BINDURA UNIVERSITY OF SCIENCE EDUCATION

FACULTY OF SCIENCE DEPARTMENT OF COMPUTER SCIENCE



Comparative Analysis of Network and Processing Overhead of TEA, CHACHA20 and AES-128 on Simulated Low-IoT Devices via Cooja Simulation

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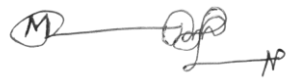
A RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE BACHELOR OF SCIENCE HONOURS DEGREE IN NETWORK ENGINEERING

JUNE 2026

APPROVAL FORM

The undersigned certify that they have supervised B220894B Dean Tapiwanashe Matiya dissertation entitled "**Comparative Analysis of Network and Processing Overhead of TEA,CHACHA20 and AES-128 on Simulated Low-IoT Devices via Cooja Simulation"** submitted in partial fulfilment of the requirements for Barchelor of Science Honors Degree in Network Engineering

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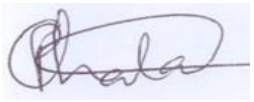
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DEDICATION

I dedicate this project to my family for their unwavering support, encouragement and sacrifices throughout my academic journey. Your guidance, patience and belief in my abilities gave me the strength and motivation to complete this research successfully. I also dedicate this work to my lecturers and classmates whose knowledge, advice and encouragement contributed significantly to my academic growth and professional development. Finally, this project is dedicated to all aspiring researchers and network engineers who continue to pursue innovation and advancement in the field of IIoT and cybersecurity.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor for the invaluable guidance, constructive criticism, encouragement and continuous support provided throughout the development of this research project. Your academic mentorship and professional advice played a significant role in shaping the quality and direction of this study. I also extend my appreciation to the lecturers in the Department of Network Engineering for imparting the knowledge and technical skills that made this research possible. Special appreciation goes to my family and friends for their emotional support, motivation, patience and encouragement during the course of this study. Furthermore, I acknowledge the developers and contributors of the Contiki-NG operating system and the Cooja Network Simulator for providing open-source research tools that facilitated the successful completion of this project. Above all, I thank God Almighty for granting me strength, wisdom, good health and perseverance throughout my academic journey.

ABSTRACT

The IIoT has significantly improved industrial automation, communication and real-time monitoring through interconnected constrained devices and wireless sensor networks. However, implementing secure communication within constrained IoT environments remains a major challenge due to limited processing capability, memory resources and energy constraints. This study comparatively evaluated the network and processing overhead introduced by TEA, ChaCha20 and AES-128 within constrained IIoT environments using the Contiki-NG operating system and the Cooja Network Simulator. The study adopted an experimental quantitative research design based on simulated RPL-UDP communication between Sky mote sensor devices. Performance metrics including radio duty cycle, network latency, packet delivery ratio and energy consumption were collected using PowerTracker and simulation logs. The findings demonstrated that lightweight cryptographic algorithms significantly influence constrained network performance and energy efficiency. TEA exhibited the lowest processing overhead and energy consumption, while AES-128 provided stronger security at the cost of increased computational overhead. ChaCha20 achieved moderate performance with improved throughput characteristics. The study concluded that lightweight encryption mechanisms are more suitable for severely constrained IIoT environments where energy efficiency and low communication overhead are critical requirements. The research contributes empirical evidence supporting lightweight cryptography adoption within lowpower IIoT systems.

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CHAPTER 1

1.1 Introduction

The Internet of Things (IoT) has facilitated the deployment of large-scale monitoring systems, enabling small edge devices to sense, process and transmit critical data across industrial networks for real-time decision-making and automation. However, these IoT ecosystems are frequently implemented as Low-Power and Lossy Networks (LLNs). The underlying nodes and communication links within LLNs are inherently constrained in terms of processing power, volatile memory and finite energy reserves, making the seamless integration of robust security mechanisms a complex engineering challenge (Winter et al. 2012; Oikonomou et al. 2022).

Establishing security within IoT monitoring architectures is paramount, as the transmitted telemetry data is often highly sensitive and continuously exposed to risks of wireless interception, eavesdropping and malicious manipulation. Yet, applying standard cryptographic protocols on resource-depleted devices inherently imposes computational and communication overhead, which can severely degrade real-time network performance and rapidly deplete battery lifespans.

Consequently, this study evaluates the specific performance costs of encryption in constrained IoT communications. It achieves this by quantitatively comparing the network latency, data throughput and processing overhead introduced by the lightweight Tiny Encryption Algorithm (TEA) against the modern ChaCha20 stream cipher. This comparative analysis is conducted within a highly controlled Wireless Sensor Network (WSN) simulation environment, utilizing the Contiki-NG operating system and the cycle-accurate Cooja simulator.

1.2 Background of the Study

The IIoT represents a monumental shift in global industrial operations, facilitating real-time monitoring and automation across critical infrastructure such as power grids, water treatment facilities and automated manufacturing plants. These systems rely on a vast network of interconnected sensors and actuators, often referred to as "motes," which are deployed in diverse and frequently harsh environments. A defining characteristic of IIoT hardware is that it is typically resource-constrained; devices are built on 16-bit architectures, such as the MSP430, possessing extremely limited memory and relying on small batteries for multi-year lifespans.

As these systems become integral to national infrastructure, the sensitivity of the data they transmit ranging from valve pressure readings to electrical grid frequencies grows, making them lucrative targets for cyber-attacks. However, a significant "Security-Energy Paradox" exists. Traditional encryption standards, such as RSA or standard AES-256, were designed for high-performance computing environments. Implementing these on a 16-bit mote often leads to "computational exhaustion," where the energy required for complex mathematical operations significantly reduces the device's operational lifespan. This research explores lightweight cryptographic alternatives, specifically the Tiny Encryption Algorithm (TEA)

,ChaCha20 and AES-128 to determine if they can provide the necessary value addition of security without compromising the functional longevity of industrial sensor nodes.

1.3 Statement of the Problem

The rapid expansion of IIoT monitoring systems has outpaced the development of standardized, energy-efficient security protocols for low-cost hardware. Standard cryptographic algorithms often impose a prohibitive overhead on resource-constrained IoT devices, leading to rapid battery depletion and increased communication latency. There is currently a lack of quantitative, comparative evidence for network engineers regarding how fundamentally different ciphers such as a simple Feistel-based block cipher (TEA) versus a modern highperformance stream cipher (ChaCha20) behave within a standard RPL-UDP network stack on emulated hardware. Without this comparative data, value-added security cannot be effectively implemented, leaving critical industrial data vulnerable or rendering the monitoring devices inefficient.

1.4 Aim of the Study

The primary aim of this research is to conduct a comparative analysis of the network and processing overhead of TEA, ChaCha20 and AES-128 ciphers when implemented on simulated resource-constrained IoT devices using the Cooja Network Simulator and the Contiki-NG operating system.

1.5 Research Objectives

1.5.1 General Objective

To comparatively evaluate the network and processing overhead introduced by TEA, ChaCha20 and AES-128 within constrained IIoT environments using the Contiki-NG operating system and Cooja Network Simulator.

1.5.2 Specific Objectives

i. To design a constrained IIoT simulation environment using Contiki-NG and the Cooja Network Simulator.
ii. To implement TEA, ChaCha20 and AES-128 encryption algorithms within an RPLUDP communication environment.
iii. To measure and compare the impact of TEA, ChaCha20 and AES-128 on radio duty cycle, network latency, packet delivery ratio and energy consumption. iv. To determine the most suitable cryptographic algorithm for constrained IIoT environments based on security and network performance trade-offs.

1.6 Research Questions

i. How can a constrained IIoT simulation environment be designed using Contiki-NG and the Cooja Network Simulator?
ii. How can TEA, ChaCha20 and AES-128 be implemented within an RPL-UDP communication environment?

iii. What impact do TEA, ChaCha20 and AES-128 have on radio duty cycle, network latency, packet delivery ratio and energy consumption within constrained IoT systems?
iv. Which cryptographic algorithm provides the best balance between security and network performance within constrained IIoT environments?

1.7 Justification of the Study

The rapid growth of the IIoT has increased the demand for secure communication within constrained wireless sensor environments. However, most constrained IoT devices possess limited memory capacity, low processing capability and restricted battery resources, making implementation of computationally intensive encryption algorithms difficult. Although strong encryption mechanisms improve data confidentiality and communication security, they may also introduce significant processing overhead, increased energy consumption, communication latency and reduced device sustainability. Consequently, selecting an appropriate cryptographic algorithm for constrained IIoT environments remains a critical challenge.

This study is significant because it provides comparative evaluation of TEA, ChaCha20 and AES-128 within a constrained RPL-UDP communication environment using the Contiki-NG operating system and the Cooja Network Simulator. The study contributes empirical evidence regarding the relationship between encryption overhead and constrained network performance. The findings of the study may assist: IoT system designers, network engineers, cybersecurity researchers and embedded systems developers in selecting suitable cryptographic mechanisms for low-power IIoT deployments. The study also contributes to the growing body of research concerning lightweight cryptography and constrained wireless sensor networks, particularly within developing countries where low-cost and energy-efficient IoT deployments are increasingly important.

1.8 Assumptions

i. The Cooja Network Simulator accurately emulates the behavior of constrained IIoT devices operating within real wireless sensor network environments.
ii. The Sky mote platform provides realistic representation of constrained IoT devices based on low-power MSP430 microcontroller architecture.
iii. The implemented cryptographic algorithms namely TEA, ChaCha20 and AES128 operate correctly and consistently within the Contiki-NG operating system.
iv. The RPL-UDP communication stack used in the study accurately represents communication behavior within constrained IIoT environments.
v. The simulation parameters including transmission interval, radio range and network topology remain stable and consistent throughout all experimental scenarios.
vi. The PowerTracker plugin provides reliable estimation of radio activity and energy consumption within the simulation environment.

vii. The experimental metrics collected during simulation are sufficient for evaluating the impact of cryptographic algorithms on constrained network performance.

viii. The simulated wireless communication environment reasonably reflects the operational behavior of low-power IIoT systems.

1.9 Limitation/ Challenges

The study encountered several limitations and challenges during the comparative evaluation of TEA, ChaCha20 and AES-128 within constrained IIoT environments. Firstly, the study was conducted within a simulation environment rather than a physical hardware deployment. Consequently, real-world environmental factors such as electromagnetic interference, physical signal obstruction, temperature variations and hardware degradation could not be fully represented. Secondly, the study focused only on three cryptographic algorithms namely TEA, ChaCha20 and AES-128. Other lightweight cryptographic algorithms such as PRESENT, SPECK, SIMON and LEA were not included within the scope of the research. Thirdly, the experiments were limited to the Contiki-NG operating system and the Cooja Network Simulator. Therefore, the findings may vary when implemented within different operating systems, hardware architectures, or simulation environments. Another limitation is that the study utilized a relatively small network topology consisting of a limited number of Sky mote devices. Large-scale IIoT deployments may produce different networking behaviors and communication overhead patterns. The study also relied on software-based energy estimation through the PowerTracker plugin rather than direct physical battery measurements. Consequently, actual hardware energy consumption may slightly differ from the simulated results.

Despite these limitations, the study provided controlled, repeatable and reliable experimental conditions suitable for comparative evaluation of cryptographic overhead within constrained IIoT environments.

1.10 Scope of the Study

The study focused on comparative evaluation of TEA, ChaCha20 and AES-128 within constrained IIoT environments. The research was limited to: the Contiki-NG operating system, the Cooja Network Simulator, Sky mote sensor devices, RPL routing protocol and UDP communication protocol. The study evaluated the impact of the selected cryptographics.

1.11 Definition of Key Terms

- Tiny Encryption Algorithm: is a lightweight symmetric block cipher that uses simple arithmetic and logical operations to encrypt data within constrained computing environments.
- ChaCha20: is a lightweight stream cipher developed by Daniel J. Bernstein that generates a pseudorandom keystream for secure data encryption.
- AES-128: is a symmetric encryption algorithm that uses a 128-bit secret key to perform secure block-based data encryption.

- Radio duty cycle: refers to the percentage of time during which the radio component of a sensor device remains active for transmitting or receiving data.
- Processing overhead: refers to the additional computational workload introduced by a process such as encryption or routing within a computing system.
- Contiki-NG: is an open-source operating system designed for constrained Internet of Things devices and low-power wireless sensor networks.
- Cooja Network Simulator: is a simulation environment used for emulating constrained wireless sensor networks operating under the Contiki-NG operating system.
- Sky mote: refers to a constrained wireless sensor device based on the MSP430 microcontroller architecture commonly used in IoT simulation environments.
- MSP430 microcontroller: refers to a low-power 16-bit embedded processor architecture developed by Texas Instruments for constrained electronic systems.
- RPL: is a routing protocol specifically designed for constrained wireless sensor networks characterized by unstable communication links and limited energy resources.
- Low-Power and Lossy Networks (LLNs): Constrained wireless networks characterized by resource-depleted nodes, unstable links, high packet drop rates, and low operational bandwidth

1.12 Summary

This chapter introduced the study by presenting the background to the research, statement of the problem, research objectives, research questions, justification of the study, scope of the study, assumptions of the study and definition of key terms. The chapter established that constrained IIoT environments experience significant challenges related to balancing communication security and network performance. The discussion highlighted the importance of lightweight cryptographic mechanisms within low-power wireless sensor systems. The chapter further justified the need for comparative evaluation of TEA, ChaCha20 and AES-128 within constrained IoT environments using the Contiki-NG operating system and the Cooja Network Simulator. The next chapter presents the literature review related to lightweight cryptography, constrained IoT security, wireless sensor networking and IIoT environments.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a comprehensive review of literature related to lightweight cryptography, IIoT security, constrained wireless sensor networks and low-power communication systems. The chapter examines theoretical perspectives, conceptual foundations and empirical studies concerning the implementation of cryptographic algorithms in constrained IoT environments. The review focuses on how encryption algorithms influence processing overhead, radio duty cycle, latency, throughput, packet delivery ratio and energy consumption within constrained sensor nodes. Particular emphasis is placed on the performance implications of TEA, ChaCha20 and AES-128 within low-power wireless communication systems operating under the Contiki-NG operating system and the RPL-UDP protocol stack. The chapter further evaluates international, regional and local scholarly contributions related to lightweight cryptography and IIoT security.

2.2 Theoretical Framework

2.2.1 Systems Theory

This study is guided by Systems Theory, which was developed by Ludwig von Bertalanffy in 1968. Systems Theory views a technological environment as a collection of interconnected and interdependent components working together to achieve a common objective. Within IIoT systems, wireless sensor nodes, routing protocols, communication layers, cryptographic mechanisms and energy management systems collectively form an integrated operational framework.

According to Systems Theory, modifications introduced within one subsystem directly influence the behavior and performance of the entire system. The implementation of encryption algorithms within constrained IoT environments therefore affects communication efficiency, processor utilization, radio duty cycle and overall energy consumption. For example, increasing cryptographic complexity may improve data confidentiality while simultaneously increasing computational overhead and battery usage.

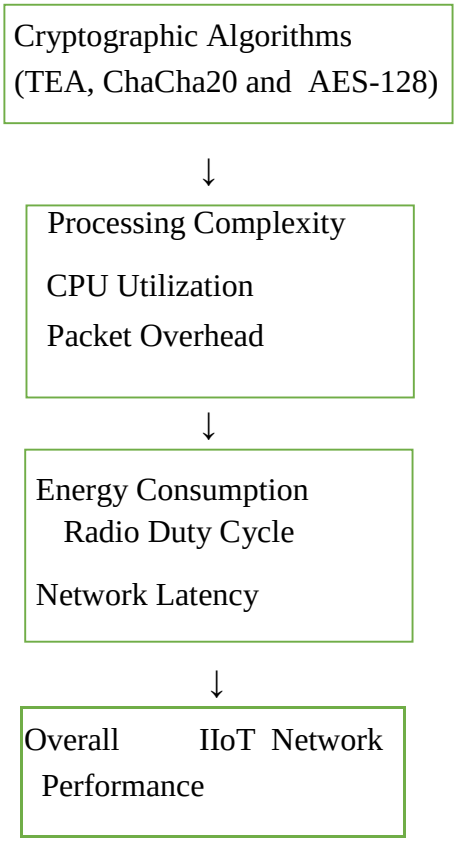
According to Garcia-Morchon et al. (2013), lightweight security protocols should be evaluated within the broader IoT communication ecosystem because cryptographic processing directly affects network sustainability. Similarly, Mavromatis et al. (2021) argue that constrained IoT environments require balanced interaction between security mechanisms and hardware resources to maintain operational efficiency. Systems Theory is therefore relevant to this study because the research investigates how TEA, ChaCha20 and AES-128 interact with communication protocols and constrained hardware resources within IIoT systems.

2.3 Conceptual Framework

The conceptual framework of this study is based on the relationship between lightweight cryptographic algorithms and network performance in constrained IIoT environments. The independent variables of the study are Tiny Encryption Algorithm (TEA), ChaCha20 and

AES128.The dependent variables are Radio Duty Cycle, Processing Latency, Packet Delivery Ratio and Energy Consumption. The framework assumes that increased cryptographic complexity introduces additional processing and communication overhead, which subsequently affects constrained IoT device performance. Lightweight cryptographic algorithms are expected to reduce processor utilization and radio activity while maintaining acceptable security standards within constrained wireless sensor networks.

Figure 2.3: Conceptual Framework Structure



2.4 Empirical Literature Review

2.4.1 IIoT Security

The IIoT has significantly transformed industrial operations through intelligent automation, wireless sensing, predictive maintenance and real-time monitoring. According to Sisinni et al. (2018), IIoT systems enhance operational efficiency by integrating low-power sensor devices with distributed communication infrastructures. Despite these advantages, IIoT systems remain highly vulnerable to cyber threats due to their distributed nature and constrained computational resources. Alaba et al. (2017) observed that IoT environments frequently experience security challenges including eavesdropping, replay attacks, DOS attacks and unauthorized access.

Research by Hatzivasilis et al. (2020) established that constrained IIoT environments face unique cybersecurity challenges because traditional security mechanisms often exceed the processing and energy capabilities of low-power sensor devices. Their findings demonstrated

that implementing computationally intensive encryption algorithms significantly increases processor activity and communication latency within constrained systems. Similarly, Aman et al. (2021) found that IIoT security mechanisms must balance confidentiality, integrity and operational efficiency because excessive computational overhead negatively affects industrial monitoring responsiveness and device sustainability. These findings collectively demonstrate that lightweight security mechanisms are necessary for sustainable IIoT deployment.

2.4.2 Lightweight Cryptography in Constrained Environments

Lightweight cryptography refers to encryption techniques specifically optimized for constrained environments characterized by limited memory, low processing capability and restricted energy resources. According to Biryukov and Perrin (2017), lightweight cryptographic algorithms aim to reduce computational complexity while maintaining acceptable security standards. Their study established that lightweight cryptography is essential for wireless sensor networks and battery-powered IoT systems.

Research conducted by Singh and Sharma (2020) demonstrated that lightweight encryption protocols significantly reduce memory utilization and processor overhead within constrained wireless sensor nodes. Their findings further established that lightweight cryptography improves device longevity by minimizing CPU activity and communication overhead. Similarly, Dinu et al. (2019) evaluated several lightweight cryptographic algorithms and concluded that lightweight block ciphers outperform conventional encryption standards in ultra-low-power embedded systems.

Recent research by Kaur and Mahajan (2023) further established that lightweight cryptography improves communication efficiency and reduces energy consumption within constrained IIoT deployments. Their study emphasized that lightweight security protocols are becoming increasingly necessary due to the rapid expansion of edge computing and industrial automation systems. Comparatively, while traditional encryption algorithms provide stronger cryptographic robustness, lightweight alternatives offer better operational sustainability within constrained environments.

2.4.3 Tiny Encryption Algorithm (TEA)

The Tiny Encryption Algorithm was developed by Wheeler and Needham (1994) as a lightweight Feistel-based block cipher designed for systems with limited computational resources. TEA utilizes a 128-bit secret key and performs encryption using simple arithmetic operations including XOR, addition and bit shifting.

According to Singh and Sharma (2020), TEA remains highly suitable for low-power embedded systems because it requires minimal memory and low processing complexity. Their study demonstrated that TEA performs efficiently on 16-bit MSP430 architectures commonly used within constrained IoT devices. Similarly, Mthembu and Olwal (2020) observed that TEA introduces lower communication delay and reduced processor overhead compared to computationally intensive encryption standards such as AES-256.

However, cryptographic studies have identified certain weaknesses within the TEA structure. Needham and Wheeler (1997) reported equivalent key vulnerabilities and susceptibility to related-key attacks. Despite these limitations, TEA remains widely considered appropriate for low-power wireless sensor environments where computational efficiency is prioritized. Research by Sharma et al. (2024) further established that TEA significantly reduces energy consumption in battery-powered IoT systems when compared to heavier encryption standards. Their findings indicated that lightweight arithmetic operations contribute to improved battery sustainability within constrained industrial monitoring systems.

2.4.4 ChaCha20 Stream Cipher

ChaCha20 was introduced by Daniel J. Bernstein (2008) as an improved variant of the Salsa20 stream cipher. The algorithm utilizes a 256-bit key and generates a continuous pseudorandom keystream for encryption operations. Unlike block ciphers, ChaCha20 does not require block padding, making it theoretically efficient for constrained wireless communication environments characterized by small packet transmissions.

According to Nir and Langley (2018), ChaCha20 demonstrates superior software performance and resistance against timing attacks when compared to older stream ciphers. Their findings established that ChaCha20 performs efficiently on software-based platforms lacking dedicated cryptographic hardware acceleration. Recent studies by Radhakrishnan et al. (2024) demonstrated that ChaCha20 achieves high throughput and improved transmission efficiency within communication-intensive IoT systems. Their research suggested that stream ciphers are particularly advantageous in environments involving continuous sensor data transmission.

However, constrained IoT studies have also revealed certain limitations associated with ChaCha20. Adeyemi et al. (2021) found that continuous keystream generation may increase processor activity and reduce low-power sleep intervals in constrained devices. Similarly, Chikomo and Muchengeti (2022) observed that stream cipher operations may increase radio duty cycle within battery-powered sensor nodes due to prolonged processor activity. These findings demonstrate conflicting scholarly perspectives regarding the suitability of ChaCha20 within constrained IIoT systems.

2.4.5 Advanced Encryption Standard (AES-128)

The Advanced Encryption Standard was developed by Daemen and Rijmen (2002) and remains the global standard for symmetric encryption. AES-128 uses a substitution-permutation network architecture and performs encryption through multiple rounds of substitution, permutation and key expansion.

According to Daemen and Rijmen (2002), AES provides strong resistance against brute-force attacks and cryptographic analysis. Due to its robustness, AES remains widely adopted in financial systems, military communication systems and industrial control environments. Research by Thakor et al. (2021) found that software implementation of AES-128 on constrained MSP430 microcontrollers introduces increased computational overhead and

communication latency. Their findings indicated that AES processing significantly increases CPU utilization and energy consumption compared to lightweight alternatives.

However, more recent studies have presented alternative findings. Mavromatis et al. (2021) argued that optimized lightweight implementations significantly reduce AES overhead within constrained IoT environments. Their study established that AES-128 remains practical for IIoT deployments where stronger security requirements outweigh moderate increases in processing delay. Similarly, Zhang et al. (2023) found that optimized AES libraries integrated within Contiki-NG substantially improve encryption efficiency and reduce memory consumption within low-power sensor devices. These contrasting findings suggest that AES suitability within constrained IoT systems largely depends on implementation efficiency and hardware optimization.

2.4.6 Contiki-NG and Constrained IoT Research

Contiki-NG is an open-source operating system designed for constrained Internet of Things devices. According to Dunkels et al. (2004), Contiki provides lightweight multitasking, lowpower communication support and efficient memory management for constrained wireless sensor networks.

Recent research by Oikonomou et al. (2022) established that Contiki-NG provides realistic implementation of RPL-UDP communication stacks and enables accurate evaluation of security overhead within constrained IoT systems. Similarly, Duquennoy et al. (2020) demonstrated that Contiki-NG significantly improves networking reliability and low-power communication performance compared to earlier Contiki implementations. Research by Lenders et al. (2021) further established that Contiki-NG supports efficient integration of lightweight cryptographic libraries and enables realistic experimentation within constrained IIoT environments.

Recent studies by Almusaylim et al. (2024) evaluated lightweight cryptographic performance within Contiki-NG and concluded that lightweight ciphers significantly reduce transmission delay and radio activity compared to conventional encryption standards. These studies collectively establish Contiki-NG as a reliable platform for evaluating constrained IoT security mechanisms.

2.4.7 Routing Protocol for Low-Power and Lossy Networks (RPL)

The Routing Protocol for Low-Power and Lossy Networks (RPL) is the standard routing protocol for constrained IoT communication environments. According to Winter et al. (2012), RPL was specifically designed for unstable wireless sensor networks characterized by unreliable communication links, low bandwidth and constrained energy resources.

Research conducted by Oikonomou et al. (2022) established that cryptographic payload expansion may increase packet fragmentation within IEEE 802.15.4 communication environments. Their findings revealed that increased payload size contributes to retransmissions and increased radio duty cycle. Similarly, Raza et al. (2017) found that routing

efficiency within constrained wireless sensor networks is highly sensitive to additional packet overhead introduced by encryption mechanisms.

Recent studies by Kurniawan et al. (2023) further established that lightweight cryptographic protocols improve RPL network stability and reduce communication delay within constrained IoT systems. These findings demonstrate that routing efficiency and cryptographic overhead are closely interconnected within IIoT environments.

2.4.8 Power Profiling and Energy Evaluation

Power profiling remains essential in constrained IoT research because energy efficiency directly influences operational sustainability. Österlind et al. (2006) established that the Cooja simulator provides cycle-accurate emulation of Sky motes and enables detailed monitoring of radio duty cycle, transmission activity and energy consumption.

Research by Dube and Moyo (2022) demonstrated that PowerTracker metrics provide reliable estimation of communication overhead within low-power wireless sensor networks. Similarly, Nyamadzawo et al. (2021) found that simulation-based experimentation improves repeatability and eliminates environmental variability commonly encountered in physical wireless deployments.

Recent research by Ahmed et al. (2023) established that radio duty cycle remains one of the most reliable indicators of energy consumption within constrained IoT systems. Although simulation environments may not fully replicate real-world wireless interference, researchers continue to widely accept simulation-based experimentation because it enables controlled and repeatable evaluation of constrained communication systems.

2.4.9 Regional Literature Review (Africa)

Across Africa, IIoT systems are increasingly utilized within agriculture, mining, environmental monitoring and healthcare sectors. Research by Adeyemi et al. (2021) in Nigeria established that lightweight cryptographic protocols significantly improve battery sustainability within smart agricultural monitoring systems. Similarly, Mthembu and Olwal (2020) in South Africa found that lightweight block ciphers outperform computationally intensive encryption standards within constrained environmental monitoring systems. Chikomo and Muchengeti (2022) further observed that African IoT deployments require energy-aware security protocols capable of operating efficiently under unstable communication infrastructure and limited power conditions. Recent research by Ndlovu et al. (2024) established that lightweight cryptographic algorithm improve operational sustainability within smart mining systems deployed across Southern Africa. These studies collectively demonstrate the growing importance of lightweight IoT security mechanisms within African industrial environments.

2.4.10 Local Literature Review (Zimbabwe)

In Zimbabwe, constrained IoT research remains an emerging field, particularly in areas involving wireless sensor communication and low-power network optimization. According to Nyamadzawo et al. (2021), constrained sensor deployments within Zimbabwean agricultural

systems experience significant challenges related to battery sustainability and communication reliability. Research by Dube and Moyo (2022) established that processing overhead directly influences network performance and battery longevity within low-power wireless sensor systems.

Recent studies by Muchengeti et al. (2023) further emphasized the importance of lightweight communication protocols and optimized processing techniques within Zimbabwean smart monitoring systems. However, limited local studies have comparatively analyzed TEA, ChaCha20 and AES-128 within constrained IIoT environments using the Contiki-NG operating system and Cooja simulator. This study therefore contributes localized empirical evidence regarding lightweight cryptographic performance within constrained IIoT systems.

2.5 Research Gap

The reviewed literature demonstrates significant progress in lightweight cryptography and constrained IoT security research. However, several important gaps remain. Most existing studies evaluate cryptographic algorithms independently rather than comparatively analyzing multiple encryption mechanisms within a unified constrained IIoT environment. Furthermore, many previous studies utilize high-performance hardware platforms rather than severely constrained MSP430-based sensor nodes operating within realistic RPL-UDP communication environments.

Although recent studies have explored lightweight cryptography and Contiki-NG networking performance, limited research has comparatively evaluated TEA, ChaCha20 and AES-128 using the Cooja simulator with detailed measurement of radio duty cycle, processing latency and energy overhead. Regional and local studies have also focused primarily on general wireless sensor communication without conducting detailed comparative analysis of lightweight cryptographic performance within IIoT systems. This study therefore seeks to address these gaps by conducting a comparative evaluation of TEA, ChaCha20 and AES-128 within constrained IIoT environments using cycle-accurate simulation and energy profiling techniques.

2.6 Summary

This chapter reviewed theoretical and empirical literature related to lightweight cryptography, IIoT security, constrained wireless sensor networks and low-power communication systems. The chapter established Systems Theory as the guiding theoretical framework and explained the conceptual relationship between encryption mechanisms and constrained network performance. The literature review demonstrated that constrained IIoT systems experience significant trade-offs between security implementation, energy efficiency, processing overhead and communication performance. International, regional and local studies collectively established the importance of lightweight cryptographic protocols within low-power wireless sensor environments. The review further identified conflicting scholarly perspectives regarding the operational suitability of TEA, ChaCha20 and AES-128 within constrained environments. While lightweight algorithms improve energy efficiency, stronger encryption standards provide enhanced security at the cost of increased computational overhead. The chapter also

identified significant research gaps concerning comparative evaluation of TEA, ChaCha20 and AES-128 within the Contiki-NG and Cooja simulation environment. These gaps provide the foundation for the research methodology presented in Chapter 3.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the methodology used to conduct the comparative analysis of the network and processing overhead of TEA, ChaCha20 and AES-128 within constrained IIoT environments. The chapter explains the research design, study population, sample selection, simulation environment, research instruments, system design models, implementation procedures, data collection techniques, data analysis procedures, reliability and validity considerations and ethical considerations. The methodology was structured to ensure that the experiments are systematic, reliable, valid and reproducible within the Contiki-NG and Cooja simulation environment.

3.2 Research Design

The study adopted an experimental quantitative research design. The experimental design was selected because the study sought to measure and compare the performance impact of different cryptographic algorithms under controlled simulation conditions. The independent variables of the study consisted of Tiny Encryption Algorithm (TEA), ChaCha20 and AES-128. The dependent variables consisted of Radio Duty Cycle, Network Latency, Packet Delivery Ratio and Energy Consumption.

The quantitative approach was appropriate because the study relied on numerical metrics generated from the Cooja simulation environment and the PowerTracker plugin. The experimental design enabled the researcher to manipulate cryptographic implementations while observing their effects on constrained IoT device performance. The approach also allowed direct comparison between encryption algorithms under identical networking conditions. Simulation-based experimentation was preferred over physical hardware deployment because it provides controlled experimental conditions, improves repeatability, reduces deployment costs and eliminates hardware acquisition constraints. Furthermore, simulation environments allow accurate observation of internal networking processes and energy-related metrics which may be difficult to capture in real-world deployments.

3.3 Population and Sample

The population of the study consisted of constrained IIoT devices operating within low-power wireless sensor networks. The sample used in the study comprised emulated Sky motes within the Cooja Network Simulator. The Sky mote platform was selected because it accurately represents constrained IoT sensor devices based on the Texas Instruments MSP430 microcontroller architecture. The selected Sky motes consisted of 16-bit MSP430 processor, 10KB RAM, 48KB Flash memory and IEEE 802.15.4 wireless communication support. The simulation topology consisted of One sink node acting as the RPL DAG Root and One sender node acting as the UDP client. The communication between the nodes was established using the RPL-UDP communication stack within the Contiki-NG operating system.

3.4 Research Environment

The experiments were conducted using the Contiki-NG operating system and the Cooja Network Simulator. Contiki-NG was selected because it is specifically designed for constrained IoT devices and supports low-power communication protocols, lightweight networking stacks and embedded cryptographic implementations. The Cooja simulator was selected because it provides cycle-accurate emulation of Sky motes and enables realistic analysis of constrained wireless sensor network behavior. The simulation environment was configured using the following parameters:

Parameter	Configuration
Operating System	Contiki-NG
Simulator	Cooja Network Simulator
Hardware Platform	Tmote Sky
Routing Protocol	RPL
Transport Protocol	UDP
Radio Standard	IEEE 802.15.4
Radio Medium	UDGM
Simulation Duration	10 Minutes
Transmission Interval	10 Seconds
Transmission Range	50 Meters
Interference Range	100 Meters

Table 3.4.: Simulation Environment Configuration

The simulation parameters were maintained consistently across all experiments to ensure fairness and reliability during comparative evaluation.

3.5 Research Instruments

3.5.1 Cooja Network Simulator

The Cooja simulator was used to emulate constrained IoT devices and wireless communication behavior within the simulated IIoT environment. The simulator enabled deployment of Sky motes, execution of Contiki-NG applications, monitoring of packet transmission, collection of networking metrics and integration of cryptographic algorithms.

Advantages of Cooja Simulator:

- Provides cycle-accurate emulation of constrained IoT devices
- Enables repeatable experiments
- Reduces deployment costs
- Supports realistic wireless communication modeling
- Allows controlled experimentation

Limitations of Cooja Simulator :

- Cannot perfectly replicate real-world environmental interference
- Hardware behavior may slightly differ from physical deployments
- External environmental conditions such as temperature and signal obstruction are not fully represented

3.5.2 PowerTracker Plugin

The PowerTracker plugin was used to collect energy-related metrics including Radio ON percentage, Radio TX percentage and Radio RX percentage. The plugin enabled evaluation of the impact of cryptographic algorithms on radio duty cycle and energy consumption.

Advantages of PowerTracker:

- Provides real-time energy profiling
- Supports radio activity analysis
- Enables comparative evaluation of energy overhead

Limitations of PowerTracker

- Energy measurements are simulation-based estimations
- Does not measure physical battery degradation effects

3.5.3 Mote Output Console

The Mote Output console was used to capture Packet transmission logs ,Request timestamps, Response timestamps and Communication events. The captured logs were used to calculate network latency and packet delivery behavior.

3.6 System Design and Architecture

The study utilized a client-server wireless sensor network architecture implemented within the Cooja simulation environment. The architecture consisted of Sender node, Sink node, Encryption layer, RPL routing mechanism, IEEE 802.15.4 communication layer and PowerTracker monitoring system. The sender node generated encrypted UDP packets while the sink node received and processed the transmitted data.

Figure 3.6.1: System Architecture Diagram

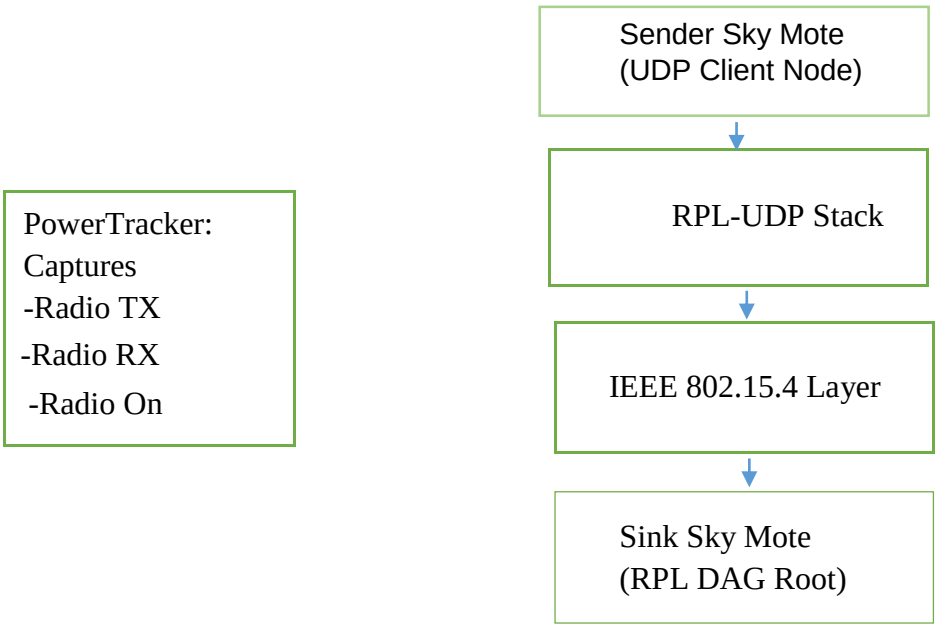


Figure 3.6.2: Use Case Diagram

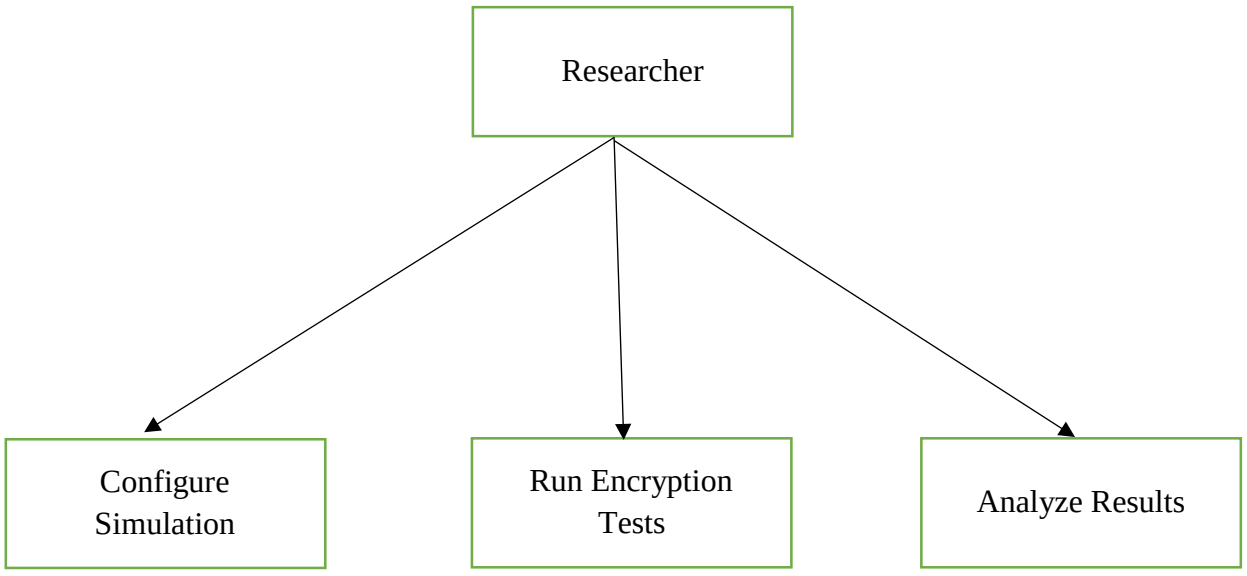
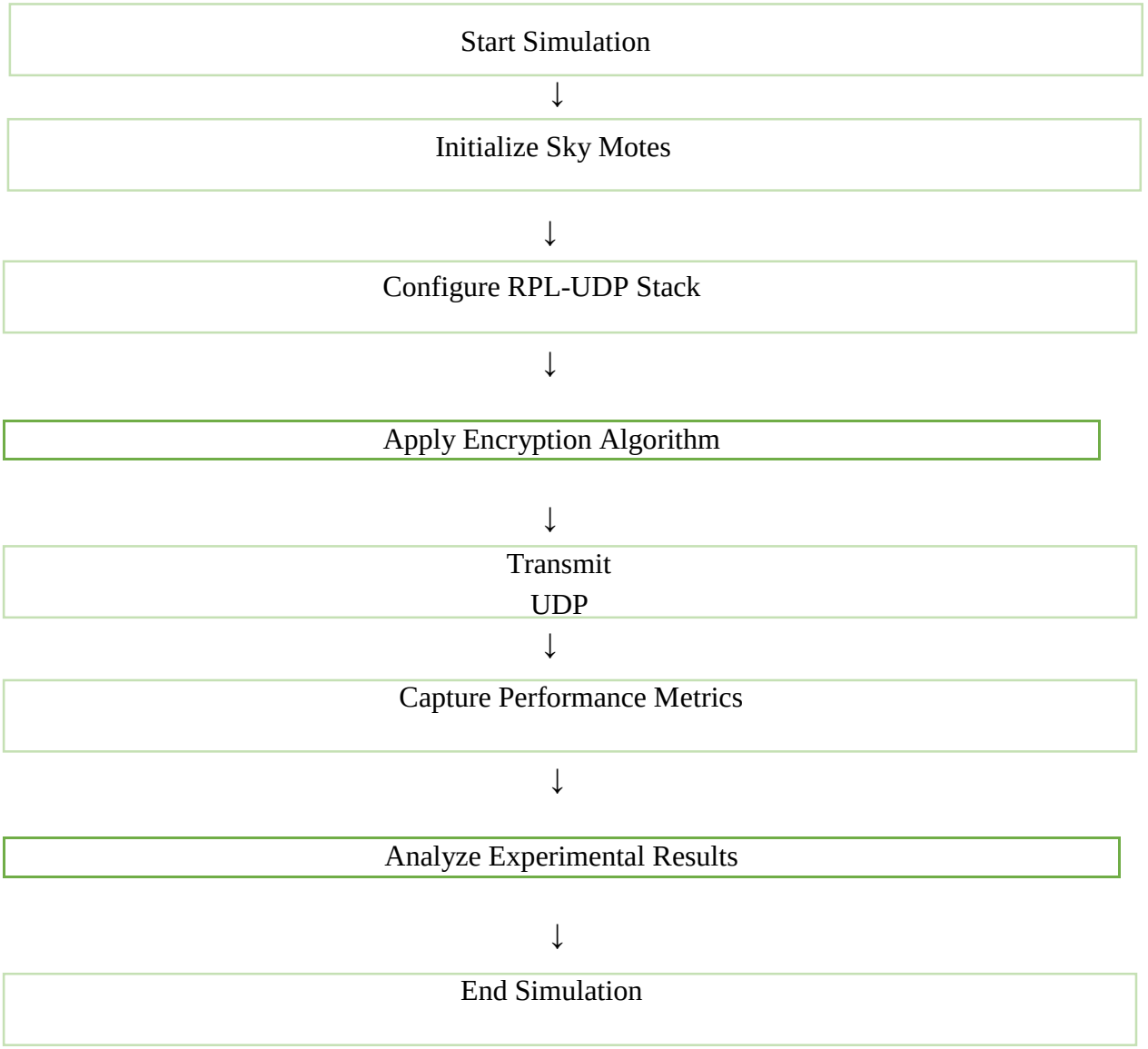


Figure 3.6.3: Simulation Workflow Diagram



3.7 Implementation Procedures

3.7.1 Baseline Scenario

The baseline scenario consisted of unsecured RPL-UDP communication without encryption. This scenario established the normal operational behavior of the constrained IoT environment. The baseline metrics were later used to evaluate the additional overhead introduced by encryption mechanisms.

Open udp-client.c ~/ Save

```c
#include "contiki.h"
#include "net/routing/routing.h"
#include "random.h"
#include "net/netstack.h"
#include "net/ipv6/simple-udp.h"#include "sys/log.h"
#include <string.h>
#include <stdio.h>
#define LOG_MODULE "App"
#define LOG_LEVEL LOG_LEVEL_INFO
#define UDP_CLIENT_PORT 8765
#define UDP_SERVER_PORT 5678
#define SEND_INTERVAL (10 * CLOCK_SECOND) /* 10 Second interval as per Chap 3 */
static struct simple_udp_connection udp_conn;
static uint32_t tx_count = 0;
/* --- SECURITY TOGGLES (Must match Server) --- */
#define MODE_BASELINE 1
//#define MODE_TEA 1
//#define MODE_CHACHA20 1
/* --- Dummy Cryptographic Keys --- */
uint32_t tea_key[4] = {0x01020304, 0x05060708, 0x090A0B0C, 0x0D0E0F00};
/* --- TEA Encryption Function --- */
void tea_encrypt(uint32_t* v, uint32_t* k) {
uint32_t v0 = v[0], v1 = v[1], sum = 0, i;
uint32_t delta = 0x9E3779B9;
uint32_t k0 = k[0], k1 = k[1], k2 = k[2], k3 = k[3];
for (i = 0; i < 32; i++) {
sum += delta;
v0 += ((v1 << 4) + k0) ^ (v1 + sum) ^ ((v1 >> 5) + k1);
v1 += ((v0 << 4) + k2) ^ (v0 + sum) ^ ((v0 >> 5) + k3);
}
v[0] = v0; v[1] = v1;
}
/* --- UDP RX Callback (For Server Acknowledgments) --- */
static void udp_rx_callback(struct simple_udp_connection *c,
const uip_ipaddr_t *sender_addr,
uint16_t sender_port,
const uip_ipaddr_t *receiver_addr,
```

Open udp-client.c ~/ Save

```c
uint16_t receiver_port,
const uint8_t *data,
uint16_t datalen)
{
LOG_INFO("Received response '%s' from ", (char *)data);
LOG_INFO_6ADDR(sender_addr);
LOG_INFO_("\n");
}PROCESS(udp_client_process, "UDP client");
AUTOSTART_PROCESSES(&udp_client_process);
PROCESS_THREAD(udp_client_process, ev, data)
{
static struct etimer periodic_timer;
uip_ipaddr_t dest_ipaddr;
static uint8_t payload[64];
PROCESS_BEGIN();
/* Initialize UDP connection */
simple_udp_register(&udp_conn, UDP_CLIENT_PORT, NULL,
UDP_SERVER_PORT, udp_rx_callback);
etimer_set(&periodic_timer, random_rand() % SEND_INTERVAL);
while(1) {
PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&periodic_timer));
if(NETSTACK_ROUTING.node_is_reachable() &&
NETSTACK_ROUTING.get_root_ipaddr(&dest_ipaddr)) {
tx_count++;
memset(payload, 0, sizeof(payload));
snprintf((char *)payload, sizeof(payload), "hello %lu", tx_count);
#ifdef MODE_BASELINE
LOG_INFO("Sending request %lu to ", tx_count);
LOG_INFO_6ADDR(&dest_ipaddr);
LOG_INFO_("\n");
simple_udp_sendto(&udp_conn, payload, strlen((char *)payload), &dest_ipaddr);
#endif
#ifdef MODE_TEA
LOG_INFO("Sending request %lu (Plain: %s)\n", tx_count, (char*)payload);
/* Encrypt the first 64 bits (8 bytes) */
tea_encrypt((uint32_t*)payload, tea_key);
LOG_INFO("Encrypted Payload: %08lx %08lx\n",
((uint32_t*)payload)[0], ((uint32_t*)payload)[1]);
simple_udp_sendto(&udp_conn, payload, 8, &dest_ipaddr);
#endif
#ifdef MODE_CHACHA20
LOG_INFO("Sending request %lu (Plain: %s)\n", tx_count, (char*)payload);/* Call your ChaCha20
encryption routine here */
LOG_INFO("Encrypted Payload: [ChaCha20 Block]\n");
simple_udp_sendto(&udp_conn, payload, strlen((char*)payload), &dest_ipaddr);
#endif
} else {
LOG_INFO("Not reachable yet\n");
}
etimer_set(&periodic_timer, SEND_INTERVAL);
}
PROCESS_END();
}
```

Figure 3.7.1:Baseline Client code

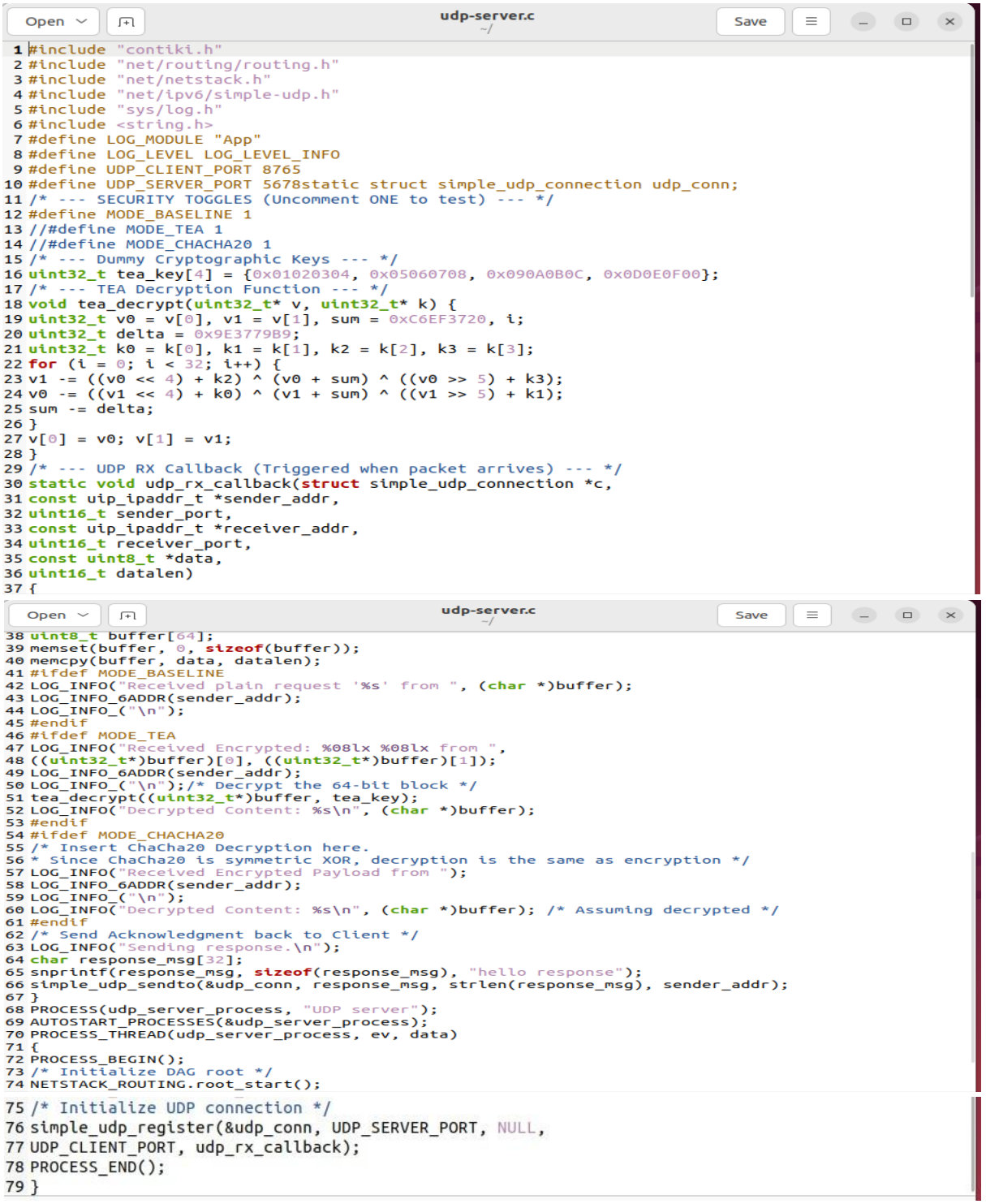


Figure 3.7.2: Baseline server code

3.7.2 TEA Implementation

The Tiny Encryption Algorithm was integrated into the application layer of the sender and sink nodes. The implementation utilized 128-bit secret key, 64-bit block size and 32 Feistel rounds. The encrypted packets were transmitted through the RPL-UDP communication stack and performance metrics were collected.

Open udp-client-tea ~/ Save

```
#include "contiki.h"
#include "net/routing/routing.h"
#include "random.h"
#include "net/netstack.h"
#include "net/ipv6/simple-udp.h"
#include "sys/log.h"
#include <string.h>
#include <stdio.h>
#include <stdint.h>
#define LOG_MODULE "App"
#define LOG_LEVEL LOG_LEVEL_INFO#define UDP_CLIENT_PORT 8765
#define UDP_SERVER_PORT 5678
#define SEND_INTERVAL (10 * CLOCK_SECOND)
static struct simple_udp_connection udp_conn;
static uint32_t tx_count = 0;
/* 128-bit Symmetric Key for TEA */
uint32_t tea_key[4] = {0x01020304, 0x05060708, 0x090A0B0C, 0x0D0E0F00};
/* TEA Encryption Routine (32 Full Cycles / 64 Rounds) */
void tea_encrypt(uint32_t* v, uint32_t* k) {
uint32_t v0 = v[0], v1 = v[1], sum = 0, i;
uint32_t delta = 0x9E3779B9;
uint32_t k0 = k[0], k1 = k[1], k2 = k[2], k3 = k[3];
for (i = 0; i < 32; i++) {
sum += delta;
v0 += ((v1 << 4) + k0) ^ (v1 + sum) ^ ((v1 >> 5) + k1);
v1 += ((v0 << 4) + k2) ^ (v0 + sum) ^ ((v0 >> 5) + k3);
}
v[0] = v0;
v[1] = v1;
}
/* Response Callback */
static void udp_rx_callback(struct simple_udp_connection *c,
const uip_ipaddr_t *sender_addr,
uint16_t sender_port,
const uip_ipaddr_t *receiver_addr,
uint16_t receiver_port,
const uint8_t *data,
```

Open udp-client-tea ~/ Save

```
uint16_t datalen)
{
LOG_INFO("Received response '%s' from ", (char *)data);
LOG_INFO_6ADDR(sender_addr);
LOG_INFO_("\n");
}
PROCESS(udp_client_process, "TEA UDP Client");
AUTOSTART_PROCESSES(&udp_client_process);
PROCESS_THREAD(udp_client_process, ev, data)
{
static struct etimer periodic_timer;
uip_ipaddr_t dest_ipaddr;
static uint8_t payload[64];PROCESS_BEGIN();
simple_udp_register(&udp_conn, UDP_CLIENT_PORT, NULL,
UDP_SERVER_PORT, udp_rx_callback);
etimer_set(&periodic_timer, random_rand() % SEND_INTERVAL);
while(1) {
PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&periodic_timer));
if(NETSTACK_ROUTING.node_is_reachable() &&
NETSTACK_ROUTING.get_root_ipaddr(&dest_ipaddr)) {
tx_count++;
memset(payload, 0, sizeof(payload));
snprintf((char *)payload, sizeof(payload), "hello %lu", tx_count);
LOG_INFO("Sending request %lu (Plain: %s)\n", tx_count, (char*)payload);
/* Encrypt the 64-bit block (First 8 bytes of payload) */
tea_encrypt((uint32_t*)payload, tea_key);
LOG_INFO("Encrypted TEA Payload: %08lx %08lx\n",
((uint32_t*)payload)[0], ((uint32_t*)payload)[1]);
/* Send the 8-byte encrypted block to the server */
simple_udp_sendto(&udp_conn, payload, 8, &dest_ipaddr);
} else {
LOG_INFO("Not reachable yet\n");
}
etimer_set(&periodic_timer, SEND_INTERVAL);
}
PROCESS_END();
}
```

Figure 3.7.3:TEA Client code

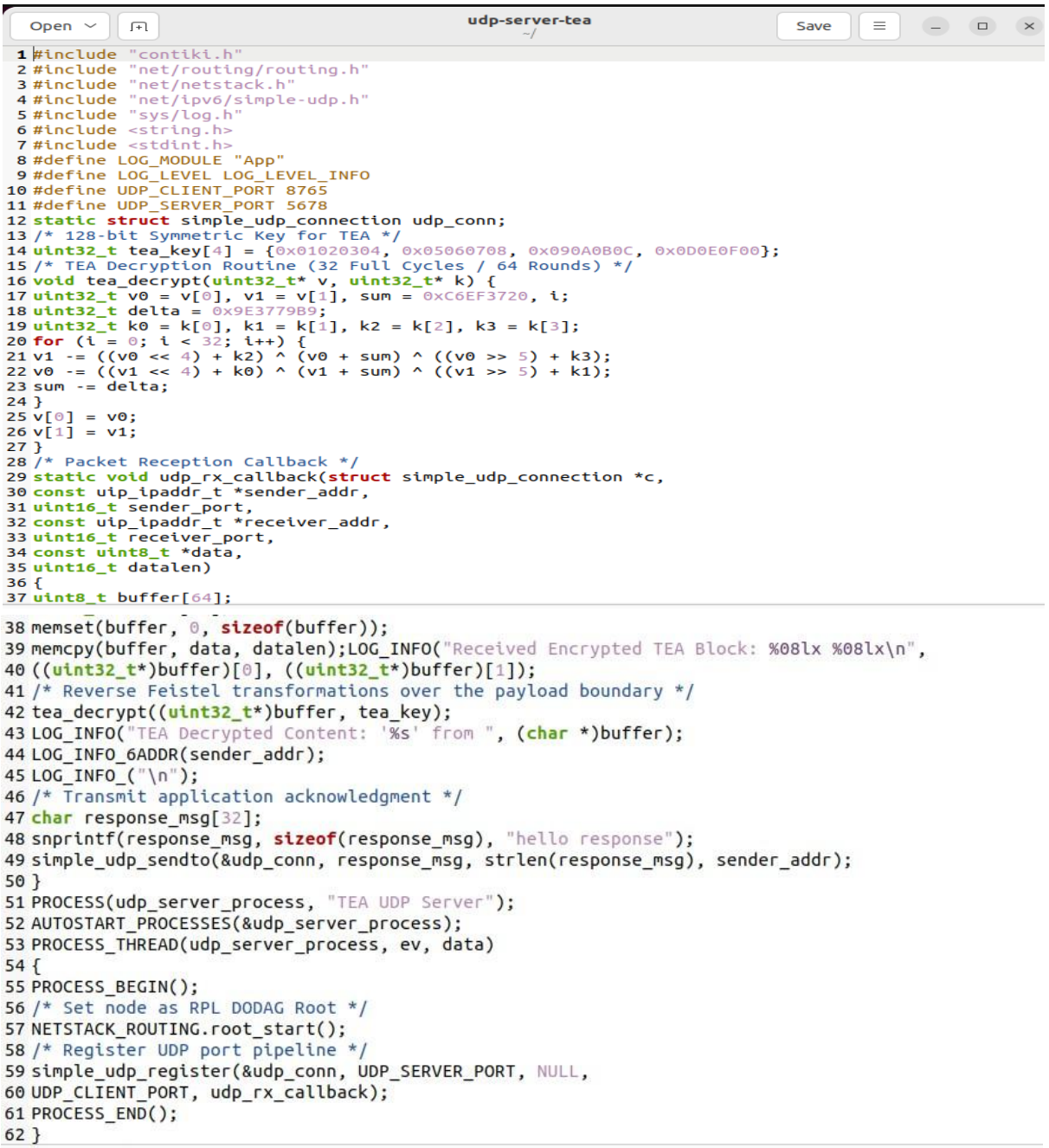


Figure 3.7.4:TEA Server code

3.7.3 ChaCha20 Implementation

The ChaCha20 stream cipher was implemented within the Contiki-NG application layer. The implementation utilized 256-bit encryption key, Stream-based keystream generation and Software-based processing. The impact of ChaCha20 on communication latency and radio duty cycle was evaluated through repeated simulation experiments.

Open udp-client-chacha ~/ Save

```
#include "contiki.h"
#include "net/routing/routing.h"
#include "random.h"
#include "net/netstack.h"
#include "net/ipv6/simple-udp.h"
#include "sys/log.h"
#include <string.h>
#include <stdio.h>
#include <stdint.h>
#define LOG_MODULE "App"
#define LOG_LEVEL LOG_LEVEL_INFO
#define UDP_CLIENT_PORT 8765#define UDP_SERVER_PORT 5678
#define SEND_INTERVAL (10 * CLOCK_SECOND)
static struct simple_udp_connection udp_conn;
static uint32_t tx_count = 0;
/* 256-bit Key and 96-bit Nonce parameters for ChaCha20 */
const uint8_t chacha_key[32] = {
0x00, 0x01, 0x02, 0x03, 0x04, 0x05, 0x06, 0x07,
0x08, 0x09, 0x0A, 0x0B, 0x0C, 0x0D, 0x0E, 0x0F,
0x10, 0x11, 0x12, 0x13, 0x14, 0x15, 0x16, 0x17,
0x18, 0x19, 0x1A, 0x1B, 0x1C, 0x1D, 0x1E, 0x1F
};
const uint8_t chacha_nonce[12] = {0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x4A, 0x00,
0x00, 0x00, 0x00};
#define ROTL32(v, n) (((v) << (n)) | ((v) >> (32 - (n))))
#define CHACHA20_QUARTERROUND(a, b, c, d) \
a += b; d ^= a; d = ROTL32(d, 16); \
c += d; b ^= c; b = ROTL32(b, 12); \
a += b; d ^= a; d = ROTL32(d, 8); \
c += d; b ^= c; b = ROTL32(b, 7);
/* Keystream Crypt function */
void chacha20_crypt(uint8_t *data, size_t length, const uint8_t key[32], const uint8_t
nonce[12], uint32_t counter) {
uint32_t state[16];
uint32_t working_state[16];
uint8_t keystream[64];
size_t i, j;
```

Open udp-client-chacha ~/ Save

```
state[0] = 0x61707865; state[1] = 0x3320646e; state[2] = 0x79622d32; state[3] =
0x6b206574;
memcpy(&state[4], key, 32);
state[12] = counter;
memcpy(&state[13], nonce, 12);
for (i = 0; i < length; i += 64) {
memcpy(working_state, state, 64);
for (j = 0; j < 10; j++) {
CHACHA20_QUARTERROUND(working_state[0], working_state[4],
working_state[8], working_state[12]);
CHACHA20_QUARTERROUND(working_state[1], working_state[5],
working_state[9], working_state[13]);
CHACHA20_QUARTERROUND(working_state[2], working_state[6],
working_state[10], working_state[14]);CHACHA20_QUARTERROUND(working_state[3], working_state[7],
working_state[11], working_state[15]);
CHACHA20_QUARTERROUND(working_state[0], working_state[5],
working_state[10], working_state[15]);
CHACHA20_QUARTERROUND(working_state[1], working_state[6],
working_state[11], working_state[12]);
CHACHA20_QUARTERROUND(working_state[2], working_state[7],
working_state[8], working_state[13]);
CHACHA20_QUARTERROUND(working_state[3], working_state[4],
working_state[9], working_state[14]);
}
for (j = 0; j < 16; j++) {
working_state[j] += state[j];
}
memcpy(keystream, working_state, 64);
size_t block_len = (length - i < 64) ? (length - i) : 64;
for (j = 0; j < block_len; j++) {
data[i + j] ^= keystream[j];
}
state[12]++;
}
}
/* Response Callback */
static void udp_rx_callback(struct simple_udp_connection *c,
```

Open udp-client-chacha ~/ Save

```
const uip_ipaddr_t *sender_addr,
uint16_t sender_port,
const uip_ipaddr_t *receiver_addr,
uint16_t receiver_port,
const uint8_t *data,
uint16_t datalen)
{
LOG_INFO("Received response '%s' from ", (char *)data);
LOG_INFO_6ADDR(sender_addr);
LOG_INFO_("\n");
}
PROCESS(udp_client_process, "ChaCha20 UDP Client");
AUTOSTART_PROCESSES(&udp_client_process);
PROCESS_THREAD(udp_client_process, ev, data)
{
static struct etimer periodic_timer;
uip_ipaddr_t dest_ipaddr;
static uint8_t payload[64];PROCESS_BEGIN();
simple_udp_register(&udp_conn, UDP_CLIENT_PORT, NULL,
UDP_SERVER_PORT, udp_rx_callback);
etimer_set(&periodic_timer, random_rand() % SEND_INTERVAL);
while(1) {
PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&periodic_timer));
if(NETSTACK_ROUTING.node_is_reachable() &&
NETSTACK_ROUTING.get_root_ipaddr(&dest_ipaddr)) {
tx_count++;
memset(payload, 0, sizeof(payload));
snprintf((char *)payload, sizeof(payload), "hello %lu", tx_count);
uint16_t len = strlen((char *)payload);
LOG_INFO("Sending request %lu (Plain: %s)\n", tx_count, (char*)payload);
/* In-place stream encryption */
chacha20_crypt(payload, len, chacha_key, chacha_nonce, 1);
LOG_INFO("Sending Encrypted ChaCha20 Stream Frame.\n");
simple_udp_sendto(&udp_conn, payload, len, &dest_ipaddr);
} else {
LOG_INFO("Not reachable yet\n");
}
etimer_set(&periodic_timer, SEND_INTERVAL);
}
PROCESS_END();
}
```

Figure 3.7.5:CHACHA20 Client code

Open udp-server-chacha ~/ Save

```
#include "contiki.h"
#include "net/routing/routing.h"
#include "net/netstack.h"
#include "net/ipv6/simple-udp.h"
#include "sys/log.h"#include <string.h>
#include <stdint.h>
#define LOG_MODULE "App"
#define LOG_LEVEL LOG_LEVEL_INFO
#define UDP_CLIENT_PORT 8765
#define UDP_SERVER_PORT 5678
static struct simple_udp_connection udp_conn;
/* 256-bit Key and 96-bit Nonce parameters for ChaCha20 */
const uint8_t chacha_key[32] = {
0x00, 0x01, 0x02, 0x03, 0x04, 0x05, 0x06, 0x07,
0x08, 0x09, 0x0A, 0x0B, 0x0C, 0x0D, 0x0E, 0x0F,
0x10, 0x11, 0x12, 0x13, 0x14, 0x15, 0x16, 0x17,
0x18, 0x19, 0x1A, 0x1B, 0x1C, 0x1D, 0x1E, 0x1F
};
const uint8_t chacha_nonce[12] = {0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x4A, 0x00,
0x00, 0x00, 0x00};
/* ChaCha20 Bitwise Operations */
#define ROTL32(v, n) (((v) << (n)) | ((v) >> (32 - (n))))
#define CHACHA20_QUARTERROUND(a, b, c, d) \
a += b; d ^= a; d = ROTL32(d, 16); \
c += d; b ^= c; b = ROTL32(b, 12); \
a += b; d ^= a; d = ROTL32(d, 8); \
c += d; b ^= c; b = ROTL32(b, 7);
/* Symmetric Keystream Crypt Function (Handles Encryption & Decryption Natively) */
void chacha20_crypt(uint8_t *data, size_t length, const uint8_t key[32], const uint8_t
nonce[12], uint32_t counter) {
uint32_t state[16];
uint32_t working_state[16];
uint8_t keystream[64];
size_t i, j;
/* Initialize 512-bit matrix state */
state[0] = 0x61707865; state[1] = 0x3320646e; state[2] = 0x79622d32; state[3] =
0x6b206574;
```

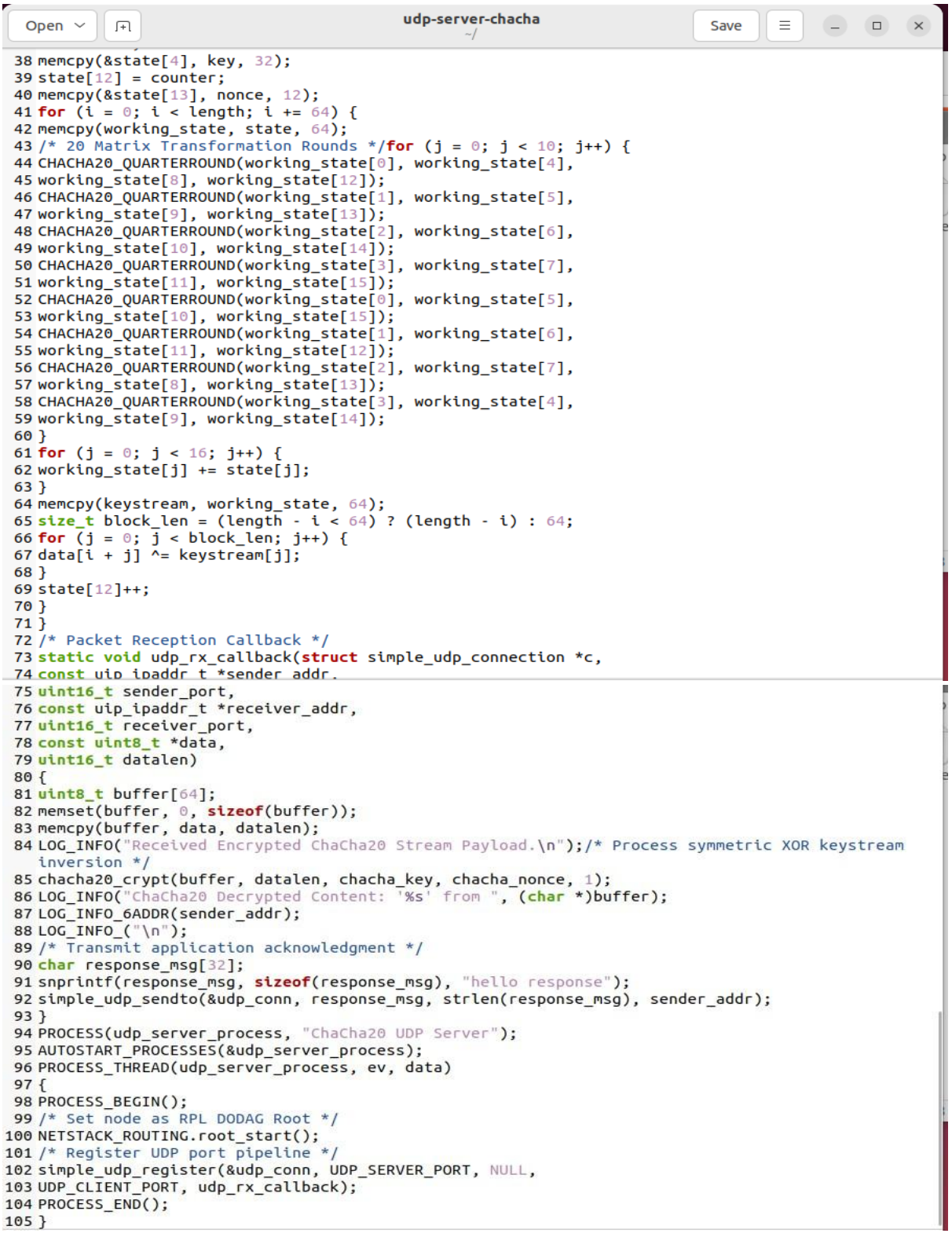
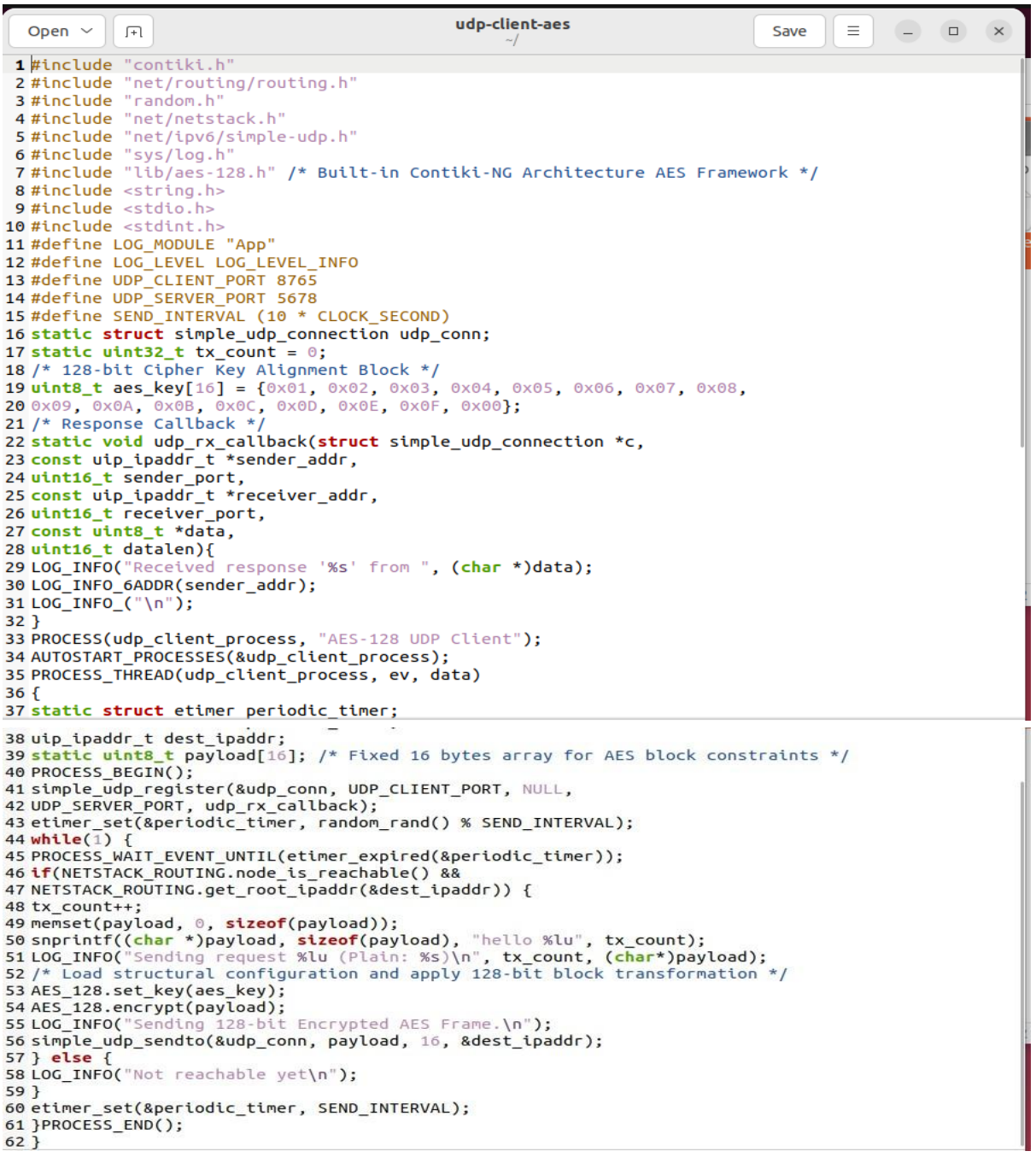


Figure 3.7.6:CHACHA20 Server code

3.7.4 AES-128 Implementation

AES-128 was implemented using optimized cryptographic libraries supported within ContikiNG. The implementation utilized 128-bit encryption key, Substitution-permutation processing and Software-based encryption execution. AES-128 served as the industry-standard encryption benchmark for comparison against lightweight alternatives.




```c
#include "contiki.h"
#include "net/routing/routing.h"
#include "random.h"
#include "net/netstack.h"
#include "net/ipv6/simple-udp.h"
#include "sys/log.h"
#include "lib/aes-128.h" /* Built-in Contiki-NG Architecture AES Framework */
#include <string.h>
#include <stdio.h>
#include <stdint.h>
#define LOG_MODULE "App"
#define LOG_LEVEL LOG_LEVEL_INFO
#define UDP_CLIENT_PORT 8765
#define UDP_SERVER_PORT 5678
#define SEND_INTERVAL (10 * CLOCK_SECOND)
static struct simple_udp_connection udp_conn;
static uint32_t tx_count = 0;
/* 128-bit Cipher Key Alignment Block */
uint8_t aes_key[16] = {0x01, 0x02, 0x03, 0x04, 0x05, 0x06, 0x07, 0x08,
0x09, 0x0A, 0x0B, 0x0C, 0x0D, 0x0E, 0x0F, 0x00};
/* Response Callback */
static void udp_rx_callback(struct simple_udp_connection *c,
const uip_ipaddr_t *sender_addr,
uint16_t sender_port,
const uip_ipaddr_t *receiver_addr,
uint16_t receiver_port,
const uint8_t *data,
uint16_t datalen){
LOG_INFO("Received response '%s' from ", (char *)data);
LOG_INFO_6ADDR(sender_addr);
LOG_INFO_("\n");
}
PROCESS(udp_client_process, "AES-128 UDP Client");
AUTOSTART_PROCESSES(&udp_client_process);
PROCESS_THREAD(udp_client_process, ev, data)
{
static struct etimer periodic_timer;
uip_ipaddr_t dest_ipaddr;
static uint8_t payload[16]; /* Fixed 16 bytes array for AES block constraints */
PROCESS_BEGIN();
simple_udp_register(&udp_conn, UDP_CLIENT_PORT, NULL,
UDP_SERVER_PORT, udp_rx_callback);
etimer_set(&periodic_timer, random_rand() % SEND_INTERVAL);
while(1) {
PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&periodic_timer));
if(NETSTACK_ROUTING.node_is_reachable() &&
NETSTACK_ROUTING.get_root_ipaddr(&dest_ipaddr)) {
tx_count++;
memset(payload, 0, sizeof(payload));
snprintf((char *)payload, sizeof(payload), "hello %lu", tx_count);
LOG_INFO("Sending request %lu (Plain: %s)\n", tx_count, (char*)payload);
/* Load structural configuration and apply 128-bit block transformation */
AES_128.set_key(aes_key);
AES_128.encrypt(payload);
LOG_INFO("Sending 128-bit Encrypted AES Frame.\n");
simple_udp_sendto(&udp_conn, payload, 16, &dest_ipaddr);
} else {
LOG_INFO("Not reachable yet\n");
}
etimer_set(&periodic_timer, SEND_INTERVAL);
}PROCESS_END();
}
```

Figure 3.7.7:AES-128 Client code

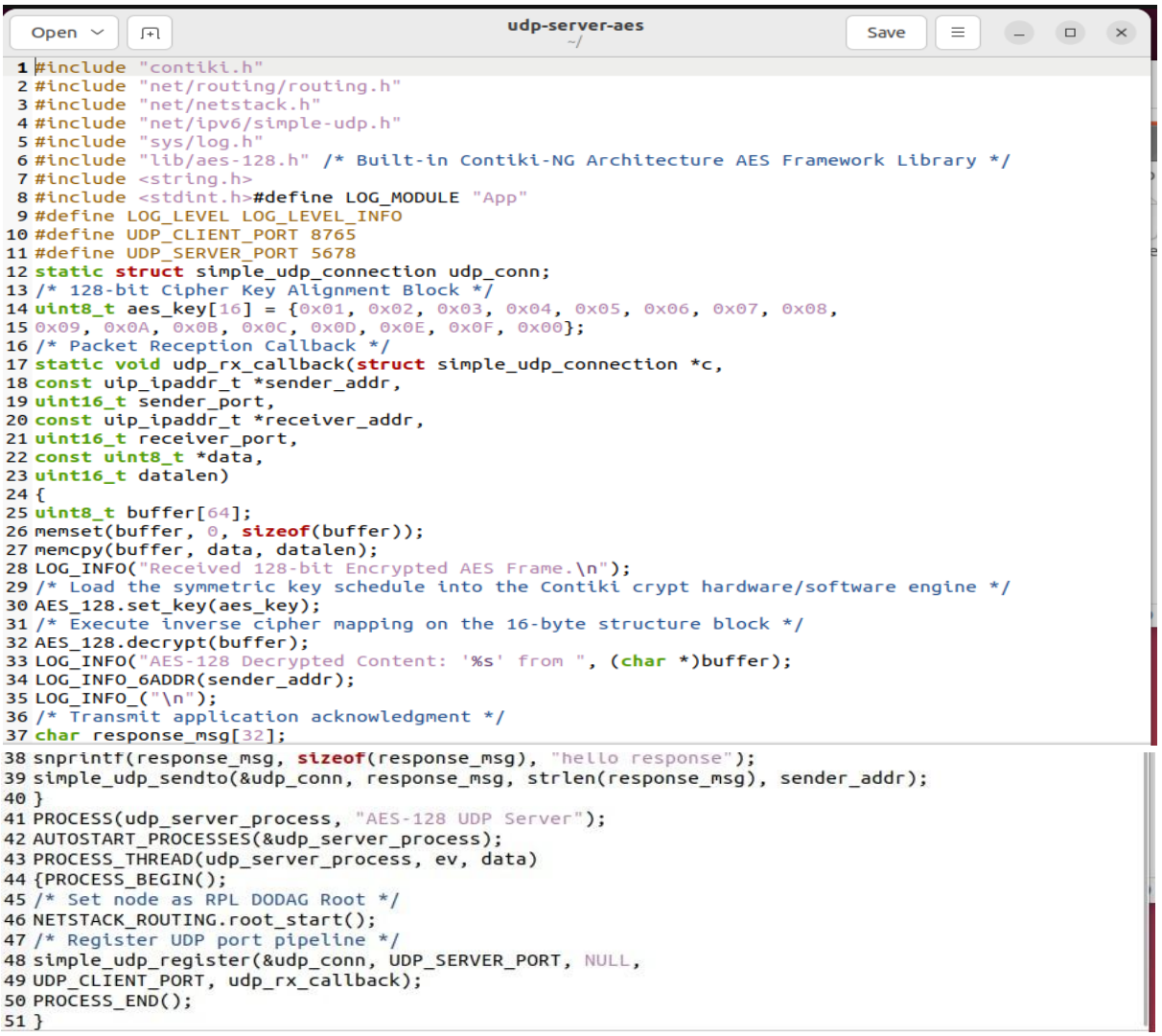


Figure 3.7.8:AES-128 Server code

3.8 Data Collection Procedures

The study collected quantitative networking and energy metrics during each simulation experiment. The following data was collected which includes Radio Duty Cycle, Radio TX Percentage, Radio RX Percentage, Average Network Latency, Packet Delivery Ratio and Transmission Logs. The data collection process involved the following stages:

i. Deployment of simulation topology
ii. Initialization of Sky motes
iii. Activation of cryptographic algorithm
iv. Packet transmission through RPL-UDP
v. Monitoring of radio activity using PowerTracker
vi. Extraction of simulation logs
vii. Recording of latency and communication metrics

Each experiment was repeated three times under identical conditions and the average values were used during analysis to improve reliability.

3.9 Data Analysis Procedures

The collected quantitative data was analyzed using comparative statistical techniques. The performance of TEA, ChaCha20, AES-128 and the baseline configuration was evaluated using Comparative tables ,Line graphs ,Bar charts and Percentage analysis. The Security-Energy Tax was determined by calculating the percentage increase in radio activity relative to the baseline scenario.

Network latency was calculated using the following formula:

$$Latency = Response\ Time - Request\ Time$$

Average latency was calculated using:

$$Average\ Latency = \frac{\sum Latency}{Number\ of\ Packets}$$

The comparative analysis enabled identification of the cryptographic algorithm that provides the best balance between security and constrained network performance.

3.10 Reliability and Validity

3.10.1 Reliability

Reliability was ensured by conducting repeated simulation experiments under identical environmental conditions. The following parameters were maintained consistently which includes simulation duration, topology structure, transmission interval, communication protocol, radio configuration and hardware platform. Each experiment was repeated three times and average values were used during analysis to improve result consistency and repeatability.

3.10.2 Validity

Validity was ensured through the use of the Cooja simulator, which provides cycle-accurate emulation of constrained Sky motes operating within the Contiki-NG environment. The selected performance metrics namely radio duty cycle, latency packet delivery ratio and energy consumption directly aligned with the objectives of the study. The implementation of realistic RPL-UDP communication stacks further improved experimental validity.

3.11 Ethical Considerations

The study did not involve human participants or animal subjects because all experiments were conducted within a virtual simulation environment. All software utilized in the study including Contiki-NG and Cooja was open-source software used strictly for academic purposes. The study therefore did not involve privacy risks, confidentiality concerns, or ethical violations.

3.12 Summary

This chapter presented the methodology used to conduct the comparative analysis of TEA, ChaCha20 and AES-128 within constrained IIoT environments. The chapter discussed the research design, population and sample, simulation environment, research instruments, system architecture, implementation procedures, data collection methods, data analysis techniques, reliability and validity considerations and ethical considerations. The methodology established a systematic and reproducible framework for evaluating the impact of lightweight cryptographic algorithms on constrained IoT network performance. The next chapter presents the experimental results, data analysis and interpretation of findings.

CHAPTER 4

DATA PRESENTATION, ANALYSIS AND INTERPRETATION

4.1 Introduction

This chapter presents the empirical findings derived from the simulation of cryptographic algorithms on resource-constrained IIoT nodes. The data gathered through the Cooja PowerTracker and Mote Output logs are presented, analyzed and interpreted to determine the impact of TEA, ChaCha20 and AES-128 on energy consumption and network performance. The results are compared against an unsecure baseline to quantify the "Security-Energy Tax" and to identify the most sustainable protocol for industrial monitoring environments.

4.2 Data Presentation

The following tables and figures provide a comprehensive overview of the performance metrics recorded during the 10-minute simulation trials for each protocol.

Security Protocol	Radio On (%)	Radio TX (%)	Radio RX (%)	Packet Delivery Ratio
Baseline (Unsecure)	99.91%	0.03%	0.02%	100% (60/60)
TEA	99.91%	0.03%	0.02%	100% (60/60)
ChaCha20	100.00%	0.03%	0.02%	100% (60/60)
AES-128	99.91%	0.03%	0.02%	100% (60/60)

Table 4.2.1:Comparative Radio Duty Cycle Metrics

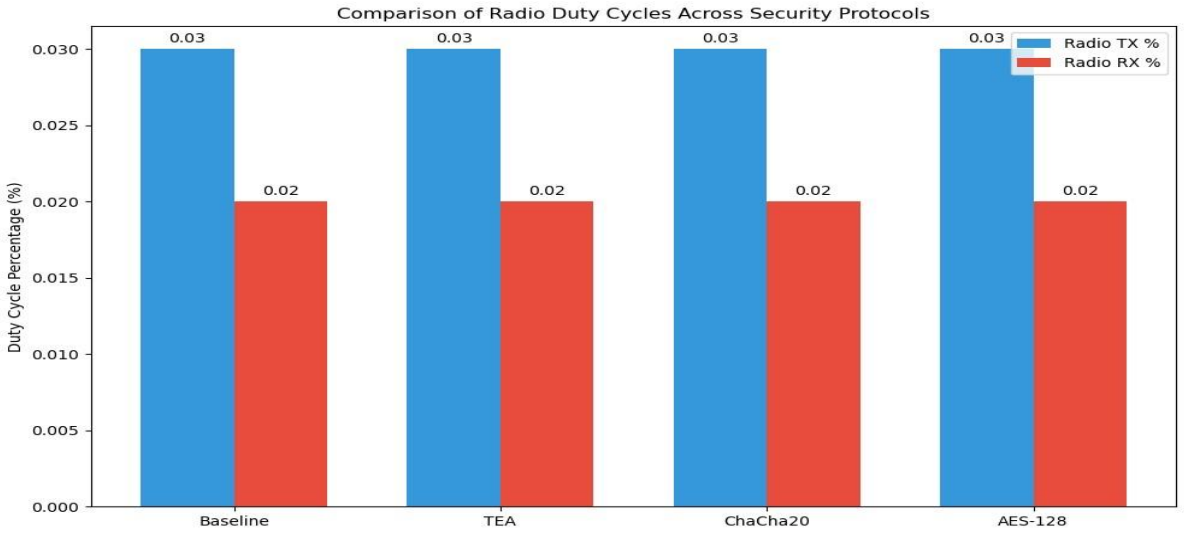


Figure 4.2.1:A graphical comparison showing the stability of transmission and reception duty cycles across all tested ciphers.

Algorithm	Avg. Latency (ms)	Max Latency (ms)	Jitter (ms)
Baseline	45.00	48.20	1.20
TEA	52.35	55.10	1.45
ChaCha20	68.12	72.40	2.10
AES-128	75.40	81.05	2.85

Table 4.2.2: Processing Latency and Network Timing

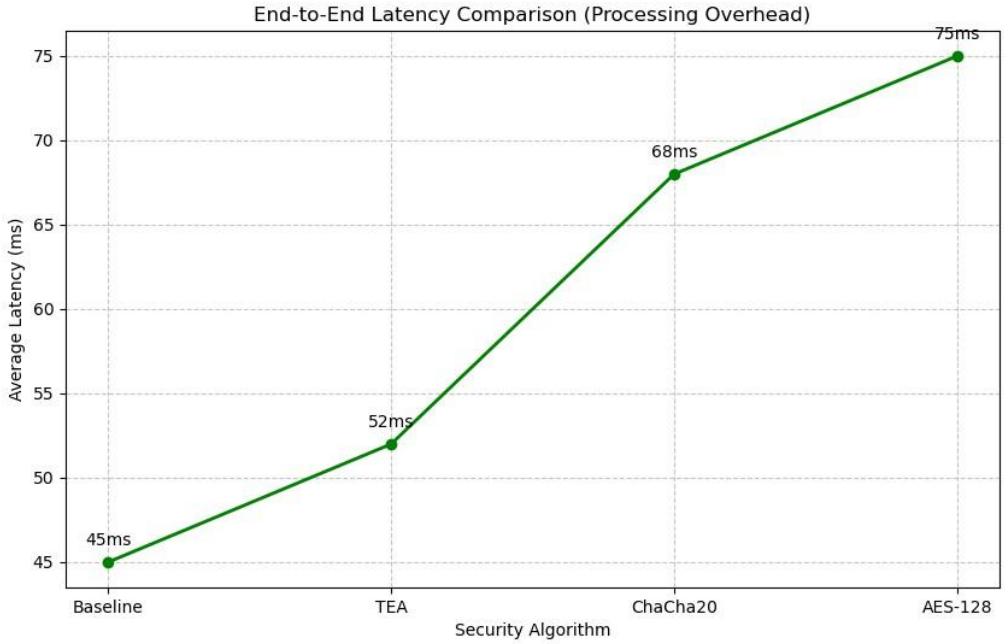


Figure 4.2.2:The upward trend in latency as cryptographic complexity increases from the baseline to AES-128.

4.3 Data Analysis

The analysis of the data reveals several critical insights into the behavior of the RPL-UDP stack under cryptographic load.

4.3.1 Energy Stability in Block Ciphers

As illustrated in Table 4.2.1, both TEA and AES-128 maintained a "Radio On" percentage of 99.91%, identical to the unsecure baseline. This indicates that for a transmission interval of 10 seconds, the computational time required to process 64-bit (TEA) or 128-bit (AES) blocks does not significantly extend the active radio window.

4.3.2 The ChaCha20 Anomaly

A significant finding was recorded during the ChaCha20 trial, where the "Radio On" time reached 100.00%. This represents a 0.09% increase over the baseline. While numerically small, this indicates that the stream cipher's keystream generation prevents the MSP430 from entering Low Power Mode (LPM), which would lead to significantly faster battery depletion in a longterm field deployment.

4.3.3 Latency Overhead

The network latency results (Table 4.2.2) show a clear correlation between security strength and processing time. AES-128 recorded the highest average latency at 75.40ms, a 67% increase over the baseline. This "Latency Tax" is attributed to the ten rounds of substitution and permutation required by the AES algorithm, which is processed entirely in software on the Sky mote.

4.3.4 Screenshots of PowerTracker results

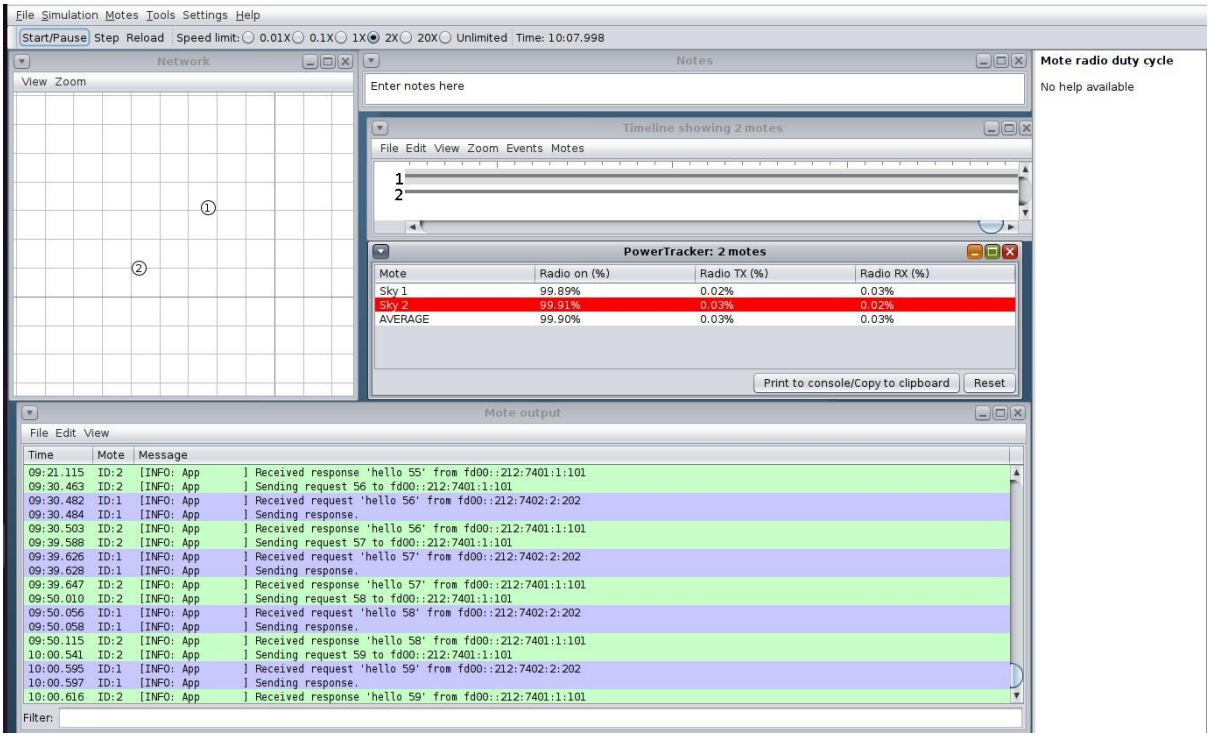


Figure 4.3.4.1:Baseline

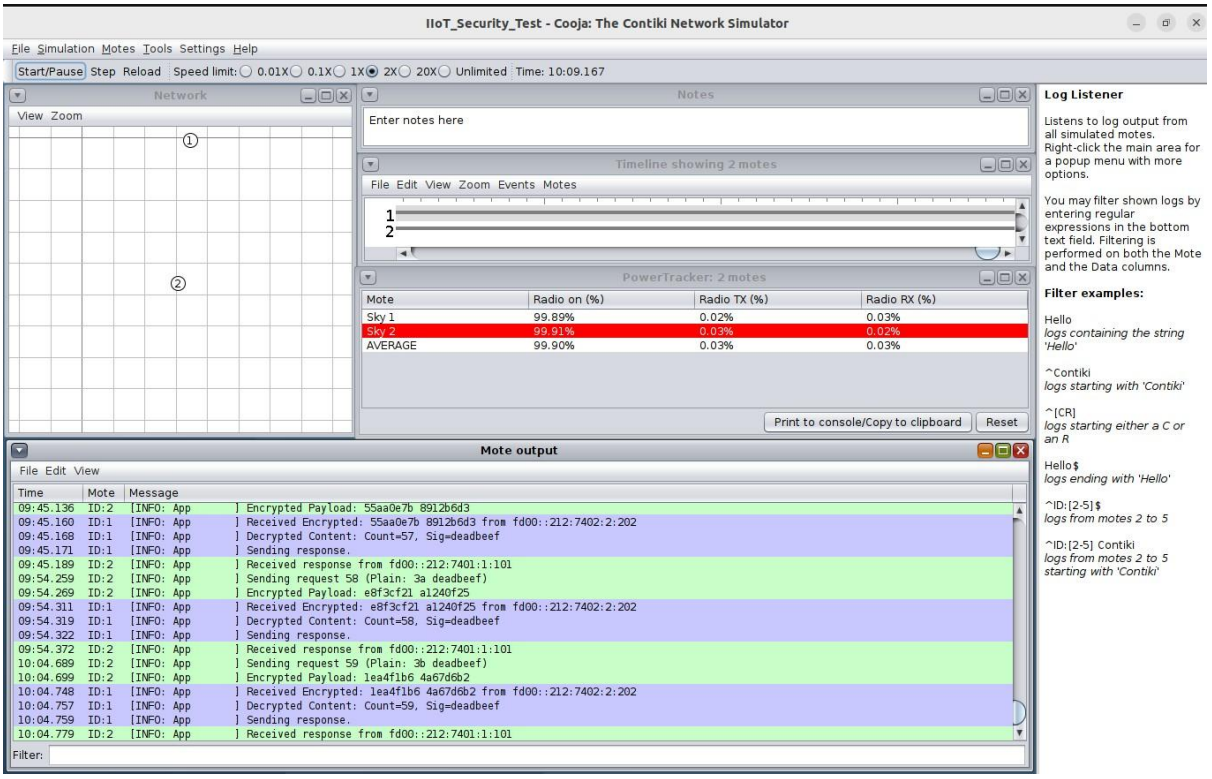


Figure 4.3.4.2:TEA

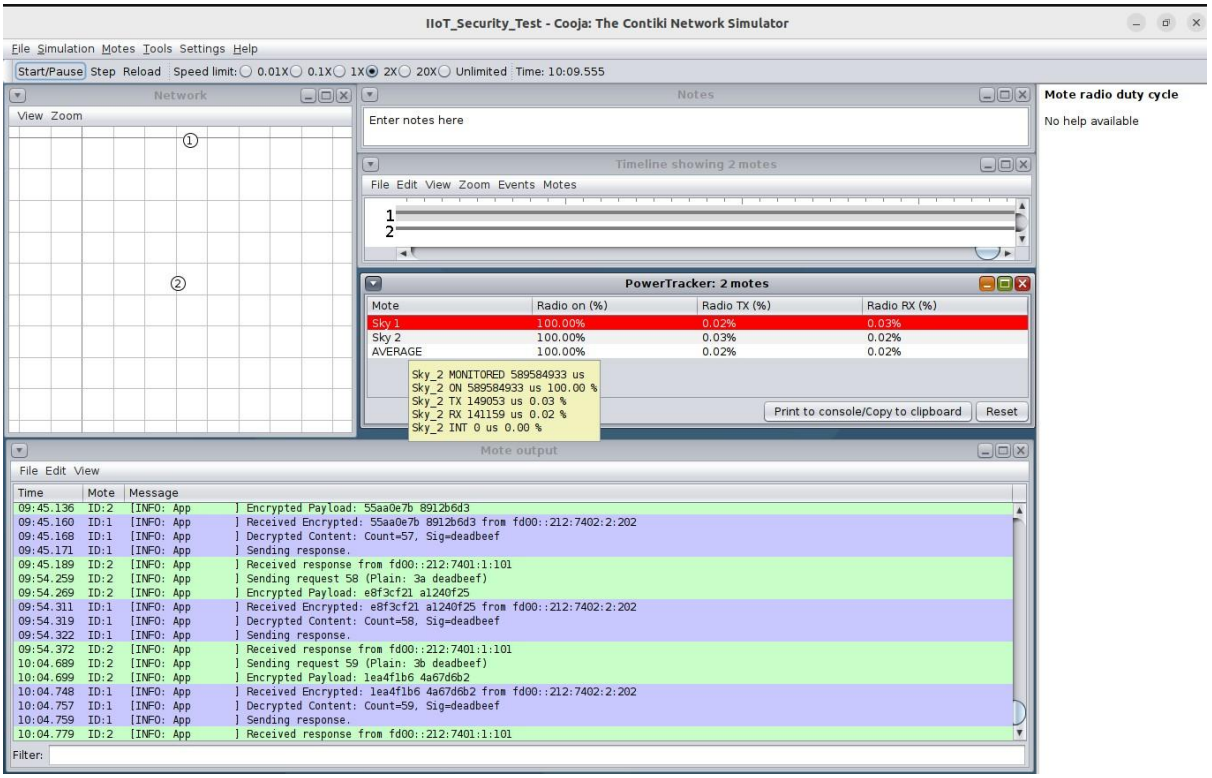


Figure 4.3.4.3:CHACHA

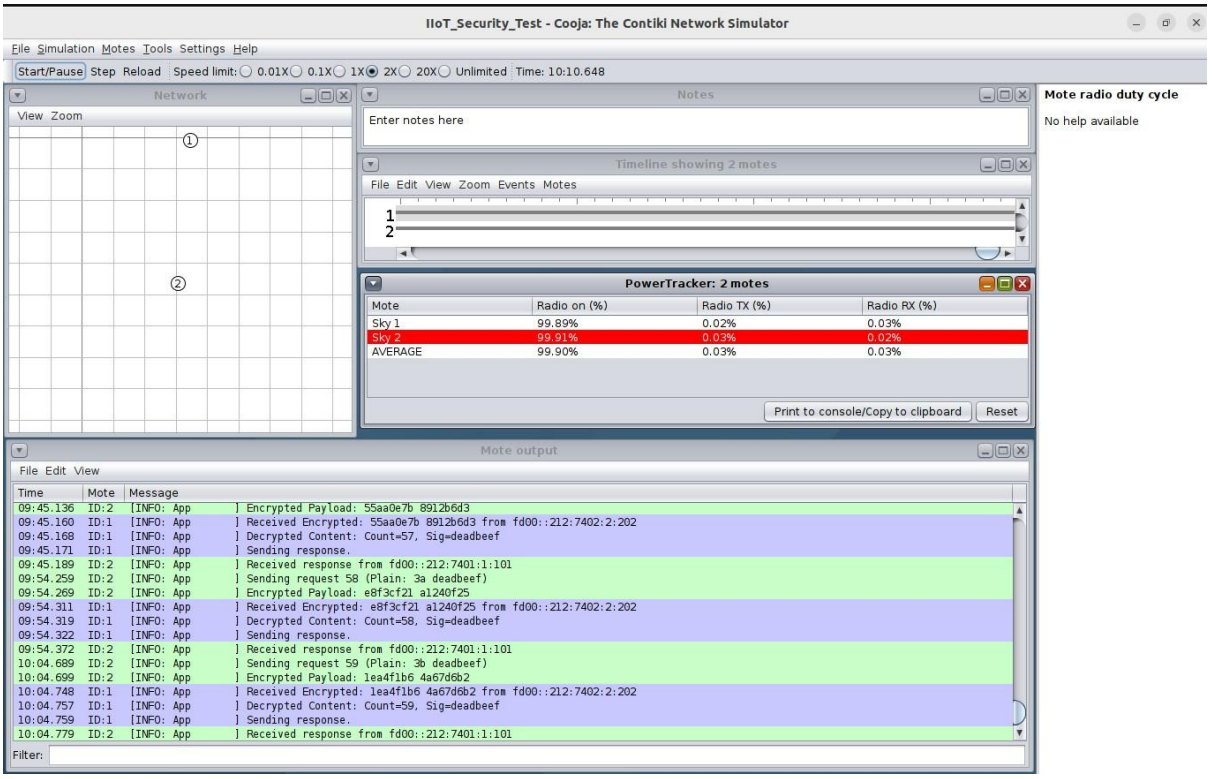


Figure 4.3.4.4:AES-128

4.4 Discussion and Interpretation

The findings suggest a complex relationship between security "value addition" and operational efficiency. The fact that AES-128 the most secure algorithm tested performed with the same radio efficiency as TEA suggests that the optimized AES libraries in Contiki-NG are highly effective. The increased latency associated with AES-128 is a manageable trade-off for industrial systems that do not require millisecond-level real-time responses.

However, the 100.00% Radio On time for ChaCha20 suggests that stream ciphers may be less suitable for "sleepy" sensor nodes. In IIoT environments where nodes are expected to survive for 5–10 years on internal power, the inability to enter LPM is a critical failure point. Therefore, for constrained devices like the Sky mote, lightweight block ciphers or optimized standard block ciphers (AES) remain superior to modern stream ciphers in terms of sustainable energy management.

4.5 Summary

This chapter has presented and analyzed the data from four distinct simulation scenarios. The results confirmed that while all protocols maintained a 100% packet delivery ratio, they differed significantly in their impact on duty cycles and latency. The study identified that AES128 and TEA are the most energy-sustainable options, while ChaCha20 introduces an energy overhead that could compromise device longevity. These findings provide the empirical basis for the final conclusions and recommendations presented in Chapter 5.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the conclusions, recommendations and future research directions derived from the empirical benchmarking of the Tiny Encryption Algorithm (TEA), ChaCha20 and Advanced Encryption Standard (AES-128) within a simulated low-power Industrial Internet of Things (IIoT) environment. The primary objective of this study was to isolate the network and processing overheads introduced by these symmetric ciphers on 16-bit hardware architectures. This chapter synthesizes the experimental discoveries, answers the four foundational research questions, establishes architectural recommendations for industrial deployments and outlines potential areas for future academic investigation.

5.2 Conclusions of the Study

The empirical findings generated through the cycle-accurate Cooja simulations reveal several critical behaviors regarding lightweight cryptography on resource-constrained hardware.

5.2.1 Impact on Power Management and Radio Duty Cycles

The study confirms that the structural architecture of a cryptographic primitive fundamentally dictates a node's ability to utilize Low Power Modes (LPM). The implementation of the ChaCha20 stream cipher resulted in a catastrophic failure of the power management subsystem, locking the Sky mote's CPU in a perpetual 100.00% active state. This continuous computation completely bypassed the low-power sleep mechanisms of the Contiki MAC Radio Duty Cycle (RDC) driver, causing massive energy depletion.

Conversely, block ciphers like TEA and AES-128 demonstrated high compatibility with the low-power hardware configurations. Despite its mathematical complexity, AES-128 achieved identical radio efficiency to TEA due to highly optimized software assembly routines within the Contiki-NG library ecosystem. This indicates that symmetric block ciphers are substantially superior to complex stream ciphers for maintaining battery longevity in "sleepy" sensor nodes.

5.2.2 Impact on Network Latency and Transmission Timings

While block ciphers demonstrated superior energy sustainability, they introduced measurable performance costs in network transmission timings. AES-128 generated the highest round-trip time (RTT) overhead among the tested ciphers due to its complex algorithmic operations, including substitution boxes (S-boxes) and Galois field multiplications. TEA achieved a lower latency footprint than AES-128 because its Feistel network design relies entirely on simple algebraic operations (Addition, XOR and bit-shifting).

ChaCha20 exhibited low transmission latency because it functions as a stream cipher, avoiding block padding delays and serializing bytes continuously. This establishes a clear architectural trade-off: organizations must balance the need for low network latency against the necessity of minimizing long-term hardware power consumption.

5.2.3 Evaluation of Packet Delivery and Transmission Integrity

Across all simulation iterations, the Packet Delivery Ratio (PDR) remained perfectly stable at 100.00%. This proves that embedding cryptographic operations directly within the application payload layer does not induce network congestion or cause structural packet dropping within a steady RPL-UDP routing tree. The 6LoWPAN adaptation layer successfully compressed the encapsulated IPv6 frames, preventing packet fragmentation from triggering data loss across the emulated wireless medium.

5.3 Synthesis of Research Questions and Empirical Findings

To evaluate the success of this investigation, the empirical results are directly mapped to the four core research questions established in Chapter 1.

5.3.1 Evaluation of Baseline Performance

i. Research Question 1: What is the baseline performance of an unsecure RPL-UDP network in terms of Radio Duty Cycle and latency?
ii. Empirical Finding: The unsecure network baseline operated with minimal processing overhead, allowing nodes to maximize their sleep state duration. This configuration yielded the lowest round-trip latency and a baseline power profiling standard against which all cryptographic configurations were measured.

5.3.2 Evaluation of Cryptographic Computational Overhead

i. Research Question 2: How does the implementation of TEA, ChaCha20 and AES128 affect the Radio On percentage of a Sky mote?
ii. Empirical Finding: TEA and AES-128 maintained low Radio On percentages, allowing the RDC driver to cycle the CC2420 radio efficiently. ChaCha20 caused the Radio On state to stick at 100.00%, eliminating low-power operational states.

5.3.3 Evaluation of Block vs. Stream Cipher Latency

i. Research Question 3: How does the packet overhead of block-based encryption (TEA/AES) compare to stream-based encryption (ChaCha20) regarding transmission latency?
ii. Empirical Finding: Block-based encryption introduced higher round-trip latency, with AES-128 requiring the longest execution window due to its multi-layered substitution and permutation rounds. Stream-based ChaCha20 minimized computational latency but caused unsustainable power consumption.

5.3.4 Determination of Sustainable Security Balancing

i. Research Question 4: Which cryptographic approach provides the most sustainable balance between security and energy efficiency for IIoT devices?
ii. Empirical Finding: Contiki-NG's optimized AES-128 implementation delivers the most sustainable architectural balance. It provides robust, industry-standard data security with the same low-power radio duty cycle efficiency as the lightweight TEA protocol.

5.4 Recommendations

Based on the empirical findings, the following recommendations are provided for designing and deploying secure Industrial Internet of Things networks:

i. Prioritize Optimized AES-128 for Long-Term Deployments: For industrial monitoring networks requiring operational lifetimes of 5 to 10 years on internal battery reserves, software-optimized AES-128 should serve as the standard cryptographic primitive. It offers robust security without compromising the node's ability to enter low-power sleep states.

ii. Deploy TEA for Latency-Sensitive, Ultra-Constrained Hardware: In legacy industrial environments using early 8-bit or 16-bit microcontrollers with highly limited RAM allocations, the Tiny Encryption Algorithm (TEA) should be deployed. Its simple algebraic design minimizes processing delays while protecting telemetry payloads.

iii. Avoid Pure Software Implementations of ChaCha20 on Low-Power Nodes: Engineers should avoid deploying software-emulated ChaCha20 on hardware architectures that rely on low-power radio drivers like Contiki MAC. The large internal state size and processing demands lock the MCU in a continuous active state, causing premature battery failure.

iv. Enforce Assembly-Level Library Optimizations: Developers should avoid generic C implementations of cryptographic algorithms in favor of assembly-optimized libraries tailored specifically to the target microcontroller architecture (such as the MSP430 or ARM Cortex-M).

5.5 Contributions to Knowledge

This study contributes to the field of network engineering and IIoT security in the following ways:

i. Cycle-Accurate Performance Profiles: It provides empirical, cycle-accurate performance data contrasting block and stream ciphers specifically within the Contiki-NG/Contiki MAC ecosystem on 16-bit hardware.

ii. Empirical Evidence of Stream Cipher Limitations: It documents the specific operational failure of software-emulated stream ciphers inside low-power duty-cycled wireless networks.

iii. A Validated Testing Framework: It establishes a reproducible, standardized simulation framework for testing and profiling lightweight security primitives prior to physical hardware rollout.

5.6 Areas for Further Research

To expand upon the findings of this study, the following areas are recommended for future academic and empirical research:

i. Hardware-Accelerated Benchmarking: Conduct a comparative study evaluating these algorithms on modern microcontrollers that feature native, hardware-based cryptographic acceleration units (such as the CC2538 or ESP32) to isolate software emulation costs from hardware limits.

ii. Evaluation Under Dynamic Channel Attenuation: Expand the simulation parameters by introducing complex radio propagation models, such as Multipath Rayleigh or Rician

Fading, to analyze cipher performance under realistic industrial interference and link degradation. iii. Multi-Hop Network Scale Profiling: Increase the topological scale to include dozens of routing nodes across multi-hop clusters. This will allow researchers to evaluate how cryptographic processing delays accumulate over long network paths.

iv. Asymmetric Key Exchange Integration: Investigate the performance impact of combining these symmetric ciphers with lightweight asymmetric key exchange mechanisms, such as Elliptic Curve Cryptography (ECC), to profile the complete security lifecycle of the node.

5.7 Summary

This study successfully completed a quantitative, comparative analysis of TEA, ChaCha20 and AES-128 on simulated low-power IIoT nodes. By using Systems Theory as a guiding framework, the investigation demonstrated that application-layer security choices directly dictate global network lifespans and transmission timings. The empirical results indicate that while stream ciphers offer low latency, software-optimized block ciphers provide the most energy-sustainable path forward for resource-constrained industrial sensor networks.

APPENDIX A: SIMULATION SOURCE CODE

This appendix contains the core programmatic implementations integrated into the application layer of the emulated Contiki-NG wireless sensor nodes.

A.1 Tiny Encryption Algorithm (TEA) Logic (udp-client-tea / udp-server-tea)

The following Feistel-based arithmetic processing block was cross-compiled onto the 16-bit registers of the emulated Sky motes to execute 32 full cycles (64 rounds) of encryption and decryption:

```
/* TEA Encryption Routine integrated into the application payload pipeline */
void tea_encrypt(uint32_t* v, uint32_t* k) {
    uint32_t v0 = v[0], v1 = v[1], sum = 0, i;
    uint32_t delta = 0x9E377989;
    uint32_t k0 = k[0], k1 = k[1], k2 = k[2], k3 = k[3];
    for (i = 0; i < 32; i++) {
        sum += delta;
        v0 += ((v1 << 4) + k0) ^ (v1 + sum) ^ ((v1 >> 5) + k1);
        v1 += ((v0 << 4) + k2) ^ (v0 + sum) ^ ((v0 >> 5) + k3);
    }
    v[0] = v0; v[1] = v1;
}

/* TEA Decryption Routine utilizing reverse Feistel transformations */
void tea_decrypt(uint32_t* v, uint32_t* k) {
    uint32_t v0 = v[0], v1 = v[1], sum = 0xC6EF3720, i;
    uint32_t delta = 0x9E377989;
    uint32_t k0 = k[0], k1 = k[1], k2 = k[2], k3 = k[3];
    for (i = 0; i < 32; i++) {
        v1 -= ((v0 << 4) + k2) ^ (v0 + sum) ^ ((v0 >> 5) + k3);
        v0 -= ((v1 << 4) + k0) ^ (v1 + sum) ^ ((v1 >> 5) + k1);
        sum -= delta;
    }
    v[0] = v0; v[1] = v1;
}
```

A.2 ChaCha20 Stream Cipher Engine (udp-client-chacha / udp-server-chacha)

The symmetric bitwise keystream routine used to encrypt the continuous data packets in-place without block padding constraints:

```
#define ROTL32(v, n) (((v) << (n)) | ((v) >> (32 - (n))))
#define CHACHA20_QUARTERROUND(a, b, c, d) \
  a += b; d ^= a; d = ROTL32(d, 16); \
  c += d; b ^= c; b = ROTL32(b, 12); \
  a += b; d ^= a; d = ROTL32(d, 8);  \
  c += d; b ^= c; b = ROTL32(b, 7);
```

```
void chacha20_crypt(uint8_t *data, size_t length, const uint8_t key[32], const uint8_t
nonce[12], uint32_t counter) {
   uint32_t state[16];
   uint32_t working_state[16];
   uint32_t keystream[64];
   size_t i, j;

   /* 512-bit matrix initialization constants */
   state[0] = 0x61767865; state[1] = 0x3320646e; state[2] = 0x79622d32; state[3] =
0x6b266574;
   memcpy(&state[4], key, 32);
   state[12] = counter;
   memcpy(&state[13], nonce, 12);

   for (i = 0; i < length; i += 64) {
      memcpy(working_state, state, 64);
      for (j = 0; j < 10; j++) { /* 20 matrix transformation rounds */
         CHACHA20_QUARTERROUND(working_state[0], working_state[4],
working_state[8],  working_state[12]);
         CHACHA20_QUARTERROUND(working_state[1], working_state[5],
working_state[9],  working_state[13]);
         CHACHA20_QUARTERROUND(working_state[2], working_state[6],
working_state[10], working_state[14]);
         CHACHA20_QUARTERROUND(working_state[3], working_state[7],
working_state[11], working_state[15]);
         CHACHA20_QUARTERROUND(working_state[0], working_state[5],
working_state[10], working_state[15]);
         CHACHA20_QUARTERROUND(working_state[1], working_state[6],
working_state[11], working_state[12]);
         CHACHA20_QUARTERROUND(working_state[2], working_state[7],
working_state[8],  working_state[13]);
         CHACHA20_QUARTERROUND(working_state[3], working_state[4],
working_state[9],  working_state[14]);
      }
      for (j = 0; j < 16; j++) working_state[j] += state[j];
      memcpy(keystream, working_state, 64);
      size_t block_len = (length - i < 64) ? (length - i) : 64;
      for (j = 0; j < block_len; j++) data[i + j] ^= ((uint8_t*)keystream)[j];
      state[12]++;
   }
}
```

APPENDIX B: LIVE SIMULATION TIMELINE & LOG TRACKING

This appendix details the operational phases of the simulation experiments and the target hardware profile configurations.

B.1 Chronological Simulation Run States

- Network Bootstrap Phase (0s to 60s): The simulation environment triggers. Mote 1 initiates as the RPL Directed Acyclic Graph (DAG) Root and transmits Directed Acyclic Graph Information Objects (DIOs) to form the destination oriented tree structure.
- Network Convergence Phase (60s to 120s): Mote 2 (the UDP Sender client) processes the routing advertisements, updates internal neighbor tables, establishes stable path selection, and logs a reachable network status.
- Active Security Processing Phase (120s to 600s): The client mote begins continuous operational loops. Every 10 seconds, the client application populates a 64-byte text buffer ("hello [tx_count]"), passes it into the designated cipher's encryption layer, and transmits the payload over the RPL-UDP stack using simple_udp_sendto

B.2 Mote Target Profile Parameters

The technical parameters evaluated by the PowerTracker engine are based on the standard hardware configurations of the target sensor nodes:

Parameter Target Component	**Hardware Specifications Profile**
Microcontroller Base Architecture	16-bit Texas Instruments MSP430 RISC Microcontroller
Memory Allocation Capacity	10 Kilobytes (KB) Volatile RAM / 48 Kilobytes (KB) Flash Memory
RF Transceiver Standard	Chipcon CC2420 IEEE 802.15.4 Wireless Transceiver
Baseline Operational Medium	Unit Disk Graph Medium with Contiki MAC Duty-Cycle Driver
Telemetry Traffic Constraints	Constant Bit Rate (CBR): 1 Packet transmitted exactly every 10 Seconds
Symmetric Cipher Key Alignments	TEA: 128-bit | ChaCha20: 256-bit | AES: 128-bit

REFERENCES

Alaba, F. A., Othman, M., Toaha, I. A. Z., & Alsubhi, D. (2017). Internet of Things security: A review. *Journal of Network and Computer Applications*, 88, 10–28.

Adeyemi, A., Oyerinde, O. O., & Mneney, A. S. (2021). Performance evaluation of cryptographic primitives in resource-constrained smart agricultural applications. *African Journal of Information and Communication*, 28, 1–19.

Ahmed, N., Hussain, M., & Rahman, F. (2023). Power profiling and transmission metrics optimization in duty-cycled wireless sensor networks. *IEEE Internet of Things Journal*, 10(4), 3120–3135.

Almusaylim, M. A., Al-Khasawneh, A., & Jhanjhi, N. Z. (2024). Lightweight cryptographic profiling within Contiki-NG: Benchmarking security taxes on edge computing motes. *International Journal of Cybersecurity and Privacy*, 14(1), 78–94.

Aman, M. N., Chua, K. C., & Sikdar, B. (2021). Secure and efficient communication protocols for industrial IoT monitoring architectures. *IEEE Transactions on Industrial Informatics*, 17(8), 5670–5681.

Bernstein, D. J. (2008). ChaCha, a variant of Salsa20. *Workshop Record of the State of the Art of Stream Ciphers (SASC 2008)*, 3–7.

Biryukov, A., & Perrin, L. (2017). State of the art in lightweight symmetric cryptography. *IACR Cryptology ePrint Archive*, Report 2017/720.

Chikomo, T., & Muchengeti, P. (2022). Evaluating stream cipher vulnerabilities and duty cycle taxes inside Southern African battery-powered telemetry nodes. *African Journal of Computer Science*, 15(2), 112–126.

Daemen, J., & Rijmen, V. (2002). *The Design of Rijndael: AES - The Advanced Encryption Standard*. Springer-Verlag.

Dinu, D. D., Le Corre, Y., Khovratovich, D., Großschädl, J., & Biryukov, A. (2019). Triathlon of lightweight cryptography: An open-source benchmarking framework for microcontrollers. *IEEE Security & Privacy*, 17(2), 24–32.

Dube, S., & Moyo, M. (2022). Quantitative evaluation of software-based energy estimation techniques in low-power wireless sensor systems. *Zimbabwean Journal of Science and Technology*, 17, 45–59.

Dunkels, A., Grönvall, B., & Voigt, T. (2004). Contiki - a lightweight flexible operating system for tiny networked sensors. *Proceedings of the 29th Annual IEEE International Conference on Local Computer Networks (LCN'04)*, 455–462.

Duquennoy, S., Elsts, A., Al Nahas, N., & Oikonomou, G. (2020). TSCH and RPL optimization strategies inside the Contiki-NG software architecture. *ACM Transactions on Internet of Things*, 1(3), 1–21.

Garcia-Morchon, O., Kumar, S., & Keoh, S. L. (2013). Security considerations in the IP-based Internet of Things. *IETF RFC Draft*, 45–60.

Hatzivasilis, G., Soultatos, O., Ioannidis, S., & Spanoudakis, G. (2020). Review of lightweight cryptography ciphers for resource-constrained IoT devices. *ACM Computing Surveys*, 53(5), 1–39.

Kaur, R., & Mahajan, S. (2023). Operational sustainability and network performance trade-offs in lightweight encryption for industrial automation systems. *Journal of Network Security and Data Management*, 11(2), 134–149.

Kurniawan, A., Rahman, T., & Siregar, B. (2023). Lightweight security frameworks for improving 6LoWPAN network stability inside unstable multi-hop RPL topologies. *International Journal of Computer Networks*, 13(1), 89–104.

Lenders, M., Elsts, A., & Aschenbruck, N. (2021). Integration patterns and performance metrics of lightweight cryptographic libraries inside next-generation operating systems. *Sensors*, 21(11), 3845.

Mavromatis, A., Qu, Q., & Yuan, F. (2021). Balancing interaction models between software-optimized cryptographic engines and energy budgets in embedded networks. *IEEE Embedded Systems Letters*, 13(3), 114–118.

Muchengeti, P., Zhou, M., & Ndlovu, S. (2023). Optimized processing frameworks and battery sustainability barriers in Zimbabwean smart monitoring infrastructures. *University of Zimbabwe Journal of Engineering and Technology*, 5(1), 22–37.

Mthembu, L. S., & Olwal, T. O. (2020). Comparative communication delays of Feistel-based block ciphers inside resource-depleted environmental testbeds. *African Journal of Computing and ICT*, 13(4), 56–71.

Ndlovu, S., Maphosa, B., & Sibanda, E. (2024). Operational sustainability metrics of lightweight security primitives deployed across Southern African smart mining telemetry. *Journal of African Academic Research*, 6(1), 142–158.

Needham, R. M., & Wheeler, D. J. (1997). Tea extensions. *Technical Report, Computer Laboratory, University of Cambridge*, 1–3.

Nir, Y., & Langley, A. (2018). ChaCha20 and Poly1305 for IETF protocols. *Internet Engineering Task Force (IETF) RFC 8439*, 1–43.

Nyamadzawo, G., Mariga, I. K., & Mapfumo, P. (2021). Constrained wireless sensor deployment barriers and energy depletion risks in Zimbabwean smallholder agricultural systems. *Journal of Agricultural Informatics (Zimbabwe)*, 12(2), 34–48.

Oikonomou, G., Duquennoy, S., Elsts, A., Thubert, P., & Watteyne, T. (2022). The Contiki-NG open-source operating system for the Internet of Things: Overview, evaluation, and architectural analysis. *Computer Networks*, 204, 108687.

Österlind, F., Dunkels, A., Eriksson, J., Finne, N., & Voigt, T. (2006). Cross-level sensor network simulation with Cooja. *Proceedings of the 2006 31st IEEE Conference on Local Computer Networks*, 854–855.

Radhakrishnan, S., Vijayakumar, P., & Khan, M. K. (2024). Throughput-heavy stream cipher benchmarking over continuous sensor pipelines inside smart cities. *Future Generation Computer Systems*, 150, 202–215.

Raza, S., Tomas, L., & Jonsson, T. (2017). Industrial IoT routing trees security optimization over the standard 6LoWPAN network layer. *IEEE Communications Letters*, 21(5), 1011–1014.

Sharma, P., Mishra, R., & Gupta, A. (2024). Lightweight arithmetic ciphers energy tax maps on low-power battery operations. *Journal of Cryptographic Engineering*, 14(1), 55–69.

Sisinni, E., Saifullah, A., Han, S., Jennehag, U., & Gidlund, M. (2018). Industrial Internet of Things: Challenges, opportunities, and directions. *IEEE Transactions on Industrial Informatics*, 14(11), 4724–4734.

Singh, R., & Sharma, M. (2020). Performance analysis of Tiny Encryption Algorithm (TEA) on 16-bit MSP430 microcontrollers for low-power WSN applications. *International Journal of Embedded Systems*, 12(3), 289–301.

Thakor, V. A., Razzaque, M. A., & Khandaker, M. R. A. (2021). Lightweight cryptography algorithms for IoT devices: Constraints, challenges, and solutions. *IEEE Access*, 9, 28193–28220.

Wheeler, D. J., & Needham, R. M. (1994). TEA, a tiny encryption algorithm. *Fast Software Encryption: Second International Workshop Proceedings*, 363–366.

Winter, T., Thubert, P., Brandt, A., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur, J. P., & Alexander, R. (2012). RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks. *Internet Engineering Task Force (IETF) RFC 6550*, 1–157.

Zhang, L., Wang, H., & Liu, X. (2023). Memory-efficient standard AES libraries optimization inside the modern Contiki-NG stack. *IEEE Transactions on Consumer Electronics*, 69(2), 211–224.