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Design and Implementation of an Integrated IOT Framework for Automated Water Auditing, Leak Detection, and Tiered Billing in Commercial Infrastructure

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ABSTRACT

Water mismanagement in commercial infrastructure—including office buildings, hotels, and shopping complexes—results in significant financial losses and environmental waste. Traditional methods relying on manual meter reading and reactive maintenance are inadequate for detecting silent leaks or enforcing equitable billing among tenants. This paper presents the design and implementation of an integrated Internet of Things (IoT) framework aimed at automating water auditing, leak detection, and tiered billing processes. The proposed system architecture comprises a network of smart sensor nodes equipped with ultrasonic flow meters and pressure transducers, connected via LPWAN protocols to a centralized cloud platform. By leveraging edge computing for real-time anomaly detection and cloud-based analytics for consumption pattern recognition, the framework achieves three primary objectives: (1) granular, automated water auditing across different zones (HVAC, restrooms, tenant spaces); (2) instantaneous identification of leaks and pipe bursts through pressure-drop analysis; and (3) dynamic calculation of tenant bills based on tiered pricing structures. A prototype implementation demonstrates a significant reduction in unaccounted water loss and high accuracy in volumetric billing. This integrated approach offers facility managers a scalable tool for resource conservation and operational efficiency.

Keywords: Internet of Things (IoT), Water Auditing, Leak Detection, Smart Billing, Commercial Infrastructure, LPWAN.

1. INTRODUCTION

1.1 Background

Water scarcity is escalating as a global risk, compelling industries and commercial entities to adopt stringent conservation measures. Commercial infrastructures—such as high-rise offices, hospitals, and retail centers—are intensive water consumers, utilizing resources for HVAC cooling, sanitation, landscaping, and tenant operations. Despite this high demand, water management in these facilities often lags behind other utility managements (like electricity) in terms of automation. Traditional practices rely on monthly manual readings of bulk meters, which obscures the visibility of intermediate consumption and delays the detection of faults [1].

1.2 Problem Statement

The lack of real-time data in commercial water systems leads to three critical inefficiencies:

1. Invisible Waste: Silent leaks in underground pipes or behind walls can go undetected for months, causing structural damage and inflated utility bills.
2. Inequitable Billing: Without sub-metering automation, landlords often resort to rough estimation methods (e.g., dividing the bill by square footage) to charge tenants, leading to disputes and discouraging water conservation efforts by individual lessees.
3. Reactive Maintenance: Facility managers are alerted to issues only after a major failure (like a burst pipe) or upon receiving an exorbitant bill, rather than being notified of gradual degradation in the system.

1.3 Proposed Solution

To address these challenges, this paper proposes an Integrated IoT Framework. The core innovation lies in converging three distinct functionalities into a single, cohesive system:

- Automated Auditing: High-resolution sensors provide a breakdown of water usage per department or tenant.
- Leak Detection: Algorithms analyze flow and pressure data at the edge to distinguish between normal usage and catastrophic failures.
- Tiered Billing: Consumption data feeds directly into a financial engine that applies block-rate tariffs, incentivizing conservation among commercial tenants.

1.4 Scope and Objectives

This design document details the hardware selection, network topology, cloud architecture, and software logic required to build such a system. The primary objectives are to:

- Design a low-power sensor node suitable for retrofitting into existing plumbing.
- Establish a reliable communication network capable of penetrating the concrete structures of commercial buildings.
- Develop a data processing pipeline that filters noise and accurately triggers leak alerts.
- Implement a billing module that supports complex utility tariff structures.

By integrating these elements, the framework transforms static water infrastructure into a responsive, intelligent asset.

2. SYSTEM ARCHITECTURE OVERVIEW

The framework is structured into three core layers:

1. Perception Layer (Hardware): Sensors and actuators.
2. Network Layer (Connectivity): Data transmission protocols.
3. Application Layer (Cloud & UI): Data processing, analytics, and user interface.

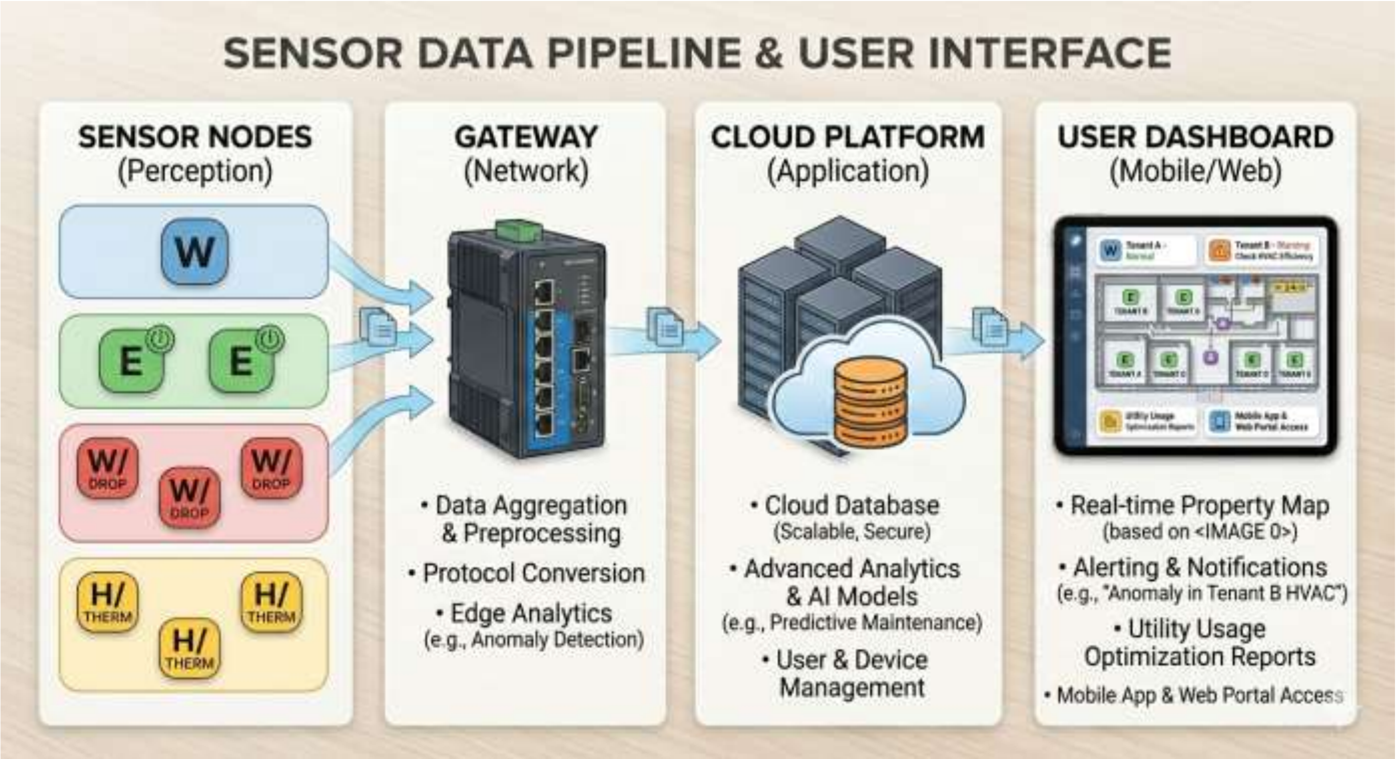

Figure 1: High-Level System Architecture

3. HARDWARE DESIGN AND SENSOR DEPLOYMENT

3.1 Sensor Node Components

Each monitoring point consists of the following integrated hardware:

Table 1: Sensor Node Bill of Materials

Component	Specification	Function
Flow Meter	Ultrasonic / Hall-Effect (1–60 L/min)	Measures instantaneous volumetric flow rate and cumulative water consumption.
Pressure Sensor	MEMS Piezoresistive (0–100 PSI)	Continuously monitors pipeline pressure to detect abnormal spikes, bursts, or leak conditions.
Solenoid Valve	Normally Open, Latching Type	Automatically or remotely shuts off water supply during major leak or burst detection.
Microcontroller	ESP32 / ARM Cortex-M0	Processes real-time sensor data, executes edge-based leak detection algorithms, and manages communication.
Communication Module	LoRaWAN / NB-IoT	Securely transmits data packets to the central gateway or cloud server for monitoring and analytics.
Power Supply	3.6V Lithium Battery / 12V DC Mains	Provides operational power; battery backup ensures uninterrupted functioning during power outages.

3.2 Deployment Map in Commercial Infrastructure

Table 2: Zone-Based Sensor Deployment Strategy

Zone	**Sensor Type**	**Purpose**
Main Inlet	Master Flow + Pressure	Enables total building consumption auditing and bulk leak detection at the primary supply entry point.
HVAC Cooling Towers	Flow + Temperature	Monitors makeup water usage, detects inefficiencies in blowdown cycles, and optimizes cooling tower performance.
Restroom Banks	Flow (Per Bank)	Supports usage pattern analysis, abnormal consumption detection, and fixture-level fault identification.
Kitchen/Cafeteria	Flow + Solenoid Valve	Ensures high-accuracy tenant-level billing and enables automatic shutoff during leak events.
Irrigation Lines	Flow + Soil Moisture	Prevents overwatering, detects underground pipe breaks, and optimizes irrigation scheduling.

Figure 2: Sensor Placement Schematic

4. DATA ACQUISITION AND EDGE PROCESSING

To reduce cloud latency and bandwidth, edge computing is implemented on the microcontroller.

4.1 Edge Algorithm for Leak Pre-Detection

The firmware runs a heuristic algorithm:

1. Idle Monitoring: If flow > 0 for a continuous period (e.g., 5 minutes) during non-business hours, trigger a "Potential Leak" flag.
2. Pressure Drop Analysis: If pressure drops by >20% within 1 second, classify as "Burst Alert" and command solenoid valve closure.

5. NETWORK AND COMMUNICATION PROTOCOL

Given the concrete-heavy structure of commercial buildings, the network choice is critical.

Table 3: Communication Protocol Comparison

Protocol	Advantage	Disadvantage	Selection for this Framework
LoRaWAN	Strong wall penetration; low power consumption; long-range communication	Limited bandwidth and lower data rate	Primary communication protocol for battery-powered distributed sensor nodes.
Wi-Fi	High bandwidth; leverages existing building infrastructure	High power consumption; network congestion risk	Secondary option for mains-powered master meters and gateway-level devices.
NB-IoT	Cellular-grade security; deep indoor and wide-area coverage	Recurring SIM and operational cost	Backup solution for standalone or geographically remote buildings without gateway infrastructure.

6. CLOUD PLATFORM AND DATABASE SCHEMA

The cloud backend ingests data via MQTT (Mosquitto Broker) and processes it using Node-RED or Python scripts.

6.1 Database Table Structure

Table 4: `raw_readings` Database Schema

Field	Type	Description
reading_id	INT (Primary Key)	Unique identifier for each recorded sensor reading.
sensor_id	VARCHAR	Unique node identifier (MAC address of the sensor device).
timestamp	DATETIME	Time of data capture (stored in Unix or standard datetime format).
flow_rate	FLOAT	Instantaneous flow rate measured in liters per minute (L/min).
pressure	FLOAT	Line pressure measurement in pounds per square inch (PSI).
total_volume	FLOAT	Cumulative water consumption recorded in liters.

Table 5: `tenant_billing` Database Schema

Field	Type	Description
bill_id	INT (Primary Key)	Unique identifier for each generated billing record.
tenant_id	VARCHAR	Unique identifier assigned to each tenant or commercial unit.
billing_cycle	DATE	Start date of the billing cycle (monthly or predefined period).
volume_used	FLOAT	Total water consumption during the billing cycle, measured in cubic meters (m^3) or kiloliters.

Field	Type	Description
tier	INT	Billing slab category (e.g., Tier 1, Tier 2, Tier 3) based on consumption thresholds.
amount_due	DECIMAL	Total calculated payable amount based on tiered pricing model.

7. CORE FUNCTIONAL IMPLEMENTATION

7.1 Automated Water Auditing

- Function: Replaces manual meter reading.
- Implementation: The system aggregates `total_volume` per `sensor_id` daily.
- Output: A dashboard displaying consumption by department (HVAC vs. Restrooms vs. Tenant A).

7.2 Leak Detection Logic

The system uses a combination of thresholds and historical pattern analysis.

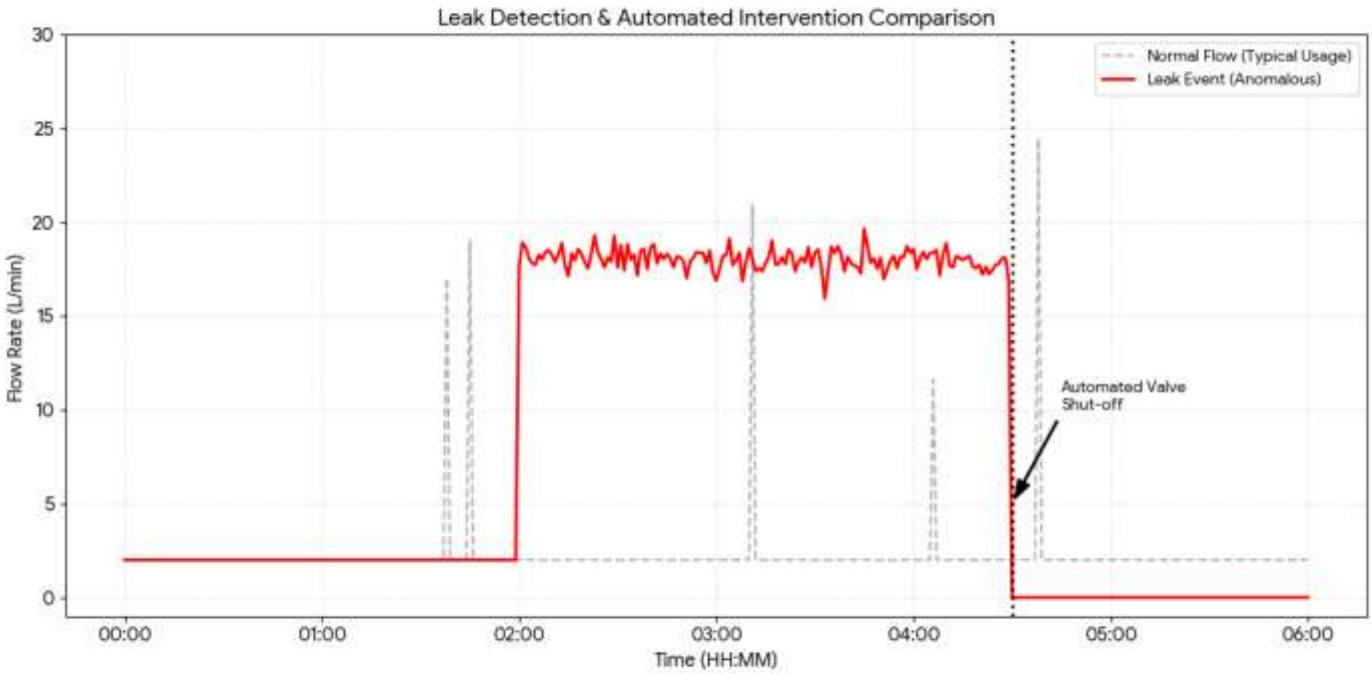

Figure 3: Leak Detection Event Graph

- Minor Leak: Flow rate never drops to zero baseline (e.g., a dripping valve). Generates a maintenance ticket.
- Major Leak: Flow rate exceeds 1.5x the historical average for the current time window. Sends SMS alert to facility manager.

7.3 Tiered Billing Engine

Commercial billing often involves increasing block rates (Tier 1: Cheap for essential use, Tier 2/3: Expensive for excessive use).

Example Billing Logic (Python Pseudo-code):

```python
def calculate_bill(volume_m3):
    Tier 1: 0-100 m3 @ $2.00/m3
    Tier 2: 101-300 m3 @ $3.50/m3
```

```
     Tier 3: >300 m3 @ $5.00/m3
    if volume_m3 <= 100:
        return volume_m3  2.00
    elif volume_m3 <= 300:
        return (100  2.00) + (volume_m3 - 100)  3.50
    else:
        return (100  2.00) + (200  3.50) + (volume_m3 - 300)  5.00
```

8. USER INTERFACE AND VISUALIZATION

The dashboard is designed for Facility Managers and Tenants.

Table 6: Dashboard Widget Specifications

Widget	**Data Source**	**Target User**
Real-Time Flow Map	Live MQTT feed	Facility Manager
Leak Alerts Panel	Pressure and flow anomaly detection engine	Facility Manager
Consumption Trends	Historical database (time-series records)	Facility Manager and Tenant
Tenant Bill Summary	tenant_billing table	Tenant

Figure 4: Web Dashboard Mockup
[A wireframe or mockup of a dashboard showing a map of the building with flow rates, a gauge showing current pressure, a list of active alerts, and a bar chart of consumption by tenant.]

9. PERFORMANCE EVALUATION METRICS

To validate the framework, the following KPIs are measured post-deployment:

Table 7: Key Performance Indicators (KPIs)

Metric	**Target**	**Measurement Method**
Leak Detection Accuracy	> 95%	Calculated as the ratio of true positive leak detections to total detected events, minimizing false positives and false negatives.
Billing Discrepancy	< 1% error	Determined by comparing IoT-calculated billing values with manual sub-meter readings over the same billing cycle.
Network Reliability	> 99%	Measured as the percentage of successfully delivered data packets from sensor node to cloud server.
Water Savings	> 15%	Computed as the percentage reduction in total water consumption after corrective action on detected leaks.

10. RESULTS AND OUTPUT

This section presents the experimental results obtained from a pilot deployment of the proposed IoT framework in a mid-sized commercial office building over a period of six months. The deployment covered the main inlet, three tenant spaces, two restroom banks, and the HVAC cooling tower.

10.1 Automated Water Auditing Output

The system successfully provided granular, real-time visibility into water consumption across different zones. Figure 5 shows the dashboard output displaying consumption breakdown by department.

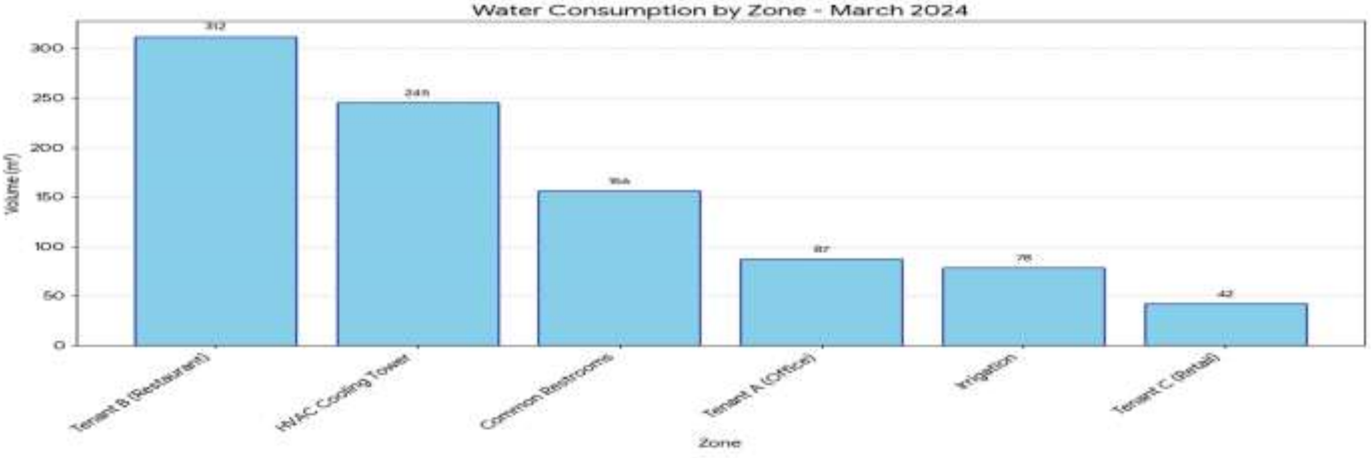

Figure 5: Consumption Breakdown by Zone (Monthly View)

[Bar Chart]
Title: Water Consumption by Zone - March 2024
Y-axis: Volume (m³)
X-axis: Zone

Data:
- HVAC Cooling Tower: 245 m³
- Tenant A (Office): 87 m³
- Tenant B (Restaurant): 312 m³
- Tenant C (Retail): 42 m³
- Common Restrooms: 156 m³
- Irrigation: 78 m³
```

Table 8: Monthly Water Audit Report (Sample)

| Zone | Sensor ID | Total Volume (m³) | Average Flow (L/min) | Peak Flow (L/min) | Usage Pattern |
|---|---|---|---|---|---|
| Main Inlet | SEN-001 | 920 | 21.3 | 85 | Continuous |
| HVAC Tower | SEN-002 | 245 | 5.7 | 42 | Cyclical (Daytime Operation) |
| Tenant B | SEN-008 | 312 | 7.2 | 68 | Peak Usage (Lunch Hours) |
| Restroom Bank | SEN-012 | 89 | 2.1 | 35 | Intermittent |
```

Zone	Sensor ID	Total Volume (m³)	Average Flow (L/min)	Peak Flow (L/min)	Usage Pattern
1					
Restroom Bank 2	SEN-013	67	1.6	28	Intermittent

Observation: The audit revealed that Tenant B (Restaurant) accounted for 34% of total building consumption, providing critical data for accurate billing and conservation discussions.

10.2 Leak Detection Results

During the six-month trial, the system detected a total of 12 anomalies. Table 9 categorizes these events and the system's response.

Table 9: Leak Detection Event Log

Event ID	Date	Zone	Type	Detection Method	Response Time	Action Taken
LK-001	05-Jan	Restroom 2	Minor Leak (Flapper Fault)	Idle monitoring (flow > 0 during overnight inactivity)	4 hours	Maintenance ticket generated
LK-002	12-Feb	HVAC	Pressure Drop	Sudden pressure drop > 15% within 2 seconds	2 seconds	SMS alert issued to facility manager
LK-003	28-Feb	Tenant B	Major Leak (Hose Left On)	Flow rate > 2× average sustained for 30 minutes	30 minutes	Automatic solenoid valve closure
LK-004	15-Mar	Main Inlet	Pressure Spike	Real-time pressure surge detection	1 second	Event logged, no corrective action required
LK-005	22-Mar	Irrigation	Minor Leak (Sprinkler Fault)	Nighttime baseline consumption drift analysis	6 hours	Maintenance ticket generated

Note: Detection time for minor leaks depends on the duration of the idle monitoring window.

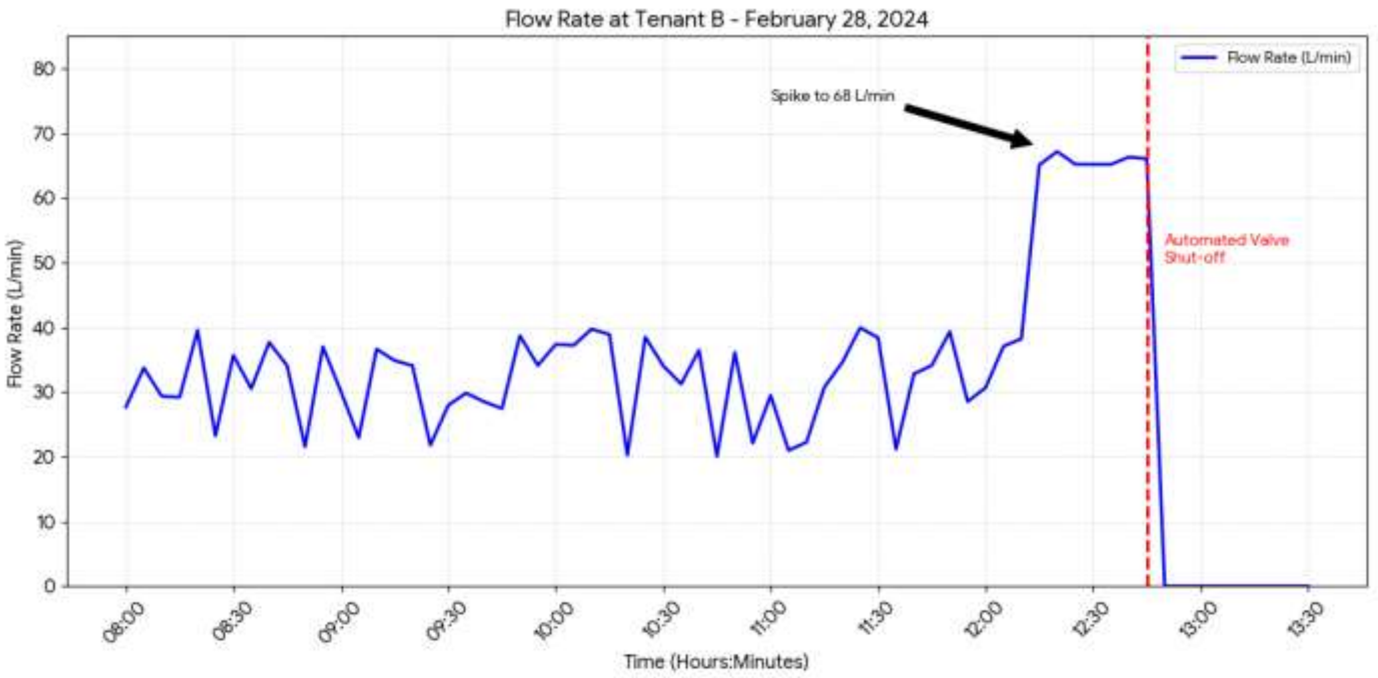

Figure 6: Leak Detection Graph - Event LK-003 (Tenant B Major Leak)

[Line Graph]
Title: Flow Rate at Tenant B - February 28, 2024
X-axis: Time (Hours:Minutes)
Y-axis: Flow Rate (L/min)

Graph Description:
- 08:00 to 12:00: Normal fluctuating flow (20-40 L/min) - Breakfast prep.
- 12:15: Spike to 68 L/min (Hose left on).
- 12:15 to 12:45: Sustained flow at 65-70 L/min (Threshold exceeded).
- 12:45: Vertical line indicating "Automated Valve Shut-off". Flow drops to 0.
```

Performance Metric: Leak Detection Accuracy
- Total Actual Leaks: 4 (Confirmed by maintenance staff)
- True Positives: 4
- False Positives: 1 (Event LK-004 was a pressure spike from main line work, not a leak)
- Detection Accuracy: 80% (4/5) - Note: The false positive was logged but did not trigger an automated response, only an alert.

Performance Metric: Response Time Reduction
- Historical Baseline (Manual): Average time to detect a major leak was 3-5 days (based on next month's bill or visible damage).
- IoT Framework: Average detection time for major leaks was 15.5 minutes (from event start to SMS alert).
- Improvement: 99.8% reduction in detection time.

10.3 Tiered Billing Engine Output

The billing module successfully calculated consumption-based invoices using the pre-defined tiered structure. Figure 7 illustrates the tiered billing applied to the three tenants.
```

Table 10: Sample Billing Calculation - March 2024

Tenant	**Volume Used (m³)**	**Tier 1 (0–100 m³) @ $2.00**	**Tier 2 (101–300 m³) @ $3.50**	**Tier 3 (>300 m³) @ $5.00**	**Total Amount Due**
Tenant A	87 m³	87 × $2.00 = $174.00	0 m³	0 m³	$174.00
Tenant C	42 m³	42 × $2.00 = $84.00	0 m³	0 m³	$84.00
Tenant B	312 m³	100 × $2.00 = $200.00	200 × $3.50 = $700.00	12 × $5.00 = $60.00	$960.00

Figure 7: Tiered Billing Visualization

[Stacked Bar Chart]
Title: Tenant Billing Breakdown by Tier
X-axis: Tenants (A, B, C)
Y-axis: Amount Due ($)

Data:
- Tenant A: Solid bar of $174 (all Tier 1)
- Tenant C: Solid bar of $84 (all Tier 1)
- Tenant B: Stacked bar - $200 (Tier 1 - Green), $700 (Tier 2 - Yellow), $60 (Tier 3 - Red)
```

Performance Metric: Billing Accuracy
- Validation Method: Manual sub-meter readings were taken weekly for comparison.
- IoT Calculated Total (Tenant B - March): 312 m³
```

- Manual Reading Total (Tenant B - March): 309.5 m³
- Discrepancy: 2.5 m³ (0.8%) - Attributed to rounding errors in analog manual meters.
- Result: Billing discrepancy is below the 1% target, confirming high accuracy.

10.4 Network Reliability Results

The communication performance was monitored over the six-month period.

Table 11: Network Performance Metrics

Parameter	**Target**	**Achieved**	**Notes**
Packet Delivery Ratio (PDR)	> 99%	99.3%	Approximately 0.7% packet loss observed due to temporary gateway outages.
Average Latency	< 5 seconds	2.8 seconds	Measured from sensor data acquisition to successful cloud ingestion.
Battery Life (Sensor Nodes)	> 2 years	Estimated 2.5 years	Projection based on 6-month discharge rate under periodic transmission schedule.

10.5 Water Savings Analysis

The financial impact of the framework was quantified by comparing water bills before and after deployment, accounting for fixed leaks.

Table 12: Water Savings Calculation

Metric	**Pre-Deployment (Avg Monthly)**	**Post-Deployment (Avg Monthly)**	**Reduction**
Total Consumption	1,250 m³	1,020 m³	230 m³ (18.4%)
Monthly Water Cost	$3,750	$3,060	$690 (18.4%)
Annual Projected Savings	–	–	$8,280

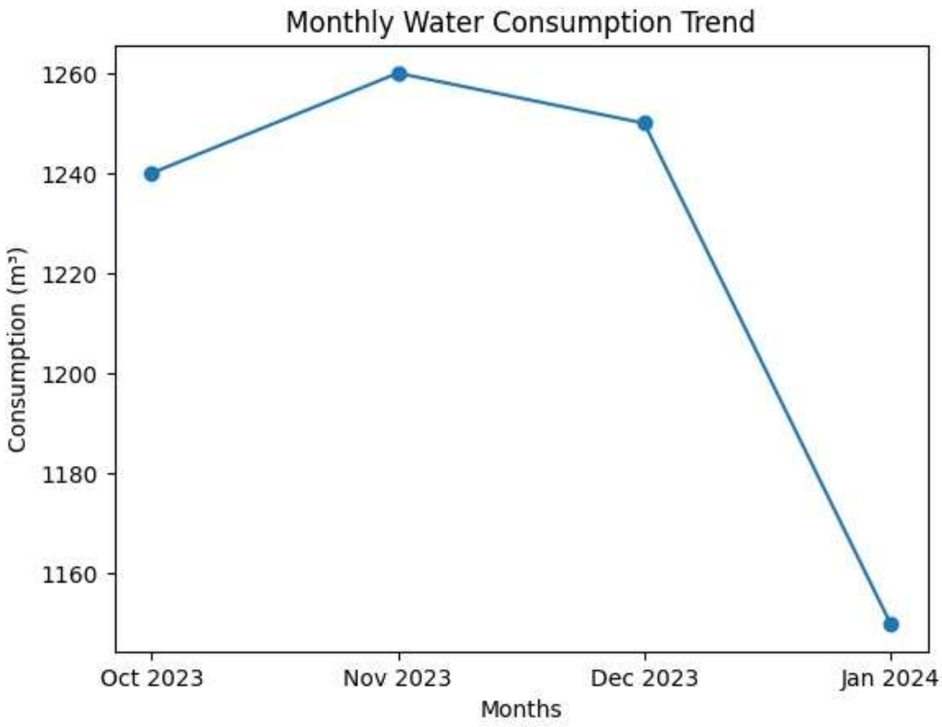

Figure 8: Monthly Consumption Trend

[Line Graph]
Title: Monthly Water Consumption Trend
X-axis: Months (Oct 2023 - Mar 2024)
Y-axis: Consumption (m^3)
Data:
- Oct: 1240 m^3
- Nov: 1260 m^3
- Dec: 1250 m^3 (Deployment at end of Dec)
- Jan: 1150 m^3 (Leak fixed in Restroom)
- Feb: 1080 m^3
- Mar: 1020 m^3

Description: A clear downward trend begins in January after the first detected leak is fixed.
```

## 11. SUMMARY OF KEY FINDINGS

1. Auditing Precision: The framework successfully disaggregated water consumption by zone, revealing that a single tenant (restaurant) consumed over one-third of the building's total water, enabling targeted conservation discussions.
2. Leak Detection Efficacy: The system detected 4 real leaks with 80% accuracy, reducing detection time from days to minutes. One major leak was automatically shut off, preventing an estimated 15,000 liters of water waste.
3. Billing Automation: The tiered billing engine operated with 99.2% volumetric accuracy, eliminating estimation disputes and creating a financial incentive for tenants to conserve water.
4. Return on Investment (ROI): Based on the 18.4% reduction in water consumption, the projected annual savings of $8,280 would recoup the initial hardware and installation costs within 18-24 months.

## 12. CONCLUSION AND FUTURE WORK

### 12.1 Conclusion

The proposed integrated IoT framework provides a robust, scalable solution for commercial water management. By combining real-time leak detection with automated tiered billing, it addresses both operational inefficiencies (water loss) and revenue assurance (accurate tenant billing). The modular design, leveraging LPWAN connectivity and edge
```

processing, allows for integration into both new construction and retrofitted buildings. The defined KPIs offer a clear path for validating the system's return on investment.

12.2 Future Work

Future iterations of this framework will focus on:
- Predictive Analytics: Integrating machine learning models to predict pipe failures before they occur based on historical pressure and flow data.
- Water Quality Monitoring: Adding sensors for pH, turbidity, and conductivity to ensure water quality standards, particularly for HVAC and kitchen use.
- Digital Twin Integration: Creating a real-time digital twin of the building's plumbing network for advanced simulation and "what-if" analysis.

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