Smart Waste Bin Monitoring & Collection Optimization System

1. System Architecture

1.1 End-to-End Overview

The proposed system is an IoT-enabled smart waste management solution designed to monitor waste bins across urban areas and optimise garbage collection operations. Each waste bin operates as an independent IoT sensing node that periodically reports its status to a centralised system. The central system performs analytics, visualisation, and route optimisation to assist municipal authorities and collection teams.

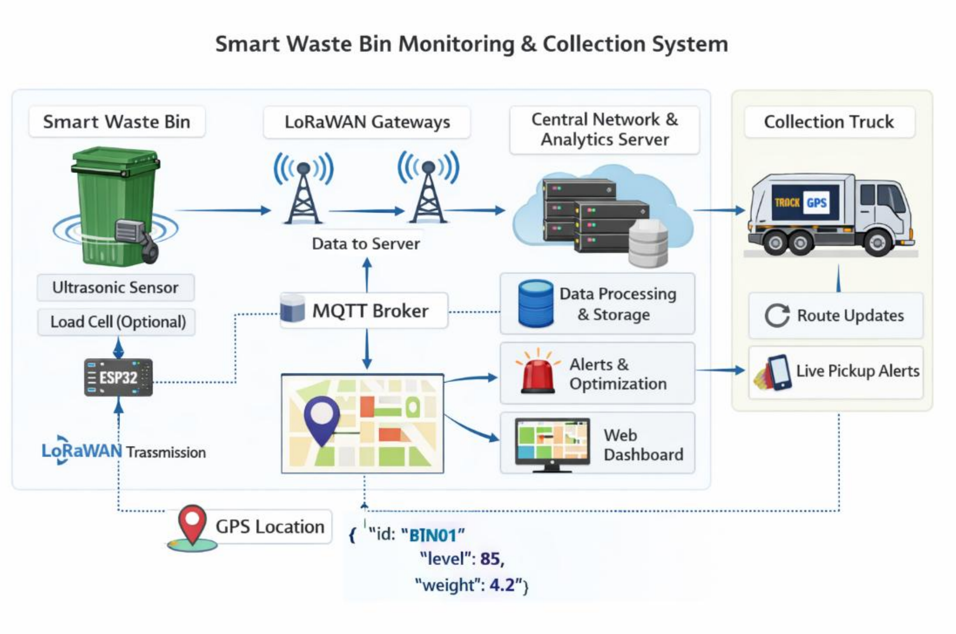

Figure 1: End-to-End IoT Architecture of the Smart Waste Bin Monitoring & Collection System

Figure 1 illustrates the complete data flow from smart waste bins equipped with sensors and ESP32 controllers to the central analytics server via LoRaWAN gateways. The processed data is visualised on a GIS-based dashboard and used to generate optimised collection routes and live truck alerts.

1.2 Sensors and Microcontroller

Sensors

- **Primary Sensor:** Waterproof Ultrasonic Sensor (JSN-SR04T)
    - Measures distance from bin lid to waste surface

- Used to calculate fill percentage
    - Suitable for outdoor deployment
- **Secondary Sensor (Optional / Selective Deployment):** Load Cell + HX711
    - Measures the physical weight of waste
    - Used for anomaly detection (e.g., heavy waste even if the bin is not full)
    - Enabled only in high-traffic or commercial zones

Microcontroller

- **ESP32**
    - Dual-core processing
    - Low-power deep sleep capability
    - Mature IoT ecosystem
    - Suitable for battery-powered, event-driven sensing nodes

---

1.3 Data Communication Method

- **LoRaWAN**
    - Long-range, city-wide coverage
    - Ultra-low power consumption
    - Supports thousands of nodes per gateway
    - No per-device data subscription cost

1.4 Computing Strategy

A **Hybrid Edge–Cloud Architecture** is used.

- **Edge (Bin Level – ESP32):**
    - Sensor data acquisition
    - Noise filtering
    - Fill percentage calculation
    - Threshold detection
    - Event-triggered transmission
- **Cloud:**
    - Data storage
    - Alert generation

- Route optimisation
- Dashboard visualization

1.5 Dashboard & Visualisation

A **GIS-integrated web dashboard** is provided for city authorities:

- Displays bin locations on a city map
- Colour-coded bin status (Normal / Warning / Critical)
- Shows fill level, weight (if enabled), and battery status
- Displays optimised collection routes for garbage trucks

---

2. Data Flow Design

2.1 End-to-End Data Flow

1. ESP32 wakes from deep sleep at scheduled intervals.
2. Ultrasonic sensor measures fill level; load cell measures weight (if enabled).
3. Local filtering and validation are performed.
4. Static GPS coordinates (configured during installation) are attached.
5. Data is packaged into a lightweight JSON payload.
6. Data is transmitted via LoRaWAN to nearby gateways.
7. Gateways forward data to the LoRaWAN Network Server.
8. The Network Server publishes clean data to the application layer.
9. Dashboards and alert systems are updated.

2.2 Protocol Selection

- **MQTT**
    - Lightweight publish–subscribe protocol
    - Low bandwidth usage
    - Suitable for large-scale IoT deployments
    - Enables real-time dashboard updates and alerts

---

3. Route Optimization Strategy

3.1 Bin Selection Logic

The system uses a **dual-trigger strategy** to determine when bins should be collected.

Triggers

- Volume Trigger: Fill level > 80%
- Weight Trigger: Weight exceeds a bin-specific threshold

Decision Logic

IF (Fill_Level > 80% AND Weight > Minimum_Valid_Weight)

OR (Weight > Bin_Weight_Limit)

→ *Add bin to pickup list*

3.2 Route Optimisation Algorithm

- Graph-based shortest path routing
- **Dijkstra's Algorithm** for shortest distance
- **Priority-based scheduling** to service critical bins first

---

3.2.1 Route Optimisation – Algorithmic Implementation

To efficiently compute the optimal garbage collection route when multiple bins require pickup, a lightweight approximation of the Travelling Salesman Problem (TSP) is used. Since exact TSP solutions are computationally expensive, a heuristic-based approach is adopted.

Algorithm Used:

- Nearest Neighbour heuristic for initial route generation
- 2-opt local optimisation for route improvement

Pseudocode:

Input:

Truck_Location

List of Critical_Bins with GPS coordinates

Steps:

1. Initialize route with Truck_Location

2. Select nearest unvisited bin (Nearest Neighbor)

3. Append bin to route

4. Repeat until all bins are visited

5. Apply 2-opt optimization to reduce total route distance

6. Output optimized pickup route

This approach provides near-optimal routes with low computational overhead, making it suitable for real-time municipal operations.

3.3 Live Truck Notification

- Truck GPS locations are tracked by the backend system.
- When a bin becomes critical:
  - The nearest available truck is identified
  - The shortest deviation route is calculated
  - A notification is pushed to the truck dashboard

Bins do not communicate directly with trucks; all coordination is handled by the central server.

3.4 Future Enhancement: Predictive Fill-Level Forecasting

In future deployments, historical fill-level data collected from bins can be used to predict future waste accumulation trends. Lightweight time-series forecasting models such as **ARIMA** can be applied to estimate when a bin is likely to reach critical capacity.

Benefits:

- Proactive scheduling instead of reactive collection
- Reduced overflow incidents
- Better utilisation of collection vehicles

Conceptual Pseudocode:

Input: Historical fill-level data

Apply ARIMA forecasting model

Predict time-to-full for each bin

Schedule pickup before critical threshold

---

4. Power Management Plan

- ESP32 operates in **Deep Sleep (~10–20 µA)** for most of the time
- Periodic wake-up (e.g., once per hour)
- Active sensing and transmission duration ~5 seconds

- Event-based transmission reduces unnecessary communication
- LoRaWAN ensures low-power long-range transmission

This design enables **multi-year battery life**.

4.1 Power Budget Estimation

The estimated power consumption of a smart bin node is calculated using typical ESP32 datasheet values under a low-duty-cycle operation model.

Operating Mode	Current Consumption	Duration
Deep Sleep	~10–20 µA	~23 hours 55 minutes
Sensor Measurement	~60–80 mA	~5 seconds
LoRa Transmission	~120 mA	< 1 second

Assumptions:

- One sensing and transmission cycle per hour
- Event-based transmission for critical alerts only

Based on these values, the system supports **multi-year battery life** under normal operating conditions.

📌 *Estimates are derived from ESP32 and LoRa module datasheets.*

---

5. Reliability & Fault Handling

5.1 Handling False Readings

- Multiple sensor readings are averaged to reduce noise
- Sudden spikes are ignored using consistency checks

5.2 Sensor Obstruction Detection

- If the ultrasonic sensor reports "full" but the load cell reports near-zero weight:
  → System flags a **Sensor Obstruction Alert**
  (e.g., a plastic bag blocking the ultrasonic sensor)

5.3 Additional Measures

- Sensor timeout detection
- Periodic calibration reference
- Battery health monitoring

---

6. Scalability & Network Considerations

6.1 Network Topology: Star-of-Stars (LoRaWAN)

The system adopts a **Star-of-Stars LoRaWAN topology**, which is the industry-standard architecture for large-scale, battery-powered IoT deployments.

- Each smart waste bin functions as an independent **LoRaWAN end device**
- Bins transmit data directly to one or more nearby gateways
- No bin-to-bin communication (no mesh networking)
- Gateways act as passive aggregation points
- A centralised LoRaWAN Network Server performs:
  - Device authentication
  - Packet de-duplication
  - Secure forwarding to the application layer

All analytics, optimisation, and coordination—including live truck notifications—are performed at the central application server.

Star vs Mesh Explanation

To support large-scale deployment across multiple city zones while maintaining low power consumption, the system adopts a star-based network topology instead of a mesh topology. Mesh networks require nodes to relay data for neighboring nodes, increasing energy consumption and system complexity. Since waste bins are battery-powered and geographically fixed, a star-based architecture is more suitable.

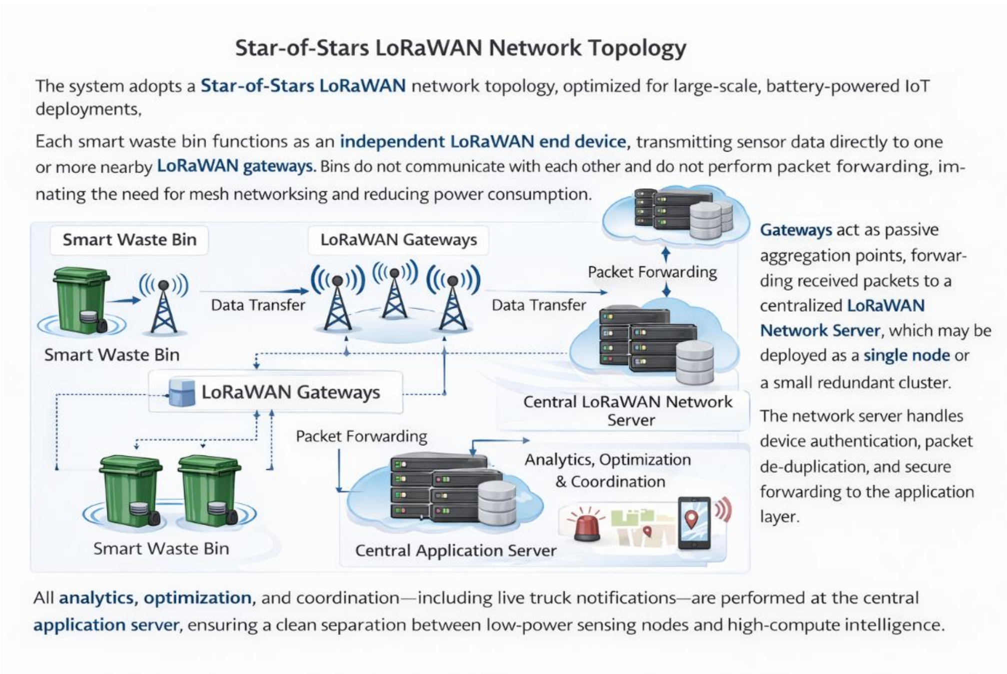

Figure 2: Star-of-Stars LoRaWAN Network Topology

Figure 2 shows the Star-of-Stars LoRaWAN topology adopted in the system. Each smart bin acts as an independent LoRaWAN end device, transmitting data directly to one or more gateways. Gateways forward packets to a centralized network server that performs authentication, de-duplication, and secure forwarding to the application layer, ensuring scalability and low power consumption.

6.2 Scalability

- One gateway can support thousands of bins
- Bins are grouped by Zone ID
- Architecture scales from:
    - Pilot deployments (10–20 bins)
    - Multi-zone systems (100+ bins)
    - Full smart-city deployments (10,000+ bins)

---

7. Cost & Feasibility Discussion

7.1 Approximate Cost per Bin

Component	Cost (₹)
ESP32	400
Waterproof Ultrasonic Sensor	850
Load Cell + HX711 (optional)	500
Battery & Enclosure	600
Total (with load cell)	**₹2,350**

7.2 Trade-Off Discussion

- Load cell increases per-unit cost
- Reduces false collection trips
- Saves fuel and labour costs
- Can be deployed selectively by zone to balance cost and accuracy

---

Conclusion

The proposed system provides a low-power, scalable, and intelligent smart waste management solution. By combining reliable sensing, efficient communication, centralised analytics, and a map-based user interface, the system enables data-driven decision-making and improves municipal waste collection efficiency.