European Cave Rescue Association

Technical Commission
Underground Communications

Meshtastic Radios

Contents

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Version History

Version	Date	Description	Author
1.0	March 2026	Initial version of Meshtastic Document	See authors above.

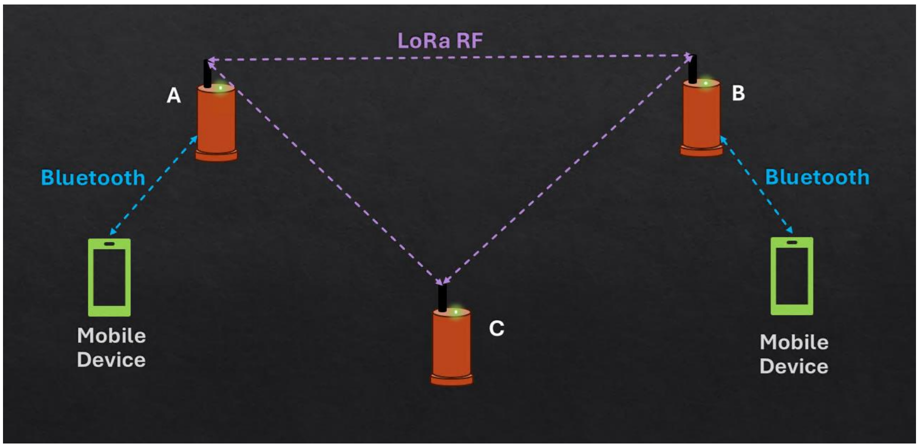
Meshtastic Background

Overview

Meshtastic is a popular community-driven radio system intended for decentralized communications. It utilizes affordable, open-source technology that allows users to connect without the need for traditional networks. By leveraging LoRa (Long Range) RF technology, Meshtastic enables devices to communicate over impressive distances, even in areas lacking cell towers and internet access and runs on hardware that is becoming much more affordable.

LoRa incorporates a couple desirable features, namely spread factor (SF) and forward error correction (FEC). These work together to trade data rate for reliability and range. The SF determines how long each text symbol is transmitted, with higher values increasing sensitivity and allowing reception of very weak signals at the cost of slower data rates. FEC adds redundancy so the receiver can reconstruct data even when some bits are corrupted by noise or interference. These mechanisms are helpful because they allow LoRa links to remain usable over long distances, through obstacles, or in noisy environments by prioritizing successful message delivery and low power operation over raw throughput. Within Meshtastic, these can be configured manually or by selecting LoRa “presets”.

Meshtastic is an open-source project started in 2017 that uses its own data format and routing protocols for building ad-hoc two-way communication networks between LoRa-compatible devices in a mesh architecture. Each node can talk to another node within range, but each node can also relay messages for other nodes. Users can individually connect to nodes via Bluetooth to a mobile device, or through serial for more advanced control.



Basic Meshtastic network example

At its core, Meshtastic employs cheap microcontrollers like the ESP32 and nRF52840, which are known for their flexibility and especially low power consumption. Popular RF module brands include LilyGo, Heltec, and RAKWireless. LoRa, and subsequently Meshtastic, operates on the Industrial, Scientific, and Medical (ISM) radio bands. This typically means users do not have to obtain licenses as long as they stay within the legal frequency and power limits. Along with frequency allocations, regional regulations set maximum power and parameters such as link budget.

Region	Frequency Range [MHz]	Max. TX Power [dBm]	Max. TX Power [mW]
EU	863-870	14	25
US	902-928	30	1000
AUS	915-928	30	1000

Since its launch, Meshtastic has attracted contributions from a global community of developers, with applications ranging from hiking and recreation to emergency response, where conventional communication tools might fail.

What sets Meshtastic apart is its capability for long-range communications, typically ranging from 2 to 5 kilometers, with remarkable records of up to 331 kilometers under optimal conditions above ground. Each device acts as both a sender and receiver, creating a mesh network among users. This decentralized networking approach enhances privacy and connectivity and makes the learning curve low.

Meshtastic ensures message integrity through robust encryption, which is crucial for users sharing sensitive information, which is desired for rescue operations that could involve medical data. The system is designed for battery efficiency, allowing devices to run for extended periods, ideal for outdoor activities. In addition to simple messaging, users can share GPS locations, making Meshtastic a versatile communication tool for various scenarios, including emergencies and outdoor adventures. Meshtastic currently supports ATAK and CalTopo, which are popular team awareness tools used by the SAR community.

LoRa for Underground Communications

As evident in this report, communication in subterranean environments like caves and tunnels presents unique challenges due to irregular spaces, potential water hazards, and the difficulty of installing communication equipment. Additionally, RF signals can obviously easily be attenuated by the earth.

The Meshtastic system is becoming increasingly relevant in this context as the radios are substantially less expensive than through-the-earth RF systems and easier to deploy than traditional wire systems. Cave systems can be particularly challenging due to their twisted passages and varying topographies. In rescue scenarios, speed is crucial, and any communication setup must withstand the conditions of high floodwaters while enabling rescuers to navigate through tight spaces.

Overall, while the idea of using mesh networks for underground communication offers great promise, there are still significant hurdles to overcome. Community efforts focus on improving reliability in these harsh conditions, combining existing technologies with practical solutions to make underground communication more effective and accessible. This not only enhances safety for exploring caves but also opens up new possibilities for adventure and exploration in subterranean environments.

Advantages & Disadvantages

When it comes to mesh radio systems operating in subterranean environments, there are advantages and challenges that need careful consideration.

Utilizing Meshtastic for underground communications offers several significant advantages, particularly in affordability, ease of use, and practicality. Compatible hardware can be sourced for less than €30 and as little as €8, making it an accessible option for various groups, including hobbyists, adventurers, and emergency responders. This low-cost entry point allows users to equip themselves without the financial strain typically associated with traditional communication systems.

In addition to being affordable, Meshtastic systems are extremely user-friendly. The straightforward setup process enables users to get their devices operational quickly, which is vital in urgent scenarios like search and rescue missions in caves or tunnels. The Meshtastic mobile app is well supported on iPhone and Android operating systems. Users don’t need extensive technical expertise; many can grasp the technology with minimal guidance.

Moreover, Meshtastic could allow for rapid deployment thanks to its self-organizing mesh ability. This is especially crucial in environments where time is of the essence, such as during emergencies or expeditions. The system’s low power consumption means it can run efficiently on batteries, ensuring that communications remain active for prolonged periods, even in remote or challenging conditions.

However, using Meshtastic comes with several limitations that must be considered. One significant drawback is that the physical geography of underground environments can severely limit radio signal propagation. Irregular terrain, moisture, and physical barriers like rock formations or water bodies can easily disrupt connectivity, making it harder to maintain a reliable communication network. Signals operating on ISM bands–such as those used by Meshtastic–are not particularly effective at penetrating solid structures. Careful placement of nodes is essential, often requiring trial and error to find the best locations where signals can relay effectively. Users might need to experiment with multiple nodes, sometimes needing to walk into the cave until the signal drops and then retracing their steps to find suitable spots to deploy.

Additionally, setting up and maintaining these systems could be time-consuming and technically demanding, especially in complex subterranean environments. Users might have to invest effort into understanding how to configure the network properly and troubleshoot issues, which can be a barrier for those without technical backgrounds.

While Meshtastic boasts energy efficiency and long battery life, a challenge lies more in managing and storing them effectively rather than endurance itself. Ensuring that multiple devices are charged and ready for action is crucial, particularly in rescue scenarios where every detail counts. Users must plan ahead to keep all equipment organized and functional, which can complicate communication efforts.

Finally, stock Meshtastic supports only up to 7 hops per message. While this is intended to reduce excessive traffic on a mesh topology, it could seriously limit the utility in a cave environment where the topology is more like a chain that could easily be longer than 7 hops.

Community Adaptations

Recognizing the unique challenges of subterranean communications, some community efforts are emerging to adapt technologies like Meshtastic for better functionality in underground environments. As far back as 2018, LoRa was introduced as a possible means of logging cave data as published in the British Cave Research Association's (BCRA's) Cave Radio & Electronics Group (CREG) journal.

One of the largest breakthroughs was achieved by the Vangelis team where the 7 hop limit was eliminated, opening a doorway to more rapid development in this area. Flamingo took a similar approach and introduced additional enhancements. ESOCAN has proposed advanced topologies to connect from caves to more remote command centres. These groups, with overlap with the Meshtastic community and cave community as a whole are continuing to improve this technology into a fieldable solution.

Vangelis

The following section is adapted from the Vangelis Github page and the CREG writeup by Paweł Krawczyk from Gloucestershire Cave Rescue Group (GCRG).

Background

Preliminary testing indicated LoRa around 868 MHz does surprisingly well in underground tunnels and better than simple AM voice radios using Professional Mobile Radios (PMR). Practical testing by Paweł Krawczyk demonstrated LoRa links working with no line of sight and establishing a stable two-way link even through up to 3 sharp tunnel bends over distances 40-70 m. Radio wave attenuation in underground tunnels has been systematically examined, with one publication exposing an interesting phenomenon of 455-915 MHz signal getting further in around-corner propagation than 2.4-5.8 Ghz (which reached further in straight tunnels). Relatively good results of LoRa in getting across obstacles can be attributed to a combination of a complex interaction of the wave with the underground cavity walls (reflection, refraction, diffraction) with LoRa's designed ability to reconstruct data from even a distorted signal.

Hardware

When using the RAK4631 platform, the bill of materials closes at around 50 GBP for a single device which is an order of magnitude less than competing solutions (cost of DIY assembly and 3D-printed case were not accounted for). The cost factor in relay-based communications is especially important as a complete cave to surface link usually requires up to a dozen of such relays (depending on the cave length), unlike the through-the-earth radios which work on the point-to-point basis (except when they don't). The primary design goal for relay-based radios is therefore low-cost of a single relay, durable construction and low-maintenance operations.

Key Enhancements

Hop Decrement Removal

Vangelis "TacMesh" radios

Being an open-source project, it was not difficult to remove the protocol restriction of maximum 7 hops and compile alternative firmware under code name "Vangelis". The modified firmware allows an unlimited number of relays and is available on GitHub (at github.com/semper-ad-fundum/vangelis) for anyone to modify and compile.

Node Placement Methodology

In the ideal case, the relays are configured on the surface only and the communications team moving through the cave should only need to (1) fetch a relay station from a hard case, (2) turn it on, (3) place it somewhere (on a rock, on an anchor) and move on to the next point. In reality, this becomes slightly more complicated in natural caves of complex cavity shape, where radio range varies, and each bend or squeeze requires making sure each new location is within the reach from the previous one. In one series you'd get a stable link over 100 m, in others it will require more dense placement.

This kind of route planning requires some kind of user interface to indicate the person placing it that the devices are in range. As of today, this can be achieved using Meshtastic app Range Tester module, which sends a numeric message on configured intervals, which essentially reduces the whole process to a simple recipe: "walk as long as you hear the beeps".

Testing and Deployment

Forest Dean Caves and Emmer Green Mines

United Kingdom - February-March 2024

Relay chains of 5-10 nodes were extensively tested in caves in Forest of Dean with the support of GCRG (Gloucester Cave Rescue Group) and in chalk mines in Emmer Green, courtesy of 89th Reading Scouts. The purpose of testing was primarily to establish practical range in real-world underground conditions, establish battery life in ambient cave temperature and additionally check overall user experience when using the nodes in a cave.

The initial testing was performed in the well-known Wet Sink cave, where a node carried down the entrance pitch continued to beep even as we crawled even through a short squeeze into the Mouse Aven, and then nearly to its bottom. A node at the bottom continued to communicate with the node at the cave entrance through two 10 m deep pitches separated by a 5 m long squeeze. The photo shows Paul Taylor (GCRG) making connectivity noted at one of the nodes.

Additional Testing

Subsequent testing indicated that the nodes equipped with a 2 dBi antenna can comfortably talk across two sharp (90º) bends over walking distance of around 40 m in a human-sized passage. Expectedly, tight meandering crawls of around 50 cm height reduced the radio range to 10-15 m. The record length was achieved in the Chunnel in Wet Sink cave, where two nodes established a link over 120 m in a quite spacious, almost horizontal tunnel, although with several rubble heaps that prevented direct line of sight. With line of sight the nodes should be easily communicating on the same distance as on the surface with the same antennas, which is around 200 m.

Range testing in spacious Emmer Green chalk mines produced even better results, as two nodes talked comfortably over 70 m of tunnel with several bends and one lower passage, although in this experiment 3 dBi antenna was used. Overall, only 3 static nodes were necessary to provide connectivity to each location in the maze-like mine extending around 250 m each direction. In the same location battery life testing was also performed where nodes were left underground for a week at ambient temperature of 12°C surviving 6 days and providing periodic updates to the surface, and then to author’s house around 1 km away. Each node was powered from a 2000 mAh battery charged full at the start of the experiment.

Lessons Learned

Cave testing indicated a number of issues with the original Meshtastic firmware, which was originally designed for fast-evolving, cloud-like networks with many peer-to-peer connections and more flat than linear topology. This design choice assumed that the maximum number of hops (sequential relays transmitting a single message) will be rarely larger than seven, which conveniently fits into three bits counter embedded in each message. The counter is decreased by each hop, thus preventing messages traversing the network endlessly. Relay-based communications, however, assumes a long chain of nodes, each of which only speaks to its two nearest neighbours, so the number of hops may be significantly longer. In our Wet Sink testing the messages traversed 7 hops before they were expired by the protocol before reaching the full chain.

Future Work

A number of intriguing open questions remain that require more systematic research in real cave and mine conditions, especially how LoRa range will be impacted by different radio settings (bandwidth, Spread Factor, Coding Rate).

The default Meshtastic settings is SF11, which translates to ~1 kbps data rate and reducing the redundancy of data to SF7 leads to tenfold increase in data rate, faster transmission, less power transmitted and longer battery life. While higher SF certainly improves “survivability” of a radio message in high-interference environment, it’s not yet clear how this actually impacts range in cave conditions.

LoRa, being an interference-resistant radio modulation, could also benefit through-the-earth communications. Yet another area of research is voice communications, which has been apparently tried in QMesh project using more sophisticated routing and error correction protocols, which unfortunately (from our point of view) also translated to more computationally expensive and energy-hungry hardware. Also, LoRa is not the only modulation created with these design principles in mind, one worth mentioning is DASH7, as of today however few beat LoRa in terms of availability of cheap hardware.

Flamingo

Background

Flamingo is a specialized fork of the Meshtastic firmware, tailored for in-cave communications and intended for rescue or expedition operations. This initiative is led by members of the Huntsville Cave Rescue Unit (HCRU) which operates in the Tennessee-Alabama-Georgia (TAG) region in USA. The project was started by Jamie Moon after being inspired to recreate the experiment demonstrated by Vangelis in 2024. Jamie brings a mechanical integration and testing background and is assisted by Bob Reese, an embedded systems expert who has implemented several innovative software modifications and utilities. The project began in March 2025 and continues to evolve with the help of several people inside and outside of HCRU. The current goal of Flamingo is to provide a reliable cave communication system that is versatile, affordable, and efficient by continuing to improve and simplify the hardware and software within it. Comprehensive documentation is available on the FLAMINGO Github page at github.com/rbreesems/flamingo.

Hardware

Currently, Flamingo has been adapted into two custom hardware implementations: a Cavenode and a Hybrid ("bridge") node, although other commercial radios (such as WisMesh Pocket) are also supported. At the time of this writing, a kit of Cavenode and Hybrid units have been delivered to HCRU for operational testing and a Hybrid development kit is being built and evaluated by a developer associated with the Hrvatska Gorska Služba Spašavanja (HGSS or Croatian mountain rescue service). A goal is to make Flamingo easily accessible to agencies who want to test out this technology so continual feedback can be collected. Both radios function as relay or personnel nodes and feature rugged, water-resistant plastic enclosures. The Cavenode features a built-in buzzer to function as haptics for rapid deployment and the Hybrid includes a folding antenna and a comms wire bridge (Continue reading for more information). The primary hardware platform for all Flamingo radios is currently the RAK4631 LoRa module paired with a WisBlock baseboard and is capable of operating up to a week on a single 18650 li-ion battery.

"Hybrid" (left) and "Cavenode" Version 2 hardware units

Performance

Current performance statistics:

- Battery life:
  - Estimated 10-14 days per charge
- Range (Radio):
  - 130-320ft (40-100m) between nodes
- Range (Wired):
  - Over 5,200ft (1.6km) of comms wire between nodes
- Ingress:
  - Water resistant (estimated IP55 for Cavenode V2)
- Weight/Volume:
  - <6oz (160g) per radio
  - <9lbs (4kg) per field kit
  - 12 Cavenodes or 8+ Hybrid nodes fit in 10L hard case

Key Enhancements

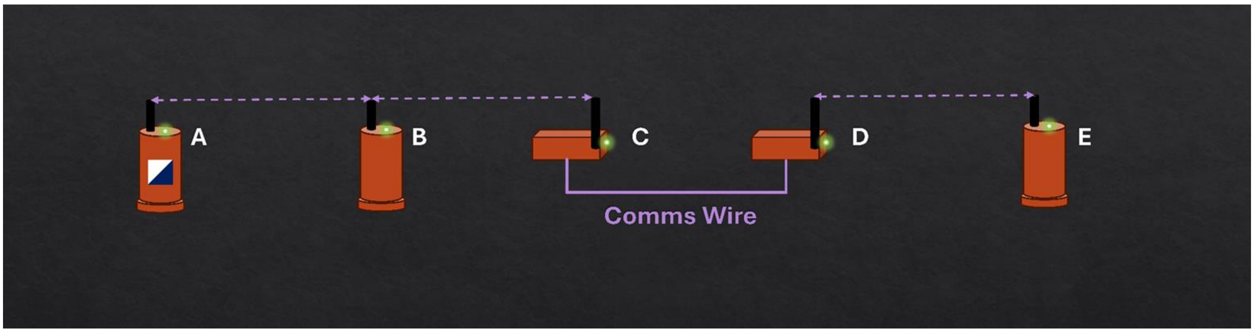
The following changes mark the major improvements made to the existing Meshtastic baseline to enable Flamingo:

Extended Maximum Hop Limit

While the stock Meshtastic firmware limits packet hops to 7, Flamingo modifies the packet header to support up to 255 hops. Unlike other forks such as Vangelis, which remove hop decrementing, Flamingo's approach maintains hopping to ensure accurate hop tracking but renders Flamingo radios incompatible with standard Meshtastic devices. This is not viewed as a negative, as in a rescue situation, it is important to vet any radios that operate on the mesh, and Flamingo radios can be assigned to members of other rescue squads if they need it during the operation. In operational testing during a joint exercise with HCRU and Chattanooga Rescue Squad, messages have been recorded traversing up to 16 hops with less than 2 minute latency.

Hard-wire Capability via RS485

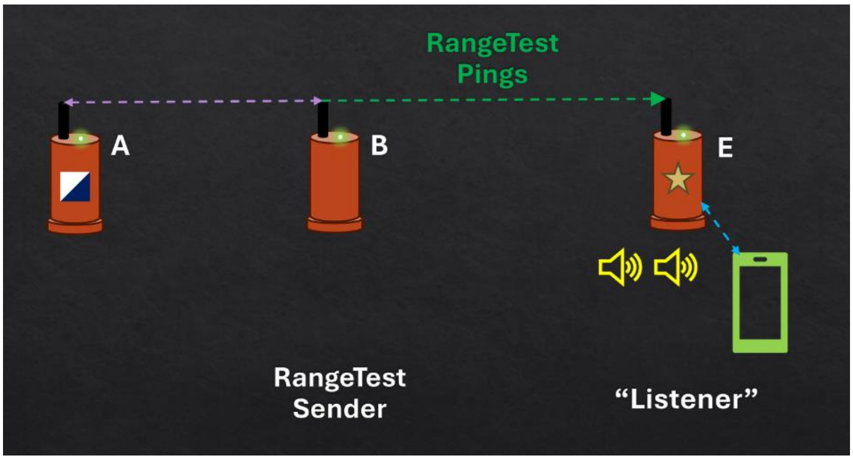
The Hybrid Flamingo nodes possess terminals that allow traditional 2-conductor cave communications wire to be used. Flamingo replaces the stock serial module with support for RS485 communication (using the RAK5802 module on the WisBlock baseboard). This allows seamless packet transmission between wireless LoRa and wired RS485 segments. RS485 uses a two-wire differential signalling system, providing robust noise rejection and supporting distances up to 700 meters at 9600 baud, with longer distances achievable at lower baud rates. Wired segments are especially useful in challenging cave topologies where wireless signals are obstructed. In a joint mock exercise, the mesh included 23 radios with three wired segments measuring 240m, 240m, and 270m. A Hybrid node interface acts as a bridge node for mixed topologies.



Example of mixed (RF and wired) network topology

Hands-Free Setup Mode

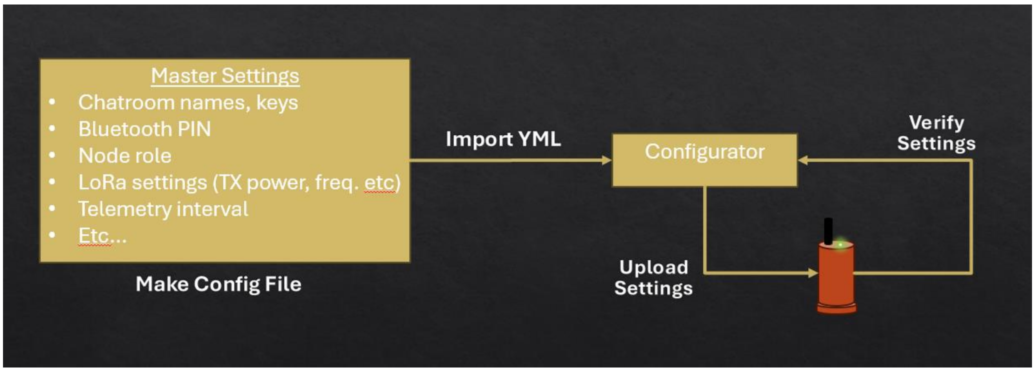
During network setup, a modification to Meshtastic's native "RangeTest" mode allows a user to request the previous node to automatically send periodic signal strength messages. Cavenodes trigger their internal buzzers to beep according to signal strength, enabling a hands-free setup workflow. The user can monitor Signal-to-Noise Ratio (SNR) to quickly place nodes at the optimal spacing, balancing network strength and resource conservation.



Using rangetest and audio haptics for setup

Batch Radio Configuration

In order to streamline setting up large quantities of radios, a custom program was created to push a predefined list of radio settings to all radios. This allows the user to create a single master list of radio settings that can include security settings (like Bluetooth pin and chatroom keys) as well as any other radio setting (like transmit power or frequency slot). The user adds settings to a YML file which the script pushes to the radios and verifies settings. Users could conceivably create and catalogue different presets based on mission loadout or application. This workflow reduces the risk of accidentally mismatching radios and allows a single user to quickly modify a batch of radios depending on the mission.



Additional Improvements

- Enhanced debug message output for comprehensive log parsing at Incident Command.
- Configurable retransmission counts for all packets, with a default of two retransmits for channel packets, significantly improving reliability over long hop chains.

Testing and Deployment

HCRU Cave Rescue Class Mock

Guffey Cave, Alabama, USA - 3 August 2025

Flamingo radios were deployed during this annual five-day certification class involving 35 students. Twenty radios were used, including seven for instructors and the remainder forming the mesh. Two wired segments (90m and 210m) were deployed to navigate complex cave sections. The mesh was set up the morning of the mock before student entry and proved invaluable when a patient placement error was quickly identified and corrected via text coordination. Over 450 messages were logged at Incident Command, and the leadership deemed the deployment a success.

HCRU/Chattanooga Mock Exercise

Tumbling Rock Cave, Alabama, USA - 27 September 2025

Flamingo radios served as the primary communications system for this mock rescue involving 50 cavers. The mesh was deployed by the communications team as initial search and rescue teams entered the cave. Approximately 23 radios were used, including three wired segments (270m, 240m, and 240m) connected by six bridge nodes, with 10 additional radios used by rescuers. The mesh extended approximately 1.4 km into the cave, where the patient was located in a vertical section 30m above the cave floor. Over 600 text messages were exchanged throughout the day, and the mesh radio deployment was declared a success.

Lessons Learned

- Radio configuration should include two channels: one for general use by all rescuers and an administrative channel for the communications team and Incident Command to perform status checks. This reduces chatter on the general channel, and the admin channel can be muted by rescuers to avoid distraction.

- Low latency and reliability are critical for communications. The LoRa mode used in Flamingo radios has evolved from LONG/FAST to MEDIUM/SLOW to SHORT/FAST to reduce latency. The extended range offered by slower speed configurations is often not realized in cave topologies, while faster modes reduce channel contention and latency. SHORT/FAST currently appears to be providing acceptable reliability.
- Node placement should be conservative to ensure reliability. Flamingo's placement strategy now uses an *average* received SNR with a threshold of greater than 3 dB as the placement criterion.
- When placing radios, use the same radio/antenna configuration for checking SNR on received packets as the radio being placed. A mistake was made in the HCRU/Chattanooga mock in that a radio with an *external* antenna was used to listen for packets to place radios with *internal* antennas (lower range), resulting in a mesh with weak links that had to be patched after initial deployment. Internal antennas are currently not recommended unless they can be improved. A second test in Tumbling Rock was done on January 23/ 2026 with the same distance (1.4 km) achieved but used only 15 radios (six bridge nodes for three wired links, nine wireless-only) in mesh. The fewer radios needed was due to using only radios with external antennas for placement and listening, resulting in a mesh with no weak communication links. The final hop count from Incident Command to target destination in this test was fifteen.
- Rescuer radios should be placed in Client Mute mode (no packet broadcasting) to avoid contention with primary radios and facilitate troubleshooting of weak links. Rescuer radios should also be given meaningful names upon issue to make communications clearer.

Future Work

Investigate Flamingo's use for cave expedition application, including automating emergency callout messaging from the cave exit to cellular/satellite services and extended battery life.

Develop improved software tools at Incident Command for managing radio configurations and automating standard replies to incoming messages.

Continue to streamline setup process and make it more hands-free

Continue to improve enclosure design

Meshocan

This section is compiled from a translated copy of Martín González Hierro's Red Meshocan manual.

Background

The Fundación Espeleosocorro Cántabro (ESOCAN) is a private, non-profit cave rescue foundation based in Cantabria, Spain, with a long-standing operational experience in underground rescue. Communications reliability has been a recurring challenge in ESOCAN's operations, particularly the tradeoff between unreliable RF radios and labour-intensive wired field telephone systems. Existing communications technology for long-term exploration or rescue operations have been traditionally addressed using a genephone cable. This system consists of a long cable (often field wire) with a basic microphone and earphone or handset at each end. The system works as a sound-powered telephone: speech vibrations are converted directly into electrical signals, so no batteries or external power are required.

In November 2025, ESOCAN began documenting its work (see www.espeleosocorro.es, adapting LoRa/Meshtastic-based radios for cave use under the name “Red Meshocan”. followed by more detailed articles later that month and in December describing architecture, deployment practices, and limitations encountered with stock Meshtastic. The work was driven internally by experienced ESOCAN rescuers and developed in dialogue with other European cave rescue and technical groups and seeks to simplify the configuration introduced by the Vangelis group.

The objective of the Meshocan network is to be able to transmit information in real time from inside the cave to the Advanced Command Post (PMA) during a rescue. To do this, it is necessary to establish communications from the PMA to the cave entrance, and from there to the accident site or along the route taken by the rescuers (or as far as possible from the entrance).

Here we have three options. One is to use conventional means of communication, either via telephone or handheld transceivers, which requires coverage at both points. The other two options are based on LoRa radios, either through the network we install or through MQTT portals ("Mosquito Network"), one at the PMA and the other at the cave entrance. With this solution, communication from the PMA to the cave entrance is done via the internet, saving us hops and the cost of laying cables.

The first option requires a rescuer at the cave entrance to act as an internal-external liaison. This generally involves a reinterpretation of the information by this rescuer and also prevents direct communication between the coordinator and the team leader. The second requires intermediate nodes between the cave entrance and the PMA if there is no direct line of sight. The third requires an internet connection at both points and a gateway, which can be two mobile phones with flat rate data plans.

Hardware

Meshocan uses commercial off-the-shelf LoRa radios compatible with Meshtastic firmware, operating in the EU 868 MHz ISM band. The focus is on small, lightweight, battery-powered nodes that can be carried and deployed by individual rescuers without special infrastructure. The hardware is intentionally low-cost—on the order of tens of euros per node—and avoids custom or proprietary radio designs.

At the PMA, a laptop is connected to the internet with a browser point to the Meshtastic client portal. A Heltec V3 LoRa radio (868MHz) is then connected over the USB port. The node has a signal amplifier that allows the antenna to be placed outside the structure and give it greater range. This board is powered via a USB-C port connected to a backup battery or, if there is a power outlet, from a USB-C mobile phone charger.

The cave relay nodes are each constructed from a 90x90x42 mm IP65 waterproof plastic box. Inside the box is foam cushioning and a Heltec V3 radio. This setup weighs 180g and costs around €40.

The team leader can use (1) a LilyGo T-Deck or (2) a Heltec unit inside a custom 3D printed enclosure. It is not waterproof but is compact, weighing only 73g.

Alternatively, the leader can use a dedicated phone and radio kit contained within a larger waterproof hard case. This costs around €137 (not including phone) and weighs 800g.

Testing and Deployment

Lanestosa Exercise

Coto Txomin, Karrantza, Spain - 1 November 2025

Initial testing was done at the national simulation carried out at the Lanestosa exercise at Coto Txomin reserve in Karrantza. Messages were sent from a mine entrance at the reserve to the PMA located at Lanestosa by a repeater node that was strategically placed on a hill by using terrain modelling.

From the cave entrance, communication nodes were deployed sequentially to extend coverage, with spacing determined by gallery morphology and observed signal quality. Each node linked to the previous one, forming a linear backbone underground.

Placement was guided using a LILYGO T-Deck radio, which provides node and signal scanning while moving through the gallery. As signal quality degrades, latency and hop count increase; when thresholds are exceeded, the position is adjusted back to the last reliable point and a node is installed. A similar method can be used via Range Test mode, which provides audible feedback to guide final placement.

Lessons Learned

Following the national simulation exercise, all nodes were upgraded with longer-range antennas, replacing the standard models. This change resulted in an estimated 40% reduction in the number of nodes required.

Although the technology nominally supported only 1+7+1 hops, limiting theoretical network depth from the cave entrance, this constraint was partially mitigated through careful mesh topology configuration, role assignment, and use of Zero Hop Repeater mode. Detailed discussion of these configurations was deferred to a subsequent study.

Future Work

ESOCAN has identified three types of conceptual Meshocan network architectures:

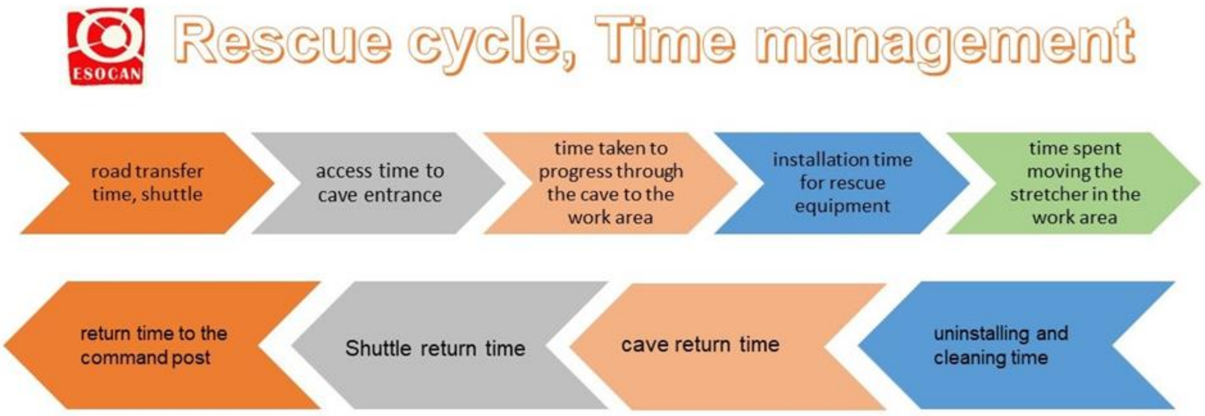
- Simple Network
    - From cave entrance (surface) into cave
- Dual Network
    - Same as Simple Network but connected back to remote PMA over surface mesh
- Advanced Network
    - Similar to Dual Network but connected back to remote PMA over MQTT internet server

ESOCAN introduced the possibility of using a MeshCore system. Unlike Meshtastic, MeshCore imposes no fixed hop limit. Multi-hop routing operates until packets reach their destination, after which routes are cached to reduce subsequent flooding. Practical limits arise from LoRa airtime, node processing, and cumulative latency: stable operation is observed up to 7 hops, latency grows between 8–15 hops, and more than 15 hops becomes unreliable. For linear cave networks with 50 nodes, a purely sequential chain would be impractical.

To maintain reliability, the network is segmented into sections of ~10 nodes, with a repeater at each segment endpoint forming a backbone. Each segment is paired with a room server connected via

USB/serial, improving delivery rates, lowering latency, and enabling remote firmware updates. This backbone architecture ensures mobile nodes require only a few hops to connect, while long-distance traffic remains stable and resilient. By combining segment repeaters and room servers, MeshCore networks achieve extended coverage in challenging cave environments without exceeding practical hop limits.

ESOCAN is investigating “meta-communication,” a concept which enables situational awareness and positioning by circuit occupation. The linear network of repeaters geo-referenced on the cave's topography will allow rescuers to know in near real time the location of the radios of the intervention teams and medical equipment (e.g. stretcher with injured person), their exact position between two repeaters, and their progress through the cave. This information, which does not require the participation of the rescuer, allows the rescue coordinator to have a clear view of the rescue situation. This facilitates logistics management, time management, anticipation of alternative rescue plans, etc. In a rescue operation in which all the agents involved carry a LoRa radio, we would have a broader view of the operation.



Work cycle of a rescue team