

# Developing a Smart Wireless Sensor Network for Waste Management in Cities

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**Abstract.** As rapid global urbanisation is expected to peak by 2050, the need for smart and sustainable infrastructure to manage and combat urban waste effectively has become increasingly urgent. This study addresses the critical issue of waste management in expanding cities through the proposal of a novel wireless sensor network (WSN) aimed at optimising waste collection and processing by assisting contemporary procedures through the integration of recent advances in networking and unmanned aerial vehicles (UAVs). With the aim of investigating the efficacy of our proposals, various assessments and analyses within the Cooja network simulator are conducted. In conjunction to this, a real-life case study of major transport stations within Whitechapel, London is also considered to provide enhanced insight into the network’s effectiveness. [The developed model demonstrates the system’s capability of enhancing waste collection services with a minimal average transmission delay of 125ms experienced across all simulated nodes.](#) Finally, the paper provides all simulation and node source code, encouraging future development and refinement in smart waste management and Internet of Things (IoT) solutions, enabling future integration with artificial intelligence for further optimisations.

**Keywords:** Wireless Sensor Network (WSN) · Smart Cities · Artificial Intelligence · Waste Management

## 1 Introduction

As the world trends closer towards implementing smart city style infrastructure in major cities, the urgency to introduce novel algorithms to revolutionise and optimise contemporary procedures becomes increasingly important. A study completed in 2017 predicts by the year 2050, most of the earth’s population will have moved to urban areas [7], forming vast cities that require smart and sustainable infrastructure to manage the needs of their citizens. With the excessive levels of

concentrated waste production this will bring to city environments, researchers have previously recommended that advancements in smart city technology are necessary to augment and improve existing waste management systems to ensure they are capable of supporting these enhanced levels of activity [2].

Previous works including [4] have explored and successfully developed individual Internet of Things (IoT) enabled smart bins. Alternatively, works such as [6] propose a method of utilising a cuckoo search algorithm to analyse waste data in order to enrich existing waste management infrastructure. The authors of [13] implemented a waste network system by utilising the long-range wide area network (LoRaWAN) protocol which can support capacity monitoring of bins on the network. However, without the utilisation of the IPv6 over low-power wireless personal area networks (6LoWPAN) protocol, dependence on the LoRaWAN protocol means the implementation doesn't support IPv6, as discussed in [5]. Additionally, in [22], Sartori et al. tested an implementation of the routing protocol for low-power and lossy networks (RPL) over LoRaWAN but identified unexpected behaviours and deemed that further work must be completed to overcome the issues presented.

Similarly, researchers have previously explored the use of unmanned aerial vehicles (UAVs) for smart waste management applications. The researchers in [23] discussed the application of UAVs and their ability to enhance existing waste management frameworks, reducing emissions through sustainable waste transportation and increasing site safety through enhanced automation. Furthermore, works completed by Figliozzi suggest that UAVs can be implemented to lower emissions, being approximately 47 times more efficient per unit distance travelled than conventional diesel vans [12]. Alternatively, recent advancements in artificial intelligence (AI) have also been applied to waste management problems to enrich existing processes. For example, Abdallah et al. analyses and reviews potential AI applications for waste management solutions [1]. Our work integrates optimally with these previous directions and can be extended in the future to utilise AI-based scheduling for more efficient waste management.

The network simulator Cooja Contiki-NG [20] has previously received extensive representation in studies that explore and simulate ad hoc networks [17,3]. The authors of [21] have used the software for simulational analysis and comparisons of both static and mobile networks, whilst in [9] researchers have used Cooja to investigate the RPL protocol for use in IoT networks. Finally, in [10] and [11], the software is used to analyse the performance of multiple nodes that are in constant communication with each other.

As previous work lacks the evaluation and simulation of an RPL-based ad hoc network for city-scale smart waste management, as shown in Table 1, we propose and simulate a novel wireless sensor network (WSN) to manage and coordinate waste management tasks. The simulation, which employs 22 nodes, addresses a gap in the existing literature, particularly concerning the complexities of large urban environments within a Cooja environment. We aim to examine and rigorously simulate a network model capable of supporting smart waste management services for network-enabled smart bins with the overall objective of enabling

more efficient and streamlined waste collection processes that take advantage of the latest technologies.

**Table 1.** A comparison of this work against other similar WSN studies for smart city waste management.

| Ref  | RPL-based | Simulation | Case Study | Full Code |
|------|-----------|------------|------------|-----------|
| This | ✓         | ✓          | ✓          | ✓         |
| [18] | ×         | ×          | ✓          | ×         |
| [27] | ×         | ✓          | ×          | ×         |
| [19] | ×         | ✓          | ✓          | ×         |
| [25] | ×         | ×          | ×          | ×         |
| [24] | ×         | ×          | ×          | ×         |

Therefore, this paper’s major contributions are presented as follows:

1. A novel method of monitoring waste services across an urban environment is proposed to improve upon contemporary waste management frameworks by merging previous research efforts in computer networking and UAV technologies.
2. A novel simulation of an extensive 22-node smart waste management network within the context of a case study that focuses on major transport stations in Whitechapel, London is completed within the Cooja network simulator.
3. All supporting source code including the full simulation environment is accessible at <https://github.com/palzino/Waste-Management-WSN>, fostering future ad hoc networking research efforts for similar smart city environments.

## 2 Background

### 2.1 Case Study

To provide a realistic focus for the assessment and validation of this work’s proposed waste management network, we are utilising a selected area of transportation stations in Whitechapel, London to act as a setting for our simulation experiments to commence.

As a major global city, with a predicted population of 10.5 million by 2035 [26], London’s expansive transportation network generates excessive levels of waste and therefore requires comprehensive waste management solutions. In 2015, the London Authorities identified that businesses and residences throughout London were producing 7 million tonnes of waste annually [8], prompting the local government to introduce a set of goals to make the city more sustainable and environmentally friendly. In 2009, it was disclosed that London’s underground tube network produces approximately 3,250 tonnes of waste across its stations and depots [14]. Since the network has only expanded and continues to expand in the future, it is paramount that scalable, next-generation waste management

technology is available to meet the city’s expansive recycling needs. The city has also expressed interest in integrating recent advancements in IoT technology to introduce improvements over contemporary waste management procedures. In July 2024, the city began experimenting with implementing RFID technology on their existing waste collection vehicles in a small set of residential areas [15]. By analysing the city’s current plan, the basis of this case study was devised as our proposals could act as a comprehensive extension of the existing framework being trialled.

Figure 1 presents the area surrounding Whitechapel, London with all London Underground, London Overground, Elizabeth Line and National Rail transport stations marked. This location has been chosen to form the case study for this work as it contains a dense amount of commercial buildings and transport stations, making it an optimal area for future smart city developments and innovations. The approximate locations of each transport station will be replicated as a node within the Cooja simulation to provide a realistic depiction of the feasibility of this work against a production implementation.

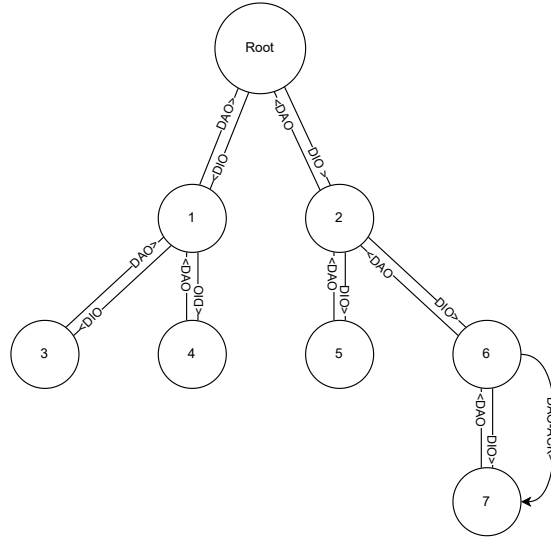


**Fig. 1.** A map of Whitechapel, London with all London Underground, London Overground, Elizabeth line and National Rail transport stations marked.

## 2.2 Routing Protocol for Low-Power and Lossy Networks (RPL)

The routing protocol for low-power and lossy networks (RPL) is a vector-based protocol that utilises a direction-orientated directed acyclic graph (DODAG) based on the IEEE 802.15.4 standard [16]. Figure 2 illustrates an example of the hierarchical structure of RPL and DODAG.

The root node is the destination where all packets flow towards. Upon a new node joining, DODAG information solicitation (DIS) messages are sent to update the graph’s structure. DODAG information objects (DIOs) are used to find



**Fig. 2.** An example RPL DODAG structure with control messages in both ingoing and outgoing directions from each numbered node [28].

upwards routes within the network, whereas destination advertisement objects (DAOs) form downwards routes.

An RPL DODAG fits well to a smart city environment by leveraging multi-hop communication to allow data to travel between high-density buildings, ensuring reliable connectivity across urban landscapes, even with physical obstructions.

### 3 Methodology

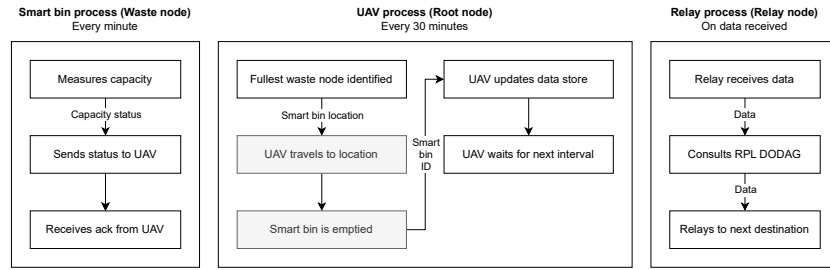
#### 3.1 Proposed Network

The proposed waste management network will feature nodes each belonging to one of three classifications, each with a different role and objective on the network. The three node types are presented as follows:

- **Root Node** - The control node that receives messages from all waste nodes as it forms the root of the RPL DODAG. Situated onboard the collection UAV, the node retains the capacity state of all waste nodes on the network, electing the fullest to be emptied when necessary and idle. The node allows time for the elected waste node to be gradually emptied before selecting the next waste node to empty.
- **Waste Node** - Placed at the location of a waste container that is equipped with the necessary sensory hardware required to measure the container's capacity. The node periodically transmits its current readings relying on the RPL DODAG to communicate its information towards the root node.

- **Relay Node** - Placed at an optimised location within the deployment area to bridge communication gaps and therefore allow the RPL DODAG to form in environments with large distances between waste nodes. In the context of the Whitechapel case study environment outlined in Section 2.1, these nodes could be located within other buildings located in the distances between transport stations.

Figure 3 presents a block diagram illustrating the process steps and execution frequency of each simulated node type as discussed above.



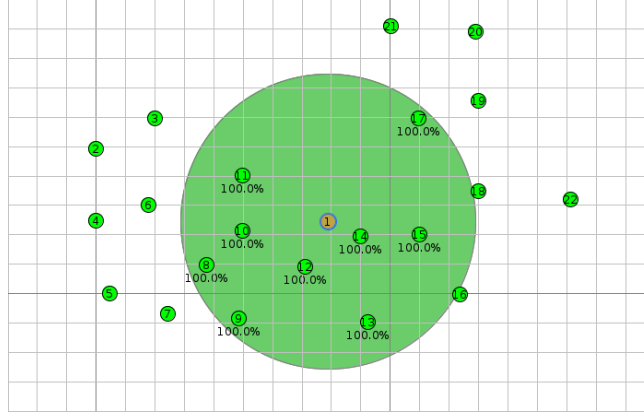
**Fig. 3.** A block diagram illustrating the process steps and execution frequency of each simulated node type.

### 3.2 Simulations

To effectively assess the efficacy of our proposed coordination network, we will conduct two simulational experiments within a Cooja environment. The details of each simulation are presented below:

- **Transmission Delays** - To verify the average transmission delays that each node will experience, all 21 waste nodes will be simulated with approximated positions based on the positioning of transport stations in Whitechapel, London as presented in Figure 1, resulting in the topology in Figure 4. Over 5 simulated hours, the differences in time between a waste node sending a reading message and the root node receiving will be recorded in milliseconds (ms) for each reading message sent on the network. Analysis of these metrics will provide insight into the communication rate of the proposed network when utilised in realistic deployments.
- **Waste Management** - To ensure the proposals are sufficient at managing waste levels, 5 waste nodes will be simulated with abstracted positions over a simulated period of 10 hours.

The chosen Cooja environment parameters which have been selected for use throughout both simulational assessments are presented in Table 2.



**Fig. 4.** A screenshot of the simulated Cooja topology with the root node at the centre of the image. The immediate communication radius of the root node is shown in green. The position of each waste node is approximated from the distribution of transport stations in the Whitechapel, London case study as depicted in Figure 1.

**Table 2.** The chosen Cooja environment parameters are to be used throughout both simulational experiments in this study.

| Parameter             | Value                |
|-----------------------|----------------------|
| Operating System      | Contiki-NG v4.9      |
| Wireless Channel Mode | UDGM (Constant Loss) |
| Seed                  | 123456               |
| Mote Type             | TMote Sky            |
| Transmission Range    | 50m                  |
| Interference Range    | 50m                  |
| Tx Ratio              | 100%                 |
| Rx Ratio              | 100%                 |

Finally, all code for recreating the simulation environment has been made accessible at <https://github.com/palzino/Waste-Management-WSN>. This will also include all simulational outputs and scripts used to analyse and make the conclusions presented in this manuscript.

### 3.3 Waste Growth Model

To realistically estimate the growth of station waste over the simulation duration, a linear mathematical model of waste growth was assumed. Equation (1) represents the station's current capacity with  $\Delta f$  denoting a discrete difference in capacity and  $f$  denoting the capacity of the station as a percentage.

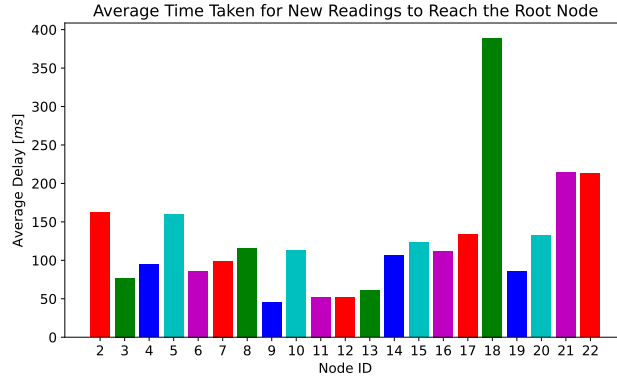
$$\Delta f = \begin{cases} r_f, & \text{if } f < 100 \text{ and } \textit{emptying} \neq \text{true} \\ -10, & \text{if } f > 0 \text{ and } \textit{emptying} = \text{true} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Station waste can be in either emptying or growing state, with  $r_f$  representing a randomly selected growth value between 1 and 5. Whilst this is an abstracted representation of waste growth suitable for our simulation which focuses on assessing transmission delays, for a more realistic model, complex non-linear mathematical growth models could also be considered.

## 4 Results

### 4.1 Transmission Delays

Figure 5 presents the average delays experienced by each node within the simulated network for a 10-hour simulation. Delays are seen to be tolerable with the majority of nodes experiencing around 100ms of latency and an overall average of 125ms whilst their readings travel through the RPL network. This demonstrates the proposed algorithm's strong efficacy and feasibility for future real-world deployments. Interestingly, Figure 5 also suggests some nodes can have drastically increased delays such as node 18. Further investigation identified that occasionally node 18's readings are dropped by the network before reaching the root node. This can cause excessive waiting periods until another reading is transmitted by the node because no packet re-delivery or fault tolerance system is implemented in the simulated network.



**Fig. 5.** A bar chart presenting the average time taken for new readings to be acknowledged by the root after they are sent from each node.

It is worth noting that whilst these behaviours appear to be potentially damaging, they present a negligible effect on the overall performance of the system as

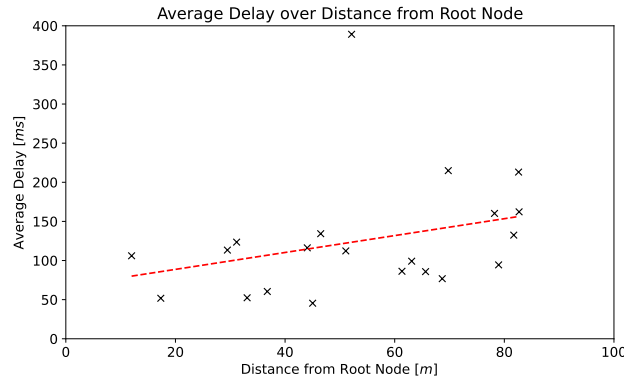
its operations are not time critical. Due to the root node's scheduling algorithm, the node will not elect a new station to be emptied until it has received readings from all stations on the network.

Figure 6 presents a plot of the average delay of each node against its measured Euclidean distance between itself and the root node denoted with  $\delta$ , as calculated using Equation (2).

$$\delta = \|\mathbf{n}_p^i - \mathbf{r}_p\| \quad (2)$$

Where  $\mathbf{n}_p^i$  is the vector position of node  $i$  and  $\mathbf{r}_p$  is the vector position of the root node.

Figure 6 shows a clear increase in average delay as the distance between the node and the root node increases. This is attributed to the increased number of hops the message has to take before arriving successfully at the root node. This could pose potential issues for deployments in sparse cities, however optimal placement of relay nodes would assist in reducing this.

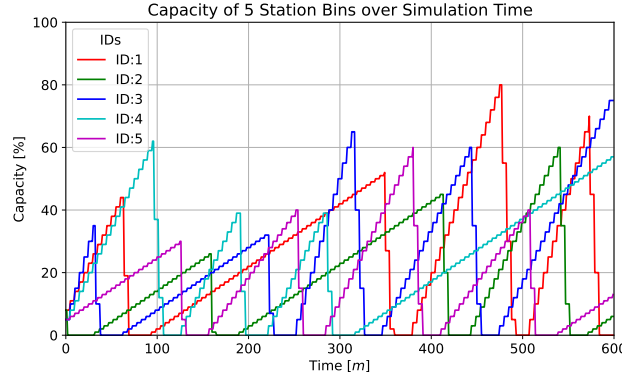


**Fig. 6.** A plot of the average delay over the measured Euclidean distance between each simulated node and the root node.

## 4.2 Waste Management

With data collected from the waste management simulation as outlined in Section 3.2, the proposed network's ability to respond promptly to raising waste levels can be analysed. Figure 7 clearly captures how at the beginning of each 30 minute interval, the fullest station is selected and gradually emptied over the remaining 30 minutes, a visualisation indicating the proposed network is capable of functioning successfully.

The variation in the steepness of each spike is caused by a station's random  $r_f$  value changing each time it is fully emptied. This behaviour has been chosen



**Fig. 7.** A plot of the capacity percentages of the 5 simulated waste nodes over a 10-hour simulation window.

to provide a more diverse representation of different station environments in the simulation.

## 5 Conclusion and Future Work

In this paper, a novel RPL-based wireless sensor network capable of supporting city-scale waste management infrastructure was proposed and evaluated. Simulation experiments carried out within the Cooja environment in conjunction with a case study based on transport stations within Whitechapel, London confirmed that the proposed algorithms are suitable and effective for further exploration and developments. Our proposed UAV-based system enhances waste management by prioritising waste bins according to their fill level and using UAVs for collection, thereby minimising emissions.

Future research efforts could extend this work by conducting more simulations that feature enhanced mathematical models for waste build-up. Additionally, future work should also be directed to investigate physical deployments of the proposals for a more effective insight into their efficacy. Additionally, extensions of our proposed network could integrate recent advances in AI and machine learning to further optimise the UAV's scheduling to respond more effectively to diverse and dynamic novel scenarios.

## References

1. Abdallah, M., Abu Talib, M., Feroz, S., Nasir, Q., Abdalla, H., Mahfood, B.: Artificial intelligence applications in solid waste management: A systematic research review. *Waste Management* **109**, 231–246 (2020). <https://doi.org/10.1016/j.wasman.2020.04.057>

2. Ahmad, S., Imran, Iqbal, N., Jamil, F., Kim, D.: Optimal policy-making for municipal waste management based on predictive model optimization. *IEEE Access* **8**, 218458–218469 (2020). <https://doi.org/10.1109/ACCESS.2020.3042598>
3. Ajayy, V., Ranga, V.: Performance analysis of rpl protocol in different nodes positioning using contiki cooja. *International Journal of Information Technology* pp. 1–7 (2024). <https://doi.org/10.1007/s41870-024-01985-w>
4. Akshayaa, S., Evangeline, R., Haritha Sree, S., Banuselvassaraswathy, B.: Smart bin for clean cities using iot. In: 2021 7th International Conference on Advanced Computing and Communication Systems (ICACCS). vol. 1, pp. 1280–1283 (2021). <https://doi.org/10.1109/ICACCS51430.2021.9441681>
5. Al-Kashoash, H.A.A., Kemp, A.H.: Comparison of 6lowpan and lpwan for the internet of things. *Australian Journal of Electrical and Electronics Engineering* **13**(4), 268–274 (2016). <https://doi.org/10.1080/1448837X.2017.1409920>, <https://doi.org/10.1080/1448837X.2017.1409920>
6. Alqahtani, F., Al-Makhadmeh, Z., Tolba, A., Said, W.: Internet of things-based urban waste management system for smart cities using a cuckoo search algorithm. *Cluster Computing* **23**, 1769–1780 (2020). <https://doi.org/10.1007/s10586-020-03126-x>
7. Anagnostopoulos, T., Zaslavsky, A., Kolomvatsos, K., Medvedev, A., Amirian, P., Morley, J., Hadjieftymiades, S.: Challenges and opportunities of waste management in iot-enabled smart cities: A survey. *IEEE Transactions on Sustainable Computing* **2**(3), 275–289 (2017). <https://doi.org/10.1109/TSUSC.2017.2691049>
8. Authority, T.G.L.: Waste and recycling — london.gov.uk. <https://www.london.gov.uk/programmes-strategies/environment-and-climate-change/waste-and-recycling> (2017), [Accessed 07-02-2024]
9. Behal, A., Sandhu, J.K., Gupta, G.: Using the cooja simulator, analysing the routing protocol (rpl) for low power and lossy networks in iot. In: 2023 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS). pp. 1–4 (2023). <https://doi.org/10.1109/SCEECS57921.2023.10061823>
10. Devey, J., Gill, P.S., Allen, G., Shahra, E., Idrissi, M.: Network-centric formation control and ad hoc communication with localisation analysis in multi-uav systems. *Machines* **12**(8) (2024). <https://doi.org/10.3390/machines12080550>, <https://www.mdpi.com/2075-1702/12/8/550>
11. Devey, J., Shahra, E., Hao, W., Mi, D., Aneiba, A., Idrissi, M.: Design and simulation of a novel leader-follower uav cluster and formation control network. In: 2024 International Joint Conference on Neural Networks (IJCNN). pp. 1–6 (2024). <https://doi.org/10.1109/IJCNN60899.2024.10650159>
12. Figliozzi, M.A.: Lifecycle modeling and assessment of unmanned aerial vehicles (drones) co2e emissions. *Transportation Research Part D: Transport and Environment* **57**, 251–261 (2017). <https://doi.org/10.1016/j.trd.2017.09.011>, <https://www.sciencedirect.com/science/article/pii/S1361920917304844>
13. Gomathy, G., Kalaiselvi, P., Selvaraj, D., Dhinakaran, D., P, A.T., Arul Kumar, D.: Automatic waste management based on iot using a wireless sensor network. In: 2022 International Conference on Edge Computing and Applications (ICECAA). pp. 629–634 (2022). <https://doi.org/10.1109/ICECAA55415.2022.9936351>
14. Hall, L.C.: Recycling underground. <https://www.london.gov.uk/who-we-are/what-london-assembly-does/questions-mayor/find-an-answer/recycling-underground-1> (2009), [Accessed: 2024-08-26]
15. Hall, L.C.: City of london 2023 to 2025 rrp: Year one update. <https://data.london.gov.uk/dataset/city-of-london-reduction-and-recycling-plan> (2024), [Accessed: 2024-08-26]

16. Kharrufa, H., Al-Kashoash, H.A.A., Kemp, A.H.: Rpl-based routing protocols in iot applications: A review. *IEEE Sensors Journal* **19**(15), 5952–5967 (2019). <https://doi.org/10.1109/JSEN.2019.2910881>
17. Khoury, D., Haddad, S., Sondi, P., Haidar, G.A., Semaan, D., Sayah, J.: Performance evaluation and analysis of lightcert4iot using cooja-contiki simulator. *IEEE Access* **12**, 122350–122362 (2024). <https://doi.org/10.1109/ACCESS.2024.3451134>
18. Longhi, S., Marzioni, D., Alidori, E., Di Buo, G., Prist, M., Grisostomi, M., Pirro, M.: Solid waste management architecture using wireless sensor network technology. In: 2012 5th International Conference on New Technologies, Mobility and Security (NTMS). pp. 1–5 (2012). <https://doi.org/10.1109/NTMS.2012.6208764>
19. Murugesan, S., Ramalingam, S., Kanimozhi, P.: Theoretical modelling and fabrication of smart waste management system for clean environment using wsn and iot. *Materials Today: Proceedings* **45**, 1908–1913 (2021). <https://doi.org/https://doi.org/10.1016/j.matpr.2020.09.190>, <https://www.sciencedirect.com/science/article/pii/S2214785320368875>, international Conference on Advances in Materials Research - 2019
20. Oikonomou, G., Duquennoy, S., Elsts, A., Eriksson, J., Tanaka, Y., Tsiftes, N.: The Contiki-NG open source operating system for next generation IoT devices. *SoftwareX* **18**, 101089 (2022). <https://doi.org/10.1016/j.softx.2022.101089>
21. Pughat, A., Bansal, B., Verma, T.: Performance evaluation of ad-hoc networks in static & mobile environment. In: 2020 6th International Conference on Signal Processing and Communication (ICSC). pp. 51–57 (2020). <https://doi.org/10.1109/ICSC48311.2020.9182732>
22. Sartori, B., Thielemans, S., Bezunartea, M., Braeken, A., Steenhaut, K.: Enabling rpl multihop communications based on lora. In: 2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob). pp. 1–8 (2017). <https://doi.org/10.1109/WiMOB.2017.8115756>
23. Sliusar, N., Filkin, T., Huber-Humer, M., Ritzkowski, M.: Drone technology in municipal solid waste management and landfilling: A comprehensive review. *Waste Management* **139**, 1–16 (2022). <https://doi.org/10.1016/j.wasman.2021.12.006>
24. Uike, V., Nawkhare, R., Sayankar, B.: Solid waste management architecture using wsn technology. *International Journal of Innovations in Engineering and Science* **7**(4), 94 (May 2022). <https://doi.org/10.46335/ijies.2022.7.4.19>, <http://dx.doi.org/10.46335/IJIES.2022.7.4.19>
25. Vishnu, S., Ramson, S.R.J., Senith, S., Anagnostopoulos, T., Abu-Mahfouz, A.M., Fan, X., Srinivasan, S., Kirubaraj, A.A.: Iot-enabled solid waste management in smart cities. *Smart Cities* **4**(3), 1004–1017 (2021). <https://doi.org/10.3390/smartcities4030053>, <https://www.mdpi.com/2624-6511/4/3/53>
26. www.macrotrends.net: London, uk metro area population 1950-2024. <https://www.macrotrends.net/global-metrics/cities/22860/london/population> (2024), [Accessed 23-11-2024]
27. Zafor, H., Mazumdar, N., Nag, A.: An energy efficient waste collection, segregation, and processing of municipal solid waste in urban area using wsn. In: 2022 IEEE 9th Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON). pp. 1–6 (2022). <https://doi.org/10.1109/UPCON56432.2022.9986468>
28. Zarzoor, A.: Optimizing rpl performance based on the selection of best route between child and root node using e-mhof method. *International Journal of Electrical and Computer Engineering* **11** (06 2020). <https://doi.org/10.11591/ijece.v11i1.pp224-231>