

Antennas & RF

Antenna selection, gain, coax, mounting, and RF fundamentals for LoRa mesh.

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☐ Start Here — Antennas & RF Guide

Antenna choice and placement together are the biggest lever you have over LoRa range - and height with clear line-of-sight usually matters more than antenna gain. This book covers antenna selection, installation, feedline, and RF fundamentals - from beginner to advanced. (See [Understanding Gain and dBi](#): optimise placement before spending money on a higher-gain antenna.)

☐ Quick Answers

- **"Do I need a better antenna?"** → [Do I need an external antenna?](#)
- **"Which antenna should I buy?"** → [Portable & Handheld Antennas](#), [Base Station & Outdoor Antennas](#), or [Directional Antennas](#)
- **"What's dBi mean?"** → [Understanding Gain and dBi](#)
- **"What cable/connector do I need?"** → [RF Connector Types Guide](#)

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➔ Related Books

- [Network Planning](#) - RF propagation, link budgets, coverage planning
- [DIY Build Guides](#) - Enclosures and physical installation

Antenna Fundamentals

Understanding Gain and dBi

Understanding Gain and dBi

Antenna gain is one of the most misunderstood topics in practical LoRa deployment. More gain is not always better - understanding what gain actually does will help you choose the right antenna for each deployment scenario.

What dBi Means

dBi (decibels relative to an isotropic radiator) measures how much an antenna concentrates radio energy in a particular direction compared to a theoretical antenna that radiates equally in all directions. An antenna with 0 dBi is a theoretical perfect sphere of radiation. An antenna with 5 dBi concentrates the same total energy into a narrower pattern.

The key insight: antennas do not add power. They redistribute it. Higher gain means more energy focused in the desired direction and less energy wasted in other directions.

Gain vs. Beam Angle

The figures below are approximate vertical (elevation) beamwidths for typical vertical omni antennas. They are illustrative, not exact: gain and beamwidth are always inversely proportional, but the actual beamwidth of a given antenna depends on its specific design. Use them to understand the trend, not as precise specifications.

Gain	Approx. Vertical (Elevation) Beamwidth — illustrative	Best Use Case
0 dBi	~80°	Indoor, short range, omnidirectional coverage needed in 3D
2 - 3 dBi	~60°	Handheld portable, varied terrain
5 dBi	~40°	Standard outdoor omni, modest height, moderate terrain
8 dBi	~20°	High-site omni with flat terrain and long-range targets

Gain	Approx. Vertical (Elevation) Beamwidth — illustrative	Best Use Case
12+ dBi	<15°	Directional point-to-point links only

The High-Gain Trap in Hilly Terrain

An 8 dBi antenna on a rooftop in hilly terrain will have a dead zone directly below and nearby because its beam is concentrated nearly horizontally. Nodes at ground level within a few hundred metres may receive a worse signal than they would from a 5 dBi antenna at the same height. For community mesh networks with nodes at varying elevations, 5 - 6 dBi is typically optimal for omni antennas at medium-height fixed sites.

Practical dB Math

The range rules below assume free-space (inverse-square) propagation. In free space, range scales as $10^{(\text{gain_dB}/20)}$, so +6 dB doubles range and +3 dB adds about 40%. In real terrain — with obstructions, vegetation, and buildings — propagation is worse than inverse-square, so the actual range gain is smaller (often only 30 - 60% for +6 dB).

- **+3 dB** = doubles effective radiated power ($\approx$ +40% range in free space; less in real terrain)
- **+6 dB** = 4× effective radiated power ($\approx$ doubles range in free space; typically only +30 - 60% in real terrain)
- **+10 dB** = 10× effective radiated power

Range does not scale linearly with power because signal propagation follows an inverse square law (or worse in real-world conditions with obstructions). Going from 22 dBm to 28 dBm is +6 dB - 4× the power - which in free space would roughly double range, but in real terrain typically yields only 30 - 60% more range.

Placement vs. Gain

Moving an antenna from ground level to a rooftop 10 metres up provides far more range improvement than switching from a 3 dBi to an 8 dBi antenna at ground level. Elevation eliminates obstructions and increases radio horizon. Always optimise placement before spending money on higher-gain antennas.

Free Space Path Loss at 915 MHz

Free space path loss (FSPL) increases with distance. At 915 MHz:

Distance	Free Space Path Loss
1 km	~91 dB
5 km	~105 dB
10 km	~111 dB
20 km	~117 dB

LoRa with SF12 has a link budget of roughly 150 - 160 dB (note: a link budget is a difference of two dBm values, so it is expressed in dB, not dBm — the exact figure depends on transmit power and antenna gain). Under ideal, fully clear line-of-sight conditions, SF12 links can reach tens of kilometres; record links far exceed this. However, real-world terrain, vegetation, building losses, and Fresnel-zone obstruction reduce achievable range dramatically, and typical installations achieve far less. See the Fresnel Zones and Link Budget pages for how to estimate realistic range for your site.

Connector Types & Coax Cable

Connector Types & Coax Cable

Using the wrong connector or cable is one of the most common and frustrating mistakes when setting up LoRa hardware. This page covers everything you need to know to buy and connect antennas correctly.

SMA vs. RP-SMA

SMA (SubMiniature version A) and RP-SMA (Reverse Polarity SMA) look nearly identical but are **not interchangeable**. Connecting a mismatched pair results in no signal or very poor signal even though the connectors physically engage.

Connector	Male	Female	Common Devices
SMA	Pin in centre, external thread	Socket in centre, internal thread	Heltec V3/V4, RAK WisBlock, many antennas
RP-SMA	Socket in centre, external thread	Pin in centre, internal thread	Some LilyGo devices, Wi-Fi routers, some Meshtastic builds

RP-SMA originates from an FCC convention for consumer Wi-Fi antenna couplings (it is an industry convention, not an FCC mandate for LoRa). It sometimes appears on LoRa boards - notably some LilyGo and inexpensive units - and is not "wrong," but it must be matched to the antenna.

Before buying an antenna: check your device datasheet or photos to confirm whether it uses SMA or RP-SMA. The Heltec V3 and V4 are generally reported to use SMA Male on the board (the antenna plugs SMA Female onto the board connector); verify against the official Heltec datasheet for your exact board revision, since some clones and variants differ.

N-Connector

N-connectors are larger, more weatherproof, and lower-loss than SMA. Used on outdoor base station antennas and feedlines. The ALFA 5 dBi Mini uses N-Male. For base station builds with significant coax runs, N-connector systems are preferred over SMA.

Coax Cable Selection

Coax cable introduces loss that subtracts directly from your effective radiated power and receive sensitivity. At 915 MHz, cable loss is significant for runs over 3 metres. The figures below are the canonical 915 MHz loss values used across this book (sourced from manufacturer datasheets, e.g. Times Microwave for LMR cable). The reference length is **100 ft (≈30.5 m)**; the dB/m column is the same value divided to a per-metre basis (per metre = dB/100 ft × 0.0328).

Cable Type	Loss at 915 MHz (dB/100 ft)	Loss at 915 MHz (dB/m)	Use Case
RG174	~28 dB/100 ft	~0.92 dB/m	Short pigtails only (<30cm); avoid for longer runs
RG316	~26 dB/100 ft	~0.85 dB/m	Short internal pigtails; better than RG174 but still lossy
RG58	~20 dB/100 ft	~0.66 dB/m	Acceptable for runs up to 3 - 5m
LMR-200	~9.9 dB/100 ft	~0.32 dB/m	Good for runs 3 - 10m; flexible
LMR-400	~3.9 dB/100 ft	~0.13 dB/m	Long runs (>10m) or base stations; less flexible

For a DIY solar repeater with the node inside the enclosure and the antenna immediately outside, a 30cm RG316 pigtail is fine. For a base station where the coax runs 10 metres from the node to the roof antenna, use LMR-200 or LMR-400.

SWR and Cable Quality

Poor-quality connectors and cables produce poor SWR readings even with a good antenna. If your NanoVNA shows unexpectedly high SWR, suspect the cable and connectors before the antenna itself. Wiggle the connector while monitoring - if SWR changes, the connector is the problem.

Weatherproofing Outdoor Connections

Outdoor N-connector and SMA connections must be weatherproofed. Water intrusion corrodes the connector and increases loss. Use self-amalgamating (self-fusing) tape: stretch it over the connector and cable and overlap each wrap by half. It bonds to itself and forms a watertight seal

without adhesive. Cover with UV-resistant electrical tape for UV protection.

Antenna Selection Guide

Portable & Handheld Antennas

Portable & Handheld Antennas

Portable antennas attach directly to your device and travel with you. The primary trade-off is between size/weight and gain. For handheld use, a compact 2 - 3 dBi antenna is usually optimal - higher gain antennas are longer and concentrate the beam horizontally, which hurts performance when you are at ground level near other nodes.

Note on prices and specs: Prices below are approximate as of 2026-06-08 and are volatile - confirm at the linked vendor before ordering. Gain and SWR figures are manufacturer/vendor-reported unless independently measured.

Community-Recommended Portable Antennas

Muzi Whip 17cm - ~\$12

A compact 17cm whip antenna weighing approximately 14g. The vendor reports a measured SWR of 1.3 at 915 MHz (muzi.works) - excellent for a whip this size, though not independently lab-verified. The community generally regards the Muzi Whip as one of the best compact options for everyday carry. Its small size means it fits in a pocket or bag without the antenna becoming an obstruction.

- **Gain:** ~2 dBi (estimated for a 17cm 915 MHz whip)
- **Length:** 17cm
- **Weight:** ~14g (approximate, unconfirmed)
- **SWR:** 1.3 at 915 MHz (vendor-reported, muzi.works)
- **Connector:** SMA

MESHTAC Gooseneck - ~\$35

A ~11.5-inch (~29cm) flexible/bendable antenna with a vendor-claimed 4 dBi gain (Rokland). The gooseneck design lets you position the antenna for best orientation regardless of how you are holding the device. Useful for vehicle or pack mounting where the device orientation varies. Note that bending a gooseneck distorts the pattern and reduces realized gain, so treat the 4 dBi figure as a best-case manufacturer claim.

- **Gain:** 4 dBi (vendor-claimed)
- **Length:** ~11.5" (~29cm)
- **Feature:** Flexible/bendable positioning

MESHTAC 2.5 dBi Whip - ~\$13

A compact 7.8" whip with 2.5 dBi gain (Rokland). Good all-around portable antenna for devices that will be used at varying heights and orientations. Affordable enough to include as a default upgrade over the stock antennas that ship with Heltec devices.

ALFA 90° Elbow - ~\$12

A 2 dBi, 7.7" antenna with a 90-degree elbow at the base (ALFA ARS-915P, Rokland). The right-angle mount keeps the antenna oriented vertically even when the device is mounted horizontally (e.g., on a belt clip or vehicle dashboard). Compact and inexpensive.

Stock Antennas

The small antennas that ship with most Heltec and LilyGo devices are functional but not optimized. They are typically short stubs (roughly 5 - 8cm, approximate) tuned broadly around 915 MHz with mediocre SWR - muzi.works, for example, reports a stock stubby antenna at SWR ~3.5 versus 1.3 for their 17cm whip. For serious use, replace the stock antenna with any of the options above. The Muzi Whip is a popular replacement for the Heltec V3.

Portable Antenna Comparison

Gain and SWR values below are manufacturer/vendor claims; prices approximate as of 2026-06-08.

Antenna	Price	Gain	Length	Notes
Muzi Whip 17cm	~\$12	~2 dBi	17cm	Best compact option; SWR 1.3 (vendor-reported)
MESHTAC Gooseneck	~\$35	4 dBi	~29cm	Flexible positioning
MESHTAC 2.5 dBi Whip	~\$13	2.5 dBi	20cm	Good all-around portable
ALFA 90° Elbow	~\$12	2 dBi	20cm	Right-angle base

Base Station & Outdoor Antennas

Base Station & Outdoor Antennas

Outdoor and base station antennas are designed for permanent weatherproof installation at height. They use larger radomes and N-connector interfaces, and are tuned more precisely than portable whips.

ALFA 5 dBi Mini - ~\$18

A compact 7" outdoor omni antenna with an N-Male connector (ALFA AOA-915-5ACM). Good starting point for a first outdoor installation or for sites where a larger antenna would cause wind loading concerns. The 5 dBi gain provides a noticeable improvement over portable whips while keeping the beam angle wide enough to cover nearby nodes at varying elevations. Price ~\$18 as of 2026-06-08 (Rokland); prices are volatile, so verify before ordering.

- **Gain:** 5 dBi
- **Height:** 7"
- **Connector:** N-Male
- **Mounting:** Mast or wall mount

RAK 5.8 dBi Fiberglass - ~\$30 - \$40

A full-size fiberglass outdoor omni antenna from RAK Wireless. Weatherproof and includes U-bolt mounting hardware. Note there are two regional SKUs: the US/915 MHz variant (RAKARG14, ~902-928 MHz) and the EU/868 MHz variant (RAKARG13, 863-870 MHz) - choose the RAKARG14 for North American 902-928 MHz use; a single antenna is not tuned for both bands. The community's most commonly recommended base station antenna for solar repeater builds. The 5.8 dBi gain is a good balance between range and beam width for typical community mesh deployments. Price ~\$30-\$40 as of 2026-06-08; treat as approximate and confirm at the RAK/Rokland store.

- **Gain:** 5.8 dBi
- **Weatherproof:** Yes

- **Mounting:** U-bolt included
- **Connector:** N-Male (antenna terminates in an N-male; use an N-female cable to connect it)

8 dBi Low Profile Outdoor - ~\$38

A 25" outdoor fiberglass antenna with 8 dBi gain and an N-Female connector. Specifications and price (~\$38 as of 2026-06-08) are approximate - identify the exact SKU and confirm its datasheet before buying. Appropriate for flat terrain where the mesh coverage area is entirely at a similar elevation to the antenna. Avoid in hilly terrain or when nearby nodes are at significantly different elevations - the narrow beam creates dead zones above and below the antenna.

- **Gain:** 8 dBi
- **Height:** 25"
- **Connector:** N-Female

FCC note: Antennas above 6 dBi (like this 8 dBi model) require a dB-for-dB conducted power reduction under FCC 15.247(b)(4) if your node runs near the 1 W (30 dBm) limit. At typical LoRa power (≤ 20 dBm) you remain well within limits, but verify if you raise TX power. There is no point-to-point gain allowance at 902-928 MHz.

Antenna Selection for Different Scenarios

Scenario	Recommended Antenna	Why
First outdoor fixed node	ALFA 5 dBi Mini	Affordable, forgiving beam pattern
Solar repeater in mixed terrain	RAK 5.8 dBi Fiberglass	Good gain, wide enough beam, weatherproof
High-site node, flat terrain	8 dBi Low Profile	Maximum horizontal range
High-site node, hilly terrain	RAK 5.8 dBi Fiberglass	Beam pattern covers elevation variation
Point-to-point backbone link	~12 dBi 900 MHz Yagi	Directional, maximum link budget

Mounting Tips

Safety first: Mounting outdoor antennas at height involves fall and power-line electrocution hazards - keep the mast's full fall-radius clear of overhead power lines and use fall protection when working at height. All permanent outdoor antennas must be grounded and surge-protected; see Grounding and Lightning Protection.

- Always mount antennas with the element vertical for standard LoRa mesh use. A horizontal-to-vertical polarization mismatch causes a large loss (commonly cited at roughly 20 dB for well-matched antennas, though real-world multipath often reduces the penalty).
- Keep the antenna away from metal surfaces. Metal nearby detunes the antenna and creates reflection patterns. As a tiered rule of thumb at 915 MHz (wavelength ≈ 33 cm): keep at least a quarter-wavelength (~ 8 cm) clearance as a minimum, a half-wavelength (~ 16 cm) preferred, and a full wavelength (~ 33 cm) for a conservative install.
- Higher is almost always better. Even 2 - 3 meters of extra height can make a significant difference in real-world conditions.
- Weatherproof outdoor N-connector connections with self-amalgamating tape.

Directional Antennas

Directional Antennas

Directional antennas concentrate RF energy in a specific direction rather than radiating omnidirectionally. They are used for point-to-point backbone links between fixed sites where maximum range is needed in a known direction.

ALFA 12 dBi Yagi - \$50+

A Yagi-Uda directional antenna with 12 dBi gain at 915 MHz. A 12 dBi Yagi has a half-power beamwidth of approximately 35° (i.e. $\pm 17^\circ$ to the half-power points) and must be aimed precisely at the target node. Used for connecting distant nodes or bridging a gap in mesh coverage across a valley or open terrain. (Pricing as of June 2026; street price varies — confirm against a current retailer listing.)

- **Gain:** 12 dBi
- **Pattern:** Directional (Yagi)
- **Use case:** Point-to-point links, extending mesh over long distances in one direction

When to Use a Directional Antenna

- You need to extend the mesh over a specific long-distance path (e.g., across a lake or through a valley cut)
- You have two sites that need reliable high-margin connectivity but no intermediate repeaters
- You want to add gain without affecting nearby nodes in other directions

When NOT to Use a Directional Antenna

- For a general community repeater that should cover all directions - a Yagi will be deaf and blind to nodes not in its beam
- When nodes are located in multiple directions from the installation point
- On handheld portable devices - you would have to point the device at the target node at all times

Aiming a Yagi

A 12 dBi Yagi has a half-power beamwidth of roughly 35° (see the antenna spec above), so aiming must be reasonably accurate:

1. Use a compass bearing to the target node.
2. Tilt slightly toward the target if it is at a higher or lower elevation.
3. Use the MeshCore or Meshtastic RSSI/SNR values from the target node to fine-tune aim while rotating the antenna.
4. Lock the mount when signal is maximised. Mark the final orientation so you can verify it has not shifted after a windstorm.

Link Budget for a Directional Link

“ **△ FCC compliance:** At 902–928 MHz the conducted output power limit is 1 W (30 dBm) referenced to a 6 dBi antenna. With a 12 dBi antenna (6 dBi above the threshold), 47 CFR § 15.247(b)(4) requires conducted power to be reduced dB-for-dB — down to **24 dBm** — capping EIRP at **36 dBm**. There is **no** relaxed point-to-point antenna allowance at 915 MHz (that exception, § 15.247(c)(1), applies only to 2.4 GHz / 5.8 GHz). Running a radio's full output into a 12 dBi Yagi for a 48.5 dBm EIRP link would be roughly 12 dB over the legal limit and is illegal under Part 15. The link budget below uses the compliant 24 dBm / 36 dBm EIRP figures. (The Station G2's higher rated output is intended for other regulatory regimes — e.g. amateur-licensed operation under Part 97 — not US Part 15 unlicensed use.)

Example: Two Station G2 nodes (–130 dBm sensitivity) with 12 dBi Yagi antennas, 20 km apart, run at the Part 15 limit:

- TX power: 24 dBm (reduced to stay legal with a 12 dBi antenna)
- TX antenna gain: +12 dBi
- EIRP: 36 dBm (the maximum legal EIRP at 902–928 MHz)
- Free space path loss at 20 km, 915 MHz: ~117 dB
- RX antenna gain: +12 dBi (less RX feedline loss — budget ~1–2 dB for real cable)
- Received power: 36 – 117 + 12 = –69 dBm (before RX feedline loss)
- RX sensitivity: –130 dBm
- Link margin: ~61 dB - more than adequate (free-space figure)

In practice, real-world obstructions and multipath reduce this margin, and the free-space figure above assumes a clear line of sight that a 20 km link does not get for free. Over 20 km the earth's curvature alone introduces roughly 23 m of path obstruction ($\approx d^2/17$ in metres/km), and the first Fresnel zone radius at midpoint is on the order of 40 m — so a real 20 km link needs substantial

combined antenna height (tens of metres) to keep the path clear. Subtract RX feedline loss as well. Treat the large margin as a theoretical ceiling, not a field-achievable number without proper line-of-sight engineering. 20 dB of link margin is considered comfortable in practice.

Testing & Tuning

NanoVNA Antenna Testing

Overview

A **NanoVNA** (Vector Network Analyzer) is the essential tool for verifying antenna performance before deployment. It measures SWR (Standing Wave Ratio) and impedance - telling you how well your antenna is matched to the 50 Ω system and whether it is resonant at 915 MHz. A 10-minute NanoVNA check before mounting an antenna can save hours of troubleshooting range problems later.

Models

Model	Screen	Frequency Range	Price
NanoVNA-H	2.8"	50 kHz - 1.5 GHz	~\$30 - 50
NanoVNA-H4	4.0"	10 kHz - 1.5 GHz	~\$50 - 70
NanoVNA-F	4.3" (metal case)	10 kHz - 1.5 GHz	~\$50 - 70

Frequency note: Common NanoVNA models (H / H4 / F) top out near **1.5 GHz**, not 3 GHz - 915 MHz sits comfortably within range. On the basic NanoVNA-H, operation above ~900 MHz uses harmonic mode with reduced dynamic range, so 915 MHz measurements are valid but recalibrate carefully; the H4 and F perform better here. Prices above are approximate as of 2026-06-08 and vary by vendor.

Kit includes: NanoVNA unit, calibration standards (Open/Short/Load), two SMA cables, USB-C charging cable.

Five-Step Testing Procedure

Step 1 - Initial Setup

1. Charge the NanoVNA via USB-C before first use.

2. Power on.
3. Set the frequency range: **START = 850 MHz, STOP = 950 MHz.**

Step 2 - Calibration (Most Critical)

Calibrate every session or any time you change the frequency range. Calibration compensates for cable and connector losses - skipping it invalidates all measurements.

1. Navigate to **Menu → CAL → CALIBRATE.**
2. Connect the **OPEN** standard → select OPEN → wait for measurement.
3. Connect the **SHORT** standard → select SHORT → wait.
4. Connect the **LOAD** (50 Ω) standard → select LOAD → wait.
5. Save calibration to a slot (0 - 4).
6. Verify: reconnect LOAD → SWR should read **~1.0**, impedance **~50+j0 Ω**. This check confirms the calibration math, not absolute accuracy; the supplied standards are adequate for hobby antenna work.

Recalibrate when: changing frequency range; moving to a significantly different temperature environment; switching to different cables.

Step 3 - Configure Display

- Set **Trace 1** to **SWR**.
- Optionally set **Trace 2** to Smith Chart or R+jX for impedance detail.
- Add a **marker at 915 MHz**.

Step 4 - Connect Antenna

Caution: Disconnect or power down the LoRa radio before connecting a NanoVNA to its antenna line. A NanoVNA is a low-power test source; applying transmit power to a NanoVNA port will damage the instrument.

- Connect antenna cable to **CH0 (Port 1)**.
- Use the shortest possible cable between the NanoVNA and antenna.
- Tighten connectors finger-tight only - do not over-torque SMA.
- **Check connector type:** LoRa antennas commonly use SMA or RP-SMA. These look identical but are not compatible - verify before connecting.

Step 5 - Interpret Results

SWR Ratings

SWR	Rating	Action
1.0 - 1.5	Excellent	Deploy with confidence
1.5 - 2.0	Good - acceptable	Fine for most deployments
2.0 - 3.0	Marginal - some power loss	Investigate connector quality
3.0+	Poor - significant loss	Replace antenna or diagnose connector

Resonant Frequency

The **lowest SWR dip** on the sweep is the antenna's resonant frequency.

- Dip **at 915 MHz** - optimal
- Dip **below 915 MHz** - antenna is slightly long (resonates lower)
- Dip **above 915 MHz** - antenna is slightly short (resonates higher)

Common Problems & Diagnosis

Symptom	Likely Cause
High SWR across entire 850 - 950 MHz band	Antenna tuned for 868 MHz (European band); damaged or loose connector; missing ground plane on whip antenna
SWR varies wildly / unstable reading	Loose connector; damaged cable - wiggle connections while watching display
Excellent SWR but poor range	SWR measures <i>impedance match only</i> , not gain. SWR and gain are independent - evaluate both. A 6 dBi antenna with moderate mismatch (2:1, ~0.5 dB loss) still beats a 0 dBi matched antenna at both short and long range; only a severe mismatch (loss exceeding the gain advantage) erases the gain benefit. Evaluate antenna gain separately.

PC Software: NanoVNA-Saver

NanoVNA-Saver is free, open-source software (Windows/Mac/Linux - search GitHub for "NanoVNA-Saver") that connects to your NanoVNA via USB and provides:

- Larger, higher-resolution graphs
- Data export (CSV)
- Smith chart display
- Touchstone (.s1p) file export for import into antenna modeling software
- Multi-antenna comparison - overlay sweeps from different antennas

Recommended for antenna selection decisions and documentation of deployed infrastructure antennas.

Common Mistakes to Avoid

- **Skipping calibration** - all measurements are invalid without calibration
- **Calibrating at the wrong frequency range** - calibration is only valid for the range it was performed at; recalibrate if you change START/STOP
- **Testing indoors near metal objects** - nearby metal detuning antennas; test in the open or simulate the actual mounting environment
- **Using adapters without accounting for electrical length** - SMA adapters add a small but measurable electrical length; minimize adapter use
- **Confusing SMA and RP-SMA** - SMA has center pin on plug; RP-SMA has center pin on jack. Forcing mismatched connectors damages both.

SWR, VSWR, and Return Loss Explained

Before deploying an antenna on your mesh node, understanding how to measure and interpret antenna performance can save you from poor coverage or potential hardware damage.

What is SWR?

Standing Wave Ratio (SWR) - more precisely Voltage Standing Wave Ratio (VSWR) - measures how well an antenna is impedance-matched to your transmission line and radio. A perfect match is 1:1. Most radios are designed for 50-ohm impedance.

- **SWR 1.0:1** - Perfect match. 100% of power transferred to antenna.
- **SWR 1.5:1** - Excellent. ~96% power transferred. Imperceptible in practice.
- **SWR 2.0:1** - Good. ~89% power transferred. Acceptable for most deployments.
- **SWR 3.0:1** - Poor. ~75% power transferred. Antenna should be investigated.
- **SWR 5.0:1+** - Bad. Significant reflected power. Can stress or damage some unprotected transmitters over time (many modern radios fold back power at high SWR to protect the power amplifier, but don't rely on it).

Note: these labels are a simple rule of thumb. Other pages in this book (NanoVNA Antenna Testing, SWR & Antenna Analyzers) use slightly different band boundaries for the same SWR values; treat any single SWR figure near a boundary as approximate and prefer the lowest SWR you can achieve.

At LoRa power levels (typically 10-30 dBm / 10mW-1W), a high SWR is unlikely to damage hardware immediately, but it does reduce effective radiated power and range. **Exception:** never transmit with the antenna disconnected (an open or shorted port is effectively infinite SWR). Even at LoRa power, repeatedly keying into no load can damage the power amplifier - always have an antenna or dummy load attached before transmitting.

Return Loss

Return loss is another way to express the same measurement, preferred by RF engineers. It is conventionally reported as a **positive** dB value, and **larger is better** (more dB = less reflected power):

$$\text{Return Loss (dB)} = -20 * \log_{10}(|\Gamma|) = 20 * \log_{10}((\text{SWR}+1)/(\text{SWR}-1))$$

where reflection coefficient $|\Gamma| = (\text{SWR}-1)/(\text{SWR}+1)$

SWR 1.5:1 $\approx$ 14 dB return loss

SWR 2.0:1 $\approx$ 9.5 dB return loss

SWR 3.0:1 $\approx$ 6 dB return loss

Higher return loss (a larger positive dB number) is better, because it means less power is being reflected back from the antenna. A return loss of 14 dB or better is considered a good antenna match. (Some instruments display the reflection coefficient S11 as a negative number, e.g. -14 dB; return loss is just the magnitude of that value, quoted as positive.)

Why Antennas Have Poor SWR

- **Wrong resonant frequency** - Antenna cut for wrong frequency. 433 MHz antennas will not match at 915 MHz.
- **Damaged antenna** - Broken internal element or damaged connector.
- **Loose or oxidized connector** - Resistance at connection point adds to mismatch.
- **Incorrect antenna for your radio's impedance** - Most LoRa radios are 50-ohm; some antennas are 75-ohm (designed for cable TV).
- **Near-field interference** - Conductive material too close to the antenna element.

Measuring SWR Without a VNA

If you don't have a NanoVNA, you can still estimate antenna performance:

- **Two-node range test** - The most practical field test. Compare RSSI/SNR at a known distance with the suspect antenna vs. a known-good stock antenna.
- **RF power meter + dummy load** - Measure forward and reflected power at the transmitter to derive SWR. Be careful with frequency coverage: inexpensive SWR/power meters often top out below $\sim$ 500 MHz, so a sub-\$50 meter may not actually cover 902-928 MHz. Meters or directional couplers that accurately cover 915 MHz generally cost more - verify the meter's rated frequency range includes 915 MHz before relying on it.
- **RSSI comparison** - Place a second node 100m away. Compare received RSSI with the suspect antenna vs. the stock rubber duck. A 3 dB higher RSSI means the receiver got about 2 $\times$ the power - i.e. one antenna outperforms the other by 3 dB in that direction.

This is a rough field comparison, not an SWR measurement, and it is sensitive to placement, orientation, and multipath.

Field Antenna Testing Without Lab Equipment

Professional antenna testing requires a vector network analyzer and anechoic chamber. Field testing with simple tools can still tell you whether an antenna is working as expected for your deployment.

The Two-Node RSSI Test

The most practical field test for comparing antennas:

1. Set up a reference node at a fixed location (indoors at a window, or on a tripod outdoors). Keep the reference node's own antenna unchanged for the whole test.
2. Connect your test antenna to the mobile node
3. Walk to a consistent test point 50-200m away
4. Record RSSI (in dBm) **at the fixed reference node** - it is the end that "hears" the antenna under test. Take several readings (e.g. 10-20 over a minute or two) and average them, since LoRa RSSI swings several dB from multipath and orientation moment to moment. View RSSI in the [Meshtastic app](#).
5. Replace the antenna on the mobile node with a known reference (stock rubber duck or a calibrated dipole)
6. Return to the same test point and record the averaged RSSI at the reference node again

The change in averaged RSSI at the reference node when you swap the test antenna approximates the test antenna's gain change: a +3 dB improvement means the new antenna has roughly 3 dB more gain than the reference, in that direction. This only holds if transmit power, position, and the reference node's antenna are all held constant, and only on the receiving end - so always read RSSI at the fixed reference node, not "either node." A single test point cannot capture pattern differences (for example, a high-gain collinear may show *less* RSSI to a nearby high-angle node despite more boresight gain), so treat the result as a rough comparison, not a precise gain measurement.

Important: Test at multiple azimuths (compass directions) for [directional antennas](#). Omnidirectional antennas should show similar RSSI regardless of direction.

Checking for Antenna Resonance with an SDR

An RTL-SDR dongle (~\$25-40 depending on model and vendor, as of 2026) can help confirm an antenna is "alive," but note that bare noise-floor observation is **not** a reliable resonance test:

1. Connect the test antenna to the SDR via an appropriate adapter
2. Open SDR# or GQRX
3. Look at the noise floor across 900-930 MHz while the antenna is connected vs. with a dummy load or no antenna
4. A working antenna will generally raise the received noise floor versus no antenna, confirming it is receiving - but a rise (or lack of one) does not cleanly prove resonance at 915 MHz, since ambient noise depends on what is transmitting nearby, not solely on antenna resonance.

This noise-floor check only tells you whether the antenna is receiving at all; it is not a resonance or SWR measurement. For a real resonance check, use a NanoVNA to measure return loss, or transmit a known low-power carrier from a second node and compare the received level across frequencies. An RTL-SDR with a noise source and a directional coupler can also reveal resonance notches, but a bare dongle cannot.

Common Field Issues and Quick Diagnosis

Symptom	Likely Cause	Quick Test
RSSI much worse than expected	Wrong frequency antenna, damaged element, or loose connector	Swap with known-good antenna; check connector seating
Range varies wildly with orientation	Antenna is directional (yagi, patch), or near-field coupling to enclosure	Mount antenna away from metal surfaces
Range degrades after outdoor installation	Water ingress into connector or pigtail	Inspect connector for corrosion; re-weatherproof
Node transmits but no one hears it	Open circuit in antenna path (broken cable, wrong adapter)	Verify continuity/SWR with a NanoVNA (receive-only) <i>before</i> transmitting, then swap the cable

Caution: Do not key or transmit with a suspected open or disconnected antenna line. Transmitting into an open or badly mismatched port can damage the radio's power amplifier. Check continuity

and SWR with a NanoVNA (which is receive-only) first, or transmit only briefly with a dummy load attached - never transmit without an antenna or dummy load connected.

Documentation for Installations

For permanent outdoor installations, document your baseline measurements:

- Date of installation
- Antenna model and supplier
- SWR at 915 MHz (from NanoVNA if available)
- RSSI to 2-3 reference nodes at known distances
- Photos of antenna mounting and connector weatherproofing

This documentation makes troubleshooting future performance issues much faster - you have a baseline to compare against.

Connectors & Regulatory Reference

RF Connector Types Guide

Choosing the wrong connector is one of the most common causes of installation failure and wasted money. LoRa devices and antennas use several different RF connector types, and they are not all interchangeable.

The critical SMA vs. RP-SMA distinction

SMA and RP-SMA (Reverse Polarity SMA) look nearly identical but are incompatible. The difference is which part has the center pin. The canonical identification rubric uses both the center contact and the thread location: **SMA male = center pin + external (outside) thread; SMA female = center socket + internal thread.** RP-SMA reverses the center contact only (the threads stay the same):

Connector type	Center contact & thread	Typical use
SMA male	Center pin + external thread (on the plug)	Antenna end; cable end that plugs into a device
SMA female	Center socket + internal thread (device/bulkhead)	Panel mount on enclosures; device ports
RP-SMA male	Center socket + external thread (center is hollow)	Wi-Fi router antennas; also legitimately used on some LoRa boards
RP-SMA female	Center pin + internal thread	Wi-Fi devices; some LoRa enclosures (e.g. certain RAK WisBlock revisions)

For LoRa 915 MHz devices: standard SMA is the more common convention, but RP-SMA is not an error — it originated in the Wi-Fi industry as a way to satisfy FCC § 15.203 (which requires a unique antenna coupling so users can't easily fit a non-compliant antenna). It is not FCC-mandated, and some LoRa products legitimately use RP-SMA. Because boards vary by revision, always verify which connector your specific device has — against the manufacturer's product page — before ordering antennas and pigtails.

How to tell them apart visually: look at the center of the connector. If the plug (male) has a visible pin sticking out, it's standard SMA male. If the male plug has a hole in the center (no pin), it's RP-

SMA male.

Common connector types in LoRa deployments

Connector	Where you'll see it	Max frequency	Notes
SMA	Most LoRa devices; most antennas	18 GHz	Standard for LoRa. Verify SMA vs RP-SMA.
u.FL / IPEX	Board-level connector on many LoRa modules (RAK4631, Heltec boards)	6 GHz	Tiny, fragile. Use pigtail adapter to reach external SMA.
N-type	Outdoor antennas; cable-to-antenna junction	~11 GHz (precision versions to 18 GHz)	Weatherproof, preferred for outdoor permanent installs over SMA.
BNC	Some test equipment	4 GHz	Rarely used for LoRa; easy to connect/disconnect.
MCX / MMCX	Some compact boards	6 GHz	Smaller than SMA; uncommon in LoRa community.

Pigtail adapters

A pigtail is a short cable that adapts between two connector types, e.g., u.FL to SMA bulkhead. Used to bring a board's internal u.FL port out to an external SMA connector through an enclosure wall.

Key rules for pigtails:

- Keep them as short as possible - 10 - 15 cm is ideal. Even "low-loss" pigtails add measurable loss at 915 MHz.
- Use RG316 or LMR-100A for short pigtails. Avoid thin RG178 (high loss) or cheap no-name coax.
- Handle u.FL connectors carefully - they're rated for ~30 insertion cycles. Don't repeatedly attach and detach.

Coaxial cable selection

The figures below are at 915 MHz, expressed both per 100 ft (the standard datasheet reference length) and per 10 ft. They are reconciled with the rest of this book's coax tables and with the Times Microwave / manufacturer datasheets.

Cable type	Loss at 915 MHz (per 100 ft)	Per 10 ft	Use case
LMR-100A	~3.9 dB	~0.4 dB	Pigtails only (under 1 m); too lossy for longer runs
LMR-200	~9.9 dB	~1.0 dB	Short runs (1 - 5 m); rooftop pigtails; default outdoor choice
LMR-400	~3.9 dB	~0.39 dB	Longer runs (5 - 20 m); tower installations; weatherproof
RG58	~10.6 dB	~1.1 dB	Avoid - too lossy for outdoor 915 MHz runs
RG8X	~4.4 dB	~0.44 dB	Acceptable for short outdoor runs; more flexible than LMR-400

Cable loss adds directly to your system's signal attenuation. At 915 MHz a 10-foot LMR-400 run costs about 0.4 dB; the same run in RG58 costs about 1.1 dB - a difference of roughly 0.4-0.7 dB over 10 ft. The gap is small at this length but widens with longer runs, which is where cable quality really matters: a 50-foot RG58 run loses ~5.3 dB versus ~2 dB for LMR-400.

Weatherproofing connections

All outdoor connector joints must be weatherproofed to prevent water intrusion and oxidation:

- **Self-amalgamating (self-fusing) tape:** Wrap from connector body up the cable. Stretch to 50% its width as you wrap - it fuses to itself and creates a waterproof seal. Best for most outdoor installations.
- **Weatherproof connector boots:** Slip-on rubber boots for N-type and SMA connectors. Less reliable than self-amalgamating tape but reusable.
- **Coax seal putty:** Moldable putty for irregular shapes and added protection under tape.

Never use standard electrical tape for weatherproofing RF connectors - it dries out, shrinks, and allows water to track along the adhesive.

FCC Regulations and EIRP Reference

Operating LoRa mesh equipment in the United States requires compliance with FCC Part 15 rules. This page summarizes the relevant regulations and explains how to calculate whether your installation is within limits.

“ **Disclaimer:** This page is a general reference for community operators. It is not legal advice. For installations with high-gain antennas or unusual configurations, consult the FCC rules directly ([47 CFR § 15.247](#), [eCFR](#)) or a licensed RF engineer.

Rules summarized as of June 2026.

The 915 MHz ISM band

LoRa mesh in North America operates in the 902-928 MHz band, designated as an ISM (Industrial, Scientific, and Medical) band. This band is available for unlicensed operation under FCC Part 15, Subpart C (Intentional Radiators).

Key rule: FCC § 15.247 governs spread-spectrum and digitally modulated operation in the 902-928 MHz band.

Power limits

Limit type	Value	Notes
Conducted output power (the primary FCC limit)	1 W (30 dBm)	Maximum power at the antenna port, valid for antennas up to 6 dBi gain; above 6 dBi the conducted power must be reduced (see below)

Limit type	Value	Notes
EIRP (Effective Isotropic Radiated Power)	≈ 36 dBm (4 W) — a derived ceiling, not an independent limit	This is simply 30 dBm conducted + 6 dBi (the maximum gain allowed before power reduction kicks in). § 15.247 does not grant a standalone 4 W EIRP allowance; you cannot reach it by pairing higher gain with full power
Antenna gain above 6 dBi	Reduce conducted power dB-for-dB above 6 dBi	EIRP stays capped at ~36 dBm — § 15.247(b)(4)

There is no extra EIRP allowance at 902-928 MHz — not even for fixed point-to-point links. If your antenna gain exceeds 6 dBi (common with [directional antennas](#)), FCC rules require you to reduce conducted transmit power by the full amount the gain exceeds 6 dBi (47 CFR § 15.247(b)(4)), which keeps maximum EIRP at 36 dBm (4 W) in every configuration. Example: a 9 dBi Yagi limits you to 27 dBm conducted; a 12 dBi antenna to 24 dBm.

You may have read about point-to-point gain allowances in § 15.247 — those provisions (§ 15.247(c)(1)) apply **only to the 2.4 GHz and 5.8 GHz bands**, not to 902-928 MHz. At 2.4 GHz a fixed point-to-point link may reduce conducted power only 1 dB for every 3 dB of gain above 6 dBi (§ 15.247(c)(1)(i)); 5.8 GHz allows extra gain with no reduction (§ 15.247(c)(1)(ii)). **Neither relief exists at 902-928 MHz** — there the full dB-for-dB reduction of § 15.247(b)(4) always applies. Canada's RSS-247 works the same way: its point-to-point exception also excludes 902-928 MHz.

Conditions behind the 1 W figure

The 1 W ceiling applies to qualifying system types: digitally modulated systems with at least 500 kHz of 6 dB bandwidth (§ 15.247(a)(2)), or frequency-hopping systems with at least 50 hopping channels (§ 15.247(b)(2); systems with 25-49 channels — permitted only when the hopping channel's 20 dB bandwidth is 250 kHz or greater, § 15.247(a)(1)(i) — are limited to 0.25 W). Digitally modulated systems are additionally limited to 8 dBm of power spectral density in any 3 kHz band (§ 15.247(e)). Common LoRa mesh presets use 125-250 kHz bandwidth, so **your device's FCC certification grant — not the rule's 1 W ceiling — defines what it is authorized to transmit**. Operating a certified device in its stock configuration is the safe harbor.

EIRP calculation

$\text{EIRP (dBm)} = \text{TX Power (dBm)} + \text{Antenna Gain (dBi)} - \text{Cable Loss (dB)}$

Example 1: Stock node with a small upgrade antenna (within limits)

Parameter	Value
TX power	22 dBm (stock SX1262-class board)
Cable loss (3 m LMR-200)	1.0 dB
Antenna gain	+5 dBi
EIRP	$22 + 5 - 1.0 = 26.0$ dBm (below 36 dBm limit ✓)

Example 2: PA-equipped rooftop repeater (within limits)

Parameter	Value
TX power	27 dBm (500 mW — PA-equipped/base-station class)
Cable loss (3 m LMR-200)	1.0 dB
Antenna gain	+5 dBi
EIRP	$27 + 5 - 1.0 = 31.0$ dBm (below 36 dBm limit ✓)

Note: 3 m of LMR-200 loses about 1.0 dB at 900 MHz (Times Microwave datasheet: ~32.6 dB/100 m). Thinner cables lose more; budget for your actual cable type and length.

Example 3: High-gain antenna requiring power reduction

Parameter	Value
TX power (attempted)	30 dBm (1 W)
Antenna gain	+9 dBi
Required reduction	Antenna gain exceeds 6 dBi by 3 dB → reduce conducted power by 3 dB
Maximum legal TX power	27 dBm (47 CFR § 15.247(b)(4))
Resulting EIRP	$27 + 9 - 0.5$ (cable) = 35.5 dBm (within 36 dBm ✓)

The reduction is computed from antenna gain alone — cable loss does **not** offset it. In Meshtastic, set `LoRa config → Transmit Power` to 27 (integer dBm; always round **down**).

Standard device compliance

Many mainstream LoRa boards (LILYGO T-Beam — FCC ID 2ASYE-T-BEAM, RAK4631 — see [RAK's certification page](#), Heltec, etc.) carry FCC certification covering their shipped configuration. **Check that your specific board has an FCC ID — uncertified clones are common.** If you use a certified device as shipped with the included antenna, or with a replacement antenna **of the same type and equal or lower gain** (47 CFR § 15.204(c)(4)), you are within the certification. A different antenna type or higher gain — even a "comparable" one — is not covered, and compliance responsibility shifts to you.

Custom installations — especially with high-gain external antennas or increased TX power settings — require you to verify EIRP compliance independently.

What happens if you exceed the limits?

Exceeding the limits is a violation of federal rules regardless of how likely enforcement is. The operator (or, for professionally installed equipment, the installer) is responsible for ensuring the system stays in compliance. The FCC can and does act on interference complaints, issuing warnings and monetary forfeitures, and any Part 15 operator must stop transmitting if notified that they are causing harmful interference (47 CFR § 15.5). The rules also exist for good reason: excessive EIRP interferes with other users of the band, including industrial IoT systems, 900 MHz ISM devices, and licensed services.

More practically: running higher power than necessary increases interference with nearby mesh nodes and doesn't improve range as much as better antenna placement would. For most installations, stock TX power with a 3–6 dBi antenna at a better location is the right operating point.

Beyond power limits, fixed transmitters must also comply with the FCC's RF human-exposure (MPE) limits under 47 CFR § 1.1310 (evaluated per § 15.247(i)/OET Bulletin 65). At 915 MHz the general-population power-density limit is roughly 0.6 mW/cm². High-gain or co-located antennas near occupied areas may require an exposure evaluation and a minimum separation distance — keep antennas out of arm's reach of people while transmitting.

Canada (ISED) rules

Innovation, Science and Economic Development Canada (ISED, formerly Industry Canada) rules for 902–928 MHz operation are similar to FCC § 15.247. The relevant standard is [RSS-247](#) (with RSS-Gen general requirements). The conducted power limit is also 1 W, but ISED's antenna-gain and e.i.r.p. provisions are written separately and are not guaranteed identical to FCC § 15.247 — verify against RSS-247 directly rather than assuming they align. RSS-247's point-to-point exception likewise does not cover 902–928 MHz. Certified devices sold in both markets carry both FCC and IC certification numbers.

Frequency coordination

The 902–928 MHz band is shared with many other services and devices, including:

- **Federal radiolocation systems (primary users)** — high-EIRP government radars; you must accept their interference
- **Part 18 ISM equipment** — Part 15 devices are secondary to it
- **Amateur radio (33 cm band)** — licensed hams may also run mesh hardware at higher power under Part 97 (47 CFR § 97.313(j))
- Other LoRa/LoRaWAN deployments
- 900 MHz Wi-Fi (802.11ah/HaLow)
- Legacy 900 MHz consumer devices (older 900 MHz analog/digital cordless phones — now largely obsolete; note that DECT 6.0 cordless phones operate at 1.9 GHz, not 900 MHz — and some baby monitors)

Part 15 operation is unprotected: you must accept interference from these services and must not cause harmful interference to them (47 CFR § 15.5).

Meshtastic and MeshCore each transmit on a single configurable channel frequency — they do **not** automatically frequency-hop. As used in mesh, these are digitally modulated (non-hopping) systems under § 15.247(a)(2), not frequency-hopping systems. If you experience interference, manually select a different frequency slot (Meshtastic: `LoRa config → Frequency Slot`; MeshCore: `set freq` via the serial CLI on repeaters/room servers, or the app's radio settings on client nodes). Coordinate with other operators in your area to avoid overlapping on the same exact frequency.

Antenna Installation and Measurement

Mast and Pole Mounting

Safety first

Erecting and climbing masts is hazardous. Before any mast work:

- **Overhead power lines:** Keep the mast's full fall radius clear of power lines - allow a clearance of at least the mast length plus 10 ft in every direction. A falling or tipping mast that contacts an overhead line can be fatal; power-line contact is the leading cause of installer electrocution.
- **Never raise a mast alone.** Use a spotter, and never raise or work on a mast in wind or near power lines without help.
- **Fall protection:** Use fall protection for any rooftop or elevated work, and do not climb push-up or telescoping masts - they are not rated to support a person.

Mast options

- **J-pipe mounts:** Common TV antenna hardware. Good for moderate antennas on walls or chimneys.
- **Galvanized conduit:** 1-1.5" Schedule 40 steel conduit. Strong, affordable, easy to work with. Suitable for short unguyed masts (commonly cited around 4-5 meters), but the safe free-standing height depends heavily on wind load and antenna weight - for taller masts or heavier antennas, guy the mast or consult a structural/EIA-222 or manufacturer guideline rather than relying on a flat height figure.
- **Telescoping push-up masts:** Aluminum sections. Easy to deploy. Common for temporary or semi-permanent installs.
- **Non-penetrating roof base:** A weighted base holds a mast on a flat roof without drilling. Ballast requirements scale with mast height and antenna wind load - 50 lb of paving blocks is a minimum for short masts only. Calculate the overturning moment for your wind zone; tall masts may need several hundred pounds of ballast or guying. An inadequately ballasted mast can blow over, becoming a falling hazard or striking power lines.

Guy wires

Masts more than about 3-4 meters free-standing (and any telescoping push-up mast above roughly 4 m) need guy wires. Use three guys at 120 degree intervals (a triangular arrangement). Use stainless cable or UV-resistant rope. Guy at 2/3 height and near the top. The exact threshold depends on mast type, antenna wind load, and exposure - guy sooner for heavier antennas or windy sites.

Grounding and lightning protection

Ground the mast and antenna with a bonding/down conductor not smaller than #10 AWG copper (NEC 810.21); #8 AWG or larger exceeds this minimum and is fine. If you drive a separate ground rod for the antenna, it **must** be bonded to the building's main grounding electrode system with at least a #6 AWG copper conductor (NEC 810/250) - grounding the mast to its own isolated rod without bonding to building ground creates a dangerous ground-potential difference and is a code violation. Install a coaxial lightning arrestor rated for 915 MHz at the building entry point and bond it to building ground. See the dedicated [grounding and lightning protection](#) page for full detail.

Key rules

- Mount antenna as high as practical, clear of obstructions
- Keep the coax run short by mounting the radio enclosure close to the antenna
- Use stainless steel hardware outdoors to prevent galvanic corrosion
- **Never power on the radio without an antenna connected** - transmitting into an open or shorted port can damage the power amplifier. LoRa transceivers (SX126x/SX127x) often survive brief keying into an open port, but sustained transmission without a proper load can cause permanent damage, so always connect the antenna (or a 50-ohm dummy load) before transmitting. This caution applies most during bench testing - see the getting-started and testing material.

SWR and Antenna Analyzers

SWR (Standing Wave Ratio) measures how well your antenna is matched to the 50-ohm feedline impedance. A well-matched antenna transfers all power to the air; a mismatched antenna reflects some power back.

SWR values

SWR	Reflected Power	Assessment
1.0:1	0%	Perfect (theoretical)
1.5:1	4%	Excellent
2.0:1	11%	Acceptable
3.0:1	25%	Poor - investigate

Common causes of high SWR

- Connector not fully tightened (most common)
- Water ingress into connector or cable
- Damaged or kinked coax
- Wrong-band antenna (e.g. 868 MHz antenna on a 915 MHz system)

NanoVNA for measurement

The common low-cost NanoVNA-H covers roughly 50 kHz to 1.5 GHz (the original NanoVNA / NanoVNA-H tops out near 1.5 GHz via harmonics, with best accuracy below ~900 MHz). Only some variants such as the NanoVNA-F V2 / V2 series reach 3 GHz. Any of these easily covers the 915 MHz band and is ideal for checking LoRa antenna systems. Check your specific model's published spec before buying. Connect to the antenna feedpoint, sweep 850-950 MHz, and look for the SWR minimum. A good 915 MHz antenna shows SWR below 1.5:1 across the 902-928 MHz band.

Important: A NanoVNA is a measurement instrument, not a transmitter port. Never key up your radio into the analyzer, and never transmit without an antenna connected - doing either can

damage the analyzer or the radio's final stage.

Most commercial LoRa antennas are pre-tuned and work fine out of the box. Measure when troubleshooting performance problems, building DIY antennas, or verifying a new cable run.

Feedline Loss Reference

At 915 MHz, cable loss is significant. A long run of cheap coax can negate the benefit of a quality antenna upgrade. This is the canonical loss table for the book; all values are at 915 MHz, sourced from manufacturer datasheets (Times Microwave for LMR types) and expressed per 100 ft of cable.

Loss at 915 MHz per 100 ft

Cable Type	Loss per 100 ft	Notes
RG-58	~20 dB	Avoid for any outdoor run over about 6 ft (2 m)
RG-8X	~12.6 dB	Acceptable for short indoor runs
LMR-200	~9.9 dB	Good for runs up to about 30 ft (10 m)
LMR-400	~3.9 dB	Use for runs over about 30 ft (10 m)
LMR-600	~2.5 dB	Very long runs; stiff and expensive

Loss scales linearly with length: divide the per-100 ft figure by 10 for a per-10 ft estimate, or multiply by 0.0328 for a per-metre estimate (for example, LMR-400 at ~3.9 dB/100 ft is ~1.28 dB per 10 m).

Practical guidance

- Rooftop install with a 10-15 ft (3-5 m) run: LMR-200 is ideal
- Runs over about 30 ft (10 m): LMR-400 minimum
- Never use RG-58 for permanent outdoor installs
- Each connector adds loss - a quality N connector adds ~0.1-0.3 dB, while cheaper or worn SMA can reach 0.5-1 dB. Either way, minimize adapters.

The proximity advantage: The best way to minimize cable loss is to mount the radio enclosure close to the antenna. A 0.5 m cable run with any cable type adds negligible loss.

Ground Planes for Monopole Antennas

A monopole antenna (vertical rod) radiates efficiently only when paired with a ground plane - a conducting surface that acts as the electrical other half of the antenna.

What counts as a ground plane

- **Vehicle roof:** Excellent. A metal roof is an ideal ground plane for NMO-mount antennas.
- **Metal enclosure:** A metal equipment housing near the feedpoint serves as a ground plane.
- **PCB ground plane:** The copper ground layers on a dev board act as a ground plane for the stock whip / helical ("rubber duck") antenna supplied with dev boards. Note that this is a *marginal* ground plane: the PCB is electrically small at 915 MHz, so performance from the stock antenna is often poor. Where range matters, mount the antenna on a proper ground plane or use a self-contained antenna rather than relying on the dev board.
- **Radials:** For antennas on non-conductive masts, attach 3-4 quarter-wave radials (8.2 cm at 915 MHz) at the base, angled 45 degrees downward.

Do commercial LoRa antennas need a ground plane?

Most commercial 915 MHz verticals designed for LoRa use a self-contained design - a balanced dipole structure, a collinear, or built-in radials - and so do not require an external ground plane. The caveat is common-mode current on the coax shield: even a "self-contained" antenna can effectively turn the feedline into part of the antenna unless it is decoupled (a choke or the antenna's own decoupling section). Check the manufacturer mounting instructions.

How to tell whether your antenna needs a ground plane: a bare whip with no visible radials and a single feed point is a monopole and needs a ground plane. An antenna labeled as a dipole, or one with a wider base section or its own radials, is self-contained. When you are unsure, check the product page, or measure SWR with and without a ground plane - a monopole that needs one will

show a clear difference.

A poorly grounded monopole can have its radiation pattern tilted upward rather than horizontal, reducing effective range. This matters mainly for DIY wire antennas and bare whips, not for self-contained commercial products.

Antenna Fundamentals

How antennas work at 915 MHz, antenna types, gain, and coverage tradeoffs.

How Antennas Work at 915 MHz

How Antennas Work at 915 MHz

An antenna is a transducer that converts electrical energy (RF current on a transmission line) into electromagnetic waves and vice versa. Understanding the physics of this conversion is essential for making informed antenna choices in LoRa mesh deployments at 915 MHz.

The Electromagnetic Wave

When alternating current flows in a conductor, it creates an oscillating electromagnetic field that detaches from the wire and propagates through space as a wave. At 915 MHz, the wavelength in free space is approximately 32.7 cm (about 13 inches), calculated by:

$$\lambda = c / f$$

$$\lambda = 300,000,000 \text{ m/s} \div 915,000,000 \text{ Hz}$$

$$\lambda \approx 0.328 \text{ m (32.8 cm)}$$

This wavelength determines the physical dimensions of resonant antenna elements. A half-wave dipole at 915 MHz is about 16.4 cm long; a quarter-wave monopole is about 8.2 cm. These are the building blocks of virtually all practical antennas.

Radiation Patterns

The radiation pattern describes how an antenna distributes power in three-dimensional space. It is typically depicted as a polar plot showing relative power density in different directions from the antenna.

- **Omnidirectional:** Radiates equally in all azimuthal (horizontal) directions, forming a donut-shaped pattern around a vertical axis. Most LoRa node antennas are omnidirectional.

- **Directional:** Concentrates energy in one or more preferred directions. Used for long-range point-to-point links or sector coverage.
- **Main lobe:** The primary direction of maximum radiation.
- **Side lobes:** Minor lobes at other angles, generally undesirable and wasting power.
- **Null:** Directions where radiated power drops to near zero. High-gain vertical antennas often have a null straight up and straight down.

Antenna Gain: dBi vs dBd

Gain is the most frequently misunderstood antenna specification. Antenna gain does not mean the antenna amplifies power - it cannot; antennas are passive devices. Gain describes how effectively an antenna concentrates available power in a specific direction compared to a reference antenna.

Reference	Symbol	What It Means	Relationship
Isotropic radiator	dBi	Gain relative to a theoretical point source radiating equally in all directions	Base reference; always used in link budgets
Half-wave dipole	dBd	Gain relative to a free-space half-wave dipole	$\text{dBd} = \text{dBi} - 2.15 \text{ dB}$

A manufacturer claiming "5 dBd gain" actually means approximately 7.15 dBi. Always convert to dBi before doing [link budget calculations](#). Be cautious of inflated gain claims on inexpensive antennas - omni gain above about 8 - 9 dBi is achievable, but it progressively narrows the vertical beamwidth, creating coverage gaps for nearby and high-angle nodes. This is the practical (not a hard physical) ceiling for terrestrial mesh: taller stacked collinears with higher gain exist, but their narrow elevation pattern makes them a poor fit for most node sites.

Isotropic vs Real Antennas

The isotropic radiator is a mathematical construct - a perfect point source that radiates uniformly in all directions. No real antenna achieves this. The simplest real antenna, the half-wave dipole, already has 2.15 dBi of gain because it concentrates radiation into its broadside plane rather than wasting energy off the ends.

Real antennas introduce additional losses: conductor resistance (ohmic loss), dielectric loss in radomes or matching components, and impedance mismatch. These losses subtract from the antenna's directivity to give its gain:

$$\text{Gain (dBi)} = \text{Directivity (dBi)} - \text{Loss (dB)}$$

$$\text{where Loss (dB)} = -10 \cdot \log_{10}(\eta), \text{ and } \eta \text{ is the efficiency fraction } (\leq 1)$$

Equivalently: Gain (dBi) = Directivity (dBi) + $10 \cdot \log_{10}(\eta)$

Since $\eta \leq 1$, the $10 \cdot \log_{10}(\eta)$ term is ≤ 0 , so gain is always $\leq$ directivity.

For example, an efficiency of $\eta = 0.90$ (90%) gives $10 \cdot \log_{10}(0.90) \approx -0.46$ dB of loss. A well-made antenna will have efficiency above 90%; cheap or electrically small antennas can fall to 50% or lower (a loss of 3 dB or more), turning claimed gain into a fiction. Note that efficiency expressed as a percentage and the loss expressed in dB are two views of the same quantity: a higher percentage means a smaller (less negative) dB loss term.

Near Field vs Far Field

The space around an antenna is divided into regions based on the character of the electromagnetic field. The boundaries below assume an antenna whose largest dimension is roughly a half-wave dipole ($D \approx 0.16$ m at 915 MHz); the radiating-near-field upper bound scales with that assumed D :

Region	Approximate Boundary	Characteristics
Reactive near field	$r < \lambda/2\pi \approx 5.2$ cm at 915 MHz	Stored energy dominates; reactive components (not yet waves); field shape varies with distance
Radiating near field (Fresnel)	~ 0.052 m to ~ 0.16 m (using $D \approx 0.16$ m, so $2D^2/\lambda \approx 0.16$ m)	Fields begin propagating but pattern shape still changes with distance
Far field (Fraunhofer)	$r > 2D^2/\lambda$	Radiation pattern stabilized; power density drops as $1/r^2$; all link budget calculations apply here

Note: the $2D^2/\lambda$ far-field criterion applies to antennas that are large compared with a wavelength. For small LoRa whips (D smaller than a wavelength), the reactive boundary $\lambda/2\pi$ dominates and the far field effectively begins at a few centimeters.

For practical LoRa mesh purposes, you are always operating in the far field - links are meters to kilometers long. The near field is relevant in two situations: when mounting antennas close to metal objects, where reactive fields can detune the antenna and alter its pattern significantly; and for RF human-exposure. The reactive near field is where RF exposure is highest - avoid placing body parts within a few wavelengths (roughly within tens of centimeters at 915 MHz) of a transmitting antenna, and consult FCC RF-exposure (MPE) guidance (FCC OET Bulletin 65 / 47 CFR 1.1310) for high-power or high-gain installations.

A key takeaway: as a rule of thumb, keep antenna elements at least $\lambda/4$ (about 8 cm at 915 MHz) away from metal surfaces, and preferably $\lambda/2$ or more; the exact clearance needed depends on the element type and ground-plane design. Even a metal enclosure lid placed too close to an antenna can shift its resonant frequency and reduce efficiency measurably - potentially by several dB, depending on proximity and geometry.

Antenna Types for LoRa Mesh

Antenna Types for LoRa Mesh

Choosing the right antenna type for a LoRa mesh deployment is one of the highest-leverage decisions you can make. In free space, doubling your effective communication range requires about +6 dB of gain (4x power); +3 dB increases range by roughly 40% at best, and real-world terrain usually delivers less. This page describes the principal antenna types used at 915 MHz and when each is appropriate.

FCC note: At 902 - 928 MHz, any antenna over 6 dBi requires reducing conducted transmit power dB-for-dB for every dB above 6 dBi (FCC 15.247(b)(4)(i)). High-gain panels and Yagis listed below are legal only with correspondingly reduced power.

Whip / Monopole Antenna

The quarter-wave monopole (whip) is the most common antenna shipped with LoRa hardware. It consists of a single radiating element approximately $\lambda/4$ long (8.2 cm at 915 MHz) mounted vertically above a ground plane.

- **Gain:** About 5.15 dBi over a perfect infinite ground plane (the 2.15 dBi dipole value plus ~3 dB from radiating into a half-space). On the small, imperfect ground planes of LoRa boards, realized gain typically falls to roughly 0 - 2 dBi - use 0 - 2 dBi for real installs and link budgets.
- **Pattern:** Omnidirectional horizontally; slight high-angle radiation
- **When to use:** Portable devices, indoor nodes, situations where the device chassis provides the ground plane (e.g., handheld meshtastic nodes)
- **Limitations:** Heavily dependent on ground plane quality; rubber duck antennas on boards often perform poorly because the PCB is too small to provide an adequate ground plane

Dipole Antenna

The half-wave dipole consists of two $\lambda/4$ elements extending in opposite directions from the feed point. Unlike the monopole, it does not require a ground plane because the two halves are balanced.

- **Gain:** 2.15 dBi (often rounded to 2 dBi)
- **Pattern:** Figure-8 in the vertical plane; omnidirectional in horizontal plane when oriented vertically
- **When to use:** Indoor fixed nodes, enclosure-mounted antennas where no ground plane exists, when a clean omnidirectional pattern is needed without ground plane effects
- **Related antennas:** Related end-fed half-wave antennas include the J-pole, Slim Jim, and end-fed half-wave (EFHW), all of which have built-in matching

Ground Plane Vertical

A ground plane vertical is a quarter-wave monopole with explicit radial elements (usually 3 - 4) extending horizontally from the base. The radials simulate an infinite ground plane, making the antenna self-contained and suitable for tower mounting.

- **Gain:** 2 - 3 dBi
- **Pattern:** Low-angle omnidirectional; superior to a simple monopole on inadequate ground plane
- **When to use:** Rooftop or tower-mounted fixed nodes where a mast cannot provide a ground plane
- **DIY-friendly:** Easy to build from brass welding rod or stiff wire; radial length = $\lambda/4$ (approximately 8.2 cm at 915 MHz)

Yagi-Uda (Yagi) Antenna

The Yagi is a directional array consisting of a dipole driven element, a reflector, and one or more directors. Each additional director increases forward gain at the cost of a narrower beamwidth.

- **Gain:** 6 - 15+ dBi depending on number of elements
- **Beamwidth:** Gain and beamwidth are inversely linked. A low-element Yagi (~6 dBi) has roughly 55 - 65° half-power beamwidth; a high-element Yagi (12 - 15 dBi) narrows to about 30 - 40°.
- **When to use:** Long-range point-to-point links, hilltop relay nodes aimed at a specific valley, extending coverage to a distant neighborhood
- **Limitations:** Must be aimed carefully; useful mainly for infrastructure links between fixed nodes, not general mesh nodes

Patch / Panel Antenna

Patch antennas are flat, planar radiators consisting of a conductive element over a ground plane. Panel antennas are directional arrays of multiple patch elements arranged in a housing.

- **Gain:** 5 - 10 dBi for single patch; 10 - 17 dBi for panels. Note that beamwidth narrows as gain increases (see below), and that panels above 6 dBi require reduced conducted power under FCC 15.247(b)(4)(i).
- **Beamwidth:** Typically 60 - 90° horizontal and 30 - 60° vertical for lower-gain panels; high-gain panels (15 - 17 dBi) are considerably narrower.
- **When to use:** Wall or building-face mounting for sector coverage; urban mesh backhaul; situations where a compact, low-profile form factor is needed
- **Advantages:** Weatherproof, low wind load, compact; good for HOA-restricted installations

Fiberglass Collinear Omnidirectional

These are the classic "white stick" antennas seen on commercial installations. They achieve omnidirectional gain by stacking multiple half-wave elements in phase, which compresses the radiation pattern vertically and increases horizontal gain. In the table below, "element" refers to radiating half-wave sections; reaching ~10 dBi of omni gain at 915 MHz takes roughly 8 stacked half-wave sections.

Configuration	Typical Gain	Physical Height (approx.)	Best Use Case
2-element collinear	5 dBi	50 - 70 cm	General outdoor fixed nodes
4-element collinear	8 dBi	1.2 - 1.5 m	High-elevation relay nodes with flat terrain
6-element collinear	10 dBi	2.0 - 2.5 m	Tower-top relay, open terrain only

Note: A 5/8-wave vertical (~20 cm, ~3 dBi) is sometimes used as a compact single-element fixed-node antenna, but it is a monopole variant, not a stacked collinear, so it is not listed in the collinear table above.

Important: Collinear antennas above 8 dBi should only be used at high elevation. At ground level, the extremely flat radiation pattern creates dead zones both above and below, meaning nodes that are close but at different elevations may not communicate reliably.

Summary Decision Matrix

Antenna Type	Gain	Pattern	Best Application
Whip/monopole	0 - 2 dBi	Omni	Portable devices, indoor

Antenna Type	Gain	Pattern	Best Application
Dipole	2.15 dBi	Omni	Indoor fixed, no ground plane
Ground plane vertical	2 - 3 dBi	Omni, low-angle	Rooftop/tower, self-contained
Collinear (5 dBi)	5 dBi	Omni, compressed	Outdoor fixed node, moderate elevation
Collinear (8 dBi)	8 dBi	Omni, flat disk	High relay node, flat terrain
Panel / Patch	10 - 17 dBi	Sector (~90° at ~10 dBi; narrower at higher gain)	Building-face sector, backhaul
Yagi	6 - 15 dBi	Directional	Point-to-point, long-range link

Antenna Gain and Coverage Tradeoffs

Antenna Gain and Coverage Tradeoffs

Antenna gain is not free - it is always traded against something else. Understanding what gain costs you is essential before choosing an antenna for a mesh deployment. The fundamental law of antenna physics is conservation of energy: an antenna cannot create power, only redistribute it.

How Gain Concentrates Signal

Consider a theoretical isotropic antenna radiating 1 watt equally in all directions. At 1 km, that power is spread over a sphere of area $4\pi(1000)^2 = 12.57$ million square meters. A 5 dBi antenna ($3.16\times$ linear gain) compresses its radiation into a narrower cone, delivering up to $3.16\times$ more power density in its peak direction (for a lossless antenna; real-antenna efficiency below 100% reduces the actual on-axis power density slightly below this figure). From the perspective of a receiver in the main beam, it is roughly equivalent to the transmitter having $3.16\times$ the power.

This is the core of EIRP (Effective Isotropic Radiated Power):

$$\text{EIRP (dBm)} = \text{Transmit Power (dBm)} + \text{Antenna Gain (dBi)} - \text{Feedline Loss (dB)}$$

FCC Part 15.247 limits **conducted** output power to 1 watt (30 dBm) for digitally-modulated / spread-spectrum systems across the entire 902 - 928 MHz band, regardless of whether the link is point-to-point or point-to-multipoint. That conducted limit is referenced to an antenna of up to 6 dBi gain, which yields up to about 36 dBm (4 W) EIRP. If the antenna gain exceeds 6 dBi, conducted power must be reduced dB-for-dB for each dB above 6 dBi (15.247(b)(4)(i)), holding EIRP at roughly 36 dBm. There is no separate, lower point-to-multipoint limit, and there is no relaxed point-to-point antenna allowance at 915 MHz - that relaxation exists only at 2.4 and 5.8 GHz. See the [directional antennas](#) page for worked examples.

Most LoRa nodes run 17 - 20 dBm conducted transmit power. At those levels you may add an antenna of up to 6 dBi with no power reduction; beyond 6 dBi you must begin reducing conducted power dB-for-dB. Because the binding constraint above 6 dBi is conducted-power reduction (not a simple EIRP cap you spend "budget" against), high-gain antennas do not give you free EIRP headroom at 915 MHz.

Elevation Angle and Radiation Pattern Compression

As gain increases, the radiation pattern in the vertical plane becomes flatter - more like a pancake and less like a donut. This is measured as the vertical beamwidth (the angle between the -3 dB points above and below the horizon). The approximate beamwidths below are typical design figures, not exact datasheet values; consult a specific antenna's datasheet for its actual pattern.

Antenna Gain	Approx. Vertical Beamwidth	Radiation Elevation Angle
2 dBi (dipole)	~75°	Broad; works at steep angles
5 dBi collinear	~35 - 40°	Slightly elevated; works for nearby nodes
8 dBi collinear	~15 - 20°	Near-horizontal; close nodes may be in null
10 dBi collinear	~10 - 12°	Essentially horizontal; nodes must be far away to be in the beam

Dead Zones Below High-Gain Antennas

This is the most commonly overlooked problem with high-gain omnidirectional antennas in mesh networks. When you mount a 10 dBi collinear antenna on a rooftop, the signal goes predominantly outward - not down. Nodes directly beneath the tower, or on the same city block, may receive weaker signal than nodes kilometers away.

The reduced-coverage radius under a vertical omni antenna can be roughly estimated as the distance at which the main beam's lower -3 dB edge first reaches ground level, assuming the beam peak sits at the horizon:

Reduced-Coverage Radius $\approx h / \tan(\theta / 2)$

Where:

- h = antenna height above nodes (meters)
- θ = full vertical beamwidth (degrees), so $\theta/2$ is the angle from the horizon down to the lower -3 dB point

Example: 10 dBi antenna at 30 m height, 10° vertical beamwidth

($\theta = 10^\circ$, so $\theta/2 = 5^\circ$):

Radius $\approx 30 / \tan(5^\circ) \approx 30 / 0.0875 \approx 343$ meters

In this example, a node within roughly 343 meters of the tower base sits below the main beam's lower edge and may receive noticeably less signal - often 10 dB or more, depending on the antenna's side-lobe levels - than a node 2 km away. Treat 343 m as an order-of-magnitude reduced-coverage radius rather than a hard dead zone: signal inside it is attenuated but rarely a true null, since real coverage close in is governed by side-lobe levels, not a sharp cutoff. In a dense urban mesh, this reduced near-in coverage can still be a serious problem.

The 3 / 5 / 8 dBi Decision Guide

Use this framework when selecting omni antenna gain for a fixed node:

Gain Choice	Use When	Avoid When
2 - 3 dBi (whip, dipole, GP vertical)	Indoor node; node surrounded by other nodes at similar elevation; portable device; building where nodes are on every floor	Outdoor exposed relay where range to distant nodes is the primary goal
5 dBi (short collinear)	Outdoor rooftop node in urban/suburban area; nodes are within 2 - 5 km; mixed elevation terrain; best all-around choice for most mesh relay nodes	Indoor use; terrain with significant elevation variation around the node
8 dBi (medium collinear)	High hilltop or tower relay overlooking flat terrain; all served nodes are at roughly the same elevation and 5 - 20 km distant; rural backbone relay	Urban environment; any situation with nodes at varying elevations; anywhere nodes might be directly below the antenna

Rule of thumb: When in doubt, choose 5 dBi for any outdoor fixed node. It provides meaningful gain improvement over a whip without creating serious dead zone problems. Reserve 8+ dBi for well-planned backbone relay sites with known terrain profiles.

Directional antennas: When gain beyond 8 dBi is needed, switch to a directional antenna (panel or Yagi) aimed at the intended coverage direction. You gain range in the beam, and the dead zone problem is inherent to the design intent - it only covers one sector anyway. Remember that any antenna above 6 dBi requires reducing conducted power dB-for-dB at 902 - 928 MHz to stay within Part 15.247.

Coax, Connectors, and Feedline

Cable selection, RF connectors, and feedline loss minimization for LoRa installations.

Coax Cable Selection Guide

Coax Cable Selection Guide

The coaxial cable connecting your LoRa radio to its antenna is a critical component that directly subtracts from your link budget. Every decibel of cable loss is a decibel less of received signal and, equivalently, a decibel less of radiated power. Understanding the tradeoffs between cable types helps you make smart choices for your deployment.

Understanding Cable Loss

Coaxial cable loss is caused by two primary mechanisms:

- 1. **Conductor (ohmic) loss:** Resistance of the inner and outer conductors dissipates RF energy as heat. Increases with frequency (skin effect drives current to conductor surface, effectively reducing conductor area).
- 2. **Dielectric loss:** The insulating material between conductors absorbs some RF energy. Also increases with frequency.

Both losses increase with frequency, which is why a cable that seems acceptable at VHF (150 MHz) can be disastrously lossy at 915 MHz. Always check specifications at or near your operating frequency.

Cable Loss Comparison at 915 MHz

Loss figures below are stated per 100 ft at 915 MHz, sourced from the manufacturer (Times Microwave LMR / Andrew-CommScope) and reference coax datasheets; the "per 10 ft" column is simply the per-100-ft figure divided by ten. Use these canonical values for all link-budget planning; other pages in this book reference this same table.

Cable Type	Outer Diam.	Loss (dB/100 ft) @ 915 MHz	Loss per 10 ft	Impedance	Flexibility
RG-174	2.8 mm	~28 dB	~2.8 dB	50 Ω	Very flexible; pigtails only
RG-58/U	5 mm	~20 dB	~2.0 dB	50 Ω	Flexible; common

Cable Type	Outer Diam.	Loss (dB/100 ft) @ 915 MHz	Loss per 10 ft	Impedance	Flexibility
RG-8X (mini 8)	6.1 mm	~12.6 dB	~1.26 dB	50 Ω	Semi-flex; good budget cable
RG-213/U	10.3 mm	~8 dB	~0.8 dB	50 Ω	Stiff; older mil-spec
LMR-100A	2.79 mm	~22.8 dB	~2.28 dB	50 Ω	Very flexible; pigtails/jumpers
LMR-200	5.4 mm	~9.9 dB	~0.99 dB	50 Ω	Semi-flexible; good midrange
LMR-400	10.3 mm	~3.9 dB	~0.39 dB	50 Ω	Semi-rigid; best low-loss practical
LMR-600	15.8 mm	~2.5 dB	~0.25 dB	50 Ω	Rigid; tower/commercial use
Andrew FSJ1-50A (1/4" Superflex)	7.1 mm	~4.4 dB (verify against CommScope datasheet)	~0.44 dB	50 Ω	Flexible hardline; pro installations

Practical Loss Examples

To illustrate the real-world impact, consider a typical outdoor node installation with 20 ft (6 m) of cable between the radio and antenna. The loss figures below are computed directly from the canonical per-100-ft table above (20 ft = 0.2 × the per-100-ft value). Range penalties assume free-space (inverse-square) propagation, where the range ratio = 10^{^(−loss_dB/20)}; real-world terrain makes the penalty smaller in some cases and larger in others, so treat these as approximate:

Cable Choice	Loss for 20 ft	Equivalent TX Power Reduction	Range Penalty (free space, approx.)
RG-58	~4.0 dB	17 dBm → 13.0 dBm (effective)	~37% shorter range
LMR-200	~2.0 dB	17 dBm → 15.0 dBm (effective)	~21% shorter range
LMR-400	~0.8 dB	17 dBm → 16.2 dBm (effective)	~9% shorter range

Cable Selection Recommendations

Short runs (under 3 ft / 1 m) - pigtails and jumpers

Use LMR-100A or RG-174. These are flexible enough to route in tight spaces and the short length keeps absolute loss acceptable (under 0.9 dB for a 3 ft run). This is the correct cable for the factory pigtail from the LoRa radio to the connector panel.

Medium runs (3 - 20 ft / 1 - 6 m)

LMR-200 is the best choice: meaningful loss improvement over RG-58, flexible enough to route around obstacles, and connectors are readily available. This is the correct choice for most outdoor node installations where the radio is inside an enclosure and the antenna is a few feet above.

Long runs (20 - 100 ft / 6 - 30 m)

LMR-400 is strongly recommended. The loss reduction over LMR-200 is significant at these lengths. For runs over 50 ft, consider whether you are better served by moving the radio closer to the antenna (POE-powered remote radio, for example).

When to upgrade your cable

Upgrade cable when feedline loss exceeds 3 dB. At 3 dB loss, you are throwing away half your transmit power before it even reaches the antenna, and your receive sensitivity is degraded by approximately 3 dB (feedline loss ahead of the radio raises the system noise figure by close to the cable loss, depending on the radio's own noise figure) - effectively halving your effective radiated power and degrading reception in both directions simultaneously. No antenna upgrade will compensate for this.

Avoiding Common Coax Mistakes

- **Never kink or crush coax.** A sharp kink or bend beyond the cable's minimum bend radius can add significant localized loss and reflections, and can permanently damage the cable. LMR-400 has a minimum bend radius of about 1 inch; exceeding this damages the shield and dielectric.
- **Waterproof all outdoor connectors.** Water ingress between the connector and cable will corrode the connection and introduce significant loss within weeks. Use self-amalgamating tape over all outdoor connections.
- **Do not daisy-chain adapters.** Each adapter adds a small amount of loss (typically well under ~0.5 dB) and a potential failure point. If you need an N to SMA connection, use a single pigtail, not an N-to-PL259 + PL259-to-BNC + BNC-to-SMA chain.
- **Store connectors facing down outdoors.** Connector faces should point downward or be shielded from direct rainfall to prevent standing water in the connector mating face.

RF Connectors for LoRa Hardware

RF Connectors for LoRa Hardware

RF connector incompatibility is one of the most common and frustrating problems when assembling LoRa mesh hardware. Knowing which connectors are standard on which hardware and understanding adapter losses will save hours of troubleshooting and return shipping.

The Principal Connector Families

SMA (SubMiniature version A)

SMA connectors are the workhorses of small-form RF hardware. They are threaded (10-32 thread) and rated to 18 GHz in standard form. Power handling is frequency-dependent: a standard SMA handles roughly 100 W at HF, derating sharply with frequency to only a few watts near 18 GHz. (At LoRa's sub-1 W transmit power this is academic; for genuinely high-power runs use N-type or larger.) Two variants cause constant confusion:

Type	Center Pin on Male	Center Pin on Female	Notes
SMA (standard)	Pin protrudes	Socket (receptacle)	Used on most professional RF equipment and high-quality antennas

Type	Center Pin on Male	Center Pin on Female	Notes
RP-SMA (Reverse Polarity)	Socket (receptacle)	Pin protrudes	An industry convention WiFi vendors adopted to comply with FCC 47 CFR 15.203, which requires a unique (non-standard) antenna coupling so the public cannot easily fit unauthorized antennas. The FCC does not mandate RP-SMA specifically — only a non-standard coupling; RP-SMA is one common way to meet that requirement. Extremely common on consumer WiFi and found on some consumer LoRa hardware.

Critical: Standard SMA and RP-SMA are physically intermateable - the threads engage and the connector tightens - but they do NOT make electrical contact. You will have a physically connected but RF-dead assembly. Always verify polarity before tightening.

Which LoRa Hardware Uses Which?

Hardware	Connector
RAK WisBlock (RAK4631, RAK19007)	U.FL / IPEX on module; SMA via the supplied IPEX-to-SMA pigtail (not a fixed enclosure connector)
Lilygo T-Beam (most versions)	SMA female (standard)
Heltec WiFi LoRa 32 v2/v3	Varies by revision: U.FL / IPEX on PCB on some boards, board-mounted SMA on others. Verify your specific board.
Meshtastic / LilyGo T-Echo	U.FL on PCB
Seeed WIO-E5 module	U.FL on module
Dragino LPS8 gateway (indoor)	SMA female
RAK Wisgate Edge (commercial gateway)	N-female (standard)
TTGO LoRa32 v2	U.FL with bundled SMA pigtail
Adafruit Feather M0 RFM95W	U.FL; use an SMA edge-launch or U.FL pigtail

Note: Connector types can vary by hardware revision. Always verify on the actual unit or current product page before ordering cables and adapters.

N-Type Connector

The N-type is a larger, weatherproof threaded connector rated to 11 GHz (standard) or 18 GHz (precision). It is the connector of choice for any serious outdoor installation - towers, rooftop

gateways, commercial deployments. N-type connectors have excellent weatherproofing when properly assembled, low contact resistance, and are designed for repeated mating cycles.

- **Used on:** Commercial gateways (Dragino, RAK Wisgate, Kerlink, MultiTech), tower-mount antennas, LMR-400 and larger cable installations
- **Loss:** Typically 0.05 - 0.1 dB per connector pair at 915 MHz
- **Availability:** Widely available; both solder and crimp versions for all major coax types

U.FL / IPEX / MHF1 Connector

U.FL (the Hirose trade name) or IPEX/MHF1 (equivalent generic and Amphenol variants) are ultra-miniature snap-lock coaxial connectors used on PCBs to connect the RF IC to an external antenna pigtail. They are rated to only about 30 mating cycles, so they are not designed for repeated disconnection.

- **Used on:** Almost all LoRa and GPS modules mounted on PCBs - Heltec, RAK module cores, TTGO, and most other SoC-level boards
- **Important:** Extremely fragile and rated for only ~30 mating cycles; do not repeatedly disconnect/reconnect. Lock in place and leave. If you need a permanent connection, solder a small bead of hot glue after mating to prevent accidental disconnection.
- **Pigtails:** Use only U.FL-to-SMA (or RP-SMA) pigtails made with RG-178 or similar micro-coax. The connector at the board end is U.FL female (socket on pigtail). The connector at the panel end should match your application (SMA, N, etc.)
- **Loss:** The U.FL connector itself adds only ~0.05 - 0.1 dB at 915 MHz; a typical U.FL pigtail (connector + thin coax) adds ~0.2 - 0.5 dB total, most of which is the thin pigtail coax.

Adapter Losses

Each adapter in the RF path adds loss and a potential failure point. Typical losses at 915 MHz:

Adapter Type	Typical Loss at 915 MHz	Notes
SMA(M) to SMA(F) barrel	0.1 - 0.2 dB	Use only when necessary; prefer direct cable
SMA to N-type	0.1 - 0.3 dB	Acceptable for indoor patch panels; not preferred outdoors
RP-SMA to SMA	0.1 - 0.2 dB	Common necessity when mixing hardware
U.FL to SMA pigtail	0.2 - 0.5 dB	U.FL connector + cable loss; unavoidable for PCB boards
PL-259/SO-239 (UHF)	0.3 - 0.8 dB	Not designed for 915 MHz; avoid entirely

Quality Matters

A cheap SMA connector or adapter purchased in a \$3 bag of 20 pieces is not equivalent to a \$5 Amphenol or TE Connectivity connector. Differences include:

- Contact resistance: quality connectors use silver or gold plating; cheap ones use brass or tin that oxidizes
- Dimensional tolerances: loose tolerances cause intermittent contact at vibration or thermal cycling
- Dielectric quality: cheap connectors use low-grade PTFE substitutes that absorb moisture
- Thread quality: soft aluminum threads strip after a few matings

For outdoor permanent installations, spend the money on proper connectors. For bench development, economy connectors are acceptable. Never use economy connectors in a deployed outdoor node.

Minimizing Feedline Loss

Minimizing Feedline Loss

Feedline loss is the silent enemy of RF system performance. Unlike antenna gain (which you buy) or transmit power (which you set), feedline loss just silently destroys the performance you already have. This page provides the tools to quantify, minimize, and budget feedline loss in your LoRa mesh installations.

The Link Budget Impact of Feedline Loss

Feedline loss hits you twice - once on transmit and once on receive. On transmit, every dB of cable loss reduces your effective radiated power by 1 dB. On receive, cable loss before the receiver's low-noise amplifier (LNA) degrades the noise figure of the entire receive chain by 1 dB per 1 dB of cable loss. (On the common SX126x/SX127x LoRa transceivers the LNA is on-chip, so essentially all feedline and connector loss precedes it.)

Example: 20 dBm TX, 5 dB cable loss, 5 dBi antenna

$\text{EIRP} = 20 \text{ dBm} + 5 \text{ dBi} - 5 \text{ dB} = 20 \text{ dBm}$

Example: Same cable with a 2 dBi antenna

$\text{EIRP} = 20 \text{ dBm} + 2 \text{ dBi} - 5 \text{ dB} = 17 \text{ dBm}$

Conclusion: 5 dB of cable loss ERODES the benefit of the better antenna.

The 5 dBi antenna with 5 dB of cable loss (EIRP 20 dBm) still beats the 2 dBi antenna with the same 5 dB of cable loss (EIRP 17 dBm) by 3 dB. What the loss destroys is the UPGRADE relative to a no-loss case: with no cable loss the 5 dBi antenna would deliver 25 dBm EIRP, so the 5 dB of cable swallowed the entire 5 dB the antenna could have given. Reducing the cable loss recovers more than the antenna upgrade itself provided.

FCC note: these EIRP figures (20 dBm, 17 dBm) are far below the limit. Under 47 CFR 15.247 the regulatory ceiling at 915 MHz is on *conducted* output power - 1 W (30 dBm) into an antenna of up to 6 dBi - with a derived EIRP ceiling of about 36 dBm (4 W). Feedline loss subtracts from EIRP, so adding cable can only move you further below the limit, never above it.

Cable Length Math

To calculate cable loss for a given run, use the loss per 100 ft specification from cable data sheets. The per-100 ft figures below are the canonical 915 MHz values from the book's feedline-loss reference (Times Microwave LMR datasheets):

Loss (dB) = (Loss per 100 ft at 915 MHz) × (Run length in feet) ÷ 100

Examples for a 15 ft run:
LMR-100A: 22.8 dB/100ft × 15/100 = 3.42 dB
LMR-200: 9.9 dB/100ft × 15/100 = 1.49 dB
LMR-400: 3.9 dB/100ft × 15/100 = 0.59 dB

For metric calculations (loss per 100 m):

Loss (dB) = (Loss per 100 m at 915 MHz) × (Run length in meters) ÷ 100

The Full System Loss Budget

Account for every component in the RF path between radio and antenna:

Component	Typical Loss	Notes
U.FL connector (at PCB)	0.2 - 0.5 dB	Present on most PCB-based LoRa boards (typical U.FL insertion loss at ~1 GHz)
U.FL-to-SMA pigtail (6")	0.3 - 0.5 dB	RG-178 pigtail from PCB to enclosure panel (RG-178 ~0.5-0.8 dB/ft at 900 MHz plus connectors)
SMA to N-type adapter	0.1 - 0.2 dB	Quality adapter, if converting at the enclosure panel
Main feedline (LMR-200, 10 ft)	~1.0 dB	From enclosure to antenna base (9.9 dB/100 ft at 915 MHz × 10/100)
N-type connector at antenna	0.1 dB	Quality N-type connector
Lightning arrestor	0.1 - 0.3 dB	If inline gas discharge tube used
Total example	~1.8 - 2.6 dB	

In this example, a real system with 10 ft of LMR-200 would have about 2 dB of total system feedline loss. This is acceptable. If you replace the LMR-200 with RG-58 (~20 dB/100 ft at 915 MHz), the 10 ft main cable alone goes from ~1.0 dB to ~2.0 dB - adding ~1 dB extra and pushing total loss toward 3 dB or more, where you start losing meaningful range. RG-58 is a poor choice at

915 MHz.

Inline Connectors Double Loss

Every barrel connector, adapter, or splice in the cable run adds loss and a potential water ingress point. For outdoor installations:

- Plan your cable routing so you can run a single unbroken cable from the enclosure to the antenna
- If you must make a field splice, use a waterproof N-type barrel connector (not SMA) and seal with self-amalgamating tape
- Adapters at the radio or antenna end are sometimes unavoidable; minimize them everywhere else

When Cable Loss Is Unavoidable: Remote Radio Head

For installations requiring very long cable runs (tower top, building rooftop with equipment room far from the rooftop), consider placing the radio module in a weatherproof enclosure directly at the antenna mounting point. Power is delivered via a long DC cable, and data is retrieved via Ethernet or WiFi (or just on-board storage). This approach reduces feedline loss to the short U.FL pigtail and short jumper, typically under 1 dB total.

Checking Your Cable with SWR

A cable that looks fine externally can have significant internal damage (crushed, kinked, or water-damaged dielectric). A quick SWR check with a NanoVNA or antenna analyzer can reveal the problem. Connect the analyzer to one end with the other end open or shorted. A healthy cable will show predictable impedance; a damaged cable will show irregular spikes or elevated VSWR at unexpected frequencies due to impedance discontinuities at the damage point.

Mounting, Grounding, and Lightning Protection

Mechanical installation, grounding systems, and lightning protection for outdoor antenna systems.

Antenna Mounting Best Practices

Antenna Mounting Best Practices

Proper antenna mounting is the difference between a node that stays up through storms and one that fails or becomes a hazard. This page covers mechanical considerations, materials, and installation techniques for outdoor LoRa mesh antennas.

SAFETY WARNING - read before raising any mast. Aluminum and steel masts are electrical conductors, and contact with an overhead power line is frequently fatal. This is the leading cause of installer electrocution. Before raising any mast, confirm clearance of **at least the full mast length plus 10 ft (3 m) from every overhead power line** in the mast's entire fall radius - if the mast were to fall or swing in any direction, it must not be able to reach a line. Additionally: use fall protection for any work at height, keep people clear of the area below where a mast or antenna could fall, and never raise a mast alone. Tall or heavily loaded masts can swing unpredictably; have a second person steady the base.

Mast Types

The mast is the structural element that holds the antenna at height. Selection depends on application, available mounting surface, and antenna weight and wind load.

Mast Type	Material	Typical Height	Best Use	Notes
J-mount / pipe mount	Galvanized steel or aluminum	0 - 0.6 m above mount point	Eave and fascia mounting; residential rooftops	Low cost; widely available; adequate for small omni antennas

Mast Type	Material	Typical Height	Best Use	Notes
Telescoping push-up mast	Aluminum sections	3 - 12 m	Temporary deployment; emergency comms	Conductive - keep clear of power lines (see safety warning above). Push-up masts generally need guying once extended past a few metres (manufacturers commonly specify guying from roughly 4 m up); not rated for permanent installation without guying. Follow the specific mast's manual.
Schedule 40 galvanized pipe	Hot-dip galvanized steel	As designed	Permanent rooftop or ground-mounted nodes	1.5" or 2" diameter accommodates most commercial antenna clamps; excellent durability
Aluminum angle/tube	6061-T6 aluminum	Variable	Lightweight permanent installations	Good where weight matters; do not use raw aluminum near dissimilar metals (galvanic corrosion)
Non-conductive fiberglass mast	Fiberglass-reinforced polymer	Variable	When RF transparency is required; stealth installations	Higher cost; consider when metal mast would detune the antenna

Standoff Distance from Metal

Metal surfaces reflect and absorb RF energy at 915 MHz. Mounting an antenna too close to metal degrades performance, shifts resonant frequency, and distorts the radiation pattern. Pattern distortion does not vanish abruptly at any one distance - it decreases continuously as separation grows - so treat the figures below as a tiered rule of thumb (at 915 MHz, $\lambda \approx 33$ cm):

- **Absolute minimum standoff from any metal surface:** $\lambda/4 \approx 8$ cm. Below this, reactive near-field coupling to the metal significantly alters antenna behavior.
- **For little discernible pattern distortion:** $\lambda/2 \approx 16$ cm or greater (a rule of thumb - distortion lessens gradually, it does not stop at exactly $\lambda/2$).
- **Conservative target for high-performance fixed installs:** a full wavelength, ≈ 33 cm, where practical. This matches the "one wavelength from metal structures" rule given on the Base Station & Outdoor Antennas page.

- **For vertical collinear antennas mounted to a metal mast:** mount the antenna's feedpoint roughly one wavelength (about 33 cm at 915 MHz) above the top of the metal mast where practical, using a non-conductive standoff bracket or fiberglass spacer. Consult the antenna's installation manual for any mast-top clearance it specifies.
- **Metal roof surfaces:** mount the antenna well clear of the metal roof plane - on the order of a wavelength or more (roughly 0.3 - 0.6 m at 915 MHz) - to clear the roof's RF reflection zone.

Exception: if the metal IS the ground plane (e.g., a quarter-wave monopole mounted to a metal enclosure lid), close proximity is intended. A monopole needs a ground plane of at least about $\lambda/4$ radius (~ 8 cm radius / ~ 16 cm diameter at 915 MHz); the 30 cm ($\approx$ one wavelength) diameter recommended here is a conservative target. Ensure the metal surface is electrically bonded to the antenna's ground reference.

J-Mount vs Direct Mount

The J-mount (also called a J-arm, chimney mount, or eave mount) is a bracket that attaches to an eave, chimney, or fence post and holds a vertical mast pipe. It is the standard residential antenna mounting solution. (Note: a "J-pole" is a type of *antenna* - an end-fed half-wave - not a mount. The bracket described here is a J-mount; don't confuse the two.)

- **J-mount advantages:** No roof penetration required; easy to install and remove; good for HOA-restricted or rental properties
- **J-mount disadvantages:** The mast end hangs below the mounting surface, limiting usable height gain; can deform in high winds if not sized correctly
- **Direct mount (U-bolt to mast):** Preferred for rooftop penetrations or wall-through installations where a base plate is attached directly to a structural surface. More permanent and secure but requires sealing any penetration against water intrusion.

Pole Diameters and Clamp Compatibility

Commercial antenna base clamps are typically designed for specific pole outside diameters. The most common:

Nominal Pipe Size	Actual OD	Compatible Clamps
3/4" Schedule 40 pipe	26.7 mm (1.05")	Clamps rated for 1" - 1.25" poles
1" Schedule 40 pipe	33.4 mm (1.32")	Clamps rated for 1.25" - 1.5" poles
1.5" Schedule 40 pipe	48.3 mm (1.9")	Clamps rated for 1.5" - 2" poles; most commercial clamps
2" Schedule 40 pipe	60.3 mm (2.375")	Heavy-duty commercial clamps

Always verify clamp OD range before ordering. Antenna manufacturers typically specify the accepted pole diameter range in the product data sheet.

UV-Rated Materials

At 915 MHz, antenna elements and enclosures are routinely exposed to direct sunlight for years. UV degradation is a real concern:

- **Antenna radomes:** Quality outdoor antennas use UV-stabilized fiberglass or ABS. Cheap antennas often use standard PVC or thin ABS that chalks and cracks within 2 - 3 years in direct sun.
- **Cable jacket:** Use UV-resistant (black polyethylene or LLDPE jacket) cable for any outdoor run. LMR-400 standard uses a black UV-resistant jacket. White or gray jacketed cables require conduit or UV protection coating if exposed.
- **Mounting hardware:** Use stainless steel (316 preferred for coastal; 304 acceptable inland) or hot-dip galvanized hardware. Zinc-plated (electroplated) hardware will rust within 2 - 5 years outdoors.
- **Cable ties:** Use UV-rated black nylon cable ties, not natural (white) ties which degrade in 6 - 18 months of sun exposure. Stainless steel cable ties are best for permanent high-UV installations.
- **Enclosures:** NEMA 4X (IP66) ABS or polycarbonate enclosures with UV stabilization are appropriate for electronics housing. Fiberglass NEMA 4X enclosures offer superior UV resistance for long-term outdoor use.

Wind Load Considerations

Antenna wind loading is a frequently overlooked mechanical consideration. A 5 dBi fiberglass omni in a 60 mph wind generates more force than most people expect:

$$\text{Approximate wind load (lbs)} = 0.00256 \times V^2 \times A \times C_d$$

Where:

V = wind velocity (mph)

A = projected area (ft²) = diameter × length

C_d = drag coefficient (~1.2 for cylinders)

Example: 1" diameter × 3 ft antenna at 70 mph wind:

$$\text{Area} = (1/12) \times 3 = 0.25 \text{ ft}^2$$

$$\text{Load} = 0.00256 \times 70^2 \times 0.25 \times 1.2 \approx 3.8 \text{ lbs bending force}$$

Same method for a 5 dBi fiberglass omni (~1.25" × 4 ft, area ≈ 0.42 ft²) at 60 mph:

$$\text{Load} = 0.00256 \times 60^2 \times 0.42 \times 1.2 \approx 4.6 \text{ lbs} - \text{acting at the top of the mast.}$$

These forces seem small but they act at the top of the mast, creating a significant bending moment (force $\times$ height) at the mounting point - that moment, not the raw force, is what overloads a mount. This is a simplified flat-plate estimate: real structural design per ASCE 7 adds height (Kz), topographic (Kzt), and gust factors that can raise the effective load roughly 1.5 - 3 $\times$, so tall masts see considerably more than this simple figure suggests.

To size a mast, compare the bending moment (force $\times$ mounting height) against the mast and mount manufacturer's published moment or load rating, and apply a generous safety margin (a 3 $\times$ rule of thumb is a reasonable starting point, but it is not a substitute for the manufacturer's rating). For tall or multi-antenna installations, account for the cumulative load of every antenna on the mast, and have the design reviewed by someone with structural experience.

Installer safety reminder: rooftop and at-height work carries fall and dropped-object hazards independent of the structure's wind rating. Use fall protection, secure tools and hardware so nothing drops onto people below, keep the area beneath the work clear, and re-check the power-line clearance warning at the top of this page before raising anything.

Grounding and Lightning Protection

Grounding and Lightning Protection

A properly grounded and surge-protected antenna installation helps mitigate the destructive effects of direct lightning strikes and the more common (but still damaging) induced transients from nearby strikes, protecting people, equipment, and buildings. No grounding or surge-protection system can fully protect against a direct strike, but a correct installation greatly reduces the risk. This page covers the components and procedures for a compliant, effective 915 MHz LoRa antenna grounding installation.

DANGER — Overhead power lines and fall hazards: Never erect, raise, lower, or position a mast or antenna where it could contact or fall into an overhead power line. Maintain a horizontal and vertical clearance of at least the mast's full length plus 10 ft from any power line. Power-line contact can be instantly fatal, and grounding does **NOT** make it safe to touch an energized structure — a mast that contacts a live line can remain lethally energized regardless of how well it is grounded. Antenna/mast contact with power lines is a leading cause of installer electrocution. Working at height also carries a serious fall hazard: use proper fall protection, never work alone, and do not raise masts in wet or windy conditions.

Why Ground Your Antenna Installation?

The goal of antenna grounding is threefold:

1. **Lightning protection:** Provide a low-impedance path to earth for direct strike energy, bypassing protected equipment.
2. **Static dissipation:** Continuously bleed off static charge that accumulates on isolated metal structures, preventing equipment damage from static discharge.
3. **Safety:** Bonding the structure to ground reduces shock hazard from fault currents and helps clear faults. Note, however, that grounding does **not** make a structure safe to touch

if it contacts an energized overhead power line — see the power-line warning above. Maintaining clearance from power lines, not grounding, is what prevents power-line electrocution.

Note: Grounding does not prevent lightning from striking. It controls where the energy goes when a strike occurs - to ground, not through your radio.

Ground Rods

The earth electrode (ground rod) is the interface between the grounding system and earth. NEC (National Electrical Code) Article 810 (for antenna systems) and Article 250 (general grounding) specify requirements:

- **Minimum rod specifications (NEC 250.52):** 5/8" diameter, 8-foot length, copper or copper-clad steel. Where a single driven rod does not have a resistance to earth of 25 ohms or less, NEC 250.53(A)(2) requires it to be supplemented by a second electrode. In practice many installers cannot measure ground resistance, so the simpler code-compliant path is to drive two rods spaced at least 6 ft apart.
- **Preferred rod (recommended upgrade, not code-required):** 3/4" diameter, 10-foot copper-clad steel lowers contact resistance in dry soils.
- **Installation:** Drive rod vertically into soil. Where rock prevents full depth, rod may be installed at a 45° angle or in a horizontal trench per NEC 250.53.
- **Connection:** Use a listed ground rod clamp (not a hose clamp). Connect the antenna grounding/bonding conductor with minimum #10 AWG copper (or #17 AWG copper-clad steel) per NEC 810.21. Heavier conductor — #6 AWG copper — is recommended for better surge handling.
- **Bonding to building ground:** The antenna ground rod must be bonded to the building's primary grounding electrode system. The conductor that bonds the antenna ground rod to the building grounding electrode system must be a minimum of #6 AWG copper (NEC 250 / intersystem bonding). Do not create an isolated "antenna ground" disconnected from the main service ground - this creates dangerous voltage differences between grounded objects during a strike.

Bonding Conductors

The bonding conductor (ground wire) connects the antenna mast, cable shield, and equipment ground to the earth electrode. Per NEC 810.21, the antenna grounding/bonding conductor must not be smaller than #10 AWG copper (or #17 AWG copper-clad steel or bronze). The #6 AWG figure below applies to the conductor that bonds the antenna ground rod to the building grounding electrode system — a different, larger requirement. The "Recommended" column reflects engineering best practice for surge handling, not a code minimum:

Component	Minimum Wire Size (NEC 810.21)	Recommended (best practice)	Notes
-----------	--------------------------------	-----------------------------	-------

Antenna mast to ground rod	#10 AWG copper	#6 AWG solid copper	#10 AWG is the NEC 810.21 minimum; #6 AWG is a recommended upgrade for better surge handling. Must be mechanically protected if exposed to physical damage (810.21).
Coax shield ground at entry	#10 AWG copper (or #17 AWG copper-clad steel)	#10 AWG copper	Ground coax shield at the building entry point (NEC 810.21). Do not use #17 AWG copper — the #17 AWG figure applies only to copper-clad steel/bronze.
Bonding antenna ground rod to building electrode	#6 AWG copper	#6 AWG solid copper	Connects antenna ground rod to the building grounding electrode system (NEC 250 / intersystem bonding termination).

Run bonding conductors in as straight a path as possible. Every bend in the conductor adds inductance, which increases impedance to fast-rise lightning transients. A ground wire with many bends is far less effective than a straight run, even if the same gauge.

Lightning Arrestors at 915 MHz

A lightning arrestor (also called a surge protector, coaxial surge protector, or gas discharge tube protector) is installed inline in the coaxial feedline, typically at the building entry point where the cable enters a weatherproof enclosure. It provides a low-impedance path to ground for surge energy while remaining essentially transparent to normal 915 MHz signals.

Types used at 915 MHz:

- **Gas discharge tube (GDT) type:** Contains a sealed gap filled with an ionizable gas. Remains open (no conduction) at normal voltages; ionizes and conducts to ground when voltage spike exceeds breakdown voltage (typically 90 - 200 V). Returns to non-conducting state after transient passes. Excellent RF transparency; virtually no insertion loss.
- **Solid-state (transient voltage suppressor) type:** Uses TVS diodes to clamp voltage. Faster response than GDT but higher capacitance. At 915 MHz, higher capacitance can cause reflections; look for units specified for 900 - 1000 MHz with insertion loss under 0.5 dB.
- **Hybrid GDT + TVS:** Best of both; GDT handles bulk energy, TVS handles fast rising edge. More expensive but preferred for high-value installations.

Recommended Arrestors for 900 MHz

LoRa

Verify the current part number, connector configuration, and insertion-loss spec against the manufacturer's datasheet before purchasing — surge arrestors are a safety component and model numbers change. The models below are representative N-female gas-tube coax arrestors that cover the 900 MHz band:

Model	Type	Connectors	Insertion Loss @ 1 GHz	Notes
Polyphaser IS-50NX-C2	GDT	N-female both ends	<0.1 dB	Industry standard; bulkhead mount; requires grounding lug
Proxicast 0-6 GHz N-Female coaxial lightning arrester (e.g., ANT-211-001)	GDT	N-female both ends	<0.2 dB	Lower-cost alternative to Polyphaser; confirm current SKU on the datasheet
Citel P8AX-900	GDT	N-female both ends	<0.3 dB	DC-blocked version available for bias-T applications
Times Microwave Times-Protect N-female gas-tube arrester	GDT	N-female both ends	<0.1 dB	2-stage gas tube; good energy handling. Confirm the exact Times-Protect SKU on the datasheet.

Installation Procedure

1. **Install the ground rod** at or near the building entry point. Drive to full depth. Connect the ground lug from the ground rod to the building's main grounding electrode system with #6 AWG copper (NEC 810.21).
2. **Mount the arrestor** at the building entry point - the location where the outdoor coaxial cable transitions from outside to inside the building. Mount it on a grounding panel or use a bulkhead mount penetration.
3. **Bond the arrestor ground lug** directly to the ground rod with the shortest possible #6 AWG (or heavier) copper conductor. #10 AWG copper is the absolute NEC 810.21 minimum, but #6 AWG is strongly preferred for strike-energy bonding. Every inch of extra length adds inductance and reduces protection effectiveness.
4. **Ground the mast** separately. Run a #6 AWG conductor from the mast base directly to the ground rod. Bond at a second lug on the ground rod or a listed bonding clamp. Ensure

the mast ground and arrestor ground tie to the same electrode, then bond to the building grounding electrode system — avoid isolated grounds.

5. **Connect outdoor cable** from antenna to the antenna (outdoor) port of the arrestor.
6. **Connect indoor cable** from the equipment (indoor) port of the arrestor to the LoRa radio or gateway.
7. **Verify continuity:** With an ohmmeter, verify that the mast, cable shield, and arrestor ground lug all measure under 1 ohm to the ground rod. This <1 ohm value is a bonding-continuity workmanship target, not the 25-ohm earth-resistance figure (which is a different measurement of the rod-to-earth resistance).

NEC Requirements Summary

Key NEC articles applicable to antenna grounding (2023 NEC). Verify every article number and conductor size against the current National Electrical Code, as interpreted by a licensed electrician, before relying on it for an inspection:

- **Article 810.21:** Grounding of outside antenna systems - grounding/bonding conductors (minimum #10 AWG copper or #17 AWG copper-clad steel), electrode requirements, bonding to the building grounding electrode system.
- **Article 810.20:** Surge protector installation location and specifications for receiving antenna systems.
- **Article 250.52/250.53:** Grounding electrode and installation requirements.
- **Article 250.94:** Intersystem bonding termination - provides a means to bond communications/antenna grounds to the building grounding electrode system. (Note: bonding of separately derived systems is a separate provision, NEC 250.30.)

Disclaimer: This page provides a general overview for reference. Always consult the current edition of the NEC and any applicable local amendments. Installation may require a licensed electrician and/or a permit depending on local code adoption and the requirements of the authority having jurisdiction (AHJ). Radio amateur and commercial operations may have additional FAA (Part 77) and FCC antenna-structure-registration (47 CFR Part 17) requirements beyond NEC scope.

RF Fundamentals for Mesh Operators

Link budgets, Fresnel zones, interference identification and mitigation at 915 MHz.

Link Budget Explained

Link Budget Explained

A link budget is an accounting of all the gains and losses in an RF communication link from transmitter to receiver. It tells you whether a link will work, by how much margin, and what changes would improve it. Every successful LoRa mesh deployment benefits from link budget analysis, even a rough one.

The Link Budget Equation

```
Received Signal Strength (dBm) =  
  TX Power (dBm)  
+ TX Antenna Gain (dBi)  
- TX Feedline Loss (dB)  
- Free-Space Path Loss (dB)  
- RX Feedline Loss (dB)  
+ RX Antenna Gain (dBi)
```

To determine if a link closes, compare the received signal strength to the receiver sensitivity:

```
Link Margin (dB) = Received Signal Strength - Receiver Sensitivity  
  
Positive margin = link works  
Negative margin = link fails  
Margin > 10 dB = comfortable link (rule of thumb)  
Margin > 20 dB = robust link suitable for marginal terrain (rule of thumb)
```

These margin thresholds are engineering rules of thumb, not fixed standards. The fade margin you actually need depends on the propagation environment: roughly 10 dB may suffice for a stable urban or line-of-sight path, while non-line-of-sight, foliage, or rain-affected links require more.

Key Parameters Defined

EIRP (Effective Isotropic Radiated Power)

EIRP is the transmitter power plus the antenna gain, minus feedline losses. It represents the effective power that would need to be fed to an isotropic antenna to produce the same field strength in the direction of maximum radiation:

$$\text{EIRP (dBm)} = \text{TX Power (dBm)} + \text{Antenna Gain (dBi)} - \text{Feedline Loss (dB)}$$

FCC Part 15.247 limits **conducted** output power to 1 W (30 dBm) in the 902 - 928 MHz band, referenced to an antenna of up to 6 dBi gain. With a 6 dBi antenna this yields up to roughly +36 dBm (4 W) EIRP — so 30 dBm is the conducted-power ceiling, not the EIRP ceiling. For antenna gain above 6 dBi, the conducted output power must be reduced dB-for-dB for each dB of gain over 6 dBi (15.247(b)(4)(i)), holding EIRP at about 36 dBm. Unlike the 2.4 GHz band, the 902 - 928 MHz band has **no** relaxed point-to-point allowance that lets you add antenna gain in exchange for reduced power — the dB-for-dB reduction applies to point-to-point links too. Always confirm against current FCC rules and your specific module's certification.

Free-Space Path Loss (FSPL)

Free-space path loss is the reduction in signal power due to the spreading of the RF wavefront as it travels through space. It is a fundamental physical loss, not a deficiency of the system:

$$\begin{aligned}\text{FSPL (dB)} &= 20 \times \log_{10}(d) + 20 \times \log_{10}(f) + 20 \times \log_{10}(4\pi/c) \\ &= 20 \times \log_{10}(d) + 20 \times \log_{10}(f) - 147.55\end{aligned}$$

Where:

d = distance in meters

f = frequency in Hz

At 915 MHz, simplified:

$$\text{FSPL (dB)} = 20 \times \log_{10}(d_{\text{km}}) + 91.65$$

Examples:

100 m: FSPL $\approx$ 71.7 dB

1 km: FSPL $\approx$ 91.7 dB

5 km: FSPL $\approx$ 105.6 dB

20 km: FSPL $\approx$ 117.7 dB

Receiver Sensitivity

Receiver sensitivity is the minimum received signal power that the radio can successfully decode. It is determined by the modulation type, bandwidth, and noise figure of the receiver. LoRa sensitivity varies dramatically with spreading factor (SF). The figures below are typical values for the SX1262 /

community measurements; the SX1276 datasheet lists values about 1 - 1.5 dB less optimistic (e.g. SF11 $\approx$ -133 dBm, SF12 $\approx$ -136 dBm):

Spreading Factor	Bit Rate (approx.)	Typical Sensitivity (dBm)	Use Case
SF7	~5.5 kbps	-123 dBm	Short range, high throughput
SF9	~1.8 kbps	-129 dBm	Medium range, normal use
SF10	~0.98 kbps	-132 dBm	Extended range
SF11	~0.54 kbps	-134.5 dBm	Long range
SF12	~0.29 kbps	-137 dBm	Maximum range

Noise Floor

The thermal noise floor is the baseline noise level a receiver must overcome, set by thermodynamics:

Noise Floor = -174 dBm/Hz + 10 × log₁₀(BW_Hz) + Noise Figure (dB)

For LoRa with 125 kHz bandwidth and 6 dB noise figure:

Noise Floor $\approx$ -174 + 51.0 + 6 = -117 dBm

LoRa's processing gain (spreading factor) allows it to decode signals below this apparent noise floor, which is why SF12 achieves -137 dBm sensitivity.

Worked Example: Urban Mesh Node Link

Let's calculate whether a LoRa mesh link at SF11 will close between two residential nodes 2.5 km apart in a suburban environment.

Parameter	Value	Notes
TX power	+20 dBm	Meshtastic node at 100 mW
TX antenna gain	+5 dBi	5 dBi collinear, rooftop mount
TX feedline loss	-1.5 dB	10 ft LMR-200 + connectors
TX EIRP	+23.5 dBm	Well under the legal limit (1 W conducted with up to 6 dBi)
Free-space path loss	-99.6 dB	2.5 km at 915 MHz
Excess path loss (urban clutter)	-10 dB	Estimated additional suburban loss
RX feedline loss	-1.5 dB	Same installation as TX node

Parameter	Value	Notes
RX antenna gain	+5 dBi	Same 5 dBi antenna
Received signal level	−82.6 dBm	$23.5 - 99.6 - 10 - 1.5 + 5$
Receiver sensitivity (SF11)	−134.5 dBm	SX1262 typical (SX1276 datasheet: $\approx$ −133 dBm)
Link Margin	+51.9 dB	Excellent; link is robust

This link has roughly 52 dB of margin - it would still work with an additional 52 dB of path loss (about 160,000× more attenuation in power terms). This illustrates why LoRa is capable of penetrating buildings and covering large distances even with modest antenna installations.

Fresnel Zones and Clearance

Fresnel Zones and Clearance

One of the most common causes of unexpectedly poor radio links is obstruction of the Fresnel zone - not just the line of sight. Even when two antennas have a clear geometric line of sight to each other, a rooftop, hilltop, or dense tree canopy can severely degrade the link if it intrudes into the Fresnel zone. Understanding Fresnel zones allows you to choose correct antenna heights and predict real-world link performance.

What Is a Fresnel Zone?

When RF energy travels from a transmitter to a receiver, it does not travel solely as a thin ray. The energy spreads into an ellipsoidal region of space around the direct path. This is because of the wave nature of radio: energy arriving at the receiver via slightly longer indirect paths can either add to or subtract from the direct signal, depending on the path length difference.

The Fresnel zones are concentric ellipsoids centered on the direct path. The first Fresnel zone contains the paths where indirect waves arrive with less than 180° of phase difference from the direct path - these waves reinforce the direct signal. Obstructions within the first Fresnel zone scatter energy and cause diffraction loss.

Key insight: you can have "clear line of sight" while still losing signal if obstacles intrude into the first Fresnel zone. A significant (near-grazing or deeper) intrusion can cost on the order of 10 - 20 dB; a light intrusion into the outer edge of the first zone costs only a few dB.

Why 60% Clearance Matters

Radio engineering rules of thumb require 60% of the first Fresnel zone radius to be clear of all obstacles for a link to experience negligible diffraction loss (less than about 0.5 dB). If clearance drops to a grazing obstruction (obstacle tip exactly on the line of sight), diffraction loss is approximately 6 dB - the textbook knife-edge value. As the obstacle penetrates past the line of sight, loss continues to climb per the knife-edge model: an obstacle tip roughly one Fresnel radius or more above the line of sight gives 15 - 25 dB or more of loss.

The figures below use a single, consistent quantity: the **clearance ratio**, defined as the obstacle's position relative to the first Fresnel radius. A ratio of +1.0 means the obstacle is a full Fresnel

radius below the line of sight (first zone fully clear); 0 means the obstacle just touches the line of sight (grazing); a negative ratio means the obstacle has crossed above the line of sight and is blocking it. Intermediate values are interpolated from the knife-edge diffraction curve (ITU-R P.526) and are approximate:

Clearance ratio (obstacle relative to first Fresnel radius) → Diffraction Loss (approx.):

+1.0 (first zone fully clear): ~0 dB loss

+0.6 (standard 60% minimum): ~0.5 dB loss

+0.4: ~3 dB loss

0 (grazing, obstacle on line of sight): ~6 dB loss

-0.2 (obstacle 20% of a Fresnel radius into the path): ~15 - 20 dB loss

Calculating the First Fresnel Zone Radius

The radius of the first Fresnel zone at any point along the path is calculated as (all distances in km, frequency in GHz, result in meters):

$$r_1 \text{ (meters)} = 17.32 \times \sqrt{(d_1 \times d_2 / (f \times D))}$$

Where:

r_1 = first Fresnel zone radius (meters)

d_1 = distance from transmitter to the obstacle (km)

d_2 = distance from receiver to the obstacle (km)

f = frequency (GHz)

D = total path length $d_1 + d_2$ (km)

At 915 MHz ($f = 0.915$ GHz) the constant $17.32 / \sqrt{0.915} = 18.1$, so:

$$r_1 \text{ (meters)} \approx 18.1 \times \sqrt{(d_1 \times d_2 / D)} \quad (d_1, d_2, D \text{ in km})$$

The Fresnel zone is widest at the midpoint of the path. At the midpoint $d_1 = d_2 = D/2$, so $d_1 \times d_2 / D = D/4$ and the general formula above reduces to the midpoint form below (the constant $17.32 / 2 = 8.66$ is the same constant, just specialized to the midpoint — not a new number to look up):

$$r_{1_max} \text{ at midpoint (meters)} = 8.66 \times \sqrt{(D_km / f_GHz)}$$

At 915 MHz, $8.66 / \sqrt{0.915} = 9.05$, so:

$$r_{1_max} \text{ (meters)} \approx 9.05 \times \sqrt{(D_km)}$$

Examples:

1 km path: $r_{1_max} \approx 9.05$ m

5 km path: $r_1_{\text{max}} \approx 20.2$ m
10 km path: $r_1_{\text{max}} \approx 28.6$ m
20 km path: $r_1_{\text{max}} \approx 40.5$ m

The 60% clearance requirement for the 5 km example means you need $0.6 \times 20.2 \approx 12.1$ m of clearance at the midpoint of the path. If there is a tree canopy at 8 m height at the midpoint, your link will experience significant diffraction loss even if you can see over it.

Practical Antenna Height Selection

To determine required antenna height, you need to know:

1. The height profile of the terrain and vegetation along the path (from topographic data or observation)
2. The point of maximum obstruction (worst-case obstacle)
3. The Fresnel zone radius at that point

Required antenna height to achieve 60% Fresnel clearance over an obstacle:

Needed clearance above obstacle = $0.6 \times r_1$ at obstacle location

Height of antenna above ground $\geq$
(Obstacle height – Earth's bulge correction)
+ $0.6 \times r_1_{\text{at_obstacle}}$
+ mast height needed to achieve this elevation

For long paths over curved earth, Earth bulge must also be added. The bulge at the **midpoint** of a path of total length D km, using the standard 4/3 Earth radius factor, is:

Earth bulge at midpoint (m) = $D_{\text{km}}^2 / 68$
(4/3 Earth radius factor for standard atmosphere)

This comes from the general bulge formula $h = d_1 \times d_2 / 17$ (d_1, d_2 in km),
evaluated at the midpoint where $d_1 = d_2 = D/2$, giving $(D/2)^2 / 17 = D^2 / 68$.

Example: a 20 km path $\rightarrow 20^2 / 68 = 400 / 68 \approx 5.9$ m of bulge at the midpoint.

Practical Implications for Mesh Deployments

Scenario	Recommendation
Urban node-to-node, 0.5 - 2 km through buildings	Fresnel zone mostly in buildings anyway; gain antenna height to maximize chance of LOS paths between building gaps
Suburban, 2 - 5 km, trees and houses	Antennas typically need to be above the tree canopy (8 - 12 m AGL is a common guideline, depending on local canopy height); verify at least 60% Fresnel clearance to intended relay nodes
Rural, 5 - 20 km, rolling terrain	Use topographic analysis; hilltop sites preferred; 30 - 50 ft antenna heights often needed to clear ridge midpoints
Long-range backbone, 20+ km	Strict Fresnel analysis required; professional path planning tools recommended; Earth bulge significant

Safety note: masts in the 30 - 50 ft range are not a casual install. They require professional-grade erection, guying, and grounding, and present serious fall and power-line hazards. Plan the lift so the full mast length plus at least 10 ft of margin stays clear of any overhead power line throughout the raise, and use qualified help.

Free tools for Fresnel zone and path analysis include HeyWhatsThat.com, Radio Mobile Online, and the SPLAT! propagation analysis tool. For critical links, use at least two independent analysis methods.

Interference and Noise at 915 MHz

Interference and Noise at 915 MHz

The 902 - 928 MHz ISM (Industrial, Scientific, and Medical) band is shared with a wide variety of devices that can interfere with LoRa mesh operation. Understanding who shares this band, how their signals manifest, and how to identify and mitigate interference is essential for reliable mesh network operation.

The 902 - 928 MHz ISM Band Landscape

LoRa mesh operates in this band under FCC Part 15.247 (digitally-modulated / spread-spectrum systems, up to 1 W conducted). Part 15.249 is a separate, much-lower-power regime (field-strength limited to roughly well under 1 mW EIRP) that LoRa mesh nodes do not and cannot use at the 17 - 30 dBm power levels described on this page. It shares this spectrum with many other systems:

Technology	Frequency Range	Modulation	Typical Power	Interference Risk
LoRa (US915 plan)	902 - 928 MHz, 64 uplink channels grouped into 8 sub-bands + 8 downlink	CSS (chirp spread spectrum)	17 - 30 dBm	N/A (desired signal)
Zigbee 900 MHz	902 - 928 MHz	DSSS	0 - 10 dBm	Low; different modulation
Z-Wave (North America)	908.42 MHz / 916 MHz	FSK/GFSK	0 - 14 dBm	Low to moderate; narrow channels in LoRa band
FHSS devices (phones, security systems)	902 - 928 MHz, frequency hopping	FHSS/FSK	Varies	Moderate; wideband hopping
900 MHz cordless phones (older)	902 - 928 MHz	FHSS or analog FM	100 mW	Moderate; common in homes
Baby monitors (900 MHz type)	902 - 928 MHz	FM/FHSS	10 - 100 mW	Moderate locally

Technology	Frequency Range	Modulation	Typical Power	Interference Risk
ISM telemetry (AMR meters, SCADA)	902 - 928 MHz	FSK/OOK	Up to 1 W conducted (same 15.247 limit as LoRa)	Low to high; site-dependent
WiFi 802.11ah (HaLow)	902 - 928 MHz	OFDM	Typically <30 dBm	Emerging; not yet widespread
Cellular Band 8 uplink	880 - 915 MHz	LTE/WCDMA	Up to 2W	Adjacent band; high-power cellular near tower can cause blocking
Cellular Band 8 downlink	925 - 960 MHz	LTE/WCDMA	Up to 43 dBm tower	Adjacent band; strong tower signal can cause receiver desensitization

Note that the co-band Part 15 devices above (such as AMR/SCADA telemetry) are bound by the same 15.247 limit of 1 W conducted as LoRa; none are licensed to exceed it.

How LoRa Handles Interference

LoRa's CSS modulation has inherent interference rejection properties. The chirp spread spectrum processing gain allows LoRa to decode signals below the noise floor, but the margin is spreading-factor dependent: the demodulation SNR limit ranges from about -7.5 dB at SF7 to about -20 dB at SF12. Only the highest spreading factors approach 20 dB below the noise floor. However, strong narrowband interferers can still cause problems:

- **Blocking/desensitization:** A strong signal anywhere near 915 MHz can saturate the LoRa radio's LNA or ADC, raising the effective noise floor and degrading sensitivity to all LoRa signals. This is the most common form of interference damage.
- **Intermodulation:** Two strong interferers at frequencies f_1 and f_2 can produce intermodulation products at $2f_1 - f_2$ and $2f_2 - f_1$ that fall on LoRa channels.
- **Direct channel co-channel interference:** This depends on how many other users land on your specific narrow LoRa channel (125/250/500 kHz), not on the total 26 MHz band width. Because Meshtastic/LoRa mesh nodes typically share a small number of common channels, co-channel collisions among mesh users are in fact common in dense deployments.

Identifying Interference

Symptoms of interference in a LoRa mesh network:

- SNR (signal-to-noise ratio) readings consistently lower than expected given [link budget calculations](#)

- Elevated RSSI on channels with no active transmissions ("noise floor rise")
- Time-of-day correlation with interference events (e.g., worse during business hours when nearby office equipment is active)
- Geographic correlation - nodes near specific buildings, industrial sites, or utility infrastructure experience worse performance
- Intermittent packet loss despite strong RSSI - suggests bursty interferers like FHSS devices occasionally hitting LoRa channels

Tools for characterizing interference:

- **LoRa channel activity detection (CAD):** Built into SX1276/SX1262; CAD detects LoRa activity on the currently-tuned channel and returns a busy/available status - it is not a spectrum scanner. To survey multiple channels, scan them sequentially or use an SDR.
- **RTL-SDR + SDR# / GQRX:** A \$25 RTL-SDR dongle can display the entire 902 - 928 MHz spectrum in real time, revealing the presence, frequency, and character of interferers
- **HackRF / Airspy:** Higher-end SDR for more detailed analysis; can capture wideband spectral views and decode modulations

Mitigation Strategies

Channel Plan Management

LoRaWAN US915 defines 64 uplink channels at 125 kHz (200 kHz spacing, 902.3 - 914.9 MHz) grouped into 8 sub-bands, plus 8 uplink channels at 500 kHz, and 8 downlink channels at 500 kHz (923.3 - 927.5 MHz). Note that Meshtastic does not use LoRaWAN channelization - it uses single configurable frequencies - so this LoRaWAN detail is tangential to most mesh users. Meshtastic and other mesh firmware may allow channel selection. If interference is identified on specific channels, reprogram nodes to avoid those frequencies. For 915 MHz LoRa in the US, the upper portion of the band (916 - 928 MHz) is less heavily used by legacy FHSS devices and may have lower ambient interference.

Antenna Selection and Placement

[Directional antennas](#) inherently reject interference from outside their main beam. The 12 dBi Yagi described on the Directional Antennas page, aimed at a target node, has substantial front-to-back rejection (typically 15 - 25 dB), meaning interferers behind the antenna are attenuated by that amount. For fixed infrastructure links experiencing interference from a known direction, switching from omni to directional can provide dramatic improvement.

Physical Separation and Height

Interference from consumer devices (baby monitors, cordless phones) drops off rapidly with distance due to their low power and proximity effects. Raising the antenna above the local RF clutter level (above rooftops, not at window height) can substantially improve SNR - often several

dB to more than 10 dB depending on the site - by placing the antenna in a "quieter" RF environment.

Filtering

Band-pass filters for 902 - 928 MHz can be installed between the antenna and the LoRa radio to reject out-of-band energy (especially cellular downlink at 925 - 960 MHz) that might cause blocking. Mini-Circuits, Johanson Technology, and similar vendors offer suitable filters:

- Look for a passband of 902 - 928 MHz with at least 40 dB rejection outside the band
- Insertion loss within passband should be under 2 dB
- Rate the filter's power handling for your maximum *conducted* transmit power (up to 1 W / 30 dBm under 15.247), not EIRP. The filter sits before the antenna, so it sees conducted power only; antenna gain (and thus EIRP) occurs after it.

Note that filtering is only effective against out-of-band interference. In-band interference (e.g., another user in the 902 - 928 MHz band) cannot be filtered without also removing the desired LoRa signal.

Firmware-Level Mitigation

- **Lower the hop timing aggressiveness:** Reducing retransmission aggressiveness in meshing firmware reduces the probability that any given packet collides with a bursty interferer
- **Use higher spreading factors:** SF11 and SF12 provide more interference rejection (processing gain) at the cost of reduced throughput
- **Enable Listen-Before-Talk (LBT):** Some LoRa firmware supports carrier sense before transmitting, reducing collisions with other ISM band users

DIY Antenna Construction

Building a 915 MHz Yagi Antenna

A yagi antenna provides significant directional gain for point-to-point links - ideal for connecting two backbone nodes across a valley, mountain, or city. Building your own 915 MHz yagi is a rewarding project that costs \$10-20 in materials vs. \$50-150 for a commercial equivalent.

Yagi Design Fundamentals

A yagi consists of three element types mounted on a boom:

- **Reflector** - Behind the dipole; slightly longer than a half-wavelength; increases gain in forward direction
- **Driven element (dipole)** - The active element connected to the feedline
- **Directors** - In front of the dipole; slightly shorter than a half-wavelength; focus the beam forward

At 915 MHz, a half-wavelength in free space is approximately 164 mm (6.4 inches). Note that a real resonant element is about 5% shorter than the free-space half-wave due to end effect, so a driven dipole element typically cuts to around 155 mm rather than the full 164 mm. Each element is cut to a specific length and spaced precisely on the boom, then tuned with a NanoVNA.

5-Element Yagi Plans for 915 MHz

A typical 5-element yagi provides approximately 9-10 dBi (roughly 7-8 dBd) gain with a tight forward beam. Reaching 12 dBi generally requires 7-8 elements. With clear line of sight, a full Fresnel zone, adequate height, and a matching antenna on the far end, such a yagi can support links of 10 km or more; the realistic range depends on transmit power, terrain, and spreading factor as much as on antenna gain, so treat long-range figures as best-case line-of-sight, not routine.

FCC compliance note: A yagi above 6 dBi exceeds the 6 dBi reference gain in FCC 15.247(b)(4)(i). When used at 902-928 MHz, conducted transmit power must be reduced dB-for-dB for every dB of antenna gain above 6 dBi (for example, a 10 dBi antenna requires conducted power

no greater than 26 dBm). The EIRP ceiling of about 36 dBm (4 W) is a derived limit (30 dBm conducted + 6 dBi), not a bonus you add gain on top of, and there is no relaxed point-to-point antenna allowance at 915 MHz.

Element dimensions (915 MHz, 5-element, nominal - tune with a NanoVNA):

Reflector: 178 mm (7.01")

Driven element: 163 mm (6.42") - center-fed dipole (trim toward ~155 mm for resonance)

Director 1: 151 mm (5.94")

Director 2: 147 mm (5.79")

Director 3: 144 mm (5.67")

Spacing from reflector:

Driven element: 49 mm (1.93")

Director 1: 115 mm (4.53")

Director 2: 210 mm (8.27")

Director 3: 330 mm (13.0")

Materials

- **Elements:** 3/16" (4.8mm) aluminum rod or welding rod. Available at hardware stores.
- **Boom:** 1/2" (12mm) square aluminum extrusion, 400mm long. Also available as wooden dowel (slightly less rigid but fine for hobby use).
- **Driven element:** Built as a split (center-fed) dipole fed through a gamma match or 50-ohm hairpin match - see the construction steps below.
- **Feedline:** Use RG-174 or LMR-195 only for a short (under ~1 m) pigtail, since RG-174 loses roughly 1 dB per metre (~30 dB per 100 ft) at 915 MHz. For any real cable run, use low-loss LMR-240 or LMR-400-class coax. SMA connector at the antenna end.
- **Hardware:** 1/4-20 stainless bolts and nylon locknuts to mount elements to boom.

Construction Steps

1. Cut all elements to specified lengths using a hacksaw or pipe cutter. Deburr ends.
2. Mark boom at element spacing positions.
3. Drill 3/16" holes through boom at each position.
4. Thread the reflector and directors through their boom holes and secure with nylon locknuts (finger-tight then 1/4 turn more). These are single, continuous rods.
5. Build the driven element as a split dipole: instead of one continuous rod, use two collinear half-elements (each about a quarter-wavelength, ~38 mm) mounted on an insulating

block at the boom center, with a small gap (~3-5 mm) between their inner ends.

6. Feed it with one of these matches:

- **Direct/gap feed (simplest):** Solder the coax center conductor to one half-element and the coax shield to the other half-element across the center gap. A bare split dipole presents roughly 50-70 ohms, close enough to test; add a current balun (a few turns of the coax through a ferrite at the feed point) to keep RF off the coax shield.
- **Gamma match (for a continuous-rod driven element):** If you prefer one solid driven rod grounded to the boom at its center, run a parallel gamma rod (about 1/10 the driven-element length) spaced ~10-15 mm alongside one half, connect the coax center to the gamma rod through a small series capacitor (a few pF, often a short coax-sleeve trombone), and bond the coax shield to the driven element at center. Adjust the gamma rod length, spacing, and capacitance for lowest SWR.

7. Weatherproof the feed point and connector after tuning.

Testing Your Yagi

After construction, verify performance:

- Use a NanoVNA to check SWR at 915 MHz. Target: SWR less than 2:1, ideally below 1.5:1. Adjust the match (and trim the driven element toward resonance) as needed.
- Compare RSSI at a fixed test point vs. a reference omni - the yagi should show roughly 6-10 dB improvement in its forward direction. Measured improvement varies with the environment, multipath, and reference antenna, so this is a typical figure, not a guarantee.
- Note the half-power beamwidth: a 5-element yagi has roughly 55 degree horizontal beamwidth. For best performance, aim within about +/-15 degrees (roughly half the half-power beamwidth) of the far station.

Building a Collinear Vertical Antenna

This page covers two simple, easy-to-build omnidirectional verticals for 915 MHz - a J-pole and a 5/8-wave vertical - both a significant improvement over the stock rubber duck antennas included with most LoRa boards. (A true multi-element collinear, which stacks several half-wave sections in phase to reach $\sim 3\text{-}6$ dBd, is described conceptually below but is a more advanced build not detailed here.) The J-pole and 5/8-wave verticals below are straightforward to build with basic tools.

How a Collinear Works

A collinear antenna consists of multiple half-wave dipole elements stacked vertically and fed in phase. Each additional element increases the gain and makes the radiation pattern more disk-shaped (more horizontal, less toward sky/ground) - which is exactly what you want for a terrestrial mesh network. Note that the two single-element verticals built on this page (the J-pole and the 5/8-wave) are *not* multi-element collinears; they are simpler designs with dipole-class gain, included here as practical starting points.

Simple J-Pole Vertical for 915 MHz

The J-pole is one of the simplest omnidirectional verticals to build. It is an end-fed half-wave radiator fed through a quarter-wave parallel matching stub (the "J") - it is **not** a collinear. Its gain is essentially that of a half-wave dipole, about ~ 0 dBd (~ 2.15 dBi); the widely-repeated " ~ 3 dBd J-pole" claim is a myth. Its real advantages are a clean omnidirectional pattern and an easy feed, not extra gain. A J-pole gives roughly 2-3 dB more than a basic quarter-wave ground plane, not 3.5 dBd.

915 MHz J-Pole dimensions:

Radiator: 163 mm (6.42") - connects to matching section

Matching section: ~ 82 mm (3.23") - quarter-wave parallel stub (half the radiator length)

Shorting bar: 40 mm (1.57") - connects bottom of radiator to top of short arm

Feed point: 37-42mm from bottom of matching section (tune for min SWR)

Material: 3/32" or 1/8" brass rod, or stiff copper wire (14 AWG solid)

Tuning the feedpoint: attach the coax at about 40 mm up from the bottom of the matching stub, sweep SWR with a NanoVNA (see the Testing & Tuning pages), and slide the tap a few millimetres up or down toward the lowest SWR at 915 MHz. The exact feed position depends on conductor diameter, so expect to fine-tune. These dimensions are a starting point - verify against a 915 MHz J-pole/Slim Jim calculator and tune with a NanoVNA.

5/8 Wave Vertical

A 5/8 wavelength vertical with a ground plane offers roughly 3 dB of gain over a quarter-wave whip - that is about 1-1.5 dBd (~3 dBi) over a dipole, **not** 3 dBd. Its main benefit is a lower takeoff angle than a quarter-wave, which is excellent for long-range terrestrial links:

5/8 wave vertical at 915 MHz:

Vertical element: 203 mm (7.99") nominal; trim ~5% shorter for end effect, tune with a NanoVNA

Ground plane radials: 4x at ~82 mm (quarter-wave), angled 45 degrees downward

Feedpoint: SMA or N connector at base

Impedance: a 5/8-wave element is NOT naturally 50 ohms - it presents capacitive reactance and generally needs a base matching/loading coil.

(Drooping radials alone match a quarter-wave, not a 5/8-wave.)

Weatherproofing a DIY Antenna

Any antenna installed outdoors needs weatherproofing to survive years of exposure. Any DIY antenna installed outdoors must also be grounded and surge-protected (see Grounding and Lightning Protection) and kept well clear of overhead power lines during and after installation; solder in a well-ventilated area.

- **UV protection:** Coat metal elements with cold galvanizing compound or clear lacquer spray. Aluminum naturally oxidizes to a protective oxide layer against bulk corrosion, but that oxide raises contact resistance at joints and connectors, so bare aluminum joints still need protection; copper and brass oxidize to patina that increases resistance - coat with lacquer.
- **Connector protection:** Wrap SMA/N connector base with self-amalgamating tape (silicone rubber tape that bonds to itself). Apply starting from the cable, overlapping onto the connector, then back. Provides a reliable weatherproof seal.
- **Mounting:** Stainless steel hardware is the practical choice; it is only moderately compatible with aluminum, so in coastal or salty environments use anti-seize or dielectric

isolation to limit galvanic corrosion. Coat any carbon steel hardware with cold galvanizing compound.

- **Housing:** For clean installations, insert the antenna inside a length of PVC pipe (Schedule 40, 3/4" inside diameter for most quarter-wave to collinear antennas). PVC is RF-transparent at 915 MHz with minimal loss.

Gain Comparison: Antennas for 915 MHz

Gains below are given in both dBd (relative to a half-wave dipole) and dBi (relative to an isotropic source). Convert with **dBi = dBd + 2.15**.

Antenna Type	Gain (dBd / dBi)	Pattern	Build Difficulty	Best Use
Stock rubber duck	-3 to 0 dBd / -0.85 to 2.15 dBi	Omnidirectional	None (included)	Portable/indoor only
Quarter-wave with radials	~0 dBd / ~2 dBi	Omnidirectional	Easy	Basic outdoor fixed
J-Pole (end-fed half-wave)	~0 dBd / ~2.15 dBi	Omnidirectional	Easy	Home repeater
5/8 wave vertical	~1 dBd / ~3 dBi (~3 dB over a quarter-wave whip)	Omni, low angle	Medium	Long-range omni
5-element yagi	~7-8 dBd / ~9-10 dBi	Directional ~55°	Medium	Point-to-point link
Commercial 5 dBi fiberglass	~3 dBd / 5 dBi	Omnidirectional	None (buy)	Outdoor repeater

Note: antennas above 6 dBi require a dB-for-dB reduction of conducted power under FCC 15.247(b)(4)(i) in the 902-928 MHz band - see the FCC Regulations and EIRP Reference page.