

Designing for Multi-Hop Reliability

Link Budget Through Multiple Hops

In a multi-hop chain, each individual link (hop) must have a positive link margin. Unlike a wired network where signal is regenerated cleanly at each switch, a LoRa repeater decodes the incoming RF signal and re-transmits at full power. The quality of the received signal at the repeater does *not* degrade the re-transmitted signal - each hop is an independent link.

However, **the weakest link in the chain determines end-to-end reliability**. If three hops each have reliabilities of 99%, 95%, and 90%, the end-to-end delivery probability is:

$$P(\text{delivery}) = 0.99 \times 0.95 \times 0.90 = 0.846 = 84.6\%$$

This is the key insight of multi-hop network design: each marginal link has an outsized negative effect on overall reliability because the probabilities multiply. A single 85% link in a three-hop chain degrades end-to-end delivery to ~70 - 75% even if the other two links are near-perfect.

Planning Hop Paths for Your Network

Before finalising repeater placement, map the expected relay chains for your most critical communication paths. The process:

1. **Draw the relay chain.** On your coverage map, trace the sequence of repeaters a message from a specific source node would traverse to reach the destination. In Meshtastic (flood routing), there may be multiple parallel paths; identify the primary path (shortest hop count with best margins) and the fallback path.
2. **Estimate link margin at each hop.** For each hop in the chain:
 - Calculate FSPL (Free Space Path Loss): $FSPL(\text{dB}) = 20 \cdot \log_{10}(d) + 20 \cdot \log_{10}(f) + 92.4$ (d in km, f in GHz)
 - Add terrain/vegetation loss (see Coverage Radius Estimation page for obstruction factors)
 - Subtract antenna gains (transmitter + receiver)
 - Link Margin = TX Power + TX Antenna Gain – Path Loss – RX Antenna Loss – RX Sensitivity

3. **Identify where margin is thin.** Any hop with less than 10 dB of margin is at risk. Flag it. Options: move the repeater to a better site, add a fill node on that hop, increase antenna gain on that link, or accept reduced reliability on that segment.
4. **Document the analysis.** Record the estimated margin at each hop. Update after each wardriving survey that provides measured RSSI/SNR data on that link.

Worked Example: Three-Hop Path Analysis

Scenario: A remote ranch (Client A) communicates with the county EOC (Destination) via three repeaters (R1, R2, R3). Meshtastic on 915 MHz, SF10/BW125. TX power: 30 dBm (1 W). Antenna gain: 3 dBi omnidirectional on all nodes. Receiver sensitivity (SF10/BW125): -132 dBm.

Hop 1: Client A ? Repeater R1 (hilltop, 4.2 km, rural open)

$$\begin{aligned} \text{FSPL} &= 20 \cdot \log_{10}(4.2) + 20 \cdot \log_{10}(0.915) + 92.4 \\ &= 12.46 + (-0.77) + 92.4 \\ &= 104.1 \text{ dB} \end{aligned}$$

Terrain loss (rural open): 0 dB additional (clear LOS)

$$\begin{aligned} \text{Link Margin} &= 30 \text{ (TX)} + 3 \text{ (TX ant)} - 104.1 \text{ (FSPL)} + 3 \text{ (RX ant)} - (-132) \text{ (sensitivity)} \\ &= 30 + 3 - 104.1 + 3 + 132 \\ &= 63.9 \text{ dB} \end{aligned}$$

Result: **63.9 dB margin** - excellent. This link is rock-solid.

Hop 2: Repeater R1 ? Repeater R2 (rooftop, 9.8 km, suburban)

$$\begin{aligned} \text{FSPL} &= 20 \cdot \log_{10}(9.8) + 20 \cdot \log_{10}(0.915) + 92.4 \\ &= 19.82 + (-0.77) + 92.4 \\ &= 111.5 \text{ dB} \end{aligned}$$

Suburban obstruction add: +12 dB (0.55 factor = approx. +5 to +15 dB additional loss)

$$\begin{aligned}
 \text{Link Margin} &= 30 + 3 - (111.5 + 12) + 3 + 132 \\
 &= 30 + 3 - 123.5 + 3 + 132 \\
 &= 44.5 \text{ dB}
 \end{aligned}$$

Result: **44.5 dB margin** - good, well above the 10 dB minimum.

Hop 3: Repeater R2 ? Destination EOC (18.5 km, suburban, EOC is in a building)

$$\begin{aligned}
 \text{FSPL} &= 20 - \log_{10}(18.5) + 20 - \log_{10}(0.915) + 92.4 \\
 &= 25.34 + (-0.77) + 92.4 \\
 &= 117.0 \text{ dB}
 \end{aligned}$$

Suburban obstruction add: +12 dB

Building penetration loss (EOC indoor): +10 dB

$$\begin{aligned}
 \text{Link Margin} &= 30 + 3 - (117.0 + 12 + 10) + 3 + 132 \\
 &= 30 + 3 - 139.0 + 3 + 132 \\
 &= 29.0 \text{ dB}
 \end{aligned}$$

Result: **29.0 dB margin** - acceptable (above 10 dB), but the EOC indoor penalty is significant. If the EOC uses a rooftop-mounted external antenna instead of an indoor unit, the 10 dB building penalty disappears and margin rises to 39 dB. Strongly recommend external antenna at the EOC.

Chain Summary

Hop	Distance	Margin (dB)	Status
Client A → R1	4.2 km	63.9	Excellent
R1 → R2	9.8 km	44.5	Good
R2 → EOC	18.5 km	29.0	Marginal (address indoor loss)

End-to-end reliability of this chain is constrained by the R2 → EOC hop. Installing an external rooftop antenna at the EOC is the highest-priority action.

SNR and RSSI Thresholds for Reliable Forwarding

Theoretical link margins are estimates. In a live network, use measured RSSI and SNR to assess actual link quality. The following thresholds are practical minimums for reliable message forwarding:

Metric	Minimum (marginal)	Target (reliable)	Good	Excellent
RSSI	-130 dBm	-120 dBm	-110 dBm	> -100 dBm
SNR	-15 dB	-10 dB	-5 dB	> 0 dB

Notes on these thresholds:

- **RSSI -130 dBm / SNR -15 dB:** Packets may be decoded but success rate is low (50 - 70%). Use only as an emergency fallback. Do not plan routes through links at this level.
- **RSSI -120 dBm / SNR -10 dB:** Practical minimum for planned routes. Expect 85 - 95% packet delivery under normal conditions. Link will degrade in rain, vegetation growth, or when nearby interference increases the noise floor.
- **RSSI -110 dBm / SNR -5 dB:** Reliable for infrastructure links. Acceptable for primary repeater-to-repeater connections. Will maintain >98% delivery in most conditions.
- **RSSI > -100 dBm / SNR > 0 dB:** Strong link. Typical of well-placed nearby repeaters. These links rarely fail under normal operating conditions.

When reviewing live network telemetry, links consistently below -120 dBm RSSI or -10 dB SNR are candidates for remediation. Check the repeater placement, antenna alignment, and cable connections. If the physical setup is already optimal, a fill node on that path may be necessary.

The Weakest-Link Rule in Practice

When troubleshooting poor end-to-end delivery on a multi-hop path:

1. Collect RSSI and SNR readings at each hop using the Meshtastic traceroute command or MeshCore path diagnostics.
2. Identify the hop with the lowest RSSI or SNR - this is your weakest link.
3. Improving the weakest link will improve end-to-end delivery more than any other intervention. Do not chase marginal improvements on already-good hops.
4. After fixing the weakest link, re-test the full chain. A new weakest link may emerge.
5. Repeat until all hops meet the >10 dB margin / > -120 dBm RSSI / > -10 dB SNR targets.

Revision #2

Created 2026-05-03 05:37:35 UTC by Mesh America Admin

Updated 2026-05-03 13:01:42 UTC by Mesh America Admin