Antenna Fundamentals

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

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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:

```
λ = c / f
λ = 300,000,000 m/s ÷ 915,000,000 Hz
λ ≈ 0.328 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	dBd = dBi − 2.15 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 - a vertical omni physically cannot achieve more than about 8 - 9 dBi without becoming so tall that its elevation angle rises and its coverage pattern degrades.

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. The efficiency of a real antenna is:

```
Gain (dBi) = Directivity (dBi) + Efficiency (dB)
```

A well-made antenna will have efficiency above 90%; cheap antennas can fall to 50% or lower, turning claimed gain into a fiction.

Near Field vs Far Field

The space around an antenna is divided into regions based on the character of the electromagnetic field:

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 ~0.3 m	Fields begin propagating but pattern shape still changes with distance

Region	Approximate Boundary	Characteristics
Far field (Fraunhofer)	$r > 2D^2/\lambda$	Radiation pattern stabilized; power density drops as $1/r^2$; all link budget calculations apply here

For practical LoRa mesh purposes, you are always operating in the far field - links are meters to kilometers long. The near field is only relevant when mounting antennas close to metal objects, where reactive fields can detune the antenna and alter its pattern significantly.

A key takeaway: keep antenna elements at least $\lambda/4$ (about 8 cm at 915 MHz) away from metal surfaces, and preferably $\lambda/2$ or more. Even a metal enclosure lid placed too close to an antenna can shift its resonant frequency and reduce efficiency by several dB.

Antenna Types for LoRa Mesh

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Choosing the right antenna type for a LoRa mesh deployment is one of the highest-leverage decisions you can make. A 3 dB improvement in antenna gain doubles your effective communication range. This page describes the principal antenna types used at 915 MHz and when each is appropriate.

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 λ/4 long (8.2 cm at 915 MHz) mounted vertically above a ground plane.

- **Gain:** Approximately 2.15 dBi over a perfect infinite ground plane; 0 - 2 dBi in practice
- **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 λ/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
- **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
- **Variants:** J-pole (a folded dipole variant with built-in matching), slim jim, end-fed half-wave (EFHW)

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:** 30 - 70° (half-power) depending on gain
- **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
- **Beamwidth:** 60 - 90° horizontal, 30 - 60° vertical for typical panels
- **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.

Configuration	Typical Gain	Physical Height (approx.)	Best Use Case

5/8λ single element	3 dBi	20 cm	Compact fixed node, limited height
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

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
Dipole	2 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°)	Building-face sector, backhaul
Yagi	6 - 15 dBi	Directional	Point-to-point, long-range link

Antenna Gain and Coverage Tradeoffs

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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× linear gain) compresses its radiation into a narrower cone, delivering 3.16× more power density in its peak direction. From the perspective of a receiver in the main beam, it is equivalent to the transmitter having 3.16× the power.

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

```
EIRP (dBm) = Transmit Power (dBm) + Antenna Gain (dBi) − Feedline Loss (dB)
```

FCC Part 15.247 limits EIRP to +30 dBm (1 watt) for spread spectrum systems in the 902 - 928 MHz band when operating with a fixed, point-to-point link with directional antennas. For point-to-multipoint operation, the limit is effectively lower. Most LoRa nodes run 17 - 20 dBm transmit power, leaving 10 - 13 dB of "antenna budget" before hitting the legal limit.

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).

Antenna Gain	Approx. Vertical Beamwidth	Radiation Elevation Angle
2 dBi (dipole)	~75°	Broad; works at steep angles

Antenna Gain	Approx. Vertical Beamwidth	Radiation Elevation Angle
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 approximate dead zone radius under a vertical omni antenna can be estimated as:

```
Dead Zone Radius ≈ h / tan(θ/2)


Where:
 h = antenna height above nodes (meters)
 θ = vertical beamwidth (degrees)


Example: 10 dBi antenna at 30 m height, 10° vertical beamwidth:
Dead Zone Radius ≈ 30 / tan(5°) ≈ 30 / 0.0875 ≈ 343 meters
```

In this example, any node within 343 meters of the tower base would be in the side lobe or null region and might receive 10 - 20 dB less signal than a node 2 km away. In a dense urban mesh, this is disastrous.

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

Gain Choice	Use When	Avoid When
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.