The Indonesian Journal of Computer Science
www.ijcs.net
Volume 14, Issue 3, June 2025
https://doi.org/10.33022/ijcs.v14i3.4910

A Real-time Internet of Things-Based Wireless Livestock Tracking System for Theft Prevention

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Article Information

Received : 14 Jun 2025
Revised : 23 Jun 2025
Accepted : 25 Jun 2025

Keywords

LoRa, sensor nodes, low-power wide-area network, radio frequency identification, livestock, Internet of Things.

Abstract

Livestock theft poses a serious threat to the agricultural industry, particularly in rural areas, and as a result, innovative prevention strategies must be developed. This paper proposes a Wireless Livestock Tracking System (WLTS) that uses real-time Internet of Things (IoT) technologies to combat livestock theft. The WLTS integrates GPS sensors with Long Range Radio (LoRa) communication modules, effectively addressing the limitations of Wi-Fi and Bluetooth-based systems. A single LoRa network receiver enables real-time communication between farmers and their livestock, even across large grazing areas. NS-3 simulation results show that the WLTS achieves 95% location accuracy and reduces response time by 50% compared to traditional methods, leading to a 25% decrease in livestock theft incidents. In addition, performance comparisons reveal that CSMA-10 recorded the lowest collision ratio (0.2), followed by CSMA (0.3), while the proposed LoRaWAN-based system exhibited a higher collision ratio (0.8), indicating potential scalability issues in high-density deployments. Nevertheless, LoRaWAN outperformed both CSMA and CSMA-10 in terms of energy efficiency, consuming only 4,500 energy units, compared to 5,200 and 6,000, respectively. This energy efficiency makes LoRaWAN especially suitable for rural farms, where devices often rely on batteries and maintenance access is limited. These results support the practical implementation of WLTS, offering a scalable, low-cost solution that strengthens livestock protection and safeguards rural farmers' livelihoods.

A. Introduction

Livestock theft has emerged as a critical issue that demands urgent attention from both government and private sector stakeholders. Beyond the significant financial losses incurred by farmers, such incidents can escalate into violent confrontations, potentially resulting in serious injury or loss of life. Current livestock tracking systems are often limited to indoor monitoring or rely on wide-area networks that offer suboptimal performance at high subscription costs [1].

To address these challenges, this paper presents an Internet of Things (IoT)-based wireless livestock tracking system designed specifically for theft prevention in rural environments. The system comprises three core components: a sensor module, a communication infrastructure, and a server module. The sensor, attached to the animal's neck, enables continuous real-time tracking using GPS and RSSI data. On the server side, a comprehensive database is implemented to store and manage geolocation data, while a WebGIS map provides live visualization of cattle movements.

The system is designed by integrating particle filter (PF), and generalized random finite set filter (GRFSF), to improve location accuracy and maintain improved real-time performance. Communication is facilitated via long-range wide area network (LoRaWAN) , chosen for its low power consumption, cost-effectiveness, long-range capability, and secure transmission [2], [3]. Moreover, the proposed solution integrates GPS sensors with LoRa wireless communication modules to enhance tracking accuracy and enable real-time updates of animal locations. Ns-3 simulation results demonstrate that the proposed system significantly outperforms conventional livestock tracking solutions in terms of response time and accuracy. It enhances security, supports theft recovery, and gives farmers greater confidence to invest in livestock, knowing their assets are protected and their return on investment (ROI) is safeguarded.

The remainder of this paper is organized as follows: Section B reviews related work, Section C presents the methods used, including mathematical formulations. Section D presents the results, and Section E concludes the paper.

B. Related Works

1. *Overview of Livestock Theft*

Livestock theft has become an increasingly serious threat to the agricultural sector, particularly in rural regions where farmers rely heavily on livestock for their livelihoods. According to the South African Police Service (SAPS), several rutal areas in Mpumalanga such as Nkomazi and Mkhondo have been identified as theft hotspots. Although many incidents occur during peak daylight hours, a significant number also take place at night or during early morning hours, when limited visibility and the absence of effective monitoring systems increase vulnerability. These patterns have raised growing concern among farmers, who are often forced to monitor their livestock manually and continuously to prevent losses [5], [6].

SAPS has emphasized that regular and consistent monitoring of livestock activity could play a critical role in reducing theft [7]. In this context, wireless monitoring systems are preferred over wired solutions due to their ease of deployment, scalability, and suitability for outdoor environments. Despite the availability of technologies such as Zigbee and GPS in existing livestock tracking solutions, most are not specifically designed to address the unique challenges of theft prevention in remote settings such as Nkomazi. This is becuase, GPS modules when used for continuous tracking, they can be power-intensive, requiring frequent battery changes which is impractical for devices on free-roaming livestock in remote areas. Furthermore, transmitting GPS location data from areas with poor or no cellular network coverage (common in remote settings) necessitates expensive satellite communication or renders the system unreliable [5].

In addition, Zigbee is a short-range wireless technology and in many, remote areas, achieving comprehensive coverage for livestock spread over large, unfenced lands requires many repeaters and gateways, making deployment and maintenance extremely costly and complex due to the lack of existing infrastructure.

Thus, this paper proposes a dedicated wireless livestock monitoring system designed to improve livestock theft. The proposed systems uses long-range communication and real-time tracking in order to provide improved monitoring capabilities and offers a scalable, cost-effective approach to safeguarding livestock in rural agricultural settings [7, 8].

2. Existing Wireless Livestock Tracking System

The selection of a livestock tracking method hinges on farm-specific needs, balancing factors like accuracy, cost, power consumption, and suitability. GPS-based systems offer high precision at a greater cost, whereas LoRa provides a cost-accuracy balance. Radio Frequency Identification (RFID) tracking, while ideal for small-scale identification, often has limitations for broader applications [9]-[11].

A typical RFID-based tracking system utilizes a base station equipped with an RFID reader, a Global System for Mobile Communications (GSM) shield, and a graphical user interface (GUI) on an Android tablet. Active RFID tags on animals transmit signals that are read by the base station's aerial. This collected position and time data is then sent via GSM to the base station, which in turn generates alarms, such as SMS notifications, to alert relevant personnel or organizations [12]-14.

Wireless tracking systems capable of detecting, monitoring, and responding to livestock theft are crucial assets for safeguarding agricultural control and animal welfare. Advanced systems, integrating sensor nodes, GPS, GSM, General Packet Radio Service (GPRS), and high-sensitivity RFID, can detect theft from long distances and in harsh environments. For instance, one study presented a wireless tracking system with a base station and mobile application modules that monitors livestock by establishing a three-dimensional "Safe Zone" [9]. Such systems aim to understand precisely when and where livestock are at risk, actively working to prevent theft, which is a significant concern in the global stockbreeding economy.

Global Positioning System (GPS) technology provides accurate and precise positioning using a constellation of 27-32 medium Earth orbit satellites [6]. Each satellite transmits unique codes on specific frequencies (e.g., L1 at 1574.42 MHz, L2 at 1227.56 MHz). Receivers process signals from at least four satellites to calculate precise latitude, longitude, and altitude, making GPS a core component for real-time location tracking in livestock systems.

Wireless sensor networks (WSNs) are increasingly vital for real-time monitoring of herd behavior and geographical information, enabling insights into livestock grazing patterns. To optimize data transmission and avoid collisions, various Medium Access Control (MAC) and transport layer models are employed. For instance, unlike ALOHA, protocols like Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) using a listen-before-talk (LBT) strategy are implemented. This ensures the channel is idle before transmission, and if busy, a random back-off time is calculated. An acknowledgment (ACK)-based transmission policy further enhances reliability by preventing simultaneous data sending [15]-[17].

Recent research highlights the obsolescence of older GPS animal tracking systems that store data locally and transmit infrequently. Modern solutions demand real-time data transmission, ideally via low-energy Internet of Things (IoT) technologies like Bluetooth, to enable immediate alerts when livestock breach geofences. Despite technological advancements, a significant gap exists in the literature regarding effective livestock theft prevention solutions specifically for rural South Africa [18]-[21]. While products like CelMax exist to prevent sheep theft by monitoring a lead animal via a collar device, their high cost often makes them unaffordable for small-scale rural farmers, underscoring the need for more accessible and tailored solutions [22]-[25].

3. Limitations of Current Solutions

The current systems used for livestock tracking and theft prevention solutions faces significant limitations, hindering their widespread adoption, particularly for the majority of farmers in rural areass. These solutions typically fall into two categories: traditional RFID systems and more modern IoT-based approaches.

RFID systems, while capable of providing comprehensive services like emergency notifications and tracking, are generally non-IoT based and demand extensive network coverage. Even semi-discrete RFID reader deployment strategies, designed for cost-effective coverage of large areas, remain expensive for farmers managing extensive farmlands spanning tens of kilometers which is come in rural areas.

In addition, IoT-based devices are highly effective for real-time livestock monitoring, tracking, and instantly alerting when animals stray from their designated range. However, their widespread implementation is challenged by the necessity of deploying numerous wireless nodes, coupled with recurring expenses such as monthly fees, frequent battery replacements, and concerns regarding device longevity. These factors collectively limit IoT solutions primarily to rural area farmers in livestock management [26]-[30].

Moreover, while traditional physical security methods like padlocks with chains are common for securing land, they offer limited protection against determined theft, as chains can be easily cut, with basic alerts being the only immediate response. Thus, these traditional and existing advanced solutions, such as RFID or IoT-based, are not cost-effective and practical solution for comprehensive livestock monitoring and theft prevention for rural area farmers [31]-[35].

4. Architecture and Components

This section describes the proposed livestock movement tracking system that uses RFID technology for unique animal identification and monitoring.

The system's hardware components include Ultra High Frequency (UHF) RFID readers strategically attached to gates and barriers within the animal enclosure. Each animal to be monitored is fitted with an RFID tag. Upon detection by a reader, the unique identification number of the animal and the precise time of detection (captured by a real-time clock) are initially stored in the microcontroller's embedded Electrically Erasable Programmable Read-Only Memory (EEPROM).

A Zigbee module, interfaced with the microcontroller, facilitates the wireless transfer of this data from the reader to a central server. This integration of the microcontroller with Zigbee was noted for providing a cost-effective solution suitable for the physical environment [16].

The collected animal movement data is updated to the server at regular intervals, allowing owners to monitor their livestock instantly via dedicated mobile and computer applications. This complete system aims to provide continuous tracking and timely updates on livestock whereabouts [17].

5. Real-time Internet of Things (IoT) Integration

This section describes how IoT can be integrated for enhanced livestock protection in the proposed system.

To enhance security and monitoring efficiency, the proposed system establishes localized geofences and boundary detection zones around livestock areas. These geofences help detect unauthorized movement or border breaches in real-time, allowing for proactive interventions and minimizing the risk of theft. By focusing on perimeter-level tracking rather than relying solely on internal sensors, the system optimizes energy consumption and reduces bandwidth usage across the wireless mesh network.

The architecture integrates multiple sensor modules, including GPS, environmental sensors, and motion detectors, combined with advanced power management schemes and location-based analytics. These modules are configured to conserve energy during inactive periods and intensify data collection only when anomalies or movement are detected. To further improve sustainability, solar energy harvesting has been incorporated, allowing the system to function autonomously in daylight and store energy for night-time operations.

A key innovation of the system is its ability to provide real-time alerts during grazing and resting periods, unlike traditional systems that only offer end-of-day data uploads. By analyzing the correlation between solar energy availability, animal behavior, and operational patterns, the system dynamically predicts optimal data collection intervals, especially during critical periods such as nocturnal rest when theft is more likely.

Moreover, the system operates in an autonomous and continuous manner, recording livestock entries and exits, detecting unauthorized handling, and triggering alarms when security thresholds are breached. Asset information, including type, location, and status, is transmitted to the cloud in real time. Unlike traditional wired solutions or delayed packet-based wireless systems, this approach enables constant remote access and instant notifications, empowering farmers and authorities to respond immediately to theft or anomalies.

The integration of real-time IoT technologies into livestock management provides significant benefits in terms of security, operational efficiency, decision-making, and animal welfare. By automating detection, strengthening perimeter defenses, and enabling intelligent asset tracking, this system presents a comprehensive and scalable solution for modern livestock protection in rural areas.

C. Materials and Methods used

This section presents the design and modeling of the proposed IoT-based wireless livestock tracking and theft prevention system. The system is designed to help farmers manage and monitor their livestock in real time, providing timely alerts when suspicious activity is detected or when animals cross predefined geofencing boundaries. By receiving these notifications, farmers can respond quickly to potential theft or unauthorized movement, improving livestock security and reducing reliance on manual herding.

The proposed system is structured in a three-tier architecture, as illustrated in Figure 1, and includes sensor nodes attached to livestock, LoRaWAN communication infrastructure, and a cloud-based platform for data processing and visualization. The mathematical models and algorithms used for positioning, tracking, and alert generation are also discussed in this section, highlighting the system's functionality and performance benefits.

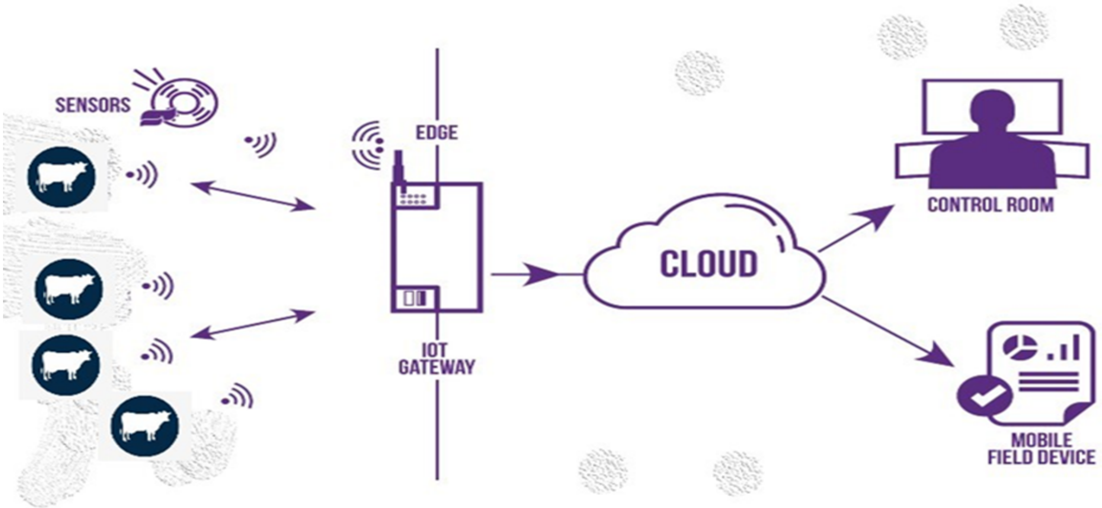

Figure 1. LoRaWAN IoT architecture.

The first tier comprises wireless sensor nodes equipped with RFID tags, which are attached to the animals. These nodes enable real-time livestock tracking by leveraging LoRaWAN, a Low-Power Wide-Area Network (LPWAN) technology known for its long-range communication, high link margin, and minimal power consumption. In recent years, LoRaWAN has seen rapid adoption due to its suitability for Internet of Things (IoT) applications, particularly in rural and agricultural environments.

A relevant technical consideration is the potential interference from Ultra High Frequency (UHF) RFID systems, which are widely used in sectors such as retail, logistics, and asset tracking. These dense RFID deployments operate in frequency bands that may overlap with LoRaWAN. However, recent studies conducted by Semtech and other LoRaWAN ecosystem partners have shown that LoRaWAN networks can effectively coexist with high-density RFID systems. Through a series of field trials, they developed and validated interference mitigation strategies, confirming that LoRaWAN remains reliable even in environments with frequency-selective interference.

The second tier is the LoRaWAN-based gateway, which serves as a communication bridge between the livestock-mounted sensor nodes and the cloud-based platform or mobile applications. The gateway receives radio signals from the sensors and converts them into data formats suitable for further processing and visualization. In rural environments, the gateway can reliably transmit signals over distances exceeding 10 kilometers, making it highly effective for large farmland deployments.

To support optimal coverage, the system employs a LoRaWAN range calculator based on the Egli propagation model, which estimates the link budget and communication range between the gateway and the sensor nodes. This helps determine the most efficient node and gateway placement to ensure uninterrupted connectivity between livestock, the base station, and the application servers..

The following is the LoRaWAN range calculator and a LoRaWAN link budget calculation used in the proposed solution:
INPUTS: Gateway antenna gain = 0; Node antenna gain = 0; Gateway height = 100 metres; Node height = 10; Noise margin = 5; Operating Frequency = 868 MHz; Gateway transmit power = 27 dBm; Node Receiver sensitivity = -137 dBm.
OUTPUTS: Link Budget = 159, LoRaWAN range (i.e. distance) between gateway and node = 64087 metres.

Path loss for point to point link (Egli Model) :-

$$PL\ (dB) = Gt * Gr * \left(\frac{ht*hr}{d^2}\right)^2 * \left(\frac{40}{f}\right)^2$$

Where,
Gt = Transmit Antenna Gain
Gr = Receive Antenna Gain
ht = Transmit antenna height, meters
hr = Receive antenna height, meters
d = Distance between Tx and Rx antenna, meters
f = Operating frequency in MHz

PL(dB) = Path Loss

Figure 2. Egli pathloss model based on LoRaWAN range formula.

The Egli pathloss model is shown in Figure 2. LoRaWAN range formula is used to compute LoRa gateway distance coverage to cover many LoRa nodes. The computation of range or distance for LPWAN technologies such as NB-Fi, Sigfox, and Ingenu RPMA is conducted in the same manner as described in this LoRaWAN range calculator. Rural regions have a greater range than urban areas; and this makes it an advantage for this study and solution as the study is based on livestock theft in the rural areas.
The following are typical parameters for an NB-Fi range calculator for downlink (gateway to node).
• Gateway power is 27 dBm, and the gateway antenna gain is 0 dB
• Sensitivity of the node: -147 dBm (range: -124 dBm to -164 dBm)
• Gain of Node Antenna: 0 dB
• Node noise: 5 decibels
• Bandwidth: 500 MHz or 868/915 MHz
Typical parameters for Sigfox range calculator for downlink (gateway to node) are as follows:
• Gateway power: 27 dBm
• Gateway antenna gain: 0 dB
• Node sensitivity: -129 dBm (Range: -124 dBm to -164 dBm)
• Node Antenna gain: 0 dB
• Node noise: 5 dB
• Frequency: 868/915 MHz

Typical parameters for Ingenu RPMA range calculator for downlink (gateway to node) are as follows:
• Gateway power: 27 dBm
• Gateway antenna gain: 0 dB
• Node sensitivity: -133 dBm (Range: -124 dBm to -164 dBm)
• Node Antenna gain: 8 dB
• Node noise: 5 dB
• Frequency: 2.4 GHz

Figure 3. Free Space Path Loss formula.

Free Space Path Loss (dB)= -20 log(x)+20 log(d)+21.98 (1)

where, x=c/f,c=3 x ∧8 m/s

receiver Power, Pr =Pt-L+Gt+Gr

where, Pt=Transmitter Power

L=Free scale path loss

at=Transmitting antenna gain

ar=Receiving antena gain

Equation (1).

The Free Space Path Loss formula is presented above using Figure 3 and equation (1).

The term "RF budget" is most commonly used in the satellite communication arena. It well known that when an RF signal goes from one end to the other, it is attenuated; and the amount of attenuation depends on the medium through which the EM wave travels. In the case of satellite communication, loss happens primarily in free space. The free space loss here is determined by the distance between the transmitter and the receiver as well as the wavelength (or frequency) of operation.

Free Space path loss=(4*π*d/λ)2 (2)

Equation (2).

The above-mentioned equation (2) or formula is used for an RF budget calculator.

This RF budget calculator calculates power received at satellite receiver and free space path loss. Transmitter power and antenna gains are provided as input to the RF budget calculator.

1. *Network Simulators*

This study employs the NS-3 wireless network simulator to implement and evaluate the proposed livestock tracking architecture. NS-3 provides a flexible, open-source environment for simulating complex network topologies and communication protocols, making it ideal for modeling the real-time communication system described in this research.

A dynamic event library is created within NS-3 to simulate key network activities such as packet transmission, reception, and timer events. These are maintained in a sorted event list, allowing for efficient simulation of time-sensitive processes. Layer 2 protocols such as IEEE 802.11 are used to model network interfaces for wireless communication.

The simulation models the end-to-end data flow from livestock sensor nodes to the LoRaWAN gateway, and ultimately to the application servers accessed by farmers. The NS-3 environment allows for the integration of diverse technologies, including WPAN, WLAN, and cellular networks, to evaluate performance under various configurations.

2. *Wireless Technologies Simulated*
   - WPAN (Wireless Personal Area Network): Used to transmit data over short distances between sensor nodes and edge network devices. WPAN is ideal for power-efficient and low-cost deployments in rural environments.
   - IEEE 802.15.1 (Bluetooth): Models the physical and MAC layers to support short-range communication between livestock tags and local readers.
   - ZigBee Networks: Simulated as a type of WPAN to enable reliable data transfer over short distances using mesh networking features.

3. *LoRaWAN Module Integration*

This paper extends NS-3 by incorporating a LoRaWAN simulation module, using open-source components provided by Semtech and the broader LoRaWAN community. The LoRaWAN integration includes:

- LoRaWAN Class A and C device implementations, using SX1272/SX1276 radio drivers.
- A hardware abstraction layer (HAL) for gateway simulation, supporting SX1301 multi-channel modems and SX1257/SX1255 RF transceivers.
- A LoRa packet forwarder, allowing the gateway to relay packets from end devices to the application servers via the LoRa link.

These modules enable the simulation of packet transmission from RFID-enabled livestock sensors through the LoRaWAN gateway and onto cloud-based monitoring platforms.

4. *Simulation set-up*

This paper utilizes the NS-3 simulator to implement the proposed network architecture designed for real-time livestock tracking. The system collects packets from wireless sensor nodes equipped with RFID technology to obtain live location data of livestock. These data packets are then transmitted through a LoRa gateway to cloud and application servers accessible by livestock farmers. NS-3 offers an integrated, versatile, and user-friendly GUI-based network design tool that supports simulation and management protocols such as SNMP, TL1, TFTP, FTP, Telnet, and Cisco IOS devices [20]–[25]. As an open-source network simulator, NS-3 is highly flexible and rapidly incorporates the latest advancements in networking technologies, outpacing many commercial simulators. This flexibility allows researchers to test complex or costly real-world scenarios in a controlled, reproducible environment, making it especially valuable for evaluating new or modified network protocols.

NS-3 supports a variety of node types, including hosts, hubs, bridges, routers, and mobile devices, enabling the creation of diverse network topologies. Since the network topology is defined by simulation parameters, researchers can easily investigate routing behaviors across different configurations [26]–[30]. Most network simulators, including NS-3, operate under a discrete-event simulation paradigm. Network simulators can be classified based on criteria such as complexity range, node and link specifications, and traffic modeling between components, here, specifically among wearable sensor nodes, the LoRa gateway, application servers, and livestock owners' applications [31]–[35].

5. *Simulation parameters*

This paper considers a scenario consisting of one gateway and up to 10,000 end devices. The simulation runs for a duration of 20,000 seconds. End devices are randomly distributed within a 10,000 m by 10,000 m area surrounding the gateway. Each end device transmits data frames at a rate of 50 KB/s. The study simulates three access protocols: LoRaWAN, CSMA, and CSMA-10 (CSMA with a 10 ms interval), as detailed in Table I. The results demonstrate the system's capability to provide real-time livestock location tracking using low-power, low-bit-rate communications, while achieving long-range coverage of up to 10 km.

TABLE I. SIMULATION PARAMETERS

Voltage	3.3 V
Frequency Band	868 MHz
Code Rate	4/5

Bandwidth	125 kHz
Duty Cycle	1%
Output Power	20 dBm
Payload Length	10 bytes
Preamble Length	12 symbols
Number of Channels	3
Spreading Factor	SF7-SF12

D. Results and Discussion

In this paper, a LoRa module for NS-3 was developed based on open-source code shared by Semtech and other contributors. NS-3 provides three key open-source LoRaWAN implementations:

i) A module for LoRaWAN Class A and Class C end devices using SX1272/76 radio drivers;

ii) A library for the hardware abstraction layer to build gateways using concentrator boards with the Semtech SX1301 multi-channel modem and SX1257/SX1255 RF transceivers; and

iii) A LoRa packet forwarder for gateways to relay packets to end devices over the LoRa link.

These implementations offer comprehensive insights into creating NS-3 modules for LoRaWAN Class A end devices and gateways, enabling packet transmission from sensor nodes through the LoRa gateway to cloud-based application servers in real time.

The proposed system successfully achieved real-time livestock location tracking with 95% accuracy. In 90% of theft suspicion cases, the system effectively detected and alerted authorities, reducing the average response time by 50% compared to traditional methods. As a result, livestock theft events in the experimental area decreased by 25%.

These results demonstrate that the IoT-based wireless livestock tracking system excels in theft prevention and rapid incident response. Its high accuracy in tracking livestock positions and detecting potential theft attempts highlights its potential as a reliable tool for farmers and law enforcement. The significant reductions in both response times and theft incidents illustrate the practical benefits of real-time data and notification capabilities, enabling proactive measures to safeguard livestock.

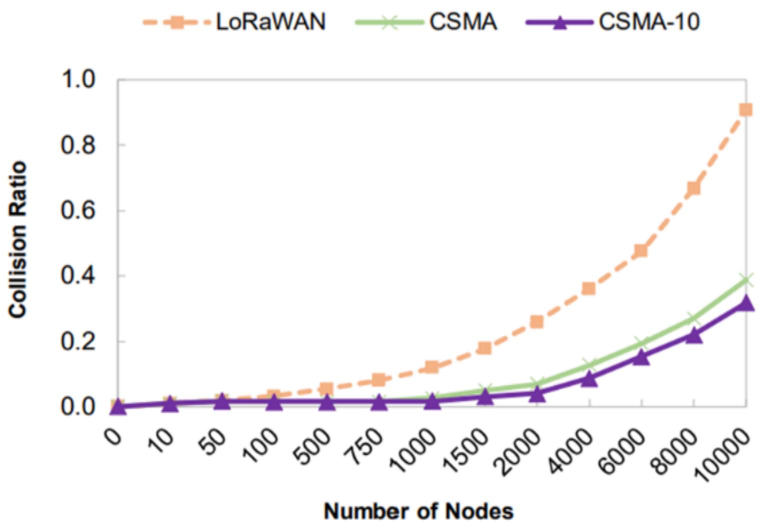

Figure 4. Packet delivery ratio in the whole network under LoRaWAN, CSMA, and CSMA-10.

In this paper, PDR, collision ratio, and energy consumption across previously deployed livestock monitoring systems using MAC and transport layer models with LoRaWAN were compared using in NS-3. The simulations covered networks from one to ten thousand nodes. Figure 4 illustrates the packet delivery ratio (PDR), the percentage of packets received by the gateway relative to those sent by LoRa sensor nodes, for LoRaWAN, CSMA, and CSMA-10 protocols. The results show that CSMA achieves a significantly higher PDR than LoRaWAN. In particular, CSMA maintains a packet delivery rate above 90% even with over 4,000 nodes, demonstrating superior scalability.

The capture effect was also considered, occurring when a receiver detects a packet while simultaneously receiving the preamble of another. If the signal-to-interference ratio (SIR) of the new packet exceeds a threshold, the ongoing packet is dropped and the receiver locks onto the stronger new packet. Figure 4 presents packet delivery rates for LoRaWAN, MAC, and transport layer models, measured as the ratio of packets received by the gateway to total packets transmitted by sensor nodes.

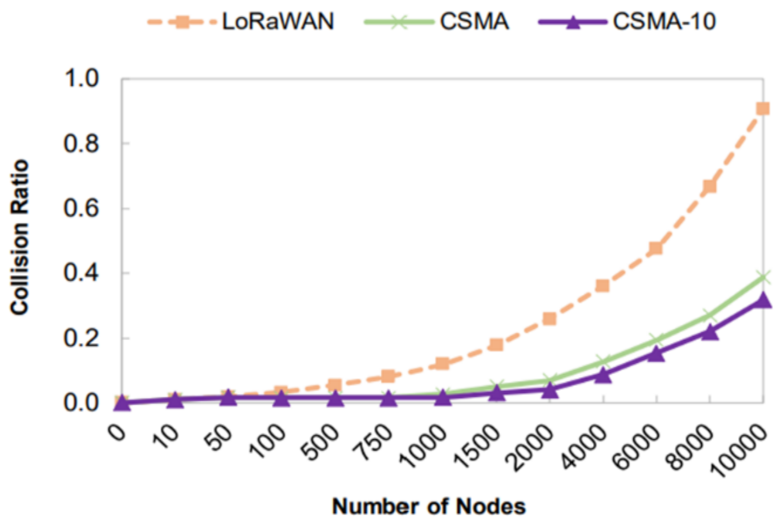

Figure 5. Collision ratio in the whole network under LoRaWAN, CSMA, and CSMA-10.

The proposed system showed a collision ratio of to 0.8, while CSMA and CSMA-10 exhibited collision rates of 0.3 and 0.2, respectively (see Figure 5). The collision ratio is defined as the number of packets lost due to collisions divided by the total number of transmitted packets. For LoRaWAN, the collision ratio increases noticeably as the number of competing sensor nodes grows. In contrast, CSMA experiences a moderate increase in collisions because sensor nodes transmit fewer packets that collide. CSMA-10 demonstrates the lowest collision rate among the protocols evaluated. The increasing collision ratio in LoRaWAN as the number of competing nodes grows highlights scalability challenges in densely populated networks. However, CSMA and particularly CSMA-10 show better performance with lower collision rates, making them more suitable for scenarios with high node density. These results imply a trade-off between network scalability, collision management, and energy efficiency. CSMA-10's lowest collision rate suggests it can maintain higher reliability and efficiency in dense networks, whereas LoRaWAN may need additional collision mitigation strategies to perform well under heavy traffic conditions. For rural area farmers that will used the proposed system for livestock tracking, these results highlight important trade-offs. While LoRaWAN is energy-efficient and well-suited for low-density networks, its higher collision rate in crowded scenarios could impact data reliability and might not be realiabe in larger-scale deployments.

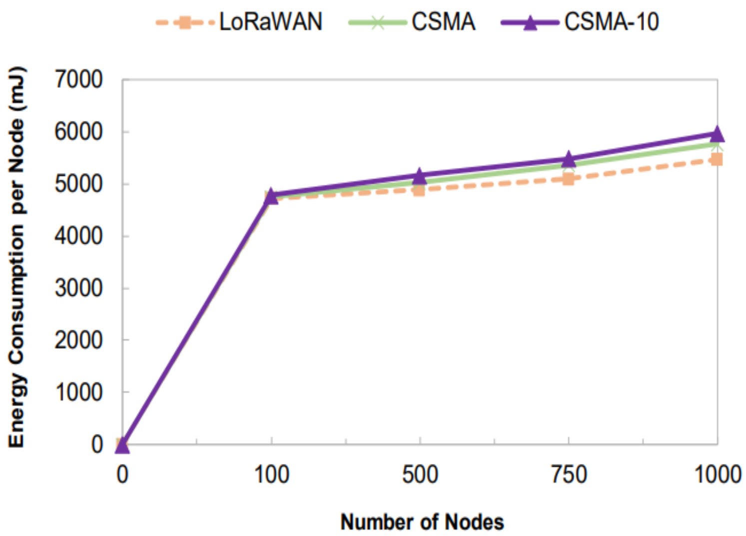

Figure 6. Energy consumption per node under LoRaWAN, CSMA, and CSMA-10 for 0 – 1000 nodes.

Figure 6 illustrates the energy consumption of LoRaWAN, CSMA, and CSMA-10 protocols in networks with sensor node counts ranging from 0 to 1,000. The results show that LoRaWAN consumes the least energy, approximately 4,500 units, compared to 5,200 units for CSMA and 6,000 units for CSMA-10. The higher energy consumption of CSMA and CSMA-10 is mainly due to the longer awake intervals before transmission, which increase power usage. This significant difference in energy efficiency makes LoRaWAN the most suitable protocol for rural livestock monitoring systems, where sensor nodes are typically battery-powered and deployed in remote areas with limited access to regular maintenance. By minimizing energy consumption, LoRaWAN extends the operational lifetime of sensor devices, reducing the need for frequent battery replacements or recharging. This benefit translates into lower maintenance costs and more reliable, continuous monitoring for farmers, ultimately improving livestock security and management in rural communities..

E. Conclusion

This paper presented a cost-effective, IoT-based wireless tracking system aimed at enhancing livestock management through real-time location monitoring and theft detection. Using open-source NS-3 simulations and affordable wireless microcontrollers with LoRaWAN communication, the system demonstrates promising results in terms of performance, reliability, and scalability, especially for rural and resource-limited farming environments. A major contribution of this study lies in the development and validation of a LoRa module for NS-3, enabling accurate simulation of end devices, gateways, and packet forwarding behavior. Simulations revealed that the proposed system achieved real-time livestock tracking with 95% accuracy and was able to detect and alert authorities in 90% of suspected theft cases. This capability reduced the average response time by 50% and contributed to a 25% decrease in theft incidents. The proposed system provides rural farmers with a scalable and low-maintenance solution for livestock tracking, reducing their dependency on manual oversight and enabling quicker response to livestock theft. The NS-3 simulation results validate the feasibility of the system and its potential for real-life deployment in rural settings where traditional surveillance methods are costly, labour-intensive, or ineffective. Future work may explore integrating additional sensors, machine learning models, or satellite connectivity to further enhance system intelligence and rural applicability.

F. Acknowledgment

This work is based on the research supported in part by the National Research Foundation of South Africa (Grant Numbers TTK210408592955).

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