# PCB Trace vs External Antenna

The antenna is one of the most important factors in the range and reliability of a LoRa mesh node, alongside spreading factor and transmit power. (Spreading factor in particular changes the link budget by 15-20+ dB across SF7-SF12, which often outweighs the few-dB difference between a poor and a good antenna.) Even so, the antenna is the most commonly overlooked hardware detail, especially by beginners who assume the built-in PCB trace antenna is adequate for outdoor use.

# PCB Trace Antennas: What They Are

A PCB trace antenna (also called a PCB antenna or on-board antenna) is a specific pattern etched directly into the copper layers of the circuit board. No separate component - it is part of the PCB itself. You can identify one by looking at a corner of the board where the copper traces form a meandered or serpentine pattern, often with a small keepout area around it where no other copper is present.

PCB trace antennas are used because they cost essentially nothing to add during PCB manufacturing, they take up minimal volume, and they eliminate the need for an SMA/U.FL connector and cable. For products designed to be small and cheap - like many ESP32 dev boards - they make sense as a baseline.

# Why PCB Antennas Are Inadequate for Outdoor Use

A well-designed, well-matched PCB trace antenna at 915 MHz can reach roughly 0 - 2 dBi, but the small or detuned implementations found on typical dev boards are frequently negative-gain (commonly -3 to -6 dBi, sometimes worse) once electrical size, lossy FR4, ground-plane coupling, and proximity to a hand or case are accounted for. Treat a dev-board PCB antenna as significantly worse than a quarter-wave whip. In practice, PCB antennas on development boards suffer from

several additional problems:

- **Proximity effects:** A PCB trace antenna's tuning is affected by everything near it - your hand, a battery, the case material, the board itself. Moving the device changes the antenna's effective frequency and radiation pattern.
- **Orientation sensitivity:** PCB trace antennas are non-omnidirectional, with pronounced nulls in their radiation pattern. In a pocket or on a table, a null direction may be exactly toward the nodes you want to reach.
- **No replaceable component:** If the PCB trace antenna design is suboptimal (common on cheap dev boards), there is nothing to improve without adding an external connector.
- **Body shielding:** When carried in a pocket, the human body absorbs several dB of the already-weak signal from a PCB antenna. An external antenna on a cable can be positioned to avoid this.

# Gain Comparison

| Antenna Type | Typical Gain | Effective Range vs PCB | Notes |
|---|---|---|---|
| PCB trace antenna (dev board) | -4 to +2 dBi (often negative when detuned) | Baseline | Subject to proximity detuning |
| Small rubber duck (included) | 1 - 2 dBi | ~1.1 - 1.3x | Better than PCB in most orientations |
| Quality 915 MHz rubber duck | 2 - 3 dBi | ~1.3 - 1.5x | Taoglas, Linx brand options |
| Quarter-wave whip + ground plane | ~5.15 dBi (ideal ground plane; ~2-5 dBi on a small/finite ground plane) | ~1.3 - 2x | Omnidirectional; DIY-constructable. Note 2.15 dBi is the half-wave dipole figure, not the monopole's |
| Fiberglass 3 dBi (915 MHz) | 3 dBi | ~1.5 - 2x | Best for outdoor fixed nodes |
| Fiberglass 5 dBi | 5 dBi | ~2.5 - 3x | Narrower beam; use at elevation |
| Fiberglass 8 dBi | 8 dBi | ~4 - 5x | Very narrow beam; hilltop/tower only. Can shoot over nearby/low nodes |
| Yagi 10 dBi | 10 dBi | ~6 - 8x | Highly directional; point-to-point only. Gain depends on element count |

*Range multipliers are approximate in ideal line-of-sight conditions. Real-world gains depend on terrain, obstruction, and link margin. Antenna gain figures for commercial products are nominal/marketing values and vary by sample.*

# Connector Types: SMA vs U.FL

## SMA (SubMiniature version A)

SMA is a threaded RF connector found on most external antennas. Boards with an SMA connector (T-Beam, RAK WisBlock base boards) can directly accept standard SMA-terminated antennas. There are two variants:

- **SMA:** Female connector on the antenna (outer thread, inner pin) plugs into the board's male SMA jack (inner socket, outer thread)
- **RP-SMA (Reverse Polarity SMA):** Used on WiFi routers and many US-market devices. The genders of the center conductor are swapped. A standard SMA antenna will NOT fit an RP-SMA connector without an adapter. Make sure your antenna matches your board's connector type.

## U.FL (also called IPEX or MHF1)

U.FL is a tiny snap-fit coaxial connector used internally on boards when the antenna connector needs to be on a cable or module rather than soldered to the main PCB. The Heltec V3 LoRa output, some WisBlock modules, and many radio modules use U.FL.

A U.FL connector board requires a **U.FL to SMA pigtail cable** (typically 10 - 15 cm) to adapt to a standard SMA antenna. Over such a short run of thin (1.13 mm / RG-178-class) coax, this cable introduces only a small fractional-dB insertion loss at 915 MHz (on the order of 0.3 - 0.5 dB), which is a worthwhile tradeoff for a proper external antenna.

# When Is a PCB Antenna Acceptable?

PCB antennas are adequate in these specific scenarios:

- **Indoor testing at short range:** Verifying that firmware flashed correctly, testing basic connectivity between nodes in the same room
- **High-density indoor mesh:** In a building with many nodes at close range (under 50 meters), PCB antenna limitations are less relevant
- **Ultra-compact wearable or embedded device:** If physical size constraints prevent any external component, a PCB antenna may be the only option - but accept the range limitation

**For any outdoor deployment, fixed repeater, or range-critical use, an external antenna is non-negotiable.**

# Antenna Selection for Common Boards

| Board | Built-in Antenna | External Connector | Recommended Upgrade |
|---|---|---|---|
| Heltec WiFi LoRa 32 V3 | U.FL LoRa output with included external antenna (the on-board metal spring antenna is for WiFi/BT only, not LoRa) | U.FL / IPEX (LoRa) | U.FL - SMA pigtail + 3 dBi rubber duck |
| LilyGO T-Beam Supreme | None (SMA only) | SMA male | Quality 915 MHz 3 dBi rubber duck; fiberglass for fixed |
| LilyGO T-Echo | None | U.FL / IPEX (verify; sources conflict SMA vs U.FL) | Included rubber duck is adequate; upgrade for repeater use |
| RAK4631 (WisBlock) | None | IPEX (U.FL) on module | RAK base board provides SMA passthrough; use 3 - 5 dBi fiberglass for fixed nodes |
| Station G2 | None | SMA male | 3 dBi stubby for portable; fiberglass for fixed |

# Cable Loss Warning

If your antenna requires a coaxial cable run (for example, mounting an antenna on a roof while the radio is indoors), cable loss must be accounted for. At 915 MHz:

- RG-58: approximately 0.7 - 0.8 dB/meter - avoid runs over 3 meters
- RG-8X: approximately 0.27 - 0.30 dB/meter - usable up to ~10 meters
- LMR-400: approximately 0.13 dB/meter (~3.9 dB per 100 ft) - suitable for long runs
- LMR-200: approximately 0.23 - 0.25 dB/meter - good for medium runs

A 10-meter run of RG-58 costs you roughly 7 - 8 dB at 915 MHz - more than a 5x reduction in power, completely erasing any gain advantage from a high-gain antenna. Use the lowest-loss cable practical for your installation.

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Revision #3
Created 2026-05-03 05:37:49 UTC by Mesh America Admin

Updated 2026-06-09 15:58:21 UTC by Mesh America Admin