Redundant Node Deployment for ACK-Free LoRa Networks: A Quantitative Framework for SNR-Driven Redundancy Planning

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***Abstract*— Reliable communication in acknowledgment-free (ACK-free) LoRa networks is challenging since retransmissions are unavailable to recover from packet losses. This paper presents a quantitative framework for determining the minimum number of redundant LoRa nodes required to meet a target packet delivery probability under specified SNR conditions. The approach integrates an analytical Frame Error Rate (FER) model with a spatial SNR mapping derived from a log-distance path loss model. Results show that redundancy is primarily beneficial within a narrow SNR transition region, whereas under very low SNR conditions, even large numbers of redundant nodes become impractical. The framework provides deployment guidelines for ACK-free LoRa networks, establishing a direct mapping between channel conditions and redundancy requirements.**

Keywords—Acknowledgment-free communication, frame error rate, LoRa, low-power wide-area networks, redundant node deployment.

I. INTRODUCTION

The expansion of the Internet of Things (IoT) has driven the adoption of Low-Power Wide-Area Networks (LPWAN) technologies. Among these, LoRa has gained popularity due to its long communication range, low energy consumption, and relatively low deployment cost [1]. Despite these advantages, reliable packet delivery remains challenging in real scenarios where signal conditions can be highly variable. Furthermore, many LoRa applications operate without acknowledgment (ACK) mechanisms to reduce energy consumption, avoid downlink congestion, or support broadcast transmissions. In these ACK-free scenarios, packet losses cannot be compensated by retransmissions. A promising alternative to improve reliability without ACKs is to deploy multiple redundant nodes that transmit identical information. However, determining how many redundant transmitters are required to meet a target reliability level under realistic channel conditions has not been sufficiently addressed. This work addresses the following research question: *Given a known channel condition characterized by SNR and a target packet success probability, what is the minimum number of redundant LoRa nodes required to achieve communication reliably?*

The main contributions are: (i) an analytical relationship between FER and required redundancy in ACK-free LoRa networks; (ii) integration of FER analysis with spatial SNR mapping enabling geographic deployment evaluation; (iii) sensitivity assessment under an illustrative receiver-impairment scenario; and (iv) practical deployment guidelines including zone-based recommendations.

II. THEORETICAL BACKGROUND

A. LoRa Physical Layer

LoRa communication is based on chirp spread spectrum (CSS) modulation. The most influential physical-layer parameter is the Spreading Factor (SF), which determines the number of chips per transmitted symbol as $N = 2^{SF}$. Increasing SF improves receiver sensitivity at the expense of reduced data rate and increased time-on-air.

B. Frame Error Rate Model

The analytical model in [1] links Symbol Error Rate (SER) to SNR. Let $\gamma = 10^{\mathrm{SNR_{dB}}/10}$ denote linear SNR. The symbol error probability is:

$$P_s \approx Q\left(\frac{\sqrt{\gamma N} - A}{D}\right)$$

where $N = 2^{SF}$ and $Q(\cdot)$ is the Gaussian Q-function. Using Gray mapping, Bit Error Probability is $P_b = \frac{1}{2}P_s$. With Hamming (7,4) coding, Codeword Error Probability is:

$$P_{cw} = 1 - (1 - P_b)^7 - 7P_b(1 - P_b)^6$$

For a frame of N_{cw} codewords:

$$FER = 1 - (1 - P_{cw})^{N_{cw}}$$

Two approximations are considered for mapping the symbol error probability to the frame error rate [1]:

- Uniform approximation: Assumes that the bits associated with a detected LoRa symbol experience the same average error probability. This representation is mainly used in the high-error region.
- Hierarchical approximation: Accounts for the unequal protection of the bit positions associated with a LoRa symbol. This approximation is preferred in the low-error region, which is particularly relevant when determining whether a link satisfies a prescribed packet-delivery requirement.

C. Redundancy Model without ACK

. In ACK-free operation, reliability is provided by multiple transmitters reporting the same information. Under statistically independent and collision-free reception events, the probability that at least one of N replicas are successfully decoded is:

$$P_{\text{success}} = 1 - \prod_{i=1}^{N} FER_i$$

For a target packet-delivery probability P_{obj}, the minimum number of redundant transmitters under homogeneous conditions is:

$$N = \left\lceil \frac{\ln(1 - P_{\text{obj}})}{\ln(FER)} \right\rceil$$

D. Illustrative Receiver-Impairment Scenario

The analysis considers an illustrative receiver-impairment scenario represented by an equivalent SNR penalty:

$$\text{SNR}_{\text{eff,dB}} = \text{SNR}_{\text{dB}} - \Delta_{\text{imp}}(SF)$$

with $\Delta_{\text{imp}}(SF)$ taking values of 1.5 dB for SF $\in \{7,9,11\}$ and 2.0 dB for SF $\in \{8,10,12\}$.

III. PROPOSED FRAMEWORK

A. FER-SNR Characterization

The analytical FER model is evaluated for each SNR, SF, and payload configuration. The hybrid rule uses hierarchical estimation when FERh $\leq$ 0.1 and uniform estimation otherwise. Table I shows simulation parameters.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Spreading Factors	7–12
Coding Rate	CR = 4/7
Payload Size	20 bytes
Bandwidth	125 kHz
SNR Range	−23 to −8 dB
P_{obj} Values	0.90, 0.95, 0.99

B. System Model and Assumptions

The framework considers redundant LoRa transmitters reporting the same event to a single gateway with the following assumptions:

1. Redundant transmissions are separated in time or frequency (no collisions)
2. Frame reception events are statistically independent
3. Co-SF interference, capture effects, and external traffic are not modeled
4. Success occurs when at least one replica is correctly decoded

These assumptions provide an optimistic analytical benchmark.

C. Spatial SNR Model

A log-distance path loss model centered at the gateway location is used:

$$\text{SNR}_{\text{dB}}(d) = \text{SNR}_{0,\text{dB}} - 10n\log_{10}\left(1 + \frac{d}{d_0}\right)$$

where $\text{SNR}_{0,\text{dB}} = -5$ dB, $d_0 = 100$ m, and $n = 2.8$ (rural environment).

Fig. 1 presents the resulting spatial SNR map. The 2D map in Fig. 1(a) shows a gradual degradation of signal quality from the gateway center toward the cell edges, while Fig.1(b) illustrates the corresponding radial profile.

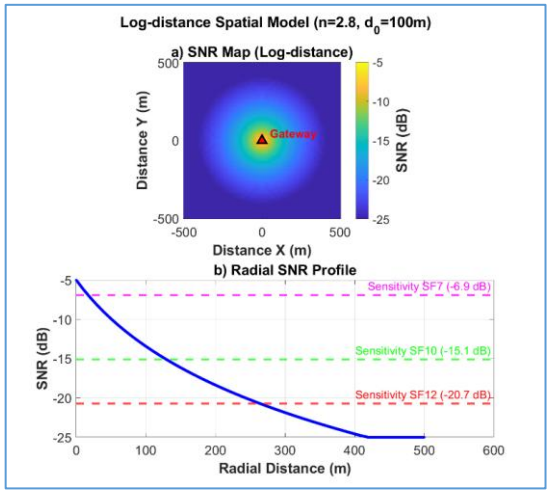


Figure 1. Spatial SNR map using the log-distance model: (a) 2D map, (b) radial profile

D. Redundancy Optimization

For each location, the framework evaluates all SFs and determines:

$$N(\text{SNR}, S, FP_{\text{obj}}) = \left\lceil \frac{\ln(1 - P_{\text{obj}})}{\ln(FER(\text{SNR}, SF))} \right\rceil$$

The optimal SF minimizes redundancy:

$$SF_{\text{opt}} = \arg\min_{SF} N(\text{SNR}, S, FP_{\text{obj}}).$$

This optimization finds the configuration that achieves the desired reliability using the smallest number of devices. It is important to note that this optimization minimizes node count but does not consider other important factors such as energy consumption, time-on-air, or duty-cycle constraints. These aspects are left for future work.

IV. PERFORMANCE AND EVALUATION.

This section presents the evaluation of the proposed redundancy-aware deployment framework. The results are organized to progressively validate the methodology: first at the physical layer through sensitivity analysis (including SF-dependent SNR penalties), then at the link level via redundancy estimation, and finally at the network level through spatial deployment recommendations. All results presented in this section include the effect of SF-dependent SNR penalties, unless otherwise stated.

A. Required SNR Thresholds

To characterize the FER-SNR relationship introduced in Section III, the required SNR threshold was determined for each spreading factor at FER = 0.01. This specific FER value is chosen because it represents a typical reliability target for many IoT applications, where a 99% packet success rate is often required. Operating at FER = 0.01 ensures that most transmitted frames are successfully decoded, which is particularly important in ACK-free scenarios where lost packets cannot be recovered through retransmissions.

Table II presents the thresholds obtained from the hybrid Hierarchical/Uniform model for both the baseline and illustrative impaired-receiver scenarios.

The obtained sensitivity values closely match theoretical LoRa references [7]. The cumulative gain from SF7 to SF12 is 13.5 dB, slightly below the theoretical 15 dB due to coding overhead and frame structure effects, as analyzed in [1]. The required SNR thresholds in the illustrative impaired-receiver scenario are shifted relative to the baseline by the assigned SF-dependent penalties of 1.5–2.0 dB. These results quantify how the assumed SNR degradation propagates to the FER thresholds.

TABLE II: REQUIRED SNR THRESHOLDS AT FER = 0.01

SF	Baseline (dB)	Impaired (dB)	Penalty
7	-8.5	-7.0	1.5 dB
8	-11.5	-9.5	2.0 dB
9	-14.0	-12.5	1.5 dB
10	-17.0	-15.0	2.0 dB
11	-19.5	-18.0	1.5 dB
12	-22.5	-20.5	2.0 dB

B. Required Redundant Nodes

Using the hybrid FER model described in Section II.B, the number of redundant nodes required to achieve a target success probability of $P_{obj} = 0.95$ was computed under the illustrative receiver-impairment scenario. The analysis was conducted across the entire SNR range of interest (-23 dB to -16 dB) and for all spreading factors SF7 through SF12, providing a comprehensive view of the redundancy requirements under various channel conditions.

Fig 2. illustrates how the required number of nodes varies with SNR for all spreading factors. The plot clearly shows the stair-step pattern of node requirements, with each SF exhibiting a sharp drop from high to low redundancy within a 2-3 dB window. For SNR values above -14 dB, SF8 through SF12 all achieve reliable communication with a single node. The stair-step pattern arises because the required number of nodes is an integer value determined by the ceiling function in the redundancy formula; each step corresponds to a range of SNR values where the same number of nodes is sufficient.

The results reveal several important insights. First, the transition from high to low redundancy occurs within a very narrow SNR window of approximately 3 dB for each SF. For instance, SF12 requires 100 nodes at −23 dB, drops to 10 nodes at −22 dB, and reaches a single node at −21 dB. Second, the table reveals the exact SNR thresholds where a single node becomes sufficient for each SF: SF12 at ≥ −21 dB, SF11 at ≥ −18 dB, SF10 at ≥ −15 dB, SF9 at ≥ −13 dB, SF8 at ≥ −10 dB, and SF7 at ≥ −8 dB. These thresholds follow a consistent pattern of approximately 3 dB per SF increment, which matches the theoretical processing gain of LoRa. Third, the data shows that redundancy is most beneficial in the marginal coverage region between the saturation point and the single-node threshold. For example, at SNR = −22 dB, deploying 10 SF12 nodes achieves 95% reliability, whereas a single node would be insufficient.

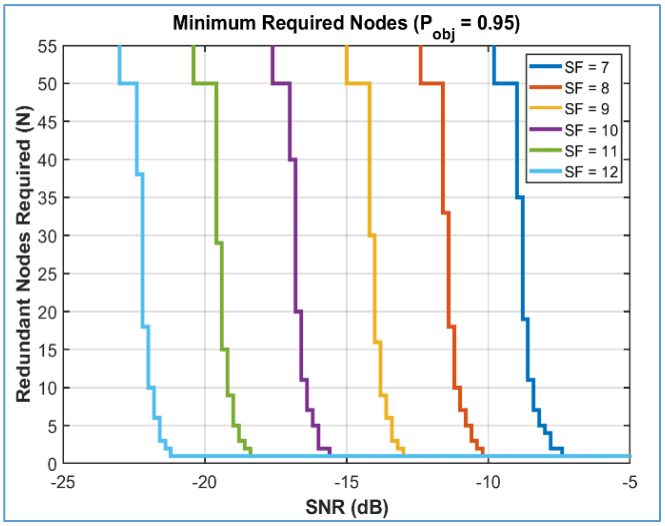


Figure 2. FER vs SNR curves for all spreading factors (with SF-dependent SNR penalties

C. Monte Carlo Consistency Check

Monte Carlo trials (100,000 per point) verify numerical implementation are shown in Table IV:

TABLE IV: MONTE CARLO CONSISTENCY CHECK

SF	**SNR**	**FER Analytical**	**FER MC**	**Error**
9	-16.5 dB	0.891	0.889	0.002
9	-13.5 dB	≈0	≈0	≈0
12	-22.5 dB	0.006	0.005	0.001
12	-19.5 dB	≈0	≈0	≈0

D. Spatial Deployment Maps

Using the log-distance path loss model with parameters $n = 2.8$ and $d_0 = 100$ m, which are representative of rural and suburban environments, the spatial distribution of the required redundant nodes and the optimal spreading factor selection were evaluated across a 1000×1000 m area. The SNR at each location was derived from the radial distance to the gateway using the log-distance model described in Section III.C, and the redundancy optimization was performed independently for each spatial point. This approach enables the generation of deployment maps that translate physical-layer channel conditions into practical node density and SF selection recommendations. Fig. 3 presents the minimum number of redundant nodes required at each spatial location. This map provides a comprehensive view of the network deployment requirements, allowing planners to visualize how redundancy needs and SF choices vary across the coverage area.

Three distinct zones emerge:

- Inner region (<250 m): single node sufficient
- Transition zone (250-300 m): 1-2 nodes needed
- Outer region (>300 m): >10 nodes required (repeaters recommended)

Optimal SF progression: SF8-9 (inner), SF10-11 (intermediate), SF12 (beyond 250 m).

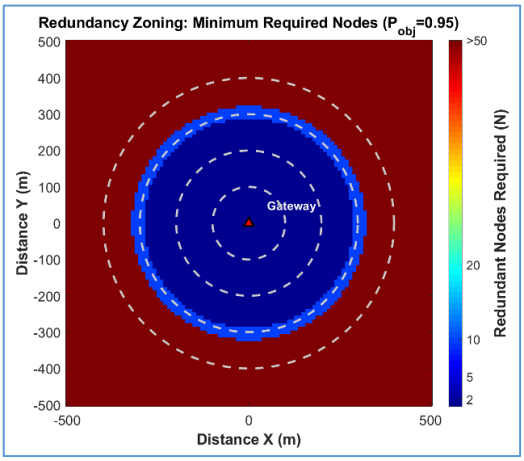


Fig. 3. (a) Minimum required redundant nodes, (b) Optimal SF for each spatial location ($P_{obj} = 0.95$)

E. Distance-Based Guidelines

Table V presents this relationship for practical deployment planning.

Using the log-distance path loss model the SNR at a given distance from the gateway can be mapped to the required number of redundant nodes.

TABLE V: DISTANCE-BASED REDUNDANCY GUIDELINES ($P_{OBJ} = 0.95$)

Distance (m)	SNR (dB)	Opt. SF	Nodes
0–100	> -13	SF8–SF9	1
100–150	-16 to -13	SF9–SF11	1
150–250	-20 to -16	SF11–SF12	1
250–300	-22 to -20	SF12	1–2
300–350	-23 to -22	SF12	10–50
> 350	< -23	SF12	>50

V. CONCLUSIONS

This paper presented an SNR-driven framework to estimate redundancy in ACK-free LoRa networks. Redundancy is most beneficial in the FER transition region. For SF12, ten transmitters increase packet delivery from ≈28% to 96% at −22 dB. Spatial analysis identifies a single-transmitter region up to ≈250 m, a transition region from 250–300 m, and rapidly increasing redundancy beyond 300 m. The model provides an optimistic benchmark under homogeneous, independent, collision-free receptions.

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