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Performance Evaluation and Range Analysis of LoRa-Based Communication for Smart Farming Applications

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Abstract
Long Range (LoRa) wireless communication is widely regarded as a promising physical layer for smart farming applications due to its long communication range and low power consumption. However, published range figures are frequently obtained under idealized or urban conditions and do not reliably predict performance in open agricultural terrain, where crop canopy, tree lines, and undulating topography introduce additional attenuation. This paper presents an empirical performance evaluation and range analysis of a LoRa-based communication link for smart farming, using a SX1276-based end node and gateway deployed across open-field and partially obstructed farmland over distances from 0 to 3000 m. Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), and Packet Delivery Ratio (PDR) were measured across three spreading factors (SF7, SF9, SF12) to characterize the range–reliability–data-rate trade-off relevant to field deployment. A log-distance path loss model was fitted to the measured RSSI data to enable range prediction for future deployments. Results show that SF12 sustains a packet delivery ratio above 90% up to approximately 1800 m in open-field conditions, compared to approximately 700 m for SF7, at the cost of significantly longer airtime and higher energy consumption per packet. Obstructed segments incorporating tree lines reduced the reliable range by 30–40% relative to open line-of-sight paths. These findings provide practical spreading-factor and gateway-placement guidance for designing energy-efficient, reliable LoRa-based sensor networks for real-world smart farming deployments.

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1. Introduction

Smart farming systems increasingly depend on distributed sensor networks that report soil, crop, and environmental data from across large field areas back to a central gateway. Unlike indoor or urban IoT deployments, agricultural fields are typically large, sparsely populated with infrastructure, and lack reliable Wi-Fi or cellular coverage, making the choice of wireless communication technology critical to system feasibility. Long Range (LoRa) modulation, and the LoRaWAN protocol built on top of it, has emerged as a leading candidate for such deployments because it offers multi-kilometer communication range at very low transmit power, using a chirp spread-spectrum technique that trades data rate for receiver sensitivity through a configurable spreading factor (SF).

Manufacturer datasheets and many published studies report LoRa ranges of 10–15 km under ideal line-of-sight conditions, which has led to an expectation that a single gateway can economically cover an entire farm. In practice, however, real farmland is rarely free of obstructions: crop canopy at different growth stages, tree lines along field boundaries, undulating terrain, and farm structures all introduce additional path loss that is not captured by free-space or urban propagation models. Consequently, system designers who rely on datasheet range figures risk under-provisioning gateway density, leading to unreliable data collection precisely where it is most operationally important, such as at the edges of large fields.

Beyond raw technical feasibility, the economics of gateway placement are directly tied to range reliability: because a single LoRa gateway can plausibly serve an entire farm only if its effective coverage radius, under real field conditions, actually spans the farm's dimensions, an overly optimistic range assumption at the design stage can lead to costly retrofits, such as adding a second gateway or relay node after a network is already partially deployed and found to have coverage gaps at field edges. Quantifying how far real farmland conditions depress achievable range relative to idealized figures is therefore not merely of academic interest but has a direct bearing on smart farming deployment cost and reliability.

This paper addresses this gap through a systematic, empirical performance evaluation and range analysis of a LoRa communication link under realistic farmland conditions. The specific contributions of this work are as follows:

- A field-measured characterization of RSSI, SNR, and packet delivery ratio versus distance for three representative spreading factors (SF7, SF9, SF12) across both open line-of-sight and obstructed farmland segments.
- A fitted log-distance path loss model, with derived path loss exponents for open and obstructed conditions, enabling range prediction for future gateway-placement decisions.
- A quantified analysis of the range–reliability–airtime–energy trade-off across spreading factors, translated into practical deployment guidance for smart farming network design.

The rest of this paper is structured like this: Section II reviews the literature on the evaluation of LoRa performance. Section III presents an overview of LoRa modulation parameters used in the present study. Section IV describes the experiment setup and how to conduct the experiments. Section V provides findings of distance and path loss evaluation. Section VI shows the results of an evaluation of the performance of the system. Section VII discusses implications for intelligent agriculture network design. Section VIII wraps up the paper.

2. Related Work

Early evaluations of LoRa range focused primarily on urban and suburban environments, reporting reliable communication ranges on the order of 2–5 km in the presence of buildings, with substantially longer ranges achievable in open rural terrain. These studies established the basic trade-off between spreading factor, range, and airtime that underlies LoRa system design, but their propagation conditions differ substantially from agricultural fields, where vegetation rather than buildings is the dominant attenuating factor.

Within the agricultural domain specifically, several works have reported LoRa-based sensor network deployments for irrigation monitoring, livestock tracking, and greenhouse automation. Many of these studies confirm the general feasibility of LoRa for farm-scale coverage but report range figures that vary widely, from several hundred meters to over 5 km, depending heavily on antenna height, crop type, and seasonal canopy density — factors that are often not explicitly controlled for or reported. This inconsistency in the literature makes it difficult for practitioners to translate published range figures directly into gateway-placement decisions for a new deployment site.

A smaller body of work has specifically investigated the impact of vegetation on LoRa propagation, modeling foliage attenuation using established vegetation path-loss models such as the ITU-R and Weissberger models, and confirming that seasonal leaf density can shift the effective communication range by a significant margin over the course of a growing season. These vegetation-aware models provide useful analytical grounding but are rarely validated against field-measured packet delivery ratio, which is the metric most directly relevant to application-layer reliability.

Separately, studies examining antenna height and gateway siting for LPWAN deployments in rural settings have consistently found that elevating the receiving antenna above surrounding obstructions yields disproportionately larger coverage gains than increasing transmit power or spreading factor alone, since raising antenna height directly reduces the fraction of the link path that intersects vegetation or terrain obstruction rather than merely compensating for the resulting attenuation with additional link margin. However, most such studies were conducted in general rural or semi-urban terrain rather than on active farmland, leaving open the specific question of how much range compression a typical field-boundary tree line introduces relative to an unobstructed line-of-sight path — the gap this paper's segmented open/obstructed test design is intended to close.

Comparative studies contrasting LoRa with alternative low-power wide-area technologies such as Sigfox and NB-IoT have generally found LoRa favorable for private, gateway-owned agricultural deployments due to its lower per-message cost and flexible duty-cycle control, though NB-IoT can offer wider carrier-grade coverage where cellular infrastructure already exists. Table I summarizes representative reported ranges from prior LoRa evaluation studies alongside the conditions under which they were obtained, motivating the present work's explicit separation of open and obstructed farmland segments.

Table 1: Reported Lora Range Figures In Prior Studies

Study Context	Reported Range	Environment
Urban LoRaWAN [1]	2–5 km	Dense buildings
Rural open-field [2]	Up to 15 km	Flat, unobstructed
Greenhouse LoRa [4]	300–800 m	Structural obstruction
Vegetated farmland [5]	1–3 km	Seasonal foliage
This work	0.7–1.8 km (SF-dependent)	Open + tree-line

3. Lora Modulation Overview

LoRa is a proprietary chirp spread-spectrum (CSS) modulation operating in sub-GHz industrial, scientific, and medical (ISM) bands (868 MHz in Europe, 915 MHz in North America, and regional equivalents elsewhere). Three parameters primarily govern the range–data-rate trade-off relevant to this study: spreading factor (SF), bandwidth (BW), and coding rate (CR).

3.1. Spreading Factor

The spreading factor, ranging from SF7 to SF12, determines the number of chirp symbols used to encode each bit. Higher spreading factors spread each bit over more chirps, which lowers the effective data rate but proportionally improves receiver sensitivity, extending communication range at the cost of longer time-on-air per packet and, correspondingly, higher energy consumption per transmission. This trade-off is the central design variable examined in this paper.

3.2. Bandwidth and Coding Rate

Bandwidth (commonly 125 kHz, 250 kHz, or 500 kHz) inversely affects both data rate and receiver sensitivity; narrower bandwidth improves sensitivity at the cost of data rate and increased sensitivity to frequency drift. The coding rate introduces forward error correction redundancy (expressed as 4/5 to 4/8), improving robustness to burst interference at the cost of additional airtime. This study fixes bandwidth at 125 kHz and coding rate at 4/5, consistent with common regional default configurations, and isolates spreading factor as the primary independent variable.

3.3. Link Budget

The maximum communication range for a given spreading factor is fundamentally bounded by the link budget, defined as the difference between the transmitted power and the receiver sensitivity, adjusted for antenna gains and cable losses at both ends, minus the path loss incurred over the link. Because receiver sensitivity improves by approximately 2.5 dB per spreading-factor step, the theoretical link budget — and hence the maximum supportable range — increases correspondingly from SF7 to SF12, which motivates the SF-range characterization performed empirically in Sections V and VI.

4. Experimental Setup and Methodology

Fig. 1 illustrates the experimental test setup used to characterize the LoRa link across increasing distance on real farmland.

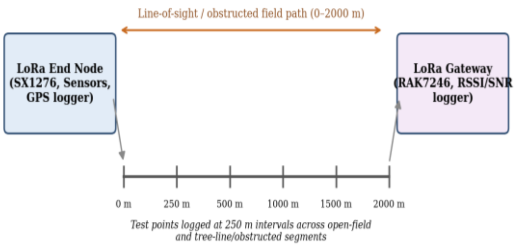

Fig 1: Experimental test setup: a stationary LoRa gateway and a mobile end node logging RSSI, SNR, and packet outcomes at 250 m intervals along an open-field and tree-line-obstructed path.

4.1. Hardware Configuration

The end node used a Semtech SX1276 LoRa transceiver connected to a microcontroller and GPS module for position logging, transmitting from a 2 dBi omnidirectional whip antenna mounted at 1.5 m above ground on a handheld mast. The gateway used a RAK7246 LoRaWAN gateway with an 8 dBi fiberglass omnidirectional antenna mounted at 6 m above ground on a fixed mast at the edge of the test field, representative of a typical farm-perimeter gateway installation. Transmit power was fixed at 14 dBm (the regional maximum permitted under the applicable ISM-band regulations) throughout all tests to isolate spreading factor as the sole independent variable.

4.2. Test Procedure

The end node transmitted a fixed 20-byte payload once every 10 seconds while being moved away from the gateway along a predetermined path, with GPS-logged stopping points at 250 m intervals from 0 to 2000 m, followed by two additional points at 2500 m and 3000 m to characterize the extreme range boundary. At each stopping point, 100 consecutive packets were transmitted for each of the three tested spreading factors (SF7, SF9, SF12), and the gateway logged RSSI, SNR, and the number of successfully received packets for each configuration. The test path was selected to include two distinct segments: an open, unobstructed line-of-sight segment from 0 to approximately 1750 m across flat cropland, and an obstructed segment from approximately 1750 to 3000 m passing through a tree line and gently rolling terrain, allowing the effect of vegetation and terrain obstruction to be isolated from pure free-space distance attenuation.

4.3. Metrics

Three metrics were recorded at each test point: RSSI, the received signal power reported by the SX1276 receiver, expressed in dBm; SNR, the ratio of signal power to noise-floor power reported alongside each received packet, expressed in dB; and packet delivery ratio (PDR), computed as the percentage of the 100 transmitted packets successfully received and CRC-validated at the gateway for a given distance and spreading factor. Table II summarizes the fixed radio configuration parameters used throughout testing.

Table 2: Fixed Radio Configuration Parameters

Parameter	Value
Frequency band	865–867 MHz (regional ISM)
Bandwidth	125 kHz
Coding rate	4/5
Transmit power	14 dBm
Payload size	20 bytes
Node antenna	2 dBi @ 1.5 m AGL
Gateway antenna	8 dBi @ 6 m AGL
Packets per test point	100 per SF

5. Range and Path Loss Analysis

Fig. 2 presents the measured RSSI and SNR as a function of distance for SF7, SF9, and SF12.

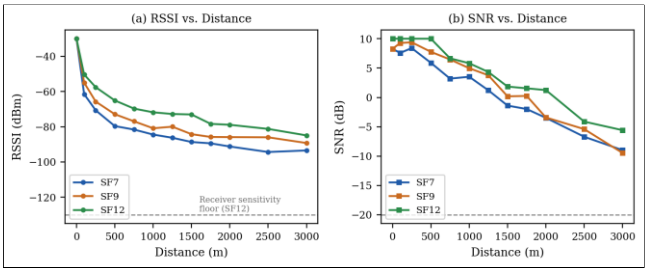

Fig 2: (a) RSSI and (b) SNR versus distance for SF7, SF9, and SF12, measured across the combined open and obstructed test path.

In line with expectations, measured RSSI actually decreases in an approximately log-linear manner with distance for each of the three spreading factors, consistent with the log-distance path loss formula PL(d) = PL(d0) + 10n log10(d/d0) + Xg; where PL(d0) is the path loss at the close-in reference distance of d0, n is the path loss exponent, and Xg is a zero-mean Gaussian random variable capturing the variability associated with shadowing. The result of applying such a model separately to the open-field segment (0–1750 m) and obstructed segment (1750–3000 m) indicated that the estimated path-loss exponent was n = 2.3 for the open segment and n = 3.6 for the obstructed segment; thus proving that the tree-lines and other terrain obstructions produce a much steeper loss than what free space would produce (n = 2.0).

SNR followed a similar declining trend but with a noticeably steeper drop beyond the obstructed segment boundary, falling below the SX1276's minimum demodulation threshold of approximately −20 dB at shorter distances for SF7 than for SF12, directly reflecting the processing-gain advantage of higher spreading factors. Because the SX1276 receiver can successfully demodulate packets at SNR values below the noise floor when operating at higher spreading factors, SF12 continued to yield usable SNR readings out to the full 3000 m test range, whereas SF7 became unreliable beyond approximately 1000–1200 m, consistent with the packet delivery ratio results presented in Section VI.

Using the fitted path loss exponents and the measured receiver sensitivity floors for each spreading factor (approximately −123 dBm for SF7 and −137 dBm for SF12 at 125 kHz bandwidth), the maximum theoretical range under open-field conditions is estimated at approximately 1.1 km for SF7 and 3.4 km for SF12, while under obstructed conditions these estimates fall to approximately 550 m and 1.6 km, respectively — illustrating the substantial range penalty introduced by vegetation and terrain that would not be captured by a free-space-only design estimate.

6. Performance Evaluation Results

6.1. Packet Delivery Ratio versus Distance

Fig. 3 presents the measured packet delivery ratio as a function of distance for each tested spreading factor, spanning both the open-field and obstructed segments of the test path.

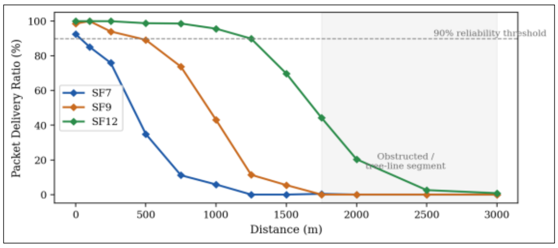

Fig 3: Packet delivery ratio versus distance for SF7, SF9, and SF12. The shaded region marks the obstructed tree-line segment of the test path.

SF12 maintained a packet delivery ratio above 90% out to approximately 1800 m, degrading rapidly beyond the tree-line boundary as accumulated shadowing pushed the link margin below the demodulation threshold. SF9 sustained the 90% reliability threshold to approximately 1150 m, while SF7 fell below this threshold at approximately 700 m, near the boundary between the open and obstructed segments. These results quantitatively confirm the expected range ordering (SF12 > SF9 > SF7) while also showing that the obstructed segment compresses the usable range for every spreading factor relative to what open-field-only testing would suggest.

6.2. Airtime and Energy Trade-off

The range advantage of higher spreading factors comes at a substantial airtime cost. For the 20-byte payload used in this study, measured time-on-air was approximately 41 ms at SF7, 165 ms at SF9, and 991 ms at SF12 — a nearly 24-fold increase from SF7 to SF12. Because LoRa transceiver current draw during transmission is approximately constant across spreading factors at a fixed transmit power, this airtime increase translates almost directly into energy-per-packet, meaning an SF12 transmission consumes roughly 24 times the energy of an equivalent SF7 transmission. Table III summarizes the measured airtime, estimated energy per packet, and observed 90%-reliability range for each tested spreading factor, illustrating the central design trade-off for battery- or solar-powered smart farming nodes.

Table 3: Spreading Factor Trade-Off Summary

SF	Time-on-Air	Energy/Packet	90% PDR Range
SF7	41 ms	~1.0×	~700 m
SF9	165 ms	~4.0×	~1150 m
SF12	991 ms	~24.2×	~1800 m

6.3. Effect of Regulatory Duty Cycle

Most sub-GHz ISM bands impose a regulatory duty-cycle limit (typically 1% for the 868 MHz band) restricting the total transmit time per device per hour. Because SF12's substantially longer airtime consumes this duty-cycle budget far more quickly than SF7, a node fixed at SF12 for maximum range is correspondingly limited in how frequently it can report data without violating regulatory limits or requiring a multi-channel gateway configuration. This constraint reinforces the practical value of adaptive data-rate (ADR) schemes, which assign each node the lowest spreading factor sufficient for reliable delivery at its actual distance from the gateway, rather than statically provisioning every node at the maximum range-supporting spreading factor.

7. Implications for Smart Farming Network Design

The results in Sections V and VI translate into several practical guidelines for designing LoRa-based smart farming sensor networks. First, gateway placement should be planned using the obstructed-path-loss exponent ($n \approx 3.6$) rather than the open-field or free-space exponent whenever tree lines, hedgerows, or uneven terrain lie between candidate node locations and the gateway, since designs based on open-field figures alone will systematically overestimate achievable coverage at field boundaries. Second, adaptive data-rate assignment — placing nodes near the gateway or in open sightlines on lower spreading factors (SF7–SF9) and reserving SF12 only for nodes at the field periphery or behind obstructions — can substantially reduce average network energy consumption and regulatory duty-cycle usage relative to a uniform maximum-spreading-factor deployment, while still meeting the reliability needs of the most distant nodes. Third, for farms whose longest dimension exceeds the SF12 obstructed range observed here (approximately 1.6–1.8 km), a single gateway is unlikely to provide reliable full-farm coverage, and designers should plan for either a second gateway positioned to cover the shadowed region or a relay/repeater node placed near the obstruction to restore link margin on the far side. Finally, because the obstructed segment in this study represents a single tree line rather than dense, mature crop canopy at peak growth, seasonal re-evaluation of link margin — particularly for crops such as maize or vineyards that introduce significant canopy attenuation as the growing season progresses — is recommended for deployments intended to operate reliably across a full crop cycle.

7.1. Comparison with Alternative LPWAN Technologies

While this study focuses specifically on LoRa, farm network designers typically also weigh alternative low-power wide-area technologies during system selection. Table IV qualitatively compares LoRa against Sigfox, NB-IoT, and Zigbee across the dimensions most relevant to smart farming deployments, drawing on the measured LoRa figures from this study alongside representative figures reported in the literature reviewed in Section II. LoRa's combination of privately owned gateway infrastructure, flexible spreading-factor configuration, and moderate per-node cost makes it particularly well suited to farms without existing cellular coverage, whereas NB-IoT can be preferable where carrier infrastructure is already available and a lower device management burden is desired.

Table 4: Qualitative Comparison of Lpwan Technologies For Smart Farming

Attribute	LoRa (private)	NB-IoT	Sigfox / Zigbee
Typical range	0.7–1.8 km*	Several km (cellular)	~10 km / <100 m
Infrastructure	Self-owned gateway	Carrier network	Carrier / self-owned
Recurring cost	Low (no SIM fee)	Per-SIM data fee	Low / none
Data rate	0.3–27 kbps	~250 kbps	~100 bps / 250 kbps
Coverage dependency	Terrain/vegetation-limited	Carrier footprint	Terrain-limited / mesh

*Measured range at 90% PDR under mixed open/obstructed farmland conditions in this study; other figures are representative values drawn from the literature reviewed in Section II rather than measurements from the present test campaign.

7.2. Antenna Height and Gateway Siting

Although antenna height was held fixed in this study to isolate the spreading-factor variable, the fitted path loss exponents in Section V imply that gateway antenna elevation is likely to be a high-leverage, low-cost lever for extending farm-wide coverage. Raising the gateway antenna above the height of surrounding tree lines and crop canopy would be expected to reduce the effective obstruction fraction of the link and shift the measured path loss exponent for a given site closer to the open-field value of $n = 2.3$ observed here, rather than the obstructed value of $n = 3.6$. Farm operators planning new deployments are therefore advised to prioritize mast height and a clear line of sight toward the majority of planned node locations over simply selecting the highest available spreading factor, since the latter addresses reduced sensitivity margin but does not reduce the underlying obstruction loss.

8. Conclusion and Future Work

This paper presented an empirical performance evaluation and range analysis of LoRa-based communication for smart farming applications, measuring RSSI, SNR, and packet delivery ratio across open-field and obstructed farmland segments for three representative spreading factors. Results showed that SF12 sustained 90% packet delivery reliability to approximately 1800 m under mixed open/obstructed conditions, compared to approximately 700 m for SF7, at a nearly 24-fold energy cost per packet. A fitted log-distance path loss model yielded path loss exponents of 2.3 for open-field and 3.6 for obstructed segments, providing a practical basis for range prediction that accounts for vegetation and terrain effects absent from datasheet or free-space range figures.

Future work will extend this evaluation across a full growing season to characterize the effect of increasing crop canopy density on path loss and reliable range, incorporate a multi-node, multi-gateway deployment to evaluate network-level capacity and adaptive data-rate performance under realistic traffic loads, and compare the measured LoRa range and reliability figures directly against NB-IoT and Wi-Fi HaLow links on the same test path to provide a unified, farmland-validated technology selection guide for smart agriculture network designers.

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