

Experimental Evaluation of LoRa Link Performance for Indoor Monitoring Environments

Bruno F. Salussolia, Vitória J. Baratella, Caio T. B. Costa and Danilo H. Spadoti

Abstract—This paper presents the design and experimental evaluation of a low-cost Long Range (LoRa)-based temperature monitoring system deployed in an operational indoor environment. Each node consists of a waterproof enclosure coupled to an NTC 10 k Ω sensor, transmitting readings every 10 minutes with a 2-year battery lifetime. LoRa link performance was evaluated in a 444 m² sales floor with two gateways and seven nodes across heterogeneous refrigerated installations, covering distances from 6.60 m to 30.4 m under Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions. The results show that all nodes achieved a combined Packet Delivery Rate (PDR) of at least 96.9% during the seven-day campaign, exceeding the 90% reliability threshold; Received Signal Strength Indicator (RSSI) values ranged from -120 dBm to -81 dBm, while Signal-to-Noise Ratio (SNR) varied from -7.0 dB to 9.3 dB, offering practical deployment guidelines for Internet of Things (IoT) monitoring in indoor environments.

Keywords—LoRa, temperature monitoring, indoor propagation, Internet of Things, supermarket.

I. INTRODUCTION

Maintaining adequate temperature control in monitored environments is essential for ensuring operational reliability, product quality, and process safety across a wide range of industrial and commercial applications. Data from the Food and Agriculture Organization of the United Nations (FAO) shows that approximately 526 million tonnes of food are lost or wasted annually due to insufficient refrigeration, which represents nearly 12% of the global food supply [1]. At the national level, the National Health Surveillance Agency (ANVISA) establishes strict guidelines for temperature control in food storage and retail, which requires continuous monitoring in order to prevent microbial growth and ensure consumer safety [2]. Even though these regulations exist, many commercial operation facilities still rely on manual temperature inspections, which are susceptible to human error, lack temporal resolution, and are incapable of providing real-time alerts in the event of equipment malfunction.

The Internet of Things (IoT) has emerged as a promising solution for automated temperature monitoring, offering low cost, reduced power consumption, scalability, and remote data access [3]. Among the available wireless technologies, Long Range (LoRa) modulation stands out for its long communication range, extended battery life, and operation in license-free sub-GHz ISM bands (915 MHz in Brazil) [4]. Its Chirp

Spread Spectrum (CSS) modulation provides inherent robustness against narrowband interference and multipath fading, making it suitable for challenging propagation environments.

Several studies have explored the use of IoT for temperature monitoring in refrigerated environments. Ramírez-Faz et al. [5] proposed a Wi-Fi-based system for retail refrigerated cabinets, demonstrating the feasibility of low-cost solutions, though Wi-Fi's limited range and higher power consumption hinder large-scale deployments. For LoRa in indoor scenarios, Liang et al. [6] showed that wall materials and floor separation significantly affect Received Signal Strength Indicator (RSSI) and packet delivery, while Ferreira et al. [7] reported that electromagnetic emissions in industrial facilities cause packet loss. Horák et al. [8] analyzed the impact of spreading factor, transmit power, and physical obstacles on signal quality, and Baratella [9] investigated LoRaWAN performance under high device density, highlighting that structural complexity and density impose specific constraints on link reliability.

Despite these contributions, the propagation characteristics of commercial indoor environments remain insufficiently explored. Such scenarios constitute hostile propagation environments characterized by a high density of metallic structures, including refrigeration cabinets and shelving systems, significant electromagnetic interference generated by multiple compressor units operating simultaneously, and highly dynamic conditions resulting from the continuous movement of people and goods. Existing studies either address different deployment scenarios or provide only limited assessments of these combined effects [5], [6], [7], [8], [9], leaving important open questions for the design and deployment of reliable monitoring systems.

In this paper, we present the development and experimental evaluation of a custom LoRa-based temperature monitoring system deployed in a real supermarket environment. The main contributions of this work are: (i) the design and implementation of low-cost sensor nodes for continuous temperature monitoring of refrigerated cabinets; (ii) a comprehensive analysis of LoRa link performance, including RSSI, Signal-to-Noise Ratio (SNR), and Packet Delivery Rate (PDR), under the challenging propagation conditions of a supermarket; and (iii) practical insights and recommendations for the deployment of LoRa-based monitoring systems in similar environments.

II. DESIGN REQUIREMENTS

The proposed monitoring system was developed to satisfy multiple technical requirements that must be carefully balanced to ensure reliable and efficient operation. The device

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must operate continuously inside refrigerated environments, which imposes constraints on physical durability, power consumption, and wireless communication performance. Balancing these constraints requires careful engineering trade-offs, as optimizing one parameter frequently compromises another.

The primary requirement is transmission reliability, motivated by both food safety considerations and regulatory obligations. ANVISA establishes requirements for temperature control in food storage and retail environments to prevent microbial growth and ensure consumer safety [2]. Beyond regulatory compliance, a system with verifiable transmission logs can serve as an auditable data source for sanitary inspections, demonstrating adherence to thermal control standards.

The device must transmit temperature readings at intervals of at most 10 minutes. This value was chosen to balance the monitoring temporal resolution against energy efficiency; if a single packet is lost, the resulting gap of up to 20 minutes remains within acceptable limits for food safety in the vast majority of commercial refrigerator types and food products [2]. Shorter intervals would improve temporal resolution but reduce battery lifetime, while longer intervals would compromise the system's ability to detect temperature variations in a timely manner. Additionally, a 10-minute period provides sufficient data points to construct a representative temperature curve for compliance analysis.

Since the sensor must be placed inside the refrigerated environment to accurately measure cabinet temperature, the hardware must withstand average temperatures as low as -25°C . External installation is generally impractical, as the device would be exposed to physical interference from store personnel, and routing the sensor through the cabinet's thermal insulation would require a structural penetration not permitted on most commercial display units. As a direct consequence of internal placement, the hardware enclosure must also be fully waterproof, since refrigerators undergo periodic defrost cycles and are subject to condensation, which can cause moisture accumulation on internal surfaces. To further minimize interventions, the device must be compact, small enough to be installed behind shelving grids, kept away from product placement areas, and unobtrusive.

The combination of waterproofing requirements and the need for low-maintenance operation makes frequent battery replacement impractical. The system is therefore designed to operate for a minimum of 24 months powered by two AAA batteries in series, reducing maintenance overhead and avoiding repeated opening of the sealed enclosure. The 24-month autonomy requirement imposes a strict power budget, the two AAA alkaline batteries connected in series provide a nominal 3V pack voltage, while retaining a nominal charge capacity of $C_{\text{AAA}} = 1200\text{mAh}$; however, at low operating temperatures, battery capacity is reduced by a conservative derating factor $\eta_T = 0.70$ adopted based on manufacturer data for alkaline cells operating near 0°C [10]. This results in an effective total charge of:

$$C_{\text{eff}} = C_{\text{AAA}} \cdot \eta_T = 840\text{mAh} \quad (1)$$

The device operates on a periodic sleep-wake schedule:

every $T = 600\text{ s}$, it wakes from deep sleep, does the startup routine and data acquisition during 420ms , transmits a LoRa packet during 46.33ms , and returns to sleep. Current and duration per phase were measured with a bench multimeter and cross-checked against datasheets. The resulting average current consumption is:

$$\bar{I} = \frac{I_{\text{startup}}t_{\text{startup}} + I_{\text{tx}}t_{\text{tx}} + I_{\text{sleep}}(T - t_{\text{startup}} - t_{\text{tx}})}{T}, \quad (2)$$

where $I_{\text{startup}} = 35\text{mA}$, $t_{\text{startup}} = 420\text{ms}$, $I_{\text{tx}} = 155\text{mA}$, $t_{\text{tx}} = 46.33\text{ms}$ and $I_{\text{sleep}} = 400\text{nA}$, which yields $\bar{I} = 36.87\mu\text{A}$. The expected battery lifetime in months is then:

$$t_{\text{life}} = \frac{C_{\text{eff}}}{\bar{I} \cdot 730} \approx 31.2, \quad (3)$$

where 730 h is the average number of hours per month. This estimate exceeds the 24-month design requirement, providing a margin to account for battery aging, temperature-dependent capacity loss, leakage currents and real-world operating variations.

Finally, the temperature sensing element consists of an external NTC 10 k Ω thermistor connected to the main enclosure via a flexible wire. This configuration decouples the electronics from the measurement point, allowing the enclosure to be positioned in the most convenient or sheltered location, while the sensor tip is placed precisely at the desired measurement point within the refrigerated space. The selected thermistors carry a manufacturer-rated $\pm 0.5^{\circ}\text{C}$ accuracy, preserved through the multi-point Steinhart-Hart calibration described in Section III-A, ensuring the integrity of the temperature data and the system's ability to meet food safety and regulatory requirements.

All the requirements mentioned above, summarized in Table I, must be satisfied while relying exclusively on commercially available off-the-shelf components at accessible cost. This approach ensures the economic viability and scalability of the proposed solution, avoiding dependence on custom-designed or specialized hardware.

TABLE I

SUMMARY OF DESIGN REQUIREMENTS

Requirement	Specification	Rationale
Transmission reliability	High PDR	Food safety; ANVISA compliance
Sampling interval	$\leq 10\text{ min}$	Timely anomaly detection
Operating temperature	Down to -25°C	Internal refrigerator placement
Waterproofing	Sealed enclosure	Condensation and defrost cycles
Battery lifetime	$\geq 24\text{ months}$ ($2 \times \text{AAA}$)	Low-maintenance operation
Form factor	Compact	Unobtrusive installation
Temperature sensor	External NTC 10 k Ω , calibrated	Accurate and flexible placement

III. DEVICE ASSEMBLY

A. Component Selection

Following the design requirements described in Section II, the sensor node architecture was built around three principal

integrated circuits: an STM32F103C8T6 microcontroller, a HopeRF RFM95W LoRa transceiver module, and a PCF8563T real-time clock. Together with an AO3401A P-channel MOSFET for power gating, these components form a system capable of sustained autonomous operation within the power and environmental constraints established beforehand.

The STM32F103C8T6 serves as the central processing unit, providing a 72MHz ARM Cortex-M3 core with 64 KB of flash and 20 KB of SRAM in an LQFP-48 package. Its peripheral set includes the SPI interface required for communication with the LoRa transceiver (MOSI, MISO, CLK, CS), an I2C bus shared with the RTC (SDA, SCL), multiple ADC channels for thermistor readout, and an SWD port for firmware programming and debugging. Crucially, its 2.0-3.6V operating range matches the voltage supplied by two series-connected AAA cells, eliminating the need for a dedicated voltage regulator and the associated quiescent current penalty.

The LoRa radio function is provided by the pre-certified HopeRF RFM95W transceiver module, which incorporates the Semtech SX1276 chipset along with the RF matching network and reference oscillator in a single SMD package. By integrating these elements at the module level, the design avoids the complexity and tuning effort of a discrete RF front-end while still achieving a receiver sensitivity of -148dBm at SF12 and a maximum transmit power of +20 dBm in the 915MHz ISM band.

Accurate scheduling of the 10-minute transmission cycle is delegated to a PCF8563T RTC in an SOIC-8 package, driven by an external 32.768kHz crystal. Rather than relying on the microcontroller's internal timers (which would require the MCU to remain at least partially active) the PCF8563T operates independently and asserts a hardware interrupt at each programmed interval. This interrupt triggers the power-up sequence described below, allowing the microcontroller and transceiver to be completely de-energized between cycles.

The power gating mechanism employs an AO3401A P-channel MOSFET (SOT-23) configured as a high-side switch on the main supply rail. When the RTC interrupt fires, the MOSFET is turned on, energizing the microcontroller. After completing the sensor acquisition and packet transmission, the firmware drives the gate control line to shut off the MOSFET, disconnecting its own supply. This self-latching topology reduces the inter-cycle current to the RTC's standby consumption plus the MOSFET's leakage, which is orders of magnitude below the deep-sleep current of the microcontroller alone.

Temperature measurement relies on an external NTC 10 k Ω thermistor with a flexible lead. A fixed 10 k Ω resistor forms a voltage divider whose midpoint is sampled by one of the STM32's ADC channels; the resulting digital value is converted to temperature through the Steinhart-Hart equation using coefficients obtained from a multi-point calibration.

Power is supplied by two AAA alkaline batteries seated in surface-mount holders whose soldered terminals ensure a reliable contact even under the thermal cycling inherent to refrigerated environments. A 915MHz spring antenna, soldered directly to the board, completes the RF chain with a form factor compact enough to fit inside the sealed enclosure.

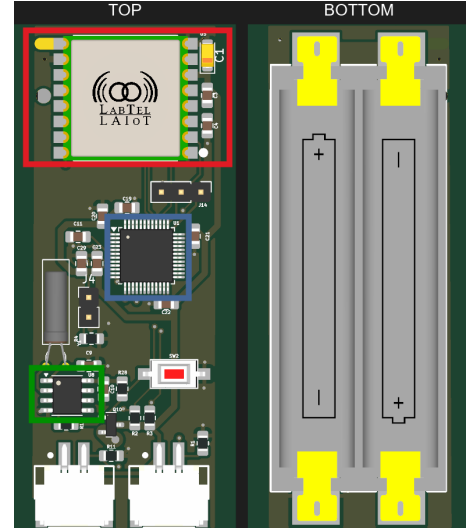


Fig. 1. PCB 3D render with main ICs highlighted. Blue box is the STM32F103C8T6 microcontroller; red box is the HopeRF RFM95W LoRa transceiver module; green box is the PCF8563T real-time clock.

B. PCB Design

The board was laid out in KiCad on a two-layer copper stackup with a standard 1.6mm FR-4 substrate. The resulting 28.5 mm x 64.9 mm rectangular outline was dimensioned to fit within the internal cavity of the AK-W-48 enclosure alongside the battery holders, without interfering with the cable gland or lid seal. Figure 1 shows a 3D render of the finished PCB, with the RFM95W, STM32F103C8T6 and PCF8563T highlighted in red, blue and green, respectively. The proposed layout balances space efficiency with accessibility for manual assembly, while keeping the RF traces properly isolated.

Signal routing is concentrated on the front layer, which carries the SPI bus to the SX1276, the I2C bus to the PCF8563T, the NTC analog traces, and the power-switching network around the AO3401A. The back layer is devoted almost entirely to a continuous ground plane, providing both a low-impedance return path for digital signals and a reference plane for the 50 Ω microstrip trace that connects the LoRa module's antenna output to the spring antenna pad. Via stitching between the front and back grounds maintains equipotential grounding across the board and reduces the risk of ground-bounce-induced noise on the ADC readings.

All discrete passives (which includes decoupling capacitors, pull-up resistors and the NTC divider network) use 0805 (2012 metric) footprints with enlarged pads for hand soldering, since the prototypes were assembled manually. Bulk energy storage on the battery rail is handled by a 100 μ F tantalum capacitor (EIA-3216-18, Kemet A case), while 100 nF ceramic capacitors placed immediately adjacent to each IC's supply pins provide high-frequency decoupling. A three-pin programming header at the board edge exposes the SWD lines (SWDIO and SWDCLK) for firmware upload and in-circuit debugging during development.

C. Physical Assembly

Assembly begins with the fully populated PCB: all components are soldered in place, the AAA batteries are inserted

into their holders, and the firmware is uploaded to the STM32 through the SWD programming header using an external debugger probe. Then, the board is placed inside the enclosure. The NTC thermistor lead is threaded through a sealed cable gland in the wall of the AK-W-48 enclosure and terminated at one of the PCB headers. This arrangement decouples the sensor from the electronics, so the enclosure can be positioned wherever mechanical access is most convenient, while the sensor tip reaches the actual measurement point inside the refrigerated cabinet.

Once the device is secured into the enclosure, the push button is pressed to start the device operation. Then, the whole setup is sealed to provide the waterproof protection required against condensation accumulation and defrost-cycle moisture, and the cover is screwed down, completing the assembly process. The finished node has no external interface other than the protruding NTC cable.

IV. TEST METHODOLOGY

The experiments were conducted in the operational sales floor of a supermarket in Brazil, covering approximately 444 m². The environment includes a variety of refrigerated installations (walk-in cold chambers, beverage coolers, open refrigerated produce displays, refrigerated counters, low refrigerated islands, and food preparation rooms) creating heterogeneous propagation conditions characterized by dense metallic structures and electromagnetic interference from multiple simultaneous compressor units. Seven sensor nodes (N1–N7) were installed across these different refrigerated environments, as detailed in Table II.

Figure 2 illustrates the floor plan of the test area with the positions of all devices used in the project. The system follows a star point-to-point topology in which each sensor node, shown by blue circles, transmits LoRa frames directly to two fixed gateway receivers G1 and G2, represented by gray diamond shapes. G1 and G2 were positioned based on existing power and Ethernet infrastructure, mounted at ≈ 2.5 m height with 915 MHz, 3 dBi antennas. Distances to each gateway range from 6.6 m to 30.4 m, encompassing both line-of-sight (LoS) and non-line-of-sight (NLoS) conditions, exemplified on Figure 2 as green and red lines, respectively. NLoS obstructions include open refrigerated displays/beverage coolers and low islands (N2, N3, N6, N7), solid walls combined with cold chamber enclosures (N1), and solid walls combined with food preparation room walls (N4, N5).

TABLE II
SENSOR NODE DEPLOYMENT

Node	Environment	G1		G2	
		d (m)	Link	d (m)	Link
N1	Cold chamber	12.23	NLoS	30.38	NLoS
N2	Bev. cooler	6.64	LoS	17.47	NLoS
N3	Produce display	24.79	NLoS	11.56	LoS
N4	Prep room	8.09	LoS	25.20	NLoS
N5	Prep room	6.59	NLoS	27.41	NLoS
N6	Refrig. counter	19.28	NLoS	19.80	LoS
N7	Refrig. island	14.27	NLoS	14.59	LoS

All nodes were configured with identical LoRa radio parameters, as listed in Table III. SF7 was selected to maximize

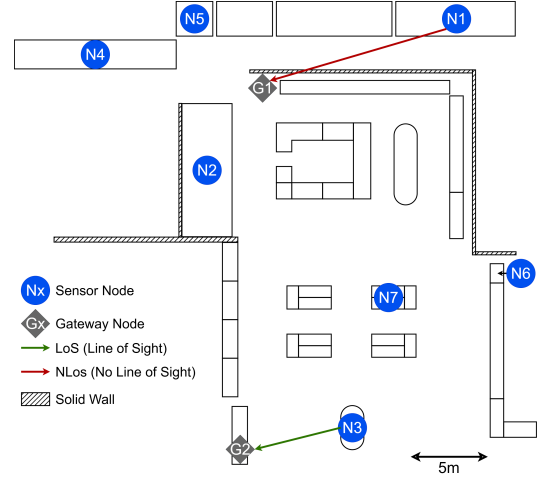


Fig. 2. Supermarket floor plan with gateway (G1, G2) and sensor node (N1–N7) positions.

the symbol rate, and the transmit power was set to 20 dBm, the maximum output power of the SX1276 transceiver [11].

TABLE III
LoRa CONFIGURATION PARAMETERS

Parameter	Value
Frequency	916 MHz
Spreading Factor	SF7
Bandwidth	125 kHz
Coding Rate	4/5
TX Power	20 dBm

Data collection ran continuously for one week under normal supermarket operating conditions, with customers and staff present throughout the measurement period, introducing mobility-induced channel variation. Each node transmitted one packet every 10 minutes, yielding a maximum of 1,008 packets per node and 7,056 total transmissions. Each packet was independently logged by both gateways, providing up to 14,112 reception events for analysis. Gateways also feed a backend dashboard with automated out-of-range alarms, outside this study's scope.

The evaluated metrics are RSSI, SNR, and Packet Delivery Rate (PDR), defined as the ratio of successfully received packets to the expected total. Link quality was classified into three levels: strong (RSSI > -90 dBm, SNR > 10 dB), moderate (RSSI between -90 and -120 dBm, SNR between 0 and 10 dB), and poor (RSSI < -120 dBm, SNR < 0 dB). These boundaries reflect the authors' experience from previous LoRa deployment projects, in which the given RSSI and SNR ranges were empirically associated with strong, moderate, and poor link quality. Notably, this boundary (SNR < 0 dB) stays above the SX1276's SF7/125 kHz demodulation floor (≈ -7.5 dB SNR) [11], a conservative margin against fading. The 90% PDR threshold follows the 10-minute sampling interval (Section II): an isolated loss yields at most a 20-minute gap, still within ANVISA limits [2].

V. RESULTS

Table IV summarizes the RSSI, SNR, and PDR measured for each node–gateway link over the seven-day campaign. The combined PDR column reports the fraction of intervals in which at least one gateway received the packet.

TABLE IV
LINK PERFORMANCE PER NODE AND GATEWAY

Node	GW	d (m)	Link	PDR (%)	RSSI (dBm)	SNR (dB)	Comb. (%)
N1	G1	12.2	NLoS	96.5	-83	9.3	97.5
	G2	30.4	NLoS	75.1	-119	-1.2	
N2	G1	6.6	LoS	97.1	-102	7.5	97.6
	G2	17.5	NLoS	54.1	-120	-5.9	
N3	G1	24.8	NLoS	95.3	-92	8.7	97.4
	G2	11.6	LoS	95.3	-81	9.2	
N4	G1	8.1	LoS	96.9	-105	5.2	96.9
	G2	25.2	NLoS	0.1	-120	-7.0	
N5	G1	6.6	NLoS	97.5	-81	9.1	98.8
	G2	27.4	NLoS	88.8	-120	-3.5	
N6	G1	19.3	NLoS	97.2	-105	5.8	99.5
	G2	19.8	LoS	97.8	-105	8.3	
N7	G1	14.3	NLoS	95.8	-91	9.1	97.9
	G2	14.6	LoS	96.0	-109	7.2	

All seven nodes achieved a combined PDR of at least 96.9%, exceeding the 90% threshold. G1 maintained a PDR above 95% for every node, whereas G2 experienced severe degradation on several obstructed links. N4→G2 received only 1 packet (0.1%), N2→G2 reached 54.1%, and N1→G2 reached 75.1%, all with RSSI values near -120 dBm and negative SNR. If only G2 were available, N1, N2, N4, and N5 would fall below the acceptable threshold. The dual-gateway configuration therefore mitigated gateway-specific coverage gaps and ensured that the combined PDR remained above the threshold in this single-layout deployment; generalization to other floor plans warrants further validation.

Mean RSSI ranged from -81 dBm (N5→G1) to -120 dBm (N2→G2), and mean SNR from 9.3 dB (N1→G1) to -7.0 dB (N4→G2), with most receptions in the moderate quality tier. Notably, the LoS/NLoS classification alone did not predict link quality: N5→G1 (NLoS, 6.6 m) achieved the best RSSI, while N4→G1 (LoS, 8.1 m) measured only -105 dBm due to attenuation from the preparation room enclosure. This indicates that obstacle composition and distance are stronger predictors than visual line of sight.

VI. COST ANALYSIS

Beyond the requirements of Section II, a key design goal was low cost, enabling affordable large-scale deployment across multiple refrigerated cabinets. Despite the constraints imposed by waterproofing, low-temperature operation, and long battery life, the total bill of materials (BOM) for a single unit amounts to approximately R\$ 120.00, encompassing all electronic components, the mechanical enclosure, and accessories. This cost-effectiveness is achieved through the exclusive use of commercially available, off-the-shelf parts. Table V presents the itemized BOM; "Populated Sensor PCB" already includes the bare board, ICs, and passives from Section III-A.

VII. CONCLUSION

This paper presented the design and experimental evaluation of a low-cost LoRa-based temperature monitoring system in an operational supermarket. All seven nodes achieved combined PDR of at least 96.9% over a one-week campaign, confirming reliable coverage at 915 MHz with SF7 across a 444 m² sales

TABLE V
BILL OF MATERIALS — UNIT COST PER DEVICE

Component	Qty	Cost (R\$)
Populated Sensor PCB	1	76.63
Waterproof Enclosure (AK-W-48)	1	15.95
AAA Alkaline Battery	2	7.54
915 MHz Spring Antenna	1	5.10
NTC 10 kΩ Sensor (2 m)	1	5.06
PCB Battery Holder	1	9.60
Total		119.88

floor despite dense metallic structures and electromagnetic interference.

Per-gateway analysis showed that individual links can degrade to near-zero PDR when traversing concrete walls at distances above 25 m, indicating that dual-gateway redundancy substantially improves reliability in this deployment. The results also indicate that obstacle composition and distance are more relevant predictors of link quality than the LoS/NLoS classification. At R\$ 120 per unit, the device meets all requirements for large-scale deployment under ANVISA regulations.

These findings are bounded by a single seven-day campaign in one supermarket layout with fixed radio parameters (Table III) and no seasonal coverage; reported RSSI, SNR, and PDR values are tied to this deployment's structure and traffic pattern, though the sensor design and methodology remain transferable to other layouts. Future work includes adaptive spreading factor selection and validation across additional layouts and seasons.

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