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IMPLEMENTATION AND ANALYSIS OF AN RFID-BASED “PAY-AS-YOU-THROW” SYSTEM FOR SMART WASTE MANAGEMENT

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Abstract
The study presents the design and development of a technological solution for implementing the “Pay-As-You-Throw” (PAYT) model in municipal waste management. The system aims to provide accurate and fair tracking of household waste bins while minimizing the possibility of manipulation and avoiding additional workload for collection teams. The developed system uses UHF long-range RFID technology integrated with onboard modules on waste collection trucks for automatic identification and reporting of emptied bins. The proposed approach ensures transparent data collection, traceability, and remote monitoring through a cloud-based infrastructure.
Keywords: PAYT, RFID, waste, management, IoT, smart cities, automation.

INTRODUCTION

The “Pay-As-You-Throw” (PAYT) principle represents a consumption-based pricing model for solid waste management, where users pay according to the amount of waste they generate. This concept, already implemented in several European countries, encourages recycling and responsible waste generation. For effective PAYT implementation, a reliable, tamper-proof system is required to track individual waste bins without creating additional tasks for the collection team.

Recent research highlights the integration of Internet of Things (IoT) and wireless sensor networks (WSN) as essential tools for enhancing waste management efficiency through real-time monitoring, route optimization, and data-driven decision-making. These technologies significantly improve sustainability, transparency, and operational effectiveness within smart city infrastructures.

Longhi et al. [1] developed a multi-layer WSN architecture for solid waste monitoring using GSM/GPRS communication with a central decision-support system. Their work demonstrated up to 50% operational cost reduction through intelligent route planning and automated data collection. Arebey et al. [2] further advanced RFID-based waste tracking by integrating RFID, GPS, and camera modules for bin identification and location verification, ensuring traceability and reducing data manipulation risks.

Purohit and Bothale [3] proposed a tag-based collection validation system that uses RFID to authenticate waste containers and verify collection events, helping municipalities reduce fraudulent reporting within PAYT frameworks. Vishnu et al. [4] later proposed a hybrid IoT network utilizing LoRaWAN and Wi-Fi for monitoring public and residential bins, extending sensor lifetime to 70 days and achieving precise fill-level reporting via color-coded graphical interfaces.

Squire et al. [5] explored the application of IoT and machine learning for optimizing municipal solid waste (MSW) collection in Australia. Their results indicated that

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environmental parameters—such as temperature, humidity, and hydrogen sulfide (H_2S)—can be correlated with predictive algorithms for dynamic collection scheduling. Niska and Serkkola [6] contributed complementary work by applying data analytics to establish waste generation profiles that support route optimization and reduce service redundancies.

Henaien et al. [7] introduced a Sustainable Smart City Solid Waste Management System (SCSWMS) integrating IoT, LoRaWAN, and Intelligent Traffic Systems (ITS), achieving up to 90% fill-level accuracy and a 29% reduction in operational costs. Sohag and Podder [8] proposed a sustainable IoT-based waste management model that leverages cloud connectivity and smart sensors for urban environments, aligning with the principles of sustainable urban development and Industry 4.0. More recently, Boubaris et al. [9] emphasized the role of RFID–IoT hybrid systems in the context of smart cities, enabling transparency between municipalities and citizens through cloud-based analytics and mobile interfaces.

Overall, the literature demonstrates that combining low-power IoT devices, RFID automation, and cloud-based analytics can yield significant improvements in municipal waste collection, reducing costs by 25–50% while improving data accuracy and accountability. Such advancements form a robust foundation for implementing PAYT systems, supporting data integrity, and promoting environmental transparency across smart city ecosystems.

EXPOSITION

The aim of this project was to design a system capable of accurately identifying each household waste bin during collection while ensuring robustness, data reliability, and operational efficiency. The system also provides digital indicators and real-time feedback for operators, allowing for monitoring of irregularities such as unmarked, damaged, or unauthorized bins.

Methodology and System Design

Technological Approach

Existing PAYT systems in Europe often use short-range RFID tags embedded in standardized bin mounts and RFID readers attached to truck forks. However, this approach requires precise alignment between the bin and the reader, which is impractical in real-world conditions and prone to human manipulation.

To address this limitation, the proposed system utilizes a UHF long-range RFID reader, commonly used in warehouse inventory management, capable of reading multiple tags simultaneously over greater distances and at higher speeds.

Tag Selection and Bin Labeling

Special UHF tags (fig.1) with large antennas were selected for enhanced read range and laminated for protection against environmental exposure. The tags were mounted inside the hinge cavity of the bin lid, ensuring protection from mechanical damage and vandalism. Each tag contains two identifiers: TID – a factory-programmed, unchangeable ID and EPC – an editable code, locked with a password after programming.

Fig. 1. *UHF tags*

Custom EPC codes were created using a defined header, sequential number, and checksum (e.g., *5E257A7E000000000000017D*). This allows the system to recognize "authorized" tags without immediate cloud communication. Both IDs (TID and EPC) were scanned and stored in a secure database, with a QR code and numerical checksum printed on the tag for visual verification.

A dedicated mobile application was developed to manage the tagging process — scanning, verification, and synchronization with the cloud system, including location data.

System Architecture

The system architecture (fig.2) consists of two main modules: the Auxiliary Module (Sensor Module) and the Main Module (Control Unit). The auxiliary module includes a UHF RFID reader, an inductive sensor for detecting the fork position, an 8-segment LED display, and dual status indicator LEDs (green/red). It is mounted at the top rear of the truck to ensure maximum protection from mechanical impacts, dust, and debris. The main control unit comprises a backup power supply, GPS receiver for location tracking, a communication modem (mobile data/Wi-Fi) for cloud connectivity, and an RS485 ModBus interface for communication with the auxiliary module. The control unit mirrors the LED indicators, which are visible to the driver through the left rear-view mirror, while an integrated light sensor automatically adjusts display brightness for night operation, ensuring both visibility and safety.

Fig. 2. *System Architecture*

The UHF-105 is a programmable long-range RFID reader designed for industrial and smart city applications such as automated waste collection, access control, and asset tracking. It operates at 902–928 MHz (US standard) or 920–925 MHz (China standard) and supports the ISO18000-6B and ISO18000-6C (EPC GEN2) protocols. The device features frequency hopping (FHSS) or fixed-frequency modes configurable via software, with an adjustable output power of 0–30 dBm and a typical reading distance of 1–5 m. It achieves a reading speed of less than 6 ms per 64-bit ID and offers dual-polarization sensitivity for improved reception. The reader includes a built-in circular (8 dB) or linear (12 dBi) polarization antenna, multiple communication interfaces (RS485, RS232, Wiegand26/34, RJ45), and operates on DC 12 V with only 1 W power consumption. It functions reliably within a temperature range of –20 °C to +80 °C and humidity from 20 % to 95 % (non-condensing). The UHF-105 supports software-controlled frequency, power, and reading intervals, making it highly adaptable for mobile waste collection vehicles and IoT-based PAYT systems requiring stable performance and efficient data transmission.

Operation Algorithm

When the truck forks are lowered, the UHF reader operates at high power to detect all nearby bins. If new (unregistered) bins are detected, the display shows the count, and the module logs EPC, TID, GPS location, and timestamp. If a detected bin is not emptied within a configurable time, the data are uploaded as a “seen but not lifted” record.

When lifting begins, the inductive sensor signals the system, triggering “reporting mode.” The reader power decreases to avoid detecting distant bins. The green LED blinks during reading, then remains steady to indicate completion. The main module stores all readings and sends data to the cloud platform, including event type (bin lifted or lift without bin), location, and time. In parallel, a signal to a DVR camera is sent to record the process for verification.

If communication between modules or the reader fails, the red LED is activated to indicate an error.

The field prototype demonstrated reliable multi-tag detection under outdoor conditions, with precise logging of all lifted bins. The dual-module architecture minimized system interference and ensured consistent data synchronization with the cloud platform. Key advantages of the developed system include automated bin recognition without operator input, real-time feedback with visual indicators, error detection for unmarked, damaged, or unauthorized bins, and minimal integration requirements with existing waste collection vehicles. The combination of UHF RFID technology and cloud-based data management proved highly effective for PAYT implementation, delivering operational transparency, reducing the potential for fraud or human error, and supporting efficient, data-driven waste management practices.

CONCLUSION

The presented study demonstrates the successful development and testing of an RFID-based PAYT (Pay-As-You-Throw) system designed to automate and improve the transparency of municipal waste collection. The integration of UHF RFID technology with a dual-module onboard system and cloud-based data management ensures accurate identification, real-time reporting, and reliable synchronization of waste collection events. Field tests confirmed the system's stability and accuracy in detecting multiple bins simultaneously, even under challenging outdoor conditions.

Overall, the implemented solution provides a practical, cost-effective, and scalable approach to fair waste billing and operational efficiency in smart city environments. By combining automation, IoT connectivity, and real-time analytics, the system contributes to the digital transformation of waste management and supports the goals of sustainable urban development and circular economy policies.

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