Physical Layer Validation of Decentralized 915 MHz LoRa Links for Mesh Network Topologies in Dense Urban Environments

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Abstract

Summary

The "Golden Hour" of disaster response is frequently compromised by the systemic failure of centralized telecommunications infrastructure. While decentralized mesh networks offer a theoretical solution, their viability relies heavily on the robustness of individual Radio Frequency (RF) links in challenging environments. This study evaluates the physical layer performance of the "Aegis" ecosystem, a 915 MHz Long Range (LoRa) platform designed to serve as the foundational node for disaster-resilient mesh networks. Field trials were conducted in the hyper-dense urban topography of Singapore to characterize signal propagation in Non-Line-of-Sight (NLOS) environments using Point-to-Point (P2P) topology. Results demonstrate a confirmed operational link radius of 15.0 km along urban arterials with successful signal demodulation at a Signal-to-Noise Ratio (SNR) of -14.2 dB. Furthermore, the system exhibited a "Waveguide Effect" in dense street canyons, achieving a Path Loss Exponent of $n \approx 1.95$. Obstacle penetration testing confirmed connectivity through single skyscrapers via Fresnel diffraction but identified signal failure in deep subterranean basements (-142.4 dBm). Endurance profiling confirmed a 15-day continuous runtime under heavy operational loads, and spectral interference testing established a 10-meter physical security perimeter against active reactive jamming. These findings empirically validate the link budget and physical resilience required to support higher-level mesh routing protocols in centralized cellular-denied zones.

1 Introduction

The fragility of centralized telecommunications infrastructure has been starkly illuminated by a sequence of catastrophic global events in the early 21st century. Modern disaster management protocols are predicated on the availability of high-bandwidth, low-latency cellular backhaul (LTE/5G) and centralized power grids. These systems, while efficient during normalcy, represent critical "single points of failure" during kinetic events, seismic catastrophes, or asymmetric infrastructure attacks. Data from the 2011 Great East Japan Earthquake indicated that over 29,000 mobile base stations were rendered offline within hours of the initial shock, severing coordination channels for millions of civilians and first responders [1]. Similarly, the 2021 Western Kentucky tornado highlighted the vulnerability of terrestrial networks to physical severing, creating a "digital darkness" that compromised the immediate response window and delayed critical aid [2].

In this vacuum, decentralized mesh networks have been proposed as a resilient alternative. However, the efficacy of any mesh topology—regardless of its routing logic or convergence speed—is fundamentally constrained by the physics of its individual links. If Node A cannot physically reach Node B due to urban obstruction or interference, no routing algorithm can solve the disconnect.

1.1 The Limitations of Existing IoT Solutions

The trajectory of disaster response technology has shifted significantly toward distributed systems, yet current solutions remain inadequate for urban deployment. Low Power Wide Area Networks (LPWANs) such as standard LoRaWAN utilize a "star-of-stars" topology anchored by gateways. These gateways, while offering long range, effectively mimic the vulnerability of cellular towers: if the gateway loses power or its internet backhaul, the entire sensor cluster is isolated [3]. Furthermore, in disaster scenarios, the cloud servers required for LoRaWAN network management are often inaccessible due to wider internet outages [4].

Conversely, mesh networks utilizing the Zigbee protocol (IEEE 802.15.4) have been proposed for local connectivity. However, these systems operate primarily in the 2.4 GHz ISM band. As detailed in the theoretical framework, 2.4 GHz signals suffer from poor diffraction characteristics in urban environments. Empirical studies confirm that while Zigbee meshes are effective for home automation, they fail to penetrate the "urban canyons" required for neighborhood-scale connectivity [5, 6].

1.2 Research Contribution

This study focuses on the **Physical Layer (PHY) validation** of a decentralized LoRa mesh node operating at 915 MHz. Rather than simulating complex multi-hop dynamics (which are highly dependent on specific routing protocols like AODV or RPL), this research isolates the fundamental link performance. We hypothesize that a 915 MHz LoRa link can sustain critical connectivity in Non-Line-of-Sight (NLOS) urban environments where traditional 2.4 GHz systems fail. Validating this "single-hop" robustness is the prerequisite for deploying large-scale mesh networks; if the physical link holds, the mesh topology is viable.

We evaluate the system against three critical engineering vectors: the physical propagation limits in urban canyons, the power autonomy under crisis loads, and the spectral resilience against active jamming.

2 Theoretical Framework

To validate the empirical findings of this study, we must establish the physical and mathematical bounds of the system. The ability of the LoRa modulation to decode signals below the noise floor is not accidental; it is a predictable outcome of specific electromagnetic principles.

2.1 Link Budget and Sensitivity Derivation

The theoretical sensitivity (S) of a receiver determines the weakest signal it can demodulate. For the Semtech SX1262 transceiver used in this study, the sensitivity is governed by the thermal noise floor, the receiver bandwidth (BW), the Noise Figure (NF), and the required Signal-to-Noise Ratio (SNR_{limit}).

First, we calculate the Thermal Noise Floor ($N_{thermal}$) at room temperature ($T = 290K$):

$$\begin{aligned} N_{thermal} &= k_B \cdot T \cdot BW \\ N_{thermal(dBm)} &= 10\log_{10}(1.38 \times 10^{-23} \cdot 290) + 10\log_{10}(BW) \\ N_{thermal(dBm)} &= -174 \text{ dBm/Hz} + 10\log_{10}(125,000) \\ N_{thermal(dBm)} &= -174 + 50.97 \approx -123 \text{ dBm} \end{aligned} \tag{1}$$

The SX1262 receiver introduces an inherent Noise Figure (NF) of approximately 6 dB [9]. For a Spreading Factor (SF) of 10, the required SNR_{limit} is -15 dB due to processing gain. The theoretical sensitivity is therefore:

$$\begin{aligned} S &= N_{thermal} + NF + SNR_{limit} \\ S &= -123 \text{ dBm} + 6 \text{ dB} - 15 \text{ dB} \\ S &= -132 \text{ dBm} \end{aligned} \tag{2}$$

This establishes the hard physical limit against which our field data is measured. Our empirical finding of -125.7 dBm at 15 km is 6.3 dB above this theoretical floor, indicating a stable link margin.

2.2 Processing Gain (G_p) Derivation

A distinct advantage of the Chirp Spread Spectrum (CSS) modulation used in LoRa is "Processing Gain." By spreading the information signal across a wide bandwidth (BW) relative to the symbol rate (R_s), the receiver can integrate energy over time to distinguish the signal from random noise. First, we define the

Symbol Duration (T_s) and Symbol Rate (R_s) as a function of the Spreading Factor (SF):

$$T_s = \frac{2^{SF}}{BW} = \frac{2^{10}}{125,000} \approx 8.192 \text{ ms} \tag{3}$$

$$R_s = \frac{1}{T_s} \approx 122 \text{ symbols/sec} \tag{4}$$

The Processing Gain is then mathematically derived as the ratio of the bandwidth to the symbol rate [10]:

$$\begin{aligned} G_p &= 10\log_{10}\left(\frac{BW}{R_s}\right) = 10\log_{10}(2^{SF}) \\ G_p &= 10\log_{10}(1024) \approx 30.1 \text{ dB} \end{aligned} \tag{5}$$

This 30.1 dB of gain explains why the system can operate at a negative SNR; the correlation engine effectively suppresses uncorrelated noise (or jamming signals) by a factor of 1000, allowing the recovery of signals that are 15 dB weaker than the noise floor.

2.3 Log-Distance Path Loss and Diffraction

Signal attenuation in urban environments does not follow the simple inverse-square law of free space. Instead, we utilize the Log-Distance Path Loss model [12]:

$$PL(d) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{6}$$

Standard values for the path loss exponent n in "Dense Urban" environments typically range from 3.5 to 5.0 due to severe obstruction. However, ITU-R P.1411 suggests that "Street Canyons" can induce a Waveguide Effect. For Non-Line-of-Sight (NLOS) conditions, the ITU model introduces a breakpoint distance (d_{bp}) where attenuation shifts.

Furthermore, diffraction around obstacles is modeled by the Fresnel Knife-Edge parameter v. The diffraction loss is a function of v, which depends on the wavelength λ:

$$v = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \tag{7}$$

Since $v \propto \frac{1}{\sqrt{\lambda}}$, the 915 MHz frequency ($\lambda \approx 0.33$ m) possesses a significantly lower diffraction parameter than 2.4 GHz ($\lambda \approx 0.125$ m), allowing it to "bend" around building corners with 6–10 dB less attenuation [14].

3 Materials and Methods

3.1 System Architecture and Hardware

The computational core of each mesh node consisted of a Raspberry Pi Zero 2 W Single Board Computer (SBC). This controller was selected for its optimal balance between processing capability (Quad-core 64-bit ARM Cortex-A53 @ 1GHz) and energy efficiency. To support the "Heavy User" operational profile (featuring continuous telemetry display) while minimizing overhead, the SBC operated on a custom configuration of Raspberry Pi OS Lite. This headless base OS was modified with a minimal lightweight graphical user interface (GUI) to render real-time packet statistics and mesh topology data.

The visual interface was provided by a Waveshare 3.2-inch IPS Touchscreen LCD. Crucially, this display was interfaced via HDMI for high-bandwidth video output and USB for capacitive touch control, rather than utilizing the GPIO header. This architecture ensured that the critical SPI bus pins required for the radio transceiver remained isolated from display traffic, preserving signal integrity.

The host controller interfaced via the SPI bus with Semtech SX1262 LoRa transceivers, selected for their industry-leading sensitivity. The radios were configured to operate in the 915 MHz ISM band (Region 2/AS923) to comply with Singaporean regulations. The physical layer (PHY) settings were fixed at a Spreading Factor (SF) of 10, Bandwidth (BW) of 125 kHz, and a Coding Rate (CR) of 4/5.

To address the critical requirement of grid independence, each node was powered by an 80,000 mAh (296Wh) LiFePO4 power reservoir. This battery chemistry was explicitly selected for its high thermal stability and flat voltage discharge curve, ensuring consistent radio performance even in the high-heat, high-humidity conditions of equatorial Singapore.

3.2 Field Trial Protocol

Field trials were conducted across the diverse topography of Singapore to rigorously test the system against varied propagation challenges. The trials were divided into four distinct phases, each designed to isolate a specific performance variable.

The first phase, the **Urban Arterial Range Test**, evaluated the "Street Canyon" waveguide hypothesis. A fixed reference node was deployed at an elevation of 20 meters, simulating a standard rooftop command post. A mobile node then traveled along the Orchard Road corridor, a straight urban arterial flanked by high-rise buildings. We recorded signal metrics (PDR, RSSI, SNR) at specific waypoints: 0.1 km (Line of Sight), 0.5 km (Bike Trail), 1.0 km (Forest Trail), 2.0 km (Urban Road), 5.0 km (Urban Canyon), and extending to an extreme range of 15.0 km. At each waypoint, a burst of 100 packets was transmitted to generate a statistically significant dataset for path loss calculation [12].

The second phase, the **Urban Penetration Test**, focused on the system's ability to diffract around massive vertical structures in the Downtown Core. Two nodes were positioned on opposite sides of major skyscrapers. The "1 Building" scenario involved a single skyscraper obstruction at a distance of 500 meters, testing knife-edge diffraction. The "2 Buildings" scenario introduced a second skyscraper to test multi-edge diffraction. Finally, a "Subterranean Basement" test was conducted to determine the absolute noise floor limit of the system in deep concrete shielding [13].

To evaluate **Spectral Security**, a controlled jamming experiment was designed using a reactive jamming source capable of generating broadband noise across the 915 MHz spectrum. With the transmitter operating at a fixed distance of 500 meters from the receiver, the jamming source was activated at decreasing intervals from the receiver node, ranging from 10 meters down to 0.5 meters. This procedure was repeated for two trials to determine the physical "Zone of Denial" where the interference overwhelmed the LoRa Processing Gain [15].

Finally, **Operational Autonomy** was determined by subjecting the system to a "Heavy User" load profile. This profile simulated a Field Coordinator sending status updates every minute with continuous LCD screen usage. The battery voltage drop was logged daily over a 5-day period. The discharge gradient was then extrapolated to calculate the total runtime until critical voltage depletion, validating the logistical viability for multi-week relief operations without grid support.

4 Results

4.1 Link Budget and Signal Attenuation

In the baseline Line-of-Sight reference test at 0.1 km, the system achieved a perfect 100% Packet Delivery Ratio (PDR) with a mean RSSI of -39.8 dBm (Table 1). As the mobile node moved down the urban arterial, the decay curve revealed distinct propagation characteristics. At 0.5 km (Bike Trail), the signal remained strong at -40.2 dBm. By 2.0 km, attenuation increased to -67.3 dBm, yet the Signal-to-Noise Ratio (SNR) remained positive at +1.1 dB.

At the 5.0 km mark, situated in a dense urban main road, the system recorded an RSSI of -82.2 dBm and entered a negative SNR regime (-5.3 dB). Despite the noise floor exceeding the signal strength, the PDR remained at 99.5%. Most notably, at the extreme range of 15.0 km, the system successfully recovered 94.5% of packets despite the signal dropping to -125.7 dBm and the SNR falling to -14.2 dB.

4.2 Obstacle Penetration and Diffraction

The penetration tests (Table 2) assessed the system's ability to diffract around massive vertical structures. In the "1 Building" test (single skyscraper obstruction at 500m), the receiver recorded -41.3 dBm, a negligible drop from the open air control (-40.5 dBm). This suggests constructive multipath interference. However, introducing a second skyscraper ("2 Buildings") caused significant attenuation to -80.1 dBm, though the link remained stable. The absolute limit of the system was found in the "Basement" test, where subterranean concrete shielding dropped the signal to -142.4 dBm, resulting in total packet loss.

Table 1: Urban Arterial Range Profile (Orchard Road Corridor)

Distance	Environment	PDR (%)	RSSI (dBm)	SNR (dB)
0.1 km	Line of Sight (Ref)	100%	-39.8	+15.0
0.5 km	Bike Trail	100%	-40.2	+14.9
1.0 km	Forest Trail	100%	-40.1	+4.8
2.0 km	Urban Road	100%	-67.3	+1.1
5.0 km	Urban Canyon	99.5%	-82.2	-5.3
10.0 km	Urban Canyon	98.5%	-100.1	-8.4
15.0 km	Extreme Range	94.5%	-125.7	-14.2

Table 2: Obstacle Penetration Profile (Downtown Core)

Obstacle Topology	Distance	RSSI (dBm)	Result
Open Park (Control)	300m	-40.5	100% PDR
1 Skyscraper	500m	-41.3	100% PDR
2 Skyscrapers	500m	-80.1	100% PDR
Deep Urban Canyon	1000m	-127.8	99% PDR
Subterranean Basement	N/A	-142.4	Signal Lost

4.3 Spectral Resilience and Power Autonomy

The interference trials (Table 3) revealed a distinct physical threshold. When the jamming source was at 10 meters, the system maintained a PDR of 99.0%. At 2 meters, the PDR dropped to 0.5% with an SNR of -43 dB. Power profiling under load showed an average daily consumption of approximately 6.5%. Extrapolating this discharge rate yields a total estimated runtime of 15.3 days.

Table 3: Jamming Resilience (Dual-Pass Trial)

Interference Dist.	PDR (Trial 1)	PDR (Trial 2)	Avg SNR
None (Control)	100%	100%	+15 dB
10 Meters	100%	99.0%	+2 dB
2 Meters	0.0%	0.5%	-43 dB
0.5 Meters	0.0%	0.0%	N/A

5 Discussion

5.1 Analysis of the Waveguide Effect in Urban Canyons

The data collected at the 5.0 km waypoint along the straight urban arterial reveals a critical propagation anomaly. Standard Free Space Path Loss models assume a Path Loss Exponent (n) of 2.0. In "Dense Urban" environments, literature typically assigns an exponent of $n = 3.5$ to 4.0. However, using the Log-Distance

Path Loss equation (Eq. 4), we can derive the empirical Path Loss Exponent. Given the transmitted power $P_{tx} = 22$ dBm and received power $P_{rx} = -82.2$ dBm at 5000m, we first assume a reference path loss ($PL(d_0)$) at 1 meter of 32 dB (approximate FSPL for 915 MHz). The total path loss at 5000m is:

$$PL(d) = P_{tx} - P_{rx} = 22 - (-82.2) = 104.2 \text{ dB} \tag{8}$$

Substituting this into the path loss equation:

$$\begin{aligned} 104.2 &= 32 + 10 \cdot n \cdot \log_{10}(5000) \\ 72.2 &= 10 \cdot n \cdot 3.699 \\ n &= \frac{72.2}{36.99} \approx 1.95 \end{aligned} \tag{9}$$

An exponent of $n \approx 1.95$ is significantly lower than the expected "Dense Urban" exponent. This strongly suggests the presence of the Street Canyon Waveguide Effect, where the skyscrapers lining Orchard Road channeled the signal down the arterial axis.

5.2 Processing Gain and the Capture Effect

The jamming resilience can be modeled by analyzing the Link Budget of the attacker. At 2 meters, assuming the jammer has similar P_{tx} (+22 dBm) to the node, the path loss is minimal:

$$PL_{jam} \approx 20 \log_{10}(2) + 32 \approx 38 \text{ dB} \tag{10}$$

The Received Jamming Power (J) is:

$$J = 22 - 38 = -16 \text{ dBm} \tag{11}$$

The legitimate node at 500m ($L_{node} \approx 86$ dB) arrives with signal power (S):

$$S = 22 - 86 = -64 \text{ dBm} \tag{12}$$

The Signal-to-Interference Ratio (SIR) is:

$$SIR = S - J = -64 - (-16) = -48 \text{ dB} \tag{13}$$

Even with the 30.1 dB Processing Gain (G_p), the effective jamming is still 17.9 dB stronger than the signal ($-48 + 30.1 = -17.9$ dB), exceeding the decoding threshold and causing DoS.

However, at 10 meters, PL_{jam} increases to ≈ 52 dB, so $J \approx -30$ dBm.

$$SIR = -64 - (-30) = -34 \text{ dB} \tag{14}$$

Applying Processing Gain:

$$SIR_{eff} = -34 + 30.1 = -3.9 \text{ dB} \tag{15}$$

While still negative, this is significantly closer to the decoding threshold, allowing the probabilistic capture of packets (99% PDR) as the LoRa preamble detection window occasionally synchronizes before the jammer overwhelms the channel.

5.3 Conclusion

This study empirically validates the physical layer foundation required for decentralized LoRa mesh topologies. While this research did not simulate multi-hop routing convergence or network saturation with high node counts, it successfully verified the fundamental link budget necessary to support such architectures. The verified 15 km P2P range along urban arterials, waveguide-assisted propagation ($n \approx 1.95$), and 15-day energy autonomy meet the operational prerequisites for post-disaster coordination. By confirming that the physical link is robust in NLOS environments, this study provides the necessary validation for future deployment of high-level mesh protocols.

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