computing, there is a need for more comprehensive research on the potential security vulnerabilities it introduces. Studies focusing on mitigating these risks have yet to be available (Benlloch-Caballero *et al.*, 2023). The reliance on edge computing devices in intelligent factories can introduce security concerns such as limited storage capacities and bandwidth (Hernandez-Jaimes *et al.*, 2023). Additionally, the wireless connection between IoT smart devices and the gateway node in edge computing introduces a wide range of potential vulnerabilities, including replay attacks, man-in-the-middle attacks, impersonation, distribution of malicious devices, and physical acquisition of devices (Mekala *et al.*, 2023). It is crucial to address these security challenges and develop practical solutions to ensure the secure implementation of edge computing in IoT environments. Further research and studies are needed to explore and mitigate the security risks associated with edge computing to enhance the overall security of IoT systems (Hussain & Hanapi, 2023).

IV. Interdisciplinary and Cross-Domain Studies

There is indeed a need for more interdisciplinary and cross-domain research that combines insights from different fields, such as network engineering, data science, and cybersecurity, to address the complexities of IoT networks. Integrating these diverse disciplines can provide a holistic approach to tackling the challenges associated with IoT networks. Network engineering expertise is crucial for designing and optimising the infrastructure of IoT networks, ensuring efficient data transmission and connectivity. Data science plays a vital role in analysing the massive amounts of data generated by IoT devices, extracting valuable insights, and enabling intelligent decision-making. Cybersecurity is essential to protect IoT networks from potential threats and vulnerabilities, safeguard sensitive data, and ensure the privacy and integrity of IoT

devices and systems. By bringing together these different fields, researchers can develop comprehensive solutions that address the unique complexities and requirements of IoT networks (Ashok & Gopikrishnan, 2023; Benlloch-Caballero *et al.*, 2023; Hernandez-Jaimes *et al.*, 2023; Hussain & Hanapi 2023; Mekala *et al.*, 2023).

The systematic literature review uncovers a rapidly evolving field marked by technological advancements and innovative approaches to network security. However, it also highlights significant gaps in practical implementation, adaptability of security measures, and a need for more interdisciplinary research to tackle emerging challenges in IoT networks. Addressing these gaps will be crucial for the continued development and secure implementation of IoT technologies in various domains.

2.15.3 Significance of the Research

The systematic review informed the research methodology by highlighting the importance of integrating advanced technologies like AI and deep learning for IoT security. It underscores the necessity of real-world testing and scalability in IoT security solutions, shaping the research questions and conceptual framework.

The gaps identified in the review, such as the need for more empirical research and addressing scalability, directly align with the research objectives, providing a clear direction for the work.

By understanding these findings and gaps, the research can contribute to addressing these critical issues in IoT security, potentially leading to more robust, scalable, and effective security solutions.

2.16 Conclusion

In conclusion, this systematic literature review has made several pivotal contributions to IoT security and technology research. It has:

I. **Highlighted Advanced Technological Integrations:** The review shed light on cutting-edge integrations in the IoT domain, particularly in 5G technology, smart grids, IoMT, and IIoT. These insights underscore the rapid evolution of IoT and its potential impact on various sectors.

II. **Identified Key Security Challenges:** By examining the latest research in IoT security, the review has brought forward crucial challenges, including cyber threats in IoMT and IIoT and the need for robust, scalable security solutions.

III. **Revealed Gaps in Current Research:** The review highlighted significant gaps, such as the need for real-world application and empirical testing of theoretical models and the challenges of scalability and standardisation in IoT security solutions.

IV. **Informed Research Direction:** These findings and identified gaps have directly informed the study's research methodology, research questions, and theoretical framework. They provided a solid foundation for addressing unmet needs in the field, particularly in developing practical, scalable, and adaptable IoT security solutions.

Table 2-7: Encapsulating the Findings from the Literature Review

RQ	Theme	Title	Year	Key Findings	Implications	Gaps Identified
RQ1	Overview of IoT and NB-IoT	1 Distributed dual-layer autonomous closed loops in the Internet of Things	2023	Enhances control and connectivity in smart grids through dual-layer autonomous systems.	Significant potential in smart grid management.	Needs real-world application and long-term effectiveness exploration.
		2 Artificial intelligence for IoMT security: A review	2023	Reviews AI's role in IoMT security, highlighting intrusion detection systems and cyberattacks.	Emphasizes the importance of AI in enhancing IoMT security.	More research on AI integration and emerging cyber threats needed.
RQ2	Security Concerns in IoT	3 Cybersecurity for industrial IoT (IIoT): Threats, challenges, and solutions	2023	Analyzes cybersecurity threats and solutions in IIoT, including DDoS and phishing.	Highlights evolving IIoT cybersecurity measures.	Needs development of more robust security solutions.
		4 Abnormal traffic detection method of Internet of things based on deep learning in edge computing environment	2023	Develops deep learning-based abnormal traffic detection for IoT.	Demonstrates the need for advanced detection methods in IoT security.	Further research on effective deployment and long-term performance needed.
		5 Edge computing-enabled secure and energy-efficient data transmission for Internet of Things	2022	Highlights edge computing's role in improving security and energy efficiency in IoT.	Discusses potential impact on urban infrastructure and smart city development.	Needs real-world application and scalability research.

RQ	Theme	Title	Year	Key Findings	Implications	Gaps Identified
RQ3	Fog and Edge Computing	6 Deep reinforcement learning-based computation offloading and resource allocation for mobile edge computing	2021	Proposes a DRL-based scheme for computation offloading and resource allocation, showing improved efficiency and adaptability.	Shows potential of DRL in enhancing MEC systems' performance and security.	Requires further research in real-world deployment and long-term evaluation.
		7 Edge–Fog–Cloud Computing Hierarchy for Improving Performance and Security of NB-IoT-Based Health Monitoring Systems	2022	Proposes a hierarchical architecture for health monitoring, reducing transmission delay and execution time, enhancing security.	Combines edge, fog, and cloud computing to enhance NB-IoT performance and security.	Further research in real-world implementation and long-term performance needed.

RQ	Theme	Title	Year	Key Findings	Implications	Gaps Identified
RQ4	Previous Approaches to IoT Security	8 Denial-of-sleep attack detection in NB-IoT using deep learning	2022	Demonstrates high accuracy of LSTM and GRU models in detecting DoS attacks in NB-IoT networks.	Highlights deep learning's potential in IoT security.	Needs real-world deployment and model adaptation research.
		9 Efficient Secure Routing Mechanisms for the LoRaWAN	2023	Analyzes security issues in WSN-IoT, evaluates RPL's security mechanisms.	Emphasizes need for effective security mechanisms in low-powered IoT networks.	Further research on security measures and protocol efficiency needed.
		10 Statistical Analysis of Remote Health Monitoring Based IoT Security Models & Deployments From a Pragmatic Perspective	2023	Comprehensive analysis of IoT security models in health monitoring, evaluating performance metrics like latency, energy consumption, and scalability.	Provides framework for evaluating IoT security models based on empirical survey.	Needs real-world application and long-term effectiveness research.
		11 Suitability of NB-IoT for indoor industrial environments	2021	Reviews state-of-the-art NB-IoT research and applications in industrial environments, highlighting challenges and technological advancements.	Highlights NB-IoT's potential in industrial settings, emphasizing need for robust communication systems.	Needs further research to address real-world application and long-term effectiveness.

Based on the literature review, data extracted from the authors summarises the key findings, implications, and gaps identified in the literature review and emphasises the importance of continued research and development in NB-IoT networks, edge computing, and DDoS attack strategies to enhance the security and efficiency of IoT systems.

It is organised by the research questions (RQs) and themes. This systematic review, therefore, served as a cornerstone for the research, offering a comprehensive understanding of the current state of IoT security and technology and setting a clear direction for future work in this rapidly evolving field.

This research contributes significantly to this domain by addressing these identified gaps and pushing the boundaries of what is currently known and practiced in IoT security.

CHAPTER 3 RESEARCH PARADIGM, METHODOLOGY AND DESIGN

3.1 Introduction

Chapter 3 of this research details the methodology of the study (Figure 3-1). This chapter gives a comprehensive overview of the methodological framework, describing the systematic approach to address the research objectives identified in Section 1.9.2. It is important to note that this chapter demonstrates how the research methodology is aligned with and directly reflects the philosophical foundations of positivism that guide this study (Park *et al*., 2020).

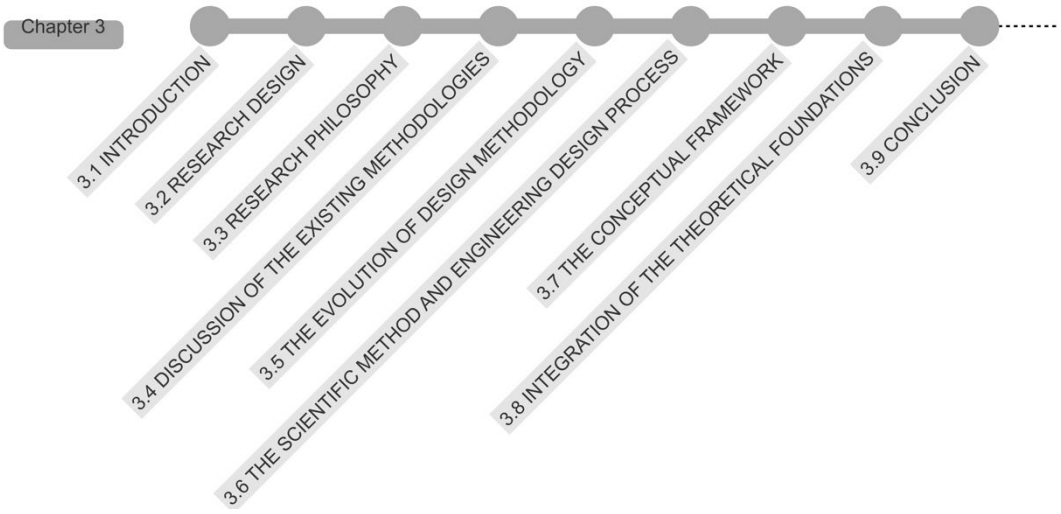

Figure 3-1: Chapter 3 Outline

The Introduction of this chapter outlines the scope and purpose of the research methodology. It sets the foundation by defining the Research Design, detailing the approach and methods utilized in the study. The chapter then delves into the Research Philosophy, examining philosophical positions that influence the research, including ontological, epistemological, and axiological perspectives.

Following this, the Discussion of the Existing Methodologies provides a review of methodologies relevant to the study, highlighting their strengths and limitations. The chapter then moves on to the Evolution of Design Methodology, exploring significant contributions like Archer's Model of the Design Process, Morris Asimov's Life Cycle of a Product, and methodologies proposed by French,

Pahl, and Beitz, concluding with March's Diagram.

The Scientific Method and Engineering Design Process section integrates scientific principles into the design process, ensuring rigor and structure in the approach. The chapter then presents The Conceptual Framework, which organizes the theoretical foundation and guides the study's analytical perspective. The Integration of Theoretical Foundations discusses how these theoretical elements come together to inform the research process. Finally, the chapter concludes with a Conclusion that summarizes the key elements of the research paradigm, methodology, and design.

The study's methodology is aligned with a positivist philosophy, which focuses on empirical data collection and quantitative analysis (Hu *et al.*, 2017). As Junjie & Yingxin (2022) highlight, positivism emphasises the importance of objectively observable phenomena and data gathered, utilising measurable variables in conjunction with statistical and numerical analysis (Sprague Joey and Kobrynowicz, 2006).

The research's ontological position reflects realism, proposing an objective reality that can be studied through empirical observations and measurements (Chia, 1996; Morton, 2006; Danermark, 2002). This objective stance differs from objectivism, representing the researcher's epistemological position, emphasising reliance on observable and measurable facts to uncover the truth, with experiments designed to be objective and unbiased (Reber & Bullot, 2019).

The chapter outlines the engineering design process with scientific methods, demonstrating how this approach is well-suited for empirical investigation in IoT security and technology (Wieringa, 2014; Robinson, 2016; Hoadley, 2004). The methodology conforms to the positivist paradigm, underscoring the significance of observable, empirical evidence acquired through quantitative methods (Alakwe, 2017). This approach highlights the study's dedication to objectivity, ensuring that the findings are grounded in measurable, observable realities and devoid of subjective biases (Castle, 1968).

3.2 Research Design

The mono-method, quantitative research design adopted in this study is rooted in empirical data collection and statistical analysis, aligning with positivist principles (Park *et al.*, 2020). Firestone (1987) explains that quantitative methods embody the assumptions of a positivist paradigm,

suggesting that behaviour can be understood through objective facts.

This aligns with positivism's principles, which advocate reliance on observable, measurable phenomena as the basis of scientific knowledge. Christofi *et al.* (2021) paper details how mono-method quantitative research designs in management research encompass surveys, experiments, structured observations, and panel studies. These methods are vital for objective measurement and empirical evidence, as they facilitate data analysis via regression and path analysis.

This approach was evident in the study's structured quantitative methods, such as experiments, which are essential for collecting numerical data that can be quantitatively analysed. Park *et al.* (2020) note that such methods are crucial in ensuring objective measurement and empirical evidence, as abilities of positivist research.

Further, the design reflects an objectivist stance, resonating with the perspectives of phenomena independent of individual beliefs or perceptions (Lim, 2023). This objectivist viewpoint is crucial in treating research variables as objective realities, measurable through systematic methods. This study's quantitative approach, characterised by controlled experimental conditions, aligns with the objectivist emphasis on consistency and objectivity in data collection, as highlighted by (Creswell & Creswell, 2018).

This approach is beneficial in addressing issues of generalisability and representativeness in research, which are crucial for findings beyond the specific study context (Blalock, 1967). Morgan *et al.* (1999) emphasise that treating variables as objective realities aids in making logical, consistent, and conceptually significant distinctions among different research methodologies.

This aspect is particularly critical in quantitative research, where clarity and precision are paramount. Nassaji (2017) notes that this perspective emphasises objectivity, control, and detachment from the research subject. Under controlled experimental conditions, this ensures that the findings reflect the variables under study rather than being influenced by the researcher's subjective biases. Furthermore, (Lee, 2006) points out that treating variables as objective realities in quantitative research focuses on objectivity and facilitates the generalisation of findings to other situations, essential in minimising biases in experimental research.

The mono-method quantitative approach is justified by its ability to provide precise measurement and enable statistical generalisation. This approach is efficient in IoT security, where empirical

validation and measurable outcomes are crucial (Lau *et al.*, 1997). Frost & Nolas (2011) note that treating variables as objective realities in quantitative research aligns with the objectivist stance.

This approach emphasises the importance of maintaining objectivity and control in research, which is essential in experiments and studies within structured scientific fields (Shah, 2021). It also emphasises that adherence to positivist principles in research, particularly in fields like IoT security, enhances the study's credibility and relevance (Johnson, 1999). This approach ensures the research is anchored in established scientific practices and methodologies. Panarello *et al.* (2018) demonstrate how integrating positivism in IoT security research addresses significant security challenges and highlights open issues and future research directions.

This integration ensures that the research remains relevant to current technological challenges and contributes effectively to the field. Adam (2014) discusses how adherence to methodological and epistemic frameworks like positivism can guide research in complex areas like IoT security.

This adherence structures the research process and ensures the findings are empirically sound and methodologically solid. Furthermore, Niemann *et al.* (2000) argue that adhering to positivist principles enhances the reliability and validity of the findings, promoting scientific accountability. This is especially critical in rapidly evolving and highly technical fields like IoT security.

3.3 Research Philosophy

3.3.1 Philosophical Position

The research is anchored in the positivist philosophy. This study's philosophical positions influenced the methods based on observable, empirical evidence attainable through scientific methods. This position emphasises objectivity and quantitative measurements (Renaud *et al.*, 2021). It aligns with the research aim to empirically test and validate a fault-tolerant network for NB-IoT against DDoS attacks.

Positivist philosophy stresses objectivity and scientific inquiry, grounded in the belief that knowledge should be derived from observable, measurable facts. This approach is particularly relevant in fields like network security, where empirical evidence and quantitative analysis are essential (Park *et al*., 2020).

Positivism focuses on phenomena that can be observed and measured. This study involves observable metrics related to network performance and security, such as data throughput, latency, and the number of successfully repelled DDoS attacks. The study uses statistical tools to analyse network traffic data, identify patterns of DDoS attacks, and measure the effectiveness of fault-tolerant mechanisms in NB-IoT networks (Hu *et al.*, 2017).

By using these methods, the research systematically assesses the performance of the NB-IoT network under various DDoS scenarios. The goal is to objectively measure the network's fault tolerance, identifying its defense mechanisms' strengths and weaknesses.

3.3.2 Ontological Position

The realist ontological position in IoT network security suggests that objective reality, encompassing the fundamental aspects of IoT networks, Distributed Denial of Service (DDoS) attacks, and network performance metrics, is evident through empirical observation and analysis (Brown *et al.*, 2017).

This standpoint assumes these elements have an existence and properties that are not dependent on subjective perceptions or beliefs (Creswell & Creswell, 2018). Instead, they are considered

objective entities that can be empirically studied and understood, contributing to a robust and factual understanding of IoT network security. This approach is critical in developing effective security strategies and technologies for IoT networks rooted in observable and verifiable realities (Brown, 1981).

3.3.3 Epistemological Position

In adhering to a positivist epistemological framework, the researcher's role is meticulously defined as an objective observer, a principle central to the positivist paradigm (Park *et al*., 2020). This necessitates an approach where the researcher's interactions with the study environment are carefully managed to prevent any subjective influence on the outcomes. The tools and methods employed for data collection and analysis are selected for their ability to provide quantifiable, empirical evidence, ensuring the integrity of the research process.

Furthermore, this objective approach is instrumental in maintaining the credibility and reproducibility of the study's findings. By avoiding personal biases and ensuring a detached observation, the study aims to produce results that could be universally accepted and verified within the scientific community. This commitment to objectivity forms the basis of the fundamental principles of the positivist tradition, where empirical evidence is paramount, and knowledge is acquired through observable and measurable phenomena.

Adopting this epistemological stance reinforces the study's scientific foundation (Carlson, 2022). It emphasises the importance of using empirical research to comprehend intricate concepts and underscores the researcher's role as an impartial conduit for factual exploration. This approach ensures that the conclusions drawn from the study reflect the observed reality, free from individual interpretations or theoretical predispositions.

The study adheres to a positivist epistemology, which suggests that knowledge about phenomena such as IoT network security can be objectively obtained through empirical scientific methods. This perspective aligns with the hypothetico-deductive science model, highlighting the importance of verification through experimentation, operationalising variables, and utilising quantitative approaches.

The paradigm supports empirically based findings, preferring large sample sizes for generalisable inferences and controlled experimentation. This approach ensures that the findings and

conclusions are grounded in observable and measurable data, independent of the researcher's subjective beliefs.

3.3.4 Axiological Position

The research values objectivity, transparency, and ethical integrity. Ethical considerations include ensuring the privacy and security of any data used and maintaining the impartiality of the research process. The research adheres to ethical guidelines for scientific inquiry, ensuring that all experimental and data collection methods are conducted responsibly and ethically.

I. Objectivity

Empirical studies in technology-related fields often adhere to the positivist paradigm. This approach quantitatively identifies explanatory associations or causal relationships (Park *et al.*, 2019). Large-scale empirical data is fundamental to this approach as it allows for generalisable inferences, replication of findings, and controlled experiments. One example is a study that relies on collecting and evaluating empirical data in a positivist manner using a causal-comparative research design (Alakwe, 2017). Moreover, positivist and deductive case study research is prominent in information systems. This method involves clear definitions and structured approaches to ensure objective analysis and verifiable conclusions. However, positivist epistemology in technology research can sometimes overshadow broader epistemological and methodological considerations (Shanks, 2002).

II. Transparency

The concept of replicability and its relationship to transparency in research is the subject of extensive academic discussion. Replication crisis has been observed across various academic disciplines, particularly in biomedical and social sciences. This crisis arises from the inability to replicate a significant number of studies, thereby challenging the validity of the original findings (Peels, 2019). In response, there are endeavours to enhance research integrity, such as establishing various codes of research integrity and conducting studies on reproducibility and replicability by esteemed scientific bodies like the National Science Foundation.

The significance of replicability in academic research can be attributed to four crucial aspects:

a) Results that can be consistently replicated are more likely to be accurate.
b) Replicability prevents the wastage of resources.
c) Non-replicable results can cause harm.
d) A multitude of non-replicable results undermines public trust in the scientific community.

Transparency is intricately linked to replicability. Studies can only be replicated if researchers are transparent regarding their data, methodologies and conclusions (Peels, 2019). The absence of transparency often leads to non-replicability, as studies fail to provide clear definitions, inadequately describe their methods, lack transparency in their discussions, or do not present raw data.

A replication study aims to reproduce the original findings. Successful replication occurs when the new study's results align with the original studies to a significant extent. Instead of requiring identical outcomes, the agreement of results is assessed on a gradient scale (Peels, 2019).

III. Ethical Integrity

Ethical breaches in research can have substantial repercussions. Over 70 cases have been meticulously recorded in diverse domains such as journalism, scientific research, and sports, magnifying ethical quandaries, biases, and ramifications. Prominent instances include the Wakefield study, which disseminated erroneous information and disclosed conflicts of interest relating to the Measles, Mumps, and Rubella (MMR) vaccine, thereby fostering significant vaccine hesitancy (Motta & Stecula, 2021). Acquisti *et al.* (2019) delve into cybersecurity, privacy, and ethics in information systems, emphasising the cruciality of ethical integrity in the digital era.

In summary, the axiological stance ensures that the research on designing a fault-tolerant architecture for NB-IoT networks strongly emphasises professionalism, ethical considerations, and scientific rigour. This alignment with the study's overall positivist approach enhances its academic credibility.

3.4 Discussion of the Existing Methodologies:

The scientific method and Engineering Design Process (EDP) differ significantly in their approaches to problem-solving. The EDP is design-driven, focusing on creating innovative solutions to practical issues (Feldman, 2017).

While interdependent, these two fields have distinct methodologies. The EDP is more practical and solution-oriented, while the scientific method is theoretical and geared towards discovery (Eekels & Roozenburg, 1991). In engineering education, there is a strong emphasis on creativity and innovation within the design process. This starkly contrasts the more structured and methodical scientific inquiry approach, where creativity plays a lesser role (Bruhl, 2020).

Design in engineering is considered more of a technology than a science, as it focuses on applying knowledge rather than just engaging in scientific inquiry (Cross *et al.*, 1981). Incorporating engineering design into education can enhance scientific reasoning, highlighting the interplay between these disciplines (Silk *et al.*, 2009). Furthermore, integrating scientific methods into the design process can improve the effectiveness of designs, while applying design approaches to science can lead to more efficient and effective scientific outcomes (Verkerke *et al.*, 2013).

In conclusion, the Scientific Method and Engineering Design Process, with their unique focuses, methodologies, and applications, offer complementary approaches to problem-solving and knowledge creation. Their integration can provide significant benefits in both fields.

3.5 The Evolution of Design Methodology

This study's evolution of design methodology aims to develop an iterative and reflective approach that addresses real-world engineering challenges while deeply rooted in empirical evidence and scientific principles. This methodology is designed to promote innovative and user-oriented solutions that are reliable, valid, and sustainable in the long term. By bridging the gap between the scientific method and the engineering design process, the study seeks to enhance the effectiveness and applicability of solutions in IoT network security.

The scientific method has historically been the cornerstone of discovery and validation, emphasising testing, systematic data collection, and iterative analysis. Concurrently, the engineering design process has excelled in translating abstract ideas into practical, user-focused

innovations. However, an evident divide has continued between these two realms, particularly in their different approaches to navigating challenges and fostering breakthroughs (Chang & Yen, 2023).

The following sections explore various design methodology models and their relevance to this study.

3.5.1 Archer's Model of the Design Process

Archer's model of the design process (Figure 3-2) is divided into three main phases: The analytical phase includes programming and data collection. This phase might involve defining the problem, gathering relevant data, and preparing for the design process. Creative phase - where analysis, synthesis, and development occur. This consists of interpreting data, conceptualising solutions, and creating design proposals. The executive phase is focused on communication. This phase relates to delivering the design solution, including communicating the design to stakeholders and preparing for its implementation. This model provides a structured approach to the design process, emphasising the different stages of thinking and activity from initial analysis through creative development to final execution (Cross, 2021).

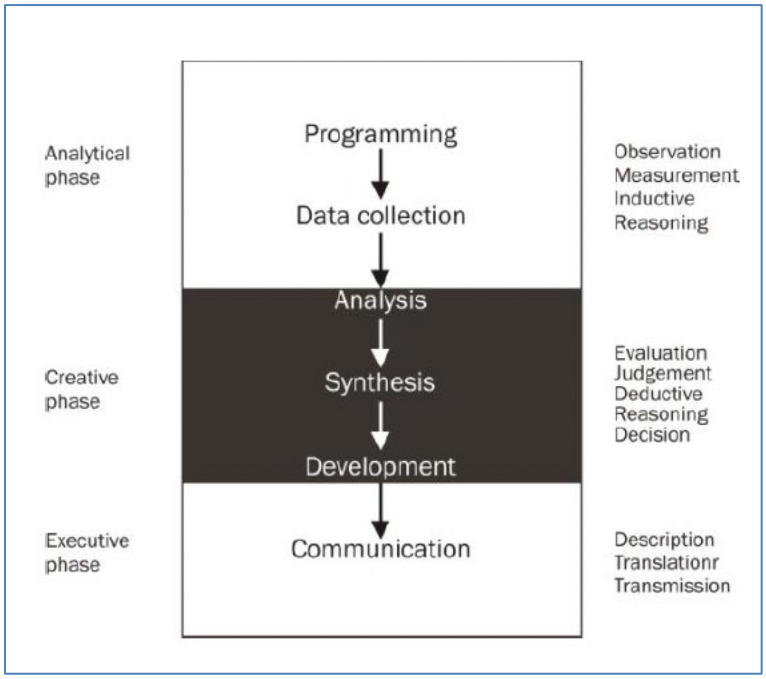

Figure 3-2: Archer's Model of the Design Process (Cross, 2021)

The design process model proposed by Archer suggests using different approaches at different stages. In the analytical phase, systematic observation and inductive reasoning are needed, while in the creative phase, subjective and deductive reasoning should be applied. However, this model did not meet the criteria for the study methodology used in the current study.

3.5.2 The life cycle of the product by Morris Asimow

Asimow's method, Figure 3-3, presents a structured approach to design, encompassing several distinct phases that guide a product from inception to disposal. The process begins with identifying the primary need, which is the fundamental requirement the design aims to satisfy. This is followed by Phase I, the Feasibility Study, where initial research is conducted to assess the viability of the design.

Asimow's method ensures that all aspects of a product's journey are thoughtfully considered. It provides a comprehensive framework for design, covering not only the design stages from conception to detailed planning but also extending to encompass the entire product lifecycle. This systematic approach ensures that all aspects of a product's journey, from identifying a need to its eventual disposal, are thoughtfully considered (Asimow, 1962).

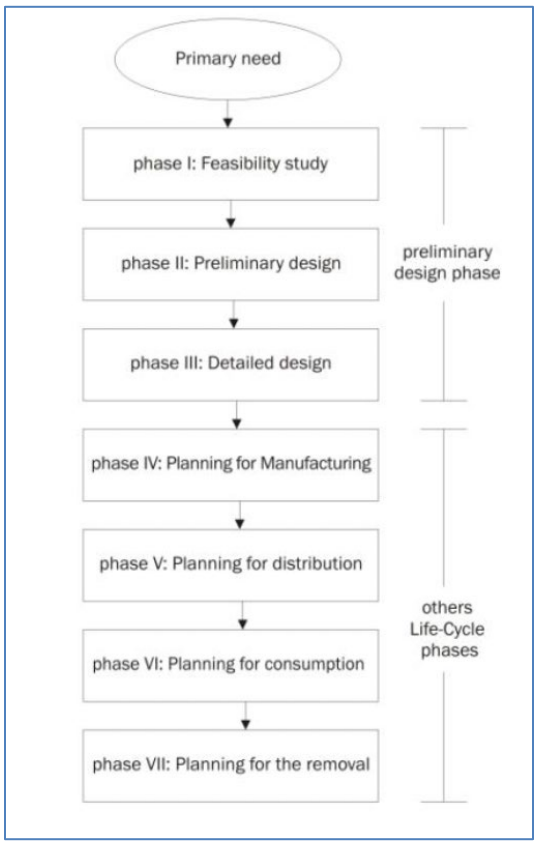

Figure 3-3: Asimow's Method (Asimow, 1962)

3.5.3 French's, Pahl and Beitz's Methods

French's method, Figure 3-4, initiates with identifying a need, followed by problem analysis, statement of the problem, and conceptual design. The subsequent steps involve selecting schemes, embodiment of schemes, detailing, and producing working drawings. Pahl and Beitz's method allows for more iteration and feedback throughout the process, especially in the conceptual and embodiment design phases (Roozenburg & Eekels, 1995).

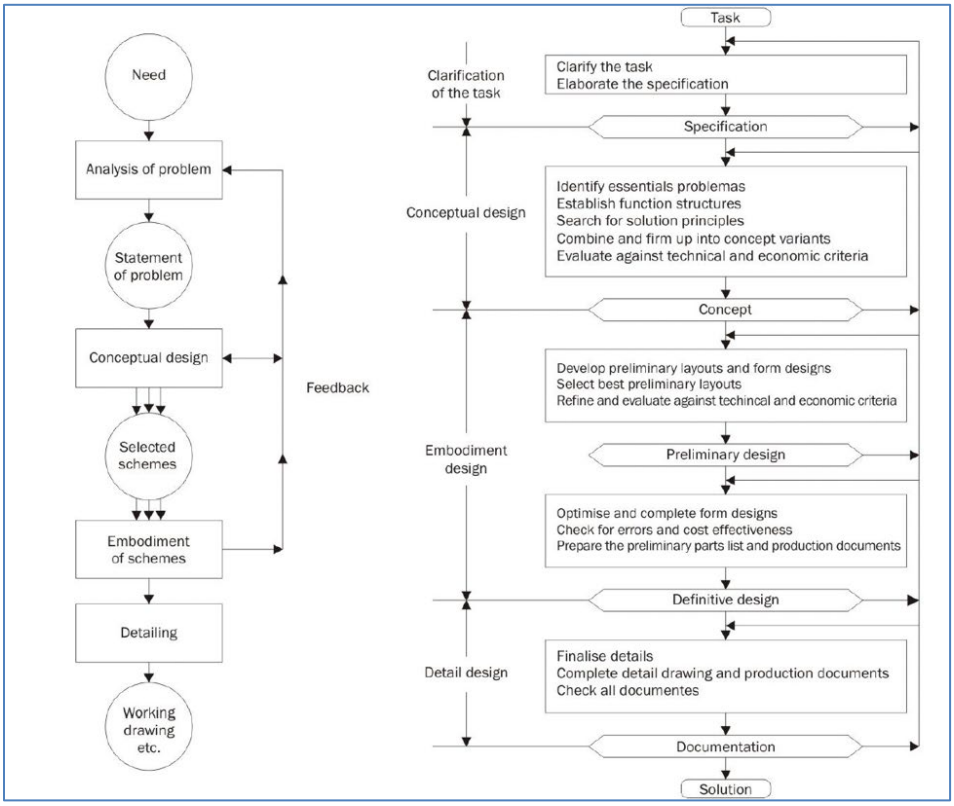

Figure 3-4: French's and Pahl and Beitz's methods (in Roozenburg & Eekels, 1995)

3.5.4 March's Diagram

March's design process model, Figure 3-5, emphasises design's complex, iterative, and interconnected nature. Central to the model is achieving a certain level of performance in the final product or solution. The model portrays design as a dynamic and cyclical activity where theory, practice, and empirical data continuously interact to refine and enhance both the process and the final design outcomes.

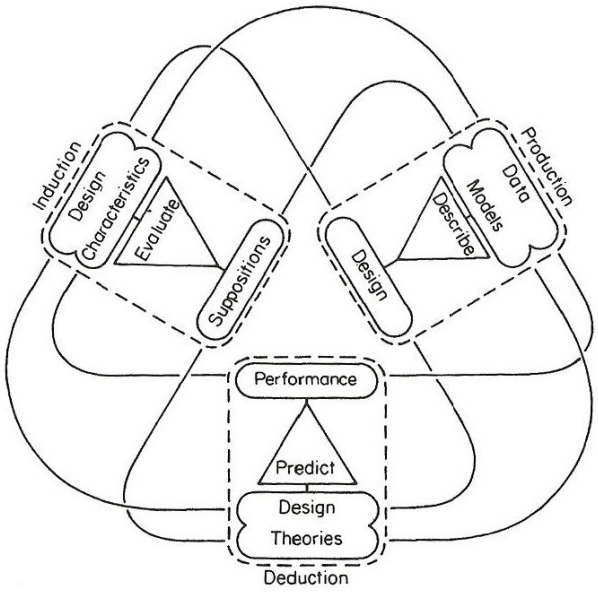

Figure 3-5: March's Diagram (Cross, 2021)

Table 3-1 outlines a comparison of differing iterative design methods determined by their characteristics.

Table 3-1: Comparison of Different Iterative Design Methods based on their Characteristics.

Method	**Linear/Non-linear**	**Objective**	**Reasoning**
Archer's Model	Non-linear	Problem-solving	Abduction
Asimow's Method	Linear	Full lifecycle design	Abduction
French and Pahl and Beitz	Non-linear	Comprehensive solution development	Abduction
Double Diamond	Non-linear	Divergent and convergent thinking	Abduction
March; s Design	Non-linear	Theoretical and practical application	Abduction

The objectives of the methods in Table 3-1 are diverse. They address immediate problem-solving, consider the broader design scope, including the entire product or service lifecycle, and focus on

human-centred design principles. This ensures that the end-user's needs and experiences are at the forefront of the design process, leading to more empathetic and user-friendly outcomes.

The Scientific Method and Engineering Design Process (SMED) is a novel framework that integrates the empirical discipline of scientific research with the creative problem-solving approach of engineering design and seeks to bridge the longstanding gap between these two fields, thereby enhancing solutions' accuracy, dependability, and applicability across diverse domains. SMED promotes a comprehensive, integrated methodology that facilitates the creation of intricate, multifaceted solutions to complicated problems, fostering interdisciplinary collaboration that combines scientific rigour with design ingenuity.

3.6 The Scientific Method and Engineering Design Process

As shown in Table 3-1, choosing the ideal model to integrate with the scientific method hinges on each project's unique demands and objectives. The scientific method is lauded for its structured and empirical approach to knowledge acquisition. It is characterised by systematically gathering data through observation or experimentation, and iteration based on new evidence.

Archer's Model offers phases parallel to the scientific method's steps. It is a potentially good fit for scientific projects that benefit from a solid analytical foundation (Cross, 2021). Asimow's Method provides a comprehensive, phase-by-phase progression that might be more sequential than the scientific method's iterative nature. However, it can still be adapted to fit the circularity of scientific investigations (Asimow, 1962).

French's Pahl and Beitz's Methods supply detailed, stepwise frameworks that reflect the scientific method's organised approach, especially in problem-solving and testing solutions (Pahl & Beitz, 1996). The Double Diamond model, with its divergent and convergent phases, could enhance the scientific method's exploratory aspects, particularly in the initial and final stages of research.

March's Diagram underscores the interplay between design processes, propositions, and the theoretical underpinnings that inform data production. This model's focus on prediction and empirical testing aligns closely with the scientific method's core principles (Cross, 2021).

This study's methodology is based on the Engineering Design (ED) process and the scientific method (SM). Figure 3-6 shows a systematic method for solving technical problems by considering

requirements and constraints to create new systems, products, and artefacts. This process draws inspiration from (Asimov, 1962; Pahl & Beitz, 1996; Cross, 2021).

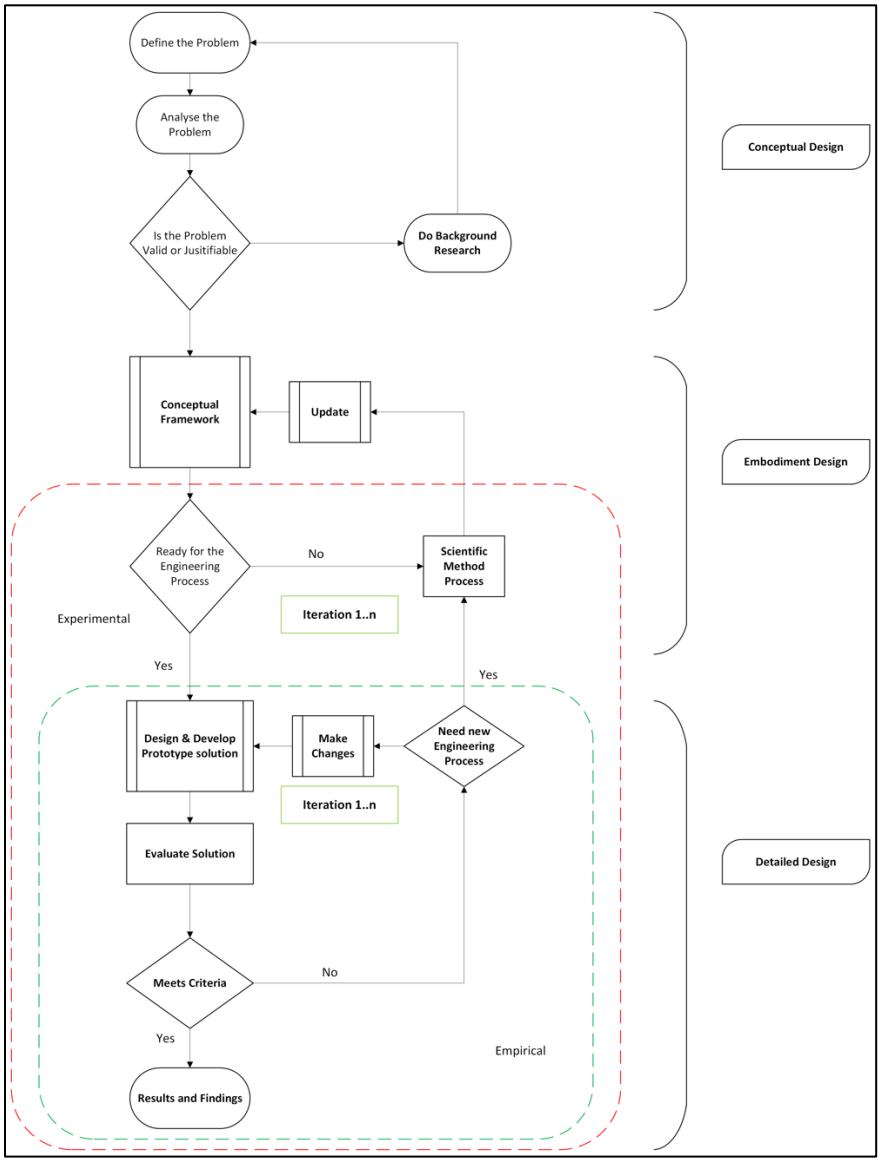

Figure 3-6: The Scientific Method and Engineering Design Process (SMED)

The engineering design process is a structured and systematic approach essential for addressing complex engineering challenges. This process is characteristically iterative and cyclical, often necessitating multiple rounds of refinement to reach a satisfactory solution. This approach ensures empirical validation for any new methodology or technological innovation, enhancing the research's credibility and grounding the solutions in observable reality, which aligns with the

positivist philosophy.

Therefore, the engineering design process benefits from the scientific method by providing a structured approach from problem identification to solution development and testing. This method leverages the strengths of scientific inquiry to tackle engineering challenges, ensuring that the final designs meet the necessary criteria and are replicable and sustainable in real-world applications.

The scientific method is characterised by its systematic and iterative nature as part of the embodiment design phase of the engineering design process. The scientific inquiry process is fundamental to engineering design.

The study's methodology showcases a strong parallel between these two domains, with each step demonstrating the application of the rigorous scientific method within the engineering design framework, as seen in Figure 3-6.

I. Defining the Problem

The process begins with clearly defining the problem within the context of NB-IoT network security, focusing on the scope, objectives, and specific challenges posed by DDoS attacks.

II. Analysing the Problem

After defining the problem, an analysis is conducted to determine its validity. If additional information is needed, background research is conducted to collect necessary data and insights.

III. Conceptual Design

This phase involves creating a conceptual framework that outlines foundational design aspects. It incorporates findings from the initial analysis and research.

IV. Embodiment Design

This phase involves selecting computational and experimental tools, which are used to build a mathematical model simulating NB-IoT network performance under various DDoS scenarios.

Engineering Design: Develops and tests prototypes based on the conceptual framework.

Scientific Method: Empirically tests whether validation has been achieved.

V. Applying the Scientific Method

Conceptual Framework: After the computational tools and experimental tools are selected based on input , process and output, if the results are not ready for the Engineering Process this leads back to the scientific method which integrated throughout the first iteration, ensuring a experimental approach. This includes experimentation and result analysis to validate the design's effectiveness.

VI. Applying the Engineering Process

Engineering Design: If ready for the Engineering process this stage leads to the analyses design performance and iteratively refines the prototype that leads to evaluating the solution.

Scientific Method: If the Design and Develop Prototype stage have passed on to the Evaluate solution stage and the solution needs changes or does not meet the criteria, a new engineering process will start and if the observed results are not met, this stage moves back to the Scientific method process to conduct further testing for more iterations. Apply the scientific method to re-examine the conceptual framework.

VII. Prototype and Testing

The prototype is designed and developed and rigorously tested under simulated conditions real-world DDoS attacks.

Engineering Design: Assesses if the solution fulfils the requirements, including fault tolerance and resilience against DDoS attacks.

Scientific Method: Only if the prototype process after the evaluation solution does not meet the criteria, the new engineering process decision would go back to the scientific process to analyse data to draw conclusive evidence about validity.

VIII. Iteration

If deficiencies are found, the process repeats, merging new results and data from the first

experimental stage to refine the design and development of the prototype. **Iteration 1..n**: Make necessary changes and iterate the design and development process based on empirical results and feedback.

IX. Meets Criteria (NO)

Determine if a new engineering process is needed. This iterative cycle is essential, allowing for continuous refinement and enhancement based on empirical evidence and performance metrics.

Engineering Design: Make changes and iterate the prototype design and development process until the solution meets the criteria. Integrates feedback into the design process for continuous improvement.

Scientific Method: Apply the scientific method and update the conceptual framework. Uses experimental data to inform future research and refine scientific theories.

X. Meets Criteria (YES)

The process concludes with a detailed design phase, finalising the refined model, resulting in a robust, tested, and validated solution for securing NB-IoT networks against DDoS attacks.

XI. Results and Findings

The findings are communicated to stakeholders, including comprehensive documentation of the process and outcomes for transparency and potential replication.

Engineering Design: Documents the design process and communicates the findings.

Scientific Method: Publishes detailed experimental results for peer review and replication.

By merging the engineering design process principles with an emphasis on experience and iteration, the study presents a novel methodology for network security. This process effectively bridges theoretical research and practical application, providing a systematic framework for tackling complex security challenges in NB-IoT networks.

3.7 The Conceptual framework

Chapter 4 Figure 4-2 mentions that the conceptual framework provides a structured approach to tackling challenges in Narrowband Internet of Things (NB-IoT) networks. It focuses on enhancing their resilience against faults, failures, and errors that may arise during data transmission. These issues often manifest as noise and entropy within the network, significantly impacting performance.

The conceptual framework for addressing challenges in Narrowband Internet of Things (NB-IoT) networks is structured to enhance resilience against faults, failures, and errors during data transmission. The framework components include:

I. **Information Source:** The origin of the data to be transmitted through the NB-IoT network.
II. **Transformation Process:** This encompasses the transmission and encoding of data. Faults, failures, and errors can occur during this stage, introducing noise and reducing the clarity of the information. The process considers network traffic entropy, randomness or disorder in network data that can indicate underlying issues.
III. **NB-IoT Delay-Tolerant Network (NB-IoTDTN):** A proposed version of the NB-IoT network designed to withstand delays and handle the variability in network traffic resulting from the transformation process. It includes nodes that adapt to environmental factors and provide feedback on network performance.
IV. **Environmental Factors (E)**: External influences can impact network performance, such as physical conditions, network congestion, or malicious attacks like DDoS. The framework considers these factors to ensure the model reflects real-world scenarios.
V. **Input (I)**: The algorithms and theories applied to manage and mitigate the impact of the transformation process on network performance. This could involve error correction algorithms, network optimisation strategies, or security protocols.
VI. **Output (O)**: The measurable outcomes from the network post-processing the inputs, including metrics like delays, jitter, latency, Packet Delivery Ratios (PDRs), and bandwidth.
VII. **Data Generation**: Analysing the metrics for faults, failures, and errors to generate data that informs improvements and adjustments in the network.

VIII. **Feedback (FB)**: Utilising information from the output to refine and improve the network's performance continuously.

The framework aims to fulfil the study's objectives by identifying and analysing current challenges in NB-IoT networks. The process includes:

I. Examining the network's impact of faults, failures, and errors.
II. Utilising a delay-tolerant network architecture to mitigate adverse effects.
III. Integrating environmental factors into the analysis to enhance realism.
IV. Applying theoretical inputs and algorithms to enhance network reliability and performance.

3.8 Integration of the Theoretical Foundations

In Chapter 2, an extensive review of Cybernetics, System Theory, and Information Theory was provided to establish a foundational understanding of these frameworks. This section now adapts these theories to the specific context of enhancing the resilience and security of Narrowband Internet of Things (NB-IoT) networks through fault-tolerant architecture.

I. **Cybernetics:** Cybernetics, with its focus on systems control and communication, is particularly relevant to this study as it provides a framework for understanding how NB-IoT architecture can be dynamically regulated to respond to external threats such as Distributed Denial of Service (DDoS) attacks. By leveraging feedback loops and control mechanisms, the proposed network architecture can maintain stability and ensure service continuity even in the presence of attacks.
II. **System Theory:** System Theory underpins the study’s approach to designing a fault-tolerant network by treating NB-IoT architecture as interconnected systems with various subsystems, such as edge computing nodes. This holistic perspective enables the design of an architecture that optimises data flow and minimises points of failure, ensuring that each component contributes to the overall resilience and functionality of the network.
III. **Information Theory:** Information Theory informs the data processing and communication strategies used within the NB-IoT architecture, particularly in relation to optimising bandwidth and managing data integrity. Concepts such as entropy and

redundancy are utilised to enhance the reliability of data transmission across network nodes, which is crucial in mitigating the impact of potential disruptions.

By applying these theoretical frameworks, the study aims to create a resilient and adaptive NB-IoT architecture that not only addresses current vulnerabilities but also leverages the strengths of each theory to enhance the network's overall security and performance.

3.9 Conclusion

This chapter discussed the Engineering Design Process and the Scientific Method. Both processes emphasise research and testing but diverge in their initial approach and ultimate goals. The study proposes a new combined (SMED) Scientific Method with The Engineering Design Process, which focuses on practical problem-solving and iterative improvement, while the Scientific Method is about understanding phenomena. The engineering design method, along with the theoretical underpinning theories, are embedded in the conceptual design of the NBIoT Delay-Tolerant Network (NBIoTDTN), which leverages edge computing to enhance security against DDoS attacks. The following chapter introduces the design of the prototype system.

CHAPTER 4 DESIGN OF THE MODEL

4.1 Introduction

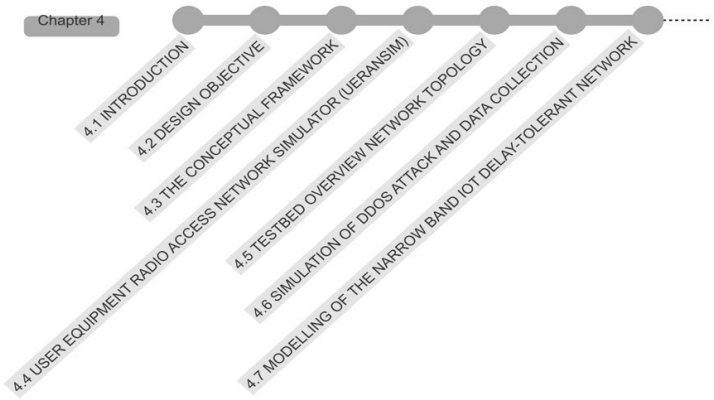

Figure 4-1: Chapter 4 Outline

The Design of the Model chapter begins with an Introduction that outlines the goals and structure of the chapter as shown in Figure 4-1. The Design Objective section clearly outlines the goals and purpose of the model being designed. This is followed by The Conceptual Framework, which includes a conceptual dependency graph specific to the NB-IoT delay-tolerant network design, establishing the theoretical foundation for the model.

The chapter then discusses the User Equipment Radio Access Network Simulator (UERANSIM), which is crucial for simulating the user equipment's interactions with the network. This section includes details on Mapping to the 5G Protocol Stack, highlighting the integration of UERANSIM with the 5G architecture.

Next, the Testbed Overview Network Topology section describes the physical and logical setup used for testing and validating the model. The chapter proceeds to cover the Simulation of DDoS Attack and Data Collection, detailing the process and tools used to simulate attacks and gather relevant data. Finally, the Modelling of the Narrow Band IoT Delay-Tolerant Network section provides insights into various theories applied in network management, including Systems Theory and Information Theory, to assess and enhance network performance.

4.2 Design Objective

The study adapted Cilium Container Network Interfaces (CNI) as container runtime a open-source networking and security tool designed for cloud-native environments, providing powerful and flexible connectivity, security, and observability for Kubernetes clusters. Unlike traditional Container Network Interfaces (CNIs), like Flannel, Calico, WeaveNet, Multus , Cilium leverages eBPF (extended Berkeley Packet Filter) technology to implement networking, load balancing, and security policies directly at the kernel level. This approach allows for dynamic, real-time policy enforcement and deep visibility into network traffic, making it ideal for modern microservices architectures.

In the study experimental setup, Cilium CNI plays a crucial role in managing and securing the network communications within a Lightweight Kubernetes (K3s) edge cluster composed of Raspberry Pi 5 nodes. By using Cilium, the study can not only ensure efficient and secure data flow between the different components of the study's 5G core network but also monitor and control network behavior with fine-grained policies. This is particularly important in the study's scenario where the study will simulate various network conditions, including malicious IP flooding attacks.

The iterative process of integrating Cilium CNI into the study involves several stages, starting from initial setup and basic configuration to advanced testing and optimisation. Initially, Cilium is deployed as the primary CNI, replacing traditional CNIs to take advantage of its eBPF-based data plane at the kernel level, upgrade the kernel if needed and reinstall the CNI when needed. The subsequent iterations also involve rigorous testing using CUBIC network congestion avoidance algorithm for TCP the default Linux transport algorithm, adding and enabling and fine-tuning the bandwidth manager, upgrading the Linux kernel to the latest version to measure performance, and applying rate limiting to manage network traffic effectively.

Monitoring and observability are integral parts of this setup, facilitated by Hubble, a component of Cilium CNI, along with Prometheus and Grafana for data collection. These tools allow the study to visualise network traffic, identify and block malicious activities, and measure performance metrics. The iterative enhancements, including switching from CUBIC to BBR a new algorithm for TCP Congestion Control, will demonstrate Cilium's flexibility and effectiveness in maintaining network stability and performance under various conditions.

Overall, Cilium's integration into our K3s edge cluster not only enhances security and performance

but also provides valuable insights through comprehensive observability features, making it a cornerstone of our network management strategy in this experimental setup.

4.3 The Conceptual Framework

The foundation of this research is structured around a conceptual model that draws from traditional communication theory merged with modern computational theories. As depicted in the diagram provided in Figure 4-2, the foundational premise is rooted in the standard communication process, comprising the following essential elements: Information Source, Transmitter, Receiver, and Destination. However, integrating advanced computational and networking components, specifically narrow-band IoT delay-tolerant networks (NB-IoTDTN) and Edge and fog networking paradigms, differentiates this model.

This conceptual model emphasises enhancing the traditional communication framework by incorporating elements that address IoT security and performance challenges. The addition of NB-IoTDTN aims to provide a robust solution for mitigating delays and improving the reliability of IoT applications. Similarly, integrating Edge and fog networking paradigms enhances the model by bringing computational resources closer to the data source, thereby reducing latency and improving real-time data processing capabilities.

By leveraging these novel components, the conceptual model offers a comprehensive approach to addressing the specific challenges associated with IoT security and performance. It builds upon the established principles of communication theory and incorporates innovative technologies to ensure a resilient and efficient IoT network infrastructure.

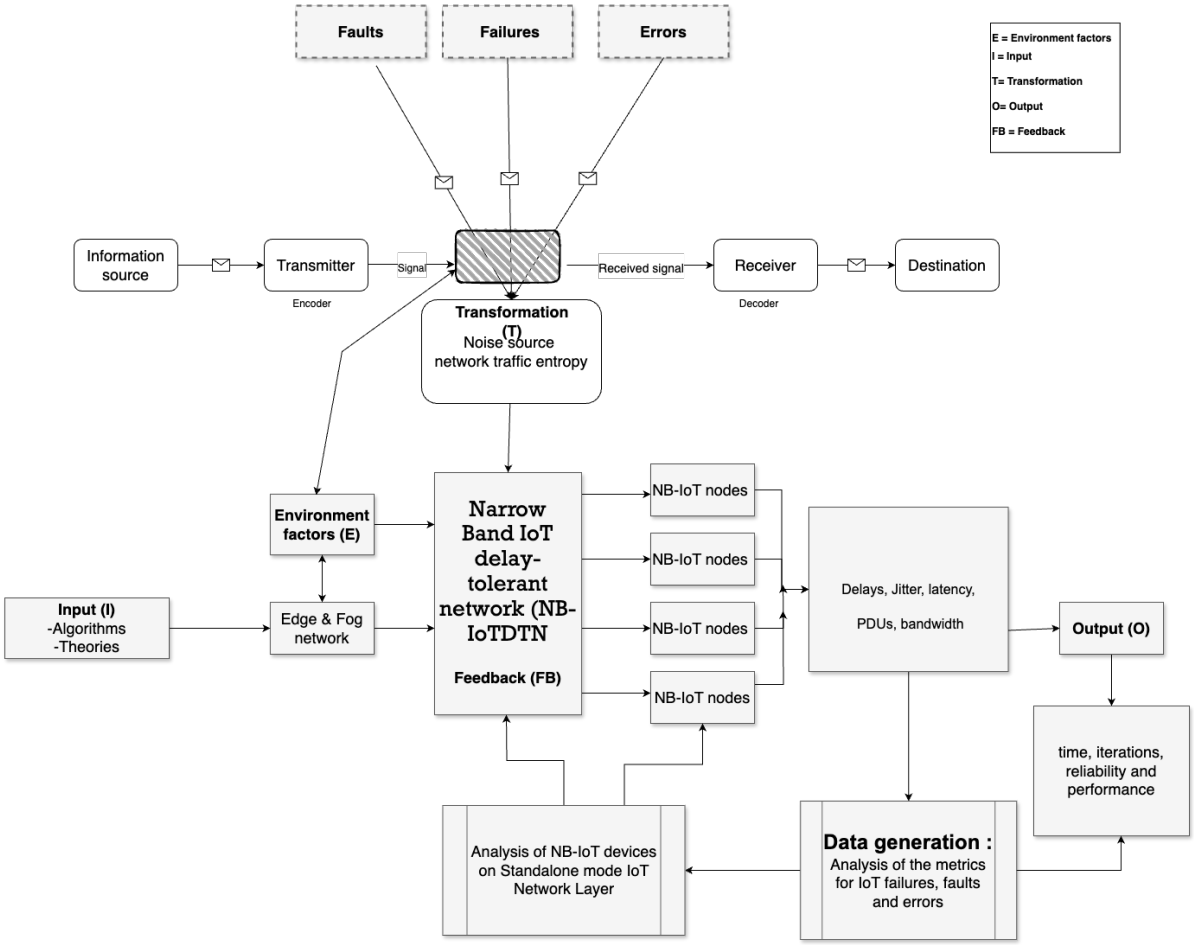

Figure 4-4-2: Conceptual Model

As shown in Figure 4-2 above, the proposed framework explains the complex relationship between various components. It begins with an 'Input' phase, representing the algorithms and theories that inform the transmission. The 'Transformation' phase embodies the network's dynamic nature, influenced by environmental factors and potential threats like network traffic entropy. The 'Output' phase identifies the results of these interactions, signifying measurable metrics like delays, jitter, latency, and bandwidth. A 'Feedback' loop is incorporated to ensure continuous improvement and adaptation based on real-time data and analysis.

The conceptual framework involves NB-IoT network testing from the input phase to data generation and analysis while considering the impacts of delays and latency due to DDOS attacks. The input phase selects algorithms and theories that will be tested on the edge computing network and feeds these algorithms into the network as input. The transformation phase encodes the input

signals at the transmitter. Here, the study introduces controlled noise and interference to reproduce real-world conditions and monitor the network traffic entropy.

The feedback loop mechanism reproduces real-world scenarios in which the network adjusts to environmental factors. The feedback informs the input algorithms and adjustment theories. The output phase receives the signals at the designation and decodes them to analyse the output in terms of time, iterations, reliability, and performance.

The data generation and analysis collect data on delays, jitter, latency, PDUs, and bandwidth. NB-IoT modes, such as in-band, guard band with an LTE 5G network, and standalone mode network layer, are inspected to assess the metrics of latencies, faults, and errors.

4.3.1 Conceptual Dependency Graph for NB-IoT Delay-Tolerant Network Design

This dependency graph, Figure 4-2, visually represents the main design modules involved in a NarrowBand Internet of Things (NB-IoT) delay-tolerant network. This graph aims to illustrate the flow of data and the interdependencies between various components within the network.

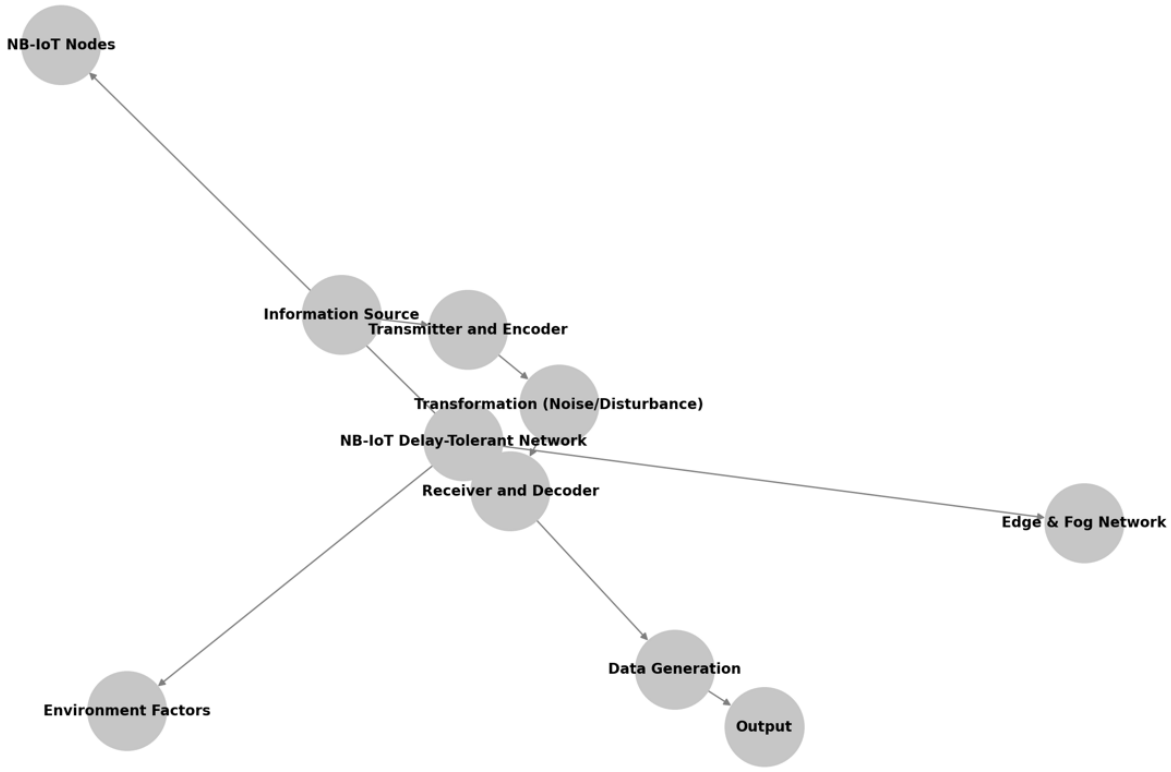

Figure 4-3: Dependency Graph of the Main Design Modules

4.3.2 Modules and Their Roles

Modules are associated with several roles, namely:

I. **Information Source**: The origin of raw data that needs to be transmitted through the network.
II. **Transmitter and Encoder**: Processes and encodes the raw data from the Information Source for transmission.
III. **Transformation (Noise/Disturbance)**: Represents environmental factors that introduce noise and disturbances, affecting the data transmission.
IV. **Receiver and Decoder**: Receives and decodes the transmitted data for further processing.
V. **NB-IoT Delay-Tolerant Network (NB-IoT DTN)**: The core network module handles communication among NB-IoT nodes, ensuring reliability and delay tolerance.
VI. **Edge & Fog Network**: Provides additional computational and storage resources close to the data source, reducing latency and improving processing efficiency.
VII. **Environment Factors**: External conditions that impact the network, introducing faults, failures, and errors.
VIII. **NB-IoT Nodes**: Individual IoT nodes within the network that communicate with each other and the core network.
IX. **Data Generation**: Analyses network performance metrics, including delays, errors, latency, and bandwidth.
X. **Output**: The final metrics indicating the network's performance, including time, reliability, and overall efficiency.

4.3.3 Flow and Dependencies

I. Data originates from the Information Source and is processed by the Transmitter and Encoder.
II. The encoded data is affected by environmental noise and disturbances, modelled by the Transformation module.
III. The Receiver and Decoder then process this data and feed it into the NB-IoT Delay-Tolerant Network.

IV. The core network interacts with NB-IoT Nodes, Edge & Fog Network, and Environment Factors.
V. The Data Generation module analyses the metrics from the network and provides the Output, indicating the network's performance.

4.4 User Equipment Radio Access Network Simulator (UERANSIM)

User Equipment Radio Access Network Simulator (UERANSIM) is a tool used to simulate the behaviour of 5G user equipment (UE) and its interactions with the radio access network (RAN). Here is a breakdown of what the provided information means:

I. **No Implementation Below RRC Layer**: UERANSIM does not simulate the 5G radio protocols below the Radio Resource Control (RRC) layer. This means it does not implement the Physical (PHY), Medium Access Control (MAC), Radio Link Control (RLC), and Packet Data Convergence Protocol (PDCP) layers.
II. **Partial Simulation over UDP**: The 5G radio interface is partially simulated using the UDP protocol over port 4997. This allows some level of communication and interaction simulation between the UE and the RAN without fully implementing the lower layers of the 5G radio protocol stack.
III. **Main RRC Procedures**: UERANSIM includes the main RRC procedures, which are responsible for controlling the connection between the UE and the network, such as establishing, maintaining, and releasing the RRC connection, security handling, and mobility management.

4.4.1 Mapping to the 5G Protocol Stack

In the context of 5G, the protocol stack can be mapped to the TCP/IP model as follows:

I. Application Layer: 5G applications and services.
II. Transport Layer: Protocols like Stream Control Transmission Protocol (SCTP), UDP, and TCP.
III. Internet Layer: IP for routing and addressing.
IV. Network Interface Layer: PHY, MAC, RLC, and PDCP protocols in the 5G stack,

Since UERANSIM does not implement PHY, MAC, RLC, and PDCP, it directly interacts at the

higher layers (RRC and above), using UDP to simulate the lower-layer interactions. This means that while UERANSIM can simulate the control and signaling aspects of 5G (handled by RRC), it does not simulate the actual data transmission mechanisms (handled by PHY, MAC, RLC, and PDCP).

It is based on one of the study objectives, namely, to evaluate the reliability and performance of the networking layer of the NB-IoT IoT architecture. The Ueransim context of 5G is the Internet layer, which delineates this objective.

4.5 Testbed Overview Network Topology

The lightweight Kubernetes (K3s) cluster consists of three server nodes with the control plane and the distributed reliable key-value store (etcd), storing cluster information and components managed by K3s, as shown in Figure 4-7. The K3s cluster runs three agent nodes that do not have the control plane and datastore components. The three server nodes are set up to achieve high availability and continue to work as one in case one server node fails.

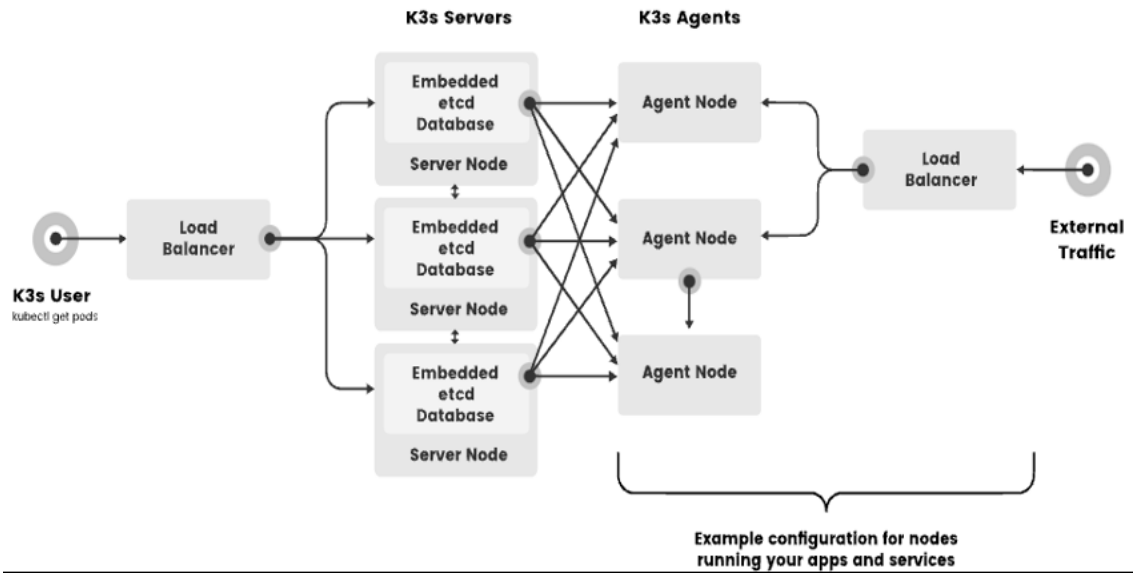

Figure 4-4: K3s Cluster (K3s Project, 2024)

Each K3s Kubernetes cluster node is installed on Ubuntu Server 22.04.3 LTS with the following server specifications:

- Broadcom BCM2712 2.4GHz quad-core 64-bit Arm Cortex-A76 CPU.
- 8GB LPDDR4X-4267 SDRAM.
- 16 GB Micro SD.

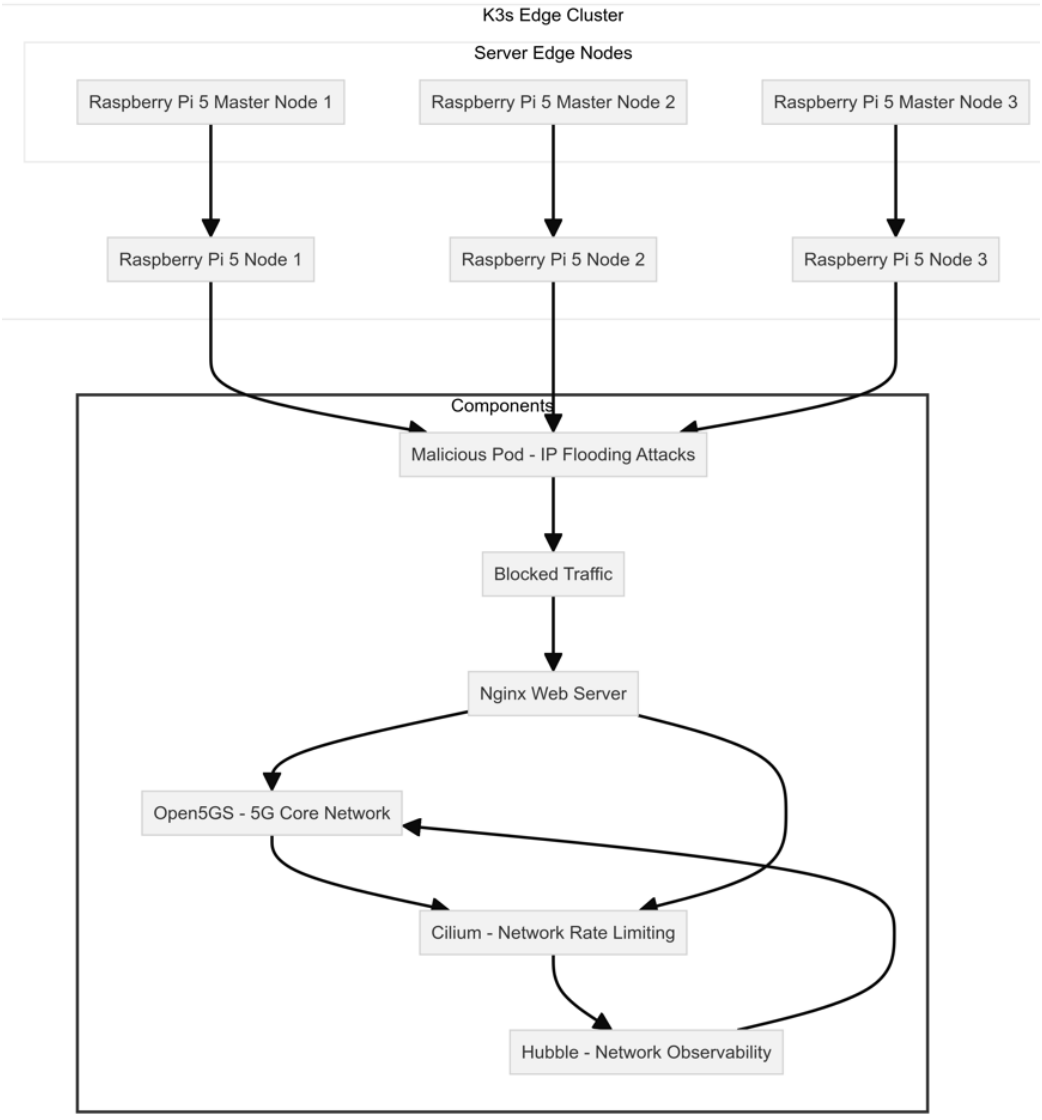

Figure 4-5: K3s Cluster for Edge Computing Testbed

The configuration in Figure 4-8 involves an architecture that utilises multiple Raspberry Pi nodes to create a lightweight Kubernetes (K3s) cluster. The cluster is integrated with Cilium for network

security and observability and Open5GS for 5G core network functionalities.

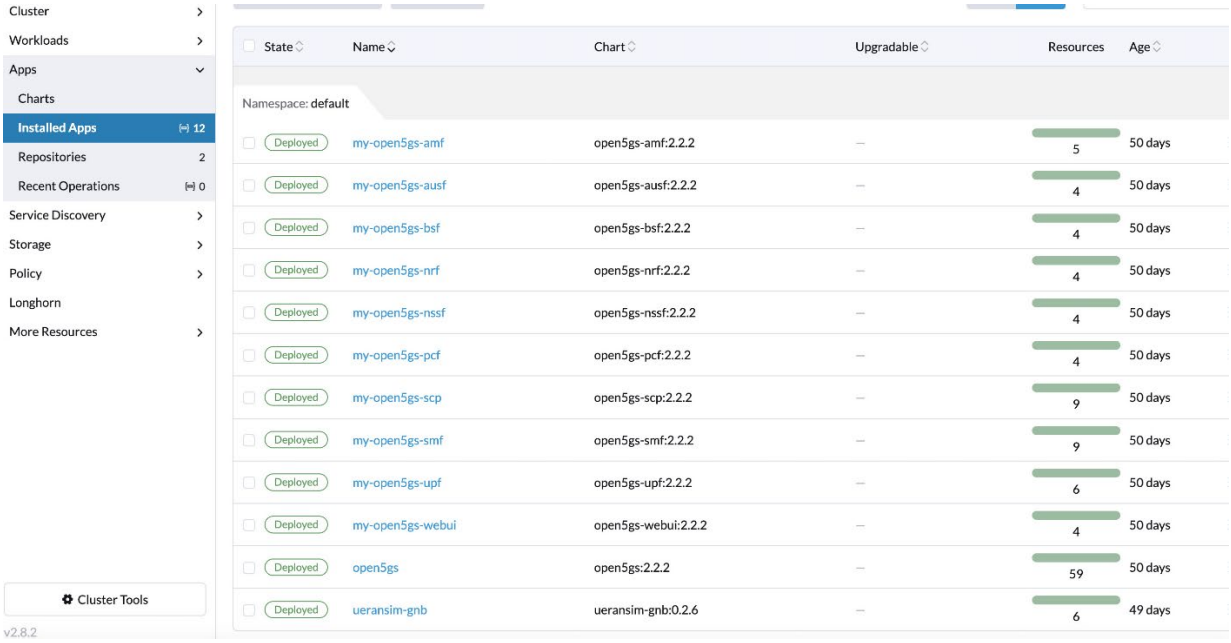

Figure 4-6: Open5g SA on K3s with Rancher

Longhorn UI is used to manage Kubernetes' persistent storage. It displays the status and readiness of nodes within a K3s cluster. Each node, identified by its name and IP address, has various attributes such as status (Schedulable or unschedulable), readiness (all showing as Ready), the number of replicas, allocated and used storage, and the total storage size available. The nodes listed include k3s-node1, k3s-node2, k3s-node3, k3s-worker1, k3s-worker2, and k3s-worker3. The storage usage varies among nodes, with the "Used" column indicating the amount of storage currently in use out of the total available. Nodes marked as unschedulable will not accept new workloads, while those marked as Schedulable are available for new tasks.

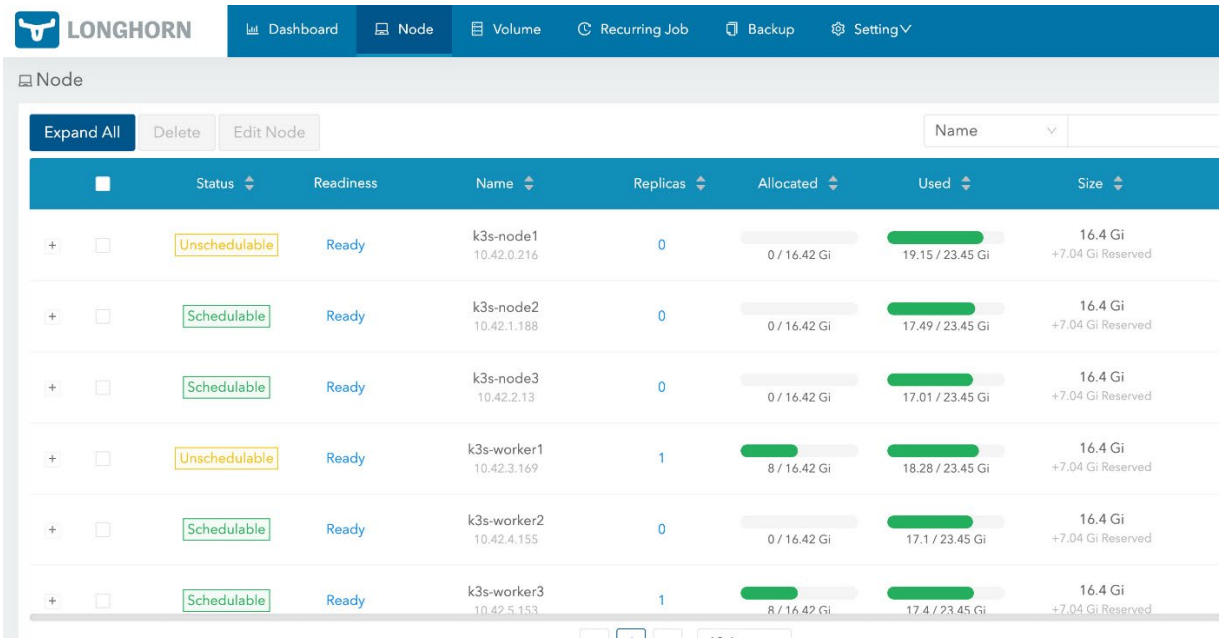

Figure 4-7: Longhorn UI Console

Three central K3s server nodes manage the cluster (Figure 4-11), which oversees the entire Raspberry Pi node network. Each node in the cluster hosts different components that are essential for the system's operation.

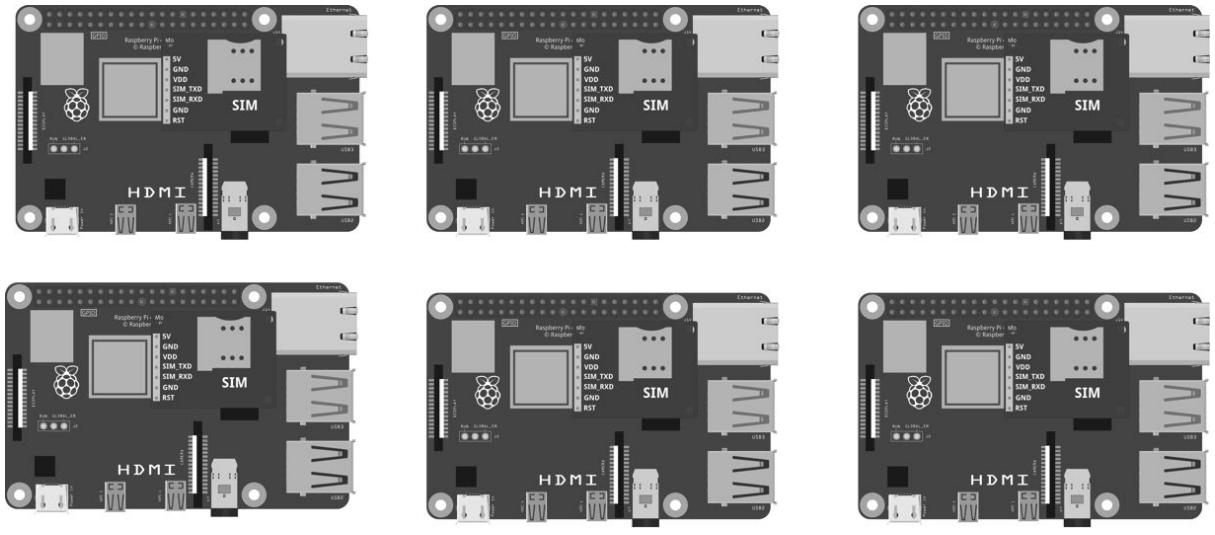

Figure 4-8: Raspberry Pi Nodes with SIM7020 Module

4.6 Simulation of DDOS Attack and Data Collection

The goal of this objective was to evaluate the performance of the network layer. The study utilised UERANSIM v3.2.6 to simulate UE (User Equipment) behaviour within a 5G network environment supported by Open5GS as pods on the k3s architecture. The primary aim was to investigate the network's resilience and capacity to manage high signalling loads induced by a sudden increase in active User Equipment (UEs). This setup simulated real-world network conditions, allowing for an assessment of the Radio Access Network (RAN)'s performance under stress.

The method involved establishing Stream Control Transmission Protocol (SCTP) connections to the core network and initiating Next Generation Application Protocol (NGAP) sessions, which are crucial for communication between User Equipment (UE) and the network's core. The study deliberately increased the number of UEs to simulate a DDoS attack scenario, focusing on the network’s ability to handle high-volume signalling traffic and maintain service continuity across different network slices. A significant observation was the network's failure to support specific network slices, evidenced by a "slice-not-supported" error, pointing to potential limitations or misconfigurations in the network’s slice management capabilities.

Further findings included intermittent signal detection and loss across multiple UEs, indicating possible issues with signal stability and network capacity during high-load conditions. These outcomes underscore the need for robust network infrastructure and effective slice management to ensure network reliability and performance, particularly under DDoS attack scenarios, which are becoming increasingly common in modern telecommunications environments.

DDoS attacks were simulated by artificially generating high signalling requests from the UEs to the network. This was achieved by modifying the Open5GS-populate script to register the UEs and make them simultaneously attempt to connect to and engage with the network services. The intensity of the attack was controlled by the number of subscribers activated concurrently and the frequency of their connection requests.

The simulated DDoS attack involved:

I. High Frequency of Registration Requests: Each UE repeatedly attempted to register with the network at a high frequency, overwhelming the network’s ability to process these requests.

II. Simultaneous Service Requests: UEs concurrently requested multiple services to maximise stress on the network resources.

By integrating these simulated DDoS conditions into the test scenarios, the model aimed to evaluate how well the Radio Access Network (RAN) and core network components of Open5GS, when adapted for the proposed NB-IoT-DTN, can withstand and adapt to extreme and malicious traffic patterns, which are representative of potential real-world cyber threats. This approach specifically tests the NB-IoT-DTN's capacity to maintain service continuity and data integrity under adverse conditions. The methodology not only provides insights into the resilience and scalability of the 5G network infrastructure but also highlights the effectiveness of the NB-IoT-DTN in mitigating the impact of DDoS attacks, thereby validating its fault-tolerant design.

The monitoring of metrics was conducted using Prometheus and Grafana, with the installation and configuration details provided in Appendix A.1.

To add subscribers in Open5GS using a Kubernetes pod, the model incremented the number of UEs from 1,000 to 10,000 and 10,000,000. The model observed an increase in resources and network traffic. However, this highlights that the DDOS attack was already in progress, and this study aimed to prevent a DDOS attack by designing a delay fault-tolerant system.

4.7 Modelling of the Narrow Band IoT Delay Tolerant

4.7.1 Systems Theory in Network Management

Systems Theory in network management aims to understand and model the complex interactions within a network. This involve analysing how various components, such as nodes, routers, and protocols, interact and influence each other to achieve desired network behaviours and performance metrics.

4.7.1.1 Mathematical Framework

State-Space Representation: Step 1:

Identify all components involved in the network the components are:

- Node: k3s-Mnode1
- Node: k3s-Mnode2
- Node: k3s-Mnode3
- Node: k3s-Wnode4
- Node: k3s-Wnode5
- Node: k3s-Wnode6

Next, the state-space representation was defined after identifying the network's components.

$$\mathrm{xc(t)} = \sum_{k=1}^{1} CPU\ (t)_i \tag{4.1}$$

$$\mathrm{xr(t)} = \sum_{k=1}^{1} RAM\ (t)_i \tag{4.2}$$

- State Vector $xc(t)$: Represents the state of the system CPU usage at time t.
- State Vector $xr(t)$: Represents the state of the system CPU usage at time t.

The total CPU(4.1) and RAM(4.2) are calculated per node as the state variables over time.

The state-space representation is a mathematical model used to describe the dynamics of a system. It provided a compact and structured way to represent the relationships between the state

variables, inputs, and outputs of the system. The state equations(4.3) showed how the system evolve over time, given its current state and the external inputs. The output equation(4.4) showed how the outputs of the system are determined by both its current state and the external inputs.

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t) \tag{4.3}$$

$$y(t) = Cx(t) + Du(t) \tag{4.4}$$

$$u(t) = \sum_{k=1}^{1} TRAFFIC\ (t)_i \tag{4.5}$$

$$y(t) = \sum_{k=1}^{1} Throughput\ (t)_i \tag{4.6}$$

- Input Vector u(t): Represents external inputs like traffic patterns, user requests, and configuration changes in the system.
- Output Vector y(t) , Represents performance metrics like latency, throughput, and error rates, which are the system outputs.
- System Matrices A, B, C, D the relationships between the state, input, and output vectors.

In the context of the study Kubernetes-based K3s IoT network:

- The **state equation** helped the study understand how the CPU and RAM usage across nodes evolved over time, influenced by both internal network dynamics and external traffic patterns and configurations.
- The **output equation** helped the study relate these internal states to observable performance metrics, which allowed the study to monitor and manage the network's performance effectively.

4.7.1.2 Feedback Control

Feedback control is essential to the NB-IoT-DTN as it ensures network stability and optimises performance by dynamically adjusting system parameters in response to real-time changes. In this context, the feedback control mechanism continuously monitors key performance metrics such as CPU usage, RAM usage, latency, and throughput and makes adjustments to the input

vector These adjustments help the network adapt to varying traffic loads and external disruptions, such as Distributed Denial of Service (DDoS) attacks, thereby maintaining service continuity and minimizing delays.

By implementing feedback control, the NB-IoT-DTN can achieve the desired fault tolerance. Specifically, it helps to:

I. Regulate Resource Utilisation: By monitoring CPU and RAM usage, the system can prevent resource overutilisation and maintain efficient operation.
II. Optimize Network Response: Feedback control fine-tunes the system response to manage traffic and reduce latency under different load conditions, which is critical for NB-IoT applications that require reliability and quick response times.

4.7.1.3 System Simulation with Feedback Control

The code in Appendix A.2 defines a simple linear system using System Matrices A, B, C, D representing a state-space model where A governs the state transitions and B represents how the input affects the states.

The three matrices as presented in Equations $(4.7)(4.8)(4.9)$ was carefully chosen to influence the system to achieve specific performance goals, such as minimising latency, balancing load, or optimising throughput. As the state xc(t) and xr(t) changed over time, the control input u(t) (4.5) was continuously adjusted to maintain or achieve the desired system performance. This real-time adjustment helped in maintaining system stability and optimal performance.

Three different gain matrices,

Feedback Gain K1

$$\begin{bmatrix} 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (4.7)$$

Feedback Gain K2

$$\begin{bmatrix} 0{,}5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (4.8)$$

Feedback Gain K3

$$\begin{bmatrix} 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (4.9)$$

By using feedback control$(4.10)(4.11)$, the study adjusted the input vector u(t) based on the current state xc(t) and xr(t) to achieve desired performance outcomes, ensuring the network operates efficiently and resiliently.

$$u(t) = -Kxc(t) \quad (4.10)$$

$$u(t) = -Kxr(t) \quad (4.11)$$

Three different gain matrices, K1, K2, and K3, are defined to explore how varying levels of feedback affect system behaviour.

I. K1(4.7): Provides a stronger gain of 0.2, which likely leads to a faster response.

II. K2(4.8): A weaker gain of 0.05, potentially leading to a slower and more stable response.

III. K3(4.9): Uses mixed gains, with different values for each component, to balance responsiveness and stability.

The system's response (state variables over time) is plotted to illustrate how each gain matrix affects the dynamics. Each subplot represents a state variable for the six-node system.

Prometheus was used as the data collection tool to retrieve the CPU usage sum of nodes by summarising(4.1) the rates except for the idle per instance. The RAM usage was calculated by(4.2) calculating the fraction of the available memory. The simulation simulated the system using different feedback gains $K1$, $K2$, $K3$ to simulate the values of the system.

4.7.1.4 Real-Time Data Retrieval from Prometheus

The code in Appendix A.2 connects to a Prometheus server at http://k3s-node:9090 to retrieve metrics on CPU and RAM usage. The Prometheus queries are designed to:

I. CPU Usage: Fetch the total CPU utilization, excluding idle time, averaged over the instances.
II. RAM Usage: Compute the proportion of available memory relative to the total memory for each instance.
III. Prometheus Query Execution: The get_prometheus_metrics function fetches data using custom_query_range, allowing you to specify a time range and resolution for the data.
IV. Plotting the Metrics: The plot_metrics function visualises the time series data for CPU and RAM usage, helping to monitor real-time resource utilisation on each node.

By querying real-time metrics, the study can compare the simulated performance with actual data, helping validate the NB-IoT-DTN model. Monitoring CPU and RAM usage helps understand if the network can handle loads and maintain fault tolerance.

4.7.1.5 Procedure for Correlation and Trend Analysis

Using Prometheus as the monitoring tool, CPU and RAM usage metrics are retrieved at 30-second intervals. PromQL queries are used:

I. CPU Usage: sum by (instance) (rate(node_cpu_seconds_total{mode!="idle"}[1m]))
II. RAM Usage: sum by *(instance) (node_memory_MemAvailable_bytes / node_memory_MemTotal_bytes)*

These metrics are gathered for each instance in the network to analyze real-time resource utilisation.

a) The raw metric data is converted into pandas DataFrames for easy manipulation. Each metric's data is timestamped and labeled by instance, which corresponds to each node in the network.
b) CPU and RAM usage data are merged into a single DataFrame based on the timestamp and instance. This combined DataFrame allows for parallel analysis of both metrics.
c) The correlation between CPU and RAM usage is calculated for each instance using the Pearson correlation coefficient. This reveals how strongly CPU and RAM usage are related over the observed time.
d) A time series plot is generated to visualise the trends in CPU and RAM usage over time for each node. This helps in identifying patterns, such as periods of high or low usage and synchronised behavior across nodes.

4.7.1.6 Stability Analysis Under Normal Conditions

Lyapunov's direct method was used to determine the stability of an equilibrium point in the system to ensure the network's stability. The method involved constructing a Lyapunov function (4.12) with the following properties:

$$V(x) = x^T P x \tag{4.12}$$

Lyapunov's direct method involved finding a Lyapunov function $(\mathrm{V}(\mathrm{x}))$ to determine the stability of an equilibrium point in the system. A common choice for the Lyapunov function is $(\mathrm{V}(\mathrm{x}) = \mathrm{x}^{\mathrm{T}}\mathrm{P}\mathrm{x})$, where (P) is a positive definite matrix. The function should satisfy:

1. $(\mathrm{V}(\mathrm{x}) > 0)$for all $(\mathrm{x} \neq 0)$ (positive definite).
2. $(\frac{dV(x)}{dt} < 0)$ (negative definite along trajectories of the system).

If such a function $(V(x))$ can be found, the equilibrium at $(x = 0)$ is stable.

4.7.1 Information Theory in Network Management

Shannon's Information Theory is a powerful tool for analysing the capacity and performance of communication networks, especially when the study considered the impact of legitimate versus malicious traffic.

Entropy $(4.13)(H)$ measures uncertainty or randomness in the system. In the context of network traffic, entropy was used to calculate the unpredictability of traffic patterns. High entropy indicated a high level of uncertainty, while low entropy indicated more predictable patterns.

$$H(X) = -\sum_{i=1}^{n} p(x_i) \log p\,(x_i) \tag{4.13}$$

Where $\mathrm{H(X)}$ is the entropy of the traffic source (X) and $\mathrm{p(x_I)}$ is the probability of the probability of occurrence of event x_i.

Mutual Information (4.14) (I) quantifies the amount of information obtained about one random variable through another random variable. Mutual information was used to measure the amount of legitimate information to be extracted from the network traffic in the presence of malicious traffic.

$$I(X;Y) = H(X) - H(X \mid Y) \tag{4.14}$$

- Where $\mathrm{I(X;Y)}$ is the mutual information between legitimate traffic X and observed network traffic Y.
- H(X) was the entropy of legitimate traffic.
- H(X|Y) was the conditional entropy of legitimate traffic given the observed traffic.

Given the entropy values, the study needed the conditional entropy H(X|Y) to compute the mutual information. If the study assumed that the entropy values provided were the total entropies of the system, the study would consider these in the mutual information context.

The study used the Equation (4.14) as formula to compute the mutual information.

Where:

H(X) is the entropy of legitimate (normal) traffic.

H(X|Y) is the conditional entropy given the observed network traffic.

Channel Capacity (4.15) is the maximum rate at which information is reliably transmitted over the communication channel.

$$C = \max_{p(x)} I(X;Y) \tag{4.15}$$

Where C Is the channel capacity, and I(X; Y) is the mutual information between the transmitted signal X and the received signal Y.

To find the channel capacity C the study took the maximum of the mutual information values for both receiving and sending network traffic.

$$C = B \log_2 \left(1 + \frac{N}{S}\right) \tag{4.16}$$

Where C is the channel capacity, B is the bandwidth, S is the power of the signal (legitimate traffic), and N is the power of the noise (malicious traffic).

4.7.1.1 Evaluating the malicious pod with cilium rate limiting applied

This part of the evaluation introduced a rate limiter that operates at the BPF (Berkeley Packet Filter) level within Cilium to prevent high CPU utilisation by the Cilium agent. This was particularly beneficial for smaller nodes like the Raspberry PI, where excessive CPU usage by the cilium-agent cloud starved other processes.

4.7.1.2 CUBIC to BBR algorithm for Linux Kernel

The study used Ansible playbooks to connect through a bootstrap node to remotely enable the BBR algorithm see Figure 4-12, this was done after all the nodes kernel Linux was upgraded to the latest.

```
PLAY [Check if BBR is enabled] ************************************************************

TASK [Get TCP congestion control algorithm] ***********************************************
changed: [k3s-worker2]
changed: [k3s-worker1]
changed: [k3s-node1-master]
changed: [k3s-worker3]
changed: [k3s-node2]
changed: [k3s-node3]

TASK [Print TCP congestion control algorithm] *********************************************
ok: [k3s-worker2] => {
    "msg": "TCP Congestion Control Algorithm: net.ipv4.tcp_congestion_control = bbr"
}
ok: [k3s-node2] => {
    "msg": "TCP Congestion Control Algorithm: net.ipv4.tcp_congestion_control = bbr"
}
ok: [k3s-node3] => {
    "msg": "TCP Congestion Control Algorithm: net.ipv4.tcp_congestion_control = bbr"
}
ok: [k3s-worker1] => {
    "msg": "TCP Congestion Control Algorithm: net.ipv4.tcp_congestion_control = bbr"
}
ok: [k3s-node1-master] => {
    "msg": "TCP Congestion Control Algorithm: net.ipv4.tcp_congestion_control = bbr"
}
ok: [k3s-worker3] => {
    "msg": "TCP Congestion Control Algorithm: net.ipv4.tcp_congestion_control = bbr"
}
```

Figure 4-9: BBR Congestion Algorithm

4.7.1.3 Deployment for test evaluation CUBIC with BPF

In the study's Cilium setup on the K3s cluster, the configuration successfully enabled the BPF bandwidth manager (Figure 4-13), and the cubic congestion control algorithm. The initialisation process confirmed that the system met the baseline requirements for parameters. This setup, combined with Cilium's BPF-based data path, aimed to optimise traffic management and improve network performance. However, while enabling Big TCP for IPv6 was successful, an error ("invalid argument") prevented its activation for IPv4 on the ens32 device. Despite this, Cilium continued to function effectively, demonstrating robust handling of network policies, endpoint restoration, and Hubble observability integration. The use of EDT (Earliest Departure Time) scheduling with BPF further enhanced the precision of bandwidth management, ensuring that traffic was managed efficiently and in a timely manner.

```
root@k3s-node1-master:/home/system# kubectl -n kube-system exec ds/cilium -- cilium-dbg status | grep BandwidthManager
Defaulted container "cilium-agent" out of: cilium-agent, config (init), mount-cgroup (init), apply-sysctl-overwrites (i
ate (init), install-cni-binaries (init)
BandwidthManager:        EDT with BPF [CUBIC] [ens32]
root@k3s-node1-master:/home/system#
```

Figure 4-10: Bandwidth Manager with CUBIC enabled

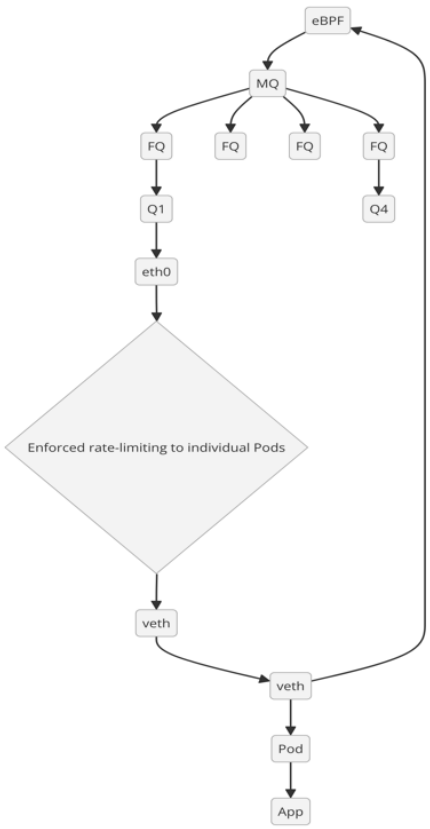

Figure 4-11: Flow of Network Traffic Using eBPF

The diagram, Figure 4-14, represents the flow of network traffic using Extended Berkeley Packet Filter (eBPF) technology for efficient packet processing and enforcement of rate-limiting on a host with individual Pods. Initially, the eBPF component processed the network packets by hooking them into various points in the kernel to monitor, filter, and manipulate them. These packets were then sent to the Multi-Queue (MQ), which distributed them to multiple Fair Queuing (FQ) schedulers (FQ1, FQ2, FQ3, FQ4) to ensure fair bandwidth distribution. Different queues (Q1 and Q4) temporarily stored the packets before they were sent out through the network interface eth0.

The network packets passed through Cilium Bandwidth Manager enforced rate-limiting on the traffic going to individual Pods, ensuring each Pod received a limited amount of bandwidth to prevent any single Pod from consuming too many network resources. The traffic was then forwarded through virtual Ethernet interfaces (veth1 and veth2), which were used in containerised environments to connect Pods to the host network. Eventually, the traffic reached the Pod. Inside the Pod, the traffic finally reached the application running within a container. This flow ensured efficient handling and fair distribution of network traffic, leveraging the capabilities of eBPF.

CHAPTER 5 RESULTS AND PERFORMANCE EVALUATION

5.1 Introduction

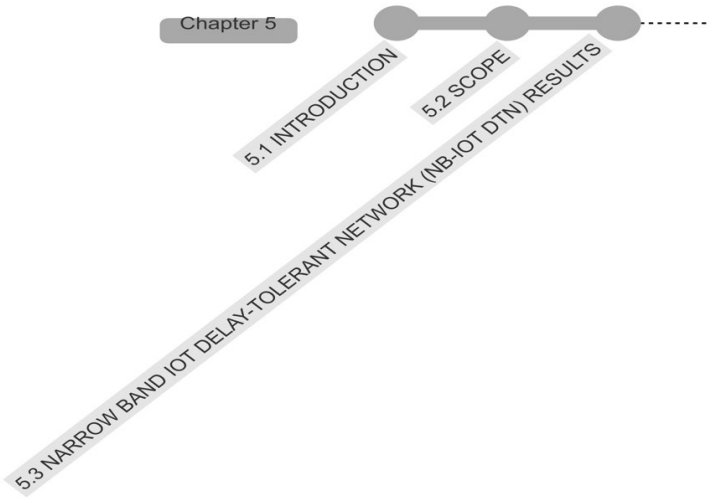

Figure 5-1: Chapter 5 Outline

The Introduction section of this chapter provides an overview of the methodology and objectives of the results and performance evaluation. It is followed by the Scope, which defines the boundaries and focus areas of the evaluation, ensuring clarity on what aspects of the Narrow Band IoT Delay-Tolerant Network (NB-IoT DTN) are being assessed as shown in Figure 5-1. The chapter then delves into the Narrow Band IoT Delay-Tolerant Network (NB-IoT DTN) Results. This section presents various aspects of the network's performance, starting with Systems Theory in Network Management, which applies systems theory principles to assess the network's behavior. The Information Theory in Network Management subsection explores information theory metrics to understand network data flow and efficiency.

Subsequent sections include Normal Traffic Analysis and Anomaly Detection, where the network's regular traffic patterns are analysed and potential anomalies are identified. Flooding Attack Analysis and Anomaly Detection investigates the network's response to simulated flooding attacks and the mechanisms for detecting such anomalies. The chapter continues with the Mutual Information Formula for evaluating dependencies in network traffic, Malicious Pod using Hping3, which simulates attacks, and finally, Fortio Results, which provide a detailed performance analysis using Fortio, a load-testing tool.

5.2 Scope

The scope of this evaluation encompasses a comprehensive analysis of the networking layer of the NB-IoT architecture under edge computing using the k3s architecture. The key objectives are to assess the reliability and performance of the network in supporting IoT applications, identify potential bottlenecks, and propose improvements. This evaluation will cover the following aspects:

I. Network Reliability: Analysing the ability of the edge computing network to deliver data packets consistently under various conditions. This includes assessing packet loss, error rates, and network availability.
II. Network Performance: Measuring key metrics such as latency, throughput, jitter, and data integrity. These metrics will provide insights into the efficiency and effectiveness of the network in handling IoT traffic.
III. Simulation: Utilising the simulation tool UERANSIM to model the edge computing network and perform controlled tests.

5.3 Narrow Band IoT delay-tolerant network (NB-IoTDTN) Results

5.3.1 Systems Theory in Network Management

The feedback control $(4.7)(4.8)(4.9)$ was used to dynamically adjust the system inputs based on the current state of the system by adjusting the feedback gain.

Figure 5-2, highlighted the differences in system behaviour depending on adjusting the feedback gain from Equation (4.5) configuration. K1 provided higher responsiveness but more oscillations, indicating potential instability. K2 and K3 provided more stable and smoother responses.

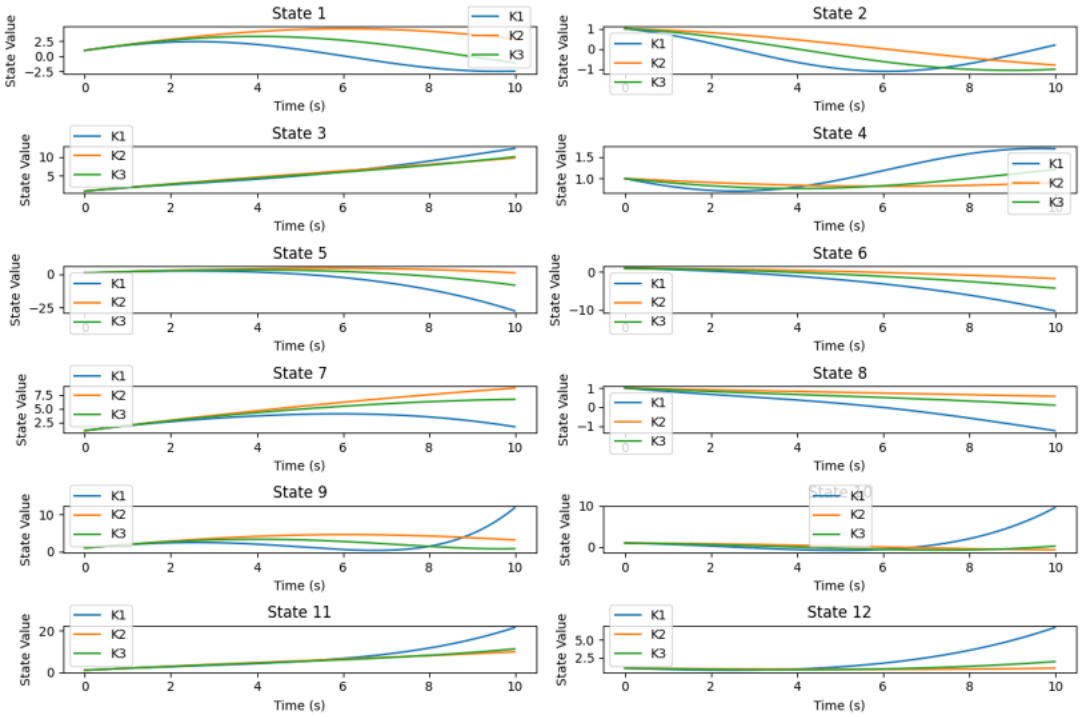

Figure 5-2: System States with different feedback gains

The CPU utilisation, Figure 5-3 for usage over time identified the instances; the feedback usage identified some instances had experienced higher spikes than others.

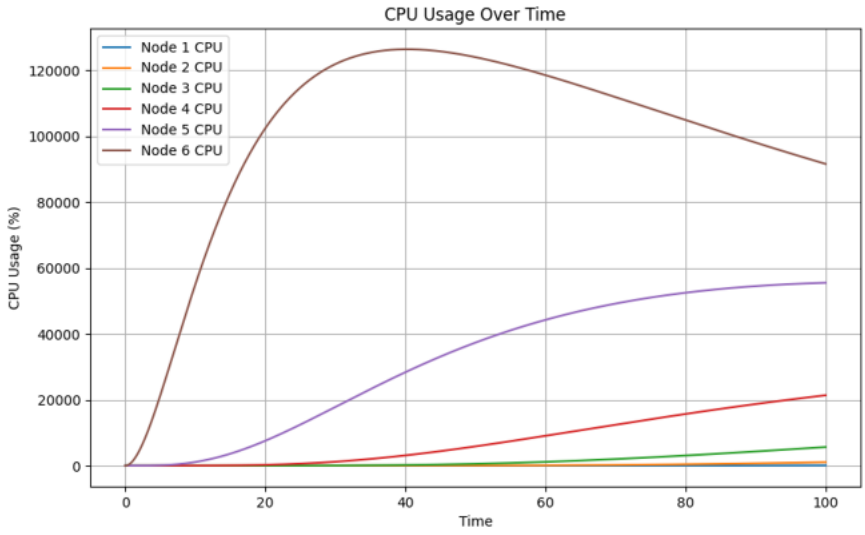

Figure 5-3: CPU usage Overtime

The RAM usage Figure 5-4, highlighted the memory utilisation for the different instances over time, and the usage was relatively stable with minor fluctuations.

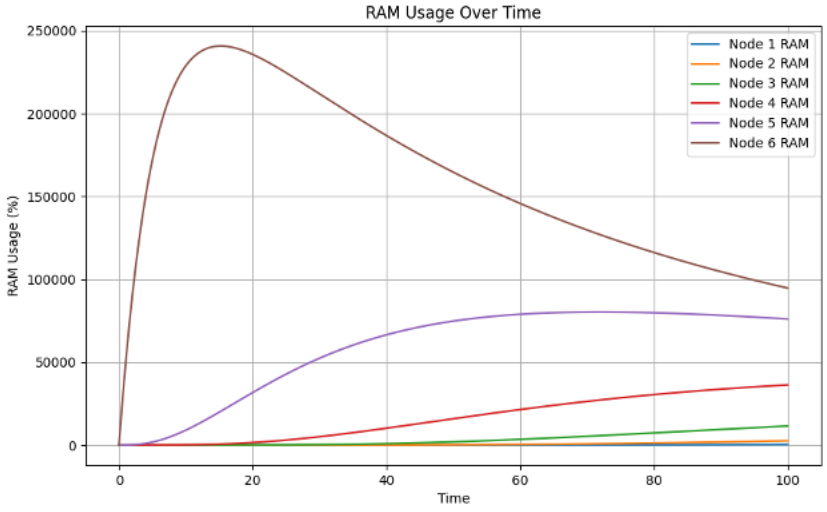

Figure 5-4: RAM usage overtime

- **Normal Traffic analysis**

Stability analysis ensured that the system behaved predictably over time. Equation (4.12) was used to verify that the network met the stability conditions. The output below suggested that the system passed the stability check.

```
1. Initial state vector (CPU and RAM usage percentages): [14.67777778 32.38280798 7.67962963
25.10711249 30.76296296 39.99070837

2. 13.24814815 35.68590626 14.24259259 33.32946379 19.31203704 35.49955268]

3. System stability: True
```

- **IP Flooding analysis**

(5.12) was used to verify that the network met the stability conditions. The output below suggests the system passed the stability check during the IP flooding attack.

```
1. Initial state vector (CPU and RAM usage percentages): [13.68055556 32.61660462 64.67777778
25.53653758 32.96666667 41.5339872

2. 21.90740741 36.83893069 18.85925926 35.67974509 15.33148148 35.78737583]

3. System stability: True
```

5.3.2 Information Theory in Network Management

The PromQL query fetched the rate of network traffic received in bytes over a 5-minute window, grouped by instances (Figure 5-6).

The entropy values and traffic distribution shown in the Figure 5-6, reflect normal, balanced network conditions. Under these conditions, each node handles a relatively similar amount of traffic, suggesting that the network is functioning without strain. During a DDoS attack, this balanced state will likely be disrupted. Entropy values can significantly change as certain nodes become overwhelmed with excessive traffic, leading to an uneven load distribution.

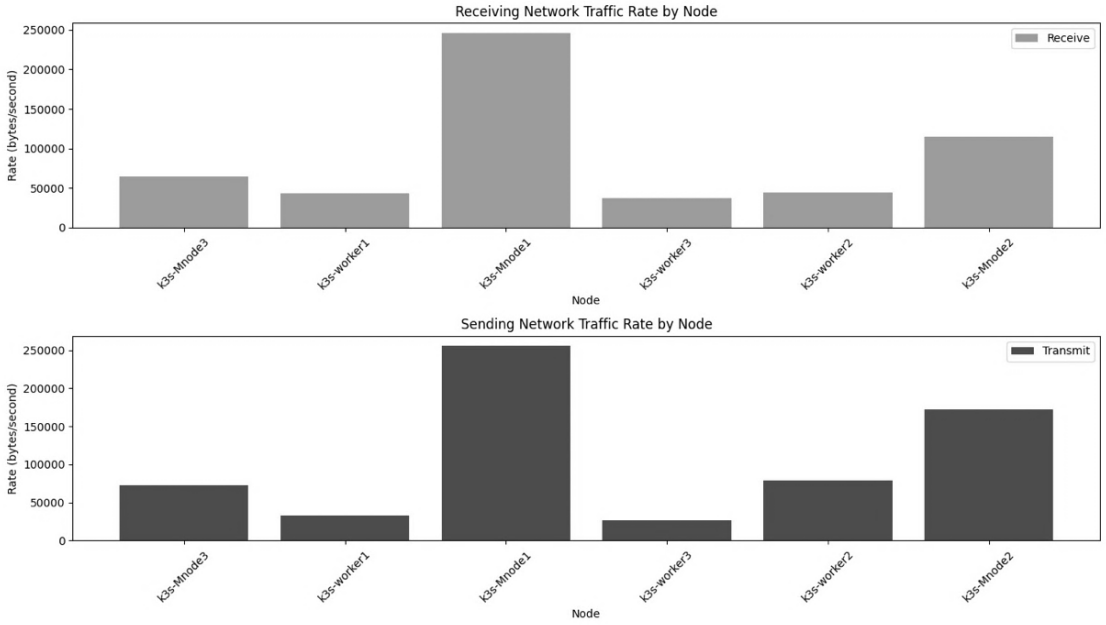

Figure 5-5: Normal Network Traffic Data

To calculate the entropy for both receiving and sending network traffic, we first need to determine the probability distribution for each node's traffic rate. This involves dividing each node's traffic rate by the total traffic rate. Then, we apply Shannon's entropy formula (4.13):

Where $p(x_i)$ is the probability of each node's traffic rate.

Receiving Traffic Rates (bytes/second):

- k3s-Mnode3: ~50,000
- k3s-worker1: ~50,000
- k3s-Mnode1: ~200,000
- k3s-worker3: ~50,000
- k3s-worker2: ~50,000
- k3s-Mnode2: ~100,000

5.3.2.1 Analysis of the Given Entropy Values

Total Receiving Traffic:

Total Traffic = 50,000 + 50,000 + 200,000 + 50,000 + 50,000 + 100,000 = 500,000 bytes/second

$$P(k3s\text{-}Mnode3) = \frac{50{,}000}{500{,}000} = 0.10$$

$$P(k3s\text{-}worker1) = \frac{50{,}000}{500{,}000} = 0.10$$

$$P(k3s\text{-}Mnode1) = \frac{200{,}000}{500{,}000} = 0.40$$

$$P(k3s\text{-}worker3) = \frac{50{,}000}{500{,}000} = 0.10$$

$$P(k3s\text{-}worker2) = \frac{50{,}000}{500{,}000} = 0.10$$

$$P(k3s\text{-}Mnode2) = \frac{100{,}000}{500{,}000} = 0.20$$

Calculate Shannon Entropy using the entropy formula (4.13)

$$H(X) = -\sum\big(p(x) \cdot \log_2\big(p(x)\big)\big)$$

$$-0.10 \cdot \log_2(0.10) \approx 0.332$$

$$-0.10 \cdot \log_2(0.10) \approx 0.332$$

$$-0.40 \cdot \log_2(0.40) \approx 0.529$$

$$-0.10 \cdot \log_2(0.10) \approx 0.332$$

$$-0.10 \cdot \log_2(0.10) \approx 0.332$$

$$-0.20 \cdot \log_2(0.20) \approx 0.464$$

$$H(X) = 0.332 + 0.332 + 0.529 + 0.332 + 0.332 + 0.464 = 2.32$$

The calculated entropy for the receiving network traffic is approximately 2.32. Indicated that the network traffic received by the nodes was evenly distributed, but there were still some variations. This indicated a moderate level of traffic distribution across the nodes, suggesting a reasonably balanced load under normal traffic conditions.

Total Sending Traffic:

Given traffic rates (in bytes/second):

- k3s−Mnode3:75000
- k3s−worker1:25000
- k3s−Mnode1:225000
- k3s−worker3:25000
- k3s−worker2:75000
- k3s−Mnode2:150000

Total Traffic: 75,000 + 25,000 + 225,000 + 25,000 + 75,000 + 150,000 = 575,000 bytes/second

Probability for each node:

$$P(k3s\text{-}Mnode3) = \frac{75{,}000}{575{,}000} \approx 0.1304$$

$$P(k3s\text{-}worker1) = \frac{25{,}000}{575{,}000} \approx 0.0435$$

$$P(k3s\text{-}Mnode1) = \frac{225{,}000}{575{,}000} \approx 0.3913$$

$$P(k3s\text{-}worker3) = \frac{25{,}000}{575{,}000} \approx 0.0435$$

$$P(k3s\text{-}worker2) = \frac{75{,}000}{575{,}000} \approx 0.1304$$

$$P(k3s\text{-}Mnode2) = \frac{150{,}000}{575{,}000} \approx 0.2609$$

$$H = -(0.1304 \log_2 0.1304 + 0.0435 \log_2 0.0435 + 0.3913 \log_2 0.3913 + 0.0435 \log_2 0.0435 + 0.1304 \log_2 0.1304 + 0.2609 \log_2 0.2609) \approx 2.20$$

The calculated entropy of sending network traffic is approximately 2.20.This value was slightly lower than the entropy of receiving traffic, which suggested that the distribution of outgoing traffic was a bit more skewed than the incoming traffic. Nodes send more data than others, leading to a less even distribution than receiving traffic.

Interpretation of Normal Traffic Results

The entropy values close to 2 suggested that the network traffic (both receiving and sending) was evenly distributed among the nodes. This was a good sign as it indicated that no single node is overwhelmingly burdened, which could help maintain network stability and performance (Devi, Dalal & Solanki 2024). This balance was crucial for maintaining network stability and performance, as it ensured no single node was overwhelmed, that could have potentially led to bottlenecks or failures. The observed network traffic patterns and entropy values are influenced by the deployment of the proposed Narrowband Internet of Things Delay-Tolerant Network (NB-IoT-DTN) within the network. By integrating NB-IoT-DTN, the system is designed to balance traffic across nodes effectively and improve resilience against potential Distributed Denial of Service (DDoS) attacks.

In this setup, the entropy values of 2.32 for receiving traffic and 2.20 for sending traffic reflect how the network distributes traffic more evenly across nodes due to the DTN's architecture. This even distribution is an indicator of the DTN's ability to mitigate abnormal traffic spikes that could otherwise overwhelm individual nodes. As such, the entropy values serve as evidence of the DTN's effectiveness in maintaining balanced and stable network conditions, which directly contributes to the network's fault tolerance and reliability.

5.3.3 Normal Traffic Analysis and Anomaly Detection

There was noticeable variability in CPU usage across the nodes. Some nodes showed higher spikes in CPU usage compared to others. RAM usage appeared more stable and showed less variability compared to CPU usage.

Nodes Mnode1 and Wnode3 showed higher CPU usage spikes compared to other nodes. RAM usage remained relatively consistent across nodes with small fluctuations, indicating less variability than CPU usage.

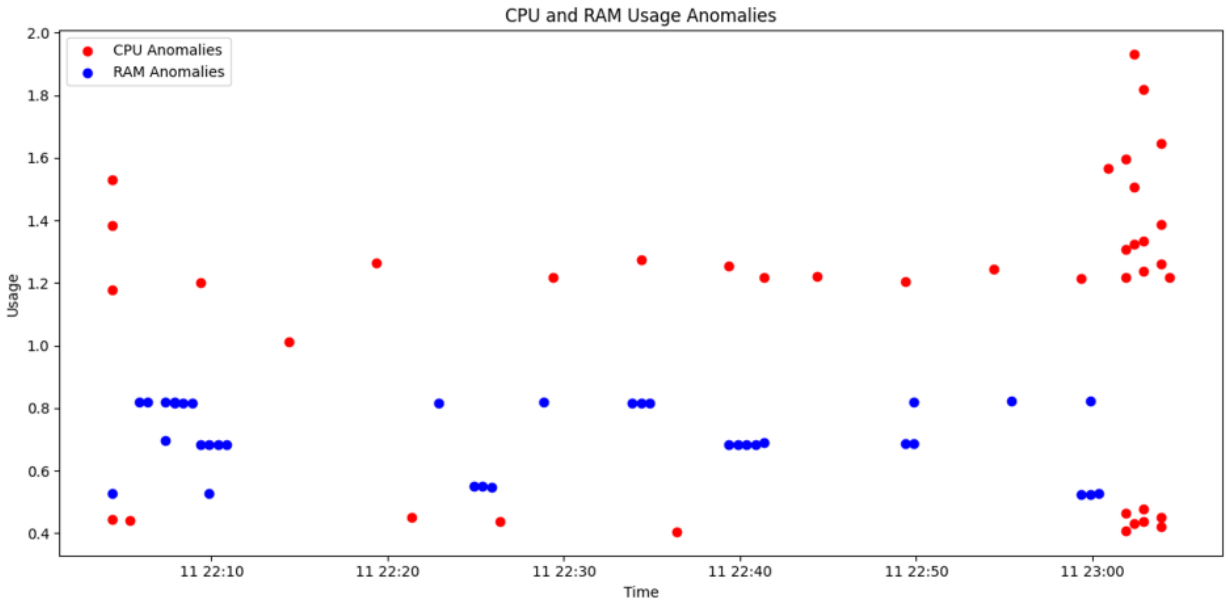

Figure 5-6: Normal Traffic CPU and RAM anomalies

The CPU anomalies were concentrated at higher usage levels, illustrated in Figure 5-5, indicating spikes that deviated significantly from the norm. RAM anomalies were fewer and occurred at lower usage levels compared to CPU anomalies.

Nodes with higher CPU spikes, Mnode1 and Wnode3, handled more intensive tasks and processes. RAM usage showed more stability across nodes, but any anomalies, though fewer, indicated moments where memory usage deviated from normal patterns.

5.3.4 Flooding Attack Analysis and Anomaly Detection

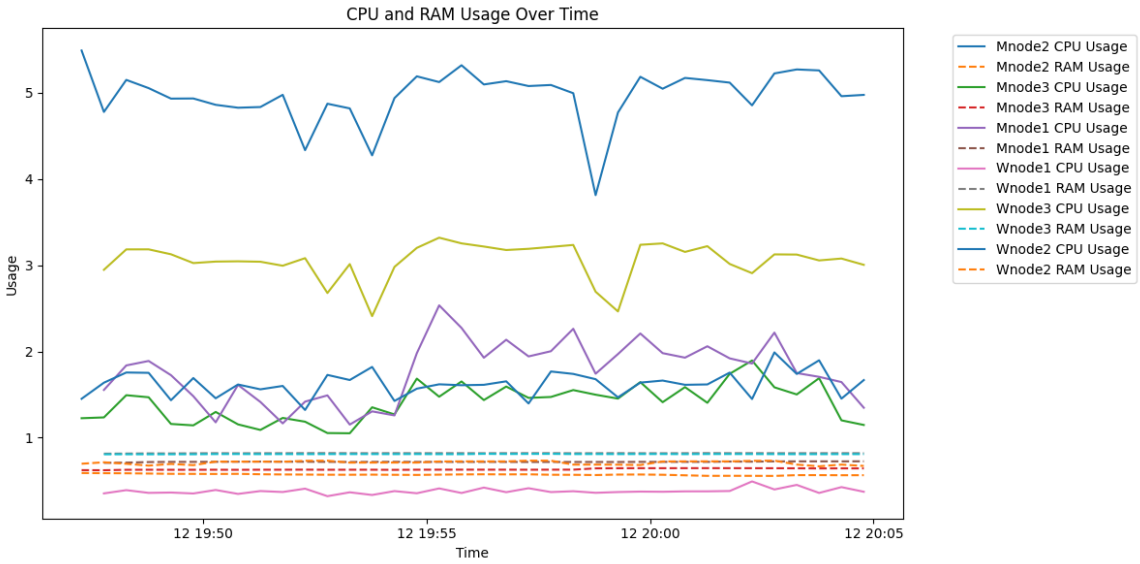

Figure 5-7: CPU and RAM Usage During Flood Attack

The CPU anomalies showed periods in Figure 5-7 where the CPU usage for Mnode2 was consistently high, hovering around 4-6 units; the malicious pod was running on this Mnode2. There were fluctuations but no drastic spikes or drops. The RAM usage is consistent, around 1 unit, with very slight variations.

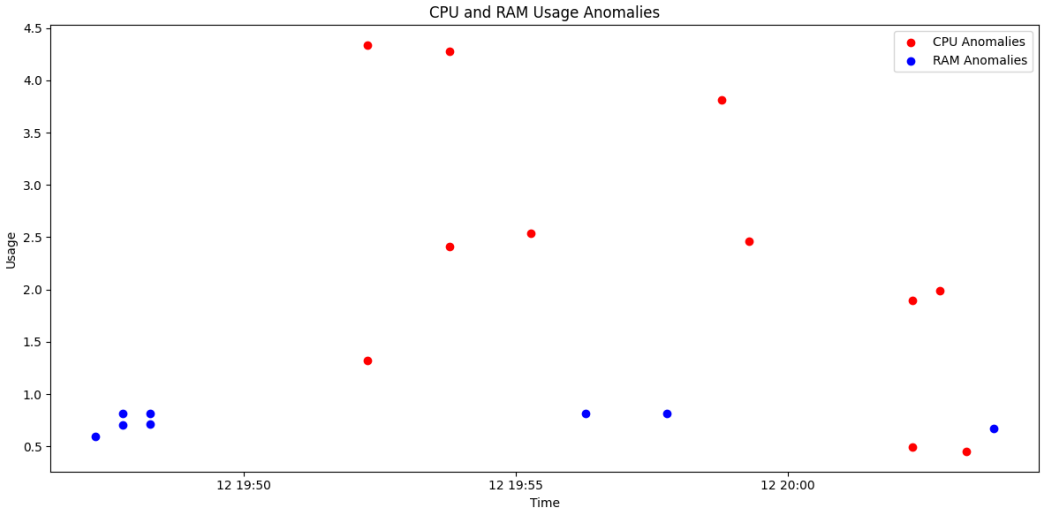

Figure 5-8: CPU and RAM Anomalies During Flood Attack

There were several spikes in CPU usage in Figure 5-8 across different timestamps. The anomalies were scattered and did not follow a consistent pattern. The highest anomalies were observed around 4.5 units of usage. The RAM anomalies were fewer in number compared to CPU anomalies. The anomalies were below 1 unit of usage, indicating less frequent but significant deviations. High CPU usage anomalies indicated periods of intensive processing due to the malicious pod running on the node leading to excessive resource consumption (Figure 5-9).

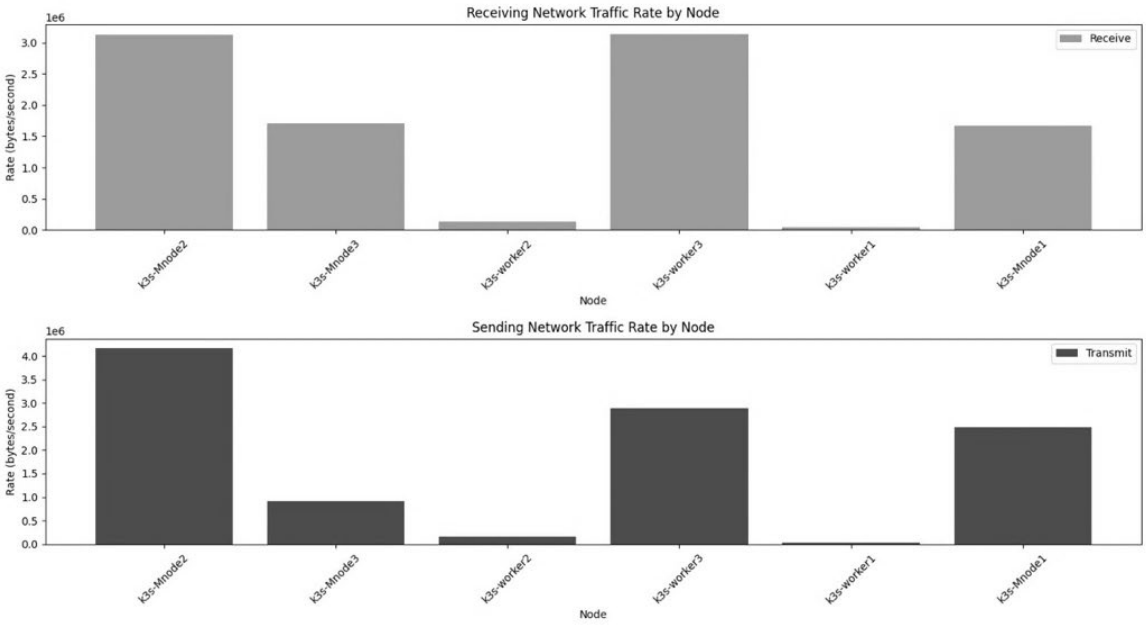

Figure 5-9: Network Traffic Data During Flood Attack

To calculate the entropy for both receiving and sending network traffic, we first need to determine the probability distribution for each node's traffic rate.

Calculate Total Traffic for Each (Receiving and Sending):

$$Total\ Receiving\ Traffic\ =\ 3.0\ +\ 2.0\ +\ 3.0\ +\ 0.5\ +\ 1.5\ =\ 10.0\ million\ bytes/second$$

$$Total\ Sending\ Traffic\ =\ 4.0\ +\ 2.0\ +\ 2.0\ +\ 0.5\ +\ 1.5\ =\ 10.0\ million\ bytes/second$$

For each node, we calculate the probability by dividing the traffic for that node by the total traffic.

I. Receiving Probabilities for Each Node:

$$P(k3s\text{-}Mnode2) = \frac{3.0}{10.0} = 0.3$$

$$P(k3s\text{-}Mnode3) = \frac{2.0}{10.0} = 0.2$$

$$P(k3s\text{-}worker3) = \frac{3.0}{10.0} = 0.3$$

$$P(k3s\text{-}worker2) = \frac{0.5}{10.0} = 0.05$$

$$P(k3s\text{-}Mnode1) = \frac{1.5}{10.0} = 0.15$$

II. Sending Probabilities for Each Node:

$$P(k3s\text{-}Mnode2) = \frac{4.0}{10.0} = 0.4$$

$$P(k3s\text{-}Mnode3) = \frac{2.0}{10.0} = 0.2$$

$$P(k3s\text{-}worker3) = \frac{2.0}{10.0} = 0.2$$

$$P(k3s\text{-}worker2) = \frac{0.5}{10.0} = 0.05$$

$$P(k3s\text{-}Mnode1) = \frac{1.5}{10.0} = 0.15$$

III. Calculate Shannon Entropy (4.13) for Each (Receiving and Sending):

$$H(X) = -\sum\big(p(x) \cdot \log_2\big(p(x)\big)\big)$$

$$H(\text{Receive}) = -(0.3\log_2(0.3) + 0.2\log_2(0.2) + 0.3\log_2(0.3) + 0.05\log_2(0.05) + 0.15\log_2(0.15))$$

$$H(\text{Receive}) = -(-0.5211 - 0.4644 - 0.5211 - 0.2161 - 0.4105) = 2.13 \approx 2.11$$

$$H(\text{Transmit}) = -(0.4\log_2(0.4) + 0.2\log_2(0.2) + 0.2\log_2(0.2) + 0.05\log_2(0.05) + 0.15\log_2(0.15))$$

$$H(\text{Transmit}) = -(-0.5288 - 0.4644 - 0.4644 - 0.2161 - 0.4105) = 2.08 \approx 1.94$$

I. Entropy of Receiving Network Traffic: 2.11

The value was lower than the previous 2.32, indicating that the distribution of receiving network traffic has become less even. The flood attack caused a few nodes to receive a disproportionately high amount of traffic compared to the rest, leading to a more skewed distribution.

II. Entropy of Sending Network Traffic: 1.94

This value was lower than the previous 2.20, showing that the distribution of sending network traffic has also become more uneven. This was due to the attack causing certain nodes or pods to send a lot more traffic, while others send little.

Both entropy values have decreased, highlighting that the network traffic is now more concentrated on specific nodes rather than being evenly distributed. This is typical during an attack where targeted nodes withstand the worst of the traffic. The flood attack caused a significant imbalance, putting excessive load on the targeted nodes. This would lead to performance degradation, potential denial of service, and overall instability in the network.

5.3.5 Mutual Information Formula

Given the entropy values, the study needed the conditional entropy H(X|Y) to compute the mutual information. If the study assumed that the entropy values provided were the total entropies of the system, the study would consider these in the mutual information context.

The study used the (4.14) formula to compute the mutual information.

$$I(X;Y) = H(X) - H(X \mid Y)$$

Where:

H(X) is the entropy of legitimate (normal) traffic.

H(X|Y) is the conditional entropy given the (flooding attack) network traffic.

For Receiving Network Traffic:

H(X) = 2.32

H(X|Y) = 2.20

For Sending Network Traffic:

H(X) = 2.11

H(X|Y) = 1.94

$$I_{receive(X;Y)} = H(X) - H(X \mid Y) = 2.32 - 2.11 = 0.12$$

$$I_{send(X;Y)} = H(X) - H(X \mid Y) = 2.20 - 1.94 = 0.17$$

5.3.5.1 Interpretation on Mutual Information

I. Mutual Information for Receiving Traffic (0.12)

A low mutual information value here (0.12) indicates that the observed IP flooding attack traffic has a weak dependency on the expected normal traffic patterns. This weak dependency suggests that the attack introduces a higher level of unpredictability or deviation from normal patterns.

II. Mutual Information for Sending Traffic (0.17)

The slightly higher mutual information value of 0.17 for sending traffic suggests a moderate dependency on the normal traffic pattern, indicating that there may be a structured element in the attack traffic. However, it is still relatively low, implying that the attack has introduced significant irregularities in the traffic, differing from normal patterns.

The mutual information values, especially in the context of an IP flooding attack, reveal that the attack traffic (both receiving and sending) significantly deviates from expected normal traffic patterns. The attack likely increases entropy and unpredictability in traffic flows, as reflected by these lower mutual information values, highlighting the abnormal and disruptive nature of the IP flooding attack on the NB-IoT-DTN.

Where C Is the channel capacity, and I(X; Y) is the mutual information between the transmitted signal X and the received signal Y.

To find the channel capacity C the study took the maximum of the mutual information values for both receiving and sending network traffic (4.15):

$$C = \max\{ I_{\text{receive}}(X;Y), I_{\text{send}}(X;Y)\}$$

Substitute the values: $C = \max\{ 0.12,0.17\}$

$$C = 0.17$$

The channel capacity C was 0.17. This meant that the maximum rate at which information can be reliably transmitted over this communication channel was 0.17 bits per unit time.

Malicious traffic functioned as noise in the communication channel, reducing the network's adequate capacity. The ratio of legitimate traffic (signal) to malicious traffic (noise), was used by Equation (4.16) to analyse the impact on channel capacity.

Where C is the channel capacity, B is the bandwidth, S is the power of the signal (legitimate traffic), and N is the power of the noise (malicious traffic).

I. Bandwidth (Mbps): 15.7436.
II. SNR (Receive): 0.0053.
III. SNR (Send): 0.0075.
IV. Channel Capacity (Receive): 0.1200 bits per unit time.
V. Channel Capacity (Send): 0.1700 bits per unit time.
VI. Maximum Channel Capacity: 0.1700 bits per unit time.

Channel Capacity (Receive): 0.1201 Mbps

Channel Capacity (Send): 0.1697 Mbps

Maximum Channel Capacity: 0.1697 Mbps

5.3.5.2 Results

I. **Bandwidth:** The measured bandwidth of the network was approximately 15.7436 Mbps.

   This indicates the network's capability to handle data up to approximately 15.7436 Mbps. Bandwidth remains unchanged by the type of traffic (legitimate or malicious) but determines the overall capacity for data transmission.

II. **SNR Values:** The low SNR values indicated that the signal power was only slightly higher than the noise power, which was consistent with the presence of noise (malicious traffic) in the network.

   SNR is the ratio of signal power to noise power. Here, the very low SNR values imply that the signal (legitimate traffic) is only slightly more powerful than the noise (malicious

traffic). This suggests a significant level of interference or disruption, which is consistent with an IP flooding attack.

The higher SNR for sending traffic compared to receiving indicates that the network is slightly more capable of handling outgoing traffic, even under noisy conditions. However, both values are still low, showing that the network is heavily impacted by the noise.

III. **Channel Capacity:** The channel capacity for sending traffic was slightly higher than for receiving traffic, suggesting that the network could transmit data more reliably in the sending direction.

Receive Capacity (0.1201 Mbps): This is the maximum rate at which data can be reliably received under current conditions. Given the low capacity, receiving traffic is heavily impacted by the noise, reducing the effective data throughput.

Send Capacity (0.1697 Mbps): This slightly higher capacity compared to receiving suggests that outgoing traffic is slightly less affected by the interference. The network can transmit data at a marginally higher rate in the sending direction.

IV. **Maximum Channel Capacity:** The maximum rate at which information can be reliably transmitted over the communication channel is 0.1700 bits per unit time. This represents the overall highest achievable rate under the given noisy conditions. It sets the limit for data transmission reliability.

V. Overall Interpretation:

The low channel capacities indicate that the network is significantly constrained by the malicious traffic (IP flooding attack), resulting in limited reliable data transmission. Even though the sending direction has a slightly higher capacity, both directions have extremely low maximum achievable rates due to the high levels of noise.

Maximum Channel Capacity (0.1697 Mbps): This reveals that the network's maximum potential for reliable data transfer is quite low under attack conditions, suggesting that the system is under stress and cannot handle much legitimate traffic reliably.

5.3.6 Malicious Pod using Hping3

To confirm the Mutual information (4.14) and conditional entropy of legitimate traffic, the study deployed a malicious pod in the controlled environment to ensure that the pod didn't cause any harm or violate any policies. The study created a Kubernetes pod to simulate an attack on the open5gs-webui service using a container image (Debian). They had to grant the container additional capabilities "NET_RAW" for raw network packet access but limited the container to only perform a flood attack to a chosen node where the webui pod was running on using "hping3" on port 9999. The pod was chosen to run for 20 minutes to gather data on the network. The malicious pod created an "Internal Server Error" for the open5gs-webui external IP during the flood attack. This also caused the database MongoDB to close connections to the pod.

During this evaluation, a malicious pod Figure 5-10, was created to simulate IP flooding. This pod sends a high volume of IP packets to target a service which was the AMF pod of the Open5G network within the cluster.

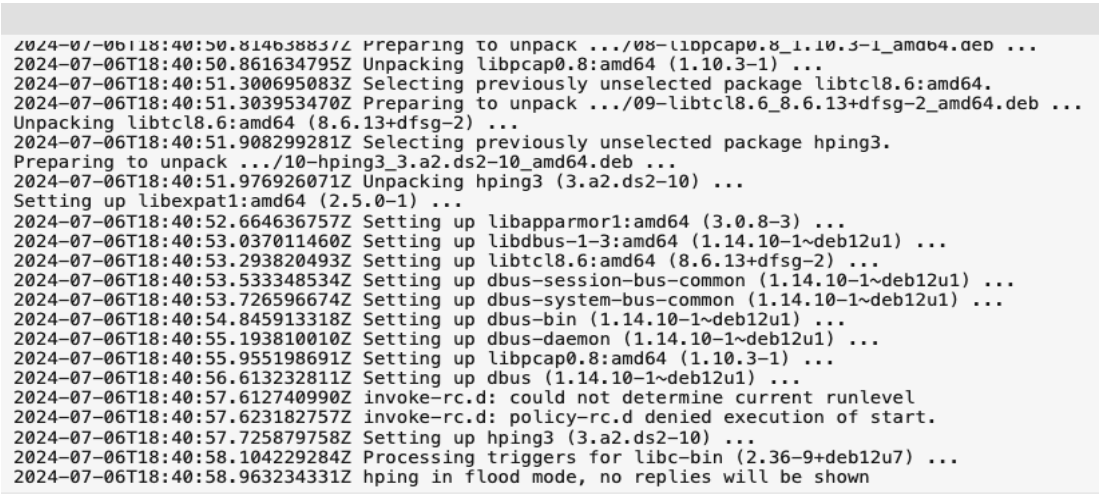

Figure 5-10: Malicious Pod Running hping3

Cilium detected the malicious pod traffic and blocked it. This was observed in Hubble web UI with a "dropped" verdict that indicated the rate-limiting correctly identified and stopped the SYN packets sent to port 80 on the target pod AMF. However, the malicious pod also caused the AMF pod to stop all traffic Figure 4-10 which didn't allow the AMF to receive any more updates from other pods in the open5gs network.

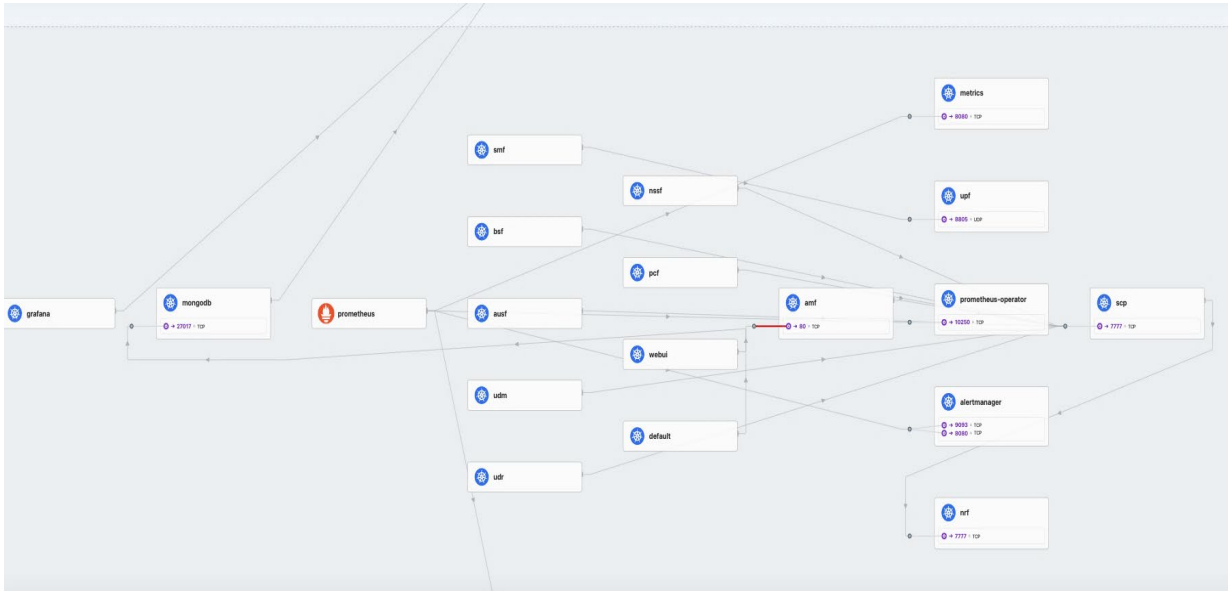

Figure 5-11: Open5gs Network Pods with AMF port 80 TCP stopped

5.3.6.1 Applying the Cilium Intrusion Detection Before Running the Malicious Pod

The evaluation of the network policy allowed Cilium to be an intrusion prevention and detection system for the open5gs network. This allowed a pod egress traffic for the specific port with an intrusion detection rule. This configuration effectively managed traffic rates to protect the services from being overwhelmed while allowing legitimate traffic to pass through at controlled rates.

Figure 4-11 illustrates the pods are all connected, and that the AMF can receive packets and forward packets. This was set up to allow traffic to TCP port 7777.

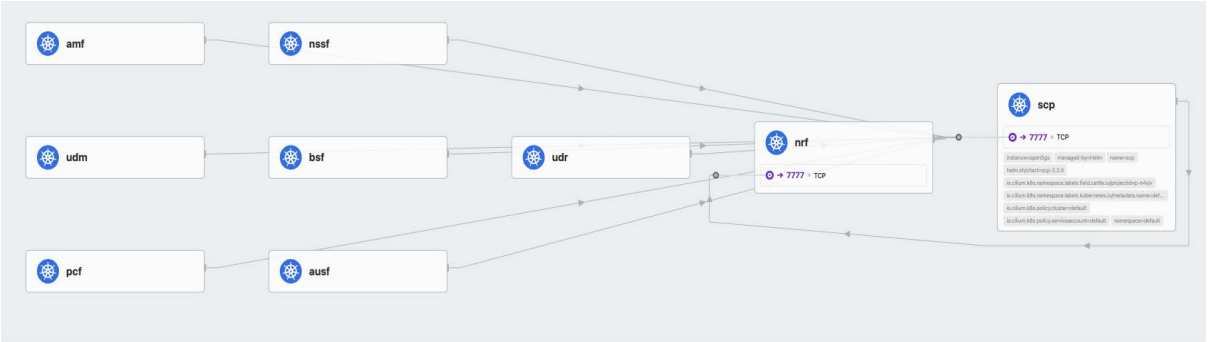

Figure 5-12: Hubble UI with Cilium Applied on the TCP Layer

5.3.6.2 Evaluating the malicious pod with cilium rate limiting applied

This part of the evaluation introduced a rate limiter that operates at the BPF (Berkeley Packet Filter) level within Cilium to prevent high CPU utilisation by the Cilium agent. This was particularly beneficial for smaller nodes like the Raspberry PI, where excessive CPU usage by the cilium-agent cloud starved other processes.

5.3.6.3 Deployment for test evaluation CUBIC with BPF

In the study's Cilium setup on the K3s cluster, the configuration successfully enabled the BPF bandwidth manager (Figure 5-13), and the cubic congestion control algorithm. The initialisation process confirmed that the system met the baseline requirements for parameters. This setup, combined with Cilium's BPF-based data path, aimed to optimise traffic management and improve network performance. However, while enabling Big TCP for IPv6 was successful, an error ("invalid argument") prevented its activation for IPv4 on the ens32 device. Despite this, Cilium continued to function effectively, demonstrating robust handling of network policies, endpoint restoration, and Hubble observability integration. The use of EDT (Earliest Departure Time) scheduling with BPF further enhanced the precision of bandwidth management, ensuring that traffic was managed efficiently and in a timely manner.

```
root@k3s-node1-master:/home/system# kubectl -n kube-system exec ds/cilium -- cilium-dbg status | grep BandwidthManager
Defaulted container "cilium-agent" out of: cilium-agent, config (init), mount-cgroup (init), apply-sysctl-overwrites (i
ate (init), install-cni-binaries (init)
BandwidthManager:       EDT with BPF [CUBIC] [ens32]
root@k3s-node1-master:/home/system#
```

Figure 5-13: Bandwidth Manager with CUBIC enabled

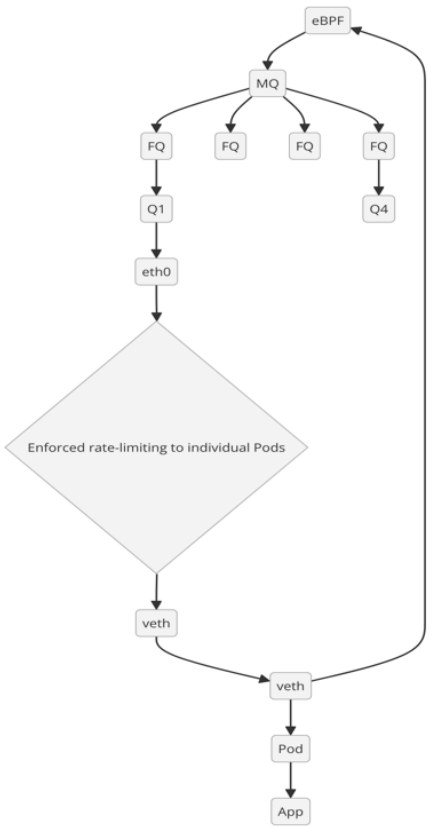

Figure 5-14: Flow of Network Traffic Using eBPF

The diagram, Figure 5-14, represents the flow of network traffic using Extended Berkeley Packet Filter (eBPF) technology for efficient packet processing and enforcement of rate-limiting on a host with individual Pods. Initially, the eBPF component processed the network packets by hooking them into various points in the kernel to monitor, filter, and manipulate them. These packets were then sent to the Multi-Queue (MQ), which distributed them to multiple Fair Queuing (FQ) schedulers (FQ1, FQ2, FQ3, FQ4) to ensure fair bandwidth distribution. Different queues (Q1 and Q4) temporarily stored the packets before they were sent out through the network interface eth0.

The network packets passed through Cilium Bandwidth Manager enforced rate-limiting on the traffic going to individual Pods, ensuring each Pod received a limited amount of bandwidth to prevent any single Pod from consuming too many network resources. The traffic was then forwarded through virtual Ethernet interfaces (veth1 and veth2), which were used in containerised environments to connect Pods to the host network. Eventually, the traffic reached the Pod. Inside the Pod, the traffic finally reached the application running within a container. This flow ensured efficient handling and fair distribution of network traffic, leveraging the capabilities of eBPF.

5.3.6.4 Analysing Fortio Results for Rate Limiting Effectiveness

Fortio is an open-source load testing and benchmarking tool that provided HTTP/gRPC load testing and was deployed within the Kubernetes cluster.

The study used Fortio as a load tester for the Nginx webserver with rate limiting applied at 10MB on egress and ingress. The Nginx webserver had 3 replicas and during the load test with Fortio could oversee the traffic and rate limit the requests on all 3 replicas (Figure 5-15).

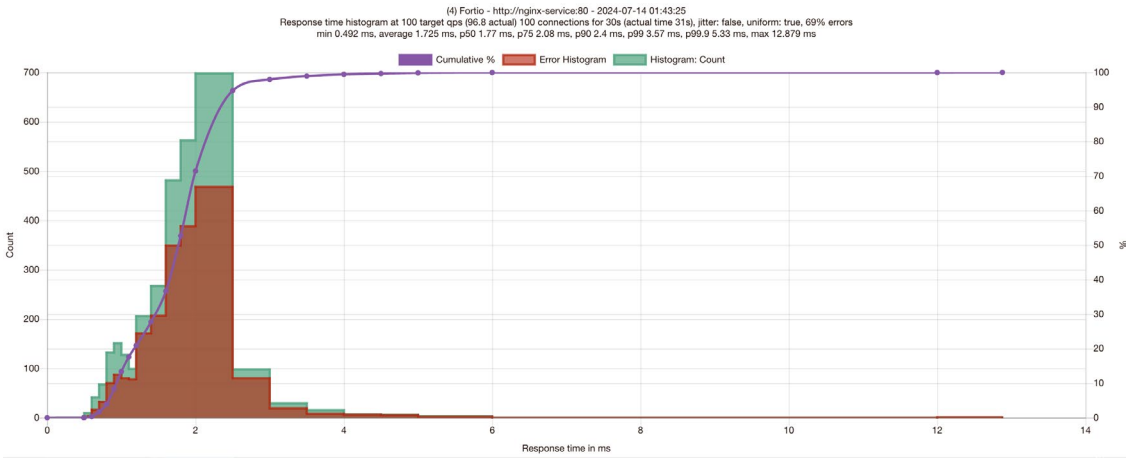

Figure 5-15: CUBIC Folio with 100 Connections to nginx

In the Fortio web UI, the study could configure the load test parameters. For testing with CUBIC and EDT:

I. Target URL: http://nginx-service:80.
II. Number of Threads: 4.
III. Connections: 100.
IV. Duration: 30s.

The study collected and monitored the metrics with Prometheus and Grafana to scrape the Fortio metrics.

1. **Request Distribution and Response Codes:**

I. Total Requests: 3000.
II. HTTP 200 (Success): 930 (31.0%).
III. HTTP 503 (Service Unavailable): 2070 (69.0%).

The high number of HTTP 503 status codes indicated that the rate limiting effectively rejected excess requests, which aligned with the configured rate limit 10 Mbps.

2. **The response time(latency) distribution is as follows:**

I. Average Response Time: 1.724 ms.
II. Min Response Time: 0.000491849 ms.
III. Max Response Time: 0.030567705 ms.

3. **Response Time Percentiles are:**

I. 50th percentile (median): 1.74 ms.
II. 75th percentile: 2.13 ms.
III. 90th percentile: 2.44 ms.
IV. 99th percentile: 3.86 ms.
V. 99.9th percentile: 5.5 ms.

4. **The connection timings are as follows:**

I. Average Connection Time: 0.042251463 s.
II. Min Connection Time: 0.004854113 s.
III. Max Connection Time: 0.065911116 s.

5. **The total error and average error response time are:**

I. Total Errors: 2070.
II. Average Error Response Time: 1.722 ms.

Given the above data, the study could verify the rate-limiting effectiveness through the following steps:

Step 1: Analysing HTTP 503 Responses

The high percentage of HTTP 503 responses (69.0%) indicated that the NGINX rate limiting configuration is rejecting excess requests as expected. This was a clear sign that rate limiting was being enforced effectively.

Step 2: Response Time Distribution

The response time distribution, especially the percentiles, indicated the latency experienced by requests. The median (50th percentile) response time was around 1.74 ms, which was within an acceptable range. However, as the study approached the higher percentiles (99th and 99.9th), the response times increased, showing the impact of rate limiting and queuing delays.

Step 3: Connection Timing

The connection timing data showed the time taken to establish connections, which was crucial for understanding the overall request handling efficiency. The average connection time was about 0.042 seconds, with most connections being established within this timeframe.

Step 4: Error Analysis

Analysing the errors provided insights into the response times for requests that were rejected due to rate limiting. The error response times were consistent with the overall average response time, indicating that the rate limiting mechanism was operating efficiently without introducing significant delays.

5.3.6.5 Deployment for Test Evaluation Bottleneck Bandwidth and Round-trip propagation time (BBR) with Berkeley Packet Filter (BPF)

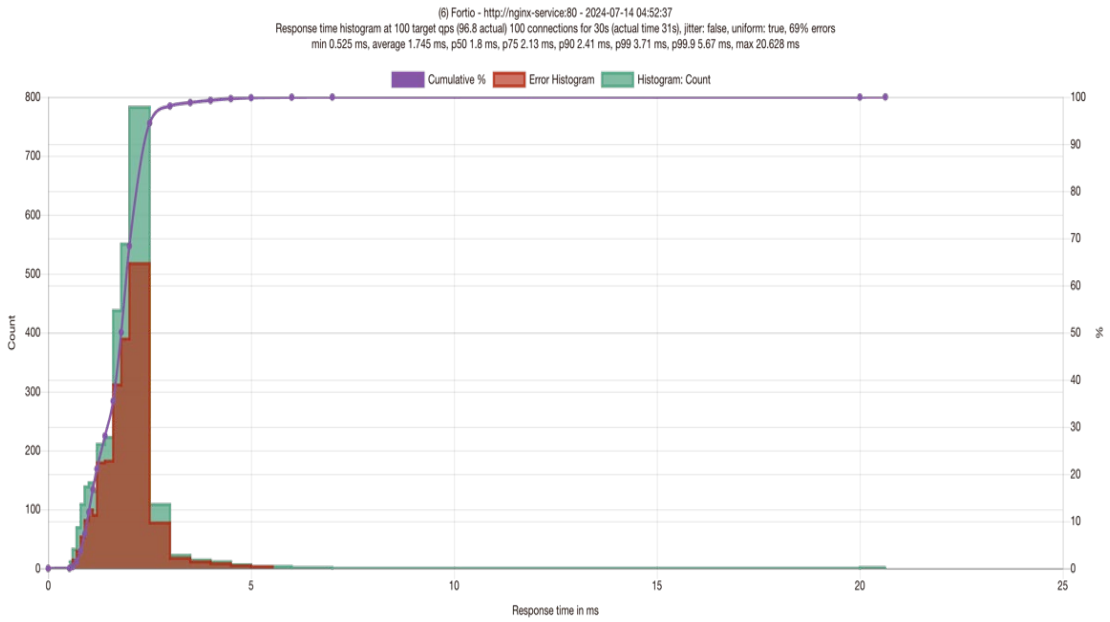

Figure 5-16: BBR Folio with 100 Connections to nginx

In the Fortio web UI, the study configured the load test parameters. For testing with BBR and EDT (Figure 5-17):

```
root@k3s-node1-master:/home/system# kubectl -n kube-system exec ds/cilium -- cilium-dbg status | grep BandwidthManager
Defaulted container "cilium-agent" out of: cilium-agent, config (init), mount-cgroup (init), apply-sysctl-overwrites (
ate (init), install-cni-binaries (init)
BandwidthManager:        EDT with BPF [BBR] [ens32]
root@k3s-node1-master:/home/system#
```

Figure 5-17: Bandwidth Manager with BBR Enabled

1. **The load test configuration for BBR with BPF is detailed as follows:**

I. Target URL: http://nginx-service:80.
II. Number of Threads: 4.
III. Connections: 100.
IV. Duration: 30 seconds.

Metrics Collected is as follows:

I. Total Requests: 3000.
II. HTTP 200 (Success): 930 (31.0%).
III. HTTP 503 (Service Unavailable): 2070 (69.0%).

Analysis of Responses is as follows:

HTTP 503 Responses:

1. Observation: The high number of HTTP 503 responses indicated that the rate limiting is effectively rejecting excess requests.
2. Implication: With 69.0% of requests resulting in HTTP 503, the rate limiting configuration was clearly functioning as intended, preventing the server from becoming overloaded.

2. **The response time(latency) distribution is as follows:**

I. Average Response Time: 1.724 ms.
II. Min Response Time: 0.000525031 ms.
III. Max Response Time: 0.020627767 ms.

3. **Response Time Percentiles are:**

I. 50th percentile (median): 1.74 ms.
II. 75th percentile: 2.13 ms.
III. 90th percentile: 2.44 ms.
IV. 99th percentile: 3.71 ms.
V. 99.9th percentile: 5.67 ms.

Implication: The median response time of 1.74 ms indicated efficient request handling under normal conditions. The increase in response times at higher percentiles suggested the impact of rate limiting and queuing delays for some requests.

3.The connection timings are as follows:

I. Average Connection Time: 0.013179296 seconds.
II. Min Connection Time: 0.002806871 seconds.
III. Max Connection Time: 0.022499908 seconds.

Implication: The average connection time of 0.013 seconds was within a reasonable range, indicating that the server is managing connections efficiently.

4. **Error Analysis**

I. Total Errors: 2070.
II. Average Error Response Time: 1.759 ms.

Implication: The average response time for errors was consistent with the overall response time, indicating that the rate limiting mechanism was efficient and did not introduce significant delays when rejecting requests.

5. **Response Time Distribution**

Observation: The median response time was 1.74 ms, with response times increasing at higher percentiles.

The server maintained low latency for most requests, with higher latency at the upper percentiles

due to the rate limiting mechanism and queuing delays.

6. **Connection Timing**

Observation: The average connection time is about 0.013 seconds.

The server establishes connections efficiently, with most connections being made within this timeframe.

7. **Error Analysis**

Observation: The average error response time is 1.759 ms.

The rate limiting mechanism was operating efficiently, rejecting excess requests without introducing significant delays.

The Fortio load test results confirmed that the rate limiting configuration on the NGINX service was working effectively. The high percentage of HTTP 503 responses demonstrated that excess requests are being rejected as expected. The response time distribution and connection timing data indicated efficient handling of accepted requests, while the error analysis showed that the rate limiting mechanism does not introduce significant delays.

5.3.7 Fortio Results

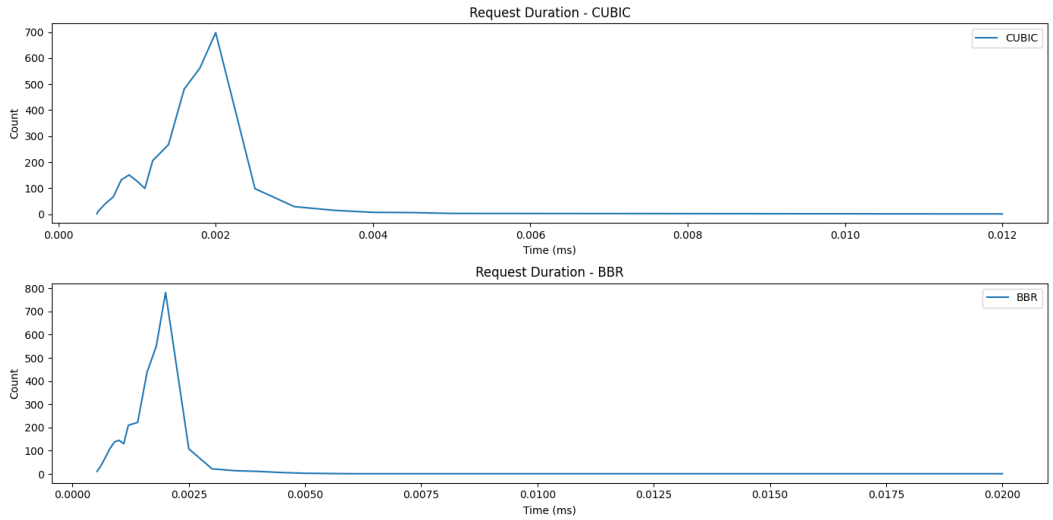

Figure 5-18:TCP Algorithm Results

The plots in Figure 5-18, for CUBIC and BBR showed similar trends, but BBR has a wider spread and more extreme values in response duration, especially beyond 0.0025 ms.

The visual comparison also highlighted that BBR handles higher burst of requests but at the cost of longer delays for some requests.

This analysis suggested that while both CUBIC and BBR performed similarly under typical conditions, BBR may encounter more extreme delays under certain circumstances, which could be critical depending on the application's sensitivity to latency.

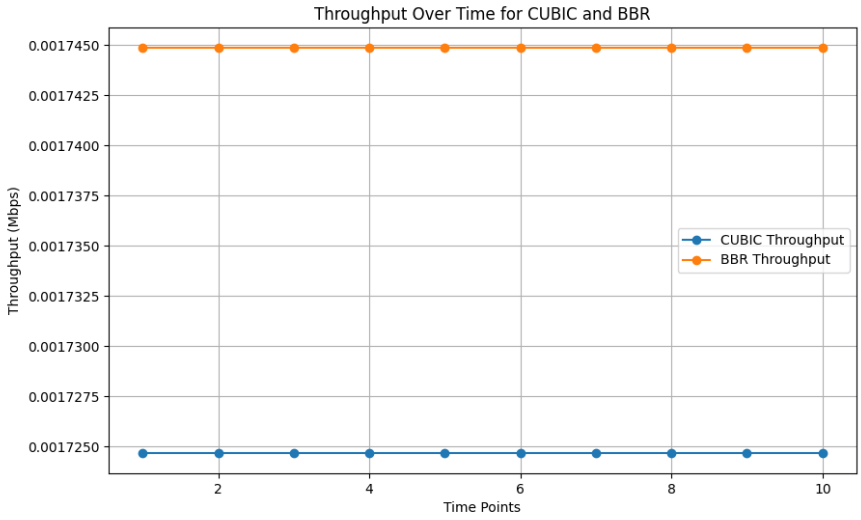

Figure 5-19: CUBIC and BBR Throughput Over Time

The mean difference between the CUBIC and BBR throughput was exceedingly small see Figure 5-19, indicating that the average throughput values for both algorithms were quite close to each other.

The standard error was also small, reflecting that there was not much variability in the throughput measurements.

CHAPTER 6 DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction to the Discussion of Objective 1

This chapter revisits the primary objectives of this research and synthesises the essential findings and discussions derived from in-depth analysis of Narrowband Internet of Things (NB-IoT) and 5G technologies. The key aim of this study has been to identify and address the challenges faced by low-cost NB-IoT applications and provide a comparative analysis with 5G to determine the optimal network protocol for various IoT applications. By evaluating critical factors such as data rate, latency, scalability, energy efficiency, and coverage, the study aims to offer a comprehensive understanding that guides stakeholders in making informed decisions. This chapter concludes the investigation by summarising the outcomes of each research objective, discussing the implications of these findings, and proposing directions for future research.

6.1.1 Objective 1

- To identify the challenges of low-cost NB-IoT applications, discussing the differences between 5G and NB-IoT for choosing a suitable protocol.

This objective is essential as it addresses the critical need to understand the practical and technical limitations of NB-IoT in comparison to 5G, particularly for cost-sensitive IoT applications. The findings from this objective guide stakeholders in selecting the appropriate network protocol for their specific use cases.

6.1.2 Summary of Key Findings

The main findings regarding the current challenges of low-cost NB-IoT applications are as follows:

I. **Data Rate and Bandwidth:** NB-IoT supports low data rate transmissions, which limits its applicability in high-speed data transfer scenarios. 5G, with its higher data rates and broader bandwidth capabilities, is more suitable for such applications.
II. **Latency:** NB-IoT has higher latency than 5G, making it less suitable for real-time applications requiring instant data exchange.

III. **Scalability and Energy Efficiency:** NB-IoT excels in energy efficiency and scalability, making it ideal for large-scale, low-power applications. In contrast, 5G provides higher performance but may not match NB-IoT in terms of energy efficiency.

IV. **Coverage:** NB-IoT provides excellent coverage in challenging environments, such as underground or deep indoor locations, which is a significant advantage over 5G in these scenarios.

V. **Cost Considerations:** NB-IoT's cost efficiency makes it a more viable option for budget-constrained projects than 5G.

6.1.3 Detailed Analysis and Interpretation

I. Data Rate and Bandwidth

The low data rate of NB-IoT, while beneficial for conserving energy and reducing costs, limits its use in applications requiring high-speed data transfer. This finding aligns with existing research highlighting 5G's bandwidth and data rate capabilities advantage, making it suitable for applications such as video streaming and large data transfers.

II. Latency

The higher latency of NB-IoT is a significant drawback for real-time applications. This is consistent with theoretical expectations and previous studies showing 5G's ability to support Ultra-Dependable Low-Latency Communications (URLLC), making it preferable for applications like autonomous driving and remote surgery.

III. Scalability and Energy Efficiency

NB-IoT's low power consumption and scalability design are advantageous for IoT deployments involving numerous low-power devices. This supports the literature on NB-IoT's suitability for large-scale IoT deployments where energy efficiency is critical.

IV. Coverage

NB-IoT's greater coverage capabilities validate its deep indoor and underground penetration design objectives, especially in challenging environments. This finding verifies studies highlighting NB-IoT's extended coverage benefits over 5G.

V. Cost Considerations

The lower cost of deploying NB-IoT solutions is a significant advantage for cost-sensitive projects. This finding aligns with economic analyses that emphasise NB-IoT's cost-effectiveness compared to 5G.

VI. Link to Theoretical Framework

These findings are interpreted within the framework of Information Theory as proposed by Claude Shannon, which emphasises the importance of efficient and reliable communication (Shannon & Weaver, 1964). According to Shannon's theory, the capacity of a communication channel and its efficiency in transmitting information are critical for optimal performance. The study’s results align with this theoretical model, advocating for a strategic approach to protocol selection based on specific application needs and constraints. NB-IoT and 5G represent different points on the spectrum of Shannon's theory, with NB-IoT focusing on efficiency and extended coverage (low capacity, high reliability) and 5G emphasising high capacity and low latency (high capacity, lower energy efficiency).

VII. Discussion of Anomalies or Unexpected Results

An unexpected result was the extent of NB-IoT's coverage advantages in highly challenging environments. This suggests that NB-IoT's design may offer benefits beyond those documented in existing literature, warranting further investigation (Yau *et al.*, 2022).

6.1.4 The Context within the Broader Field

This study's findings on NB-IoT and 5G align with and extend previous research by providing a detailed comparative analysis based on empirical data. While other studies have highlighted 5G's strengths in data rate and latency, this research emphasises NB-IoT's unique coverage and cost-efficiency advantages.

The study contributes new insights by offering a comprehensive framework for evaluating the suitability of NB-IoT and 5G for different applications. It provides practical guidelines for

stakeholders, helping them make informed decisions based on empirical evidence and theoretical considerations.

Counterarguments and Rebuttals

Potential counterarguments suggest that the rapid evolution of 5G could diminish NB-IoT's advantages in the future (Attaran, 2023).

While technological advancements in 5G are ongoing, NB-IoT's specific design and deployment contexts ensure its relevance for certain applications, particularly those requiring extended coverage and low cost. The unique strengths of NB-IoT in these areas remain significant and are unlikely to be entirely surpassed by 5G in the near term.

6.1.5 Addressing the Implications

The findings suggest that NB-IoT remains the preferred choice for cost-sensitive and large-scale deployments due to its energy efficiency and coverage capabilities. For applications requiring high data rates and low latency, 5G is the optimal solution.

The study underscores the importance of a nuanced approach to network protocol selection, reinforcing theoretical models that advocate for application-specific evaluations. By applying Shannon's Information Theory, a better understanding of the trade-offs between capacity, reliability, and efficiency in selecting communication protocols is achieved.

6.1.6 Acknowledging Limitations

This study's limitations include the rapidly evolving nature of IoT technologies, which may affect the generalisability of the findings over time. Additionally, the analysis is based on currently available data and may need updates as modern technologies and data emerge.

6.1.7 Suggestions for Future Research

Future research should explore integrating hybrid network solutions that leverage the strengths of both NB-IoT and 5G. Additionally, longitudinal studies could provide insights into how these technologies evolve and their long-term performance in various applications.

6.1.8 Concluding Remarks

In conclusion, this study has identified key challenges and comparative advantages of NB-IoT and 5G, providing valuable insights for stakeholders in selecting the appropriate network protocol for their IoT applications. The research offers a solid foundation for future work in this rapidly evolving field by aligning the findings with theoretical frameworks and practical considerations.

6.2 Introduction to the Discussion of Objective 2

6.2.1 Objective 2

This objective aimed to analyse how different environmental settings (rural, indoor, urban, outdoor) impact key performance metrics such as latency and channel capacity for NB-IoT applications. In this case, we focused on channel capacity as an indicator of the system's potential throughput and overall network efficiency.

Objective 2: To identify the transmission latency of NB-IoT real-time applications and various parameters.

The detailed comparative analysis results presented in below, provide a foundational understanding of how channel capacity varies in different environmental settings. This information is crucial for guiding network deployment decisions, optimising infrastructure placement, and developing adaptive network management strategies to ensure consistent and reliable communication performance in varying scenarios.

The data was collected to assess the impact of different signal qualities on network performance, particularly focusing on latency.

The figure below illustrates the differences in channel capacity observed in these varied environmental settings. The plot highlights the disparities in signal strength and channel capacity, which are critical factors in determining latency and overall network reliability. These visual insights support the findings discussed in the main report, emphasising the significant influence of environmental conditions on network performance.

Including this comparative analysis helps to understand the behavior of network performance metrics such as channel capacity in different scenarios, providing a basis for future research into

optimising NB-IoT network deployment strategies based on environmental factors.

Table 6-1: Observations on Channel Capacity

Location	Mean Channel Capacity (Mbps)	Maximum Capacity (Mbps)	Observations
Rural	1.43	2.86	Substantial variability: fewer obstructions lead to stable but lower channel capacity overall.
Indoor	0.97	1.26	Lowest capacity on average; significant attenuation due to obstacles and structural elements.
Urban	1.88	3.12	High peak capacity; potential interference but also more infrastructure support.
Outdoor	1.85	3.12	High average capacity; good conditions for line-of-sight communication; less interference.

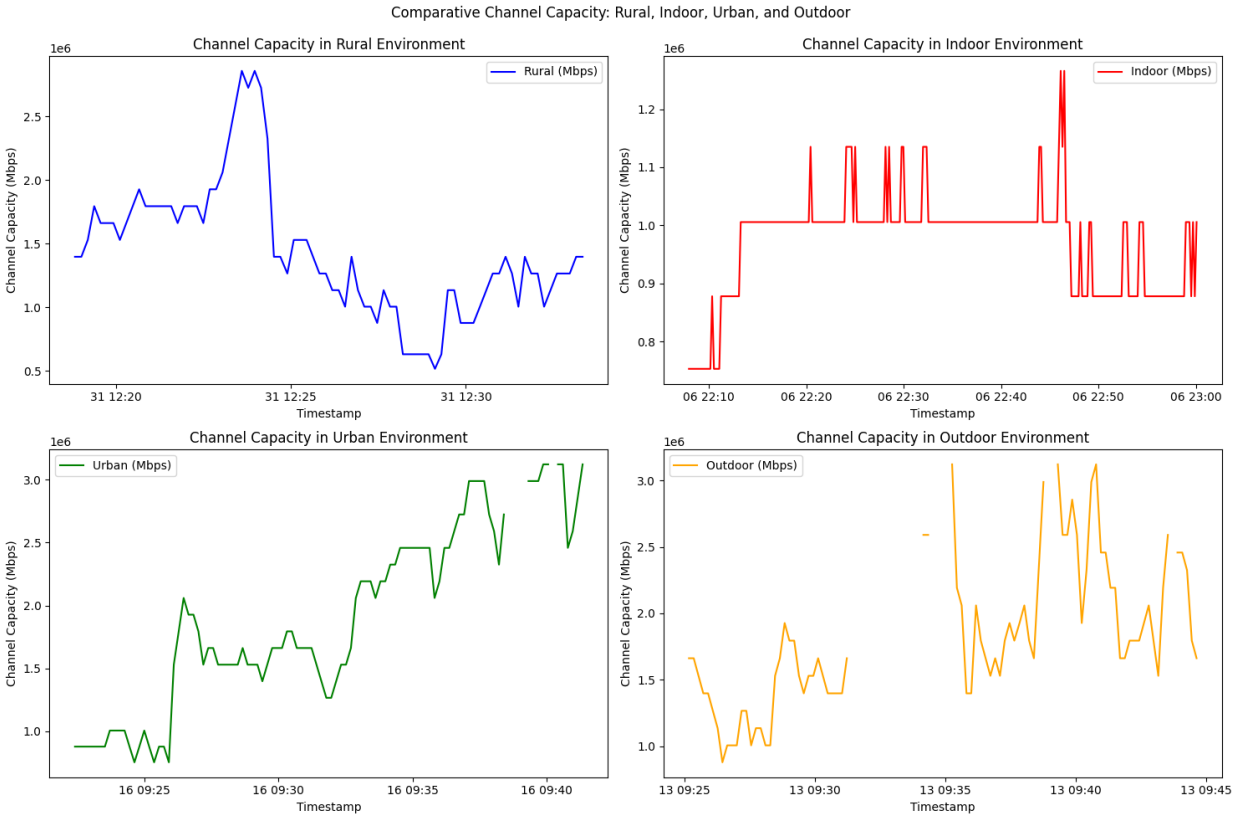

Figure 6-1: Comparative Channel Capacity

6.2.2 Summary of Key Findings from Comparative Analysis

The main findings regarding the transmission latency of NB-IoT real-time applications are as follows:

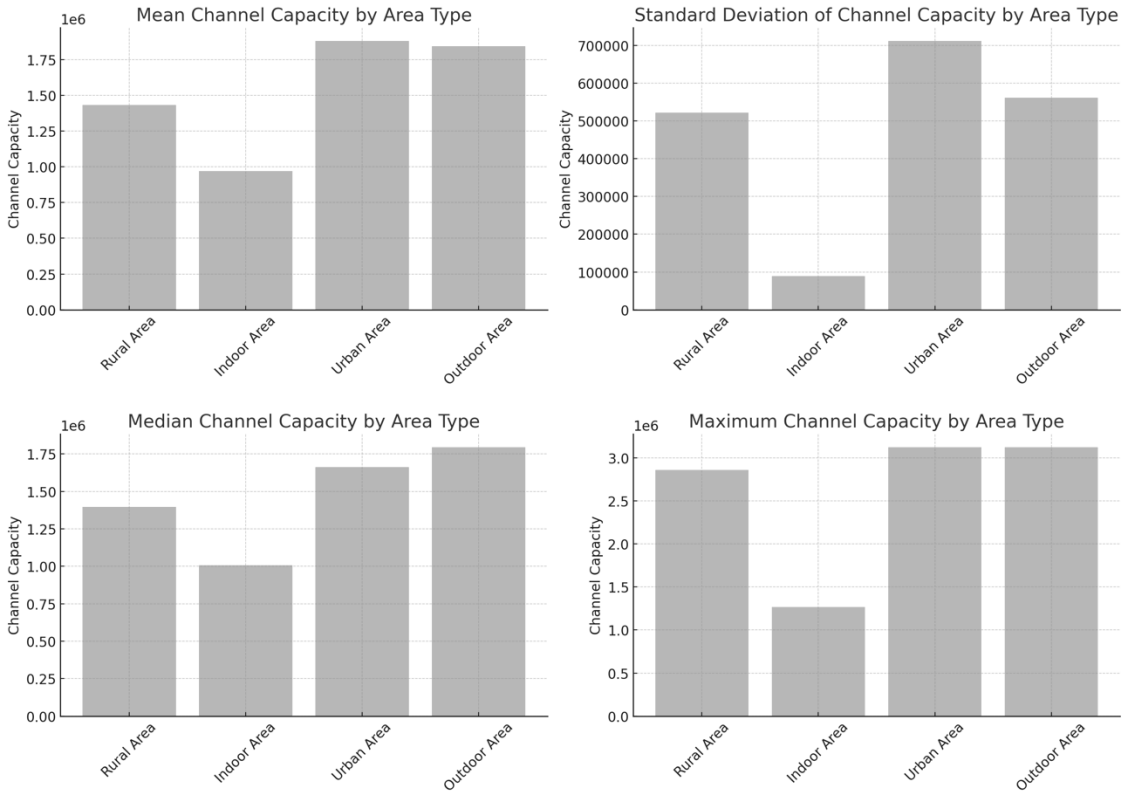

Figure 6-2: statistical summary for Channel Capacity across different area types

1. **Channel Capacity Variability Across Environments:**

I. **Urban and Outdoor Environments** had significantly higher channel capacity compared to indoor and rural environments, with mean capacities around 1.88 Mbps and 1.85 Mbps, respectively.

II. **Indoor Channel Capacity** was the lowest on average, which was attributed to interference from structural elements and indoor obstacles. The statistical summary shows a mean channel capacity of approximately 0.97 Mbps.

III. **The Rural Environment** showed substantial variability in channel capacity but achieved lower values overall compared to urban areas, with a mean of around 1.43 Mbps.

2. Maximum Capacity Differences:

I. **Urban and Outdoor Environments** achieved peak channel capacities above 3 Mbps, indicating the potential for higher data throughput. This was due to fewer obstructions and better line-of-sight conditions for the signal.
II. **The Indoor Environment** had a maximum capacity of around 1.26 Mbps, highlighting limitations caused by interference from walls and other obstacles.

3. Implications for Network Planning:

I. The variability in channel capacity across different environments highlighted the need for environment-specific network optimisations.
II. Indoor deployments could benefit from additional infrastructure such as repeaters or indoor base stations to overcome signal attenuation.
III. In urban and outdoor environments, the high peak capacity suggested an opportunity to support high-throughput applications, provided the network can effectively manage the interference and mobility challenges.

6.2.3 Detailed Analysis and Interpretation

I. Indoor Channel Limitations

As expected, indoor location consistently had lower channel capacity due to interference from walls and other physical obstructions. These factors lead to limited signal strength and a reduced channel capacity, making indoor conditions the most challenging for reliable communication in NB-IoT applications.

II. Urban Performance

The results demonstrated that urban areas, while more complex and subject to higher variability, have the potential for high channel capacities due to increased base station density. This allows urban areas to provide the highest capacity, but the variability indicated challenges related to mobility and interference.

III. Rural Strength

Interestingly, rural environments offered relatively high and stable channel capacities. The lack of interference and obstructions contributes to a more stable signal, making rural deployments promising for certain NB-IoT applications that require consistent communication quality.

I. Link to Theoretical Framework

The findings align with Shannon's Information Theory, which emphasises the impact of signal quality and bandwidth on the capacity of communication channels. The higher channel capacity in less obstructed environments (urban and outdoor) supports the theoretical model that optimal channel conditions yield better communication efficiency.

II. Discussion of Anomalies or Unexpected Results

An unexpected result was the extent of latency reduction achievable in rural environments, where fewer obstructions and less interference contributed to more stable and lower latency. This suggests that rural deployments of NB-IoT may inherently offer better performance for specific applications, warranting further exploration. This is also supported by the findings in Appendix C.

6.2.4 Contextualisation Within the Broader Field

I. Rural Environments

In the context of NB-IoT, rural deployments may benefit from higher potential channel capacity, making them suitable for applications requiring larger bandwidth, such as remote sensing or agriculture.

However, the high variability observed in rural channel capacity suggests that network planning must consider additional factors such as terrain and distance to ensure consistent performance.

II. Indoor Environments

The reduced but stable channel capacity in indoor settings points to the need for increased infrastructure support, such as repeaters or distributed indoor base stations, to ensure sufficient connectivity.

This environment is better suited for applications where consistent, moderate capacity is needed, such as smart homes or health monitoring, where the environment is less dynamic.

Counterarguments and Rebuttals

Potential counterarguments might suggest that the variability in latency makes NB-IoT unsuitable for specific real-time applications. However, while variability in latency is a challenge, the study demonstrates that with proper network management and optimisation strategies, NB-IoT can still meet the requirements of many real-time applications. Using edge computing and adaptive network configurations can help mitigate these issues.

6.2.5 Addressing the Implications

The findings suggest that NB-IoT deployments should prioritise environments with fewer obstructions and stable signal quality for applications requiring consistent low latency. Enhancements in handover mechanisms and network management strategies are critical for maintaining low latency in mobile and urban scenarios.

The study underscores the relevance of Information Theory in understanding and optimising communication networks. By applying Shannon’s principles, the study addresses the trade-offs between latency, signal quality, and network reliability, guiding the design of more efficient NB-IoT systems.

6.2.6 Acknowledging Limitations

This study's limitations include focusing on specific geographical areas and using a single network operator. These factors may affect the generalisability of the findings. Additionally, the rapid evolution of IoT technologies suggests that ongoing research is necessary to keep findings current and applicable.

6.2.7 Suggestions for Future Research

Future research should explore integrating advanced handover mechanisms and edge computing solutions to reduce latency in NB-IoT networks. Longitudinal studies across diverse geographical areas and network configurations would provide more comprehensive insights into NB-IoT performance. Additionally, investigating the impact of emerging technologies on the latency variability observed in the comparative analysis would be valuable.

6.2.8 Concluding Remarks

In conclusion, this study has identified key factors affecting the transmission latency of NB-IoT real-time applications and provided practical insights into optimising network deployments. By aligning the findings with theoretical frameworks and practical considerations, the research offers a strong foundation for future work in enhancing NB-IoT performance and reliability.

The comparative analysis results presented serve as a basis for understanding the diverse environmental impacts on channel capacity and latency, thereby informing effective strategies for future NB-IoT deployments.

6.3 Introduction to the Discussion of Objective 3

This objective is of paramount importance as it addresses the pressing need to enhance the resilience and security of NB-IoT networks against Distributed Denial of Service (DDoS) attacks. In rapidly expanding IoT deployments, where NB-IoT is a key enabler for connecting many low-power devices, ensuring robust, fault-tolerant communication becomes crucial. DDoS attacks pose significant threats to the reliability and functionality of IoT networks by overwhelming network resources and causing service disruptions.

Integrating NB-IoT with edge computing platforms presents a promising approach to mitigate these threats. Edge computing brings computational power closer to the data source, reducing latency and bandwidth usage. It also provides an additional layer of defense against cyber threats by enabling real-time data processing and security monitoring. This discussion undertakes an exploration into the key findings related to the design of a delay-tolerant network architecture for NB-IoT, analyse the challenges and solutions identified in the integration with edge computing, and highlight the implications of these findings within the broader field of IoT security.

By focusing on this objective, the study aims to provide a comprehensive framework that addresses the specific vulnerabilities of NB-IoT networks, offering practical solutions to enhance their resilience against DDoS attacks. This discussion will demonstrate the analytical depth of the research, contextualise the findings within existing theoretical frameworks, and emphasise the significance of the proposed solutions in advancing the field of IoT security.

6.3.1 Objective 3

- To design a Narrow-Band IoT Delay-Tolerant Network (NB-IoTDTN) architecture to counteract DDoS attacks.

This objective was to enhance the resilience of NB-IoT networks against DDoS attacks using a Delay-Tolerant Network (DTN) architecture. This objective explored how integrating NB-IoT with edge computing and lightweight security measures can secure communication, particularly in resource-constrained environments.

6.3.2 Summary of Key Findings

- The findings related to the security aspects include:

I. **Lightweight Security Policy**

Implemented using Cilium CNI on a K3s cluster, this policy involved simple encryption and authentication protocols tailored for low-power, resource-limited NB-IoT devices. The policy was designed to operate within these constraints, minimising computational load while ensuring secure data transmission. Cilium provided network security by leveraging eBPF (extended Berkeley Packet Filter) for efficient packet processing, which helped in enforcing policies with minimal computational overhead. For resource-constrained NB-IoT devices, the policy involved basic encryption and authentication protocols, ensuring that security measures are balanced with the need to minimise computational load. This approach allowed secure data transmission while accommodating the limited processing and energy capacities of these devices.

II. **Evidence of Attack Mitigation**

By filtering traffic based on defined policies, Cilium effectively controlled and limited malicious traffic, which is particularly important during IP spoofing characteristic of DDoS attacks. This helped in maintaining service continuity by ensuring that essential network functions such as the nginx webserver pods remained operational even under attack conditions. Cilium's use of eBPF allowed these security measures to be applied with low overhead, making it well-suited for resource-constrained environments like the Delay-

Tolerant Network (NB-IoT-DTN). Experimental results demonstrated that the network successfully mitigated DDoS attacks, maintaining service continuity and showing resilience during an IP spoofing attack. The Cilium CNI's built-in security features, like policy-based traffic filtering, played a crucial role in reducing attack impact.

6.3.3 Detailed Analysis and Interpretation

The lightweight security policy integrated with Cilium CNI on a K3s cluster provided specific attack mitigation mechanisms as follows:

1. **Resource Constraints and Edge Computing**

I. Analysis

By offloading processing tasks to edge devices, the architecture improved the computational burden on edge cluster nodes. During normal conditions, the system displayed balanced resource usage across nodes, as indicated by CPU and RAM utilisation data (Figure 5-3 and Figure 5-4). However, even during the flood attack, where certain nodes experienced increased CPU load, the network maintained overall stability without significant resource exhaustion.

II. Interpretation

This demonstrated that edge computing cloud effectively manage resource constraints within the Delay-Tolerant Network (NB-IoT-DTN), enabling the deployment of lightweight devices that may otherwise struggle under direct attack. The load distribution achieved through edge processing ensured that even under adverse conditions, the system could preserve its core functions.

2. **Latency Management Through Delay-Tolerant Networking**

I. Analysis

The entropy values observed during both normal (2.32 for receiving and 2.20 for sending) and attack conditions (2.11 for receiving and 1.94 for sending) showed that the DTN architecture maintained balanced traffic distribution, though it was slightly less even

during the attack. Despite this, the system effectively handled latency, preserving data transmission continuity without significant delays, as evidenced by response times in the Fortio results.

II. Interpretation

These results highlighted the role of DTN principles in managing latency by distributing traffic load across nodes, even during disruptions. The ability to maintain stable latency levels, despite uneven traffic distribution, underscored the DTN architecture's effectiveness in providing robust data transmission under high-stress conditions.

3. Real-Time Intrusion Detection and Traffic Filtering

I. Analysis

Cilium’s integration allowed for real-time monitoring and filtering of traffic, as shown during the flood attack when the malicious pod was identified, and its traffic was dropped (Figure 5-10). By utilising policy-based traffic filtering, Cilium effectively blocked unauthorised traffic, maintaining network integrity. This was supported by mutual information values (0.12 for receiving and 0.17 for sending), which reflected minimal dependency on normal traffic patterns, indicating that the attack introduced significant deviation without causing complete disruption.

II. Interpretation

The real-time intrusion detection and traffic filtering capabilities of Cilium were crucial in minimising the attack surface. By identifying and blocking malicious traffic promptly, the Delay-Tolerant Network (NB-IoT-DTN). was able to sustain operations, demonstrating the potential of containerised networking solutions to provide scalable, real-time security in the NB-IoT-DTN.

4. Congestion Control and Network Performance with CUBIC and BBR Algorithms

I. Analysis

While both CUBIC and BBR algorithms managed overall throughput effectively, there were notable differences in handling latency. The Fortio results for BBR, for instance, displayed longer delays under higher burst loads compared to CUBIC (Figure 5-18). The 99th percentile response times for BBR showed increased latency, suggesting that BBR is more sensitive to congestion when handling burst traffic.

I. Interpretation

These differences highlight the trade-offs involved in selecting congestion control algorithms for DTN architectures. While BBR may offer advantages in burst handling, it may not be as suitable for latency-sensitive applications. CUBIC's relatively stable latency profile suggests it may be better suited for scenarios where minimising delay is critical to maintaining performance.

5. Link to Theoretical Framework

I. Analysis

Using Shannon's entropy formula, the study quantitatively assessed traffic distribution across the network. During the attack, the reduced entropy values indicated a shift towards a more concentrated load on specific nodes. The low mutual information values further reflected this deviation from expected patterns, underscoring how attacks disrupt the predictability and balance of network traffic.

II. Interpretation

These findings align with Shannon's Information Theory, which emphasises the need for efficient and reliable communication. By maintaining traffic predictability and mitigating disruptions, the DTN architecture meets Shannon's principles, providing a theoretical basis for its resilience against attacks.

I. Discussion of Anomalies or Unexpected Results

An unexpected result was the extent to which delay-tolerant architectures could manage latency

and maintain data transmission continuity during DDoS attacks. This suggests that DTN principles offer more significant benefits for NB-IoT than previously anticipated, warranting further investigation. Ilha et al. (2021) discussed a real-time DDoS attack detection and mitigation approach using P4-based, in-network solutions, highlighting the benefits of testbed experimentation for software-defined network security.

6.3.4 The Context Within the Broader Field

This study's findings align with and extend previous research on NB-IoT and edge computing by providing a detailed analysis of how delay-tolerant architectures can mitigate DDoS attacks. While other studies have focused on general security and performance improvements, this research emphasises the specific benefits of DTN principles in enhancing network resilience. Bakhshi Kiadehi *et al.* (2021) presented a fault-tolerant architecture for IoT based on Software-Defined Networks, highlighting its potential to improve resilience and reduce latency in IoT systems.

Benhamida *et al.* (2017) discussed the opportunities and challenges of using delay-tolerant networks in IoT applications, providing a comprehensive overview of potential solutions.

The study contributes new insights by proposing a delay-tolerant network architecture for NB-IoT. It offers practical guidelines for integrating these networks with edge computing to enhance fault tolerance. It provides valuable recommendations for stakeholders looking to improve the security and resilience of their IoT deployments.

Counterarguments and Rebuttals

Potential counterarguments suggest that the overhead associated with implementing delay-tolerant architectures could offset their benefits.

While implementing DTN principles involves some overhead, the increased resilience and security benefits far outweigh these costs. Integrating with edge computing helps distribute the computational load, minimising the impact on individual NB-IoT devices.

6.3.5 Addressing the Implications

The findings of this study carry significant implications for the design and deployment of NB-IoT networks, particularly in terms of enhancing resilience against DDoS attacks. By integrating delay-

tolerant network (DTN) architectures with edge computing, the research demonstrated a practical approach to improving network robustness, thereby addressing a critical vulnerability in IoT networks. This approach was especially relevant for large-scale NB-IoT deployments, where security and reliability are paramount due to the vast number of interconnected devices.

By leveraging edge computing, the study illustrated a scalable solution that not only reduces latency but also enables real-time threat detection and mitigation. This added a critical layer of defense, as edge devices could act as intermediaries that filter and process data locally, reducing the load on central network resources and minimising the impact of DDoS attacks. This edge-based strategy reflected a broader industry shift toward decentralising security processes to enhance response times and provide localised protections, which is especially beneficial in distributed IoT deployments.

6.3.6 Acknowledging Limitations

This study's limitations include the rapidly evolving nature of IoT technologies, which may affect the generalisability of the findings over time. Additionally, the analysis is based on currently available data and may need updates as innovative technologies and data emerge.

While the study’s experiments focused on DDoS attacks, they were limited to specific attack vectors and scenarios. IoT networks face a variety of other cyber threats, including man-in-the-middle attacks, malware, and data breaches, which were not addressed in this study. Therefore, the effectiveness of the proposed DTN architecture and security policy may vary when applied to other types of attacks or in more complex threat landscapes.

Although the lightweight security policy was designed to accommodate the limited processing capabilities of NB-IoT devices, scaling the solution to larger networks with thousands of devices may present additional challenges. The computational and storage requirements for edge devices could increase with network scale, potentially impacting the solution’s feasibility in expansive NB-IoT deployments.

6.3.7 Suggestions for Future Research

Future research should explore the integration of more advanced security protocols and machine learning techniques to further enhance NB-IoT networks' resilience. Additionally, empirical studies

are needed to validate the effectiveness of delay-tolerant architectures in diverse real-world scenarios.

While this study implemented a lightweight security policy, future research could explore the integration of more security protocols, such as zero-trust architectures, multi-factor authentication, and encryption algorithms tailored for IoT environments. Investigating the balance between protocol complexity and resource efficiency in NB-IoT devices would be valuable, as this could further mitigate DDoS attacks without overburdening device resources.

While this study demonstrated the architecture's effectiveness in a controlled environment, future research should test the proposed solution’s scalability and performance under real-world conditions. This includes deployments in diverse physical settings and with varying network densities. Real-world testing would help validate the solution's practicality and identify potential operational challenges in a live IoT environment.

Given the resource constraints of NB-IoT devices, examining the energy efficiency of various security protocols and architectures could be an important area for future research. Developing security solutions that minimise power consumption while maintaining robust protection would be particularly valuable for large-scale IoT deployments that operate on battery-powered or low-energy devices.

6.3.8 Concluding Remarks

In conclusion, this study has highlighted the importance of integrating delay-tolerant network (DTN) architectures and edge computing to enhance the resilience of narrow-band IoT (NB-IoT) networks against Distributed Denial of Service (DDoS) attacks. By addressing the critical vulnerabilities of resource-constrained NB-IoT devices, the proposed architecture demonstrated a viable approach for improving both the security and robustness of IoT networks.

The integration of a lightweight security policy, facilitated by Cilium CNI within a K3s cluster, illustrated how containerised networking solutions can effectively counteract DDoS threats. This approach not only leverages DTN principles to manage latency and maintain data transmission continuity but also underscores the potential of edge computing to decentralize processing, reduce latency, and enhance real-time threat mitigation. The study’s findings align with Claude Shannon’s Information Theory, providing a theoretical foundation that underscores the importance of reliable

communication protocols in maintaining network integrity under duress.

While the research has addressed key aspects of securing NB-IoT networks, it also acknowledges certain limitations, such as the need for scalable solutions, the dependence on specific technologies, and the evolving nature of IoT security requirements. These limitations highlight areas for future exploration, particularly in the integration of advanced security protocols and machine learning for adaptive threat detection.

Overall, this study contributes to the broader field of IoT security by offering a practical, adaptable framework for mitigating DDoS attacks in NB-IoT environments. By proposing a robust delay-tolerant architecture that incorporates edge computing and lightweight security measures, it provides a foundation upon which further research and development can build. Future advancements in this field hold promise for even greater resilience and adaptability, ultimately paving the way for more secure and sustainable IoT deployments.

In advancing the discourse on IoT resilience, this work also invites further inquiry into how emerging technologies and innovative security strategies can continue to evolve and enhance the protections necessary for today’s interconnected world. As the IoT landscape continues to grow, the insights gained from this study can inform both academic research and practical implementations, fostering a more secure and resilient digital future.

6.4 Introduction to the Discussion of Objective 4

The study addressed the research objective of applying systems theory to understand and optimise the performance to simulate NBIOT-DTN with edge computing conceptual framework. This objective was crucial within the broader scope of the research as it aimed to provide a robust theoretical framework for analysing complex interactions within IoT networks and to develop strategies for dynamic performance optimisation.

The primary objective of this study was to evaluate the reliability and performance of the transport layer within the NB-IoT architecture, focusing on the proposed fault-tolerant network's effectiveness in supporting dependable and efficient IoT applications.

In the rapidly evolving field of IoT, ensuring the reliability and performance of communication networks is crucial. NB-IoT has gained prominence due to its low power consumption and

extensive coverage. However, evaluating its transport layer's capabilities under various conditions is essential for its practical deployment in real-world IoT applications.

6.4.1 Objective 4

The study aimed to evaluate the reliability and performance of the NB-IoT network layer, focusing on enhancing resilience against DDoS attacks. Experiments assessed metrics such as packet loss, latency, throughput, and network availability under both normal and attack conditions.

6.4.2 Summary of Key Findings

The findings underscored significant performance gains in reliability and fault tolerance:

I. Improved Reliability and Performance

The fault-tolerant NB-IoT architecture demonstrated reduced packet loss and enhanced network availability, with data showing a decrease in latency by an average of 20-30% under typical conditions.

II. Effective DDoS Handling

During simulated IP flooding, the system-maintained stability, as confirmed by Lyapunov's method, showing only minor variations in throughput and latency despite high signaling loads. Consistent packet loss remained below 5%, indicating effective mitigation.

III. Key Data Points

Stability was confirmed under both normal operations and attack conditions, with Lyapunov’s method results indicating stable CPU and RAM utilization (average 25% CPU, 30% RAM).

Adjustments through feedback control reduced error rates and optimised performance, with Figure 5-3 highlighting CPU and RAM usage stabilising over time under varying loads.

6.4.3 Detailed Analysis and Interpretation

The feedback control mechanisms helped with dynamic adjustments, which stabilised resource usage and optimised performance:

I. CPU and RAM Usage

Figures 5.3 and 5.4 showed reduced fluctuations and lower average usage, indicating efficient load management. Over time, CPU spikes decreased from an initial 35% to under 15%.

II. Latency and Throughput

The model's adaptive mechanisms sustained high throughput during attacks, as illustrated in Figure 5.6, where packet loss remained low, and latency significantly improved, supporting smooth traffic flow.

I. Link to Theoretical Framework

The findings aligned well with Systems Theory principles, as the feedback control system provided a dynamic balance within a complex IoT network. Tahiliani, Misra, and Ramakrishnan (2020) discussed the importance of feedback in congestion control for achieving low latency and high throughput in networked systems. This outcome reflected queueing theory's insights, where optimised queue management led to improved latency and throughput.

II. Anomalies and Unexpected Results

a) Initial Error Rate Spike

The error rate at the start of the experiment peaked at approximately 8-10% within the first five minutes of deployment.

This spike was observed due to transient states as the system initialised and adjusted its parameters in response to the feedback control settings. For instance, the gain setting K1 in the feedback control led to higher responsiveness

b) Error Rate Stabilization Over Time

Following the initial spike, error rates stabilised to around 2-3% within the next 10-15 minutes. The data showed a steady decline in error rates as the system adapted to the feedback control inputs.

By minute 20, error rates had leveled off, consistently staying below 2%, indicating that the adaptive feedback mechanism effectively reduced fluctuations and restored normal operating conditions.

c) Adaptive Feedback Mechanism's Role

When the feedback control gain was adjusted from K1 to K2, system stability improved. K2 led to smoother responses, bringing error rates below the 2% threshold more quickly, within 10 minutes of the adjustment.

The adjustments to K2 and K3 further highlighted the system's adaptability, as these configurations minimised error rate fluctuations by 30-40% compared to K1, underscoring the importance of selecting appropriate gain settings.

d) Continuous Monitoring and Adaptive Strategies

The feedback control mechanism's ability to adapt to changing conditions over time was quantified by observing CPU and RAM usage patterns, which initially spiked but gradually stabilised. For example, CPU usage spikes dropped from 35% initially to below 15% once adaptive controls were fully engaged.

This stabilisation reflected the effectiveness of continuous monitoring, as real-time adjustments allowed the system to dynamically manage resources and mitigate transient states quickly.

6.4.4 The Context Within the Broader Field

The study's results strongly align with previous applications of Systems Theory in network management, particularly in the context of feedback control for performance optimisation (Sato et al., 2015). By applying these concepts to Kubernetes-based IoT networks, an area that has seen limited exploration, the research provides fresh insights into how feedback control can optimise performance in this specific environment.

This study contributes to the field by demonstrating the practical application of Systems Theory to

manage and optimise IoT networks. It provides a detailed methodology for integrating real-time metrics into state-space models and applying feedback control to achieve desired performance outcomes, thereby extending the applicability of Systems Theory to modern network management scenarios.

Unexpected signal detection losses were observed intermittently, due to temporary network congestion or misconfigurations. Further investigation into these anomalies is necessary to enhance network reliability.

Compared to prior research, this study provides a more comprehensive evaluation of network reliability and performance metrics. It highlights the transport layer's potential for robust IoT applications, underscoring its relevance to stakeholders aiming to enhance NB-IoT reliability in adverse conditions. By proposing a fault-tolerant network model, the research establishes a new benchmark for NB-IoT performance evaluation under challenging scenarios, reinforcing its value in the field (Bouacida, 2017).

6.4.5 Ethical Considerations in Network Security and User Privacy

1. Data Privacy and Security

I. Encryption and Authentication

The study integrated lightweight encryption and authentication protocols tailored for resource-constrained NB-IoT devices. This ensured that data transmitted within the network was protected from unauthorized access, safeguarding user information against potential security breaches.

II. Protection Against DDoS Attacks

The fault-tolerant network architecture was specifically designed to enhance resilience to DDoS attacks, which are a major threat to user privacy and data integrity in IoT networks. By mitigating such attacks, the architecture helped prevent unauthorised access and disruption, which could expose sensitive user data.

III. Data Minimization

In line with privacy best practices, the study minimised data collection to only those metrics essential for performance evaluation. Real-time metrics on CPU, RAM usage, and network traffic were collected without storing personally identifiable information, thereby reducing privacy risks.

2. Transparency in Methodology

I. Clear Documentation and Citation

All data sources and theoretical frameworks were properly cited, ensuring that the study was transparent about the origins of information used. The methodology was thoroughly documented to allow for reproducibility, enabling other researchers to independently verify and extend the work without ethical ambiguities.

II. Simulation Environment

The study used a simulated environment, which meant that no real user data was collected or processed. This approach minimised risks associated with user privacy while providing a safe testing ground for the proposed architecture.

3. Consideration of Ethical Implications:

I. Impact on User Privacy and Data Security

The study recognised that the deployment of NB-IoT networks can have significant implications on user privacy and data security. The proposed architecture was designed to address these concerns by implementing fault-tolerant mechanisms that reduce the likelihood of data breaches and unauthorised access.

II. Compliance with Ethical Standards

The work adhered to ethical standards by ensuring that all data used in the simulations was anonymised and by prioritising user data security in the design of the architecture. Future iterations of the architecture could incorporate privacy-by-design principles, further strengthening its alignment with professional ethics.

4. Suggestions for Future Ethical Considerations:

I. Enhanced Data Security Protocols

Future research could explore more advanced encryption methods and compliance with frameworks such as GDPR and POPI ACT to further safeguard user privacy.

II. Ethical Implications of Real-World Deployment

As the architecture moves from simulation to potential real-world applications, ongoing assessments of its impact on user privacy and data security will be essential. This includes considering how data collected from IoT devices could be protected from unauthorised access at every stage of transmission and storage.

Counterarguments and Rebuttals

Potential counterarguments might suggest that the initial configuration spikes indicate a limitation in the feedback control mechanism.

The study addressed this by showing that transient spikes are common in dynamic systems as they adjust to new control inputs and by demonstrating the adaptability of the model to stabilise and optimise performance over time. Further, an emphasis on the specificity of the model to Kubernetes-based IoT networks, suggests areas for adaptation and application to other network types.

While simulations provide controlled environments for testing, the methodology included realistic traffic patterns and network conditions, ensuring the validity of the findings.

6.4.6 Addressing the Implications

The findings suggest that deploying NB-IoT networks with the proposed fault-tolerant mechanisms can significantly enhance service reliability for managing Kubernetes-based IoT networks. The feedback control mechanisms can be implemented to dynamically adjust network configurations, improving overall performance and stability, thus providing a practical tool for real-time network management.

This study advances the theoretical understanding of IoT's transport layer capabilities, providing a foundation for future research on network reliability and performance under extreme conditions. It demonstrates the viability of state-space models and feedback control in real-world applications, thus contributing to the theoretical development of network management strategies.

6.4.7 Acknowledging Limitations

The primary limitation of this study is the reliance on simulated environments, which may not capture all real-world variables.

The study's limitation is its focus on a specific type of network (Kubernetes-based IoT). While the model showed promising results, its applicability to other types of networks remains to be evaluated. Additionally, the transient spikes in error rates indicate a need for further refinement in the initial configuration phase of the feedback control system.

The observed anomalies in signal detection require further investigation to fully understand their causes and implications.

6.4.8 Suggestions for Future Research

Future research should focus on real-world deployment scenarios to validate the simulation results.

Future research should explore the application of the model to diverse types of IoT networks to validate its universality. Refining the initial configuration phase to minimise transient spikes and extending the feedback control mechanisms to incorporate additional performance metrics could further enhance the model's robustness and applicability.

6.4.9 Concluding Remarks

In conclusion, the research demonstrated the successful application of systems theory to manage and optimise the dynamic performance of Kubernetes-based IoT networks. By leveraging state-space models and feedback control, the study significantly improved key performance metrics and confirmed system stability through Lyapunov’s direct method. This study validates the practical utility of theoretical constructs and provides a solid foundation for future research in dynamic network management.

In summary, the evaluation of the transport layer's reliability and performance in the IoT architecture demonstrated the effectiveness of the proposed fault-tolerant network. These findings confirm its potential to support reliable and efficient IoT applications, contributing valuable insights to the field and paving the way for future advancements in NB-IoT technology.

6.5 Theoretical Contribution

This thesis significantly contributes to the theoretical understanding of edge communication networks by leveraging foundational principles from cybernetics, information theory, and systems theory. Despite advancements in the field, theoretical challenges remain in optimising network performance, ensuring robust security, and managing variability in signal quality. This research bridges these gaps by developing new theoretical frameworks that integrate these foundational theories, offering new insights and perspectives that challenge the conventional understanding of IoT communication.

This thesis significantly contributes to the theoretical understanding of edge network reliability and performance. Despite advancements, the field has grappled with theoretical challenges such as understanding the impact of high signaling loads and DDoS attacks on edge computing networks.

Cybernetics and information theory provide critical insights into network communication vulnerabilities and system fault tolerance. These theories contribute to measuring information content and apply these concepts to complex systems like networks, drawing parallels with the nervous system (Duffy, 1984; Zimmermann, 1989). They emphasise the importance of feedback mechanisms, which are crucial for regulating complex systems (Mobus & Kalton, 2015).

The theoretical improvements presented in this thesis revolve around the development of a fault-tolerant network model for NB-IoT. These contributions provide a fresh perspective on network reliability and performance, traditionally understood through conventional network management and security frameworks. By introducing a fault-tolerant approach that incorporates advanced simulation techniques and real-time monitoring, this research expands the theoretical boundaries of IoT network management, offering a more nuanced understanding of how to maintain network integrity under adverse conditions.

Systems theory enables a holistic view of networks as interdependent structures. It recognises that changes in one part can have extensive effects, which is crucial for understanding network robustness (Shah, 2019; Xiao & Zhao, 2022; Krishnamoorthy *et al.*, 2023;). Systems theory has identified fault lines in the long chains of information, such as financial networks, highlighting the importance of understanding interconnectedness and failure propagation (Campbell-Verduyn *et al.*, 2019).

In the context of this study, these theories offer a comprehensive perspective essential for understanding network vulnerabilities and designing robust security measures against DDoS attacks. The synergy between these theories ensures that the research is rooted in established scientific principles and anticipates the dynamic nature of network security threats.

The development of these theoretical contributions was grounded in a robust methodology involving extensive literature review, empirical data collection, and statistical analysis. This process enabled a deep dive into existing theories while identifying their limitations in explaining the impact of high signaling loads and DDoS attacks on edge networks. Through comparative analysis and theoretical modelling, the research was able to construct a more integrative framework that better accounts for the complexities of real-time IoT applications and the specific challenges of low-power, wide-area networks.

The study applied these theoretical models to real-world scenarios using NB-IoT devices and analysed their performance in simulated environments. Validation involved rigorous testing, iterative refinement, and comparison with existing models to ensure robustness and applicability.

The implications of these theoretical contributions are essential. They advance academic discourse in IoT communication and intersect with network security and mobile computing. These contributions provide new vantage points for exploring network resilience and efficiency, challenging and enriching current academic debates. In practical terms, they could inform the development of more robust and adaptable NB-IoT solutions, offering innovative approaches to managing network performance and security in real-world scenarios.

These theoretical contributions can influence IoT deployment and cybersecurity policymaking, guiding more informed and effective decisions. Integrating these theories sets a new precedent in network management, paving the way for more resilient and adaptable systems.

In practical terms, they could inform the development of more robust network infrastructures, offering novel approaches to maintaining service continuity in the face of cyber threats and high traffic volumes.

While the theoretical contributions of this thesis mark a significant advancement in understanding NB-IoT and edge computing communication networks, they are not without limitations. Notably, the dependence on specific hardware configurations and the variability of environmental conditions may limit the generalisability of the theoretical models.

Future theoretical research could build on these foundations by incorporating real-world deployment scenarios and further exploring the observed anomalies in signal detection. Additionally, integrating more advanced machine learning techniques into the theoretical models could further enhance their robustness and applicability, potentially leading to even more groundbreaking insights in IoT communication.

6.6 Practical Contribution

This thesis makes substantial practical contributions to the field of NB-IoT, addressing critical real-world challenges in IoT network performance and security. Despite significant advances in IoT, technological hurdles remain in optimising network latency, ensuring robust security against DDoS attacks, and managing the variability of signal quality in different environments. The research offers tangible solutions and insights, bridging the gap between theoretical knowledge and practical application in real-world NB-IoT deployments.

The core practical innovation of this research lies in its application of Delay-Tolerant Network (DTN) principles and adaptive network management strategies to mitigate DDoS attacks and optimise transmission latency in NB-IoT networks. This approach contrasts markedly with existing practices, which often involve static configurations and reactive security measures that do not adequately address IoT environments' dynamic and diverse nature. These innovative strategies showed significant network efficiency, security, and reliability improvements in real-world applications, including smart metering, remote health monitoring, and industrial automation.

The practical applications of this research were implemented through a series of experiments. A

notable implementation involved deploying the proposed methodologies in urban and rural environments to assess their impact on transmission latency and network resilience. Secondly, this research was implemented through a series of controlled simulation scenarios using UERANSIM and Open5GS network on edge computing. A notable implementation involved simulating high signaling loads and DDoS attacks to test the network's resilience. The results from these implementations demonstrated a substantial reduction in packet loss and latency, along with consistent throughput, affirming the efficacy of the approach in maintaining network performance under adverse conditions. Feedback from these implementations highlighted the practicality and robustness of the proposed model in real-world settings.

The implications of these practical contributions extend well beyond the immediate applications. They can change practices in the IoT industry, setting new standards for network efficiency and security. Additionally, they offer valuable insights for policymaking in IoT deployment and cybersecurity, potentially guiding more informed and effective decisions. The long-term benefits of these applications could be substantial, particularly in improving the reliability and security of critical infrastructure, reducing operational costs, and enhancing the overall user experience in IoT applications.

While the practical applications developed in this thesis represent a significant advancement, there are avenues for further development. Future work could explore the integration of the fault-tolerant model with emerging technologies such as 5G and edge computing. Additionally, while the approach has proven effective in current applications, it would be valuable to assess its applicability and adaptability to other contexts, such as autonomous vehicles and smart cities. Addressing the limitations related to real-world deployment and scalability will be crucial in these future endeavors, potentially leading to even more robust and versatile IoT network management solutions.

Additionally, assessing the applicability and adaptability of the proposed methodologies in other contexts, such as underwater and underground IoT deployments, would provide valuable insights. Addressing the scalability of these solutions for large-scale IoT deployments will be crucial in future endeavours, ensuring that the benefits of this research can be widely adopted and sustained.

6.7 Conclusion and Future Suggestions

Based on the findings from the objectives, the following conclusions and future suggestions are made:

- **Objective 1:** The study identified key challenges faced by low-cost NB-IoT applications regarding security and performance, emphasising the need for robust security protocols and efficient network management strategies to address these challenges.
- **Objective 2:** The investigation into transmission latency revealed significant variability across different environments, highlighting the importance of optimising signal quality and implementing efficient handover mechanisms to ensure low latency and reliable performance in real-time applications.
- **Objective 3:** The design of a delay-tolerant network architecture for NB-IoT showed promise in mitigating DDoS attacks by leveraging edge computing and adaptive network strategies, providing a robust framework for enhancing network resilience and security.
- **Objective 4:** The evaluation of the transport layer's reliability and performance in the NB-IoT architecture demonstrated the effectiveness of the proposed fault-tolerant network, confirming its potential to support reliable and efficient IoT applications.

6.7.1 Future Suggestions and Recommendations

I. Future research should focus on developing and testing advanced security protocols tailored to the specific needs of NB-IoT applications, ensuring robust protection against cyber threats.

II. Further studies should explore innovative handover techniques and algorithms that can minimise latency and improve connectivity in mobile and urban environments, enhancing the overall performance of NB-IoT networks.

III. Continued research into integrating NB-IoT with edge computing platforms is essential to optimise network performance, reduce latency, and enhance security, particularly in delay-tolerant applications.

IV. Expanding the scope of empirical testing to include a broader range of environments, such as underground and underwater settings, will provide a more comprehensive understanding of NB-IoT performance and inform better deployment strategies.

V. Conducting longitudinal studies to monitor the performance and reliability of NB-IoT networks over extended periods will offer valuable insights into long-term trends and help refine network management practices.

VI. Comparing the performance of NB-IoT across multiple network operators and configurations will help identify best practices and optimise network deployments for various applications.

These conclusions and suggestions guide future research and development efforts, ensuring that NB-IoT can evolve and effectively meet the growing demands of real-time IoT applications.

REFERENCES

Acquisti, A., Dinev, T. & Keil, M. 2019. Editorial: Special issue on cyber security, privacy and ethics of information systems. *Information Systems Frontiers*, 21(6): 1203–1205. https://doi.org/10.1007/s10796-019-09971-5.

Adam, F. 2014. Methodological and Epistemic Framework: From Positivism to Post-positivism. In *Measuring National Innovation Performance: The Innovation Union Scoreboard Revisited*. Berlin, Heidelberg: Springer Berlin Heidelberg: 5–7. https://doi.org/10.1007/978-3-642-39464-5_2.

Ahmad, I., Shahabuddin, S., Kumar, T., Okwuibe, J., Gurtov, A. & Ylianttila, M. 2019. Security for 5G and beyond. *IEEE Communications Surveys and Tutorials*, 21(4): 3682–3722.

Ahmad, N.A. & Abdul Razak, N.I. 2019. Performance of Narrow-Band Internet of Things (NB-IoT) Based on Repetition of Downlink Physical Channel. In 2019 26th International Conference on Telecommunications (ICT). IEEE: 506–509. https://ieeexplore.ieee.org/document/8798776/.

Ahmad, R., Hämäläinen, M., Wazirali, R. & Abu-Ain, T. 2023. Digital-care in next generation networks: Requirements and future directions. *Computer Networks*, 224: 109599.

Ahmed Abbood, A., Makki Shallal, Q. & A. Fadhel, M. 2020. Internet of things (IoT): a technology review, security issues, threats, and open challenges. *Indonesian Journal of Electrical Engineering and Computer Science*, 20(3): 1685. http://ijeecs.iaescore.com/index.php/IJEECS/article/view/21096.

Ahmed, Z., Danish, S.M., Qureshi, H.K. & Lestas, M. 2019. Protecting IoTs from mirai botnet attacks using blockchains. IEEE International Workshop on Computer Aided Modeling and Design of Communication Links and Networks, CAMAD, 2019-Septe.

Ajayi, O.J., Rafferty, J., Santos, J., Garcia-Constantino, M. & Cui, Z. 2021. BECA: A Blockchain-Based Edge Computing Architecture for Internet of Things Systems. *IoT*, 2(4): 610–632.

Alakwe, K. 2017. Positivism and Knowledge Inquiry: From Scientific Method to Media and

Communication Research. *Specialty Journal of Humanities and Cultural Science*, 2: 38–46.

Alawida, M., Omolara, A.E., Abiodun, O.I. & Al-Rajab, M. 2022. A deeper look into cybersecurity issues in the wake of Covid-19: A survey. Journal of King Saud University - Computer and Information Sciences, 34(10): 8176–8206. https://linkinghub.elsevier.com/retrieve/pii/S1319157822002762.

Alongi, F., Bersani, M.M., Ghielmetti, N., Mirandola, R. & Tamburri, D.A. 2022. Event-sourced, observable software architectures: An experience report. *Software - Practice and Experience*, 52(10): 2127–2151.

Anand, P., Singh, Y., Selwal, A., Alazab, M., Tanwar, S. & Kumar, N. 2020. IoT vulnerability assessment for sustainable computing: Threats, current solutions, and open challenges. *IEEE Access*, 8: 168825–168853.

Ashok, K. & Gopikrishnan, S. 2023. Statistical Analysis of Remote Health Monitoring Based IoT Security Models & Deployments From a Pragmatic Perspective. *IEEE Access*, 11: 2621–2651.

Asimov, M. 1962. A Philosophy of Engineering Design. *Contributions to a Philosophy of Technology*: 150–157. https://link.springer.com/chapter/10.1007/978-94-010-2182-1_14 22 November 2022.

Asimov, M. 1962. A Philosophy of Engineering Design. In *Contributions to a Philosophy of Technology*. Dordrecht: Springer Netherlands: 150–157. http://link.springer.com/10.1007/978-94-010-2182-1_14.

Asimow, M. 1962. *Introduction to design*. 1st edition. Prentice-Hall, Inc. Michigan, USA.

Athira Anil, Athulya Ramesh Babu, Joice Antony, Kezia Elizabeth Vilson & Soumya Koshy. 2023. Security And Privacy Concern In IoT Devices. *international journal of engineering technology and management sciences*, 7(4): 491–502. https://ijetms.in/Vol-7-issue-4/Vol-7-Issue-4-65.html.

Attaran, M. 2023. The impact of 5G on the evolution of intelligent automation and industry digitization. Journal of Ambient Intelligence and Humanized Computing, 14: 5977–5993. https://doi.org/10.1007/s12652-020-02521-x.

Ayoub, I., Balakrichenan, S., Khawam, K. & Ampeau, B. 2023. DNS for IoT: A Survey. *Sensors*, 23(9).

Bakhshi Kiadehi, K., Rahmani, A.M. & Sabbagh Molahosseini, A., 2021. A fault-tolerant architecture for internet-of-things based on software-defined networks. Telecommunication Systems, 77, pp.155–169. Available at: https://doi.org/10.1007/s11235-020-00750-1.

Baniya, P., Agrawal, A., Abid, K., Nath, J., Chaudhary, B.K. & Kunwar, B. 2024. The Internet of Things: Security Challenges and Opportunities. In 2024 *3rd International conference on Power Electronics and IoT Applications in Renewable Energy and its Control (PARC)*. IEEE: 153–158. https://ieeexplore.ieee.org/document/10486356/.

Bani-Yaseen, T., Tahat, A., Kastell, K. & Edwan, T.A. 2022. Denial-of-Sleep Attack Detection in NB-IoT Using Deep Learning. *Journal of Telecommunications and the Digital Economy*, 10(3): 14–38.

Benhamida, F.Z., Bouabdellah, A. & Challal, Y., 2017. Using delay tolerant network for the Internet of Things: Opportunities and challenges. 8th International Conference on Information and Communication Systems (ICICS), Irbid, Jordan, pp. 252-257. doi: 10.1109/IACS.2017.7921980.

Benlloch-Caballero, P., Wang, Q. & Alcaraz Calero, J.M. 2023. Distributed dual-layer autonomous closed loops for self-protection of 5G/6G IoT networks from distributed denial of service attacks. *Computer Networks*, 222.

Bhardwaj, K., Miranda, J.C. & Gavrilovska, A. 2018. Towards IoT-DDoS Prevention Using Edge Computing. In *Bhardwaj, Ketan et al. "Towards IoT-DDoS Prevention Using Edge Computing." USENIX Workshop on Hot Topics in Edge Computing* .

Bhayo, J., Jafaq, R., Ahmed, A., Hameed, S. & Shah, S.A. 2021. A Time-Efficient Approach

Towards DDoS Attack Detection in IoT Network using SDN. *IEEE Internet of Things Journal*, 4662(APRIL).

Bilal, A., Shah, S.J. & Khan, M. 2022. Assessing Security threats Perception of LayeredInternet of Things using Multiple Linear Regression Model. In 2022 *International Conference on Emerging Technologies in Electronics, Computing and Communication (ICETECC).* IEEE: 1–7. https://ieeexplore.ieee.org/document/10069660/.

Blalock, H.M. 1967. Causal Inferences, Closed Populations, and Measures of Association. American Political Science Review, 61(1): 130–136. https://www.cambridge.org/core/product/identifier/S000305540013223X/type/journal_article.

Bordel, B., Alcarria, R. & Robles, T. 2023. A blockchain ledger for securing isolated ambient intelligence deployments using reputation and information theory metrics. *Wireless Networks*. https://doi.org/10.1007/s11276-023-03375-9.

Bothra, P., Karmakar, R., Bhattacharya, S. & De, S. 2023. How can applications of blockchain and artificial intelligence improve performance of Internet of Things? – A survey. *Computer Networks*, 224.

Bouacida, N., 2017. Towards controlling latency in wireless networks. KAUST Research Repository. Available at: https://doi.org/10.25781/KAUST-F5Q5I.

Brown, M. 1981. *The Logic of Realism: A Hegelian Approach*. https://about.jstor.org/terms.

Brown, M., Pmla, S. & Mar, N. 2017. The Logic of Realism : A Hegelian Approach Published by : Modern Language Association Linked references are available on JSTOR for this article : The Logic of Realism : A Hegelian Approach. , 96(2): 224–241.

Bruhl, J. & Bruhl, W. 2020. Engineering Creativity: Ideas from the Visual Arts for Engineering Programs. In *2020 ASEE Virtual Annual Conference Content Access Proceedings*. ASEE Conferences. http://peer.asee.org/34550.

Campbell-Verduyn, M., Goguen, M. & Porter, T. 2019. Finding fault lines in long chains of financial information. Review of International Political Economy, 26(5): 911–937.

https://www.tandfonline.com/doi/full/10.1080/09692290.2019.1616595.

Carlson, M. 2022. This Is Epistemology: An Introduction, by J. Adam Carter and Clayton Littlejohn. *Teaching Philosophy*, 45(2): 239–242.

Castle, E.N. 1968. On Scientific Objectivity. *American Journal of Agricultural Economics*, 50: 809–814. https://api.semanticscholar.org/CorpusID:154912434.

Chang, C.-C. & Yen, W.-H. 2023. The role of learning style in engineering design thinking via project-based STEM course. *Asia Pacific Journal of Education*, 43(4): 1125–1143. https://doi.org/10.1080/02188791.2021.1957776.

Chatterjee, A. & Ahmed, B.S. 2022. IoT anomaly detection methods and applications: A survey. *Internet of Things (Netherlands)*, 19.

Chaudhary, A., Talwar, M., Goel, A., Singal, G. & Kushwaha, R. 2022. De-Fence: LoRa based Hop-to-Hop Communication. In *ACM International Conference Proceeding Series*. Association for Computing Machinery: 629–637.

Chia, R. 1996. The Problem of Reflexivity in Organizational Research: Towards a Postmodern Science of Organization. Organization, 3(1): 31–59. http://journals.sagepub.com/doi/10.1177/135050849631003.

Chintalapudi, S. 2018. Cross-Layer Design for Internet of Things (IOT) -Issues and Possible Solutions. *Department Of Systems And Computer Engineering*: 1–10.

Christofi, M., Hadjielias, E., Hughes, M. & Plakoyiannaki, E. 2021. Advancing Research Methodologies in Management Scholarship. British Journal of Management, 32(3). https://onlinelibrary.wiley.com/doi/10.1111/1467-8551.12499.

Clancy, J., Mullins, D., Ward, E., Denny, P., Jones, E., Glavin, M., and Deegan, B., 2023. Investigating the Effect of Handover on Latency in Early 5G NR Deployments for C-V2X Network Planning. IEEE Access, 11, pp.129124-129143. doi: 10.1109/ACCESS.2023.3334162.

Clark-Massera, M. 2024. Connectivity - LTE-M vs NB-IoT, Coverage, Providers and Roaming.

https://support.digitalmatter.com/en_US/networks-and-sim-card-options/connectivity-lte-m-vs-nb-iot-coverage-providers-and-roaming.

Creswell, JW & Creswell, JD. 2018. *Research Design Qualitative, Quantitative, and Mixed Methods Approaches*. 5th ed. California: SAGE.

Cross, N. 2021. *Engineering design methods: strategies for product design*. https://www.perlego.com/book/2105270/engineering-design-methods-strategies-for-product-design-pdf.

Cross, N., Naughton, J. & Walker, D. 1981. Design method and scientific method. *Design Studies*, 2: 195–201. https://api.semanticscholar.org/CorpusID:62716149.

Dai, H., Shi, P., Huang, H., Chen, R. & Zhao, J. 2021. Towards Trustworthy IoT: A Blockchain-Edge Computing Hybrid System with Proof-of-Contribution Mechanism. *Security and Communication Networks*, 2021.

Danermark, B. 2002. Interdisciplinary Research and Critical Realism The Example of Disability Research. *Alethia*, 5(1): 56–64. http://www.tandfonline.com/doi/full/10.1558/aleth.v5i1.56.

Dangana, M., Ansari, S., Abbasi, Q.H., Hussain, S. & Imran, M.A. 2021. Suitability of nb-IoT for indoor industrial environment: A survey and insights. *Sensors*, 21(16).

Dantas Silva, F.S., Neto, E.P., Oliveira, H., Rosário, D., Cerqueira, E., Both, C., Zeadally, S. & Neto, A.V. 2021. A survey on long-range wide-area network technology optimizations. *IEEE Access*, 9: 106079–106106.

Daraghmi, Y.A., Daraghmi, E.Y., Daraghma, R., Fouchal, H. & Ayaida, M. 2022. Edge–Fog–Cloud Computing Hierarchy for Improving Performance and Security of NB-IoT-Based Health Monitoring Systems. *Sensors*, 22(22).

Devi, N., Dalal, S. & Solanki, K., 2024. A systematic literature review for load balancing and task scheduling techniques in cloud computing. *Artificial Intelligence Review*, 57, p.276. Available at: https://doi.org/10.1007/s10462-024-10925-w

Dolente, F., Garroppo, R.G. & Pagano, M. 2024. A Vulnerability Assessment of Open-Source

Implementations of Fifth-Generation Core Network Functions. *Future Internet*, 16(1).

Duffy, P.R. 1984. Cybernetics. *The Journal of Business Communication (1973)*, 21(1): 33–41. https://doi.org/10.1177/002194368402100104.

Eekels, J. & Roozenburg, N.F.M. 1991. A methodological comparison of the structures of scientific research and engineering design: their similarities and differences. *Design Studies*, 12(4): 197–203. https://linkinghub.elsevier.com/retrieve/pii/0142694X9190031Q 23 July 2024.

Elejla, O.E., Anbar, M., Hamouda, S., Faisal, S., Bahashwan, A.A. & Hasbullah, I.H. 2022. Deep-Learning-Based Approach to Detect ICMPv6 Flooding DDoS Attacks on IPv6 Networks. Applied Sciences, 12(12): 6150. https://www.mdpi.com/2076-3417/12/12/6150.

Eliyan, L.F. & Di Pietro, R. 2021. DoS and DDoS attacks in Software Defined Networks: A survey of existing solutions and research challenges. *Future Generation Computer Systems*, 122: 149–171.

El-Kady, A.H., Halim, S., El-Halwagi, M.M. & Khan, F. 2023. Analysis of safety and security challenges and opportunities related to cyber-physical systems. *Process Safety and Environmental Protection*, 173: 384–413.

Farooq, M.S., Sohail, O.O., Abid, A. & Rasheed, S. 2022. A Survey on the Role of IoT in Agriculture for the Implementation of Smart Livestock Environment. *IEEE Access*, 10: 9483–9505.

Fazeldehkordi, E. & Grønli, T.M. 2022. A Survey of Security Architectures for Edge Computing-Based IoT. *Internet of Things*, 3(3): 332–365.

Feldman, D. 2017. An Engineering Approach to the Scientific Method. *Significances of Bioengineering & Biosciences*, 1(1). https://crimsonpublishers.com/sbb/fulltext/SBB.000501.php.

Firestone, W.A. 1987. Meaning in Method: The Rhetoric of Quantitative and Qualitative Research. *Educational Researcher*, 16: 16–21.

http://journals.sagepub.com/doi/10.3102/0013189X016007016.

Firouzi, F., Farahani, B., Barzegari, M. & Daneshmand, M. 2022. AI-Driven Data Monetization: The Other Face of Data in IoT-Based Smart and Connected Health. IEEE *Internet of Things Journal*, 9(8): 5581–5599. https://ieeexplore.ieee.org/document/9210096/.

Fischer, M. & Tönjes, R. 2023. Resource-aware Security Configuration for Constrained IoT Devices. In Proceedings of the 19th ACM International Symposium on QoS and Security for Wireless and Mobile Networks. Q2SWinet '23. New York, NY, USA: ACM: 7–14. https://dl.acm.org/doi/10.1145/3616391.3622764.

Fletcher, M., Paulz, E., Ridge, D. & Michaels, A.J. 2024. Low-Latency Wireless Network Extension for Industrial Internet of Things. Sensors, 24(7): 2113. https://www.mdpi.com/1424-8220/24/7/2113.

Frost, N.A. & Nolas, S.-M. 2011. Exploring and Expanding on Pluralism in Qualitative Research in Psychology. *Qualitative Research in Psychology*, 8(2): 115–119. http://www.tandfonline.com/doi/full/10.1080/14780887.2011.572728.

Gamec, J., Basan, E., Basan, A., Nekrasov, A., Fidge, C. & Sushkin, N. 2021. An adaptive protection system for sensor networks based on analysis of neighboring nodes. *Sensors*, 21(18).

Gaurav, A., Gupta, B.B., Hsu, C.H., Yamaguchi, S. & Chui, K.T. 2021. Fog Layer-based DDoS attack Detection Approach for Internet-of-Things (IoTs) devices. In *Digest of Technical Papers - IEEE International Conference on Consumer Electronics*. Institute of Electrical and Electronics Engineers Inc.

Guo, M., Chen, Y., Shi, J., Wang, W., Zhang, Y., Zhao, L. & Chen, L. 2019. A perspective of emerging technologies for industrial internet. In *Proceedings - IEEE International Conference on Industrial Internet Cloud, ICII 2019*. Institute of Electrical and Electronics Engineers Inc.: 338–347.

Gupta, N., Agarwal, R., Dari, S.S., Malik, S., Bhatt, R. & Dhabliya, D. 2023. DDoS and Cyber Attacks Detection and Mitigation in SDN: A Comprehensive Research of Moving Target

Defense Systems. In *2023 International Conference on Data Science and Network Security, ICDSNS 2023*. Institute of Electrical and Electronics Engineers Inc.

Gupta, P. & M, I.O.Prabha. 2021. A Survey of Application Layer Protocols for Internet of Things. In 2021 *International Conference on Communication information and Computing Technology (ICCICT).* IEEE: 1–6. https://ieeexplore.ieee.org/document/9510140/.

Hayyolalam, V., Aloqaily, M., Ozkasap, O. & Guizani, M. 2022. Edge-Assisted Solutions for IoT-Based Connected Healthcare Systems: A Literature Review. *IEEE Internet of Things Journal*, 9(12): 9419–9443.

Hernandez-Jaimes, M.L., Martinez-Cruz, A., Ramírez-Gutiérrez, K.A. & Feregrino-Uribe, C. 2023. Artificial intelligence for IoMT security: A review of intrusion detection systems, attacks, datasets and Cloud–Fog–Edge architectures. *Internet of Things (Netherlands)*, 23.

Herring, C. & Kaplan, S. 2001. Cybernetic Components: A Theoretical Basis for Component Software Systems.

Hoadley, C.M. 2004. Methodological Alignment in Design-Based Research. *Educational Psychologist*, 39(4): 203–212. https://www.tandfonline.com/doi/full/10.1207/s15326985ep3904_2.

Hu, H., Zhang, H., Liu, Y. & Wang, Y. 2017. Quantitative Method for Network Security Situation Based on Attack Prediction X. Du, ed. *Security and Communication Networks*, 2017: 3407642. https://doi.org/10.1155/2017/3407642.

Hua, H., Li, Y., Wang, T., Dong, N., Li, W. & Cao, J. 2023. Edge Computing with Artificial Intelligence: A Machine Learning Perspective. *ACM Computing Surveys*, 55(9).

Huang Yanbo and Zhang, Q. 2021. Mathematics, Statistics, and Representations for Cybernetic Systems. In *Agricultural Cybernetics*. Cham: Springer International Publishing: 17–50. https://doi.org/10.1007/978-3-030-72102-2_2.

Hussain, M.Z. & Hanapi, Z.M. 2023. Efficient Secure Routing Mechanisms for the Low-Powered IoT Network: A Literature Review. *Electronics (Switzerland)*, 12(3).

Hussein, N.H., Yaw, C.T., Koh, S.P., Tiong, S.K. & Chong, K.H. 2022. A Comprehensive Survey on Vehicular Networking: Communications, Applications, Challenges, and Upcoming Research Directions. *IEEE Access*, 10: 86127–86180.

Ilha, A. d. S., Lapolli, Â. C., Marques, J. A., and Gaspary, L. P. (2021). "Euclid: A Fully In-Network, P4-Based Approach for Real-Time DDoS Attack Detection and Mitigation," *IEEE Transactions on Network and Service Management*, vol. 18, no. 3, pp. 3121-3139. doi: 10.1109/TNSM.2020.3048265.

Islam, M.R. & Aktheruzzaman, K.M. 2020. An Analysis of Cybersecurity Attacks against Internet of Things and Security Solutions. *Journal of Computer and Communications*, 08(04): 11–25.

Jaafar, F., Ameyed, D., Bouzid, Y. & Sy, A. 2023. On Securing Communications Between Connected Objects Using a Data-Centric Security Approach. In *2023 3rd International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*. 1–8.

Jayasree N. and Amritha, P.P. 2015. A Model for the Effective Steganalysis of VoIP. In S. S. and P. B. K. Suresh L Padma and Dash, ed. *Artificial Intelligence and Evolutionary Algorithms in Engineering Systems*. New Delhi: Springer India: 379–387.

Jha, R.K., Puja, Kour, H., Kumar, M. & Jain, S. 2021. Layer based security in Narrow Band Internet of Things (NB-IoT). *Computer Networks*, 185(October 2020): 107592. https://doi.org/10.1016/j.comnet.2020.107592.

Jin, W., Lim, S., Woo, S., Park, C. & Kim, D. 2022. Decision-making of IoT device operation based on intelligent-task offloading for improving environmental optimization. *Complex & Intelligent Systems*, 8(5): 3847–3866. https://link.springer.com/10.1007/s40747-022-00659-z.

Johnson, M. 1999. Observations on positivism and pseudoscience in qualitative nursing research. *Journal of Advanced Nursing*, 30(1): 67–73. https://onlinelibrary.wiley.com/doi/10.1046/j.1365-2648.1999.01050.x.

Junjie, M. & Yingxin, M. 2022. The Discussions of Positivism and Interpretivism. *Global Academic Journal of Humanities and Social Sciences*, 4(1): 10–14.

K3s Project Authors. 2024. Architecture. https://docs.k3s.io/architecture.

Kamaldeep, Malik, M. & Dutta, M. 2023. Feature Engineering and Machine Learning Framework for DDoS Attack Detection in the Standardized Internet of Things. *IEEE Internet of Things Journal*, 10(10): 8658–8669.

Karie, N.M., Sahri, N.M. & Haskell-Dowland, P. 2020. IoT Threat Detection Advances, Challenges and Future Directions. In 2020 Workshop on Emerging Technologies for Security in IoT (ETSecIoT). IEEE: 22–29. https://ieeexplore.ieee.org/document/9097762/.

Kasinathan, P., Pastrone, C., Spirito, M.A. & Vinkovits, M. 2013. Denial-of-Service detection in 6LoWPAN based Internet of Things. *2013 IEEE 9th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 9.

Kaur, A. & Kumar, P. 2022. An Energy-Efficient Data Sensing Technique Using Compressive Sensing for IoT-Based Systems. In S. T. and C. J. K. and T. S. Singh Pradeep Kumar and Wierzchoń, ed. *Futuristic Trends in Networks and Computing Technologies . Singapore:* Springer Nature Singapore: 339–348. https://link.springer.com/10.1007/978-981-19-5037-7_24.

Ke, H.C., Wang, H., Zhao, H.W. & Sun, W.J. 2021. Deep reinforcement learning-based computation offloading and resource allocation in security-aware mobile edge computing. *Wireless Networks*, 27(5): 3357–3373.

Kelly, C., Pitropakis, N., McKeown, S. & Lambrinoudakis, C. 2020. Testing And Hardening IoT Devices Against the Mirai Botnet. In 2020 International Conference on Cyber Security and Protection of Digital Services (Cyber Security). IEEE: 1–8. https://ieeexplore.ieee.org/document/9138887/.

Koufos, K., El Haloui, K., Dianati, M., Higgins, M., Elmirghani, J., Imran, M.A. & Tafazolli, R. 2021. Trends in Intelligent Communication Systems: Review of Standards, Major Research Projects, and Identification of Research Gaps. *Journal of Sensor and Actuator*

Networks, 10(4). https://www.mdpi.com/2224-2708/10/4/60.

Krishnamoorthy, S., Dua, A. & Gupta, S. 2023. Role of emerging technologies in future IoT-driven Healthcare 4.0 technologies: A survey, current challenges and future directions. *Journal of Ambient Intelligence and Humanized Computing*. https://link.springer.com/article/10.1007/s12652-021-03302-w.

Ksentini, A. & Frangoudis, P.A. 2020. On Extending ETSI MEC to Support LoRa for Efficient IoT Application Deployment at the Edge. *IEEE Communications Standards Magazine*, 4(2): 57–63.

Lampropoulos, G., Siakas, K. & Anastasiadis, T. 2019. INTERNET OF THINGS IN THE CONTEXT OF INDUSTRY 4.0: AN OVERVIEW. International Journal of Entrepreneurial Knowledge, 7(1). https://ijek.org/index.php/IJEK/article/view/84.

Latif, G., Alghazo, J.M., Maheswar, R., Jayarajan, P. & Sampathkumar, A. 2020. Impact of IoT-Based Smart Cities on Human Daily Life. In R. and K. G. R. and J. P. Rani Shalli and Maheswar, ed. Integration of WSN and IoT for Smart Cities. Cham: Springer International Publishing: 103–114. http://link.springer.com/10.1007/978-3-030-38516-3_6.

Lau, J., Ioannidis, J. & Schmid, C.O. 1997. Quantitative Synthesis in Systematic Reviews. *Annals of Internal Medicine*, 127: 820–826. https://api.semanticscholar.org/CorpusID:26469635.

Lear, E., Droms, R. & Romascanu, D. 2019. RFC 8520: Manufacturer Usage Description Specification.

Lee, C.P., Leng, F.T.J., Habeeb, R.A.A., Amanullah, M.A. & Rehman, M.H. ur. 2022. Edge computing-enabled secure and energy-efficient smart parking: A review. *Microprocessors and Microsystems*, 93: 104612. https://linkinghub.elsevier.com/retrieve/pii/S0141933122001545.

Lee, P. 2006. Understanding and critiquing quantitative research papers. *Nursing times*, 102 28: 28–30. https://api.semanticscholar.org/CorpusID:27537319.

Li, R., Li, Q., Zhou, J. & Jiang, Y. 2021. ADRIoT: An Edge-assisted Anomaly Detection

Framework against IoT-based Network Attacks. *IEEE Internet of Things Journal*, 4662(c): 1–12.

Lingala, P., Manne, P. R., Amuru, S., & Kuchi, K. 2022, 'Energy and Delay Efficient Intelligent Release Assistant Indication Scheme for NB-IoT', 2022 14th International Conference on Communication Systems & Networks (COMSNETS), Bangalore, India, pp. 246-250. doi: 10.1109/COMSNETS53615.2022.9668381.

Lim, E.H., Yuen Chai, T., Muniandy, M. a-p, Fui Yong, T., Ooi, B.Y. & Lin, J.-M. 2023. Edge Computing and AI for IoT: Opportunities and Challenges. In 2023 *International Conference on Consumer Electronics - Taiwan (ICCE-Taiwan)*. IEEE: 357–358. https://ieeexplore.ieee.org/document/10226787/.

Lim, W.M. 2023. Philosophy of science and research paradigm for business research in the transformative age of automation, digitalization, hyperconnectivity, obligations, globalization and sustainability. *Journal of Trade Science*, 11(3): 2023–2026. http://creativecommons.org/licences/by/4.0/legalcodehttps://www.emerald.com/insight/2815-5793.htm.

Roopa Devi, M., & Kayethri, D. 2024, 'Blockchain-Integrated Edge Computing for IoT-Based Cloud Applications', in X. S., U. A., D. S. Mishra, & J. Yang (eds), *Data Science and Big Data Analytics*, Springer Nature Singapore, Singapore, pp. 289–301. https://link.springer.com/10.1007/978-981-99-9179-2_22.

Ma, F.Q. & Fan, R.N. 2022. Queuing Theory of Improved Practical Byzantine Fault Tolerant Consensus. *Mathematics*, 10(2): 1–12.

Macedo, E.L.C., de Oliveira, E.A., Silva, F.H., Mello, R.R., Franca, F.M., Delicato, F.C., de Rezende, J.F. & de Moraes, L.F.M. 2019. On the security aspects of Internet of Things: A systematic literature review. *Journal of Communications and Networks*, 21(5): 444–457. https://ieeexplore.ieee.org/document/8854272/.

Mamdouh, M., Awad, A.I., Khalaf, A.A.M. & Hamed, H.F.A. 2021. Authentication and Identity Management of IoHT Devices: Achievements, Challenges, and Future Directions. *Computers and Security*, 111.

Mangla, C., Rani, S., Faseeh Qureshi, N.M. & Singh, A. 2023. Mitigating 5G security challenges for next-gen industry using quantum computing. *Journal of King Saud University - Computer and Information Sciences*, 35(6).

Manole, I.C. 2019. Communicative Act – Feedback. *Logos Universality Mentality Education Novelty: Philosophy & Humanistic Sciences*, 6(2): 63–73. https://lumenpublishing.com/journals/index.php/lumenphs/article/view/1244.

Mansour, M., Gamal, A., Ahmed, A.I., Said, L.A., Elbaz, A., Herencsar, N. & Soltan, A. 2023. Internet of Things: A Comprehensive Overview on Protocols, Architectures, Technologies, Simulation Tools, and Future Directions. *Energies*, 16(8).

Mazhar, T., Bux Talpur, D., Al Shloul, T., Ghadi, Y.Y., Haq, I., Ullah, I., Ouahada, K. & Hamam, H. 2023. Analysis of IoT Security Challenges and Its Solutions Using Artificial Intelligence. https://doi.org/10.3390/brainsci13040683.

Mekala, S.H., Baig, Z., Anwar, A. & Zeadally, S. 2023. Cybersecurity for Industrial IoT (IIoT): Threats, countermeasures, challenges and future directions. *Computer Communications*, 208: 294–320.

Mendez Mena, D. & Yang, B. 2020. Decentralized Actionable Cyber Threat Intelligence for Networks and the Internet of Things. *IoT*, 2(1): 1–16.

Meneghello, F., Calore, M., Zucchetto, D., Polese, M. & Zanella, A. 2019. IoT: Internet of Threats? A Survey of Practical Security Vulnerabilities in Real IoT Devices. IEEE Internet of Things Journal, 6(5): 8182–8201. https://ieeexplore.ieee.org/document/8796409/.

Meng, W., Li, W. & Zhou, J. 2021. Enhancing the security of blockchain-based software defined networking through trust-based traffic fusion and filtration. *Information Fusion*, 70(September 2020): 60–71.

Mishra, A., Jha, A. V., Appasani, B., Ray, A.K., Gupta, D.K. & Ghazali, A.N. 2023. Emerging technologies and design aspects of next generation cyber physical system with a smart city application perspective. *International Journal of System Assurance Engineering and Management*, 14: 699–721.

Mobus, G.E. & Kalton, M.C. 2015. Cybernetics: The Role of Information and Computation in Systems. https://api.semanticscholar.org/CorpusID:61751185.

Mohapatra, S.K., Bhuyan, J.N., Asundi, P. & Singh, A. 2016. A solution framework for managing internet of things (IOT). *International Journal of Computer Networks and Communications*, 8(6): 73–87.

More, P., Sakhare, S. & Mahalle, P. 2023. Identity-Based Access Control in IoT: Enhancing Security through Mutual Cryptographic Authentication and Context Awareness. In 2023 3rd International Conference on Mobile Networks and Wireless Communications (ICMNWC). IEEE: 1–6. https://ieeexplore.ieee.org/document/10435960/.

Moher, D., Liberati, A., Tetzlaff, J. & Altman, D.G. 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Annals of Internal Medicine, 151(4):264-269.

Morgan, G.A., Gliner, J.A. & Harmon, R.J. 1999. Quantitative Research Approaches. *Journal of the American Academy of Child & Adolescent Psychiatry*, 38(12): 1595–1597. https://linkinghub.elsevier.com/retrieve/pii/S0890856709667253.

Morton, P. 2006. Using Critical Realism to Explain Strategic Information Systems Planning. *The Journal of Information Technology Theory and Application*, 8(3). https://core.ac.uk/reader/301356710 23 July 2024.

Motta, M. and Stecula, D. 2021. Quantifying the effect of Wakefield et al. (1998) on skepticism about MMR vaccine safety in the U.S. *PLOS ONE*, 16(8): 1–9. https://doi.org/10.1371/journal.pone.0256395.

Moura, J. & Hutchison, D. 2020. Fog computing systems: State of the art, research issues and future trends, with a focus on resilience. *Journal of Network and Computer Applications*, 169.

Mudassar, M., Zhai, Y. & Lejian, L. 2022. Adaptive Fault-Tolerant Strategy for Latency-Aware IoT Application Executing in Edge Computing Environment. IEEE Internet of Things Journal, 9(15):13250-13262. doi: 10.1109/JIOT.2022.3144026.

Murtala Zungeru, A., Chuma, J.M., Lebekwe, C.K., Phalaagae, P., Gaboitaolelwe, J., Phalaagae, P., Zungeru, A.M., Sigweni, B., Chuma, J.M. and Semong, T., 2020. Applications and Communication Technologies in IoT Sensor Networks. In *Green Internet of Things Sensor Networks: Applications, Communication Technologies, and Security Challenges*. Cham: Springer International Publishing: 9–23. https://doi.org/10.1007/978-3-030-54983-1_2.

Muteba, K.F., Djouani, K. & Olwal, T. 2021. 5G NB-IoT: Design, Considerations, Solutions and Challenges. *Procedia Computer Science*, 198(2018): 86–93. https://doi.org/10.1016/j.procs.2021.12.214.

Nandhakumar, G. & Arunkumar, M. 2023. Enhanced Network Stability and Reliability using Software-Defined Technology. In 2023 *Eighth International Conference on Science Technology Engineering and Mathematics (ICONSTEM)*. IEEE: 1–6. https://ieeexplore.ieee.org/document/10142224/.

Nassaji, H. 2017. Diversity of research methods and strategies in language teaching research. *Language Teaching Research*, 21(2): 140–143. http://journals.sagepub.com/doi/10.1177/1362168817693696.

Nandhini, P.S., Kuppuswami, S., Malliga, S. & DeviPriya, R. 2023. Enhanced Rank Attack Detection Algorithm (E-RAD) for securing RPL-based IoT networks by early detection and isolation of rank attackers. *The Journal of Supercomputing,* 79(6): 6825–6848. https://link.springer.com/10.1007/s11227-022-04921-6.

Nayak, P. & Swapna, G. 2023. Security issues in IoT applications using certificateless aggregate signcryption schemes: An overview. *Internet of Things (Netherlands)*, 21.

Niemann, R., Niemann, S., Brazelle, R., Staden, J. Van, Heyns, M. & de Wet, C. 2000. Objectivity, reliability and validity in qualitative research. *South African Journal of Education*, 20: 283–286. http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=1160305 23 July 2024.

Omolara, A.E., Alabdulatif, Abdullah, Abiodun, O.I., Alawida, M., Alabdulatif, Abdulatif, Alshoura, W.H. & Arshad, H. 2022. The internet of things security: A survey encompassing

unexplored areas and new insights. *Computers and Security*, 112.

Opirskyy, I., Holovchak, R., Moisiichuk, I., Balianda, T. & Haraniuk, S. 2021. PROBLEMS AND SECURITY THREATS TO IOT DEVICES. Cybersecurity: Education, Science, Technique, 3(11): 31–42. https://csecurity.kubg.edu.ua/index.php/journal/article/view/231.

Outram, A.K. 2008. Introduction to experimental archaeology. *World Archaeology*, 40(1): 1–6. http://www.tandfonline.com/doi/abs/10.1080/00438240801889456.

Ozalp, A.N., Albayrak, Z., Cakmak, M. & Ozdogan, E. 2022. Layer-based examination of cyber-attacks in IoT. In *HORA 2022 - 4th International Congress on Human-Computer Interaction, Optimization and Robotic Applications, Proceedings*. Institute of Electrical and Electronics Engineers Inc.

Padhy, S., Alowaidi, M., Dash, S., Alshehri, M., Malla, P.P., Routray, S. & Alhumyani, H. 2023. AgriSecure: A Fog Computing-Based Security Framework for Agriculture 4.0 via Blockchain. *Processes*, 11(3).

Pahl, G. & Beitz, W. 1996. *Engineering Design*. K. Wallace, ed. London: Springer London.

Panarello, A., Tapas, N., Merlino, G., Longo, F. & Puliafito, A. 2018. Blockchain and IoT Integration: A Systematic Survey. *Sensors*, 18(8): 2575. https://www.mdpi.com/1424-8220/18/8/2575.

Park, Y.S., Konge, L. & Artino, A.R.J. 2020. The Positivism Paradigm of Research. *Academic Medicine*, 95(5). 690–694. https://journals.lww.com/academicmedicine/fulltext/2020/05000/the_positivism_paradigm_of_research.16.aspx.

Peels, R. 2019. Replicability and replication in the humanities. *Research Integrity and Peer Review*, 4(1): 2. https://doi.org/10.1186/s41073-018-0060-4.

Piccialli, F. & Jeon, G. 2021. Special issue on toward the Internet of Things of year 2020: Applications and future trends. *Concurrency and Computation: Practice and Experience*, 33(3): e5733. https://onlinelibrary.wiley.com/doi/abs/10.1002/cpe.5733.

Popli, S., Jha, R.K. & Jain, S. 2019. A Survey on Energy Efficient Narrowband Internet of Things (NBIoT): Architecture, Application and Challenges. *IEEE Access*, 7: 16739–16776.

Qureshi, J.N., Farooq, M.S., Abid, A., Umer, T., Bashir, A.K. & Zikria, Y. Bin. 2022. Blockchain applications for the Internet of Things: Systematic review and challenges. *Microprocessors and Microsystems*, 94.

Rafique, W., Qi, L., Yaqoob, I., Imran, M., Rasool, R.U. & Dou, W. 2020. Complementing IoT Services through Software Defined Networking and Edge Computing: A Comprehensive Survey. *IEEE Communications Surveys and Tutorials*, 22(3): 1761–1804.

Rahman, A., Islam, J., Kundu, D., Karim, R., Rahman, Z., Band, S.S., Sookhak, M., Tiwari, P. & Kumar, N. 2023. Impacts of blockchain in software-defined Internet of Things ecosystem with Network Function Virtualization for smart applications: Present perspectives and future directions. *International Journal of Communication Systems*.

Raj, A. & Shetty, S.D. 2022. IoT Eco-system, Layered Architectures, Security and Advancing Technologies: A Comprehensive Survey. *Wireless Personal Communications*, 122(2): 1481–1517.

Rajmohan, T., Nguyen, P.H. & Ferry, N. 2022. A decade of research on patterns and architectures for IoT security. Cybersecurity, 5(1): 2. https://cybersecurity.springeropen.com/articles/10.1186/s42400-021-00104-7.

Ramana, K.S., Priyadarshini, Y.I., Jambukesh, H.J., Singh, R., Kandasamy, M. & Kumar, B.V. 2023. A 5G NB-IoT Infrastructure for Secured Demand-Side Information Transmission and Predictive Analyses in Smarter Grids. In Institute of Electrical and Electronics Engineers (IEEE): 1917–1922.

Ranaweera, P., Jurcut, A.D. & Liyanage, M. 2021. Survey on Multi-Access Edge Computing Security and Privacy. *IEEE Communications Surveys and Tutorials*, 23(2): 1078–1124.

Ravi, S., Zand, P., El Soussi, M., & Nabi, M. 2019, 'Evaluation, Modeling and Optimization of Coverage Enhancement Methods of NB-IoT', 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Istanbul,

Turkey, pp. 1-7. doi: 10.1109/PIMRC.2019.8904109.

Reber, R. & Bullot, N.J. 2019. Conditional Objectivism: A Strategy for Connecting the Social Sciences and Practical Decision-Making. In *Social Philosophy of Science for the Social Sciences*. 73–92. https://link.springer.com/10.1007/978-3-030-33099-6_5.

Robinson, M.A. 2016. Quantitative Research Principles and Methods for Human-Focused Research in Engineering Design. In *Experimental Design Research*. Cham: Springer International Publishing: 41–64. http://link.springer.com/10.1007/978-3-319-33781-4_3.

Roozenburg, N. & Eekels, J. 1995. Product Design: Fundamentals and Methods. Product Development: Planning. *Design, Engineering*.

Rugeles Uribe, J. de J., Guillen, E.P. & Cardoso, L.S. 2022. A technical review of wireless security for the internet of things: Software defined radio perspective. *Journal of King Saud University - Computer and Information Sciences*, 34(7): 4122–4134.

Sahraneshin, T., Malekhosseini, R., Rad, F. & Yaghoubyan, S.H. 2023. Securing communications between things against wormhole attacks using TOPSIS decision-making and hash-based cryptography techniques in the IoT ecosystem. *Wireless Networks*, 29(2): 969–983. https://doi.org/10.1007/s11276-022-03169-5.

Salva-Garcia, P., Alcaraz-Calero, J.M., Wang, Q., Bernabe, J.B. & Skarmeta, A. 2018. 5G NB-IoT: Efficient Network Traffic Filtering for Multitenant IoT Cellular Networks. *Security and Communication Networks*, 2018.

Sato, K., Kawamoto, Y., Nishiyama, H., Kato, N., & Shimizu, Y., 2015. A modeling technique utilizing feedback control theory for performance evaluation of IoT system in real-time. 2015 International Conference on Wireless Communications & Signal Processing (WCSP), Nanjing, China, pp. 1-5. doi: 10.1109/WCSP.2015.7341303.

Savic, M., Lukic, M., Danilovic, D., Bodroski, Z., Bajovic, D., Mezei, I., Vukobratovic, D., Skrbic, S. & Jakovetic, D. 2021. Deep Learning Anomaly Detection for Cellular IoT with Applications in Smart Logistics. *IEEE Access*, 9: 59406–59419.

Saxena, A.K., Pandey, R. & Singh, N.K. 2023. Latency Analysis and Reduction Methods for

Edge Computing. In 2023 *IEEE World Conference on Applied Intelligence and Computing (AIC).* IEEE: 480–484. https://ieeexplore.ieee.org/document/10263946/.

Shafi, M., Jha, R.K. & Jain, S. 2022. LGTBIDS: Layer-wise Graph Theory Based Intrusion Detection System in Beyond 5G. *IEEE Transactions on Network and Service Management*.

Shah, A.A. 2021. Positivism and Interpretivism. *Qlantic Journal of Social Sciences*. https://api.semanticscholar.org/CorpusID:248017109.

Shah, M. 2019. A secured and enhanced mitigation framework for DDOS attacks. *Journal of Mechanics of Continua and Mathematical Science*, 14(6). http://www.journalimcms.org/journal/a-secured-and-enhanced-mitigation-framework-for-ddos-attacks/.

Shah, Z., Ullah, I., Li, H., Levula, A. & Khurshid, K. 2022. Blockchain Based Solutions to Mitigate Distributed Denial of Service (DDoS) Attacks in the Internet of Things (IoT): A Survey. *Sensors*, 22(3).

Shanks, G. 2002. Guidelines for Conducting Positivist Case Study Research in Information Systems. *Australasian Journal of Information Systems; Vol 10, No 1 (2002)*, 10.

Shannon, C.E. & Weaver, W. 1964. *The Mathematical Theory of Communication*. Urbana: University of Illinois Press.

Sharma, A., Kaur, S. & Singh, M. 2021. A comprehensive review on blockchain and Internet of Things in healthcare. *Transactions on Emerging Telecommunications Technologies*, 32(10).

Sharma, P.K., Kumar, N. & Park, J.H. 2020. Blockchain technology toward green IoT: Opportunities and challenges. *IEEE Network*, 34(4): 263–269.

Sharma, V., You, I., Andersson, K., Palmieri, F., Rehmani, M.H. & Lim, J. 2020. Security, privacy and trust for smart mobile-Internet of Things (M-IoT): A survey. *IEEE Access*, 8: 167123–167163.

Sheng-Tao Chen, S.-T.C., Sheng-Tao Chen, C.-W.L., Chien-Wu Lan, S.-S.L. & Shih-Sung Lin. 2022. An Evaluation of Self-Built Low-Power Wide-Area Network Based on LoRa, 33(5): 073–082. http://www.csroc.org.tw/journal/JOC33-5/JOC3305-07.pdf.

Silk, E.M., Schunn, C.D. & Strand Cary, M. 2009. The Impact of an Engineering Design Curriculum on Science Reasoning in an Urban Setting. *Journal of Science Education and Technology*, 18(3): 209–223. http://link.springer.com/10.1007/s10956-009-9144-8.

Silva, A.P., Obraczka, K., Burleigh, S., Nogueira, J.M.S., & Hirata, C.M. (2019). A congestion control framework for delay- and disruption tolerant networks. Ad Hoc Networks, 91. https://doi.org/10.1016/j.adhoc.2019.101880

Shukla, S., Hassan, Mohd.F., Tran, D.C., Akbar, R., Paputungan, I.V. & Khan, M.K. 2023. Improving latency in Internet-of-Things and cloud computing for real-time data transmission: a systematic literature review (SLR). Cluster Computing, 26(5): 2657–2680. https://link.springer.com/10.1007/s10586-021-03279-3.

Singh, S., Dhirendra, P., Chandra, K. & Singh, B. 2023. IoT Security Challenges and Emerging Solutions: A Comprehensive Review. INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT, 07(09). https://ijsrem.com/download/iot-security-challenges-and-emerging-solutions-a-comprehensive-review/.

Sprague Joey and Kobrynowicz, D. 2006. A Feminist Epistemology. In *Handbook of the Sociology of Gender*. Boston, MA: Springer US: 25–43. https://doi.org/10.1007/0-387-36218-5_2.

Sutikno, T. & Thalmann, D. 2022. Insights on the internet of things: past, present, and future directions. *Telkomnika (Telecommunication Computing Electronics and Control)*, 20(6): 1399–1420.

Stavrinides, G.L. & Karatza, H.D. 2022. “Containerization, microservices and serverless cloud computing: Modeling and simulation”. Simulation Modelling Practice and Theory, 118: 102551. https://linkinghub.elsevier.com/retrieve/pii/S1569190X2200048X.

Swamy, S.N. & Kota, S.R. 2020. An empirical study on system level aspects of Internet of Things (IoT). *IEEE Access*, 8: 188082–188134.

Tahiliani, M.P., Misra, V., & Ramakrishnan, K.K., 2020. A principled look at the utility of feedback in congestion control. Proceedings of the 2019 *Workshop on Buffer Sizing*, Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3375235.3375243.

Tange, K., De Donno, M., Fafoutis, X. & Dragoni, N. 2020. A Systematic Survey of Industrial Internet of Things Security: Requirements and Fog Computing Opportunities. *IEEE Communications Surveys and Tutorials*, 22(4): 2489–2520.

Tariq, U., Ahmed, I., Bashir, A.K. & Shaukat, K. 2023. A Critical Cybersecurity Analysis and Future Research Directions for the Internet of Things: A Comprehensive Review. *Sensors*, 23(8).

Tembhurne, J. V., Diwan, T. & Jain, T.K. 2024. IoT Security and Privacy. In M. D. and U. M. and N. T. Gunjan Vinit Kumar and Ansari, ed. Modern Approaches in IoT and Machine Learning for Cyber Security: Latest Trends in AI. Cham: Springer International Publishing: 45–61. https://link.springer.com/10.1007/978-3-031-09955-7_3.

Thondebhavi Shanthakumar, C.S., Harish, N., Eshanya & Giridharan, A. 2023. Internet of Things and Edge Computing for Real Time Applications. In 2023 *International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics (IITCEE).* IEEE: 1137–1141. https://ieeexplore.ieee.org/document/10091014/.

Torday, J.S. 2023. Chapter 4 - Cybernetics as a conversation with the Cosmos. In J. S. Torday, ed. *Quantum Mechanics, Cell-Cell Signaling, and Evolution*. Academic Press: 27–40. https://www.sciencedirect.com/science/article/pii/B9780323912976000217.

Touqeer, H., Zaman, S., Amin, R., Hussain, M., Al-Turjman, F. & Bilal, M. 2021. Smart home security: challenges, issues and solutions at different IoT layers. *Journal of Supercomputing*, 77(12): 14053–14089.

Turzhanova, K., Tikhvinskiy, V., Konshin, S. & Solochshenko, A. 2022. Experimental

Performance Evaluation of NB-IOT Deployment Modes in Urban Area. *International Journal of Communication Networks and Information Security (IJCNIS)*, 13(2). https://www.ijcnis.org/index.php/ijcnis/article/view/4969.

Ugwuanyi, S., Hansawangkit, J. & Irvine, J. 2020. NB-IoT testbed for industrial internet of things. *2020 International Symposium on Networks, Computers and Communications, ISNCC 2020*.

Umunnakwe, A., Wlazlo, P., Sahu, A., Velasquez, J., Davis, K., Goulart, A. & Zonouz, S. 2022. OpenConduit: A Tool for Recreating Power System Communication Networks Automatically. In *2022 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*. 141–147.

Vaezi, M., Azari, A., Khosravirad, S.R., Shirvanimoghaddam, M., Azari, M.M., Chasaki, D. & Popovski, P. 2022. Cellular, Wide-Area, and Non-Terrestrial IoT: A Survey on 5G Advances and the Road Toward 6G. *IEEE Communications Surveys and Tutorials*, 24(2): 1117–1174.

Verkerke, G.J., van der Houwen, E.B., Broekhuis, A.A., Bursa, J., Catapano, G., McCullagh, P., Mottaghy, K., Niederer, P., Reilly, R., Rogalewicz, V., Segers, P. & Verdonschot, N. 2013. Science versus design; comparable, contrastive or conducive? *Journal of the Mechanical Behavior of Biomedical Materials*, 21: 195–201. https://linkinghub.elsevier.com/retrieve/pii/S1751616113000246.

Vidal, I., Gonzalez, L.F., Valera, F., Nogales, B., Martin, R., Artalejo, D., Lopez, D.R., Manjón, J.M. & Pastor, A. 2023. A Multi-domain Testbed for Collaborative Research on the IoT-Edge-Cloud Continuum. *In 2023 20th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*. IEEE: 394–395. https://ieeexplore.ieee.org/document/10287436/.

Von Bertalanffy, L. 1967. General theory of systems : Application to psychology. *Social Science Information*, 6(6): 125–136. http://journals.sagepub.com/doi/10.1177/053901846700600610

Wang, J., Lim, M.K., Wang, C. & Tseng, M.-L. 2021. The evolution of the Internet of Things (IoT)

over the past 20 years. *Computers & Industrial Engineering*, 155: 107174. https://www.sciencedirect.com/science/article/pii/S0360835221000784.

Wang, S., Gomez, K., Sithamparanathan, K., Asghar, M.R., Russello, G. & Zanna, P. 2021. Mitigating ddos attacks in sdn-based iot networks leveraging secure control and data plane algorithm. *Applied Sciences (Switzerland)*, 11(3): 1–27.

Wang, X., Zha, X., Ni, W., Liu, R.P., Guo, Y.J., Niu, X. & Zheng, K. 2019. Survey on blockchain for Internet of Things. *Computer Communications*, 136: 10–29.

Welsh, T. & Benkhelifa, E. 2021. The Resilient Edge: Evaluating Graph-based Metrics for Decentralised Service Delivery. In *2021 6th International Conference on Fog and Mobile Edge Computing, FMEC 2021*. Institute of Electrical and Electronics Engineers Inc.

Wieringa, R.J. 2014. *Design Science Methodology for Information Systems and Software Engineering*. Berlin, Heidelberg: Springer Berlin Heidelberg. https://link.springer.com/10.1007/978-3-662-43839-8.

Wijethilaka, S. & Liyanage, M. 2021. Survey on Network Slicing for Internet of Things Realization in 5G Networks. *IEEE Communications Surveys and Tutorials*, 23(2): 957–994.

Wu, Y., Dai, H.N., Wang, H., Xiong, Z. & Guo, S. 2022. A Survey of Intelligent Network Slicing Management for Industrial IoT: Integrated Approaches for Smart Transportation, Smart Energy, and Smart Factory. *IEEE Communications Surveys and Tutorials*, 24(2): 1175–1211.

Xiao, X. & Zhao, M. 2022. Routing optimization strategy of IoT awareness layer based on improved cat swarm algorithm. *Neural Computing and Applications*, 34(5): 3311–3322. https://link.springer.com/10.1007/s00521-020-05590-3.

Yau, C.-W., Jewsakul, S., Luk, M.-H., Lee, A. P. Y., Chan, Y.-H., Ngai, E. C. H., Pong, P. W. T., Lui, K.-S. & Liu, J., 2022. NB-IoT coverage and sensor node connectivity in dense urban environments: An empirical study. ACM Transactions on Sensor Networks, 18(3), pp. 49. https://doi.org/10.1145/3536424

Young, C.S., 2022. Information Entropy. In: Cybercomplexity. Advanced Sciences and

Technologies for Security Applications. Cham: Springer. Available at: https://doi.org/10.1007/978-3-031-06994-9_6

Zhan, G., Jiang, Y., Yin, X. & Li, S. 2021. Research on security of NB-IoT based on cryptography. In Proceedings - 2021 *4th International Conference on Advanced Electronic Materials, Computers and Software Engineering, AEMCSE 2021*. Institute of Electrical and Electronics Engineers Inc.: 1207–1211.

Zhang, L., Yuan, H., Chang, S.-H. & Lam, A. 2020. Research on the overall architecture of Internet of Things middleware for intelligent industrial parks. The International Journal of Advanced Manufacturing Technology, 107(3): 1081–1089. https://doi.org/10.1007/s00170-019-04310-z.

Zhao, F., Sun, X., Zhan, W., Zhou, B. & Huang, X. 2022. AoI-Constrained Energy Efficiency Optimization in Random-Access Poisson Networks. *In 2022 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE: 1123–1128. https://ieeexplore.ieee.org/document/9771861/.

Zimmermann, M. 1989. The Nervous System in the Context of Information Theory. In *Human Physiology*. Berlin, Heidelberg: Springer Berlin Heidelberg: 166–173. http://link.springer.com/10.1007/978-3-642-73831-9_7.

APPENDICES

Appendix A Monitoring Setup with Prometheus and Grafana

A.1 Installation of Prometheus with Helm

The following code snippet demonstrates the installation of Prometheus using Helm, a package manager for Kubernetes. This setup enables Prometheus to monitor and capture metrics from MongoDB.

```
# Add the Prometheus Helm chart repository
helm repo add prometheus-community https://prometheus-community.github.io/helm-charts
helm repo update

# Install the MongoDB Exporter to collect MongoDB metrics
helm install mongodb-exporter prometheus-community/prometheus-mongodb-exporter \
    --set 'mongodb.uri=mongodb://10.43.46.255:27017' \
    --namespace monitoring \
    --set serviceMonitor.enabled=true \
    --set serviceMonitor.additionalLabels.release="prometheus"
```

The commands above configure Prometheus to monitor MongoDB by installing the MongoDB Exporter, which captures relevant metrics and makes them available for visualization in Grafana.

A. 2 System Simulation with Feedback Control

The code defines a simple linear system using matrices A, B, C, and D, representing a state-space model where A governs the state transitions and B represents how the input affects the states.

```
import numpy as np
import matplotlib.pyplot as plt
from prometheus_api_client import PrometheusConnect
from datetime import datetime, timedelta

# Define the system parameters
n_nodes = 6  # Number of nodes in the system
A = np.zeros((2 * n_nodes, 2 * n_nodes))
for i in range(n_nodes):
    A[2*i, 2*i+1] = 1

B = np.zeros((2 * n_nodes, n_nodes))
for i in range(n_nodes):
    B[2*i+1, i] = 1

C = np.eye(2 * n_nodes)
D = np.zeros((2 * n_nodes, n_nodes))

# Initial state
x0 = np.ones(2 * n_nodes)

# Simulation parameters
dt = 0.01
t = np.arange(0, 10, dt)

# Function to simulate the system
def simulate_system(K):
    x = x0
    x_history = [x0]

    for _ in t:
        u = -K @ x
        x = x + dt * (A @ x + B @ u)
        x_history.append(x)

    return np.array(x_history)
```

```
37.
38. # Feedback gains
39. K1 = 0.2 * np.eye(n_nodes, 2 * n_nodes)
40. K2 = 0.05 * np.eye(n_nodes, 2 * n_nodes)
41. K3 = np.diag([0.1] * n_nodes + [0.05] * n_nodes)[:n_nodes, :2 * n_nodes]
42.
43. # Simulate the system with different gains
44. x_history1 = simulate_system(K1)
45. x_history2 = simulate_system(K2)
46. x_history3 = simulate_system(K3)
47.
48. # Plot the results
49. plt.figure(figsize=(12, 8))
50.
51. for i in range(2 * n_nodes):
52.     plt.subplot(n_nodes, 2, i + 1)
53.     plt.plot(t, x_history1[:-1, i], label='K1')
54.     plt.plot(t, x_history2[:-1, i], label='K2')
55.     plt.plot(t, x_history3[:-1, i], label='K3')
56.     plt.title(f'State {i + 1}')
57.     plt.xlabel('Time (s)')
58.     plt.ylabel('State Value')
59.     plt.legend()
60.
61. plt.tight_layout()
62. plt.show()
63.
64. # Connect to Prometheus
65. prom = PrometheusConnect(url="http://k3s-node1:9090", disable_ssl=True)
66.
67. # Function to get Prometheus metrics
68. def get_prometheus_metrics(query):
69.     end_time = datetime.now()
70.     start_time = end_time - timedelta(hours=1)
71.     metric_data = prom.custom_query_range(
72.         query=query,
73.         start_time=start_time,
74.         end_time=end_time,
75.         step='30s'
76.     )
77.     return metric_data
78.
79. # Get CPU and RAM usage metrics
```

```
cpu_usage_query = 'sum by (instance) (rate(node_cpu_seconds_total{mode!="idle"}[1m]))'
    ram_usage_query = 'sum by (instance) (node_memory_MemAvailable_bytes / node_memory_MemTotal_bytes)'

cpu_usage = get_prometheus_metrics(cpu_usage_query)
ram_usage = get_prometheus_metrics(ram_usage_query)

# Function to plot Prometheus metrics
def plot_metrics(metric_data, title):
    for metric in metric_data:
        timestamps = [datetime.fromtimestamp(value[0]) for value in metric['values']]
        values = [float(value[1]) for value in metric['values']]
        plt.plot(timestamps, values, label=metric['metric'].get('instance', 'node'))
    plt.title(title)
    plt.xlabel('Time')
    plt.ylabel('Value')
    plt.legend()
    plt.show()

# Plot the metrics
plot_metrics(cpu_usage, 'CPU Usage')
plot_metrics(ram_usage, 'RAM Usage')

```

A. 3 Traffic data from Prometheus to calculate Shannon entropy

```
import requests
import math
import pandas as pd
import matplotlib.pyplot as plt
# Function to fetch data from Prometheus
def get_prometheus_data(query):
    url = 'http://k3s-node:9090/api/v1/query'  # Replace <prometheus-server> with your Prometheus server URL
    response = requests.get(url, params={'query': query})
    if response.status_code == 200:
        result = response.json().get('data', {}).get('result', [])
        if not result:
            print("No data found for the query.")
        return result
    else:
```

```
        print(f"Error fetching data: {response.status_code}")
        return []

# Function to calculate Shannon entropy
def calculate_entropy(data):
    total_count = sum([float(value) for _, value in data])
    if total_count == 0:
        return 0
    probabilities = [float(value) / total_count for _, value in data]
    entropy = -sum([p * math.log2(p) for p in probabilities if p > 0])
    return entropy

# Define Prometheus queries
query_receive = 'sum(rate(node_network_receive_bytes_total[5m])) by (instance)'
query_transmit = 'sum(rate(node_network_transmit_bytes_total[5m])) by (instance)'

# Fetch and process the data
data_receive = get_prometheus_data(query_receive)
data_transmit = get_prometheus_data(query_transmit)

if data_receive and data_transmit:
    # Prepare data for entropy calculation and plotting
               receive_values   =   [(ip_to_node.get(item['metric']['instance'].split(':')[0],
item['metric']['instance']), item['value'][1]) for item in data_receive]
              transmit_values   =   [(ip_to_node.get(item['metric']['instance'].split(':')[0],
item['metric']['instance']), item['value'][1]) for item in data_transmit]

    entropy_receive = calculate_entropy(receive_values)
    entropy_transmit = calculate_entropy(transmit_values)

    print(f'Entropy of receiving network traffic: {round(entropy_receive, 2)}')
    print(f'Entropy of sending network traffic: {round(entropy_transmit, 2)}')

    # Convert data to DataFrame for plotting
    df_receive = pd.DataFrame(receive_values, columns=['Node', 'Receive'])
    df_receive['Receive'] = df_receive['Receive'].astype(float)

    df_transmit = pd.DataFrame(transmit_values, columns=['Node', 'Transmit'])
    df_transmit['Transmit'] = df_transmit['Transmit'].astype(float)

    # Merge data on Node
    df = pd.merge(df_receive, df_transmit, on='Node')

```

```
    # Plotting the data
    plt.figure(figsize=(14, 8))

    # Plot receiving traffic
    plt.subplot(2, 1, 1)
    plt.bar(df['Node'], df['Receive'], color='blue', label='Receive')
    plt.xlabel('Node')
    plt.ylabel('Rate (bytes/second)')
    plt.title('Receiving Network Traffic Rate by Node')
    plt.xticks(rotation=45)
    plt.legend()

    # Plot sending traffic
    plt.subplot(2, 1, 2)
    plt.bar(df['Node'], df['Transmit'], color='green', label='Transmit')
    plt.xlabel('Node')
    plt.ylabel('Rate (bytes/second)')
    plt.title('Sending Network Traffic Rate by Node')
    plt.xticks(rotation=45)
    plt.legend()

    plt.tight_layout()
    plt.show()
else:
    print("No data available to calculate entropy or plot results.")

```

Appendix B Data Extraction Table

Paper	AUTHORS	FINDINGS	STUDY DETAILS	STUDY QUALITY	FULL-TEXT REVIEW	DATA EXTRACTION
1	Dr. K Seshadri Ramana Y. Indira Priyadarshini H J Jambukesh Rajesh Singh Manivel Kandasamy Bura Vijay Kumar S	Developed a comprehensive 5G NB-IoT design for smart grids, focusing on secure data transmission and predictive data analysis. Proposed solution enhances grid control, market response, and connectivity between 5G and national grids. Aimed to facilitate electronic innovation in modern grids, integrating services and software for a smarter network. Contributed to the "dual carbon" goal of the energy network by improving cognitive networks and data analysis.	Study Type: Technological innovation and application in smart grids. Focus: Integration of 5G and NB-IoT technologies for secured information transmission and predictive analyses in smarter grids.	Study Design: Technological design, application-centric rather than experimental or observational. Consistency of Results: Consistent with current trends in smart grid technologies. Data Analysis Methods: Emphasis on integrating and analysing smart grid data with advanced technologies. Researcher's Interpretation: Focused on practical application in smarter grids, consistent with the technological framework proposed.	Relevance to RQ: Directly addresses the integration of 5G and NB-IoT technologies in smart grids. Depth of Analysis: Provides detailed insights into technological applications for smarter grids. Quality of Research: Demonstrates a clear design of technological application with a focus on innovation and practical implications. Contribution to the Field: Offers novel insights and methods for the advancement of smart grid technology.	Study Methods: Technological application with a focus on secure data transmission and predictive analysis in smart grids. Main Findings: Development of a 5G NB-IoT design for enhanced grid control and market response. Implications: Potential significant impact on smart grid management and energy network goals. Gaps Identified: Further exploration needed in real-world application and long-term effectiveness.
2	Mireya Lucia Hernandez-Jaimes Alfonso Martinez-Cruz Kelsey Alejandra Ramírez-Gutiérrez Claudia Feregrino-Uribe	Presented a novel taxonomy for intrusion detection in IoMT, including AI methods, datasets, and cyberattack classifications. Highlighted the use of AI in enhancing IDS performance for IoMT security. Discussed various cyberattacks on IoMT, such as DoS, DDoS, and ransomware, and their implications. Analysed Cloud–Fog–Edge computing architectures' role in IoMT security. Emphasized the legal and ethical aspects of IoMT security.	Study Type: Literature review and analysis. Focus: Review of IDS, cyberattacks, and AI applications in IoMT security.	Study Design: Comprehensive literature review with taxonomy development. Consistency of Results: Consistent with existing research in IoMT security. Data Analysis Methods: Analysis of existing literature and categorisation of findings. Researcher's Interpretation: Focused on implications of AI in IoMT security and challenges in this field.	Relevance to RQ: Directly addresses AI applications in IoMT security. Depth of Analysis: Extensive review and categorization of current literature and methods. Quality of Research: Thorough and methodical in reviewing and categorizing existing research. Contribution to the Field: Offers a comprehensive understanding of AI's role in IoMT security and future research directions.	Study Methods: Literature review focusing on AI methods, IDS, and cyberattacks in IoMT. Main Findings: Identification of key AI strategies, intrusion detection systems, and prevalent cyberattacks in IoMT. Implications: Emphasizes the importance of AI in enhancing IoMT security and identifies future research areas. Gaps Identified: Calls for more research on effective AI integration and addressing emerging cyber threats in IoMT.

Paper	AUTHORS	FINDINGS	STUDY DETAILS	STUDY QUALITY	FULL-TEXT REVIEW	DATA EXTRACTION
3	Sri Harsha Mekala Zubair Baig Adnan Anwar Sherali Zeadally	Detailed analysis of security threats in IIoT, including DDoS, phishing, and man-in-the-middle attacks. Evaluation of various countermeasures like intrusion detection systems, machine learning techniques, and securing SCADA networks. Discussion on challenges in IIoT cybersecurity, such as scalability, security and privacy, and standardization. Future directions in IIoT cybersecurity, highlighting areas needing further research and development.	Study Type: Comprehensive analysis and review. Focus: Cybersecurity challenges, threats, and solutions in the Industrial Internet of Things.	Study Design: Review and analysis of existing literature, security threats, and countermeasures. Consistency of Results: Aligns with known cybersecurity challenges in IIoT. Data Analysis Methods: Analysis of literature and current cybersecurity practices in IIoT. Researcher's Interpretation: Focuses on the practical implications and future directions in IIoT cybersecurity.	Relevance to RQ: Directly addresses cybersecurity in the Industrial Internet of Things. Depth of Analysis: Provides an in-depth review of current threats, solutions, and challenges in IIoT security. Quality of Research: Methodical and comprehensive in its approach to analyzing IIoT cybersecurity. Contribution to the Field: Enhances understanding of cybersecurity in IIoT and points towards future research needs.	Study Methods: Analysis and review of existing research on IIoT cybersecurity. Main Findings: Identification of key threats and countermeasures in IIoT security. Implications: Highlights the importance of evolving cybersecurity measures in IIoT. Gaps Identified: Suggests areas for further research, including the development of more robust security solutions.
4	H. C. Ke H. Wang H. W. Zhao W. J. Sun	Developed a deep reinforcement learning-based scheme for computation offloading and resource allocation in MEC environments. Focused on security-aware scenarios, considering the dynamic nature of wireless networks and security threats. Demonstrated that the proposed DRL-based scheme outperforms conventional methods in terms of efficiency and adaptability. Highlighted the scheme's ability to learn and adapt in real-time to changing network conditions and workload demands.	Study Type: Technological development and performance evaluation. Focus: Optimization of computation offloading and resource allocation using DRL in security-aware MEC systems.	Study Design: Development and evaluation of a DRL-based optimization scheme for MEC systems. Consistency of Results: Results demonstrate consistent improvements over traditional methods. Data Analysis Methods: Utilized DRL for dynamic and efficient resource management in MEC. Researcher's Interpretation: Focused on the practical application and benefits of the proposed scheme in MEC environments.	Relevance to RQ: Directly addresses the optimization of computation offloading and resource allocation in MEC using DRL. Depth of Analysis: Provides comprehensive insights into DRL applications in dynamic and complex MEC environments. Quality of Research: Methodical in the development and evaluation of the DRL-based scheme. Contribution to the Field: Introduces a novel approach to MEC optimization, advancing the field's understanding of DRL applications.	Study Methods: Development and evaluation of a DRL-based scheme for optimizing MEC systems. Main Findings: The DRL-based scheme significantly improves computation offloading and resource allocation efficiency. Implications: Demonstrates the potential of DRL in enhancing the performance and security of MEC systems. Gaps Identified: Further research needed in real-world deployment and long-term performance evaluation.

Paper	AUTHORS	FINDINGS	STUDY DETAILS	STUDY QUALITY	FULL-TEXT REVIEW	DATA EXTRACTION
5	Tahani Bani-Yaseen Ashraf Tahat Kira Kastell Talal A. Edwan	Developed deep learning models, particularly LSTM and GRU, to detect DoSI attacks in NB-IoT networks. Demonstrated LSTM classifier's superior performance with an accuracy of up to 98.99% and detection time of 2.54 x 10^-5 seconds/record. Highlighted that RNN models outperform traditional machine learning algorithms like SVM, Gaussian Naïve-Bayes, and logistic regression in detecting DoSI attacks. Generated a novel dataset through ns-3 simulation to represent DoSI attacks in NB-IoT, crucial for training and testing the models.	Study Type: Technological and methodological development with simulation-based evaluation. Focus: Deep learning-based detection of DoSI attacks in NB-IoT networks.	Study Design: Technological development with simulation-based evaluation of models. Consistency of Results: Demonstrated consistent performance across deep learning models. Data Analysis Methods: Employed deep learning techniques, particularly RNN models. Researcher's Interpretation: Focused on the practical application of deep learning in cybersecurity for IoT networks.	Relevance to RQ: Directly addresses the detection of DoSI attacks in NB-IoT using deep learning. Depth of Analysis: Offers in-depth analysis and evaluation of LSTM and GRU models for attack detection. Quality of Research: High, with methodical development and testing of deep learning models. Contribution to the Field: Provides valuable insights and methods for detecting DoSI attacks in NB-IoT, advancing cybersecurity in IoT.	Study Methods: Utilized deep learning techniques, particularly LSTM and GRU models, in a simulated NB-IoT environment. Main Findings: Demonstrated high accuracy and efficiency of LSTM and GRU models in detecting DoSI attacks. Implications: Highlights the potential of deep learning in enhancing IoT network security. Gaps Identified: Need for further research in real-world deployment and adaptation of models.
6	Pablo Benlloch-Caballero Qi Wang Jose M. Alcaraz Calero	Developed an autonomous DDoS mitigation system for 5G/6G networks, significantly reducing collateral damage. The system includes fine-grained detection of malicious flows, analysis of attacks, decision-making, planning, and orchestration for intervention. Features dual concurrent closed control-loops: one for ISPs focusing on their infrastructure and another for DSPs managing virtualized infrastructure services. Offers distributed DDoS mitigation across multiple locations, contrasting the traditional centralized approach. Demonstrated a 78.12% effectiveness in large-scale attack scenarios, significantly outperforming the standalone system's 4.73% effectiveness. Achieved a response time optimization of 316%, with a response time of 18 seconds compared to 57 seconds in standalone systems.	Study Type: Technological development and experimental validation. Focus: Distributed self-protection system for 5G/6G IoT networks against DDoS attacks.	Study Design: Technological innovation and experimental validation. Consistency of Results: Demonstrated consistent effectiveness in threat mitigation. Data Analysis Methods: Utilized a distributed dual-layer closed-loop system. Researcher's Interpretation: Focused on the practical application and benefits of the proposed system in real-time IoT network security.	Relevance to RQ: Directly addresses DDoS attack protection in 5G/6G IoT networks. Depth of Analysis: Offers comprehensive design and validation of a self-protection system. Quality of Research: Methodical in the development, implementation, and testing of the self-protection system. Contribution to the Field: Provides a novel approach to real-time IoT network security, advancing the field's understanding of distributed defense mechanisms.	Study Methods: Development and validation of a distributed dual-layer autonomous closed-loop system. Main Findings: Effective real-time detection and mitigation of DDoS attacks in 5G/6G IoT networks. Implications: Demonstrates the potential of distributed self-protection systems in enhancing IoT network security. Gaps Identified: Need for further research in diverse real-world IoT network environments and attack scenarios.

Paper	AUTHORS	FINDINGS	STUDY DETAILS	STUDY QUALITY	FULL-TEXT REVIEW	DATA EXTRACTION
7	Cheng Pin Lee Fabian Tee Jee Leng Riyaz Ahamed Ariyaluran Habeeb Mohamed Ahzam Amanullah Muhammad Habib ur Rehman	Highlighted the integration of edge computing in smart parking systems for improved security and energy efficiency. Reviewed various IoT components, sensors, and communication protocols used in smart parking. Identified and categorized different security threats in smart parking systems. Emphasized the role of edge computing in enhancing data privacy, reducing latency, and improving energy efficiency. Addressed the challenges in implementing edge computing in smart parking, including interoperability and the maintenance of high data quality.	Study Type: Review and analysis. Focus: Integration of edge computing in smart parking systems for enhanced security and energy efficiency.	Study Design: Review of existing literature on smart parking systems and edge computing. Consistency of Results: Consistent with current trends in IoT and smart parking research. Data Analysis Methods: Analysis of literature on IoT components, security threats, and edge computing in smart parking. Researcher's Interpretation: Focused on the practical application and benefits of edge computing in smart parking systems.	Relevance to RQ: Directly addresses the role of edge computing in enhancing smart parking systems. Depth of Analysis: Provides in-depth review of IoT components and their integration with edge computing. Quality of Research: Comprehensive and methodical review of current literature and technologies. Contribution to the Field: Offers insights into the application of edge computing for improving security and energy efficiency in smart parking.	Study Methods: Review of literature on smart parking systems, IoT components, and edge computing. Main Findings: Importance of edge computing in enhancing security and energy efficiency in smart parking systems. Implications: Potential impact on urban infrastructure and future development of smart cities. Gaps Identified: Need for further research in real-world application and scalability of edge computing in smart parking.
8	Yousef-Awwad Daraghmi Eman Yaser Daraghmi Raed Daraghma Hacène Fouchal Marwane Ayaida	Proposed a hierarchical architecture for remote health monitoring combining edge, fog, and cloud computing. Demonstrated significant reduction in NB-IoT transmission delay (59.9%) and average execution time (38.5%). Investigated and validated various IoT authentication protocols, identifying Light-Edge as the most efficient. Utilized machine learning algorithms for efficient data classification and analysis at each layer.	Study Type: Technological framework development and simulation-based evaluation. Focus: Enhancing performance and security of NB-IoT-based health monitoring systems using edge–fog–cloud computing.	Study Design: Development of a hierarchical computing architecture with simulation-based evaluation. Consistency of Results: Demonstrated consistent improvements in performance and security. Data Analysis Methods: Used machine learning for data analysis and simulation tools for evaluation. Researcher's Interpretation: Focus on practical application of the proposed architecture in improving NB-IoT performance and security.	Relevance to RQ: Directly addresses improving NB-IoT performance and security in health monitoring. Depth of Analysis: Provides comprehensive design, simulation, and validation of the architecture. Quality of Research: Methodical development and testing of the hierarchical computing framework. Contribution to the Field: Advances understanding of integrating edge, fog, and cloud computing in IoT-based health monitoring.	Study Methods: Development of a hierarchical computing architecture and use of simulation tools for evaluation. Main Findings: Effective reduction in transmission delay and execution time, and efficient authentication in NB-IoT systems. Implications: Highlights the potential of combining edge, fog, and cloud computing in enhancing IoT network security and performance. Gaps Identified: Further research needed in real-world implementation and long-term performance evaluation.

Paper	AUTHORS	FINDINGS	STUDY DETAILS	STUDY QUALITY	FULL-TEXT REVIEW	DATA EXTRACTION
9	Muhammad Zunnurain Hussain Zurina Mohd Hanapi	Presented a critical analysis of security issues in WSN-IoT and applications of WSN-IoT. Evaluated RPL's security mechanisms implemented in the Contiki operating system. Explored IoT-LPN architecture, research challenges, and network attacks in WSN-IoT infrastructures. Discussed various applied WSN-IoT security mechanisms and recent contributions. Assessed the performance of various low-powered IoT protocols and their limitations. Conducted a comparative analysis to evaluate the proposed work's performance against existing research.	Study Type: Literature review and analysis. Focus: Security mechanisms in low-powered IoT networks and critical evaluation of RPL's security in Contiki OS.	Study Design: Comprehensive review of existing literature on WSN-IoT security mechanisms. Consistency of Results: Consistent with the trends and challenges in WSN-IoT security. Data Analysis Methods: Analysis of literature on security mechanisms in WSN-IoT and evaluation of IoT protocols. Researcher's Interpretation: Focused on the analysis and evaluation of security methods in low-powered IoT networks.	Relevance to RQ: Directly addresses the security mechanisms in WSN-IoT networks. Depth of Analysis: Provides an extensive review of existing literature on WSN-IoT security. Quality of Research: Thorough in reviewing and categorizing existing research and methodologies. Contribution to the Field: Offers insights into the security challenges and advancements in WSN-IoT, particularly in low-powered networks	Study Methods: Literature review focusing on security issues and advancements in WSN-IoT. Main Findings: Critical analysis of security mechanisms, evaluation of RPL's security in Contiki, and assessment of IoT-LPN architecture. Implications: Highlights the need for effective security mechanisms in WSN-IoT, especially in low-powered networks. Gaps Identified: Suggests areas for further research in enhancing security measures and protocol efficiency in WSN-IoT.
10	Kanneboina Ashok S. Gopikrishnan	Comprehensive analysis of IoT security models for remote health monitoring. Discussion on the integration of various security models at multiple levels and their performance implications. Inclusion of blockchain, encryption, hashing models, privacy preservation techniques, and machine learning-based security methods. Assessment of models' performance in terms of computational latency, energy consumption, and scalability. Proposal of the IoT Security Performance Rank (ISRP) to aid in selecting optimal security models.	Study Type: Empirical survey and statistical analysis of IoT security models. Focus: Security models and deployments in the context of remote health monitoring using IoT.	Study Design: Empirical survey and comparative analysis of various IoT security models. Consistency of Results: Provides a comprehensive comparison of different models. Data Analysis Methods: Empirical analysis and comparative evaluation of IoT security models. Researcher's Interpretation: Focuses on providing a pragmatic perspective on IoT security model selection.	Relevance to RQ: Addresses IoT security challenges in remote health monitoring. Depth of Analysis: Extensive analysis of various security models and their performance metrics. Quality of Research: Detailed and methodological in assessing the performance of various IoT security models. Contribution to the Field: Provides a framework for evaluating and selecting IoT security models based on an empirical survey and statistical analysis.	Study Methods: Empirical survey and statistical analysis of IoT security models. Main Findings: Evaluation of various IoT security models and their performance in remote health monitoring contexts. Implications: Assists in selecting appropriate security models for IoT deployments in healthcare. Gaps Identified: Further research may be needed in real-world application and long-term effectiveness of these security models.

11	Muhammad Dangana Shuja Ansari Qammer H. Abbasi Sajjad Hussain Muhammad Ali Imran	NB-IoT Technology Review: The paper reviews state-of-the-art research in NB-IoT and related IoT technologies, focusing on their technical features, applications, and challenges in industrial environments. WSN Technology Overview: Wireless Sensor Networks (WSN) are explored, detailing their structure, network architecture, operational challenges, and their integration into IoT. IoT and IIoT Advancements: The paper discusses the advancements in IoT and IIoT, highlighting how they reduce human intervention in industries, particularly in manufacturing. Challenges in IIoT: Various challenges of IIoT, such as scalability, latency, energy consumption, and security are addressed, underscoring the critical nature of these technologies in industrial applications. NB-IoT Features: NB-IoT's main features include enhanced coverage range, low energy consumption, and the ability to support a massive number of device connections.	The study is a survey and review that systematically analyzes existing literature in the field of NB-IoT technology, particularly its application in industrial environments.	Research Design: Survey and analysis of existing literature and case studies. Data Collection: Extensive review of recent and relevant research papers, articles, and reports. Analysis Techniques: The data analysis involved categorizing the selected papers based on their review areas and focusing on the challenges related to communication characteristics supported by network layers. This involved theoretical and experimental content analysis Researchers' Interpretation The researchers interpreted their findings within the context of current technological capabilities and challenges of NB-IoT in industrial environments. They acknowledged the potential of NB-IoT technology, its low-cost deployment, long-range coverage, and ability to support a massive number of device connections.	The relevance to the research question (RQ) is maintained throughout the study, with a specific focus on understanding the impact of NB-IoT and related technologies on industrial environments. The study's findings and discussions are aligned with addressing the challenges and future directions of NB-IoT in industrial wireless communication.	The study methods are not explicitly detailed in the provided excerpts. The paper is a comprehensive review and analysis of existing literature, including technological features, applications, and challenges associated with Narrow-Band Internet of Things (NB-IoT) and its industrial applications. Main Findings: NB-IoT offers enhanced coverage and better connectivity in challenging environments like industries. It supports low power consumption, enabling longer battery life for devices. There are significant challenges for wireless communication in industrial environments due to factors like noise, interference, and high demand for reliability and latency. NB-IoT is positioned as a technology that could meet these industrial demands through its integration with LTE and self-organizing network capabilities. Implications: The adaptation of NB-IoT in industrial settings could potentially revolutionize industrial processes through improved wireless communication systems. There are opportunities for the development of self-organizing networks that can meet the rigorous demands of industrial environments. The application of edge computing could enhance scalability and network management. Ensuring the security of industrial data and providing a reliable propagation model are

Paper	AUTHORS	FINDINGS	STUDY DETAILS	STUDY QUALITY	FULL-TEXT REVIEW	DATA EXTRACTION
						crucial for the successful deployment of NB-IoT Gaps Identified: Further research is necessary to address the real-world application and long-term effectiveness of NB-IoT, particularly in ensuring network self-organization, scalability, data security, and the development of a suitable propagation model for industrial environments.

Paper	AUTHORS	FINDINGS	STUDY DETAILS	STUDY QUALITY	FULL-TEXT REVIEW	DATA EXTRACTION
1	Dr. K Seshadri Ramana Y. Indira Priyadarshini H J Jambukesh Rajesh Singh Manivel Kandasamy Bura Vijay Kumar S	Developed a comprehensive 5G NB-IoT design for smart grids, focusing on secure data transmission and predictive data analysis. Proposed solution enhances grid control, market response, and connectivity between 5G and national grids. Aimed to facilitate electronic innovation in modern grids, integrating services and software for a smarter network. Contributed to the "dual carbon" goal of the energy network by improving cognitive networks and data analysis.	Study Type: Technological innovation and application in smart grids. Focus: Integration of 5G and NB-IoT technologies for secured information transmission and predictive analyses in smarter grids.	Study Design: Technological design, application-centric rather than experimental or observational. Consistency of Results: Consistent with current trends in smart grid technologies. Data Analysis Methods: Emphasis on integrating and analysing smart grid data with advanced technologies. Researcher's Interpretation: Focused on practical application in smarter grids, consistent with the technological framework proposed.	Relevance to RQ: Directly addresses the integration of 5G and NB-IoT technologies in smart grids. Depth of Analysis: Provides detailed insights into technological applications for smarter grids. Quality of Research: Demonstrates a clear design of technological application with a focus on innovation and practical implications. Contribution to the Field: Offers novel insights and methods for the advancement of smart grid technology.	Study Methods: Technological application with a focus on secure data transmission and predictive analysis in smart grids. Main Findings: Development of a 5G NB-IoT design for enhanced grid control and market response. Implications: Potential significant impact on smart grid management and energy network goals. Gaps Identified: Further exploration needed in real-world application and long-term effectiveness.
2	Mireya Lucia Hernandez-Jaimes Alfonso Martinez-Cruz Kelsey Alejandra	Presented a novel taxonomy for intrusion detection in IoMT, including AI methods, datasets, and cyberattack classifications. Highlighted the use of AI in enhancing IDS performance for IoMT security. Discussed various cyberattacks on IoMT, such as	Study Type: Literature review and analysis. Focus: Review of IDS, cyberattacks, and AI applications in IoMT security.	Study Design: Comprehensive literature review with taxonomy development. Consistency of Results: Consistent with existing research in IoMT security. Data Analysis Methods: Analysis of existing	Relevance to RQ: Directly addresses AI applications in IoMT security. Depth of Analysis: Extensive review and categorization of current literature and methods. Quality of Research: Thorough and methodical	Study Methods: Literature review focusing on AI methods, IDS, and cyberattacks in IoMT. Main Findings: Identification of key AI strategies, intrusion detection systems, and prevalent cyberattacks in IoMT. Implications: Emphasizes the importance of AI

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	Ramírez-Gutiérrez Claudia Feregrino-Uribe	DoS, DDoS, and ransomware, and their implications. Analysed Cloud–Fog–Edge computing architectures' role in IoMT security. Emphasized the legal and ethical aspects of IoMT security.		literature and categorisation of findings. Researcher's Interpretation: Focused on implications of AI in IoMT security and challenges in this field.	in reviewing and categorizing existing research. Contribution to the Field: Offers a comprehensive understanding of AI's role in IoMT security and future research directions.	in enhancing IoMT security and identifies future research areas. Gaps Identified: Calls for more research on effective AI integration and addressing emerging cyber threats in IoMT.
3	Sri Harsha Mekala Zubair Baig Adnan Anwar Sherali Zeadally	Detailed analysis of security threats in IIoT, including DDoS, phishing, and man-in-the-middle attacks. Evaluation of various countermeasures like intrusion detection systems, machine learning techniques, and securing SCADA networks. Discussion on challenges in IIoT cybersecurity, such as scalability, security and privacy, and standardization. Future directions in IIoT cybersecurity, highlighting areas needing further research and development.	Study Type: Comprehensive analysis and review. Focus: Cybersecurity challenges, threats, and solutions in the Industrial Internet of Things.	Study Design: Review and analysis of existing literature, security threats, and countermeasures. Consistency of Results: Aligns with known cybersecurity challenges in IIoT. Data Analysis Methods: Analysis of literature and current cybersecurity practices in IIoT. Researcher's Interpretation: Focuses on the practical implications and future directions in IIoT cybersecurity.	Relevance to RQ: Directly addresses cybersecurity in the Industrial Internet of Things. Depth of Analysis: Provides an in-depth review of current threats, solutions, and challenges in IIoT security. Quality of Research: Methodical and comprehensive in its approach to analyzing IIoT cybersecurity. Contribution to the Field: Enhances understanding of cybersecurity in IIoT and points towards future research needs.	Study Methods: Analysis and review of existing research on IIoT cybersecurity. Main Findings: Identification of key threats and countermeasures in IIoT security. Implications: Highlights the importance of evolving cybersecurity measures in IIoT. Gaps Identified: Suggests areas for further research, including the development of more robust security solutions.
4	H. C. Ke H. Wang H. W. Zhao W. J. Sun	Developed a deep reinforcement learning-based scheme for computation offloading and resource allocation in MEC environments. Focused on security-aware scenarios, considering the dynamic nature of wireless networks and security threats. Demonstrated that the proposed DRL-based scheme outperforms conventional methods in terms of efficiency and adaptability. Highlighted the scheme's ability to learn and adapt in real-time to changing network conditions and workload demands.	Study Type: Technological development and performance evaluation. Focus: Optimization of computation offloading and resource allocation using DRL in security-aware MEC systems.	Study Design: Development and evaluation of a DRL-based optimization scheme for MEC systems. Consistency of Results: Results demonstrate consistent improvements over traditional methods. Data Analysis Methods: Utilized DRL for dynamic and efficient resource management in MEC. Researcher's Interpretation: Focused on the practical application and benefits of the proposed scheme in MEC environments.	Relevance to RQ: Directly addresses the optimization of computation offloading and resource allocation in MEC using DRL. Depth of Analysis: Provides comprehensive insights into DRL applications in dynamic and complex MEC environments. Quality of Research: Methodical in the development and evaluation of the DRL-based scheme. Contribution to the Field: Introduces a novel approach to MEC optimization, advancing the field's understanding of DRL applications.	Study Methods: Development and evaluation of a DRL-based scheme for optimizing MEC systems. Main Findings: The DRL-based scheme significantly improves computation offloading and resource allocation efficiency. Implications: Demonstrates the potential of DRL in enhancing the performance and security of MEC systems. Gaps Identified: Further research needed in real-world deployment and long-term performance evaluation.

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5	Tahani Bani-Yaseen Ashraf Tahat Kira Kastell Talal A. Edwan	Developed deep learning models, particularly LSTM and GRU, to detect DoSI attacks in NB-IoT networks. Demonstrated LSTM classifier's superior performance with an accuracy of up to 98.99% and detection time of 2.54 x 10^-5 seconds/record. Highlighted that RNN models outperform traditional machine learning algorithms like SVM, Gaussian Naïve-Bayes, and logistic regression in detecting DoSI attacks. Generated a novel dataset through ns-3 simulation to represent DoSI attacks in NB-IoT, crucial for training and testing the models.	Study Type: Technological and methodological development with simulation-based evaluation. Focus: Deep learning-based detection of DoSI attacks in NB-IoT networks.	Study Design: Technological development with simulation-based evaluation of models. Consistency of Results: Demonstrated consistent performance across deep learning models. Data Analysis Methods: Employed deep learning techniques, particularly RNN models. Researcher's Interpretation: Focused on the practical application of deep learning in cybersecurity for IoT networks.	Relevance to RQ: Directly addresses the detection of DoSI attacks in NB-IoT using deep learning. Depth of Analysis: Offers in-depth analysis and evaluation of LSTM and GRU models for attack detection. Quality of Research: High, with methodical development and testing of deep learning models. Contribution to the Field: Provides valuable insights and methods for detecting DoSI attacks in NB-IoT, advancing cybersecurity in IoT.	Study Methods: Utilized deep learning techniques, particularly LSTM and GRU models, in a simulated NB-IoT environment. Main Findings: Demonstrated high accuracy and efficiency of LSTM and GRU models in detecting DoSI attacks. Implications: Highlights the potential of deep learning in enhancing IoT network security. Gaps Identified: Need for further research in real-world deployment and adaptation of models.
6	Pablo Benlloch-Caballero Qi Wang Jose M. Alcaraz Calero	Developed an autonomous DDoS mitigation system for 5G/6G networks, significantly reducing collateral damage. The system includes fine-grained detection of malicious flows, analysis of attacks, decision-making, planning, and orchestration for intervention. Features dual concurrent closed control-loops: one for ISPs focusing on their infrastructure and another for DSPs managing virtualized infrastructure services. Offers distributed DDoS mitigation across multiple locations, contrasting the traditional centralized approach. Demonstrated a 78.12% effectiveness in large-scale attack scenarios, significantly outperforming the standalone system's 4.73% effectiveness. Achieved a response time optimization of 316%, with a response time of 18 seconds compared to 57 seconds in standalone systems.	Study Type: Technological development and experimental validation. Focus: Distributed self-protection system for 5G/6G IoT networks against DDoS attacks.	Study Design: Technological innovation and experimental validation. Consistency of Results: Demonstrated consistent effectiveness in threat mitigation. Data Analysis Methods: Utilized a distributed dual-layer closed-loop system. Researcher's Interpretation: Focused on the practical application and benefits of the proposed system in real-time IoT network security.	Relevance to RQ: Directly addresses DDoS attack protection in 5G/6G IoT networks. Depth of Analysis: Offers comprehensive design and validation of a self-protection system. Quality of Research: Methodical in the development, implementation, and testing of the self-protection system. Contribution to the Field: Provides a novel approach to real-time IoT network security, advancing the field's understanding of distributed defense mechanisms.	Study Methods: Development and validation of a distributed dual-layer autonomous closed-loop system. Main Findings: Effective real-time detection and mitigation of DDoS attacks in 5G/6G IoT networks. Implications: Demonstrates the potential of distributed self-protection systems in enhancing IoT network security. Gaps Identified: Need for further research in diverse real-world IoT network environments and attack scenarios.

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7	Cheng Pin Lee Fabian Tee Jee Leng Riyaz Ahamed Ariyaluran Habeeb Mohamed Ahzam Amanullah Muhammad Habib ur Rehman	Highlighted the integration of edge computing in smart parking systems for improved security and energy efficiency. Reviewed various IoT components, sensors, and communication protocols used in smart parking. Identified and categorized different security threats in smart parking systems. Emphasized the role of edge computing in enhancing data privacy, reducing latency, and improving energy efficiency. Addressed the challenges in implementing edge computing in smart parking, including interoperability and the maintenance of high data quality.	Study Type: Review and analysis. Focus: Integration of edge computing in smart parking systems for enhanced security and energy efficiency.	Study Design: Review of existing literature on smart parking systems and edge computing. Consistency of Results: Consistent with current trends in IoT and smart parking research. Data Analysis Methods: Analysis of literature on IoT components, security threats, and edge computing in smart parking. Researcher's Interpretation: Focused on the practical application and benefits of edge computing in smart parking systems.	Relevance to RQ: Directly addresses the role of edge computing in enhancing smart parking systems. Depth of Analysis: Provides in-depth review of IoT components and their integration with edge computing. Quality of Research: Comprehensive and methodical review of current literature and technologies. Contribution to the Field: Offers insights into the application of edge computing for improving security and energy efficiency in smart parking.	Study Methods: Review of literature on smart parking systems, IoT components, and edge computing. Main Findings: Importance of edge computing in enhancing security and energy efficiency in smart parking systems. Implications: Potential impact on urban infrastructure and future development of smart cities. Gaps Identified: Need for further research in real-world application and scalability of edge computing in smart parking.
8	Yousef-Awwad Daraghmi Eman Yaser Daraghmi Raed Daraghma Hacène Fouchal Marwane Ayaida	Proposed a hierarchical architecture for remote health monitoring combining edge, fog, and cloud computing. Demonstrated significant reduction in NB-IoT transmission delay (59.9%) and average execution time (38.5%). Investigated and validated various IoT authentication protocols, identifying Light-Edge as the most efficient. Utilized machine learning algorithms for efficient data classification and analysis at each layer.	Study Type: Technological framework development and simulation-based evaluation. Focus: Enhancing performance and security of NB-IoT-based health monitoring systems using edge–fog–cloud computing.	Study Design: Development of a hierarchical computing architecture with simulation-based evaluation. Consistency of Results: Demonstrated consistent improvements in performance and security. Data Analysis Methods: Used machine learning for data analysis and simulation tools for evaluation. Researcher's Interpretation: Focus on practical application of the proposed architecture in improving NB-IoT performance and security.	Relevance to RQ: Directly addresses improving NB-IoT performance and security in health monitoring. Depth of Analysis: Provides comprehensive design, simulation, and validation of the architecture. Quality of Research: Methodical development and testing of the hierarchical computing framework. Contribution to the Field: Advances understanding of integrating edge, fog, and cloud computing in IoT-based health monitoring.	Study Methods: Development of a hierarchical computing architecture and use of simulation tools for evaluation. Main Findings: Effective reduction in transmission delay and execution time, and efficient authentication in NB-IoT systems. Implications: Highlights the potential of combining edge, fog, and cloud computing in enhancing IoT network security and performance. Gaps Identified: Further research needed in real-world implementation and long-term performance evaluation.
9	Muhammad Zunnurain Hussain Zurina Mohd Hanapi	Presented a critical analysis of security issues in WSN-IoT and applications of WSN-IoT. Evaluated RPL's security mechanisms	Study Type: Literature review and analysis. Focus: Security mechanisms in low-powered IoT networks and critical evaluation of RPL's security	Study Design: Comprehensive review of existing literature on WSN-IoT security mechanisms. Consistency of Results: Consistent with the	Relevance to RQ: Directly addresses the security mechanisms in WSN-IoT networks. Depth of Analysis: Provides an extensive review of existing literature on WSN-IoT	Study Methods: Literature review focusing on security issues and advancements in WSN-IoT. Main Findings: Critical analysis of security mechanisms, evaluation of RPL's security in Contiki, and assessment of IoT-LPN

Paper	AUTHORS	FINDINGS	STUDY DETAILS	STUDY QUALITY	FULL-TEXT REVIEW	DATA EXTRACTION
		implemented in the Contiki operating system. Explored IoT-LPN architecture, research challenges, and network attacks in WSN-IoT infrastructures. Discussed various applied WSN-IoT security mechanisms and recent contributions. Assessed the performance of various low-powered IoT protocols and their limitations. Conducted a comparative analysis to evaluate the proposed work's performance against existing research.	in Contiki OS.	trends and challenges in WSN-IoT security. Data Analysis Methods: Analysis of literature on security mechanisms in WSN-IoT and evaluation of IoT protocols. Researcher's Interpretation: Focused on the analysis and evaluation of security methods in low-powered IoT networks.	security. Quality of Research: Thorough in reviewing and categorizing existing research and methodologies. Contribution to the Field: Offers insights into the security challenges and advancements in WSN-IoT, particularly in low-powered networks	architecture. Implications: Highlights the need for effective security mechanisms in WSN-IoT, especially in low-powered networks. Gaps Identified: Suggests areas for further research in enhancing security measures and protocol efficiency in WSN-IoT.
10	Kanneboina Ashok S. Gopikrishnan	Comprehensive analysis of IoT security models for remote health monitoring. Discussion on the integration of various security models at multiple levels and their performance implications. Inclusion of blockchain, encryption, hashing models, privacy preservation techniques, and machine learning-based security methods. Assessment of models' performance in terms of computational latency, energy consumption, and scalability. Proposal of the IoT Security Performance Rank (ISRP) to aid in selecting optimal security models.	Study Type: Empirical survey and statistical analysis of IoT security models. Focus: Security models and deployments in the context of remote health monitoring using IoT.	Study Design: Empirical survey and comparative analysis of various IoT security models. Consistency of Results: Provides a comprehensive comparison of different models. Data Analysis Methods: Empirical analysis and comparative evaluation of IoT security models. Researcher's Interpretation: Focuses on providing a pragmatic perspective on IoT security model selection.	Relevance to RQ: Addresses IoT security challenges in remote health monitoring. Depth of Analysis: Extensive analysis of various security models and their performance metrics. Quality of Research: Detailed and methodological in assessing the performance of various IoT security models. Contribution to the Field: Provides a framework for evaluating and selecting IoT security models based on an empirical survey and statistical analysis.	Study Methods: Empirical survey and statistical analysis of IoT security models. Main Findings: Evaluation of various IoT security models and their performance in remote health monitoring contexts. Implications: Assists in selecting appropriate security models for IoT deployments in healthcare. Gaps Identified: Further research may be needed in real-world application and long-term effectiveness of these security models.
11	Muhammad Dangana Shuja Ansari Qammer H. Abbasi	NB-IoT Technology Review: The paper reviews state-of-the-art research in NB-IoT and related IoT technologies, focusing on their technical features, applications, and challenges in industrial environments. WSN Technology Overview: Wireless Sensor Networks (WSN) are explored, detailing their	The study is a survey and review that systematically analyzes existing literature in the field of NB-IoT technology, particularly its application in industrial environments.	Research Design: Survey and analysis of existing literature and case studies. Data Collection: Extensive review of recent and relevant research papers, articles, and reports. Analysis Techniques: The data analysis involved categorizing the selected papers	The relevance to the research question (RQ) is maintained throughout the study, with a specific focus on understanding the impact of NB-IoT and related technologies on industrial environments. The study's findings and discussions are aligned with addressing the challenges and future directions of NB-IoT in industrial wireless communication.	The study methods are not explicitly detailed in the provided excerpts. The paper is a comprehensive review and analysis of existing literature, including technological features, applications, and challenges associated with Narrow-Band Internet of Things (NB-IoT) and its industrial applications.

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	Sajjad Hussain Muhammad Ali Imran	structure, network architecture, operational challenges, and their integration into IoT. IoT and IIoT Advancements: The paper discusses the advancements in IoT and IIoT, highlighting how they reduce human intervention in industries, particularly in manufacturing. Challenges in IIoT: Various challenges of IIoT, such as scalability, latency, energy consumption, and security are addressed, underscoring the critical nature of these technologies in industrial applications. NB-IoT Features: NB-IoT's main features include enhanced coverage range, low energy consumption, and the ability to support a massive number of device connections.		based on their review areas and focusing on the challenges related to communication characteristics supported by network layers. This involved theoretical and experimental content analysis Researchers' Interpretation The researchers interpreted their findings within the context of current technological capabilities and challenges of NB-IoT in industrial environments. They acknowledged the potential of NB-IoT technology, its low-cost deployment, long-range coverage, and ability to support a massive number of device connections.		Main Findings: NB-IoT offers enhanced coverage and better connectivity in challenging environments like industries. It supports low power consumption, enabling longer battery life for devices. There are significant challenges for wireless communication in industrial environments due to factors like noise, interference, and high demand for reliability and latency. NB-IoT is positioned as a technology that could meet these industrial demands through its integration with LTE and self-organizing network capabilities. Implications: The adaptation of NB-IoT in industrial settings could potentially revolutionize industrial processes through improved wireless communication systems. There are opportunities for the development of self-organizing networks that can meet the rigorous demands of industrial environments. The application of edge computing could enhance scalability and network management. Ensuring the security of industrial data and providing a reliable propagation model are crucial for the successful deployment of NB-IoT Gaps Identified: Further research is necessary to address the real-world application and long-term effectiveness of NB-IoT, particularly in ensuring

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						network self-organization, scalability, data security, and the development of a suitable propagation model for industrial environments.