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An IoT-Based Sensor Mesh Network Architecture for Waste Management in Smart Cities

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Abstract—**This paper introduces an Internet of Things (IoT) sensor mesh network architecture designed for smart bin management in urban areas with limited access to Long Range Wide Area (LoRa) networks. The research primarily focuses on deploying this mesh network to minimize infrastructure requirements while ensuring broad coverage and real-time monitoring. The system operates with a minimal number of gateways and integrates fill level sensors that communicate within the mesh, enabling continuous waste level data collection. Compared to traditional waste management systems that rely on fixed routes and schedules, this architecture provides a more adaptive and scalable solution. Conventional methods often fail to accommodate fluctuating waste generation patterns, leading to inefficiencies such as overflowing or underutilized bins. By leveraging real-time monitoring, the proposed mesh network improves waste collection efficiency and optimizes resource allocation. The study was implemented in Tangier, Morocco, where the results demonstrated the system's potential to improve urban waste management through reliable data-driven decision-making and optimized collection processes. Its deployment in Tangier underscores the feasibility and benefits of IoT mesh networks in building sustainable and efficient waste management solutions, particularly in rapidly expanding urban areas with constrained connectivity infrastructure.**

Keywords—**Internet of Things (IoT), sensor mesh network, smart Bin management, smart waste collection**

I. INTRODUCTION

The global Internet of Things (IoT) market is expected to grow significantly, from $662.21 billion in 2023 to $3,352.97 billion by 2030[1], at an average growth rate of 26.1%. This rapid expansion highlights the increasing adoption of IoT technologies across various sectors, particularly in Smart Cities (SC), where they enhance operational efficiency, cost reduction, service optimization, and risk management. Waste management is one of the critical urban challenges that IoT addresses through real-time monitoring and data collection capabilities [1], enabling the development of smart, interconnected systems that improve sustainability and resource utilization.

Traditional waste management approaches often struggle to handle the complexities and increasing volumes of urban waste. Smart waste management systems leveraging IoT aim to enhance efficiency by dynamically optimizing collection routes based on real-time data, reducing operational costs, and minimizing environmental impact. Low-power communication technologies such as Low Power Wide Area Networks (LPWAN), including LoRaWAN, have proven particularly effective due to their wide coverage, low power consumption, and scalability. However, alternative network architectures are required in urban environments where LoRaWAN access is limited.

This study investigates the deployment of an IoT sensor mesh network for smart bin management, specifically designed for urban areas with limited LoRa connectivity. The proposed architecture employs a minimal number of gateways while ensuring extensive coverage through a mesh topology. Fill-level sensors within the network enable continuous monitoring, and the collected data is forwarded to a central server to optimize waste collection operations. The system aims to reduce operational costs while minimizing the environmental footprint.

A case study conducted in Tangier, Morocco, evaluated the system's practical applicability. The results demonstrate that the mesh network successfully enables real-time data collection, leading to improved waste collection efficiency through optimized routing and resource allocation. By dynamically adapting to varying waste levels, the system minimizes inefficiencies such as overfilled or underutilized bins.

The paper concludes with recommendations for future research, emphasizing the further optimization of collection routes using predictive analytics based on bin fill-level data. Future work may also explore the integration of additional IoT technologies to enhance the adaptability and scalability of the system in different urban environments.

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[1] https://www.fortunebusinessinsights.com/industry-reports/internet-of-things-iot-market-100307

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II. RELATED WORK

A. *IoT Paradigm*

The “Internet of Things”, as termed by Kevin Ashton in 1999 [2], refers to an interconnected system where the Internet communicates with the physical world through ubiquitous sensors [3]. Its growing adoption is driven by its impacts on the economy, society, and environment. These impacts have been amplified due to COVID-19 management needs, with applications ranging from e-health to smart homes and transportation. IoT’s potential is realized through a technology stack, often conceptualized in layers within the IoT Architecture Reference Model, initially developed in 2010 by the IoT Architecture project (IoT-A) [2]. This model consists of three main layers: perception, network (communication), and application and service layers, but the number of layers may vary depending on the specific context and implementation [4].

The 3-layer architecture reference model

The 3-layer IoT Architecture Model comprises perception, network, and application and service layers [5], as illustrated in Fig. 1.

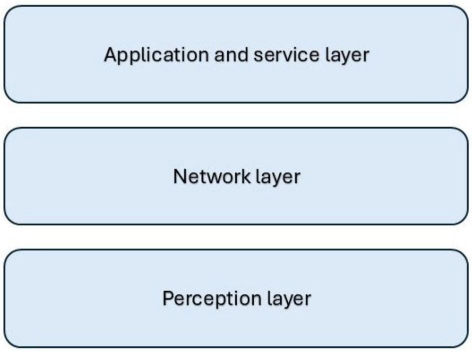

Fig. 1. IoT 3-layer reference model.

The perception layer of IoT collects data through sensors for real-time insights. The network layer ensures secure data transfer with efficient communication technologies. The application and service layer leverages collected data using analytics [6]. These layers use specific evolving technologies, including sensor technologies, wireless communication, edge computing, cloud computing, and big data platforms.

B. *Enabling Technologies*

IoT is powered by a stack of technologies that work together to connect devices, facilitate data transfer, and enable the use of that data for actionable insights. These enabling technologies can be broadly categorized into the three layers previously explained: the perception layer, Network layer, and application and service layer. Each of these layers leverages certain key technologies.

In the IoT architecture, the perception layer is essential for real-time data collection from sensors and devices. Key components include sensors that capture environmental factors autonomously and devices that feature a holder, controller, sensors, and actuators. Controllers can be coded in languages like C, C++, and Arduino, while actuators that enable motion and control in various forms are coded in Arduino, Raspberry Pi, and Programmable Logic Controllers (PLCs) for industrial applications. Overall, this layer serves as the cornerstone for data acquisition and control in IoT systems.

In the IoT network layer, key technologies address varied connectivity needs. These technologies provide a range of connectivity options tailored for specific IoT applications. Bluetooth Low Energy (BLE) and Near Field Communication (NFC) are designed for short-range tasks in wearables and smart homes. Long-Term Evolution for Machines (LTE-M) facilitates high-speed data exchange ideal for industrial automation, while Narrowband Internet of Things (NB-IoT) operates on low-frequency channels suitable for smart metering and environmental monitoring. LPWAN, including technologies like LoRa, is used for long-range, low-power applications in sectors like smart city applications and agricultural sensors. LPWAN technologies promise long-range, low-power consumption, and low cost for both devices and infrastructure, and can connect a massive number of devices.

Finally, the application and service layer in the IoT model focuses on real-time monitoring, analysis, and decision-making. Key technologies include Cloud Computing for centralized data management, Edge Computing for low-latency real-time decisions, and Web Services for seamless device-application integration.

In some applications like waste management, smart lighting, and smart parking management for smart cities, LPWAN technologies are well-suited.

Characteristics of LPWAN technologies

Both LoRaWAN [7] and other LPWAN (Low Power Wide Area network) technologies aim to provide wide-area network coverage for IoT devices and applications that require low power consumption and long-range connectivity. These technologies are designed to support IoT applications that do not demand high data rates but require long battery life and extensive coverage.

Table 1 outlines the main characteristics of LPWAN.

TABLE I. CHARACTERISTICS OF LPWAN TECHNOLOGIES

LPWAN Features	Description
Low power consumption	Due to low data rates, LPWAN technologies are suitable for devices that need to operate with small batteries for extended periods. This is crucial for applications where recharging batteries frequently is impractical.
Wide area coverage	Capable of covering several kilometers in urban areas and tens of kilometers in rural areas.
Low data rate	Supports the transmission of small data amounts at infrequent intervals.
Cost effective	Lower deployment and operational costs compared to traditional cellular networks.
Scalability	Can support many devices within a single network.
Reliability in urban settings	Effective data transmission in environments with closely spaced buildings and basements, better than higher-frequency signals.

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[2] Internet of things architecture | IOT-A | project - cordis. (n.d.). https://cordis.europa.eu/project/id/257521

The following sections highlight IoT-enabled waste management in smart cities, focusing on operational efficiency and cost-effective implementations in urban settings with limited infrastructure.

C. IoT-Enabled Waste Management in the Context of Smart Cities

A smart city is a municipality that leverages Information and Communication Technologies (ICT) to enhance operational efficiency, foster public information sharing, and improve the quality of government services and citizen well-being. According to Ref. [8], who have extensively researched smart cities, six primary dimensions can be distinguished: smart economy, smart mobility, smart governance, smart environment, smart living, and smart people, as shown in Fig. 2. These dimensions encompass various aspects of the city's functioning and are supported by ICT components, including IoT technologies such as sensors, devices and, actuator, along with software applications for data collection, storage, and analysis.

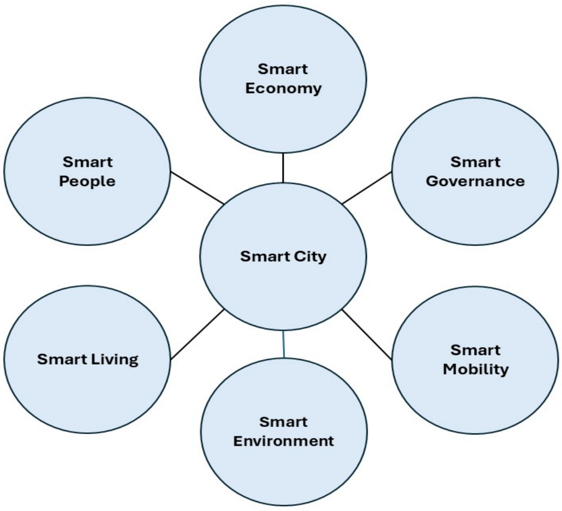

Fig. 2. Smart city dimensions, adapted from [9].

The growth of population and rapid urbanization has resulted in a significant increase in waste generation, rendering traditional waste management methods obsolete and costly. To address the needs of smart cities and improve the quality of life for citizens while preserving the environment, a revolution in waste management practices was necessary. Smart waste management has emerged as a strong response and a key driver in adapting to the variations in waste generation patterns, such as fluctuations during breaks, seasons, and special occasions.

Traditionally, waste management involves a set of activities, including collection, transportation, cleaning, disposal, and recycling [10]. Solid waste management specifically focuses on waste generated by households, which can be categorized into four main types: domestic waste (produced by households), street waste, green waste (referring to organic waste such as garden trimmings), and rubble (construction and demolition waste).

In urban and rural areas, waste management is typically the responsibility of the municipality. For instance, in main urban areas in Morocco, solid waste collection is carried out by private operators contracted by the municipality, according to specific guidelines[3] *(Ministère de l'Energie, des Mines, de l'Eau et de l'Environnement)*. The involvement of private firms aims to improve collection efficiency.

Nowadays, IoT technology plays a vital role in enhancing this efficiency. IoT enables the management and monitoring of various aspects of waste management, including:

- On-board tracking and geolocation of vehicles to optimize route planning, fuel usage, and reduce congestion.
- Monitoring the completion of sweeping and cleaning circuits [11].
- Capturing, analyzing, and monitoring environmental data using sensors [12].

Monitoring the filling levels of containers [13].

The first three aspects do not require LPWAN architectures, as they utilize existing Global Positioning System (GPS) and cellular infrastructure (GSM/GPRS–Global System for Mobile Communications/General Packet Radio Service):

1) Sweeping carts: These are equipped with IoT devices and return to collection centers for recharging.
2) Collection vehicles: The equipment installed on trucks and other collection vehicles recharges directly from the vehicles' batteries.

The challenge of broadband and low power arises only for monitoring the filling levels of containers. Once mounted at a fixed location, the containers remain stationary, except for wear and tear on plastic containers due to harsh environments.

The remainder of this paper will focus on architectures that provide effective contributions to the problem of monitoring the filling levels of containers.

The following section will offer an overview of existing sensor network architectures for smart monitoring of the filling levels of containers, with or without implementation.

D. An Overview of Sensor Network Architectures for Smart Monitoring of The Filling Levels of Containers

As noted by Abdallah *et al.* [13] present a GIS-based smart waste collection system designed to optimize routes based on real-time bin fill levels. The system aims to reduce travel time, costs, and emissions associated with waste collection. Utilizing LoRaWAN for wireless communication, the system integrates weight sensors (load cells) and level sensors (ultrasonic, capacitance, optical) to monitor fill levels. The architecture emphasizes LoRaWAN for efficient data transmission between smart bins and a central control unit. The design and implementation involved field surveys, a knowledge-based

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[3] Ministère de l'Energie, des Mines, de l'Eau et de l'Environnement. (n.d.). Modèle de convention pour la gestion déléguée des services de propreté [PDF document]. Retrieved from https://pndm.environnement.gov.ma/sites/default/files/DAO_proprete_Convention.pdf

algorithm, GIS tools, and simulation scenarios to validate the system's effectiveness.

As stated by Vishnu, *et al.* [14], an IoT-based architecture is proposed that leverages LoRaWAN and Wi-Fi for the real-time monitoring of waste bins in both public and residential areas. The research aims to optimize waste management processes by utilizing two types of networks: LoRaWAN for Public Bin Level Monitoring Units (PBLMUs) and Wi-Fi for Home Bin Level Monitoring Units (HBLMUs). Integrated sensors are connected to both PBLMU and HBLMU, which communicate with a central monitoring station through end sensor nodes. The design and experimental validation of end nodes were performed, though the system has not been deployed on a large scale. Under hypothetical conditions, the life expectancy of a PBLMU was estimated to be approximately 70 days.

According to Roy *et al.* [15], an IoT-based smart bin allocation and vehicle routing system is proposed for solid waste management in South Korea. Tested in the districts of Gwanak and Guro in Seoul, the system uses a combination of Wi-Fi and GSM for communication, with Wi-Fi modules (ESP8266) transmitting real-time data from the smart bins to a Central Monitoring System (CMS). Sensors detect waste levels in the bins, and the network architecture facilitates improved efficiency and reduced costs through intelligent data transmission and routing optimization

Yerraboina *et al.* [16] discusses the development and implementation of a smart bin system using ultrasonic sensors and GSM/GPRS modules for real-time monitoring of waste levels. The existing network infrastructure relies on GSM/GPRS modules for communication between smart bins and the central monitoring system. The smart bins, equipped with ultrasonic sensors, send real-time fill level data to a central server, which is then displayed on a web-based dashboard for waste management authorities. The design and experimental setup were conducted, but the exact battery life of the system was not specified.

Yusof *et al.* [17] describe the design and implementation of a smart waste bin system that utilizes ultrasonic sensors and GSM modules for real-time waste level monitoring. The system employs GSM modules for communication and integrates sensors to monitor waste levels, transmitting data to a central server. The architecture includes creating a real-time monitoring interface for efficient waste management. The design and experimental setup were completed, although the specific battery life of the system was not detailed in the document.

All the studies discussed in these papers utilize various sensors to collect field data, particularly the fill levels of bins, and then communicate with a central server for decision-making, such as scheduling collection plans based on the fill status of the bins.

E. Comparative Analysis of Smart Waste Management Systems

These papers provide a clear picture and use cases of using different protocols for monitoring the filling levels of containers and optimizing collection operations.

All studies use various sensors to collect field data, particularly bin fill levels, and then communicate with a central server for decision-making, including scheduling collection plans based on bin status. Sensors used include weight sensors (load cells) and level sensors such as ultrasonic, capacitive, and optical sensors.

For communication between bins and the server, different protocols are used, notably Wi-Fi. The paper by the authors in Ref. [15]. does not explicitly confirm the availability of Wi-Fi in the specific areas where the smart bins are deployed. However, the proposed system relies on Wi-Fi modules for data transmission, indicating that the implementation assumes the availability of Wi-Fi networks in these areas. Ensuring Wi-Fi coverage is crucial for the system's effectiveness in real-world applications.

The use of GSM networks in Refs. [16, 17] is a relatively easy solution to implement given the availability of GSM/GPRS networks. However, it is costly, with disadvantages such as higher battery consumption and subscription costs compared to LoRaWAN.

In works relying on LoRaWAN [13, 14], it is assumed that a LoRaWAN network already exists, which may not be the case in the specific scenarios discussed in these papers. LoRaWAN offers advantages in terms of battery efficiency and cost-effectiveness, but its implementation can be challenging without an existing network.

TABLE II. COMPARISON OF IOT-BASED SMART WASTE MANAGEMENT ARCHITECTURES

Study	Technologies	Infrastructure hypothesis	Implementation	Cost and battery consumption
[13]	LoRaWAN, GIS	Requires existing LoRaWAN infrastructure	Field surveys and simulations	Low cost if LoRaWAN exists. High battery life.
[14]	LoRaWAN, Wi-Fi	Requires existing LoRaWAN infrastructure and Wi-Fi connectivity	Experimental validation only	Low cost for LoRaWAN; moderate for Wi-Fi. Moderate to high battery life.
[15]	Wi-Fi, GSM	Requires available Wi-Fi and GSM network	Tested in Gwanak and Guro districts, Seoul	Moderate to high cost. Moderate battery life.
[16]	GSM/GPRS	Requires GSM/GPRS network for communication	Development and Experimental Setup	High cost; subscription and energy costs. Moderate battery life.
[17]	GSM	Requires GSM network for communication	Development and experimental setup	High cost; subscription and energy costs. Moderate battery life.
This study	LoRaWAN, GSM/GPRS	No existing LPWAN required	Fully implemented and deployed in Tangier, Morocco	Low cost. High battery life.

In conclusion, each approach has distinct advantages and disadvantages. LoRaWAN provides better energy efficiency and lower costs but requires existing infrastructure. Wi-Fi allows high data transfer rates but depends on reliable coverage and higher power consumption. GSM/GPRS, while easily available and reliable, incurs higher costs and power usage, limiting its long-term effectiveness. For all these works, it is assumed that Wi-Fi or LoRaWAN networks already exist.

Table II provides a comparative analysis of the IoT-based smart waste management architectures discussed, including the work presented in this study. The comparison focuses on the technologies employed, infrastructure requirements, implementation status, and cost considerations.

Across urban environments, particularly in developing countries, a core issue is the lack of an established LoRa network or any similar Low-Power, Wide-Area Network (LPWAN) technology. Such networks are crucial for electronic sensors that track the level of bin filling and need to transmit data efficiently while conserving battery life. This is a significant advantage over more power-intensive options like GSM and Wi-Fi.

The remainder of this paper addresses the challenge of monitoring the fill levels of waste containers to generate optimized collection routes in areas where an established LoRa network or similar LPWAN technology is either lacking or very limited.

1) Cost-effective architecture: Emphasizes creating a cost-effective architecture that minimizes the number of required gateways and reduces infrastructure costs, ensuring practical implementation in urban settings with limited connectivity.
2) Battery management for fixed bins: Tackles the constraint of battery management for sensors, especially when recharging is impractical, such as in fixed waste bins, focusing on optimizing battery life for long-term, reliable operation.

III. AN IOT SENSOR NETWORK ARCHITECTURE FOR SMART BIN MANAGEMENT IN SMART CITIES

In waste management, traditional collection strategies follow predetermined schedules, frequencies, and route plans, as illustrated in Fig. 3. These plans, established through agreements between waste management operators and local governments, ensure comprehensive coverage of all urban zones, including residential, administrative, economic, and touristic areas. Furthermore, each vehicle is assigned predefined circuits and a fixed operational schedule.

However, this rigid approach does not account for variations in waste generation, which fluctuate seasonally or during special events. These fluctuations impact resource allocation, vehicle utilization, fuel consumption, and emissions, leading to inefficiencies.

To address these challenges, advanced waste management strategies prioritize real-time monitoring of bin fill levels, enabling:

- Monitoring waste collection operations on the ground - using real-time data to track the progress and efficiency of waste collection.
- Identifying filled bins that require immediate attention –ensuring timely and efficient collection services by monitoring which bins reach capacity.
- Optimizing collection routes based on actual demand - analyzing fill-rate data enables dynamic adjustment of routes to prioritize fuller bins, saving time and resources.

This study develops a cost-effective and efficient smart bin management system in Tangier, Morocco, where no LoRaWAN communication infrastructure is available. Due to financial and technical constraints, GSM/GPRS networks were not a viable alternative, given their high cost and excessive power consumption.

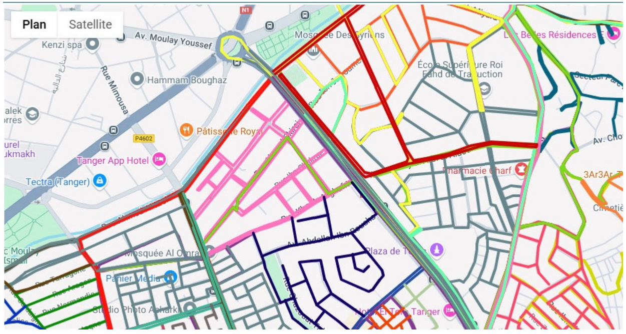


Fig. 3. An example of predefined circuits.

The initial deployment in Tangier required the installation of multiple gateways across the city to collect sensor data and transmit it to central servers at specified intervals. However, this approach incurred significant costs, as each gateway required a continuous power supply, a stable internet connection, and substantial acquisition expenses.

The typical architecture is depicted in Fig. 4:


Fig. 4. Architecture with multiple gateways.

The proposed solution, which constitutes the focus of this study, involves the implementation of a synchronized IoT mesh network for fill-level sensors, significantly reducing the number of required gateways to only a few, depending on the geographical area covered.

This approach addresses three main challenges: optimizing battery life to manage high-power consumption associated with GSM/GPRS networks, minimizing the number of required gateways to reduce infrastructure costs, and ensuring effective operation in urban settings with limited connectivity and no access to established public or private LoRaWAN networks.

The following section presents the methodology and proposed architecture, covering key aspects such as device implementation, data transmission mechanisms, GPS integration, and real-time data monitoring and analytics.

A. Methodology

The design and implementation of the IoT mesh network involved the following steps:

1) The creation of mesh network

The creation of a mesh network for fill level sensors involved developing custom firmware to enable communication within the network. Each sensor was equipped with a transceiver, allowing it to act as both a data transmitter and relay point. Sensors were strategically arranged to optimize data paths, utilizing multi-hop communication to ensure data from all sensors could reach the gateway. Dynamic routing protocols were implemented to allow automatic adjustment of data transmission paths based on sensor availability and connectivity, ensuring continuous data flow even if some sensors failed. This design significantly reduced the number of required gateways, minimizing infrastructure costs and simplifying the network architecture.

Mesh networks are typically established between sensors connected to the power grid, continuously powered by external sources. The innovation in our case lies in creating a mesh network between sensors that are battery-powered, with a lifespan of at least five years. Furthermore, a unique aspect of our design is that all sensors enter sleep mode to conserve energy and wake up simultaneously for data transmission, after which they return to sleep. This synchronized sleep-wake cycle ensures energy efficiency and extended operational life

2) Synchronization and power management

Synchronization and power management of the sensors were optimized by integrating a time synchronization protocol into the sensor firmware, ensuring all sensors operated on a synchronized schedule to conserve battery life.

Between data transmission intervals, sensors entered an ultra-low-power sleep mode, as shown in Fig. 5, reducing power consumption to 378 uA, thus extending the battery life to 3,651 days (10 Years) on a 2 × 1,800 mAh battery.

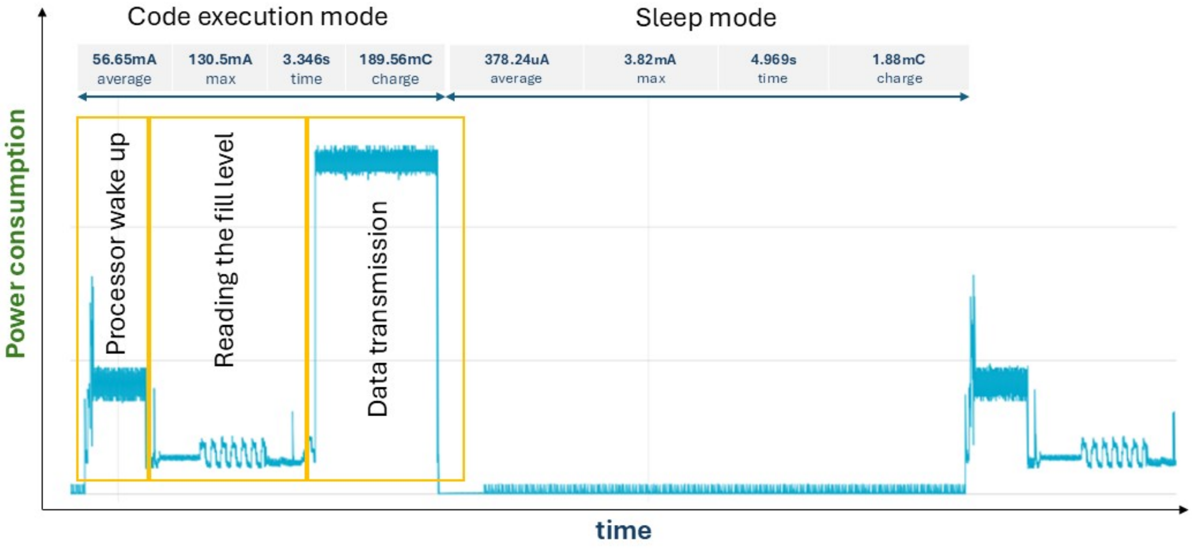


Fig. 5. Battery consumption by mode.

A wake-up scheduling mechanism coordinated the sensors' brief power-up periods for data transmission, minimizing energy usage and ensuring timely updates. Additionally, sensors were equipped with battery monitoring capabilities, allowing them to report battery status alongside fill level data, facilitating proactive maintenance and ensuring continuous network operation.

Nevertheless, two major challenges emerged during this process:

1) Desynchronization over time: over time, the sensors lose synchronization. Some would wake up late, missing the data transmission window. This led to data loss, not just from the late sensors but also from those relying on them to relay data to the gateway.
2) Mass synchronization difficulties: synchronizing thousands of sensors to wake up and transmit data at the exact same moment, then return to sleep to conserve battery life, was a daunting task, especially when done manually.

Indeed, time synchronization is a critical aspect of the mesh network architecture for several reasons related to battery conservation as:

- Coordinated sleep and wake cycles
- Reduced idle listening
- Optimized data transmission windows
- Prolonged sensor lifespan

To address these challenges, two technical solutions were proposed and used:

3) *Use of advanced RTCs (Real-Time Clocks)*

Sensors were equipped with highly precise RTCs, as shown in Fig. 6, that included features for aging and temperature compensation. These RTCs were integral in helping the sensors' microprocessors accurately enter and exit deep sleep mode at scheduled times, ensuring effective synchronization across all sensors.

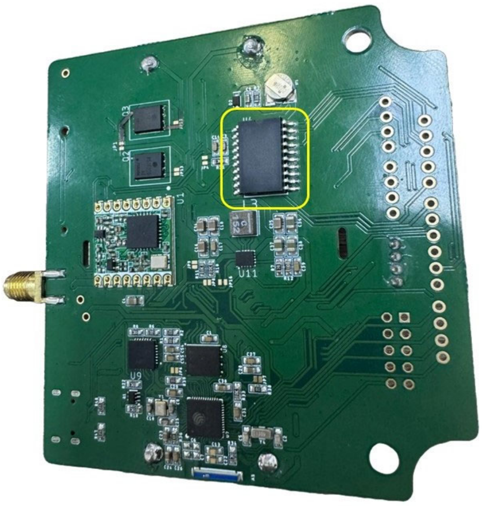


Fig. 6. Real-Time Clock (RTC) module used for precise time synchronization in the IoT mesh network.

The RTC that was used in our application is the DS3232 from Maxim Integrated, which is an extremely Accurate I²C-Integrated RTC/TCXO/Crystal.

4) *Use of GPS modules for time sync*

To achieve precise synchronization across multiple sensors, an approach was employed using disconnectable GPS modules like the SIM39EA from SIMCom. These GPS modules were temporarily connected to sensors via M.2 connectors, allowing each sensor to receive accurate time data derived from the GPS signal. The GPS module extracts highly precise Coordinated Universal Time (UTC) from satellite signals, which is then transmitted to the sensor's Real-Time Clock (RTC) via a standard I2C interface. The RTC is updated to reflect the correct time, enabling the sensor to timestamp its operations accurately. Once the synchronization process is complete, the GPS module is disconnected and used with another sensor, optimizing resource utilization and reducing costs.

The SIM39EA module was chosen for its compact size, low power consumption, and high sensitivity, making it ideal for portable and embedded applications. It supports standard GPS outputs, such as NMEA sentences and Pulse-Per-Second (PPS) signals, ensuring reliable and precise time synchronization. The module's compatibility with M.2 connectors facilitates easy temporary connections. By leveraging the SIM39EA's capabilities, this solution ensures all sensors operate with synchronized time, critical for applications requiring precise data alignment, such as multi-sensor systems or distributed networks. Fig. 7 represents the Disconnectable GPS module used for time synchronisation.

By implementing advanced RTCs and enhanced use of GPS modules, the challenges of desynchronization and mass synchronization were effectively addressed. These solutions ensured that the sensor network remained highly synchronized, conserving battery life and maintaining reliable data transmission.

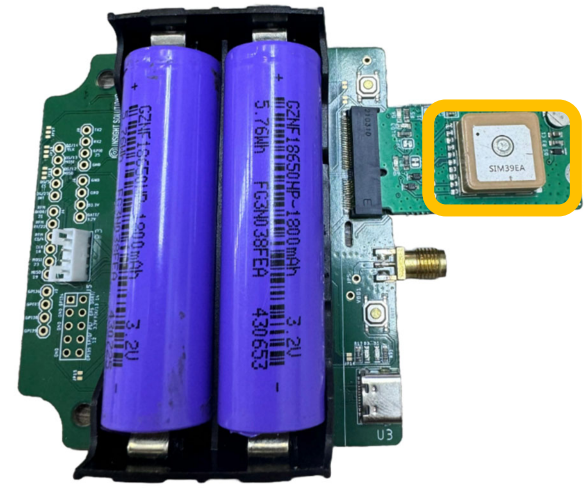


Fig. 7. Disconnectable GPS module used for time synchronization in the IoT mesh network.

The following section details the proposed mesh network architecture.

B. *Proposed Mesh Network Architecture*

The system, including the software and hardware, implements the three-layer architecture reference model.

1) *Device*

TABLE III. KEY COMPONENTS OF THE PERCEPTION LAYER

Component	**Function/Description**
Battery and charging system	Autonomous operation without the need for a continuous source of electric current.
Fill level sensors	Detect the fill levels of waste bins using ultrasonic distance sensor.
Embedded software	Controls the operation of the sensors, managing data collection, processing, synchronization, and communication.
Advanced RTCs	Ensure precise timekeeping for synchronized sleep and wake cycles, conserving battery life. The extracted time data from the GPS module is saved in the RTC. The RTC is programmed to wake the microprocessor after exactly 3600 seconds or a predefined interval. The microprocessor enters an ultra-deep sleep mode to conserve battery power, while the RTC maintains the accurate timing.
Disconnectable GPS modules	Provide accurate time data to the RTCs, ensuring initial synchronization of all sensors.
Microprocessors	Control the operation of the sensors, executing the embedded software.
Batteries	Provide power to the sensors, ensuring continuous operation.
Transceivers	Enable communication between sensors within the mesh network.
GPS module	The GPS module is inserted into the M.2 connector and detected by the microprocessor.

The perception layer is the foundation of the synchronized mesh network system, responsible for collecting and processing raw data from the physical environment. This layer includes several key components and phases to ensure efficient data collection, synchronization, and power management.

The key components of the perception layer as well as their main functions are outlined in Table III.

Fig. 8 represents the associated electronic board:

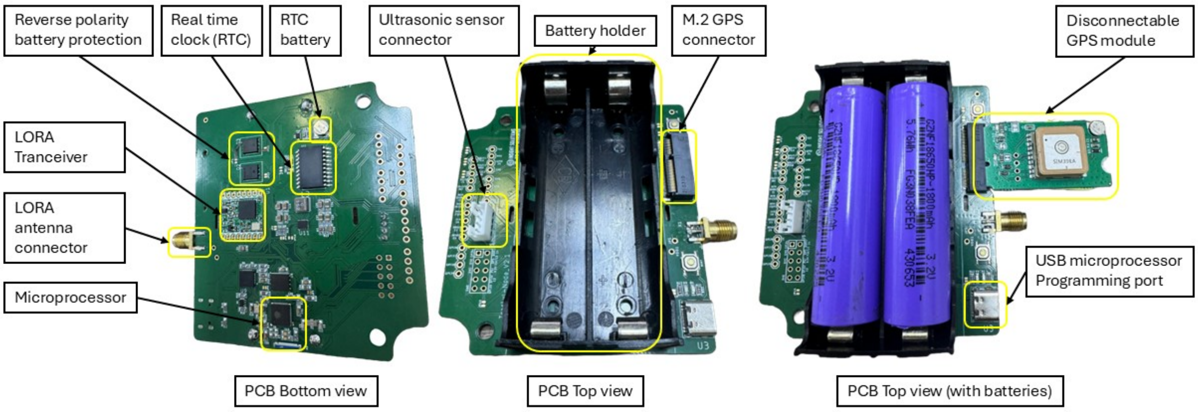


Fig. 8. Electronic board.

2) *Data forwarding*

The key components responsible for the data forwarding layer and their main functionalities are outlined in Table IV.

This detailed explanation of the network layer highlights the processes involved in data trans-mission, synchronization, and aggregation, ensuring efficient and reliable communication within the synchronized mesh network for waste bin fill level monitoring.

3) *Real-time data monitoring and analytics*

The application layer provides tools for real-time monitoring, data analysis, and decision-making [18], offering interfaces for users to interact with the system effectively.

The key components of the application layer as well as their main functionalities are outlined in Table V.

TABLE IV. KEY COMPONENTS FOR DATA FORWARDING

Component	**Function/Description**
Mesh Network	- Interconnected network of sensors relaying data. - Enables long-range communication without multiple gateways. - Sensors form a mesh network upon deployment - Establishes multiple communication paths for data transmission.
Gateways	- Receive aggregated data from sensors. - Transmit data to central servers. - Data formatted in JSON and sent via HTTPS. - Interface between network layer and application layer.

TABLE V. KEY COMPONENTS OF THE APPLICATION LAYER

Component	**Function/Description**
Central servers, implementing producers and consumers and message queues	- Handle data reception, processing, and storage from the gateways
User Interfaces	- Offers user-friendly interfaces like mobile apps or Web applications for various stakeholders, including waste management personnel and city administrators. - Facilitates interaction with the system, enabling users to view data, configure settings, and receive notifications
Data Analytics Software	- Enables real-time monitoring of waste bin fill levels, sensor status, and network health - Provides tools and algorithms for analyzing data to derive insights.

Fig. 9 illustrates the system architecture, highlighting the communication flow from IoT-equipped bins to the central servers and application layer. The perception layer consists of node sensors deployed on waste bins, interconnected via a LoRa mesh network. These sensors relay the fill levels data, to a connected gateway using the energy-efficient LoRa protocol. The network layer handles data transmission from the gateway to central servers via GSM/GPRS or other protocols, using HTTP POST requests formatted in JSON. A message queue at the server ensures reliable delivery of incoming data, even under high loads. The application and service layer processes this data through multiple consumers threads, stores it in a central database, and exposes it via APIs and services for real-time monitoring, reporting, and decision-making. This architecture ensures efficient, scalable, and reliable communication and data management for smart waste management operations.

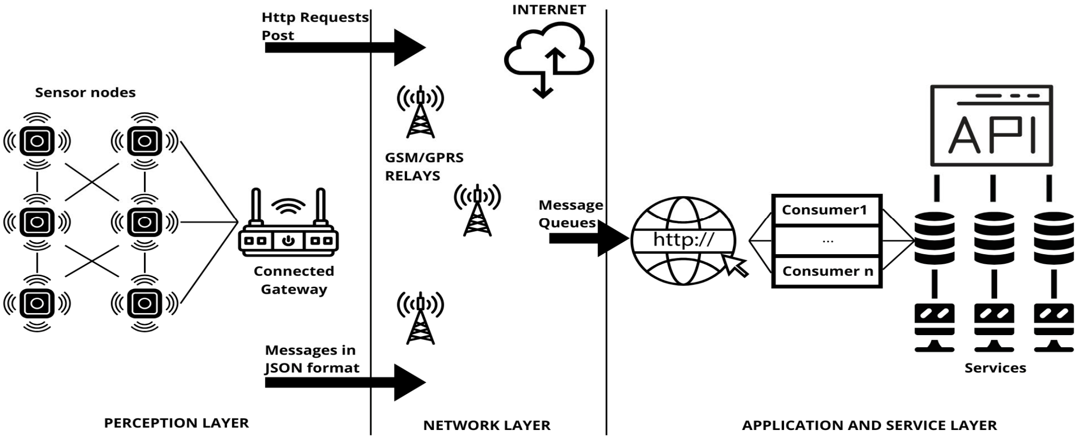


Fig. 9. Modes and formats of communication between edge devices and servers.

In the upcoming chapter, the practical aspects of the system's implementation will be explored. These tests are crucial as they verify the system's functionality in real-world environments and identify potential areas for improvement. Results from deploying the system in Tangier, Morocco, will be shared, demonstrating how the IoT-enabled system operates in real-world conditions and transmits data in real-time.

IV. CASE STUDY IN TANGIER, MOROCCO

Tangier is a major city in northern Morocco that has a population of approximately 1.5 million people [19]. The city has been experiencing growth due to its important status as a business hub and port, as well as a touristic destination. Tangier is projected to witness a population surge of 16.45% over the next seven years.

A. Traditional Waste Collection Strategy

The traditional waste collection strategy in Tangier relies on predetermined routes and frequencies, planned according to an agreement between waste management operators and local authorities. These plans aim to provide comprehensive coverage across all city zones, including residential, administrative, economic, and touristic areas. The schedules are fixed, with collection routes following a consistent pattern regardless of actual waste generation levels. To ensure compliance, RFID systems are used to tag bins and equip trucks with antennas, verifying that all bins are collected as scheduled. Additionally, trucks are equipped with GPS devices to ensure adherence to the predetermined routes.

Fig. 10 illustrates an installation of RFID systems in trucks that collect bins and in the bins themselves.

Fig. 10. RFID system for identifying and tracking waste bins.

Fig. 11 is an extraction from the monitoring Web application that depicts bin collection status using RFID systems. Green bins indicate emptied bins, while red bins indicate bins that have not been collected yet for the selected analysis time interval.

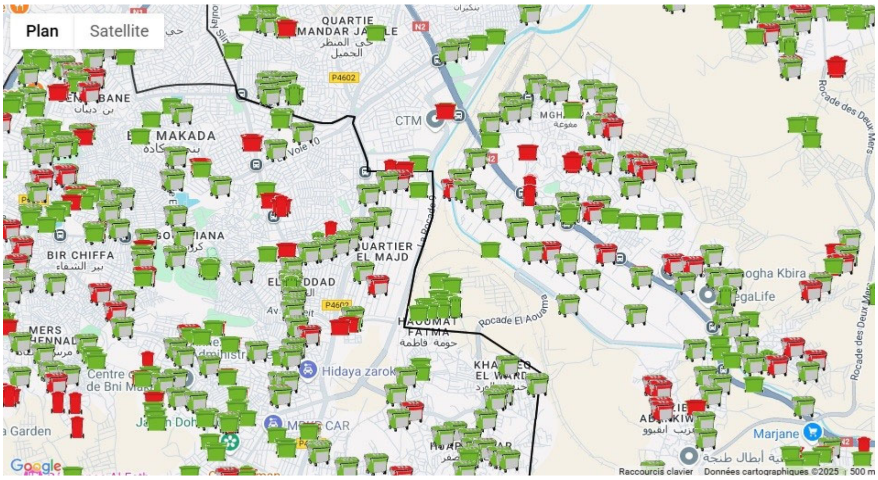


Fig. 11. Monitoring of waste bin collection.

However, this rigid strategy does not accommodate seasonal or occasional fluctuations in waste generation, leading to inefficiencies. High-demand areas may experience bin overflows, while nearly empty bins in other zones result in wasted resources, increasing fuel consumption, operational costs, and environmental impact. The lack of real-time data monitoring and adaptive routing exacerbates these issues, leading to suboptimal resource utilization and higher maintenance costs. Although RFID and GPS systems ensure route compliance, the traditional approach is limited by its inability to adapt to real-time conditions. This highlights the need for a more flexible, data-driven approach to waste collection, which can dynamically adjust to changing waste generation patterns.

To address these inefficiencies, it is crucial to identify locations with the highest demand for waste collection and propose the most cost-effective and efficient routes based on distance traveled. By optimizing collection paths, the overall operational costs can be reduced while ensuring effective waste management practices.

B. Deployment of IoT Sensor Mesh Network Architecture

1) System overview

In the initial setup, 455 above-ground trash containers were equipped with fill level sensors to enhance waste collection efficiency. Initially, data transmission from these sensors was proposed to be supported by 28 gateways and 34 signal repeaters, forming a network that enabled data transfer to central servers.

In the enhanced architecture, the system transitioned to a mesh network to reduce the costs and simplify the installation process. The mesh network allowed sensors to relay data through intermediate sensors, reducing the need for multiple gateways. Consequently, the number of required gateways was decreased to two, and no repeaters were necessary. This approach utilized existing sensors to create a robust, interconnected network, enhancing data transmission coverage and reducing infrastructure costs.

2) Deployment details

The deployment process involved several key steps. The deployment of the mesh network involved reconfiguring the existing fill level sensors and setting up a new network topology, as depicted in Fig. 12.

The sensors were reprogrammed to operate as nodes within the mesh network, enabling them to communicate and relay data efficiently. Two strategically placed gateways ensured optimal coverage and connectivity across the entire network. Unlike the initial implementation, no additional repeaters were required, simplifying the deployment process and reducing infrastructure costs.

Battery efficiency was a significant focus during this phase. Some sensors experienced increased battery usage due to their data-relaying role. To address this, lower Spreading Factors (SF) were employed in most cases, reducing transmit power and conserving battery life. The spreading factor in wireless communication, especially in LoRa technology, balances data transmission speed and range. Lower SF results in faster transmission but shorter range, while higher SF allows for longer range at a slower rate. Adjusting the SF optimizes battery life and signal reliability, ensuring efficient data transmission. In the mesh network implementation, using lower SF helped conserve battery power, while higher SF was used for reliable long-distance communication. In extreme cases, where higher SF was necessary, battery sizes were doubled to compensate for increased power consumption.

Fig. 12. The IoT mesh network typology.

3) Operational workflow

In the initial setup, each fill level sensor installed in the trash containers periodically measured the fill levels. When a sensor detected that a container was nearing capacity, it transmitted this data wirelessly to the nearest gateway. The gateways collected data from multiple sensors and relayed it to the central servers. In cases where direct communication with a gateway was obstructed by buildings or other structures, signal repeaters were used to retransmit the signals, ensuring reliable data transmission to the central servers.

In the enhanced architecture, the operational workflow of the mesh network was more dynamic and adaptive. Each fill level sensor in the trash containers periodically measured the fill levels. Sensors that were out of direct communication range with the gateways transmitted their data through neighboring sensors, creating multiple hops until the data reached the gateways. This multi-hop communication ensured efficient data relay, regardless of the sensor and gateway location. The 2 gateways collected data from the mesh network and transmitted it to the central servers for processing and analysis. The mesh network’s self-healing capabilities ensured continuous operation and data integrity by automatically rerouting data through alternative paths if a sensor or communication path failed.

4) Improved data transmission efficiency in he enhanced architecture

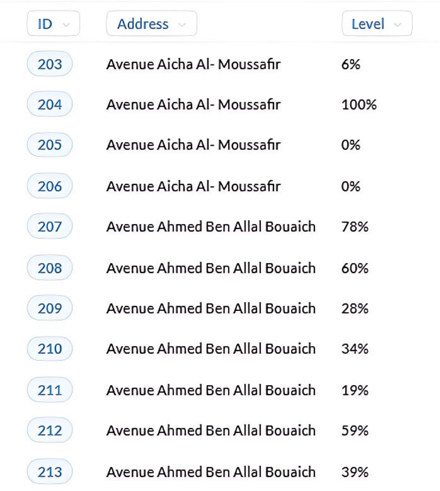
In the previous architecture with multiple gateways, the system achieved a 98% efficiency rate in terms of data successfully reaching the gateways. Over a period of one month, 2% of the 455 sensors—equivalent to approximately 9 sensors—were out of reach due to citizen interaction with the trash containers. In many cases, citizens moved containers equipped with sensors into building basements, locations with poor signal coverage, or other areas entirely out of the gateways’ communication range. These obstructions prevented the sensors from transmitting data, leading to data loss and impacting the accuracy of real-time monitoring and analytics.

The enhanced mesh network architecture effectively resolved this issue through its multi-hop communication capabilities and self-healing design. Even when containers were moved into basements, areas with poor coverage, or other obstructed locations, the system could rely on neighboring sensors in nearby containers to relay the data. This ensured that information from all sensors eventually reached the gateways, regardless of their physical location. As a result, the monthly data loss in the new architecture was reduced to just 0.5%—or approximately 2 sensors—a significant improvement over the previous 2% loss. This enhancement was particularly valuable in dynamic urban environments, where citizen interaction with trash containers is common, making the enhanced architecture a more robust and adaptive solution for real-time waste management.

Fig. 13 illustrates data forwarded to the platform including the fill level.

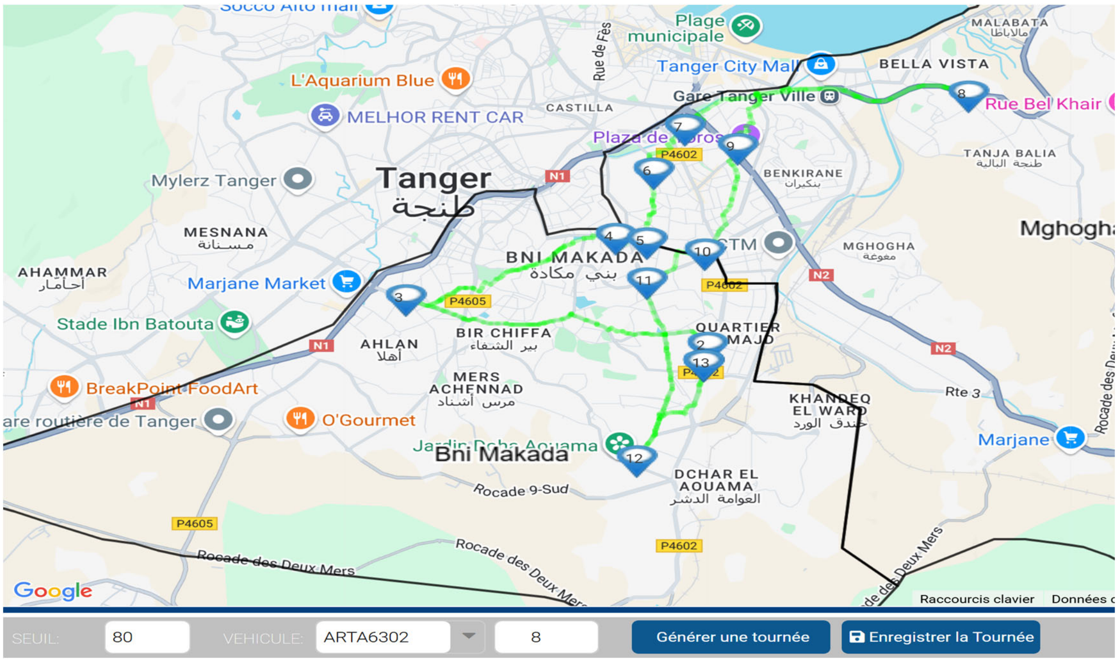
5) Results

In addition to implementing a cost-effective IoT sensor infrastructure, providing extensive area coverage, and saving energy consumed by the devices, the new infrastructure enabled the retrieval of bin fill level data. This allows for the generation of optimized routes based on the actual fill levels of the bins rather than traditional routes based on historical data.



ID	Address	Level
203	Avenue Aicha Al- Moussafir	6%
204	Avenue Aicha Al- Moussafir	100%
205	Avenue Aicha Al- Moussafir	0%
206	Avenue Aicha Al- Moussafir	0%
207	Avenue Ahmed Ben Allal Bouaich	78%
208	Avenue Ahmed Ben Allal Bouaich	60%
209	Avenue Ahmed Ben Allal Bouaich	28%
210	Avenue Ahmed Ben Allal Bouaich	34%
211	Avenue Ahmed Ben Allal Bouaich	19%
212	Avenue Ahmed Ben Allal Bouaich	59%
213	Avenue Ahmed Ben Allal Bouaich	39%

Fig. 13. The fill level of bins as reported in the platform.



SEUIL: 80 VEHICULE: ARTA6302 8

Fig. 14. Generated route in the driver's tablet.

The optimization algorithm for route planning is beyond the scope of this article and may be addressed in a separate contribution. Fig. 14 displays the corresponding optimized route generated for the driver's tablet based on bin fill levels.

The mesh network implementation offered several advantages over the initial deployment using gateways:

- Reduced infrastructure costs: The mesh network implementation offered significant cost savings compared to the initial deployment using gateways and repeaters. Initially, the system required 28 gateways, each costing $350, and 34 repeaters at $200 each, resulting in a total hardware cost of $16,600. By transitioning to a mesh network, the number of gateways was reduced to just 2, eliminating the need for repeaters and lowering the hardware cost to $700, saving $15,900. Additionally, each gateway required a GSM 4G connectivity subscription costing $10 per month. Over 7 years, the initial setup's connectivity cost would have totaled $23,520, whereas the optimized setup's cost is just $1,680, saving $21,840. Overall, the transition to the mesh network reduced both hardware and operational expenses, achieving total savings of $37,740 over 7 years while simplifying deployment and infrastructure requirements.

- Wide area coverage: The ability of the mesh network to relay data through intermediate sensors provided more extensive coverage. Each sensor covered an area approximately equal to a circle with a radius of 25 meters, contributing to a total effective coverage of 88.95 hectares across the city. On average, each of the 455 sensors provided effective coverage for approximately 1,955 m², ensuring comprehensive coverage.
- Optimized Battery Usage and Energy Efficiency: The use of lower spreading factors in LoRaWAN communication reduced battery consumption in most cases. Spreading factors balance data rate, range, and energy efficiency: lower spreading factors (e.g., SF7) enable faster data transmission and lower power consumption, while higher spreading factors (e.g., SF12) improve range at the cost of increased energy usage. In scenarios requiring higher spreading factors, increasing battery size addressed the issue, ensuring efficient sensor operation without frequent battery replacements. LoRaWAN communication is inherently more energy-efficient compared to GSM. LoRaWAN consumes an average of 56 mA per second (Fig. 5), while GSM requires an average 300 mA per second. Since each sensor requires approximately 4 seconds to transmit its data, LoRaWAN consumes only 224 mA per transmission, whereas GSM consumes 1,200 mA. This results in an energy saving of 976 mA per transmission, translating to an 81.33% reduction in power consumption.

In conclusion, the enhanced architecture mesh network provided significant improvements in terms of cost reduction, coverage, and operational efficiency. Despite the challenges related to increased battery consumption for some sensors, the overall benefits of the mesh network made it a superior solution for optimizing waste collection operations.

Throughout this chapter, the creation and synchronization of a mesh network for waste management sensors was outlined, significantly reducing the need for multiple gateways by enabling data transmission through intermediate sensors. Challenges such as desynchronization and mass synchronization of thousands of sensors were addressed using precise RTCs and GPS modules for exact time synchronization, ensuring efficient sleep mode operations and conserving battery life. Additionally, the wireless sensor network architecture includes passive RFID technology for data collection and trucks with GPS/GPRS modules for geolocation and data forwarding. This system accurately collects and transmits critical data to servers in JSON format for optimal processing. Real-time monitoring of bin fill levels and dynamic route optimization based on data analysis significantly enhance operational efficiency and environmental sustainability by minimizing resource wastage and optimizing waste collection routes.

V. CONCLUSION

The increasing adoption of IoT technology is driving transformation across multiple sectors, including urban waste management. This study demonstrated the potential of IoT sensor mesh networks in addressing key challenges in smart bin management, particularly in environments with limited access to LPWAN infrastructure. By implementing a cost-effective and scalable architecture, the system enables real-time monitoring of bin fill levels, optimizing waste collection operations while reducing resource consumption and operational inefficiencies.

The deployment of this solution in Tangier, Morocco, validated its effectiveness in providing continuous data transmission and dynamic route optimization, offering a significant improvement over conventional collection methods that rely on fixed schedules and static routes. The ability to adapt waste collection to real-time conditions enhances both operational efficiency and sustainability.

Future research should focus on further optimizing waste collection strategies through predictive modeling and integration of additional parameters, such as pedestrian density, key infrastructure needs (schools, hospitals, tourist areas), and seasonal fluctuations. Additionally, forecasting the capacity of waste collection vehicles to ensure timely disposal will require the development of a real-time adaptive information system capable of adjusting collection routes dynamically.

Effectively managing these complexities will be essential for the continuous improvement and scalability of IoT-driven waste management solutions, contributing to the development of more resilient, intelligent, and sustainable urban environments.

CONFLICT OF INTEREST

The authors declare no conflict of interest

AUTHOR CONTRIBUTIONS

Meryam Belhiah: Methodology, data analysis, writing—original draft, review, and editing; Moaad El Aboudi: Conceptualization, hardware development, software implementation, visualization, writing—original draft, review, and editing; both authors had approved the final version.

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