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OPTIMIZATION OF LORAWAN GATEWAY PLACEMENT IN WASTE CONTAINER MONITORING SYSTEMS WITH ADR CONSIDERATION

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ОПТИМІЗАЦІЯ РОЗМІЩЕННЯ LORAWAN GATEWAY У СИСТЕМАХ МОНІТОРИНГУ КОНТЕЙНЕРІВ ВІДХОДІВ З УРАХУВАННЯМ МЕХАНІЗМУ ADR

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Abstract

This article examines the placement of LoRaWAN gateways for urban waste-container monitoring. The practical question is straightforward: how can a city obtain stable telemetry from many battery-powered container nodes without installing more gateways than are actually needed? In many planning schemes the answer is reduced to geometric coverage. Such a reduction is unsafe for this application, because the radio channel is affected by the morphology of the district, the type and position of the container, additional shielding losses, and the way in which the Adaptive Data Rate (ADR) mechanism reacts to RSSI and SNR at node locations. The paper therefore proposes a placement method in which coverage, service quality, average spreading factor, node energy consumption and the number of gateways are treated jointly in one objective function. The formulation is adapted to waste-container monitoring, including above-ground and underground bins, irregular node distribution, heterogeneous urban development and the requirement for reliable telemetry delivery. In this interpretation, gateway placement is not only a question of drawing a coverage radius on a map; it is also a question of creating channel conditions in which ADR can move a significant share of nodes to more economical transmission modes without losing communication reliability. The proposed approach can be used to reduce unnecessary LoRaWAN infrastructure, justify installation points and improve the operation of smart waste management systems in urban areas.

Key words: *LoRaWAN, smart waste management, gateway, ADR, network coverage, IoT, waste container, LPWAN.*

Анотація

У статті розглянуто задачу оптимізації розміщення LoRaWAN gateway у міських системах моніторингу контейнерів відходів. Актуальність дослідження зумовлена необхідністю побудови енергоефективної та масштабованої інфраструктури smart waste management, здатної забезпечити стабільну передачу телеметричних даних від великої кількості сенсорних вузлів за мінімально можливої кількості gateway. Показано, що традиційний підхід до планування LoRaWAN-мереж, заснований лише на зоні геометричного покриття, не враховує вплив міського середовища, типу контейнерів, умов радіопоширення та особливостей роботи механізму Adaptive Data Rate. Встановлено, що ADR є штатним інструментом LoRaWAN для адаптації параметрів передавання до умов каналу, однак його ефективність безпосередньо залежить від просторового розташування gateway та фактичних значень RSSI і SNR у точках встановлення кінцевих вузлів. На цій основі запропоновано метод оптимізації кількості та координат gateway, який поєднує критерії покриття, якості обслуговування, середнього spreading factor, енерговитрат вузлів і кількості gateway у єдину цільову функцію. Особливістю підходу є врахування специфіки систем моніторингу контейнерів відходів, зокрема наявності наземних і підземних контейнерів, неоднорідності забудови, нерівномірності розташування вузлів та вимог до гарантованої доставки даних. Запропонований метод дає змогу розглядати розміщення gateway не лише як задачу просторового покриття, а як задачу забезпечення таких умов каналу, за яких ADR переводить більшість вузлів у більш енергоефективні режими передавання без погіршення надійності зв'язку. Практична цінність роботи полягає у можливості зменшення надлишковості LoRaWAN-інфраструктури, обґрунтованого вибору точок встановлення gateway та підвищення ефективності функціонування smart waste management систем у міському середовищі.

Ключові слова: *LoRaWAN, smart waste management, gateway, ADR, покриття мережі, IoT, контейнер відходів, LPWAN.*

1. Introduction. Municipal services are increasingly being transferred to digital monitoring and decision-support platforms. Waste collection is one of the clearest examples: fill-level sensors installed in containers make it possible to adjust collection routes, avoid overflow, reduce unnecessary vehicle runs and improve the sanitary condition of urban areas. For this class of tasks, LPWAN technologies are attractive because the nodes usually send small packets, work from batteries and remain in fixed positions for a long time. LoRaWAN is widely used in such conditions, as it combines long-range communication with low energy consumption and a relatively simple deployment model. [1; 2]

Field trials and experimental studies show that LoRaWAN can be used for waste-container monitoring in real cities. Nevertheless, they also show that the quality of the radio link is not determined by distance alone.

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A container placed below ground level, a metal lid, dense building blocks or a low gateway mounting point may change the link budget more strongly than the nominal range of the technology suggests. For this reason, gateway placement based only on an assumed coverage radius may lead either to unstable data transmission or to redundant infrastructure [3; 4].

The issue becomes more important when ADR is taken into account. In favorable radio conditions ADR can reduce the spreading factor, shorten packet airtime, decrease transmission energy and increase the practical capacity of the network. However, ADR works effectively only when the node has a sufficient channel margin. Thus, the placement of gateways should be formulated not merely as a coverage task, but as the creation of radio conditions under which most waste-container nodes can operate in efficient ADR modes [5; 6].

Analysis of Recent Research and Publications. The available literature may be grouped into several lines of work. One line studies LoRaWAN as a communication technology for smart-city and IoT applications, with attention to range, throughput, energy consumption and robustness. A second line focuses on smart waste management, including fill-level sensing, collection logistics and data acquisition from distributed containers. A third line deals with LoRaWAN gateway placement and increasingly uses multicriteria or metaheuristic optimization procedures [3-5; 7; 8].

These lines of research, however, are often only loosely connected. Papers on waste monitoring usually give more attention to the sensor unit or route optimization, while gateway placement is described rather generally. In contrast, many placement studies use an abstract network model and do not explicitly include the properties of waste-container systems: underground bins, local shielding, differences between container materials and the uneven spatial distribution of the nodes [3; 4].

The ADR-related studies are also relevant for the present work because they demonstrate the influence of adaptive data-rate control on packet delivery and battery use. Yet ADR is rarely introduced as a criterion during the spatial planning of a LoRaWAN network for waste-container monitoring. This leaves a practical and methodological gap: gateway locations should be evaluated together with the expected ADR behavior of the end nodes, rather than after the placement problem has already been solved [6].

Purpose and Objectives of the Study. The purpose of this paper is to develop a method for selecting LoRaWAN gateway locations in waste-container monitoring systems while explicitly considering the ADR mechanism. The intended result is a configuration that limits the number of gateways but still provides the required quality of telemetry transmission.

To reach this purpose, the study solves the following tasks: analysis of LoRaWAN use in smart waste management; identification of the main factors that determine link quality between container nodes and gateways in an urban environment; justification of ADR consideration at the planning stage; formulation of a mathematical model for comparing gateway configurations; construction of an objective function that combines infrastructure cost, service quality and energy-related indicators; and description of a procedure for determining the number and coordinates of gateways for this class of systems.

2. Materials and methods of research. The object of the study is the LoRaWAN infrastructure of the urban waste container monitoring system, in particular the interaction of container sensor nodes with the gateway under different radio propagation conditions and the operation of the Adaptive Data Rate mechanism. The subject of the study is the methodological principles for choosing the number and coordinates of LoRaWAN gateways, taking into account channel quality indicators, energy efficiency of end nodes and requirements for guaranteed delivery of telemetric data.

The main hypothesis of the study is that the placement of the gateway, optimized not only by the criterion of geometric coverage, but also by the expected values of RSSI, SNR, spreading factor, packet delivery ratio and energy consumption of nodes, provides better conditions for the operation of ADR and allows to increase the functional efficiency of the LoRaWAN network without an unjustified increase in the number of gateways.

The following assumptions are made in the work: container sensor nodes are considered stationary; the coordinates of containers and candidate gateway installation points are known or can be obtained from the city GIS database; the frequency of uplink message transmission is specified; the impact of seasonal environmental changes, temporary interference, and short-term radio channel fluctuations is taken into account in a generalized manner through a margin in signal level and additional losses for complex container types.

The adopted simplifications include: using an aggregated model of signal propagation loss; representing the impact of underground or partially shielded containers through an additional attenuation coefficient; evaluating the ADR mode based on predicted RSSI and SNR values without modifying the standard LoRaWAN protocol; considering ADR downlink commands as an auxiliary mechanism for setting transmission parameters without detailed modeling of network server queues.

The study was performed as a computational and analytical modeling. At the first stage, a set of container nodes was formed with coordinates, container type, building conditions, and expected data transmission

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intensity. At the second stage, a set of candidate gateway installation points was specified, taking into account the installation height, power availability, network connectivity, and engineering constraints on equipment placement.

The theoretical basis of the study was the methods of radio planning of LPWAN networks, multi-criteria optimization, comparative analysis of alternative configurations and formalization of objective functions. For each pair «container node – gateway» signal losses, expected RSSI and SNR values were estimated, after which the gateway with the best reception conditions was determined and the possible operation mode of the node was predicted using the ADR mechanism.

The software implementation of the algorithmic part provides for the possibility of using Python, MATLAB, Julia or GIS-oriented environments with geoprocessing modules. Within the framework of this article, the software is considered as a tool for reproducing calculation procedures: enumerating permissible gateway configurations, calculating network quality criteria and selecting the option with the minimum value of the integral objective function.

This section provides only the initial methodological provisions, assumptions, simplifications and the procedure for conducting the study. Quantitative results, comparison of configurations, graphical dependencies and their interpretation are presented in the following sections of the article, since it is there that the solutions to the tasks set in the work are reflected.

Main Body of the Study

1. Features of the Operating Environment of Waste Container Monitoring Systems.

Unlike many IoT networks with more freely distributed end devices, a waste-container monitoring system is tied to municipal infrastructure. Container locations depend on building density, the street network, the organization of collection routes and the rules for arranging container sites. The radio channel is further affected by the bin material, installation depth, wall and lid construction, nearby buildings, vegetation and other local obstacles [3; 8].

Underground containers and partially shielded metal bins create the most difficult radio conditions. A node located close to a gateway may still have a poor link if the antenna is screened by the container body or by the surrounding structure. Conversely, an above-ground plastic bin at a larger distance may provide a better signal. Another practical feature is the nonuniform load: some containers generate telemetry more frequently because they fill faster, and this increases the importance of stable communication and sufficient network capacity [3; 8].

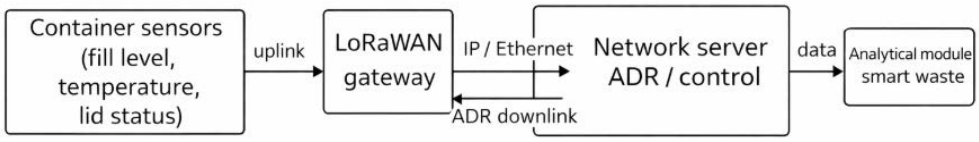


Fig. 1. Generalized architecture of a LoRaWAN-based waste container monitoring system

Figure 1 summarizes the data flow in a LoRaWAN-based waste monitoring system. The sensor node sends telemetry through one or more gateways to the network server and then to the analytical module. Control messages, including ADR-related downlink commands, return through the same communication chain. Therefore, the choice of gateway positions affects not only radio coverage but also the ability of the system to manage transmission parameters and maintain a stable monitoring process.

2. The Role of ADR in Improving LoRaWAN Network Efficiency

In LoRaWAN, ADR adjusts transmission parameters according to the observed channel state. This is especially useful for stationary container nodes: once the channel is sufficiently stable, the network server may assign a lower spreading factor and, where appropriate, reduce transmit power. The practical effects are shorter airtime, lower energy consumption and a smaller load on the radio channel [5; 6].

Poor gateway placement cannot be corrected by ADR alone. If many nodes remain in low-SNR areas, the network has to keep them in more robust but less economical modes. This increases the average spreading factor and accelerates battery discharge. For that reason, this study treats ADR not as a protocol to be modified, but as an indicator of whether the spatial configuration of gateways is technically successful [5; 7].

3. Formalization of the Gateway Placement Problem

Consider an urban district with n waste containers, each represented by a LoRaWAN end node. The set of containers is denoted by B={b1,b2,...,bn}. For every element of this set, the coordinates, container type, surrounding urban conditions and expected transmission intensity are specified. The possible gateway

locations form the set G={g1,g2,...,gm}; for each candidate point, coordinates, installation height and infrastructural restrictions are known.

For every container-gateway pair, path loss is evaluated with regard to distance, urban morphology, gateway height and additional losses introduced by the container type. In this way, the model shifts from a simplified coverage-radius description to an engineering estimate of the expected channel parameters.

$$Lij = Lpath(dij, ci, hj) + Lcont(ti) \quad (1)$$

$$RSSI_{ij} = P_{tx} + G_{tx} + G_{rx} - L_{ij} \quad (2)$$

$$SNR_{ij} = RSSI_{ij} - N_0 \quad (3)$$

For each container, the gateway with the best predicted reception conditions is then assigned as the active one. This assignment is important because it determines the likely operating mode of the node after ADR decisions are made.

$$j^*(i) = \arg\max SNRij, \ j \in G^* \quad (4)$$

4. Consideration of ADR in the Model

To include ADR behavior in the model, each node is assigned a predicted operating mode. This mode is described through a function that links RSSI and SNR to the probable spreading factor.

$$SFi = f(SNRi, RSSIi) \quad (5)$$

$$\bar{SF} = (1/n) \Sigma SF_i \quad (6)$$

A lower average spreading factor means shorter packet airtime and, in most operating scenarios, lower transmission energy and better network scalability. For this reason, the average spreading factor is used as one of the key criteria when comparing gateway configurations.

5. Evaluation of Energy Consumption and Quality of Service

For waste-container monitoring, sensor autonomy is a critical engineering requirement. In most deployments the node is battery-powered, so the energy used for measurement, local processing and radio transmission must be controlled. Among these components, transmission energy is the most sensitive to the ADR-selected mode [2; 4].

$$Ei = Esense,i + Eproc,i + Etx,i \quad (7)$$

$$E_{tx,i} = N_i \cdot e(SF_i, P_{tx,i}, l_i) \quad (8)$$

$$\bar{E} = (1/n) \Sigma E_i \quad (9)$$

$$PDR = N_{recv} / N_{sent} \quad (10)$$

$$Q = (1/n) \Sigma I(SNR \geq SNR_{min} \wedge SF \leq SF_{max} \wedge PDR_i \geq PDR_{min}) \quad (11)$$

The indicator Q describes the share of containers for which the minimum acceptable telemetry conditions are satisfied. It prevents a formal situation in which a node is counted as covered although its packet delivery, SNR or spreading factor is unsuitable for reliable operation.

6. Objective Function of Optimization

An integral objective function is used to compare gateway configurations. It combines infrastructure complexity, communication reliability, ADR-related operating mode and the expected energy consumption of the sensor network.

$$J = \alpha Ngw + \beta\bar{SF} + \gamma(1 - PDR) + \delta\bar{E} + \mu(1 - Q) \quad (12)$$

Minimizing J means searching for a configuration that avoids unnecessary gateways, keeps packet delivery at an acceptable level, reduces the average spreading factor and preserves node autonomy. This differs from traditional planning, where the coverage indicator usually dominates the decision [7; 9].

Figure 2 gives a simple interpretation of this compromise. Adding gateways may reduce the average spreading factor and improve the conditions for ADR operation, but the gain decreases after a certain point. The optimization problem is therefore not to install the maximum possible number of gateways, but to find the point at which service quality and infrastructure cost are balanced [7].

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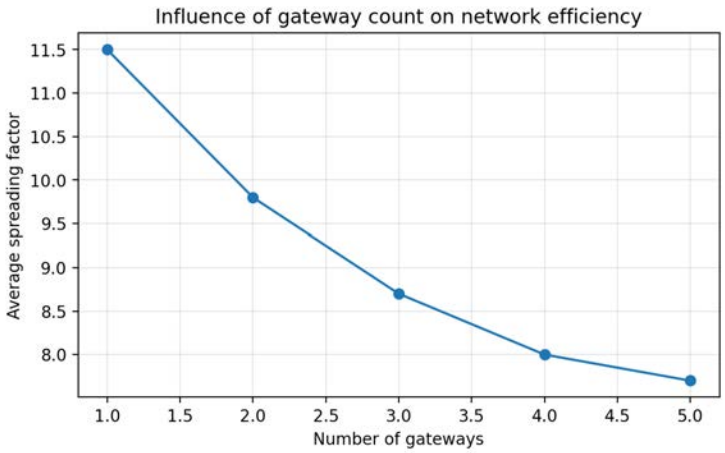


Fig. 2. Illustration of the influence of the number of gateways on the average spreading factor and network efficiency

7. Formal Algorithm for Determining the Optimal Gateway Configuration

The proposed procedure can be implemented as a sequence of engineering steps. First, data are collected on container coordinates, container types and local urban conditions. Next, a list of possible gateway mounting points is formed; only points that satisfy height, power-supply and installation constraints are kept [5].

For each node-gateway pair, the channel parameters are estimated. The best gateway is selected for every node, the expected ADR mode is predicted, and the quality indicators of the whole configuration are calculated. The admissible configuration with the smallest value of the integral criterion J is then selected.

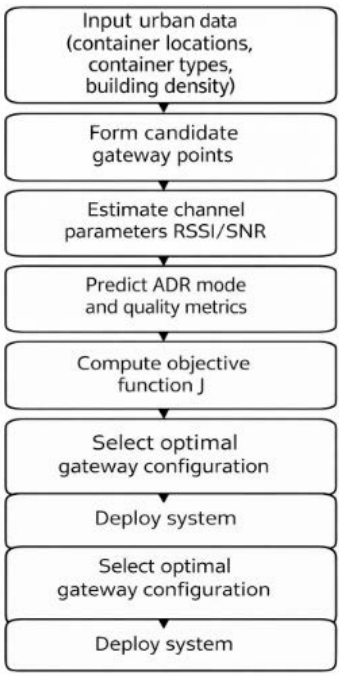


Fig. 3. Flowchart of the algorithm for selecting the optimal LoRaWAN gateway configuration

Figure 3 presents this sequence from the input urban data to the final gateway configuration. Such a representation is useful for later implementation in software, including GIS-based tools for infrastructure planning [5; 7].

8. Pseudocode of the Algorithm and an Example of Software Implementation

For reproducibility, the general logic of the algorithm is written below as pseudocode. The same structure can be implemented in Python, MATLAB, Julia or in a GIS environment that supports geoprocessing.

for config in candidate_gateway_sets:

```
metrics = []
for node in waste_nodes:
   links = evaluate_links(node, config)
   best_link = select_by_max_snr(links)
   sf = predict_sf(best_link.snr, best_link.rssi)
   energy = estimate_energy(node, sf, best_link.tx_power)
   metrics.append((sf, energy, best_link.pdr))
J = alpha*count(config) + beta*avg_sf(metrics) \
   + gamma*(1-pdr(metrics)) + delta*avg_energy(metrics) \
   + mu*(1-service_share(metrics))
update_best_config_if_needed(config, J)
```

The pseudocode shows only the core calculation loop. In a practical tool it may be supplemented with radio-propagation modules, clustering of candidate points, restrictions on installation sites and GIS layers describing building density or terrain [7; 9].

9. Criteria for Evaluating the Network Configuration

Table 1 lists the criteria used to evaluate a LoRaWAN gateway configuration for a waste-container monitoring network.

Table 1

Criteria for evaluating LoRaWAN gateway configuration in waste container monitoring systems

Criterion	Symbol	Mathematical expression	Meaning of the criterion	Optimization direction
Number of gateways	Ngw	$Ngw = \|G^*\|$	Infrastructure complexity and cost	minimum
Average spreading factor	SFavg	$\bar{SF} = (1/n)\,\Sigma\, SFi$	ADR efficiency in the network	minimum
Average node energy consumption	Eavg	$\bar{E} = (1/n)\,\Sigma\, Ei$	Sensor autonomy	minimum
Packet delivery success	PDR	$PDR = Nrecv / Nsent$	Reliability of telemetry communication	maximum
Share of nodes with guaranteed service	Q	$Q = (1/n)\,\Sigma\, I(\cdot)$	Quality of network service	maximum
Share of nodes at high SF	RhighSF	$RhighSF = N(SF \geq SFthr) / n$	Assessment of load and scalability	minimum
Integral criterion	J	$J = \alpha Ngw + \beta\bar{SF} + \gamma(1 - PDR) + \delta\bar{E} + \mu(1 - Q)$	Generalized selection criterion	minimum

Together, these criteria provide a more informative assessment than coverage alone. The inclusion of ADR-dependent indicators makes the evaluation closer to the real operation of a LoRaWAN network in a smart waste management scenario [7; 9].

Computational Study of the Effectiveness of the Proposed Method

To check the applied usefulness of the proposed method, a model-based computational study was performed for a typical urban district. Two placement approaches were compared: a baseline approach aimed mainly at continuous coverage, and the proposed approach, where the configuration is assessed by ADR behavior, average spreading factor, packet delivery ratio, node energy consumption and the share of containers with guaranteed service. This type of comparison corresponds to the current formulation of LoRaWAN gateway placement problems [4; 8].

1. Initial Data and Simulation Scenarios

The simulated district measured 2.4 x 1.8 km and included a nonuniform distribution of container sites: a dense central area, a medium-density residential part and a peripheral area with fewer obstacles. The model included 60 containers; 25% of them were treated as underground or partially shielded. Eight candidate gateway points were placed on roofs of administrative and municipal buildings.

In Fig. 4, black squares mark the gateways selected by minimizing the integral criterion, while empty squares show alternative candidate points considered during optimization. This visual distinction is important because the best functional configuration is not always the same as a visually uniform coverage pattern.

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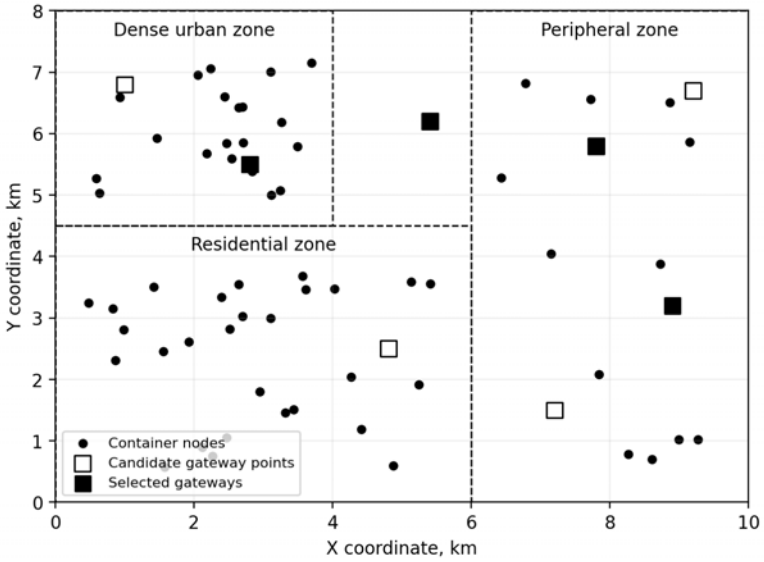


Fig. 4. Layout of the model urban district with container nodes and candidate gateway installation points

Table 2

Initial parameters of the computational study

Parameter	Symbol	Value
Number of containers	n	60
Share of underground containers	rug	25%
Number of candidate gateway points	m	8
Minimum acceptable packet delivery ratio	PDRmin	0.95
Maximum allowable spreading factor	SFmax	10
Average uplink transmission period	Ttx	30 min
Additional loss for underground containers	Ladd	24–26 dB
Weight coefficients of the objective function	α, β, γ, δ, μ	0.30; 0.20; 0.20; 0.15; 0.15

The parameters in Table 2 represent a medium-scale urban case with dense building blocks, areas of easier radio propagation and a noticeable share of containers with additional signal loss. The chosen limits for PDR and SF allow the configurations to be judged not only by reachability, but also by the actual quality of telemetry service.

2. Comparison with the Baseline Gateway Placement Method

Two methods were compared in the computational study. The baseline method selected gateways mainly to cover container nodes with a minimal number of infrastructure points and did not include ADR explicitly. The proposed method used the integral objective function and therefore favored configurations that reduce average spreading factor, improve the share of nodes with guaranteed service and decrease end-device energy consumption.

Table 3

Comparison of the baseline and proposed approaches

Approach	N_gw	$\bar{SF}$	PDR	E_avg, mWh/day	Q	J
Baseline, 2 gateways	2	10.8	0.84	1.84	0.68	4.73
Proposed, 2 gateways	2	10.1	0.89	1.62	0.76	4.26
Baseline, 3 gateways	3	9.6	0.90	1.52	0.79	4.28
Proposed, 3 gateways	3	8.5	0.95	1.22	0.89	3.66
Baseline, 4 gateways	4	8.8	0.94	1.31	0.87	4.02
Proposed, 4 gateways	4	7.6	0.98	1.05	0.95	3.41
Baseline, 5 gateways	5	8.2	0.96	1.18	0.91	4.08
Proposed, 5 gateways	5	7.2	0.985	0.98	0.97	3.50

The values in Table 3 show that, for every considered number of gateways, the proposed method gives higher PDR, lower average spreading factor and lower daily node energy consumption. In the studied scenario, the minimum value of the integral criterion J was obtained for four gateways, which indicates a reasonable balance between infrastructure cost and telemetry quality.

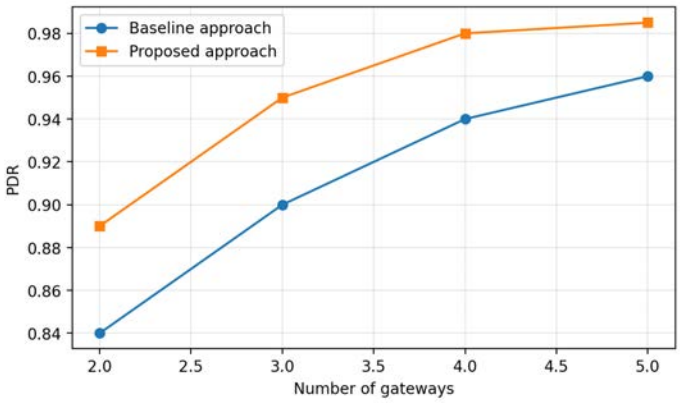


Fig. 5. Packet delivery ratio versus the number of gateways

Figure 5 shows that PDR grows as the number of gateways increases in both approaches. At the same time, the proposed method reaches a higher delivery ratio for the same gateway count because it takes into account not only coverage, but also the channel margin needed for effective ADR operation.

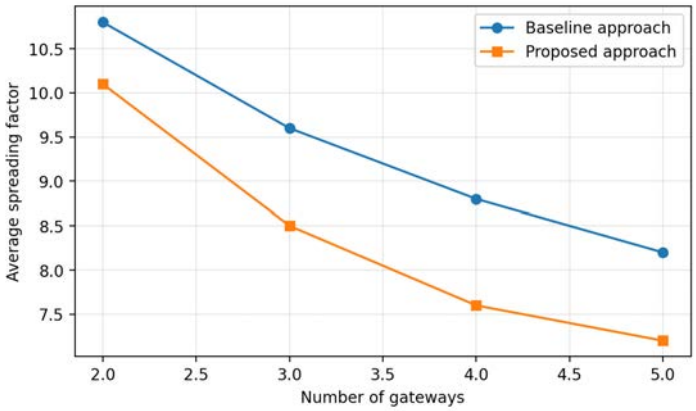


Fig. 6. Average spreading factor versus the number of gateways

Figure 6 shows the corresponding change in average spreading factor. The ADR-aware placement reduces this value more strongly, which means shorter airtime, better scalability and a lower probability of collisions in dense urban deployments.

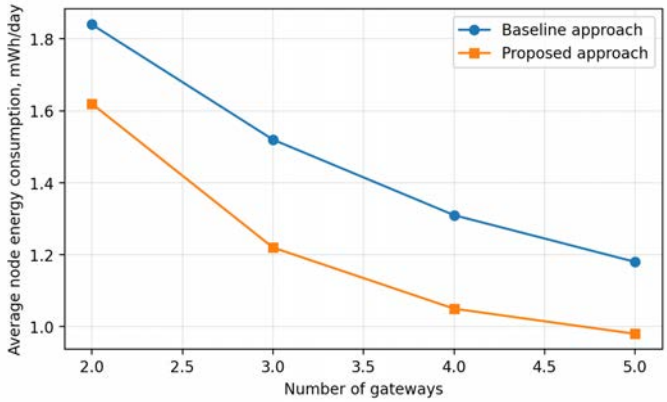


Fig. 7. Average node energy consumption versus the number of gateways

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Figure 7 shows the effect on node energy consumption. Better gateway geometry and lower spreading factors reduce the daily energy demand of the sensor nodes. For battery-powered waste-container sensors, this translates into longer intervals between maintenance operations.

3. Sensitivity Analysis with Respect to the Share of Underground Containers

The influence of underground containers was also evaluated. When their share increased from 10% to 35%, the average spreading factor in the baseline approach increased by about 11-14%, while the proposed method showed an increase of 7-9%. This suggests that ADR-aware gateway placement is more resistant to the difficult radio conditions created by shielded and underground containers [3; 4].

These results show that the proposed approach is not limited to a formal mathematical statement. It produces measurable gains in the main network and operational indicators, which allows the work to be treated as a computational and analytical study rather than as a general review.

3. Discussion of Results. The proposed approach has several advantages over conventional LoRaWAN planning. The first is that it reflects the specific operating conditions of waste-container monitoring: different container types, unequal access to the radio channel and nonuniform telemetry intensity. In this setting, simple coverage is not enough, because it does not guarantee efficient ADR operation or acceptable energy consumption [1; 7; 9].

A second result is the combination of infrastructural and functional criteria in a single objective function. This allows the designer to see the compromise between the number of gateways and the quality of network operation. In practical terms, the method helps avoid both underdeployment, when many nodes are forced to work at high spreading factors, and overdeployment, when additional gateways do not provide a proportional improvement in service quality.

The method also has limitations. Accurate use requires reliable container coordinates, a map of the urban environment, a list of feasible gateway installation points and estimates of additional losses for different container types. Even with approximate data, however, the model can be used for preliminary design and for comparing several LoRaWAN deployment options.

Scientific Novelty. The scientific novelty of the results is the proposed method for optimizing LoRaWAN gateway placement in waste-container monitoring systems. In contrast to placement approaches based mainly on geometric coverage, the method includes the influence of ADR on functional network performance [5; 7].

In the proposed formulation, ADR is not treated as an independent protocol-optimization problem. Instead, it is used as a criterion for judging the quality of the spatial gateway configuration through average spreading factor, sensor-node energy consumption, packet delivery and the share of containers with guaranteed service.

Practical Significance. The practical significance of the results is their possible use in the design and modernization of municipal LoRaWAN waste-monitoring systems. The method helps justify both the number of gateways and their coordinates under real urban constraints, which can reduce redundant infrastructure and improve telemetry stability [3; 7].

The results can also support GIS-oriented decision-support systems, LoRaWAN coverage simulation tools and applied software for planning smart waste management infrastructure. The expected practical effect is a lower average spreading factor, shorter packet airtime, longer sensor-node autonomy and more rational use of network resources.

4. Conclusions. The paper addressed the optimization of LoRaWAN gateway placement in waste-container monitoring systems with consideration of ADR. It was shown that planning based only on geometric coverage is insufficient, since it does not reflect container type, urban radio conditions or the operating requirements of ADR.

The study proposed a mathematical model and an objective function that include the number of gateways, average spreading factor, packet delivery ratio, average node energy consumption and the share of containers with guaranteed service. A formal algorithm was presented, together with an example of software implementation.

The practical value of the approach is the justified selection of gateway installation points, lower infrastructure redundancy and more stable telemetry service for waste containers. Further work should include GIS integration, numerical modeling for specific city districts and experimental validation of the proposed method.

Conflict of interest. The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship, or other, that could influence the study and its results presented in this article.

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Use of artificial intelligence. The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

Authors' contribution. Hryhorii Rozhkov – conceptualization, source analysis, writing the main text; Klymenko Iryna– methodology, editing, forming conclusions and checking the consistency of the structure.

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