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 - 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:

```
Gain (dBi) = Directivity (dBi) − Loss (dB)
  where Loss (dB) = −10 · log10(η), and η is the efficiency fraction (≤ 1)

Equivalently: Gain (dBi) = Directivity (dBi) + 10 · log10(η)
  Since η ≤ 1, the 10·log10(η) term is ≤ 0, so gain is always ≤ directivity.
```

For example, an efficiency of $\eta = 0.90$ (90%) gives $10 \cdot \log10(0.90) \approx -0.46$ 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

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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 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 (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 = λ/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

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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 up to 3.16× 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× 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 **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 ≈ h / tan(θ / 2)


Where:
 h = antenna height above nodes (meters)
 θ = full vertical beamwidth (degrees), so θ/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
(θ = 10°, so θ/2 = 5°):
Radius ≈ 30 / tan(5°) ≈ 30 / 0.0875 ≈ 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.