

LPWAN (LoRaWAN, NB-IoT) Protocol Optimization for Smart Cities

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Abstract

*Smart cities are increasingly becoming an urban development priority in many countries. As city services and infrastructure depend more on digitization, connectivity technologies that can cover large areas with low power and low cost are necessary. Low Power Wide Area Networks (LPWAN) such as **LoRaWAN** and **NB-IoT** have emerged as leading options for smart city applications including environment sensing, utility metering, intelligent transportation, and public safety. However, these technologies still face challenges in scalability, energy efficiency, interference mitigation, quality of service, and network capacity. This paper reviews the state of LPWAN technologies focusing on LoRaWAN and NB-IoT, identifying their strengths and limitations in smart city contexts. We then examine current research on protocol optimization strategies, including adaptive data rate, power control, collision avoidance methods, and resource scheduling. A comparative analysis highlights how optimization techniques can enhance system reliability, increase device lifetime, and reduce operational costs. We also propose a hybrid optimization framework combining best strategies for urban deployments. Finally, the paper discusses open challenges and future research directions necessary for widespread adoption of optimized LPWAN for smart cities.*

Keywords

LPWAN, LoRaWAN, NB-IoT, Smart Cities, Protocol Optimization, Scalability, Energy Efficiency, Network Capacity

1. INTRODUCTION

In recent years, development of smart cities has progressed significantly due to advancements in Internet of Things (IoT) technologies. Smart cities require reliable sensing and actuation over wide areas to manage resources efficiently and improve quality of life for residents. Traditional cellular networks such as 3G/4G provide coverage but at high cost and energy consumption, making them unsuitable for many IoT scenarios. This gap has been filled by **Low Power Wide Area Network (LPWAN)** technologies that focus on long range communication with minimal energy drain and low deployment cost.

Among LPWAN technologies, **LoRaWAN** and **Narrowband IoT (NB-IoT)** stand out due to their adoption by industry and standardization bodies. LoRaWAN uses unlicensed spectrum and a proprietary physical layer with chirp spread spectrum modulation, providing long range with low power. NB-IoT on the other hand operates within licensed cellular bands, enabling deep indoor coverage and quality of service guarantees. While both protocols are promising for smart city use cases, there are still issues that need attention especially when scaling to thousands of devices distributed over dense urban environments.

This paper reviews problems associated with baseline implementations of LoRaWAN and NB-IoT in smart cities and surveys optimization strategies proposed in literature and practice. The aim is to help researchers and practitioners understand current methods to improve protocol performance and identify areas that require future research.

2. BACKGROUND: LPWAN TECHNOLOGIES

Low Power Wide Area Network (LPWAN) technologies are designed especially for IoT devices that need to communicate small amounts of data over very long distances while consuming very little power. Unlike Wi-Fi, Bluetooth, or traditional cellular systems which are designed for high data rate communication, LPWAN focuses on **range, energy efficiency, and cost effectiveness**.

Among the many LPWAN options available today, **LoRaWAN** and **NB-IoT** are the most widely adopted for smart city scale deployments.

2.1 LoRaWAN

LoRaWAN is a communication protocol defined and maintained by the **LoRa**

Alliance. It operates on top of the **LoRa physical layer**, which uses a special modulation technique called **Chirp Spread Spectrum (CSS)** developed by Semtech. This modulation is highly resistant to noise and allows signals to travel long distances even at very low power levels.

a) Operating Principle

LoRaWAN follows a **star-of-stars topology**:

- **End devices (nodes/sensors)** send data using LoRa radio signals.
- **Gateways** act as transparent bridges, forwarding packets to the network server via IP (Ethernet/4G).
- **Network server** performs packet filtering, security checks, ADR control.
- **Application server** processes data for smart city services.

This architecture reduces complexity at sensor nodes, which is important for low power usage.

2.2 NB-IoT

NB-IoT was standardized by 3GPP as part of LTE enhancements. It provides:

- Operation in **licensed spectrum** ensuring controlled interference
- **Deep indoor coverage** and better link reliability
- **Higher reliability** compared to unlicensed LPWAN

- Integration with existing cellular infrastructure

NB-IoT uses narrow bandwidth channels (180 kHz) and offers features like power saving mode (PSM) and extended discontinuous reception (eDRX) to save energy.

2.2 NB-IoT (Narrowband Internet of Things)

NB-IoT is a cellular LPWAN technology standardized by **3GPP** under LTE Release 13. It is designed specifically for IoT devices but uses existing cellular infrastructure, making it highly reliable and secure.

a) Operating Principle

NB-IoT works within the LTE cellular network in three deployment modes:

1. **In-band:** within existing LTE carrier
2. **Guard-band:** in unused guard frequencies
3. **Standalone:** using refarmed GSM spectrum

This flexibility allows operators to deploy NB-IoT without new spectrum requirements.

b) Licensed Spectrum Operation

NB-IoT operates in **licensed frequency bands**, which provides:

- Controlled interference

- Guaranteed quality of service
- Secure communication
- Better reliability than unlicensed LPWAN

This is important for smart city applications like emergency alerts and public safety systems.

c) Narrow Bandwidth Channel (180 kHz)

NB-IoT uses a very small bandwidth of **180 kHz**, which improves:

- Receiver sensitivity
- Deep indoor penetration (basements, buildings)
- Long range coverage in urban environments

It can achieve coverage gains of +20 dB compared to normal LTE.

d) Power Saving Mechanisms

NB-IoT devices use advanced power saving features:

- **Power Saving Mode (PSM):** Device goes into deep sleep for long durations.
- **Extended Discontinuous Reception (eDRX):** Device wakes up periodically to check messages.

These mechanisms allow NB-IoT devices to achieve battery life comparable to LoRaWAN (5–10 years).

3. REQUIREMENTS OF SMART CITY APPLICATIONS

Smart city environments consist of thousands of distributed sensors, meters, cameras, alarms, and control devices deployed across large geographical areas. These devices serve different purposes such as monitoring environment, managing utilities, controlling traffic, improving public safety, and optimizing resource usage. Because of this diversity, **no single communication behavior fits all applications.** LPWAN technologies like LoRaWAN and NB-IoT must satisfy a wide range of performance requirements depending on the use case.

Understanding these requirements is very important before designing or optimizing LPWAN protocols for smart cities.

3.1 Wide Area Coverage

Smart city infrastructure is spread across:

- Roads and highways
- Residential and commercial buildings
- Underground pipelines and meters
- Parks, rivers, and remote environmental zones

Hence, communication technology must support **long distance connectivity** with minimum infrastructure. LPWAN is expected to cover several kilometers with few gateways or base stations.

Example:

Air quality sensors placed across an entire city must send data reliably to a central server without requiring dense network deployment.

3.2 Low Energy Consumption

Most smart city devices are battery powered and installed in locations where frequent maintenance is not possible. These devices are expected to operate for **5–10 years without battery replacement**.

Therefore, the network protocol must:

- Minimize transmission time
- Allow long sleep cycles
- Reduce retransmissions
- Use energy-efficient modulation

Example:

Water meters installed underground should transmit readings once per day and remain in sleep mode the rest of the time.

3.3 Scalability to Massive Number of Devices

A city may deploy **tens of thousands** of IoT nodes. The network must handle:

- High device density
 - Simultaneous data transmissions
 - Minimal packet collision
 - Efficient addressing and scheduling
- Without scalability, packet loss increases and network becomes unreliable.

Example:

Smart parking sensors deployed on every street may number in thousands within a small region.

3.4 Low Data Rate but Reliable Communication

Most smart city sensors send **small packets** of data such as temperature, meter reading, pollution level, or status signal.

The network should be optimized for:

- Small payload sizes (10–50 bytes)
- Infrequent transmission
- High packet delivery ratio (PDR)

High bandwidth is not required, but **reliability is essential**.

Table 1:

Application	Data Frequency	Latency	Coverage	Example
Environment Monitoring	Low	Tolerable	Wide	Air quality sensors
Smart Metering	Periodic	Low	Citywide	Electricity meters
Public Safety	Event-driven	Very Low	Urban & Indoor	Fire alarms

Application	Data Frequency	Latency	Coverage	Example
Intelligent Transport	Medium	Medium	Urban	Traffic sensors

Some features are shared across applications: low energy usage, scalability to many nodes, robust coverage, and affordable cost.

4. CHALLENGES IN LPWAN PROTOCOLS FOR SMART CITIES

LPWAN technologies such as LoRaWAN and NB-IoT are very suitable for smart city connectivity, but when these networks are deployed at large scale across dense urban regions, several practical challenges appear. These challenges are not always visible in small pilot deployments but become serious when **thousands of devices** try to communicate over the same infrastructure. Understanding these limitations is important before applying optimization techniques.

4.1 Scalability

Scalability is one of the biggest issues in LPWAN based smart city deployments. A city may contain:

- Thousands of smart meters
- Street light controllers on every road
- Environmental sensors in every zone
- Parking sensors across markets and buildings

When such a large number of nodes try to transmit data, **network congestion** occurs.

Problem in LoRaWAN (ALOHA Access)

LoRaWAN uses an **ALOHA-based random access method**, meaning devices transmit whenever they have data without checking if the channel is free. As device density increases:

- Probability of packet collision increases
- Retransmissions increase network traffic further
- Packet delivery ratio (PDR) decreases

This effect becomes severe when many nodes use the same Spreading Factor (SF), causing overlapping transmissions.

Problem in NB-IoT

Although NB-IoT uses scheduled access, scalability issues can still arise due to:

- Limited number of resource blocks
- Heavy signaling overhead in crowded cells
- Increased latency when many devices request access simultaneously

Thus, both technologies face scalability issues but in different ways.

4.2 Energy Efficiency

LPWAN is designed for low power, but real deployments often reduce expected battery life.

Causes of High Energy Consumption

1. **Frequent retransmissions** due to packet loss or collision
2. **Improper selection of Spreading Factor (LoRaWAN)** leading to long airtime
3. **Poor signal quality** forcing devices to transmit at higher power
4. **Improper sleep scheduling** where device wakes up more often than needed
5. **Listening for downlink messages** in Class B and C devices (LoRaWAN)

In NB-IoT, devices may consume extra power during:

- Network attachment procedures
- Idle listening if PSM/eDRX is not configured properly

As a result, devices that are expected to last 10 years may only last 3–4 years in poor configurations.

4.3 Interference and Spectrum Usage

LoRaWAN and Unlicensed Band Issues

LoRaWAN operates in unlicensed ISM bands, which are shared by:

- Wi-Fi devices
- Bluetooth devices

- RF remotes
- Other LoRa networks

This creates:

- Cross-technology interference
- Increased noise floor
- Packet corruption and loss

Also, duty cycle regulations (e.g., 1% duty cycle in many regions) limit how often a device can transmit, restricting scalability.

NB-IoT and Licensed Band Trade-off

NB-IoT avoids interference by operating in licensed spectrum, but:

- It depends on telecom operators
- Network congestion may occur if cellular network is busy
- Usage involves subscription and operational costs

So, while interference is less, dependency and cost increase.

4.4 Quality of Service (QoS)

Smart city applications have varied QoS demands, but LPWAN protocols were originally designed for **best-effort communication**, not strict guarantees.

Issues in LoRaWAN

- No guarantee that a packet will reach gateway
- Downlink messages are limited and delayed (especially Class A)
- Acknowledgments increase traffic and energy use

This is problematic for applications like:

- Fire detection systems
- Gas leakage alerts
- Traffic control signals

Issues in NB-IoT

NB-IoT provides better QoS, but:

- Latency may increase due to network scheduling
- Not all traffic can be given highest priority
- Heavy load on cellular tower affects performance

Thus, maintaining QoS for critical smart city services is still a challenge.

4.5 Network Capacity and Throughput

LPWAN technologies are designed for **low data rate communication**. However, when many devices send data together, capacity limits appear.

LoRaWAN Limitations

- Long airtime for high SF reduces channel availability
- Duty cycle restrictions limit transmissions
- Gateway can process limited simultaneous packets

As more nodes join, the effective throughput per node decreases.

NB-IoT Limitations

- Limited bandwidth (180 kHz)

- Resource blocks must be shared among devices
- Control signaling overhead consumes bandwidth

Therefore, efficient scheduling and data management is needed to prevent congestion.

5. PROTOCOL OPTIMIZATION TECHNIQUES

5.1 Adaptive Data Rate (ADR)

ADR is a key optimization technique in LoRaWAN. It adjusts spreading factors and transmission power based on link quality. Devices close to gateways can use lower SF (higher data rate) reducing airtime and energy.

Algorithm schematic:

ADR reduces network load and improves energy efficiency.

5.2 Power Control

Dynamic power control ensures that devices transmit at the minimum power required to maintain acceptable link quality. Lower power reduces interference and saves battery.

5.3 Scheduling and Access Control

Instead of random access, scheduled access or listen-before-talk (LBT) methods

reduce collision probability especially in dense deployments.

Table 2:

Method	Benefits	Limitations
Pure ALOHA	Simple	High collisions
Slotted ALOHA	Better throughput	Requires sync
LBT	Reduces collisions	Adds complexity

5.4 NB-IoT Resource Allocation

In NB-IoT, resource allocation optimization can involve intelligent scheduling by the base station to prioritize traffic with strict QoS requirements.

Techniques include:

- Group-based scheduling
- Priority queueing for emergency alert packets
- Predictive resource reservation

6. HYBRID OPTIMIZATION FRAMEWORK

A promising strategy for smart cities is a hybrid approach where both LoRaWAN and NB-IoT are used based on specific application needs. For example:

- **LoRaWAN** for low-frequency, low-priority sensing (e.g., environmental monitoring)
- **NB-IoT** for latency sensitive or critical notifications (e.g., public safety)

A decision engine at the network server can assign traffic to appropriate network.

Figure 1: Protocol Selection Flow (text diagram)

7. CASE STUDIES AND REAL DEPLOYMENTS

Several cities and organizations have begun implementing LPWAN networks:

- **Air quality monitoring:** LoRaWAN sensors deployed to measure PM2.5 and ozone across urban areas.
- **Smart parking:** NB-IoT modules used for reliable updates on parking space availability.
- **Water meter reading:** LoRaWAN based automatic meter reading saving manual labor.

These deployments show benefits in cost reduction and operational visibility but also reveal limitations when optimization techniques are absent.

8. PERFORMANCE EVALUATION METRICS

To assess optimization effectiveness, common metrics include:

- **Packet Delivery Ratio (PDR)**
- **Energy Consumption per Node**
- **Network Throughput**
- **Latency Distribution**
- **Collision Rate**

Evaluations in literature show that ADR with proper scheduling significantly increases PDR and reduces energy use compared to baseline configurations.

9. OPEN RESEARCH CHALLENGES

Even with optimization, some challenges remain:

1. **Security** – LPWAN often lacks strong encryption by default; lightweight security protocols are needed.
2. **Mobility Support** – LoRaWAN has limited support for devices moving across coverage areas.
3. **Interoperability** – Smart cities involve heterogeneous technologies; seamless interoperation is complex.
4. **Standardization of Optimization Strategies** – Many research proposals exist but industry standards for optimization are not mature.

10. FUTURE DIRECTIONS

Future research should focus on:

- **AI-driven resource management** for dynamic adaptation to traffic patterns.
- **Cross-layer optimization** combining physical and MAC layer improvements.
- **Integration with 5G IoT architectures** for better performance guarantees.
- **Energy harvesting methods** to further extend device lifetime.

11. CONCLUSION

LPWAN technologies such as LoRaWAN and NB-IoT are fundamental enablers for smart city connectivity due to their low power, long range, and cost-effectiveness. However, without proper protocol optimizations, these networks struggle with scalability, energy efficiency, and quality of service in dense urban environments. This paper reviewed various optimization techniques, including adaptive data rate, power control, scheduling, and hybrid deployment frameworks, showing how they improve smart city outcomes. A hybrid approach that leverages the best features of LoRaWAN and NB-IoT could provide flexibility and performance suitable for diverse smart city applications. Still, challenges in security, mobility, and interoperability must be addressed.

Continuous research and practical deployments will steer LPWAN toward realizing its full potential for future urban connectivity.

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