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RESEARCH ARTICLE

IoT-Enabled Intelligent Garbage Management System for Smart City: A Fairness Perspective

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ABSTRACT Waste management has been identified as a critical problem underpinning the vision of sustainable cities. Despite existing efforts to tackle this challenge, traditional approaches still undermine resource allocation and utilization for the task. Most methods have overlooked the fairness problem found in the garbage-collection transportation units, producing noticeable varying active time differences among the participating units. The integration of Internet of Things (IoT) to waste management has recently been an emerging trend, which offers coordinated garbage collection benefiting from IoT networks. This work investigates utilization of LoRa technology for such a purpose and argues the importance of fairness perspective in actuating the truck agents for collecting the wastes in a given region. Through enabling reliable waste data exchange by a proper design and specification of the LoRa network, we can then cast the collection issue as a capacitated vehicle routing problem with a well-formulated objective function. To improve the fairness in the waste management, we propose an objective function that incorporates both the total distance covered by all the trucks and overall distance dispersion from individual trucks. Numerical simulation demonstrates the superiority and consistency of the fairness-based optimum solution in both minimizing the total distance and achieving the fairness.

INDEX TERMS Fairness, garbage collection, IoT, LoRa, smart city, waste management.

I. INTRODUCTION

The notion of the smart city originates from several technical perspectives that reflect user-oriented, responsive, and automatic feedback [1]. It ultimately aims to improve public welfare and wellbeing taking forms of good governance [2], efficient and autonomic operation [1], [3]. In a real-world scenario, this concept has been mainly enabled by Information and Communication Technology (ICT) and widely applied to urban sectors such as health building monitoring, waste management, air quality checking, noise monitoring, city energy consumption tracking, smart lighting, public building automation [2], road traffic optimization, and management, parking service [4], agricultural management as well as road incident detection and mitigation [5].

Among the abovementioned application sectors, effective garbage management has drawn the attention of several governments. One of the prevalent examples is Malaysia where effective garbage management is seen as one of the prerequisites to achieve a Developed Country status. For this reason, National Space Agency Malaysia (ANGKASA) under the Ministry of Science Technology, Innovation Malaysia (MOSTI) has taken an initiative to develop a Smart Waste Management System with the main objective

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to develop a service delivery engine that is capable of exploiting smart geospatial technologies to support city operation including in managing, using and exploring spatial data with scientific analysis in all possible phases of the decision making process in an organization [6].

Apart from being a national strategy, effective waste management has became a challenging issue for the Malaysian government. As in 2015, the Ministry of Urban Wellbeing, Housing, and Local Government Malaysia reported [7] that there were 15 − 18 kilotons of waste produced daily resulting up to 7.772.402 tons per year. There were only 76% to 80% of these waste, which were collected regardless of the government's huge expenses. This is partially caused by the fixed-weekly waste collection and collection route that does not consider the actual volume of each bin. As a consequence, garbage is collected when they are half-empty and, thus, making trucks are under-utilized. Besides, these trucks also miss certain regions during their collection time. Hence, it is important to devise an efficient automated smart waste management system to improve the collection process.

Many researchers have developed various smart Garbage Management System (GMS) focusing on either architectural or mechanism aspect. In studies that concentrate on architectural perspective [8], [9], [10], [11], a GMS is essentially designed as a reactive monitoring service that detects bin level and notifies the authorities to empty the waste. Each bin is equipped with a sensing device to measure the current volume. If the algorithm estimates the level beyond a threshold value, then a message will be dispatched via its communication device either a Wi-Fi transmitter or a GSM modem to the control facility. Among these studies, the authors of [12] considered a two-way communication factor that occurs between the bin, truck, and control center. Meanwhile, the works focusing on strategies aim to optimize the sequence of bin collection that resembles a Vehicular Routing Problem (VRP). The problem becomes even more realistic when a constraint of the weight capacity, Capacitated VRP (CVRP), is considered in the formulation. Different approaches have been used to solve the problem, such as mathematical programming [13], [14], heuristics [15], [16], [17] and meta-heuristics [18], [19], [20], [21], [22], [23], [24].

Although the aforementioned studies have been able to achieve the optimum collection plan from an accumulative distance perspective, there remains an issue of fairness of the travelled distance of collecting trucks. Typical strategies have mainly focused on solving CVRP where the sum of the distance of all vehicles must be as minimum as possible. However, a problem may arise from the solution, which is a noticeable variation of the total distances traveled by each vehicle. This situation could be less desirable by operators because different drivers might potentially have a large discrepancy on the collection route. These drivers are typically paid on the accrued time basis, not performance-basis. Therefore, a more realistic algorithm is needed to compute optimum routes concerning the fairness aspect of the different traveled distances.

This paper proposes a novel routing algorithm to address the fairness issue that arises from a pure CVRP-based solution with the following main contributions:

- We formulate the fairness perspective as the distance-dispersion problem of the different traveled distances among the trucks.
- We incorporate the formulated fairness variable into a novel strategy, namely fairness-based optimum solution (FBOS), aiming at maximizing the overall utilization based on the accumulated travel distance and distance dispersion.
- We demonstrate the inherent trade-off in the CVRP-based solution and highlight its discrepancy. We then propose a two-factor metric to facilitate the user's preference.
- We design and evaluate the FBOS in the Internet of Things (IoT) environment utilizing the LoRA capability and mobility factors. Our results indicate that the FBOS has a comparable effective performance to the conventional CVRP-based methods.

The remainder of this paper is organized as follows. We initially compare the state-of-the-art GMS algorithms in Section II. We then review the system model used in Section III. Subsequently, we describe the CVRP-based solution and its trade-offs in Section IV. We next discuss the details and performance of the FBOS in Section V and VI, respectively. Finally, we conclude our work in Section VII by showing the key highlights of the paper.

II. RELATED WORK

A. URBAN WASTE MANAGEMENT

Solid waste or garbage is generally included daily things that have been used before being discarded which belong to the households, institutes, markets, etc. including food waste, newspapers, clothing, furniture, batteries, etc. The volumes of solid waste are increasing day by day due to rapid population growth and overconsumption of non-renewable stuff. According to [25] and [26], Malaysian domestic daily waste production rate was estimated at 0.5 − 0.8 kg/person and the accumulated national waste will be at least 9 million kg/year by 2020 [27].

Waste management is the actions taken to manage waste from the inception to its disposal involves the generation, separation, storage, collection, transportation, treatment and disposal of waste with the monitoring to ensure the process followed the regulation [7], [26]. Most of the waste management is likely to be disposed of at a landfill or burn in the open air which these two habits are actually hazardous to the environment and also demand a huge management cost. Normally, local authorities or contractors are organizations that are responsible to manage the waste collection and disposal process [28], [29].

In [30], it aims to forecast urban solid waste generation in Sousse, Tunisia, using sequential artificial intelligence models, specifically long short-term memory (LSTM) and bidirectional LSTM (BLSTM), to predict the needed number of waste bins based on monthly waste generation data. The methodology highlights the advantage of these models in handling time-series data for more accurate waste bin prediction, compared to traditional methods. A key advantage is their ability to process sequential data effectively, but they may face limitations with very small datasets. The solution's key features include the use of advanced sequential models for predicting waste generation patterns, which improves the efficiency of waste management planning.

In the context of integrating blockchain technology into smart city waste management systems, recent scholarly discussions emphasize its transformative potential for enhancing transparency, traceability, and operational efficiency [31]. A pivotal study surveyed the application of blockchain in this domain, advocating for a framework that utilizes smart contracts to automate and secure waste management processes. This approach is celebrated for its ability to provide real-time tracking and ensure compliance with environmental regulations, addressing critical challenges such as data privacy and scalability. However, the literature also cautions against the nascent technology's limitations, suggesting a focused direction for future research to refine and adapt blockchain solutions for comprehensive waste management strategies in urban settings.

In the literature on smart solid waste management, a noteworthy contribution is the exploration of a blockchain-enabled Vehicular Ad-Hoc Network (VANET) framework, [32] which integrates Internet of Things (IoT) and Ultra-High Frequency (UHF) technologies. This study presents an innovative approach to enhance operational efficiency and security, facilitating real-time tracking and automated detection in waste management processes. While the solution offers significant advantages in terms of data security and operational transparency, it also acknowledges potential limitations related to the computational intensity of blockchain and the physical robustness of UHF tags. Key features highlighted include the system's ability to ensure secure communication across IoT devices and improve the reliability of waste collection services, marking a significant advancement in urban waste management practices.

In contemporary research on urban waste management, a significant study introduces MARBLE, an autonomous service robot system designed for improved efficiency through multi-agent route planning and cooperative operations. Reference [33] This paper's methodology, centered around the use of simulated annealing algorithms for route optimization, illustrates a novel approach to reducing energy consumption and operational costs in urban environments. Highlighting the dual benefits of environmental sustainability and cost-effectiveness, the research acknowledges the challenges of computational demands and scalability. Key innovations include autonomous robotic integration with central control systems for enhanced real-time operational management, positioning this study as a vital contribution to smart city waste management solutions.

Waste management has been a big concern in city planning across urban to rural areas because of the service cost and the numbers of landfills demand. Poor and unplanned waste management has contributed impacts to traffic congestion, fuel consumption, and human health due to climate change and pollutant emissions. For example, an impromptu and high usage of trucks in the waste collection process had caused waste in fuel consumption which also can cause air pollutants because of the gas emitted. The partially full bin when collected resulted in unnecessary wastage of truck capacities. Moreover, an extensive amount of money been spent in this sector.

B. IOT APPLICATION ON GMS

The prospect of welfare and wellbeing-purpose brought by smart city [3] have motivated several local governments to apply the concept in urban life [1]. Its implementation success could be solely determined by whether the investments in human and social capital and ICT could fuel improvement in urban management through participatory government [3]. For this reason, the deployment of Urban IoT could provide a simple, economical, and robust communication infrastructure [2], [34]. It also opens an opportunity to simplify various management in urban life such as transportation and parking, surveillance, public service maintenance, and waste management [2].

Despite the potential benefit of Urban IoT application especially on GMS, there have been few works done on real-time waste bin monitoring. Mostly, related studies [10], [12] proposed reactive monitoring system powered by radio communication and image processing capability. The authors of [10] have devised a real-time monitoring device for a smart bin in the region of Pudong (Shanghai). The solution integrates a digital camera with several technologies to degree and locates the fill stage and weight of the packing containers. A camera and ultrasonic sensor are attached to bins to collect waste data including height, shape, and area of the waste. Meanwhile, a sensor to measure the weight of the waste is attached at the bottom of the bin. The measurement data are then transmitted to main control using a GPRS module and used as input to map, monitor, and plan collection routes. Although this study has demonstrated the use of cameras and sensors, it has not used WSN for further data representation and the quality of the captured image is still low. Its implementation cost could be further lowered with the use of WSN and RFID for data exchange and tagging purposes.

Similarly, a solid waste monitoring system integrating camera, RFID, and GPRS as a module called Black Box was proposed in [12]. This module is attached to a waste bin truck and has the main responsibility to transmit data to the control center via wireless network. The established connection between the bins-trucks and trucks-control station exchanges bin status and control message. The bin level is estimated using Otsu's methodology where the input image is compared with the reference image in the central database. However, the accuracy of the bin level highly depends on the quality of images captured by operators. The truck stop area will greatly affect the capture angle and thus determines how good the input image. Besides this caveat and multi-technology integration, the solution has yet to facilitate real-time information making it less accurate to actual bin level.

More complex waste management was proposed in [35] where a virtual information hub was introduced to facilitate collaborative interaction between units. The exchange medium, smart space, allows GMS to retain and update relevant information on a real-world situation. It is designed based on ontologies capability to describe the relationship between physical entities and to store the data. There are two main components in smart space such as Semantic Information Broker (SIB) and Knowledge Processors (KP). SIB has the main responsibility of contextual deduction while KP''s main duty is to process data and transmit to KP. These two elements allow further analysis and prediction for bin collection resulting in real-time response. Besides this intelligent component, the study incorporates IoT components in the system model, such as sensor-installed bin and local processing unit using Raspberry Pi, and smartphone application to facilitate citizen collaborates with the system. Despite the anticipative technology, Smart-M3 requires a huge investment especially in implementation, operation, and maintenance as it requires many KPs implemented in each bin, Light Pole, and Control Center.

In [36], the researchers proposed a system that collect bin status information with the identity. Each bin is installed with an active RFID tag and ultrasonic sensor while RFID reader is installed on any approved troop or in a mobile sink, a vehicle of existing organized transportation systems. Finally, the mobile sink is responsible for forwarding all the data collected to the management system via Bluetooth and Wi-Fi communication technology for further analysis. The strength is low in cost. However, the system adopted partially real-time response and considered fill level data to represent the bin status. The proposed system also does not support a wireless network communication for further data integration.

Besides the above mentioned solutions, GMS aiming at reducing human resources and efforts was devised in [11] and [37]. In these studies, a web-based application was used as an interface between its end-user and system backend. While the website in [11] shows the current status of bins, the HTML page of [37] serves as payment gateway and user identification service. In addition to these specific purposes, both studies do not provide an optimum collection route. Even, the technique used in this reference lacks of measurement capability.

From [38], it presents an automated and secure garbage management scheme using unmanned any vehicle (UxV) technology, integrated with a deep learning (DL) model and blockchain, aimed at minimizing human effort in traditional garbage management systems. The methodology involves using various UxVs for automated garbage collection from both ground and sea surfaces, employing a lightweight DL model for accurate garbage detection, and leveraging blockchain for secure tracking of hazardous garbage. The solution offers advantages such as high accuracy in garbage detection, improved Quality of Service (QoS) through reduced latency and enhanced security, and a novel approach for hazardous garbage tracking. However, limitations include the potential for decreased system performance due to the computational demands of the DL model and blockchain integration. Key features include the use of MISH and rectified linear unit activation functions for improved garbage detection, multiaccess edge computing for enhanced QoS, and a private blockchain network for secure garbage tracking.

Within the scholarly discourse on leveraging IoT for enhancing Smart Waste Management Systems (SWM) in smart cities, a systematic review stands out for its comprehensive analysis of existing literature on the subject. Reference [39] This review meticulously sifts through numerous studies to shed light on the deployment of IoT technologies and smart garbage bins (SGBs) in SWM, highlighting the significant strides in efficiency and environmental sustainability these innovations offer. Despite the clear benefits, the review does not shy away from addressing the technological and integration challenges that persist, suggesting a pathway for future research. The elucidation of IoT's real-time monitoring capabilities, alongside the strategic optimization of waste collection routes and the crucial involvement of various stakeholders, contributes a critical perspective to the ongoing evolution of waste management practices in urban environments.

In [40], a study on a Convolutional Neural Network (CNN)-Based Smart Waste Management System emerges, leveraging TensorFlow Lite and LoRa-GPS Shield within an IoT framework. The investigation aimed to refine waste segregation and monitoring through advanced deep learning techniques, highlighting the system's adeptness in accurate waste classification and real-time bin status tracking. Despite its innovative application, the system grapples with limitations such as computational constraints on Raspberry Pi devices and challenges in dataset comprehensiveness for waste recognition. Key contributions include the implementation of real-time waste sorting and efficient communication protocols, presenting a significant advancement in smart waste management technologies.

C. VEHICLE ROUTING PROBLEM (VRP)-BASED SOLUTION

In many research studies, the waste collection problem of the municipality is designed as a vehicle routing problem (VRP), which return an effective collection route. There are a few number of constraints that are considered in the studies. Vehicle capacity constraints or capacitated vehicle routing problem (CVRP) is the most common constraints studied by these researchers. Many researchers have been modelling the waste collection in CVRP approaches but with a different algorithm and tools [41]. However, a limited number of studies have been done for smart bin technologies for waste collection and route optimization.

In early years, conventional mathematical programming algorithms like linear programming [13] and mixed integer programming [14], [16] have been applied in the optimization of waste collection. However, this method seems to have fewer weaknesses that they are less effective for large-scale problems as more components need to be considered for the optimization, which resulting in a complicated solution approach.

A heuristic approach been introduced to overcome the limitations of the first method as it able to overthrow huge computational time problem. The most popular and effective heuristic approaches are the nearest neighbourhood search algorithm [15] and greedy algorithm [16], [17]. However, their lack of precision with longer execution times for the waste collection is the weaknesses of these approaches.

Nowadays, meta-heuristics techniques been widely applied in waste collection. This approached able to yield sufficiently good solutions for the collection optimization even with the incomplete information given or limited computational capacity. A few meta-heuristics approaches that are popular are ant colony optimization (ACO) [18], genetic algorithms [19], and particle swarm optimization(PSO) [20], [21], [22], [23], [24].

However, few studies have combined technologies with best-developed algorithms in waste management sector. In [42], researchers introduced a framework adopting traceable data that collected from the integrated smart bin and truck with a heuristic approach in a simulation environment. They consider different optimal capacity levels and extensive risk parameters in their study to compare optimization results obtain. The following table summarizes the modelling approaches applied in few types of research for waste collection route optimization.

III. OVERVIEW OF THE PROPOSED IoT-ENABLED GMS

A. NETWORK COMPONENTS

The proposed GMS consists of three primary components such as Smart Bin, Control Center, and Dump Truck. Each of these components has the following description and capability:

1) Smart Bin is an improved version of typical garbage container as it has two additional submodules. First, it has an ultrasonic sensor enabling it to measure its current waste volume. Second, it has communication module that supports two-way coordination with Control Center. Such a collaborative feature has been made possible by a IoT-supporting device, e.g. Arduino or RaspberryPi. In our proposed system, the Smart Bins transmit their data to Control Center via nearby Access Points (APs).
2) Control center is the main actor in SWMS with two key roles. As a communication facilitator, it has a responsibility to handle data transmitted by Smart Bins, including bin volume, and waste collection data. The second role is coordinator where it has to calculate the best collection route for dump trucks, and regulate the dispatch time.
3) Dump truck has a main responsibility of transporting waste from assigned Smart Bins. These trucks follow the collection sequence starting from the Control Center to Dumping Point.

B. NETWORK ARCHITECTURE

Fig.1 depicts the network architecture of proposed GMS. As seen on Fig.1, all APs communicate with nearby Smart Bins and APs. There are two communication phases in the proposed GMS such as upcasting and broadcasting. In the first stage of coordination, the Smart Bins update their status and upload it to the Control Center. Due to the short communication range of Smart Bins, the waste volume data are initially transmitted to APs. Then, these data are forwarded to other APs within their communication range until they reach the terminal point. This strategy implies several connections between multiple APs until any of these AP range extends to the Control Center. As the coverage area of APs' are overlapping with each other, each of them is interconnected and covers the full area of the architecture. Therefore, packet loss is very unlikely to occur as blank spot area is minimized.

Meanwhile in the broadcasting phase, Control Center transmits a query message of to all Smart Bins. Such a memo will trigger all Smart Bins uploading their current waste volume level. Then, based on the provided information, a fairness-based optimum algorithm will be executed by Control Center, producing routes assigned to Dump Trucks. These trucks will follow the route sequence with the Control Center and Dumping Point as the initial and terminal point, respectively.

C. NETWORK TOPOLOGY

A network topology is a schematic layout of underlying communication elements, e.g. links, end devices, and switching devices. It is the topological structure of a network and may be depicted physically or logically. Also, it is an application of graph theory where communicating devices are modeled as nodes and the connections between the devices are modeled as links or lines between the nodes.

In the proposed system architecture, we design a two-tier topology connecting all edge devices and core system. The alignment combines two distinct network layout, such as point-to-point and star. While the former layout bridges all communication between AP-AP and AP-Control Center, the latter connects an AP to its nearby Smart Bins. The composite setup can provide good coverage and reliability for a metropolitan-area network.

D. TECHNOLOGY SELECTION

Given the scenario of the proposed GMS shown in Fig. 2, network architecture illustrated in Fig. 1, we summarize

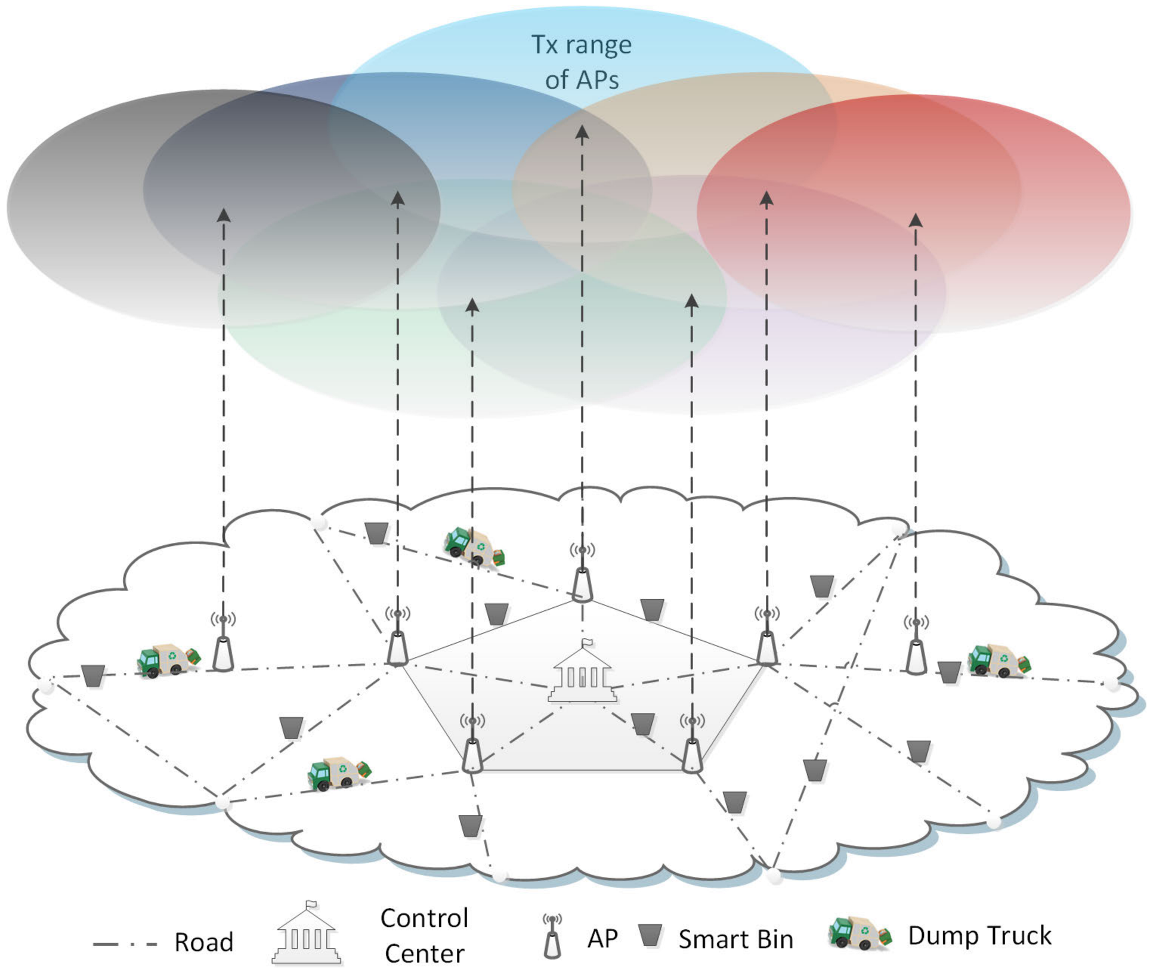

FIGURE 1. Network Architecture of proposed GMS.

the specifications and limitations of existing wireless technologies in Table 1. Then, we elaborate each aspect in Section III-D1-III-D5.

1) DATA RATE AND LATENCY

In the proposed GMS, the actors need to coordinate with the control station. This contact can utilize short messages which do not require a high data rate capability. Acceptable data rate is required for establishing the communication session. Also, there is no real-time application used in the proposed system. Therefore, any technology listed in Table 1 can be a viable option for implementation.

2) COVERAGE RANGE

As shown in Fig. 2, the implementation area can be in kilometer units, e.g. a district or a town. It is preferable to have less number of AP since it has less complexity of installation and maintenance. This aspect becomes one of determining factors in selecting the best technology. Based on Table 1, WiMAX, GSM, and LoRa is more suitable to GMS as they can cover more than 10 km radius area.

3) OPERATING BANDS

Another important factor is the operating bands since operation in a licensed band incurs a license cost. Also, flexible operating frequency band is needed as GMS can be implemented in different regions. For example, in Europe LoRa operates in the range of 868/433 MHz frequency band, whereas, in United States it operates in 915 MHz.

4) LESS-ENERGY CONSUMPTION

Energy remains one of critical issues in remote sensing implementation. In GMS, most of components used by actors are energy-constrained as they are only powered by battery. This is also an effort to reduce expense as the proposed system does not rely on commercial electricity service. Therefore, wireless standard with low energy usage is highly preferable in the proposed system.

5) DEPLOYMENT COST

In this final aspect, we look into the potential deployment cost using each wireless standard. In case of WiFi, the cost will be high as the installation requires a lot of APs

TABLE 1. Comparison of existing wireless technologies.

2*Aspects	Standards					
	WiFi	XBee	LTE	GSM	WiMAX	LoRa
Max. data rate	3.5 Gbps	250 Kbps	326 Mbps	9.5 Kbps	134 Mbps	50 Kbps
Max. coverage range	250 m	1.6 km	5 km	$\leq$ 10 km	$\leq$ 30 miles	$\geq$ 10 km
Low-latency support	✓	-	✓	✓	✓	✓
Less-energy consumption	✓	✓	✓	✓	✓	✓
Unlicensed band availability	✓	✓	-	-	Conditional	✓
Deployment cost	High	Medium	High	High	High	Low

because its narrow coverage. Meanwhile, XBee can offer lower deployment cost than WiFi. Network installation with LTE, WiMAX, and GSM will be high as it requires licensed band. Unlike the aforementioned technologies, LoRa requires low cost as its transmission range is high and it can work with unlicensed band.

Based on the above discussion, LoRa is the most suitable technology for the network implementation since it fulfils all important requirement of the proposed system.

IV. PROBLEM FORMULATION

The route optimization problem in GMS has a similarity with CVRP in terms of the constraint used in the solution. The objectives of CVRP are to minimize the number of vehicles needed to serve the customers and minimize travel time for each vehicle. In other words, it calculates a route that minimizes the utilization level of vehicles used to serve customers‘’ demand in a single session from the same depot. For this reason, several meta-heuristic methods have been proposed to obtain a near-optimum solution. However, the recent algorithms produce an unfair result of travel distance for each driver where the first distance in an n sequence will always be shorter than the last one ($D_1 \ll D_n$).

In contrast to the abovementioned caveats, this study aims to minimize the variance of distance traveled by each dump truck. We propose a novel fitness metric to reach the optimality of short distance and a high degree of fairness. To this end, we set up the parameters to reduce the management by (2) minimizing the accumulated travel distance of each truck, (3) reducing the required capacity to pick up, and (4) minimizing the travel time of each truck. In brief, the cost-effective of GMS can be obtained when (2) the number of trucks is minimized which is achievable by maximizing the utilization level of truck‘’s capacity, or (3) the travel distance of each truck is minimized by using the shortest path in the collection process.

Let $\mathcal{N}$ is the set of Smart Bin where $\mathcal{N} = \{n_1, n_2, \ldots, n_N\}$, $\forall N \in Z^+$. The set of optimum path $\mathcal{P}$ for M trucks is denoted by $\mathcal{P} = \{p_1, p_2, \ldots, p_M\}$; $\forall M \in Z^+$, where $p_i = \{n_1, n_2, n_3, \ldots, n_k\}$ and $k \neq N$; $p_i \subset \mathcal{N}$. Also, let D_i is a set of distance travelled by i-th truck in p_i. A solution set S_i is a set of possible combination $\mathcal{P}$ such that $S = \{\mathcal{P}_1, \ldots, \mathcal{P}_n\}$. The parameter derived to satisfy the optimum path solution are as follows:

1) The total distance travel from depot to the dumpsite by M number of trucks during a waste collection process is minimum.
2) The fairness value FD of the solution set is also minimum and denoted by

$$\mathrm{FD} = \min\left(\mathrm{FD}_i, \ldots, \mathrm{FD}_n\right),$$

where

$$\mathrm{FD}_i = \sum_{j=1, i\neq j}^{n} |d_i - d_j|. \quad (1)$$

Then, based on these parameters, the best path will be chosen based on either the shortest-path output or the minimum FD. However, this selection only can not guarantee the value also satisfy another parameter. Following subsection IV-A will elaborate this claim.

A. SAMPLE SCENARIO

Fig.2 illustrates the city map used in this sample scenario. During a garbage collection phase, the Control Center (CC) selects the bins having volume higher than certain threshold value. Then, it calculates M and $\mathcal{P}$ for collection assignment to Dumpsite (D). Let us consider following assumption

1) The number of Smart Bin (NB) is 16, with each capacity (CB) of 50. The total capacity for this collection (TCB) is 800.
2) Each truck has a maximum capacity (TB) of 200. Thus, the number of truck required M = 4.

For the first parameter defined, suppose we have $|S| = 4$ and each of i-th entry of S has assigned route starting from CC to D. Then, the first possible solution set is $S_1 = \{\{8, 9, 1, 2\}, \{3, 4, 7, 13\}, \{11, 20, 21, 18\}, \{17, 16, 15, 6\}\}$ with a distance of $D_1 = \{33, 31, 35, 36\}$ and a total travel distance TD_1 of 135. Herein, p_2 has the least travel distance of 31. Similarly, we obtain $S_2 = \{\{13, 17, 16, 15\}, \{3, 4, 7, 6\}, \{8, 9, 1, 2\}, \{11, 20, 21, 18\}\}$, $D_2 = \{26, 30, 33, 28\}$ and $\mathrm{TD}_2 = 117$. Applying similar action to S_3 and S_4, we may obtain $S_3 = \{\{1, 2, 3, 4\}, \{9, 8, 7, 6\}, \{13, 17, 16, 15\},$

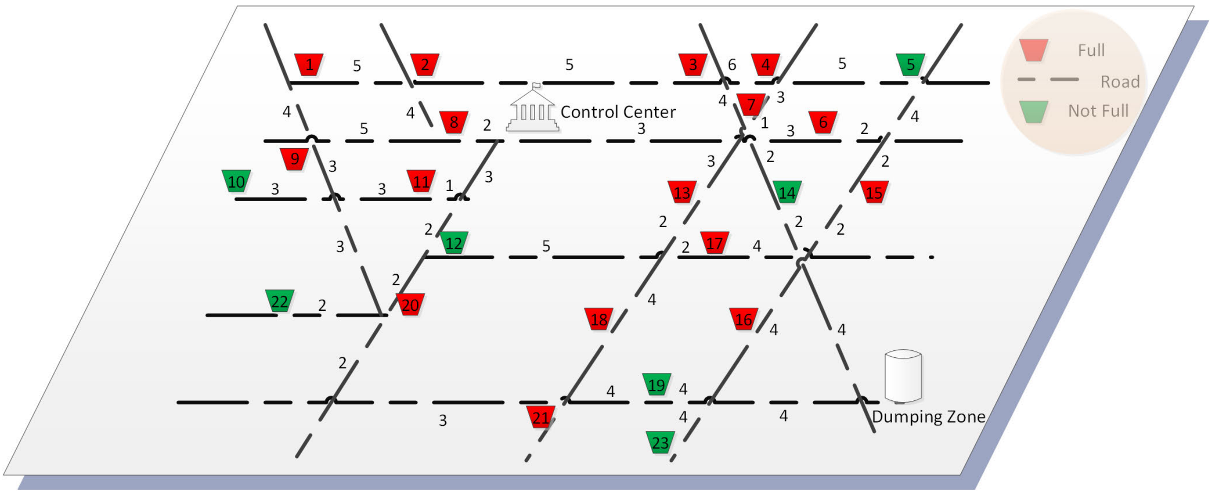

FIGURE 2. Scenario used in proposed Garbage Management System (GMS).

$\{11, 20, 21, 18\}\}$ and $S_4 = \{\{8, 9, 20, 11\}, \{1, 2, 3, 4\}, \{13, 18, 21, 16\}, \{7, 6, 15, 17\}\}$, respectively. The distance of these sets are $D_3 = \{39, 32, 26, 28\}$ and $D_4 = \{35, 39, 30, 26\}$. Therefore, the best solution satisfying the first parameter is S_2 as it minimizes the travel distance.

Next, the second parameter concerns FD for each entry of S. Based on the Eq. (1), we obtain $\text{FD}_1 = |(33-31)| + |(33-35)| + |(33-36)| = 7$. Similarly, for the rest of S entry we obtain $\text{FD}_2 = 9$, $\text{FD}_3 = 31$, $\text{FD}_4 = 18$. As a result, S_1 is chosen as the solution because it has the least *TD* dicrepancy.

B. THE TRADE-OFF

From the discussion in Section IV-A, we have noticed that both case produces different final result. The first approach prefers the optimum path based on the shortest path, while the second one considers the fairness issue with a less-optimum final cost. Based on these two situations, we propose an optimum solution for the cost minimization problem by minimizing the number of trucks required for each collection activity and assuming all dump trucks have equal capacity.

V. FAIRNESS-BASED OPTIMUM SOLUTION (FBOS)

By considering maps and configuration i.e., generation, bins, bin capacity, truck capacity, CVRP-based optimization attempts to minimize the cost of garbage collection via deployment of truck agents as sketched in Section IV. In the following we discuss our main proposal of alternative cost representation that considers fairness among individual trucks‘‘ travelling distances. More specifically, we aim to improve the distance fairness via a well-designed waste management algorithm to calculate and optimize the effective path for collection.

A. FAIRNESS SOLUTION

In the current body of knowledge, most CVRP-based solutions mainly focus on representing the cost element as a travelling distance. As a consequence, these algorithms compute their optimal solution that minimizes the total accumulated distance covered by all their mobile agents, e.g. shortest accumulated path. A major deficiency of this approach is that there can be a large variation of travel distance covered by each moving unit, which may not be desirable in some scenarios, such as the use of mobile units from different providers. In such a case, the agents may have travelled some kilometers prior to their next assignment, making a high discrepancy between them.

A sole metric of measuring distance fairness can be obtained as follows. We argue that a distance fairness can be achieved if the resulting garbage collection algorithm leads to approximately equal distances among the truck agents. In other words, a truck's travelling distance should not deviate too much from the average travelling distance, averaged across different truck agents.

Inspired by the statistics field, a proper measure that can capture such a distance dispersion is standard deviation [43]. In the GMS context, the fairness of the trucks deployment can be specifically formulated as follows.

Proposition 1: Consider the formulation in Section IV with N dump trucks from a given region. The travel distance for $i-th$ truck's route $p_i \in \mathcal{P}$ is D_i. A truck i has a total distance $\text{TD}_i = \sum_{i=1}^{N} d_i, d_i \in D_i$. Then, the cumulative total distance $\text{CD} = \sum_{i=1}^{N} \text{TD}_i$. A fair solution is achieved if the dispersion value

$$\text{SD} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(d_i - \frac{\text{CD}}{N}\right)^2} \tag{2}$$

is minimized within solution set S.

The use of the dispersion measure in Proposition 1 allows us to construct and develop meta-heuristic algorithms for CVRP-based optimization that achieves fairness. In this case, the rather than the accumulated distance, the optimization objective is given by Eq. (2). Since fairness is the primary objective, the resulting solution may not necessarily minimize the overall travelling path.

B. PROPOSED FBOS

By incorporating both the distance and fairness parameters, we propose that the optimal garbage collection should concurrently minimize the accumulated distance and distance dispersion. While achieving both may be infeasible in many cases, it is imperative to introduce a new metric that captures the trade-off between the two parameters and allows for flexible specification on the relative importance between them. This cost metric is given by proposition 2.

Proposition 2: Consider the assumption used in Proposition 1 and distance dispersion *SD* defined in Eq. (2). An algorithm can achieve the optimal solution for a waste collection problem if it minimizes an objective function

$$\mathrm{DF} = w_d \mathrm{CD} + w_f \mathrm{SD}, \tag{3}$$

where $w_d + w_f = 1$. The w_d and w_f denotes weighted coefficients for TD and SD, respectively.

Remark that w_d and w_f allow users to tune how the algorithm calculates the optimal solution. In the case of $w_d = w_f = 0.5$, a user treats both the accumulative distance and fairness equally in the CVRP optimization. Meanwhile, in an extreme case where $w_d = 1$ and $w_f = 1$, the optimization objective reduces to the original shortest accumulated path and fairness functions, respectively.

VI. NUMERICAL RESULTS AND DISCUSSION

A. LORA NETWORKING ANALYSIS

The performance of the proposed FBOS will be measure based on two prominent metrics such as Throughput (Thr) and Delay (Dly), which are calculating using the Eq. 4 and Eq. 5, respectively.

$$\mathrm{Thr} = \sum_{i=1}^{N} \frac{T_v}{T_t} \tag{4}$$

$$\mathrm{Dly} = \sum_{i=1}^{N} T_t \tag{5}$$

where T_v is the Total Volume of Collected Garbage by i-th Track (kg) and T_t is the total time to reach CC from the last node of a path and last node to CC (s).

This study considers 200 to 600 transmitting nodes which implanted into smart bins and deployed randomly. These devices are set to transmit their packets to gateways and it forwards them to server via reliable transmission medium. These gateways use SX1301 module with European region channel configuration. Then, in order to provide better illustration on how LoRA can be utilized into network setup, we design simulation so that LoRA limitation can be observed as well. Although in real implementation smart bins transmit much less frequently, our scenarios attempt to evaluate the protocol in more frequent transmission, and various number of gateway. For instance, this study uses interval of packet transmission ranging from 30 - 120 seconds, and number of gateway ranging from 1 to 49.

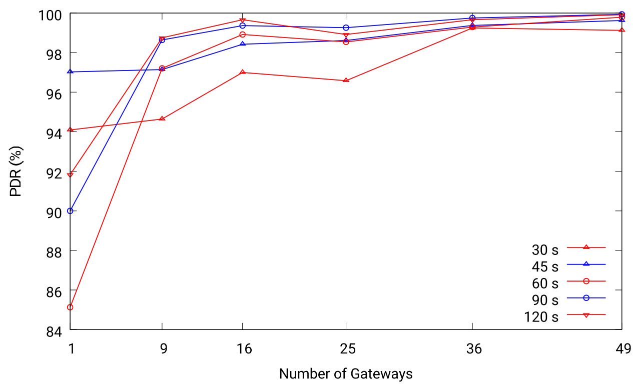

FIGURE 3. PDR.

Some experiments scenario which includes different combination of the number of transmitting and gateway nodes are performed to evaluate packet delivery rate (PDR), delay, and interferenced packet ratio in LoRA. The transmission interval time of smart bins are set identical with randomized initial value in range of the interval value. Thus, a scenario with 30 seconds of transmission interval will provide 0 - 30 seconds of initial packet sending time. It is then followed by sequential transmission in next 30 seconds.

Although 1 LoRA gateway is theoretically able to provide signal coverage in 10×10 km area, our experiment has showed that acceptable packet delivery rate is difficult to achieve. Our first result (3) illustrates the delivery rate for 600 nodes According to the result, the setup is only able to provide approximately 97% rate of successful delivery with packet transmission interval of 45 seconds. Increasing the interval can not provide better result since the number of transmitted and received packet will be much less. This is due to the random behavior of transmission time and smart bin geolocation will affect wider range of initial sending time and gateway reception path, respectively. In addition, it can be seen that 25 gateways can provide acceptable result ($\geq$96%) for 600 nodes. This is because of gateway's receiver and channel configuration used in this simulation can handle multiple decoding on overlapping packet transmission effectively.

Figure 4 represents the number of transmitted packets during the simulation period. LoRA has specified duty cycle mechanism which limits channel usage. Our simulation incorporates European configuration which uses 3 sub-bands with 0.1%, 1% and 10% utilization rate. The setup regulates the channel availability for both transmitting and receiving packets. Whenever a sub-band achieve its usage limits, corresponding nodes must wait a certain time. A 30-second interval packet transmission setup experienced the duty cycle regulation most. In contrast, 120-second interval packet has the least number of transmission due to less frequent transmission.

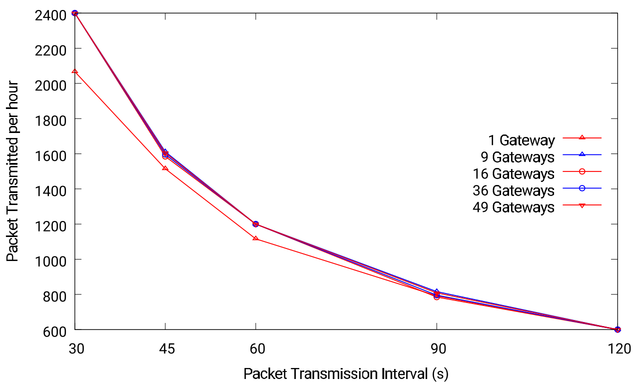

FIGURE 4. Transmitted Packets.

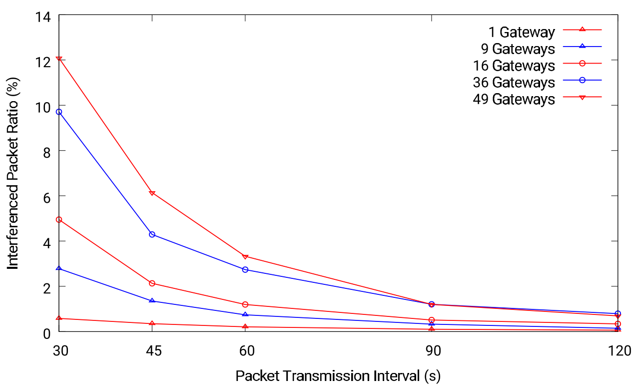

FIGURE 5. Interferenced Packet Ratio.

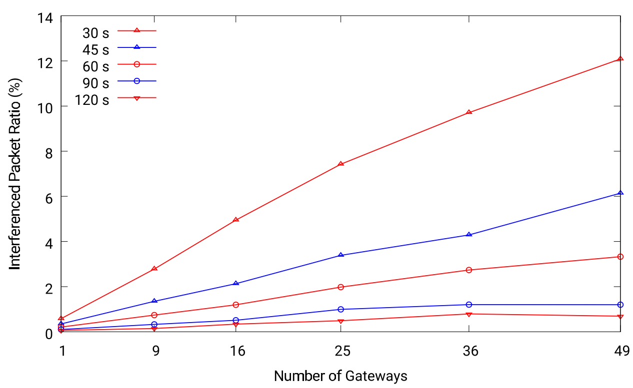

FIGURE 6. Interferenced Packet Ratio.

Figure 5 and 6 suggest the percentage of received packet under interference condition using different packet transmission interval and number of gateways setup, respectively. It is obvious that the less value of the setup contribute less interferenced packet ratio. This is due to less number of gateway and less-frequent packet transmission inflict on lower channel sub-bands utilization rate in the network.

B. GARBAGE COLLECTION OPTIMIZATION

In order to obtain numerical results, we implement the FBOS in Section V-B using the genetic algorithm in Algorithm 1 as a meta-heuristic solver. This algorithm consists of four

Algorithm 1 FBOS for Waste Management

0: READ T ← readTopology() {read topology from a file}
0: INITIALISE G ← Ginitial {initiation of Generations}
0: INITIALISE B ← Binitial {define bin to be visited}
0: INITIALISE BC ← BCinitial {define bin capacity}
0: INITIALISE TC ← TCinitial {define truck capacity}
0: GENERATE population Pi ← generate(B,BC,TC) {generate individuals}
0: EVALUATE Pi ← evaluate(Pi,T) {calculate the fitness value}
0: **for** i = 1 to G **do** {iteration of G}
0: CONVERT Ci ← encode(Pi) {into chromosome form}
0: Oi ← findOffspring(Pi,Ci) {selecting 2 best fitness}
0: Oi ← Crossover(Oi) {using 1 single point crossover}
0: Oi ← mutation(Oi) {swapping 2 point in individual}
0: CONVERT Oi ← decode(Oi) {convert each chromosome}
0: Pi ← updatePopulation(Pi,Oi) {replace worst fitness}
0: Pi ← evaluate(Pi,T) {calculate the fitness value}
0: **endfor**=0

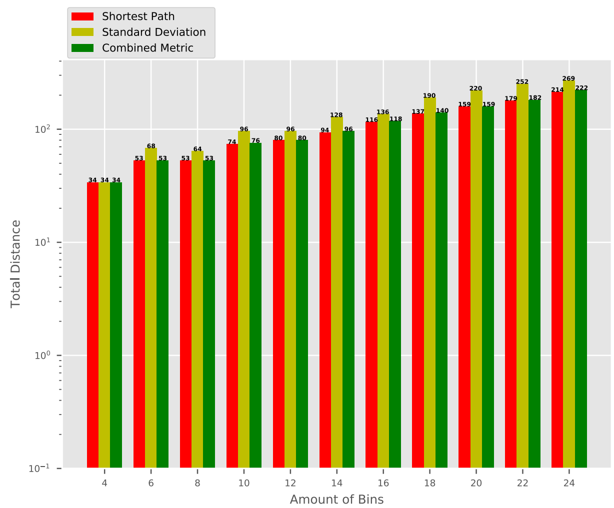

FIGURE 7. Total distance covered by all the trucks against the number of bins for sole-distance, sole-fairness and equal distance-fairness cases in CVRP optimization.

processes, namely selection of two top fitnesses, crossover by using 1 single point, mutation by using 2 points, and fitness calculation. Aligning with the objective function in Proposition 2, the fitness value is calculated by using *DF* as the combined total distance and dispersion value in Eq. 3.

We next evaluate the consistency of the FBOS in Algorithm 1 by comparing the extreme cases (sole shortest distance $w_d = 1, w_f = 0$ and sole fairness $w_d = 0, w_f = 1$) with the equal distance-fairness consideration $w_d = w_f = 0.5$. Fig. 7 and 8 depict the results of these three cases in terms of the total distance covered by the trucks and the dispersion value against the number of bins. We can clearly see from both figures that the sole fairness case, whilst achieving the fairest solution, may lead to a total distance that is the worst. Meanwhile, the equal distance-fairness case shows an outstanding performance. Although, this may slightly trade-off the fairness achievement, its total distance performance closely reassembles the sole shortest distance case, which is optimal for the given total distance criterion.

From the above results, we can infer the desirability of incorporating the two parameters, namely the total distance

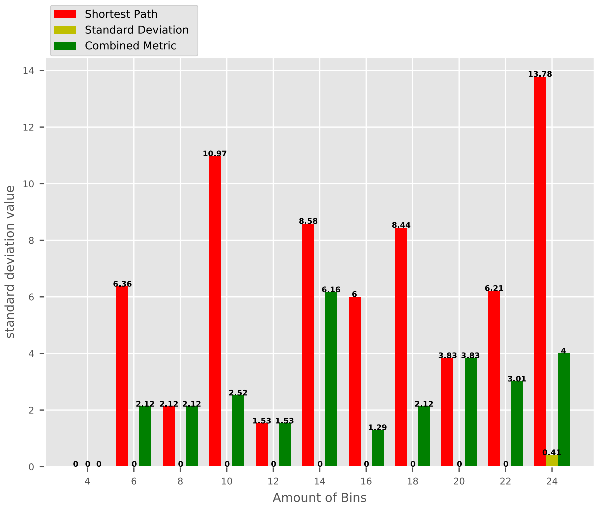

FIGURE 8. Dispersion value for truck's distances against the number of bins for sole-distance, sole-fairness and equal distance-fairness cases in CVRP optimization.

and dispersion, with appropriate weights in the overall FBOS. The implemented GA for FBOS herein can achieve a proper balance between the cumulative distance and fairness when the weights are set identical (i.e., $w_d = w_f = 0.5$). This shows that the proposed metric in Eq. (3) consistently performs as intended and describes an accurate tradeoff between the distance and fairness.

VII. CONCLUSION

This paper has investigated an IoT-enabled Garbage Management System (GMS) to obtain the optimum fairness performance among mobile garbage-collection units. We have started with the comparison of the approaches based on two different parameters, namely the accumulated distance and the distance dispersion. This comparison has shown rather varying behaviors of the two parameters in advocating the optimum collection-route solution. This has motivated us in proposing a two-factor metric to accommodate the user preference on the shortest path and minimum travel distance dispersion. Our formulation has shown that the weighted factors can tune the optimal CVRP-based solution. As a proof of concept, we have proposed the system model used in the GMS and evaluate its performance based on the FBOS objective formulation. We have subsequently justified the appropriate wireless technologies that focus on the deployment cost, maintenance effort and cost. Numerical experiments have been used to demonstrate the reliable performance of the proposed wireless network implementation in terms of throughput and delay.

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