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Doctoral School of Electronics, Telecommunications and Information Technology

Ph.D. THESIS SUMMARY

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ENERGY-EFFICIENT SMART METERING USING NB-IoT AND LoRaWAN: ADAPTIVE TRANSMISSION AND OPTIMIZED GATEWAY DEPLOYMENT STRATEGIES

SOLUȚII DE CONTORIZARE INTELIGENTĂ FOLOSIND TEHNOLOGIILE NB-IoT ȘI LoRaWAN: TRANSMISIUNE ADAPTIVĂ ȘI STRATEGII PENTRU PLASAREA OPTIMĂ A STAȚIILOR DE BAZĂ (GATEWAY)

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Content

Chapter 1 Introduction

The Internet of Things (IoT) is a branch of engineering that connects physical devices, or miniatures, to achieve specific goals [1]. It has gained importance due to the rapid growth of networked smart devices with embedded wireless sensing and communication [2]. IoT ecosystems include processors, sensors, and communication modules that collect, transmit, and act on data, these devices send sensor data through gateways or edge devices to the cloud for analysis [3]. Low-power wide-area network (LPWAN) technologies are key to IoT, offering low-cost, long-range connectivity with minimal power use—enabling applications across sectors from agriculture to smart cities [4].

1.1 Research Problem, Objectives and Contributions

The widespread adoption of IoT for smart metering promises better energy management, but challenges remain in achieving low cost, compactness, energy efficiency, reliability, and scalability. NB-IoT and LoRaWAN can show inconsistent real-world performance, with LoRaWAN's data rate and coverage trade-offs and gateway placement being key concerns. Smart metering also demands highly energy-efficient operation and faces risks from network congestion as device density grows. To address these issues, this thesis aims to:

1. Conduct a comprehensive review and comparative analysis of NB-IoT and LoRaWAN for smart metering.
2. Rigorously benchmark both technologies through simulations and experiments, focusing on energy efficiency, coverage, and reliability.
3. Propose and implement a novel gateway placement strategy for LoRaWAN using hybrid optimization algorithms.
4. Design an adaptive transmission algorithm to improve the energy efficiency of smart meters by minimizing unnecessary transmissions.

Table 1.1 summarizes the main research contributions, aligned with the core research questions:

Table 1.1 *Main research contributions*

No.	Research Question (RQ)	Contribution Type
RQ1	What are the critical design aspects, performance requirements, and emerging challenges associated with communication technologies in smart metering systems?	Comprehensive Technology and Design Analysis
RQ2	What are the key performance characteristics and limitations of NB-IoT and LoRaWAN for smart metering applications?	Comparative Evaluation
RQ3	How can gateway placement for LoRaWAN networks be optimized to enhance coverage, reliability, and efficiency?	Optimization Algorithms
RQ4	What strategies can be employed to improve the energy efficiency of smart metering nodes through adaptive transmission?	Real-Time Algorithm Design

1.2 Scopes of the research

This research focuses on optimizing NB-IoT and LoRaWAN for smart metering applications. The scopes of this study are as follows:

1. Study based on 3GPP standards for NB-IoT and LoRaWAN architecture.
2. Deploys smart meters, NB-IoT modules (Quectel BG96), LoRaWAN end-devices (Dragino LG308), microcontrollers (Arduino Uno), and power sensors (PZEM-004T) for data acquisition.
3. Power Profiler Kit (PPK) used for real-time energy measurement.
4. MATLAB-based evaluation of network efficiency under various conditions.
5. Key performance metrics: latency, energy consumption, packet loss, bit error rate (BER), RSSI, and SNR.
6. Comparative analysis of LoRaWAN spreading factors (SF7 vs. SF12).
7. Simulation conducted using HTZ Communications software.
8. Hybrid PSO-DE algorithm for gateway placement optimization using python.
9. Implementation of real-time adaptive transmission algorithms for smart meters.

1.3 Thesis content

Chapter 2: Presents a literature review on IoT-based smart metering, focusing on NB-IoT and LoRaWAN, highlighting technical architectures, communication challenges, and research gaps.

Chapter 3: Evaluates NB-IoT and LoRaWAN using MATLAB/Simulink and Python simulations, alongside real-world tests with nRF9160 DK and Pycom nodes. Key metrics include transmission time, BER, energy use, and signal quality under varying conditions.

Chapter 4: Analyzes LoRaWAN performance using SF7 and SF12 in urban settings. A PSO-DE optimization algorithm is proposed for gateway placement, improving coverage and reducing packet loss.

Chapter 5: Prototypes a smart metering system with Arduino Uno and PZEM-004T. Energy profiling is conducted with PPK2, and a custom data reduction algorithm reduces transmission load and extends battery life.

Chapter 6: Summarizes findings, contributions, and dissemination, and outlines future work in adaptive communication and LPWAN optimization.

Chapter 2 An overview of Smart meter and communications Technologies involved

Smart meters have become essential in modern energy systems, enabling real-time data exchange, dynamic pricing, and improved grid stability. This chapter reviews smart meter technologies and their supporting communication systems, focusing on MDMS and AMI components. It evaluates wired and wireless networks based on coverage, throughput, and energy efficiency, and explores recent advances like adaptive algorithms for reducing energy use and optimizing transmissions. The chapter synthesizes market trends, technical developments, and research to highlight current challenges and opportunities in building resilient, energy-efficient smart metering systems.

2.1 Smart meter

The IoT is a modern paradigm of computer networks with numerous applications in the industrial and technology sectors [5]. In smart grids, IoT facilitates communication among agents, making it a useful tool for decision-making [6]. The use of IoT in an energy system drives the growth of microgrids by enabling secure remote monitoring and control of internal distributed energy resources [7, 8].

The management of huge amounts of data in the smart grid necessitates the use of a safe, dependable, and cost-effective communication technology. Communications technologies allow bidirectional data exchange between the smart grid's various entities [9]. Advanced Meters Infrastructure is the most current iteration of smart metering (AMI). This system combines AMR and AMM to perform technical measurements, tasks, and customer-oriented services across the system [10, 11].

2.2 Communications technologies involved in the SM

There is various telecommunication systems used in smart metering applications, thereby being classified as wired and wireless.

2.2.1 Wireless communication technologies

Smart grid communication is typically structured into three layers [12]; HAN (Home Area Network), NAN (Neighbourhood Area Network) and WAN (Wide Area Network).

For HAN, we considered ZigBee, Bluetooth, and Wi-Fi [13]. ZigBee, based on IEEE 802.15.4, offers low power consumption and up to 100m range at 250 kbps, making it ideal for low-data smart grid applications [14] [15]. Wi-Fi, compliant with IEEE 802.11 standards, supports higher data rates (up to 1 Gbps) at the cost of higher energy use and lower scalability [16]. Bluetooth, based on IEEE 802.15.1, offers up to 721 kbps over short distances (0–100 m), ideal for in-home, low-energy communication [17]. For NAN and WAN, we evaluated SigFox, LoRaWAN, Wi-SUN, NB-IoT, and WiMAX, SigFox operates in the ISM 868 MHz band with long range (up to 50 km rural, 10 km urban) and low data rate (100 bps), offering a good balance between coverage and energy use [13, 18, 19]. Wi-SUN, based on IEEE 802.15.4g, provides 300 kbps over distances up to 5 km, using sub-GHz ISM bands [20]. WiMAX, based on IEEE 802.16, supports data rates up to 100 Mbps with ranges up to 10 km, making it suitable for distribution networks [17, 30]. Our focus is on LoRaWAN and NB-IoT: LoRaWAN, developed by the LoRa Alliance, uses chirp spread spectrum for long-range, low-power communication, making it suitable for battery-operated smart metering in energy, water, or gas [21, 22, 23]. NB-IoT, based on 3GPP LTE, operates in licensed spectrum and leverages existing LTE infrastructure [24, 25, 26].

2.2.2 Wired communication technologies

Power Line Communication (PLC) uses existing power lines to transmit high-frequency data (kHz to MHz). Its low deployment cost, reliability, and high throughput make it suitable for Smart Grid communications, especially in dense urban areas. PLC can be categorized as narrowband or broadband. Another wireline option is Digital Subscriber Line (DSL), which transmits digital data over telephone lines. Additionally, optical communication offers high-speed (Gbps) data transfer over long distances with strong resistance to electromagnetic interference [27, 28].

2.3 Related work

The advancement of IoT in smart metering systems relies heavily on efficient LPWAN architectures and communication protocols. Many studies have explored LoRaWAN and NB-IoT technologies, focusing on energy efficiency, real-time applications, and network performance. A comparative study [29] examined five performance indicators for both technologies, revealing NB-IoT's consistency with larger payloads and LoRaWAN's strength in low-latency scenarios. Other works [38-41], assessed performance under harsh conditions and urban settings, including integration into 5G [30] and comparisons with NB-Fi [31]. Field tests [44, 45] highlighted deployment challenges and interference in dense environments. Several studies focused on smart metering applications using LoRaWAN: Asres et al. [32] developed a remote area energy meter, Slaný et al. [33] designed a smart water management system, and Piechowiak et al. [34] proposed gateway placement algorithms. Hseiki et al. [35] introduced a secure smart meter design. Other works explored use cases across smart buildings, campuses, and agriculture. Regarding optimization techniques, studies addressed gateway placement and packet loss, while some researchs evaluated signal quality and localization using LoRaWAN. Svertoka et al. [36] and Cruz et al. [37] optimized LoRaWAN coverage using k-NN and EPSO, respectively. Machine learning methods and PSO-based solutions were also applied to gateway placement and spreading factor assignment. On the NB-IoT side, studies covered topics such as EDT support, energy-efficient channel coding, cloud-based energy monitoring, and smart metering in urban/rural settings. A summary of related works vs. our contribution is provided in Table 2.1, highlighting that our study is the first to focus on real-time adaptive transmission to optimize energy efficiency at the IoT node level.

Table 2.1 *Summary of some related works*

Ref.	Year	Summary	Use an algorithm to reduce packet transmission
[38]	2020	Proposes a decentralized metering architecture for IoT devices to measure their own energy usage.	No
[39]	2021	Discusses a smart energy meter using LoRa-WAN and IoT for extended range and reduced power usage.	No
[40]	2022	Describes an IoT-enabled smart energy meter using LoRaWAN for PV systems, focusing on real-time data delivery.	No
[41]	2023	Develops an IoT smart energy meter for real-time monitoring and energy efficiency in metering.	No
[42]	2023	Develops an IoT-based smart energy monitoring system using NB-IoT and cloud to automate meter readings and reduce energy consumption.	No
[43]	2024	Describes the development of an NB-IoT-based IoT gateway for energy metering, enhancing smart meter connectivity and reducing operational costs.	No
Ours	2024	Proposed an efficient algorithm to optimize the IoT Node Energy connected with NB-IoT / LoRaWAN.	Yes

2.4 Chapter conclusions

Provides a comprehensive review of smart metering architectures and communication technologies. Highlights the strengths and limitations of both wired and wireless solutions, emphasizing the critical need for energy efficiency, interoperability, and secure, scalable communications in future smart grid deployments. The output of this chapter has been published as:

K.A. Al-Sammak, S.H. Al-Gburi, I. Marghescu, *Communications Systems in Smart metering: A Concise Systematic Literature Review*, in **Proceedings of the 2022 14th International Conference on Communications (COMM)**, Bucharest, Romania, **16–18 June 2022**, pp. 1–9, **IEEE, DOI: 10.1109/COMM54429.2022.9817154.**

Chapter 3 Evaluation of NB-IoT and LoRaWAN for Smart Metering Using Simulations and Real-World Experiments

This chapter assesses the scalability of IoT-based smart metering by comparing NB-IoT and LoRaWAN through simulations and hardware experiments. Using MATLAB/Simulink, Python, and device tests, we analyze spectrum efficiency, resource use, energy consumption, and signal quality. Results provide practical guidance for choosing and optimizing reliable, energy-efficient smart metering technologies.

3.1 An Evaluation of the functionality of NB-IoT for smart metering applications

The efficacy of NB-IoT for smart meter applications is evaluated in terms of spectral efficiency and resource utilisation. This section analysed the NB-IoT-based smart meters using Simulink's state flow toolbox (Rel.2016) described in [44]. We evaluated NB-IoT performance across varying user equipment counts (240–3,150) and payload sizes (100, 150, 250 bytes), focusing on spectral efficiency and resource utilization. As UE numbers rise, resource sharing increases due to limited bandwidth, leading to higher utilization per UE. Spectral efficiency improves with more UEs for 100 and 150-byte payloads, peaking at 3,150 UEs. For 250 bytes, efficiency peaks around 1,680 UEs, then plateaus, highlighting the impact of payload size on network performance.

3.2 A Comprehensive Assessment of LoRaWAN and NB-IoT Performance Metrics Under Varied Payload Data Sizes

The performance of LoRaWAN and NB-IoT was evaluated using a simulation platform. The simulation platform was developed using MATLAB and Simulink. The following performance metrics were evaluated, Transmission time, Energy consumption, Resource utilization and Bit error rate (BER). Our results show that both NB-IoT and LoRaWAN exhibit increased resource usage with larger payloads. NB-IoT consistently uses fewer resources, making it more efficient for larger data sizes, while

LoRaWAN's resource usage grows more sharply. Bit error rates rise with payload size for both. NB-IoT offers faster transmission due to its higher data rate but consumes more energy. In contrast, LoRaWAN, though slower, is more energy-efficient per transmission. Ultimately, choosing between the two depends on specific application needs—speed vs. energy efficiency.

3.3 Analysis of LoRaWAN and NB-IoT Technologies for Enhanced IoT Deployments: An Experimental Study

3.3.1 LoRaWAN EXPERIMENT

This experiment investigated how wireless metrics such as RSSI and SNR relate to geographic location in IoT deployments. Using Pycom's Pytrack and FiPy for precise geolocation, and a Pygate LoRaWAN gateway for TTN connectivity, we demonstrated that RSSI-based localization offers a cost-effective, hardware-free solution for location-based IoT. Payloads from TTN were decoded and processed in Python, enabling robust analysis of signal quality.

Results show that RSSI consistently decreases with distance from the gateway, as expected, while SNR values display more variability, suggesting influence from both distance and additional environmental or technical factors. This highlights the complementary roles of RSSI and SNR in ensuring reliable LoRaWAN IoT communication.

3.3.2 NB-IoT EXPERIMENT

This study assessed the nRF9160's power efficiency in NB-IoT networks under varying RSRP levels, categorized as good-to-moderate (–43 to –74 dBm) and weak (–78 to –99 dBm). Power consumption was measured during idle, transmission, and GPS modes, showing a clear correlation with signal quality—stronger RSRP enabled stable connections and lower power usage, while weaker RSRP increased consumption due to transmission challenges. The impact of PSM and eDRX modes on battery life was also highlighted. Results confirm that optimizing for signal quality is crucial for energy-efficient NB-IoT operation. In our study, we summarize RSRP values range through all the cases as:

a) Cases 1-3, 6, and 7: RSRP ranged from –43 to –74 dBm, indicating good to moderate signal strength, enabling stable connections and lower power consumption.

b) Cases 4-5, 8-10: RSRP ranged from –78 to –99 dBm, indicating weak signal strength, leading to higher power usage due to increased transmission effort and connectivity challenges. Figure 3.3 shows the difference between two cases (7 and 10).

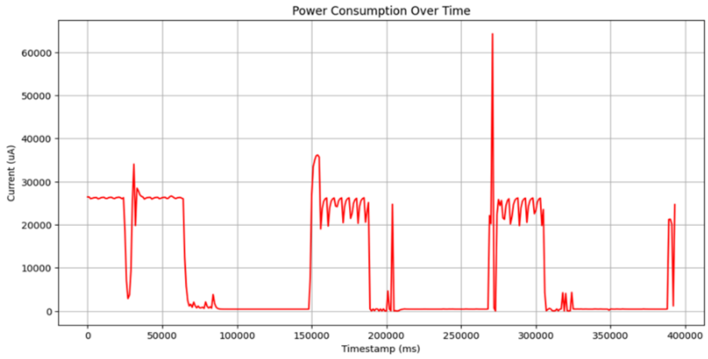


Figure 3.1 *The Results of Power for Experiment-Cases (7)*

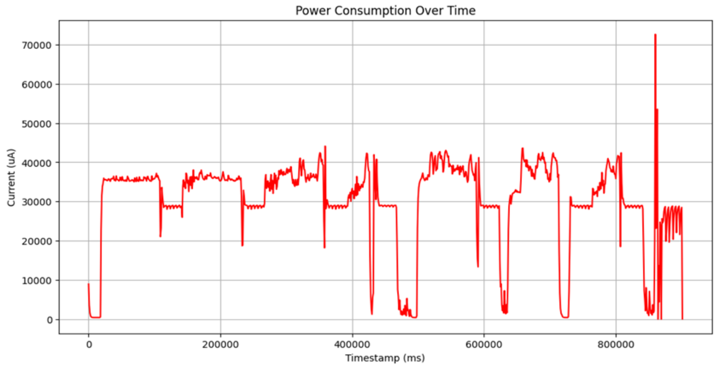


Figure 3.2 *The Results of Power for Experiment-Cases (10)*

3.4 Chapter conclusions

Presents the first in-depth empirical comparison of NB-IoT and LoRaWAN for smart metering. NB-IoT offers robust connectivity but with higher power consumption, while LoRaWAN excels in energy efficiency but requires careful network planning. The output of this chapter has been published as:

- **K.A. Al-Sammak,** S.H. Al-Gburi**,** I. Marghescu, A.M. Drăgulinescu, C. Marghescu, N.A.H. Al-Sammak, *An Experimental Study of Power Consumption in Narrowband IoT Devices*, in **Proceedings of the 2024 15th International Conference on Communications (COMM)**, Bucharest, Romania, **03–04 October 2024**, pp. 1–6, **IEEE, DOI: 10.1109/COMM62355.2024.10741514.**
- **K.A. Al-Sammak**, S.H. Al-Gburi, N.A.H. Al-Sammak, G. Suciu, *An Evaluation of the Functionality of NB-IoT for Smart metering Applications*, in **Proceedings of the International Conference on Intelligent and Fuzzy Systems (INFUS 2025)**, Istanbul, Turkey, **29–31 July 2025**.
- **K.A. Al-Sammak**, S.H. Al-Gburi**,** C. Marghescu, A.M. Drăgulinescu, G. Suciu, A.G. Abdulqader, *A Comprehensive Assessment of LoRaWAN and NB-IoT Performance Metrics Under Varied Payload Data Sizes*, in **Proceedings of the 2024 16th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)**, Iași, Romania, **27–28 June 2024**, pp. 1–5, **IEEE, DOI: 10.1109/ECAI61503.2024.10607481.**

Chapter 4 Optimizing LoRaWAN Network Performance through Hybrid PSO-DE Gateway Placement algorithm and Spreading Factor

In dense urban areas, LoRaWAN performance depends on gateway placement and spreading factor (SF) settings, especially in multi-floor buildings. This chapter uses a hybrid PSO-DE algorithm to optimize the network and compares SF7 and SF12 configurations. Experiments with Adeunis FTD devices and Dragino gateways across building floors at Politehnica University of Bucharest highlight these effects.

4.1 Experimental Setup and Data Processing

Experiments in a mixed-architecture, high-temperature, and high-humidity area involved manual packet transmissions and real-time TTN monitoring. A custom decoder extracted temperature, GPS, RSSI, SNR, and packet counts. K-Means clustering was used for detailed signal performance analysis.

4.2 SF7 vs SF12: Signal and Packet Loss Analysis

4.2.1 Packet loss:

To calculate the percentage of packet loss for each floor and spreading factor, we use the formula:

$$Packet\ Loss\ Percentage = \left(\frac{Number\ of\ packets\ lost}{Total\ packets\ sent}\right) \times 100 \tag{4.1}$$

Using the provided data from our collected data and by applying the equation (4.1) we got the results in Table 4.1:

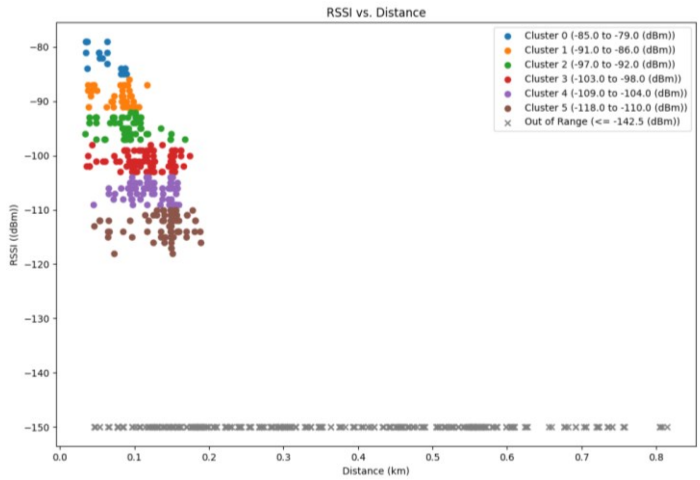
Table 4.1 *The lost packets overall the building levels in SF7 and SF12*

Floor	Lost Packets (SF7)	Packet Loss % (SF7)	Lost Packets (SF12)	Packet Loss % (SF12)
Ground Floor	405	54.36%	372	51.67%
1st Floor	417	55.97%	278	38.61%
3rd Floor	247	33.15%	91	12.64%
5th Floor	623	83.62%	504	70.00%
Top of Building	102	13.69%	60	8.33%

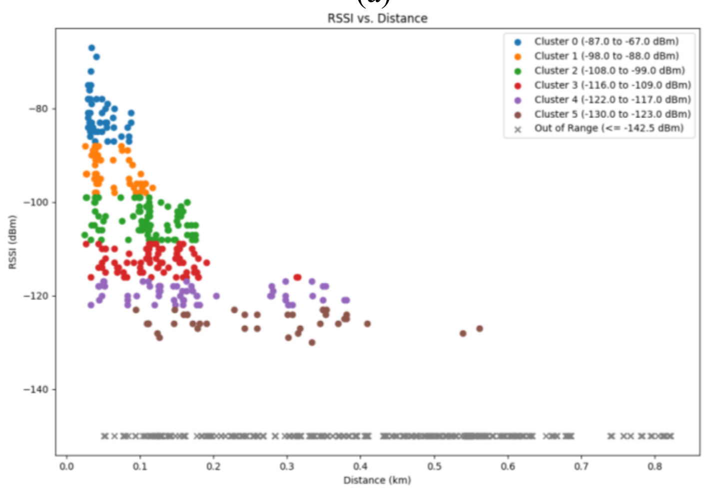
4.2.2 RSSI and SNR Analysis:

RSSI and SNR measurements for SF7 and SF12 were compared across multiple floors (Figures 4.1 and 4.2). On the ground floor (Figure 4.1.a), SF7 initially provided strong RSSI but suffered rapid degradation and high packet loss (54.4%), while SF12 (Figure 4.1.b), showed slower RSSI decline and lower loss (51.7%), making it more reliable for longer distances. As floor levels increased, SF12 consistently outperformed SF7—maintaining stronger RSSI and SNR, and resulting in significantly lower packet loss, especially in obstructed environments (e.g., 38.6% on the first floor, 12.6% on the third, and 8.3% at the top floor). Both SFs struggled on the fift h floor, but SF12 remained more robust overall.

SNR trends (Figure 4.2) mirrored RSSI results: SF12 maintained a broader and more stable SNR range across all floors, resulting in fewer transmission failures compared to SF7, whose SNR dropped sharply with distance and obstructions. Overall, SF12 proved more reliable for indoor, multi-floor LoRaWAN deployments, especially where obstacles or range are concerns.

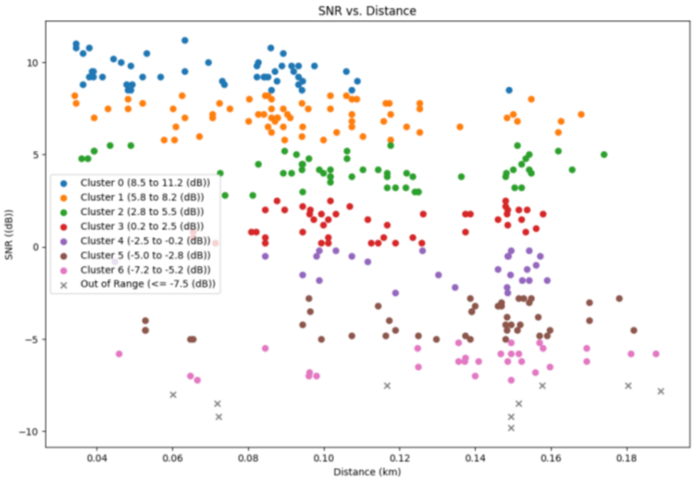


(a)

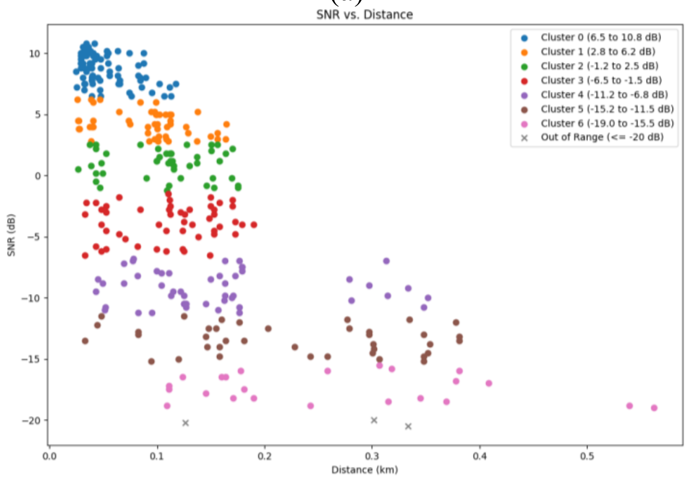


(b)

Figure 4.1 *(a) RSSI VS. Distance ground floor gateway, SF 7, (b) RSSI VS. Distance ground floor gateway, SF 12*



(a)



(b)

***Figure 4.2** (a) SNR Vs. Distance ground floor, SF7, (b) SNR Vs. Distance ground floor, SF12*

4.3 Proposed Method for Gateway Placement

The Hybrid approach used Particle Swarm Optimization (PSO) algorithm [45] and Differential Evolution (DE) algorithm [46], the proposed method uses an advanced metaheuristic approach to optimize multiple conflicting objectives in LoRaWAN, maximizing RSSI and SNR while minimizing packet loss. This ensures optimal network performance for gateways at various building floor levels. The objective function is evaluated using equation (4.2) .

$$cost(weights) = \alpha \cdot norm_{rssi} + \beta \cdot norm_{snr} + \gamma \cdot norm_{packet_{loss}} \quad (4.2)$$

The following shows the used algorithm:

Algorithm1: Hybrid Particle Swarm Optimization + Differential Evolution (PSO + DE)
1. Input:
2. RSSI: Array of RSSI values for each floor
3. SNR: Array of SNR values for each floor
4. Packet_loss: Array of packet loss values for each floor
5. Label: Descriptor (e.g., 'SF12', 'SF7')
6. Output:

Optimized weights (alpha, beta, gamma)
Optimized scores for each floor
Begin
// Normalize the input data
$\mathrm{norm}_{\mathrm{rssi}} = (\mathrm{rssi} - \min(\mathrm{rssi}))/(\max(\mathrm{rssi}) - \min(\mathrm{rssi}))$
$\mathrm{norm}_{\mathrm{snr}} = (\mathrm{snr} - \min(\mathrm{snr}))/(\max(\mathrm{snr}) - \min(\mathrm{snr}))$
$\mathrm{norm}_{\mathrm{packet}_{\mathrm{loss}}} = 1 - (\mathrm{packet}_{\mathrm{loss}} - \min(\mathrm{packet}_{\mathrm{loss}}))/{(\max(\mathrm{packet}_{\mathrm{loss}}) - \min(\mathrm{packet}_{\mathrm{loss}}))}$
//Optimize using PSO
best_weights_pso = optimize_with_pso($\mathrm{norm}_{\mathrm{rssi}}$,n $\mathrm{orm}_{\mathrm{snr}}$, $\mathrm{norm}_{\mathrm{packet}_{\mathrm{loss}}}$)
Function optimize_with_pso(norm_rssi, norm_snr, norm_packet_loss)
Initialize PSO with specific parameters
For each iteration:
Update positions and velocities of particles
Evaluate cost function:
$\mathrm{cost(weights)} = -1 \cdot (\alpha \cdot \mathrm{norm}_{\mathrm{rssi}} + \beta \cdot \mathrm{norm}_{\mathrm{snr}} + \gamma \cdot \mathrm{norm}_{\mathrm{packet}_{\mathrm{loss}}})$
Update particle velocities and positions based on personal and global best
Return best weights (α, β, γ) from PSO
//Fine-tune using DE
best_weights_de = optimize_with_de(best_weights_pso, $\mathrm{norm}_{\mathrm{rssi}}$,n $\mathrm{orm}_{\mathrm{snr}}$, $\mathrm{norm}_{\mathrm{packet}_{\mathrm{loss}}}$)
Function optimize_with_de(best_weights_pso, $\mathrm{norm}_{\mathrm{rssi}}$, $\mathrm{norm}_{\mathrm{snr}}$, $\mathrm{norm}_{\mathrm{packet}_{\mathrm{loss}}}$)
Set bounds for alpha, beta, and gamma
Initialize population around best_weights_pso
For each generation:
Perform mutation, crossover, and selection based on the DE cost function
Return best weights found by DE
//Calculate and normalize final scores:
final_scores = calculate_scores(floors, rssi, snr, $\mathrm{packet}_{\mathrm{loss}}$, best_weights_de)
Function calculate_scores (floors, rssi, snr, $\mathrm{packet}_{\mathrm{loss}}$, best_weights):
$\mathrm{total}_{\mathrm{weights}} = \alpha + \beta + \gamma$
$\mathrm{normalized}_{\mathrm{alpha}} = \alpha/\mathrm{total}_{\mathrm{weights}}$
$\mathrm{normalized}_{\mathrm{bete}} = \beta/\mathrm{total}_{\mathrm{weights}}$
$\mathrm{normalized}_{\mathrm{gamma}} = \gamma/\mathrm{total}_{\mathrm{weights}}$
For each floor:
$optimized_{score} = (normalized_{alpha} \cdot norm_{rssi}) + (normalized_{beta} \cdot norm_{snr}) + (normalized_{gamma} \cdot norm_{packet_{loss}})$
Store $\mathrm{optimized}_{\mathrm{score}}$ for the floor
Return dictionary or data frame containing floors and their corresponding optimized scores
//Display results:
Output the best_weights_de and final_scores
Visualize scores on a bar chart with a color map reflecting the score intensity
End Algorithm

The Hybrid PSO + DE optimization algorithm revealed that placing the gateway on the top floor provided the best network performance. For single gateway deployments, the top floor is optimal for both SF7 and SF12, providing strong signals and low packet loss, while for third floor is a good secondary choice for SF12. The fifth floor should be avoided due to interference, and the ground floor can serve as a backup for SF7 if higher placements are not feasible. In multiple gateway scenarios, including the top floor in any combination consistently minimizes packet loss (as low as 0.83% for SF12) and maximizes network performance. The best results are achieved with configurations like Ground + Top or Top + 1st + 3rd floors, while combinations involving the fifth floor underperform, and excluding the top floor leads to high packet loss (often over 30%). Overall, strategic placement—especially prioritizing the top floor—is more effective than simply increasing the number of gateways.

4.4 A Comparative Study of Real and Simulated Environments

This section compares LoRaWAN performance using SF7 and SF12 through real-world experiments and HTZ simulations under summer conditions. Below, in Table 4.2, we summarize the configurations for each gateway along with their corresponding settings to illustrate the setup comprehensively:

Table 4.3 *Simulation parameters configuration*

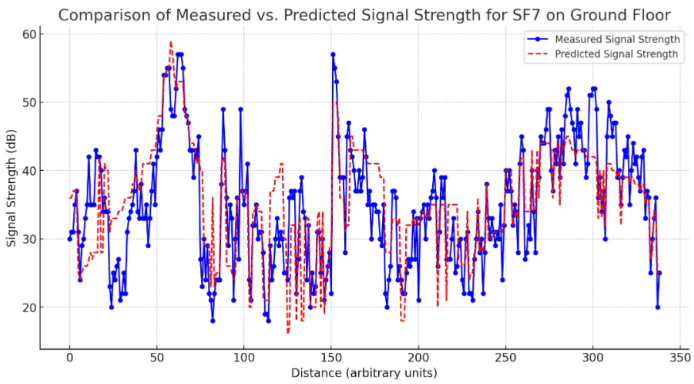
Parameter	Ground Floor	3rd Floor	Top of Building
Frequency (MHz)	868.100	868.100	868.100
Antenna Height (m)	2.00	15.00	45.00
Tx/Rx Gain (dB)	5.00	5.00	5.00
Bandwidth (kHz)	125.00	125.00	125.00
Nominal Power (W)	0.02511886	0.02511886	0.02511886
E.I.R.P (W)	0.07943282	0.07943282	0.07943282
Antenna Size (m)	0.17	0.17	0.17
Beamwidth (°)	360.00	360.00	360.00
Propagation Model	Deterministic	Deterministic	Deterministic
Additional Features	Reflections, Ducting	Reflections, Ducting	Reflections, Ducting

The simulation matrices give insights into signal stability, transmission accuracy, and received signal consistency. In Table 4.4 ,we summarized the output values of these three matrices across different building levels.

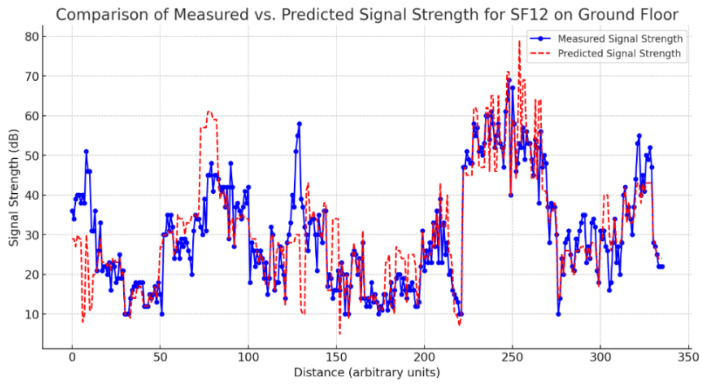
Table 4.4 *Simulated signal strength metrics across floors*

Floor Level	Spreading Factor	Standard Deviation	Average Error	Correlation Factor
Ground	SF7	5.76 dB	0.51 dB	0.77
	SF12	8.39 dB	0.33 dB	0.82
Third	SF7	6.48 dB	0.12 dB	0.90
	SF12	8.23 dB	1.83 dB	0.84
Top	SF7	6.90 dB	0.45 dB	0.73
	SF12	11.01 dB	0.77 dB	0.58

A comparison of measured vs. predicted values for SF7 and SF12 at the ground floor gateway reveals key differences as shown in (Figure 4.3) SF12 displays more pronounced changes, whereas SF7 remains relatively stable.



(a)



(b)

Figure 4.3 *Comparison of Measured VS. predicted signal strength on the ground floor gateway, (a) For SF7, (b) For SF12*

4.5 Chapter conclusions

Introduces and validates a hybrid PSO-DE algorithm for optimal LoRaWAN gateway placement. Demonstrates that strategic gateway deployment, especially on upper floors, dramatically improves coverage and reduces packet loss, confirming that network performance depends more on placement optimization than on the number of gateways. The output of this chapter has been published as:

- **K. A. Al-Sammak**, S. H. Al-Gburi, I. Marghescu, A.-M. C. Drăgulinescu, C. Marghescu, A. Martian, N. A. M. Alduais, and N. A. H. Al-Sammak, *Optimizing LoRaWAN Gateway Placement in Urban Environments: A Hybrid PSO-DE Algorithm Validated via HTZ Simulations*, in **Technologies, vol. 13, no. 6, p. 256, 17 June 2025, DOI: 10.3390/technologies13060256, ISI Q1 (2025). WOS:001514625000001.**

Chapter 5 Optimizing IoT Energy Efficiency: Real-Time Adaptive Algorithms for Smart Meters with LoRaWAN and NB-IoT

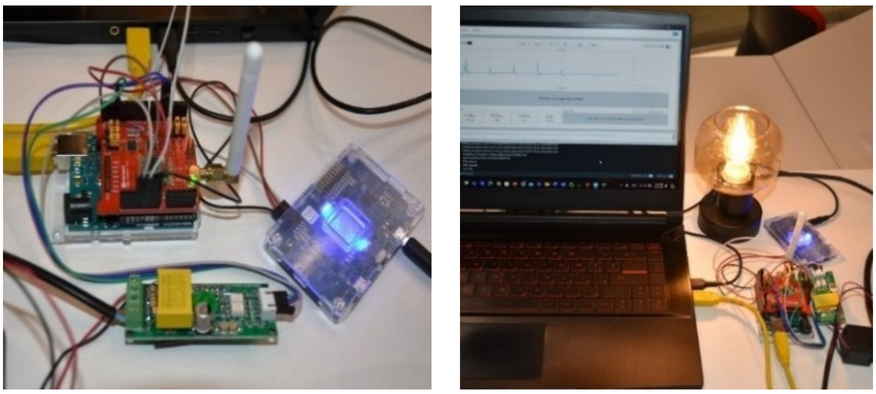
IoT-enabled smart grids support real-time energy monitoring, but battery-powered meters struggle with frequent transmissions and network congestion. While LPWANs like LoRaWAN and NB-IoT help, efficiency is limited by redundant data. This chapter presents an adaptive algorithm that sends data only when significant electrical changes occur, reducing unnecessary transmissions. Tested on a real setup, the algorithm cut transmissions by over 76% and reduced energy spikes by up to 88.5%.

5.1 System Overview and Methodology

This work uses a structured approach to evaluate data transmission efficiency and energy optimization in IoT smart metering with LoRaWAN and NB-IoT, comparing performance with and without the adaptive algorithm. The study covers system design, implementation, and performance analysis across multiple phases.

5.1.1 LoRaWAN Network Architecture:

The smart metering system uses an Arduino Uno with a Dragino LoRa Shield to collect and transmit energy data to an LG308 Gateway. The gateway sends this data to TTN, which manages routing, security, and cloud integration. Figure 5.1 presents an overview of the architecture system implemented using LoRaWAN.

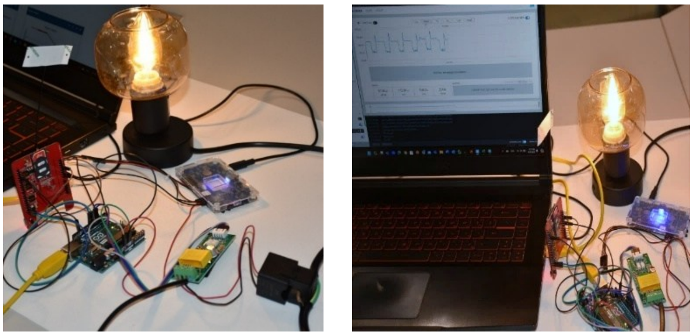


(a) (b)

Figure 5.1 *Setup of a smart meter system utilizing LoRaWAN*

5.1.2 NB-IoT Network Architecture:

The end device uses an Arduino Uno with a BG96 NB-IoT module to transmit data over the cellular network to ThingSpeak, a cloud platform for storing and visualizing smart meter parameters. This setup enables real-time analysis of energy data from the IoT node. Figure 5.2 illustrates the system architecture implemented using NB-IoT technology.



(a) (b)

Figure 5.2 *Setup of a smart meter system utilizing NB-IoT*

5.2 System Workflow and Software Implementation

The experimental setup used Arduino Uno devices with either a Dragino LoRa Shield (LoRaWAN) or BG96 module (NB-IoT), transmitting data to TTN or ThingSpeak. Both systems adaptively adjusted transmission intervals based on data changes. Tests ran for 6 hours under identical conditions, comparing standard fixed-interval transmissions to an optimized method that reduced power use by sending data only when significant changes occurred.

5.2.1 Standard Transmission (Without Algorithm):

In the standard LoRaWAN and NB-IoT systems, the Arduino Uno collects data from the PZEM004T meter and transmits it at fixed intervals, regardless of parameter changes. All data is sent to the respective network (TTN for LoRaWAN, ThingSpeak for NB-IoT).

5.2.2 Optimized Transmission (With Algorithm)

The proposed energy management algorithm leverages adaptive transmission periods, efficient session management, and selective data transmission to optimize power consumption in IoT-based systems, especially those using LoRaWan and NB-IoT protocols. This proposal focuses on extended operating life and reduced power consumption without losing data trustworthiness. The following are the optimization algorithms we have used in our work systems in each scenario:

Algorithm 1: Optimized LoRaWAN Energy Management

```
Input:
    TX_INTERVAL: Initial transmission interval
    LMIC: LoRaWAN communication library
    PZEM-004T: Sensor for collecting electrical parameters (Smart meter)
Output:
    Optimized power consumption for IoT-Node (Smart meter)
    Transmission status
Begin
  //System Initialization
    Initialize serial communication
    Set RX window parameters for increased timing tolerance
    Attempt to restore network session from EEPROM or initiate joining process
    Initialize PZEM-004T sensor for data collection
  //Main System Workflow
    Set TX_INTERVAL for data transmission
    Handle network events (EV_JOINING, EV_JOINED, EV_TXCOMPLETE, EV_JOIN_FAILED)
        - Manage joining
        - Save session
        - Implement power-saving actions
  //Data Reading and Transmission
    Function do_send():
        If transmission is ongoing:
            Print "Transmission in progress"
            Return
        Else:
            Read sensor data
            Validate and calculate rate of change
            If significant change detected:
                Prepare and send payload
                Reset TX_INTERVAL
            Else:
                Increase TX_INTERVAL
                Enter sleep mode
  //Entering Sleep Mode
    Enter deep sleep mode after data transmission or if no significant change detected
  //Event Handling for Network Operations
    Use onEvent() to:
        Handle network events
        Store session details in EEPROM
  //Loop for Running System Continuously
    Continuously run LMIC event loop using os_runloop_once()
End Algorithm
```

Algorithm 2: Optimized NB-IoT Energy Management

```
Inputs:
    TX_INTERVAL: Initial transmission interval.
    PZEM-004T: Sensor for collecting electrical parameters (Smart meter).
Outputs:
    Optimized power consumption for IoT-Node (Smart meter).
```

6. Transmission status.
7. Begin
8. //System Initialization//
9. Set up serial communication for BG96 and PZEM-004T.
10. Configure BG96 network settings (e.g., APN, network mode for NB-IoT, and band settings).
11. Attempt to restore previous network session from EEPROM; if unavailable, initiate network registration.
12. Initialize the PZEM-004T sensor for data collection.
13. //Main System Workflow//
14. Set TX_INTERVAL for data transmission.
15. Handle network events to manage:
16. Registration and connection to the NB-IoT network.
17. Data transmission status (e.g., success or failure).
18. Session management to save details for reconnection and manage power-saving actions.
19. //Data Reading and Transmission//
20. Use do_send() function to handle data transmission:
21. If transmission is ongoing, show status and exit the function.
22. Otherwise, proceed with the following steps:
23. Read Sensor Data: Collect voltage, current, power, energy, frequency, and power factor from PZEM-004T and store in array St.
24. Validate Data: Ensure each reading is valid; if any reading is invalid (e.g., NaN values), show an error message and skip further processing.
25. Calculate Rate of Change: Compare current readings (St) with previous readings (St_1) and calculate the rate of change for each metric.
26. Significant Change Check:
27. If significant change detected:
28. Prepare a payload with sensor values.
29. Send the payload to the cloud server (ThingSpeak) using HTTP GET request via BG96.
30. Print “Data should be sent to the cloud”.
31. Reset TX_INTERVAL to its initial value.
32. Update St_1 with the current readings for future comparisons.
33. If no significant change:
34. Print “No need to send data”.
35. Increase TX_INTERVAL for reduced transmission frequency.
36. Enter sleep mode to conserve power.
37. //Continuous System Operation//
38. Run the NB-IoT event loop continuously.
39. End Algorithm

5.3 Results and Analysis

This section presents the experimental results for LoRaWAN and NB-IoT smart metering, comparing standard and optimized data transmission using the proposed adaptive algorithm. Without optimization, LoRaWAN and NB-IoT showed high current consumption (>23,000 µA and >90,000 µA, respectively; (Figure 5.4 and Figure 5.5). The adaptive algorithm reduced LoRaWAN current to under 10,000 µA and NB-IoT to below 60,000 µA, while also cutting transmitted packets by 76.11% (LoRaWAN) and 86.81% (NB-IoT).

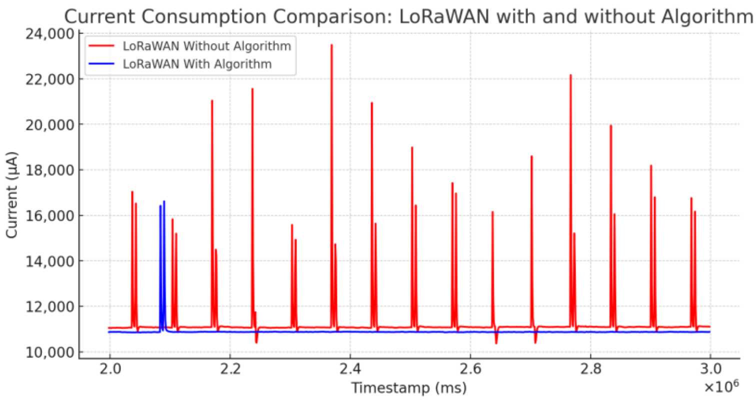


Figure 5.3 *Results of current consumption(µA) for LoRaWAN*

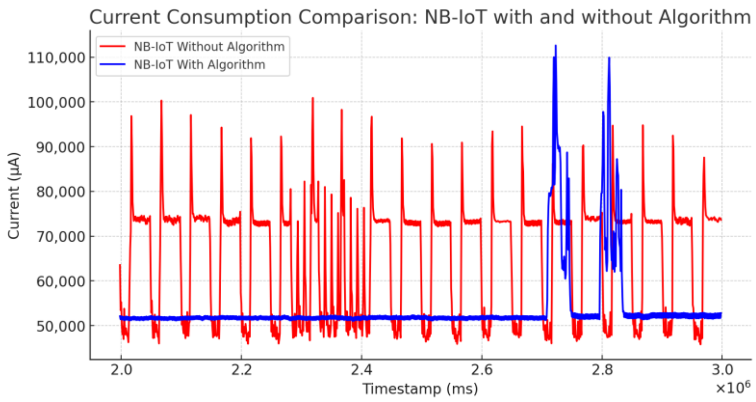


Figure 5.4 *Results of current consumption(µA) for NB-IoT*

The adaptive algorithm reduced energy spikes by 88.5% in LoRaWAN (from 80 to 5 spikes) and by 87.3% in NB-IoT (from 600 to 75 spikes). Raising the data transmission threshold further decreased packet counts, showing the algorithm's ability to filter redundant data. Overall, this approach lowers power consumption, minimizes unnecessary transmissions, and greatly improves energy efficiency in both LoRaWAN and NB-IoT smart metering applications.

5.4 Chapter conclusions

An adaptive transmission algorithm was developed and tested, significantly reducing unnecessary data transmissions and energy consumption in both NB-IoT and LoRaWAN smart metering systems. The results demonstrate substantial energy savings, supporting scalable and sustainable smart metering. These findings have been published as:

- **K.A. Al-Sammak**, S.H. Al-Gburi**,** I. Marghescu, A.-M.C. Drăgulinescu, C. Marghescu, A. Martian, N.A.H. Al-Sammak, G. Suciu, K.M.A. Alheeti, *Optimizing IoT Energy Efficiency: Real-Time Adaptive Algorithms for Smart metering with LoRaWAN and NB-IoT*, in **Energies**, **18(4), 987, 18 February 2025**, **DOI: 10.3390/en18040987**, **ISI Q3, WOS: 001431808900001.**

Chapter 6 Conclusions and Future Works

6.1 Research Findings and Contributions

This thesis systematically addresses key research questions in the context of LPWAN-based smart metering, validated through extensive experimentation and resulting in several high-impact contributions and published works.

RQ1: What are the critical design aspects, performance requirements, and emerging challenges for communication technologies in smart metering systems?

Finding: Provided a comprehensive review and systematic comparison of wired and wireless smart metering technologies, analyzing essential criteria such as coverage, scalability, latency, energy efficiency, and security.

Contribution: Identified core requirements and emerging challenges, including deep coverage, energy constraints, and protocol integration, laying a foundation for robust and efficient smart metering communications.

Related Published Work:

- **K.A. Al-Sammak**, S.H. Al-Gburi, I. Marghescu, *Communications Systems in Smart metering: A Concise Systematic Literature Review*, in **Proceedings of the 2022 14th International Conference on Communications (COMM)**, Bucharest, Romania, **16–18 June 2022**, pp. 1–9, **IEEE, DOI: 10.1109/COMM54429.2022.9817154.**

RQ2: What are the key performance characteristics and limitations of NB-IoT and LoRaWAN for smart metering applications?

Finding: Delivered the first empirical, side-by-side evaluation of NB-IoT and LoRaWAN for smart metering, combining simulations and real-world experiments. LoRaWAN is shown to be more energy efficient but sensitive to gateway placement; NB-IoT is more robust but consumes more energy, especially in poor signal conditions.

Contribution: Established critical trade-offs and deployment considerations for technology selection, directly informing best practices for real-world smart metering rollouts.

Related Published Work:

- **K.A. Al-Sammak,** S.H. Al-Gburi**,** I. Marghescu, A.M. Drăgulinescu, C. Marghescu, N.A.H. Al-Sammak, *An Experimental Study of Power Consumption in Narrowband IoT Devices*, in **Proceedings of the 2024 15th International Conference on Communications (COMM)**, Bucharest, Romania, **03–04 October 2024**, pp. 1–6, **IEEE, DOI: 10.1109/COMM62355.2024.10741514.**

- **K.A. Al-Sammak**, S.H. Al-Gburi**,** C. Marghescu, A.M. Drăgulinescu, G. Suciu, A.G. Abdulqader, *A Comprehensive Assessment of LoRaWAN and NB-IoT Performance Metrics Under Varied Payload Data Sizes*, in **Proceedings of the 2024 16th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)**, Iași, Romania, **27–28 June 2024**, pp. 1–5, **IEEE, DOI: 10.1109/ECAI61503.2024.10607481.**
- **K.A. Al-Sammak**, S.H. Al-Gburi, N.A.H. Al-Sammak, G. Suciu, *An Evaluation of the Functionality of NB-IoT for Smart metering Applications*, in **Proceedings of the International Conference on Intelligent and Fuzzy Systems (INFUS 2025)**, Istanbul, Turkey, **29–31 July 2025**.

RQ3: How can gateway placement for LoRaWAN networks be optimized to enhance coverage, reliability, and efficiency?

Finding: Introduced and validated the GateOpt PSODE hybrid optimization framework (PSO + DE), leveraging real signal data and clustering to determine optimal gateway locations. Demonstrated that top-floor gateways consistently yield the best coverage and lowest packet loss, while the addition of gateways without strategic optimization can reduce overall network performance.

Contribution: Pioneered a practical, multi-criteria optimization approach for cost-effective and reliable LPWAN infrastructure in multi-story buildings.

Related Published Work:

- **K. A. Al-Sammak**, S. H. Al-Gburi, I. Marghescu, A.-M. C. Drăgulinescu, C. Marghescu, A. Martian, N. A. M. Alduais, and N. A. H. Al-Sammak, Optimizing LoRaWAN Gateway Placement in Urban Environments: A Hybrid PSO-DE Algorithm Validated via HTZ Simulations, in **Technologies, vol. 13, no. 6, p. 256, 17 June 2025, DOI: 10.3390/technologies13060256, ISI Q1 (2025), WOS:001514625000001.**

RQ4: What strategies can be employed to improve the energy efficiency of smart metering nodes through adaptive transmission?

Finding: Developed and experimentally validated an adaptive transmission algorithm that transmits only on significant parameter changes, reducing packet count by up to 87% and energy spikes by up to 88% for both LoRaWAN and NB-IoT devices.

Contribution: Demonstrated a scalable, cross-technology solution for substantial energy savings and congestion reduction in smart metering networks.

Related Published Work:

- **K.A. Al-Sammak**, S.H. Al-Gburi**,** I. Marghescu, A.-M.C. Drăgulinescu, C. Marghescu, A. Martian, N.A.H. Al-Sammak, G. Suciu, K.M.A. Alheeti, *Optimizing IoT Energy Efficiency: Real-Time Adaptive Algorithms for Smart metering with LoRaWAN and NB-IoT*, in **Energies**, **18(4), 987, 18 February 2025**, **DOI: 10.3390/en18040987**, **ISI Q3, WOS: 001431808900001**.

These findings collectively advance the field of smart metering by bridging theoretical gaps with practical solutions—delivering new comparative insights, optimization algorithms, and adaptive methods to enable the next generation of reliable, energy-efficient, and scalable IoT-based metering systems.

6.2 Author Publications

[1] **Journal:** **K. A. Al-Sammak**, S. H. Al-Gburi, I. Marghescu, A.-M. C. Drăgulinescu, C. Marghescu, A. Martian, N. A. M. Alduais, and N. A. H. Al-Sammak, *Optimizing LoRaWAN Gateway Placement in Urban Environments: A Hybrid PSO-DE Algorithm Validated via HTZ Simulations,* in **Technologies, vol. 13, no. 6, p. 256, 17 June 2025, DOI: 10.3390/technologies13060256, ISI Q1 (2025), WOS:001514625000001.**

[2] **Journal**: **K.A. Al-Sammak**, **S.H. Al-Gburi,** I. Marghescu, A.-M.C. Drăgulinescu, C. Marghescu, A. Martian, N.A.H. Al-Sammak, G. Suciu, K.M.A. Alheeti, *Optimizing IoT Energy Efficiency: Real-Time Adaptive Algorithms for Smart metering with LoRaWAN and NB-IoT*, in **Energies**, **18(4), 987, 18 February 2025**, **DOI: 10.3390/en18040987**, **ISI Q3, WOS: 001431808900001**.

[3] **Conference:** **K.A. Al-Sammak,** S.H. Al-Gburi, I. Marghescu, A.M. Drăgulinescu, C. Marghescu, N.A.H. Al-Sammak, *An Experimental Study of Power Consumption in Narrowband IoT Devices*, in **Proceedings of the 2024 15th International Conference on Communications (COMM)**, Bucharest, Romania, **03–04 October 2024**, pp. 1–6, **IEEE, DOI: 10.1109/COMM62355.2024.10741514.**

[4] **Conference:** **K.A. Al-Sammak**, S.H. Al-Gburi, C. Marghescu, A.M. Drăgulinescu, G. Suciu, A.G. Abdulqader, *A Comprehensive Assessment of LoRaWAN and NB-IoT Performance Metrics Under Varied Payload Data Sizes*, in **Proceedings of the 2024 16th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)**, Iași, Romania, **27–28 June 2024**, pp. 1–5, **IEEE, DOI: 10.1109/ECAI61503.2024.10607481.**

[5] **Conference:** **K.A. Al-Sammak**, S.H. Al-Gburi, I. Marghescu, *Communications Systems in Smart metering: A Concise Systematic Literature Review*, in **Proceedings of the 2022 14th International Conference on Communications (COMM)**, Bucharest, Romania, **16–18 June 2022**, pp. 1–9, **IEEE, DOI: 10.1109/COMM54429.2022.9817154.**

[6] **Conference:** **K.A. Al-Sammak**, S.H. Al-Gburi, N.A.H. Al-Sammak, G. Suciu, *An Evaluation of the Functionality of NB-IoT for Smart metering Applications*, in **Proceedings of the International Conference on Intelligent and Fuzzy Systems (INFUS 2025)**, Istanbul, Turkey, **29–31 July 2025**.

[7] **Journal**: S.H. Al-Gburi, **K.A. Al-Sammak**, I. Marghescu, C.C. Oprea, A.-M.C. Drăgulinescu, N.A.M. Alduais, K.M.A. Alheeti, N.A.H. Al-Sammak, N.A.H. *EffRes-DrowsyNet: A Novel Hybrid Deep Learning Model Combining EfficientNetB0 and ResNet50 for Driver Drowsiness Detection* in **Sensors, 25, 3711, 13 June 2025, DOI:10.3390/s25123711, ISI Q2 (2025), WOS:001516386400001.**

[8] **Journal**: S.H. Al-Gburi, **K.A. Al-Sammak**, I. Marghescu, C.C. Oprea, A.-M.C. Drăgulinescu, G. Suciu, K.M.A. Alheeti, N.A.M. Alduais, N.A.H. Al-Sammak, *Introducing a Novel Fast Neighbourhood Component Analysis–Deep Neural Network Model for Enhanced Driver Drowsiness Detection* in **Big Data and**

Cognitive Computing, **9(5), 126, 08 May 2025**, DOI: 10.3390/bdcc9050126, **ISI Q1 (2025), WOS: 001497786100001.**

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[10] **Conference:** S.H. Al-Gburi**, K.A. Al-Sammak**, K.M.A. Alheeti, G. Suciu, A.G. Abdulqader, *Driver Behavior Assessment with Different ML Models Using EEG and Physiological Data – A Comparative Study*, in **Proceedings of the 2024 16th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)**, Iași, Romania, **27–28 June 2024**, pp. 1–6, **IEEE, DOI: 10.1109/ECAI61503.2024.10607554.**

[11] **Journal:** S. H. Al-Gburi, **K. A. Al-Sammak**, I. Marghescu, and C. C. Oprea, *State of the Art in Drivers' Attention Monitoring – A Systematic Literature Review***, Karbala International Journal of Modern Science**, vol. 9, no. 1, Jan. 2023, **DOI: 10.33640/2405-609x.3278. Scopus Q2.**

[12] **Conference**: S.H. Al-Gburi, **K.A. Al-Sammak**, N.A.A. Almosa, G. Suciu, N.A.H. Al-Sammak, *Comparative Analysis of Logistic Regression and SVM Models for Drowsiness Detection in Drivers*, in **Proceedings of the International Conference on Intelligent and Fuzzy Systems (INFUS 2025)**, Istanbul, Turkey, **29–31 July 2025**.

[13] **Conference:** G. Suciu, C. Stalidi, **K.A. Al-Sammak**, S.H. Al-Gburi, M.-A. Sachian, *Integrated Solution Based on Innovative Digital Technologies for Smart Ports*, **FOR-FREIGHT Project White Paper**, BEIA Consult International, Bucharest, Romania, **2023**, available at: https://www.for-freight.eu/publications/.

6.3 Future Works

Future research directions to further extend this work include:

- Apply machine learning for real-time adaptive transmission based on network and environmental conditions.
- Use blockchain to improve security and transparency in smart metering.
- Develop renewable-powered IoT nodes for longer, sustainable operation.
- Test algorithm scalability in larger, diverse IoT networks.

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