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, so the RF leaving each repeater is clean. But a packet that is only marginally decoded may contain bit errors or fail its CRC and be dropped — so each hop's received signal quality still determines whether the packet survives that hop. The re-transmitted signal is clean, but a weak receive at a repeater can still break the chain.

This is why **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:

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P(delivery) = 0.99 × 0.95 × 0.90 = 0.846 = 84.6%
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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 with two near-perfect (~99%) links yields about 0.85 × 0.99 × 0.99 ≈ 83% end-to-end. If the other two links are also only moderate (~90% each), end-to-end delivery drops to roughly 70%.

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(dB) = 20-log₁₀(d) + 20-log₁₀(f) + 92.45 (d in km, f in GHz)
   - Add terrain/vegetation loss (see Coverage Radius Estimation page for obstruction factors)
   - Add receiver antenna gain; subtract any receiver feedline/connector loss
   - Link Margin = TX Power + TX Antenna Gain − Path Loss + RX Antenna Gain − RX Feedline Loss − RX Sensitivity (all in dB, with TX power and sensitivity in dBm)
3. **Identify where margin is thin.** A common planning rule of thumb is to flag any hop with less than 10 dB of margin as at-risk. (This is a heuristic, not a fixed standard — planners use anywhere from ~6 dB in benign environments to ~20 dB where high availability or heavy fading is expected.) 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: 22 dBm (~160 mW) — the SX1262 chip maximum used by stock Meshtastic/MeshCore radios. (FCC Part 15.247 permits up to 30 dBm / 1 W conducted in 902 - 928 MHz, but reaching that requires an external power amplifier, and antenna gain above 6 dBi requires a 1-for-1 dB power reduction to stay within the 36 dBm EIRP limit. The figures below assume the buildable 22 dBm.) 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)

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FSPL = 20-log₁₀(4.2) + 20-log₁₀(0.915) + 92.45
 = 12.46 + (−0.77) + 92.45
 = 104.1 dB

Terrain loss (rural open): 0 dB additional (clear LOS)
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Link Margin = 22 (TX) + 3 (TX ant) − 104.1 (FSPL) + 3 (RX ant) − (−132) (sensitivity)
 = 22 + 3 − 104.1 + 3 + 132
 = 55.9 dB
```

Result: **55.9 dB margin** - excellent. This link is rock-solid.

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

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FSPL = 20-log₁₀(9.8) + 20-log₁₀(0.915) + 92.45
 = 19.82 + (−0.77) + 92.45
 = 111.5 dB

Suburban obstruction add: +12 dB (unsourced rule-of-thumb clutter allowance; suburban
 clutter at 915 MHz commonly runs roughly +5 to +15 dB. For a rigorous estimate use a
 named model such as ITU-R P.1546 or COST-231 Hata.)

Link Margin = 22 + 3 − (111.5 + 12) + 3 + 132
 = 22 + 3 − 123.5 + 3 + 132
 = 36.5 dB
```

Result: **36.5 dB margin** - good, well above the 10 dB minimum.

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

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FSPL = 20-log₁₀(18.5) + 20-log₁₀(0.915) + 92.45
 = 25.34 + (−0.77) + 92.45
 = 117.0 dB

Suburban obstruction add: +12 dB
Building penetration loss (EOC indoor): +10 dB (construction-dependent; building
 penetration at 915 MHz ranges roughly 5 to 25+ dB. See ITU-R P.2109.)

Link Margin = 22 + 3 − (117.0 + 12 + 10) + 3 + 132
 = 22 + 3 − 139.0 + 3 + 132
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```
= 21.0 dB
```

Result: **21.0 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 about 31 dB. Strongly recommend external antenna at the EOC.

Chain Summary

Hop	Distance	Margin (dB)	Status
Client A → R1	4.2 km	55.9	Excellent
R1 → R2	9.8 km	36.5	Good
R2 → EOC	18.5 km	21.0	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 thresholds below are approximate planning heuristics, not measured constants. They are also spreading-factor dependent: the figures here assume a mid-range preset (around SF9 - SF10). LoRa's SNR decode floor ranges from roughly −7.5 dB at SF7 down to about −20 dB at SF12, and at SF11/SF12 a link can decode reliably well below −120 dBm RSSI (sensitivity is around −131 dBm at SF11/250 kHz and −137 dBm at SF12/125 kHz). Treat the cutoffs as *margin relative to your preset's sensitivity* rather than fixed absolute numbers.

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 (approximate, and SF-dependent — assume roughly SF9 - SF10 here):

- **RSSI −130 dBm / SNR −15 dB:** A rough rule of thumb is a 50 - 70% success rate at a mid-range SF — packets may be decoded but unreliably. (At SF12 these levels are

comfortably decodable.) 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 at a mid-range SF. As a heuristic, expect roughly 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 near the marginal end of the scale for your preset 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 per-hop SNR readings using the Meshtastic traceroute command (from firmware ≥ 2.5 it records the route back along with the Signal-to-Noise Ratio for each link — it reports SNR, not RSSI), or MeshCore path diagnostics. Per-link RSSI must be read locally from the node, not via traceroute.
2. Identify the hop with the lowest SNR (or locally-measured RSSI) - 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 your margin and SNR targets for the preset in use.

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