LoRa Cave Radios - “FLAMINGO”

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2 July 2025
Huntsville Grotto Program

Introduction

Bio

- Started caving in 2018
- Joined Huntsville Grotto in 2020
- HCRU member since Aug 2022

Day Job

- Autonomous systems test engineer at DoD contractor

Other Passions

- GIS, Remote Sensing, photography
- Tinkering/inventing
- RC and basic radios

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Project Overview

LoRa radios for cave communication with focus on rescue applications

Outline

1. Cave comms background
2. Objectives
3. Implementation
4. Field Test Series
5. Conclusions
6. Next Steps

Meshtastic

- **Lo**ng-**Ra**nge (LoRa) low power radio protocol for IoT* devices
- Off-grid, self-organizing mesh network using LoRa radios
  - No WiFi or cell service needed
- Open-source and community-developed
- Supports seamless user operation with iOS and Android mobile apps
- Enables AES128 encrypted messaging and location sharing
- Natively supports CalTopo (and ATAK) integration

**Internet of Things*

Current HCRU Comms Tech

Existing HCRU cave communication options:

- Electric analog voice intercoms (military phones) using conductive wire
  - Bulky, cumbersome
  - Intercoms are vintage technology (not sustainable)
- Runners
  - Slow
  - Potentially risky
- VHF/UHF radios
  - Not useful for in-cave

TP-6N phone, similar to HCRU systems

Other Cave Comms Options

Many devices are obsolete, expensive, or still in development

- Cavelink V4 VLF Radio - $1,400
    - Tested to 1.3km (~4,200ft)
    - Closed-source
- Nicola 3 Radio - $1,200
    - 1km (~3,300ft) max recorded distance
- CAVE-SYS Leaky Feeder Radio - $7,000
    - 9mm cable (similar weight to HCRU comms wire)
    - 14 hrs max battery life
- ERMES Digital system - $7,000
    - Verified to 2.4km (~7,800ft)
- Sybet SPELLCOM Mesh Radios - $20,000+
    - 50m spacing
    - 2.5 days battery life

ECRA, Technical Commission Underground Communications, Catalog of Communication Devices, Version 1.50, 8 April 2025

Other Cave Comms Options

Recent efforts

- Blackbird Field Phone
  - Proof of concept intended to replace aging field phones
- BuecherNet
  - Semi-permanent network of UHF radios (with one wired section)
  - Runs at low power (batteries replaced annually)

Meshtastic in Caves

"Semper ad Fundum*/Vangelis" project

- Created by cavers/developers from Virginia
- Originally used RakWireless "WisBlock" radios enclosed in a "TacMesh" 3D printed enclosure
- Tested in a handful of caves
- Using stock Meshtastic firmware and special "Pingbot" device for building network
- Removed decrementing hop count from firmware to overcome 7-hop limit

Credit: Phillip Balister & Paul Walko

**Translation: "Always going deeper"*

Application for HCRU

Advantages of LoRa for cave comms:

- Messaging is **text-based**
  - Provides definitive data versus ambiguity/interpretation over voice comms
- **Faster deployment** time
  - Reduces need for routing through cave
- Interoperable with team situational awareness tools (i.e. CalTopo)
  - Seamlessly integrate with GPS's and/or land systems on surface

Disadvantages:

- ISM radios heavily rely on line-of-sight, especially in underground environment
- Multiple radios are needed, each with independent power supplies
- Some advanced configuration may require specialized training

Objectives

Goals & Acceptance Criteria

Acceptance Criteria

Determine if mesh radios are suitable alternative to wire:

1. Cost per meter of comms is less than wire or commercial alternatives
2. Weight per meter is less than wire and phones
3. Average deployment time is less than laying wire
4. System can be ruggedized to handle caving environment
5. System is easy to scale and train people to use

Methods

Implementation

Default Meshtastic Firmware

- Currently supported by the Meshtastic community
- FREE!
- Includes useful base code, especially mobile phone apps (robust)

Limitations

- Limited to maximum “hop” limit of 7
- Geared towards ease-of-use
- Wide variety of hardware geared toward static outdoor use
  - Some mobile options

Custom Firmware

“FLAMINGO” - Forward Link And Mesh Interconnect Network Ground Operations

Bob Reese’s custom firmware

- Branched from Meshtastic v2.5.20
- Added 4 bytes to header (increased from 16 to 20 bytes)
  - 1 byte for “hop_limit” – Decrements after each rebroadcast
  - 1 byte for “hop_start” – Initial hop count at initialization
  - 2 bytes for “magicnumber” – Isolates system from stock/other incompatible Meshtastic radios
- Hop limit currently expanded to soft limit of 32 (true limit is 255!)
- Additional improvements (see test slides)

Deployment

- Built and verified custom firmware on bench (surface)
  - Firmware is catalogued in Github repo
- Created configuration file (*.YML) to standardize all radio settings for their respective roles
  - Custom Python scripts allow user to **quickly flash standardized settings to radios**
- Developed test plan to systematically evaluate system

Hardware

- Initially built 7x "TacMesh"-style radios
  - Built off of RAKWireless RAK4631 (RAK19003 I/O board)
  - Same testbed used by original Vangelis test

Test Loadout

- Primary **Surface Node** (x1)
  - Wismesh Pocket
- **Cave Nodes** (x9)
  - 7x TacMesh and 2x Wishmesh Pockets
  - One temporarily designated as range-test "Listener Node"

TacMesh radio assembly

WisMesh Pocket

Hardware Performance

Water ingress

- Passed various spray tests
- Failed submersion test
  - Due to porosity of 3D printed material
- Estimated IP55

Battery life

- **1+ week** expected life for single charge
  - 6 days to reach 47% battery
  - Included 2 nights reaching sub-freezing temps

In-Cave Test #1

Tumbling Rock Cave
4 April 2025

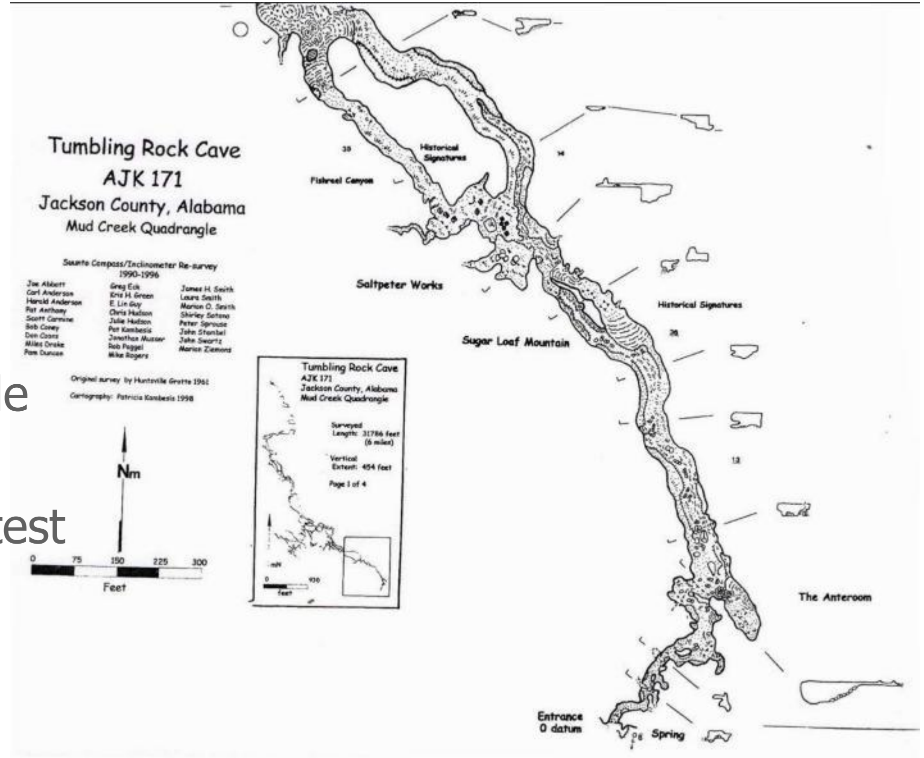
Test Objectives

1. Verify custom firmware can **transmit message past more than 7 nodes**
2. Quantify how far into cave we can get with all available nodes
3. Characterize performance through various in-cave terrain

Cave Selection

Tumbling Rock Cave Preserve

- One of most heavily visited and thus more likely for rescue events
- Notable landmarks for estimating node placement
- Depth and accessibility conducive to test
- Proximity to test team



Participants

Name	Role
Bob Reese	“IC”/Surface Node tech.
Jamie Moon	Listener Node tech.
Brad Tannehill	Node placement tech.
Chris Tran	Mapper
Abby Diering	Photographer
Walter King	Runner

Setup

1. Set up Surface Node
    a. Set up PC (with power supply) and Python Command-Line Interface (CLI)
    b. [OPTIONAL] Establish GPS signal or manually enter GPS location
    c. Start Range Test (transmission) at 30s intervals
2. Turn on Listener Node
    a. Start Range Test receiving
    b. Set mobile device to audibly ping during each range test

Building Chain

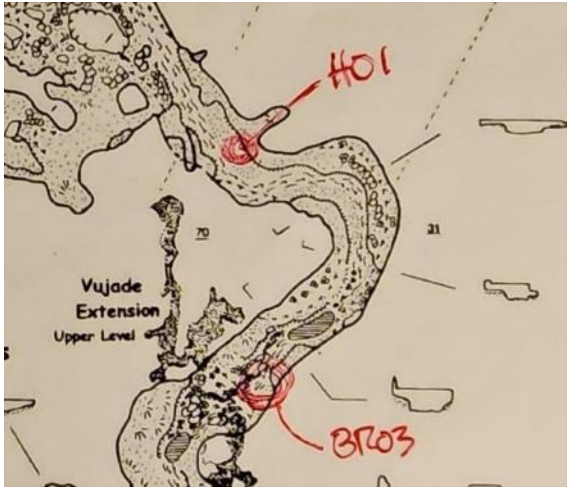
1. Proceed into cave, using paired phone to observe pings
2. Stop movement where pings begin to drop off
3. Backtrack slightly until pings return with no perceivable loss
4. Emplace *second* cave node and power on
5. Use newest node to send status update to Surface Node
    a. Surface Node replies to verify newest node placement is ok
6. Continue moving original Listener Node forward, dropping new nodes using steps 1-3

Building Chain

- Placed 9 nodes throughout cave
  - 1 was added in middle to bolster weak part of chain (messages getting dropped)
- Some adjustments were made to reduce signal loss
- Marked locations on map
- Experimented with hands-free concept for Listener node
  - Tactical chest mount courtesy of Chris Tran

Final Node

- H01 (mobile Listener Node) was placed around the stream curve across from the "Handprint Wall"
- Successfully exchanged multiple messages with surface
  - **Throughput improved once range-test was stopped**



Test #1 Results

Observations & Conclusions

Initial Test Results

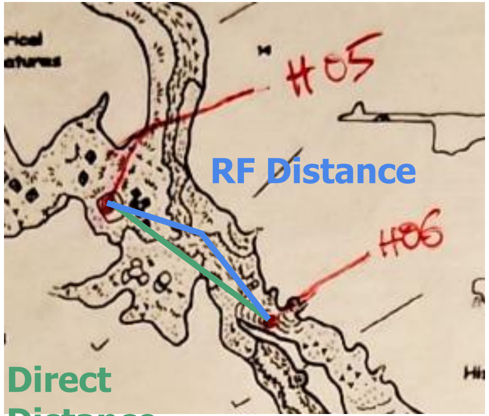
- Successfully exchanged text messages from surface to deep into Tumbling Rock Cave using Meshtastic radios
- Made it past “Elephant’s Feet” near “Handprint Wall”
  - Roughly **600m/2,000ft** deep
- Exceeded native Meshtastic hop limit of 7
  - Successfully demonstrated 8 hops
  - Validated HopMod custom firmware functionality
- Setup time was ~2.5 hrs, which included adjustments/experimentation
  - Teardown time was <30mins

Mesh Geometry Stats

Chain distance estimate

- Direct distance:
  - Bee-line distance between nodes
- RF/Passage distance:
  - Approximation of RF path distance (around tunnel geometry)
- Roughly **600m/2,000ft** reached

Note: Only used 2D distances for estimate



Node A	Node B	#	Est. Direct Distance [m]	#	Est. RF Distance [m]	Uncertainty [±m]
BR01	H02		36		22	5
H02	H03		18		60	5
H03	H04		105		108	5
H04	H06		83		86	5
H06	H05		49		49	7
H05	H07		109		112	7
H07	BR02		95		102	10
BR02	BR03		41		44	8
BR03	H01		36		50	8
	Total Chain		**552**		**632**	

Time Study

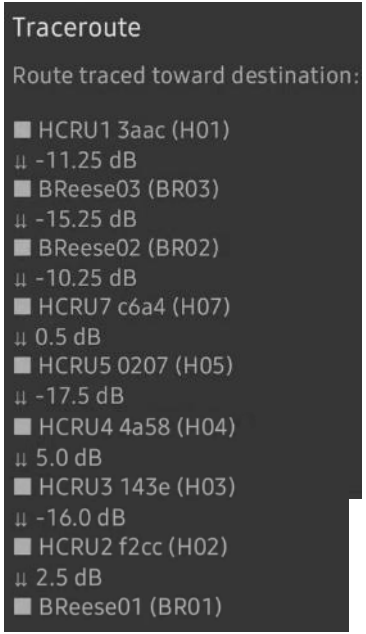
- Total setup time was roughly 2.5hrs
  - First attempt and time efficiency was not priority
  - Includes time for readjusting placement and running comms checks
- Network teardown duration = 24 minutes
  - If target locations were predetermined, **setup** could be this fast

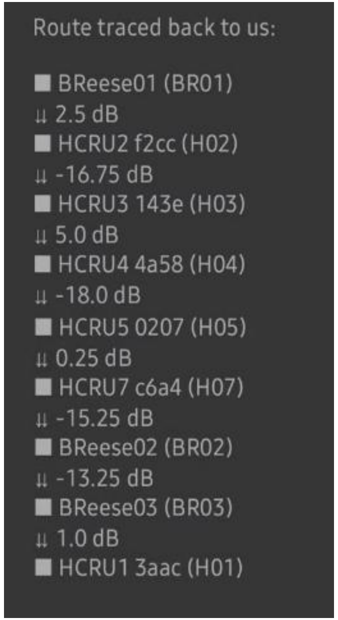
Node	Approx. Setup Time [min]
H02	12
H03	6
H04	10
H06	14
H05	
H07	25
BRO2	29
BRO3	43
H01	35
Elapsed	**151**

Hop Mod Validation

Final Traceroute results

- Chain went through all nodes but H06
    - Skipped intermediary node
- **8 hops** from surface to/from final cave node
    - Validated functionality of HopMod





Tunnel Attenuation

- Sharp turns attenuate signal
- Low ceilings appear to attenuate signal
  - As also observed by Vangelis
- Larger, straighter boreholes result in better range (not surprisingly)
- Sometimes switching from one side of the cave to another can make or break connection

Network Congestion

- Messages take upward of 1+ minute round trip to get to and from surface
- Constant Range-Test pings from surface node caused congestion on the network
- Running Traceroute was often unreliable for larger hop numbers
    - Probability of traceroute success exponentially decreased with number of hops
    - Range-Test pings were silenced when running Traceroute
        - It’s likely there was interference/congestion between Traceroute and Range-Test pings

Direct Messaging

- Sending messages to broadcast channel may not be as robust as direct messages
- Direct messages notifies sender of:
    - **Acknowledgement** of nearest node and
    - **Delivery confirmation** at receiver
        - May replace “Ack” procedure
- Disadvantages
    - No other technicians utilizing other nodes will hear messages sent

Lessons Learned

- Monitoring Received Signal Strength Indication (RSSI) is user-intensive for Listener Node operator
  - No realtime RSSI display
- Listening for range-test pings is unreliable
  - Binary: **doesn’t provide quantifiable RSSI info**
  - Pings are interrupted by other operations (such as Traceroute)
- Using *hopping* Range-Test packets from Surface Node caused congestion
- Better antennas or other radio modes may improve signal

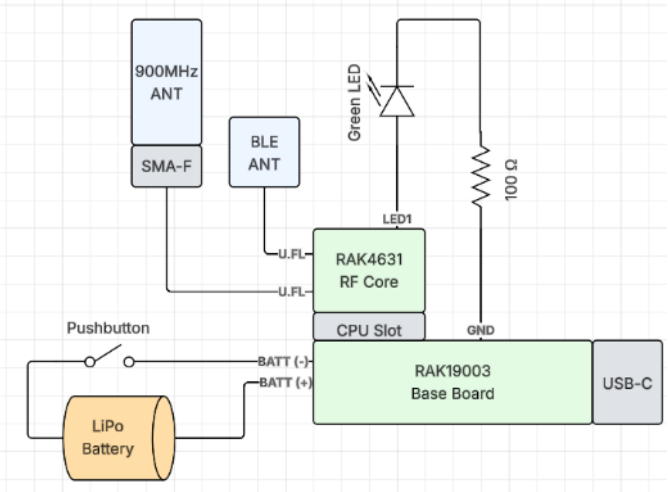
In-Cave Test #2

Tumbling Rock Cave
6 June 2025

Hardware Enhancements

Hardware updates

- Larger whip antennas to be evaluated
  - Unfortunately have to be installed once in-cave
- LED status indicator added to all TacMesh Nodes



Cave Node architecture

Firmware Enhancements

Notable updates

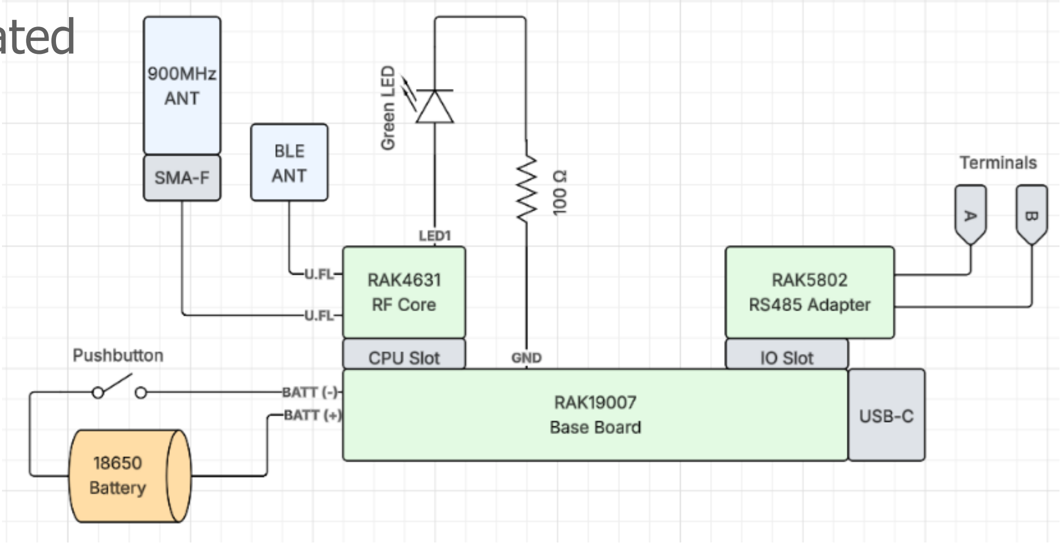
- Nodes with OLED screens will now **display RSSI** and SNR for received messages
- Added admin commands to remotely control Range Test
    - "ADRT on" turns on range test
    - "ADRT on hop" turns on range test that hops (propagates down chain)
    - "ADRT off" turns off range test
    - "ADRT delay <15 | 30 | 60>" select preset range test period (seconds)
- Firmware support for RS485 bridge (see next slide)
- Serial logging improved

Wire Bridge

RAK5802

Specialized Nodes

- 4x specialized nodes have RAK5802 RS485 modules installed
- Enables tying together two RF nodes through tight passages where RF can be highly attenuated
    - **Supports using existing HRCU cave wire**



Wired Bridge architecture

LoRa Modes

- Meshtastic features preset “LoRa” modes
- Default is “Long/Fast”
- “Medium/Slow” would provide:
  - Slightly reduced link margin
  - Slightly reduced data rate
  - **Additional error correction**
  - Reduced air time (reduced collisions and latency)

Radio Preset	Alt Preset Name	Data-Rate	SF / Symbols	Coding Rate	Bandwidth	Link Budget
Medium Range / Slow	Medium Slow	1.95 kbps	10 / 1024	4/5	250 kHz	150.5dB
Long Range / Fast	Long Fast	1.07 kbps	11 / 2048	4/5	250 kHz	153dB

Radio Loadout

- 7x TacMesh Radios
- 4x Wismesh Pocket Radios
  - 1x designated as Listener
- 4x Wired Bridge prototype nodes
  - Packaged in quick and simple tackle boxes

Waterproof case can carry 11 nodes

Prototype Wired Bridge box

Test Objectives

Primary

1. Evaluate baseline network with **new antennas**
2. Evaluate baseline network with **different LoRa modes**
3. Validate **RSSI visualization** method

Secondary

1. Expand baseline network distance with quantity of 9
2. Extend network to 9+ hops
3. Demonstrate haptics (LED/buzzer)
4. Demonstrate RF/Wire bridge

Personnel

Name	Role
Bob Reese	"IC"/Surface Node tech.
Jamie Moon	Listener Node tech.
Chris Tran	Secondary node tech./Videographer
Tom Barthel	Mapper
Stephen Estevez	Photographer/Support
Daniel Mote	Support
Jimmy Farrar	Support

Test Scenarios

- Recording RSSI between each node pair as we go
    - Compare signal performance of each possible change

Case	Description	# Nodes	Antenna	LoRa Preset	Objective 1	Objective 2
1-A	T-Rock 1 baseline	9	1/4 Wave	Long/Fast	Measure RSSI between each node	Run 3x traceroutes from end to surface
1-B	T-Rock 1 new antennas	9	1/2 Wave	Long/Fast	Measure RSSI between each node	Downselect antenna
~~2-A~~	~~T-Rock 1 moderate speed~~	~~9~~	~~TBD~~	~~Long/Moderate~~	~~Measure RSSI between each node~~	~~Run 3x traceroutes from end to surface~~
2-B	T-Rock 1 slow speed	9	TBD	Medium/Slow	Measure RSSI between each node	Downselect LoRa preset
3	Chain expansion	10+	TBD	TBD	Rebuild chain to reach as far as possible	Verify Bridge (wire) nodes work in mixed net

Test #2 Results

Observations & Conclusions

Results

- Successfully reached far end of Totem Gallery using hybrid network
    - Expanded to **~3,000ft** into cave
- Introduced new antennas (slight improvement)
- Evaluated alternative LoRa mode
- Expanded mesh to **11 hops**
- Validated RS485 bridge nodes in mixed network (using comms wire)
- Validated RSSI visualization tool

“Med/Slow” Mode Evaluation

- RSSI was not significantly improved
- Initial perception was that **error rate was improved** (fewer lost messages)
- Since performance wasn’t significantly reduced, team used Med/Slow for remaining tests

Node	Time Placed [HH:MM]	RSSI [dBm]	From Sender
BR01			
H01	18:05	-113	BR01
H02	18:07	-108	H01
H03	18:11	-84	H02
H04	18:14	-66	H03
H05	18:18	-85	H04
H06	18:22	-110	H05
BR02			H06
H07			BR02
BR03	18:43		H07
WB01	18:55	-115	BR03
WB02	19:28	0	WB01
BR04	20:01	-110	WB02
BR05	20:21	-114	BR04

Usability Enhancements

LED indicator

- LED indicator and reflective tape worked fairly well

RSSI Visualization

- RSSI readout allowed tech to **reliably predict edge of dropoff** region
- “ADRT” admin commands proved extremely useful
  - Eliminating hopping RangeTest pings relieved congestions

Wired Bridges

- Wired Bridge nodes provide **reliable comms through tight/breakdown passage**
- Operators can easily hook up with standard comms wire
- No special setup is needed for bridge radios

New Antennas

- Possible slight (+7dBm) increase
  - Wide variation (Std. Dev. ±20 dBm)
- Additional bench test supported measurable improvement of alternative antenna
- Size of new antenna must be taken into consideration

In-cave RSSI

Stock Antenna [dBm]	New Antenna [dBm]	Delta [dBm]
-110	-105	5
-122	-84	38
-88	-68	20
-72	-84	-12
-83	-112	-29
-112	-108	4
-118	-93	25
-111	-112	-1
-122	-106	16
	Mean	**7**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Stock	17	-1406	-82.70588235	1.220588235
Amazon	18	-1384	-76.88888889	5.633986928

ANOVA

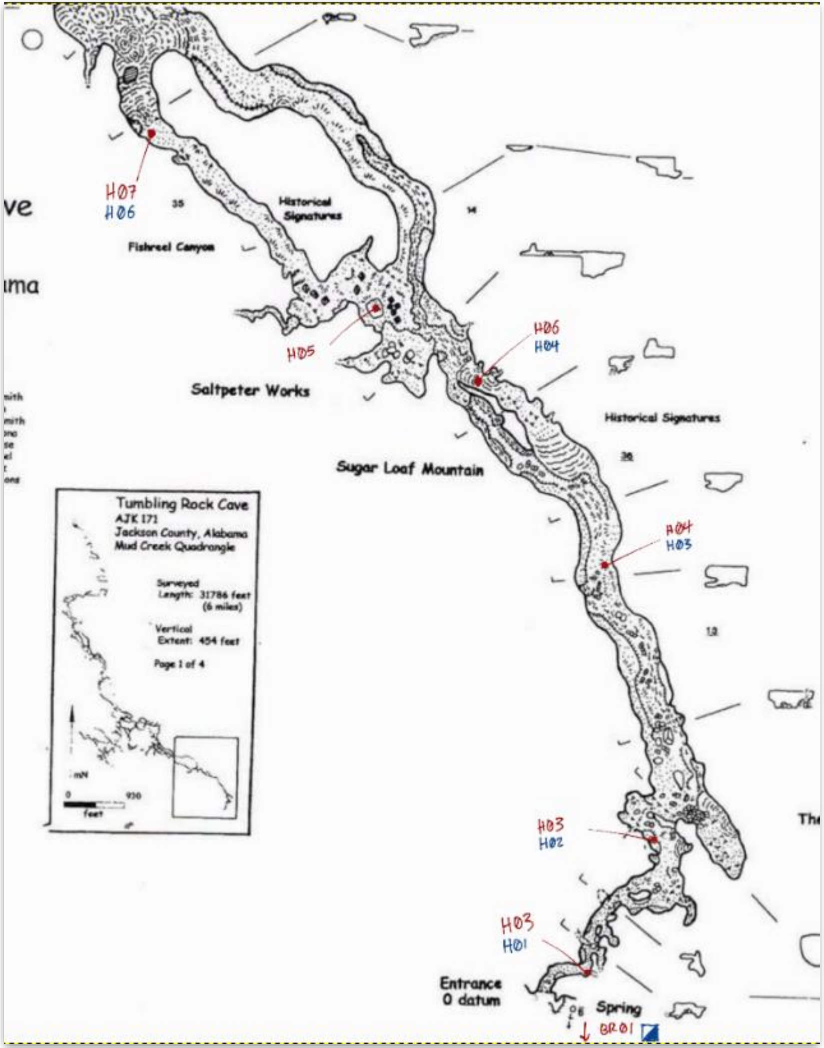
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	295.8356676	1	295.8356676	84.66581372	1.24709E-10	4.139252496
Within Groups	115.3071895	33	3.494157259			
Total	411.1428571	34				

Single-Factor ANOVA for bench test

Map

Legend

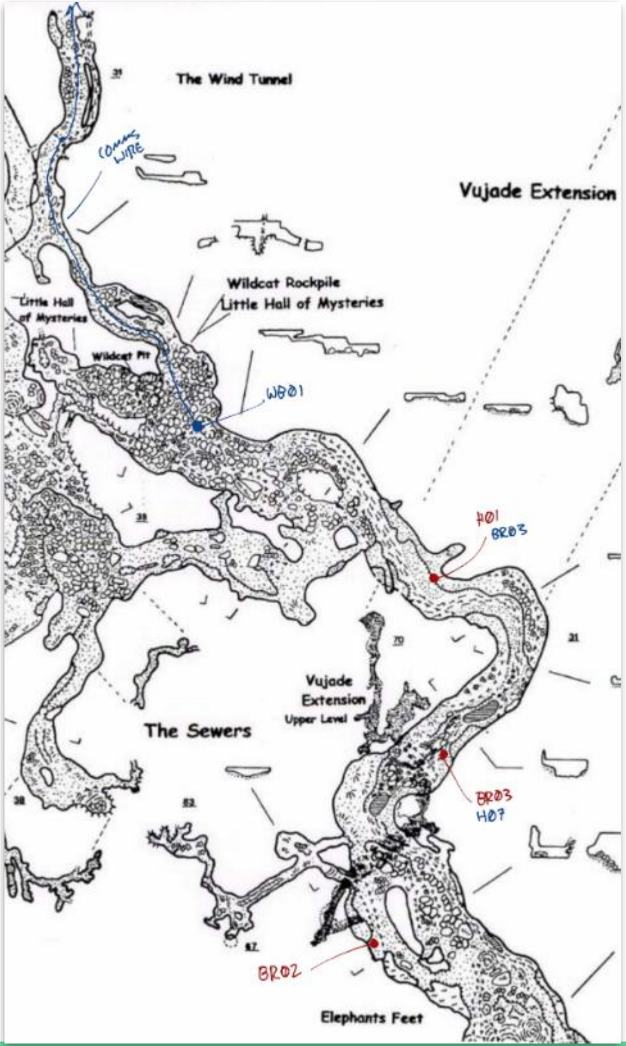
- 4/4/25 test
- 6/6/25 test

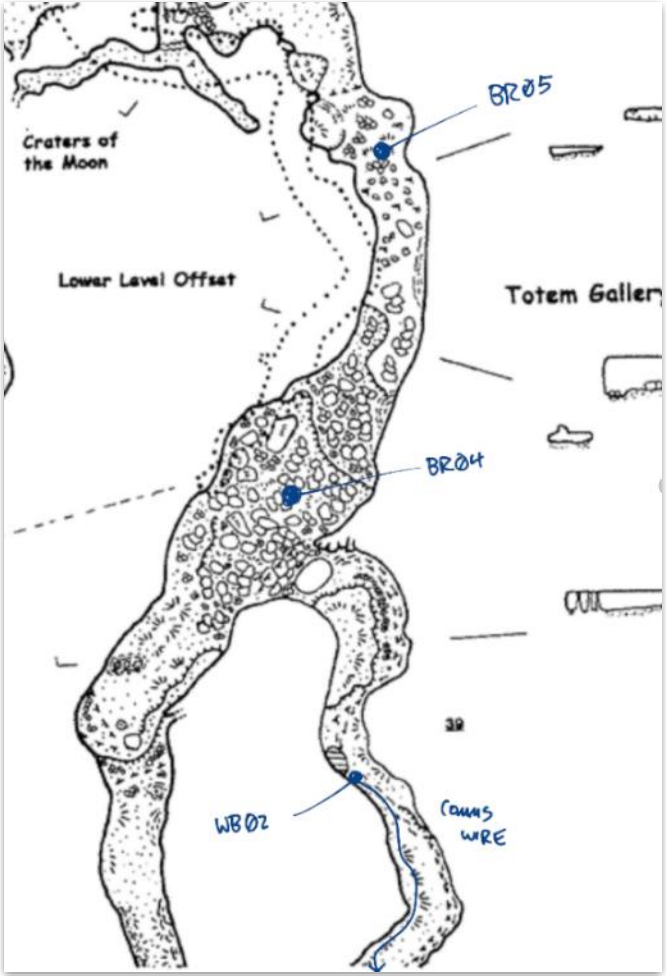


Map

Legend

- 4/4/25 test
- 6/6/25 test





Mesh Geometry Stats

Chain distance estimate

- Direct distance:
  - Bee-line distance between nodes
- Passage distance:
  - Approximation of signal path distance (around tunnel geometry)
- Roughly **900m/3,000ft** reached

Note: Only used 2D distances for estimate

Node A	Node B	Est. Direct Distance [m]	Est. Passage Distance [m]	Uncertainty [±m]
BRO1	H01	36	22	5
H01	H02	58	65	5
H02	H03	109	112	5
H03	H04	87	91	5
H04	H05	49	49	7
H05	H06	111	114	7
H06	BR02	85	90	10
BR02	H07	42	45	8
H07	BR03	36	51	8
BR03	WB01	58	58	5
WB01	WB02	112	183	1
WB02	BR04	34	34	8
BR04	BR05	42	43	6
	Total Chain [m]	**839**	**957**	
	Chain [ft]	2753	3140	

Vertical Cave Test

8 June 2025
Falling Cave (aka Balcony Sink)

Quick Look

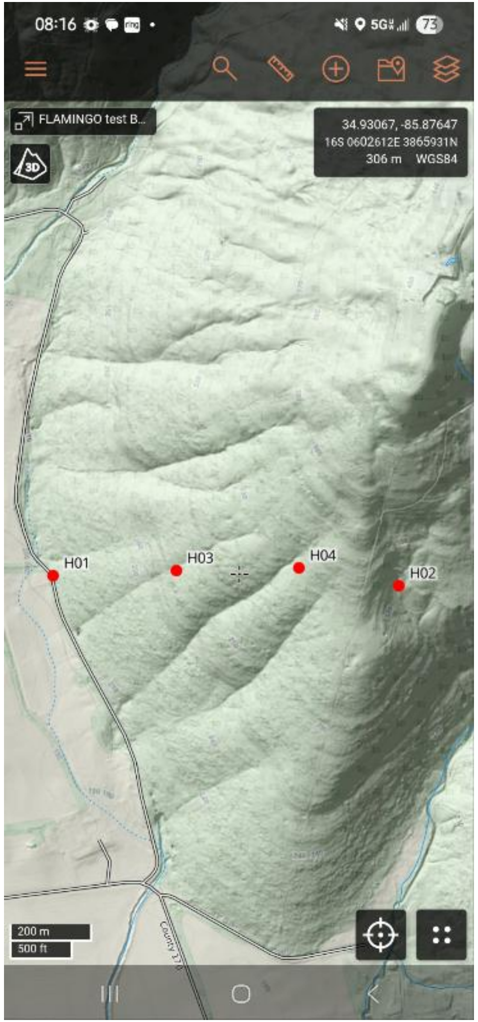
- Tested TacMesh network from trailhead into upper passage
- Demonstrated feasibility of radio network in **vertical** application
- Surface Nodes **withstood thunderstorm** for portion of test

Method

- Used one radio as mobile Listener Node
- RSSI readout (on phone toast notifications) allowed placement to be optimized while hiking

Surface Nodes

1. First node placed inside car near trailhead
2. Two nodes placed along trail



Surface Nodes

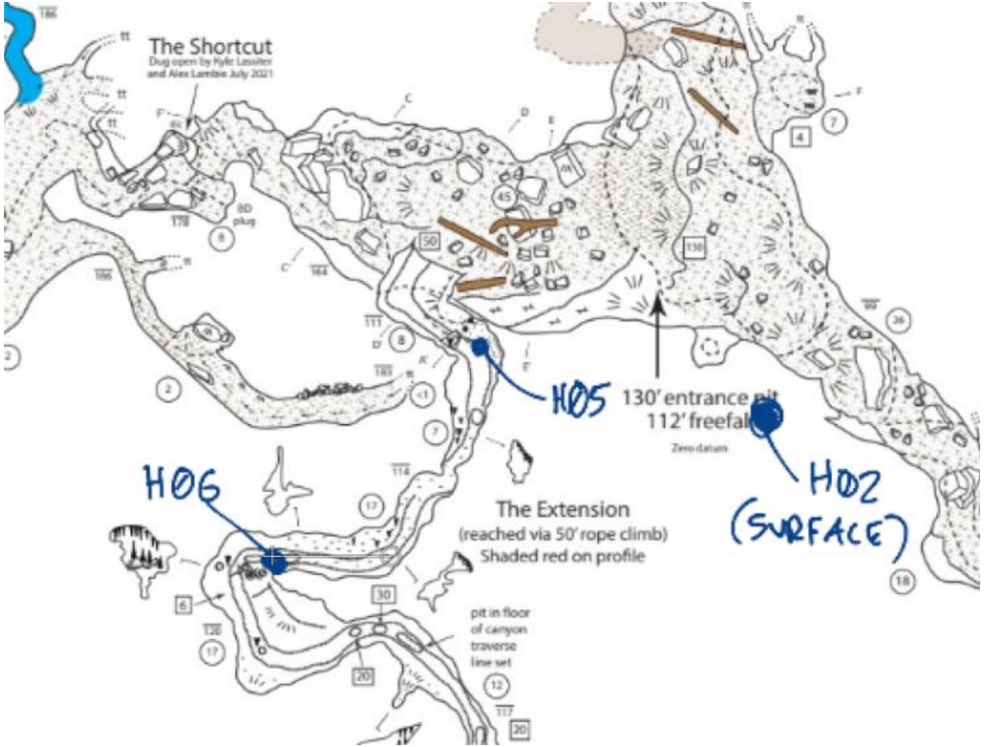
- Reached near lip of main pit with fourth Surface Node
- Thunderstorm hit as last caver was finishing rappel

Cave Nodes

- Placed two additional nodes along upper passage
- Decided not to place last node as it was in winding area

Map

- Reached *roughly* 30-40m down the Extension passage
- Included hop from surface, down into pit, and funneling several metres into the passage



Conclusions

- Radios work in **vertical** application
    - Better attachment points for harnesses is desired
- TacMesh enclosures survived **heavy rainfall**
- Reached from upper passage back to car node
    - A couple messages may have failed to deliver during heaviest rainfall
        - Suspected due to attenuation between weakest surface nodes

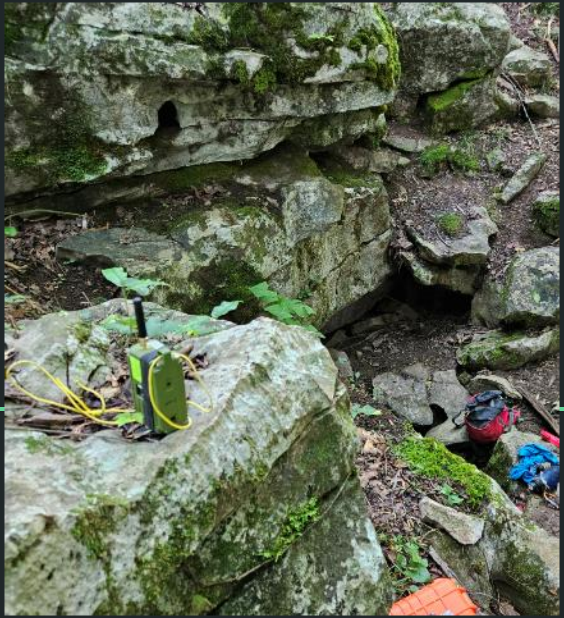
Lessons Learned

- A more hands-free visualization method would be helpful for placing radios on the go

- Connecting car node to internet using MQTT could allow cavers to reach callout personnel, emergency services, etc

Operational Test

Guffey Cave
27 June 2025

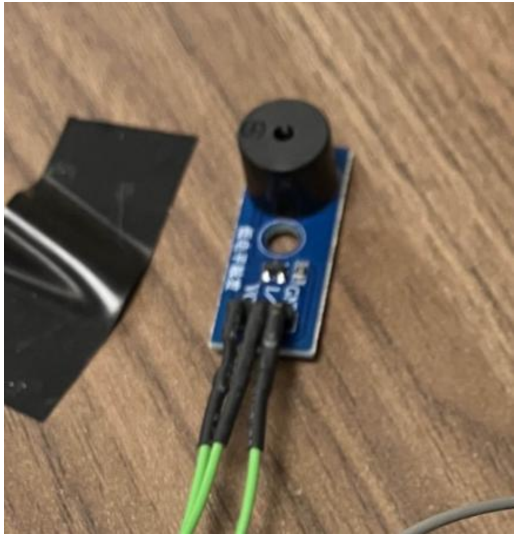


Enhancements

Hardware updates

- Added active buzzer to Listener Node (BR05)
  - Allows Listener operator to space nodes hands-free
  - Can easily be added to nodes as standard feature

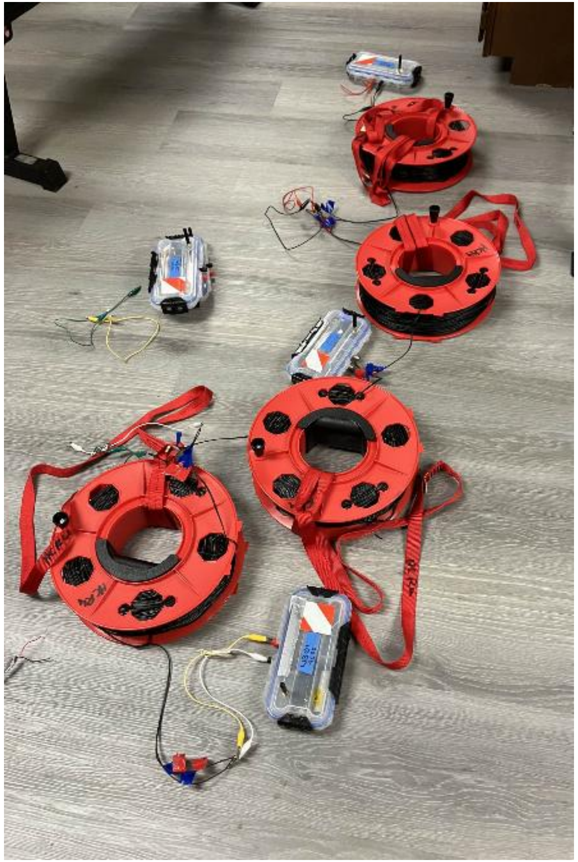
RSSI Range [dBm]	Beeps	Indication
≥-90	1X	Good Signal
-110 to -90	2X	Moderate Signal
<-110	3X	Marginal Signal



Wired Bridge Testing

- Informed maximum driving distance for given baud rates
- Lowest baud rate (4800b/s) is still 4x faster than "Medium/Slow" LoRa data rate
- More than 2x bridge nodes can utilize the same wire (i.e. can daisy-chain)

	A	B	C	D	E	F	G	H
1	RS485	Distance (ft)						
2	Speed (bits/sec	100	730	1300	2100	2400	2700	3300
3	230400	NO	NO	NO	NO	NO	NO	NO
4	115200	YES	NO	NO	NO	NO	NO	NO
5	57600	YES	YES	NO	NO	NO	NO	NO
6	38400	YES	YES	NO	NO	NO	NO	NO
7	19200	YES	YES	YES	NO	NO	NO	NO
8	9600	YES	YES	YES	YES	YES	NO	NO
9	4800	YES	YES	YES	YES	YES	YES	YES



Test Objectives

Primary

1. Identify node placement for potential instructor network for upcoming HCRU Cave Rescue course
2. Estimate setup time
3. Evaluate **audio haptics**

Loadout

Role	Type	Qty
Listener	WisMesh Pocket w/ Buzzer	1
Wired Bridge	Prototype Box	6
RF Node	TacMesh	7
RF Node	WisMesh Pocket	4
Comms Wire	800ft Spool	3
Comms Wire	900ft Spool	1

Personnel

Name	Role
Bob Reese	“IC”/Surface Node tech.
Jamie Moon	Listener Node tech.
Andy Sheaff	Wire technician
Chris Cargal	Wire technician
Jimmy Farrar	Support

Method

1. Ran one wire from entrance to end of spool (800ft) between bridge nodes
2. Used RF to span across the Pump Room
3. Ran second spool of wire to the center of Grand Central
4. Continued RF network north to just outside of Little India

NOTE: 2x relay nodes will span from IC at road to node at cave entrance (validated in separate test)

Method

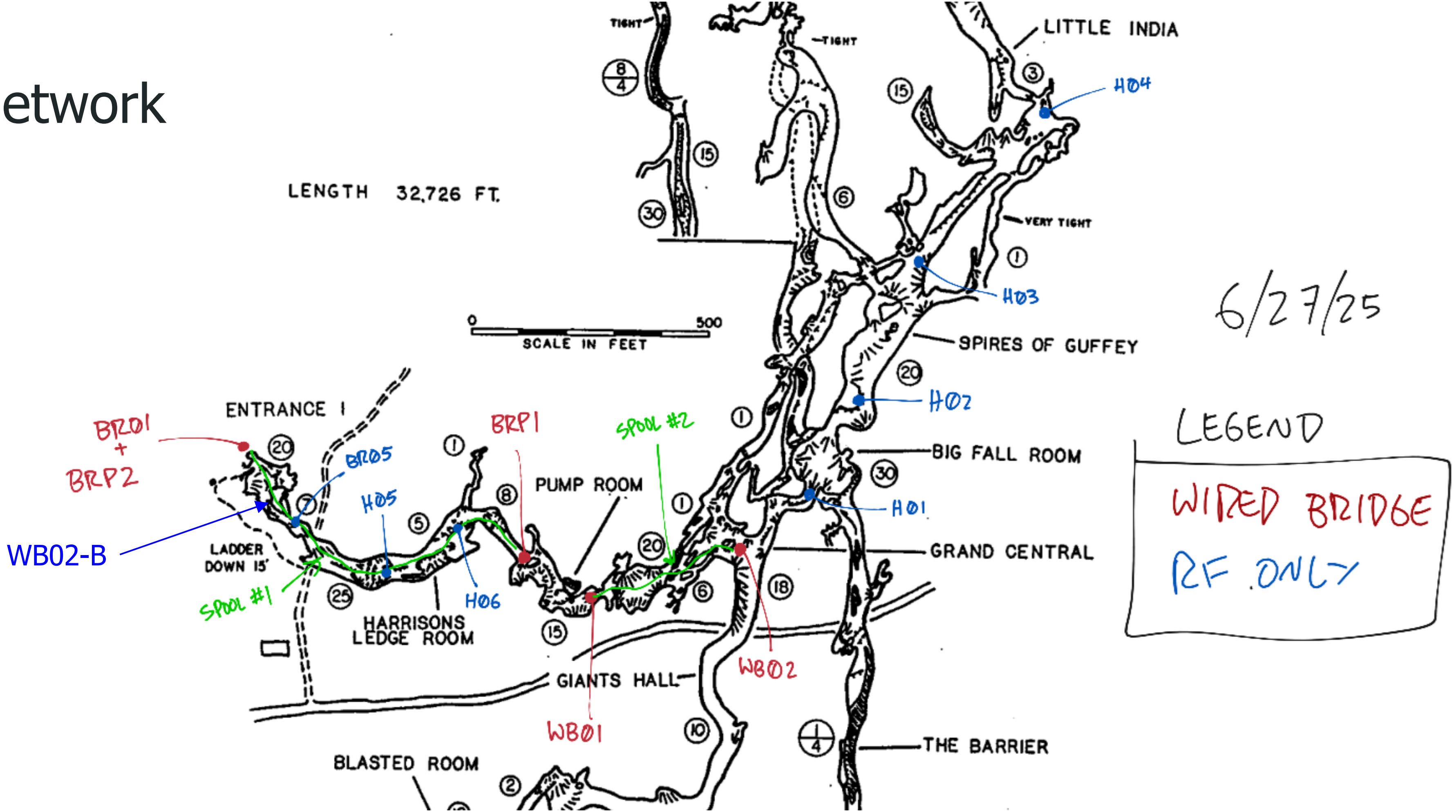
After objectives were met, network was retrofitted

1. Pulled end of Spool #1 back to the bottom of the 15ft ladder
2. Replaced Spool #1 with 3 wireless nodes
    a. **Reduced wire usage** to two partial spools total
    b. **Reduced setup time** for next iteration

Operational Test Results

Observations & Conclusions

Network



LENGTH 32,726 FT.
0
500
SCALE IN FEET
TIGHT
TIGHT
LITTLE INDIA
H04
VERY TIGHT
H03
SPIRES OF GUFFEY
H02
BIG FALL ROOM
H01
GRAND CENTRAL
THE BARRIER
ENTRANCE 1
BR01 + BRP2
BR05
H05
WB02-B
LADDER DOWN 15'
SPOOL #1
HARRISONS LEDGE ROOM
H06
BRP1
PUMP ROOM
SPOOL #2
GIANTS HALL
WB01
WB02
BLASTED ROOM
6/27/25
LEGEND
WIRED BRIDGE
RF ONLY

Network Geometry

Total distance:

- Roughly **2,400ft**

Note: Only used 2D distances for estimate

Node A	Node B	Est. Direct Distance [m]	Est. Passage Distance [m]	Est. Passage Dist. [ft]	Uncertainty [±m]
BRP2	BR05	61	61	201	8
BR05	H05	67	70	230	8
H05	H06	54	55	181	8
H06	BRP1	48	57	188	8
BRP1	WB01	50	51	167	8
WB01	WB02	101	101	330	8
WB02	H01	58	61	199	8
H01	H02	69	69	228	8
H02	H03	98	99	324	8
H03	H04	126	127	415	8
	Total Chain [m]	**711**	**750**		
	Chain [ft]	2334	2462		

Deployment Time

Wire-laying

- Average ~19 minutes for each original spool
    - Roughly ~28ft per minute

RF nodes

- Average ~13 minutes between nodes
    - Roughly 33-38ft per minute
    - *Includes adjustment/experimentation time*
- Rapid deployment is closer to ~4 minutes per node

Scenario

Estimated <1.5 hr total setup time for Guffey network for HCRU course

Original Name	Time Placed	Est. dt [min]	Est. Dist [m]	Deployment Speed [m/min]	Note
BRP2	5:00				Initial Entrance bridge node
WB02-B	5:07	7.5	60	8	Spool #1 from Entrance to overlook above base of Ladder
BR05	5:10	2.7	30	11	
H05	5:16	6.1	67	11	
H06	5:21	4.9	54	11	
BRP1	5:25	4.3	48	11	Should be replaced with regular RF node
WB01	5:30	4.6	50	11	Start of Spool #2
WB02	5:42	12.6	101	8	End of Spool #2
H01	5:48	5.3	58	11	
H02	5:54	6.2	69	11	
H03	6:03	8.9	98	11	
H04	6:14	11.4	126	11	

Conclusion

Takeaways and Ongoing Work

Summary

- Successfully demonstrated hybrid Meshtastic network in multiple real cave environments
  - Exchanged text messages from within cave to (beyond) entrance to representative IC locations
  - Demonstrated 11 hops
  - Reached well over 2000ft in less than 1.5hr deployment time
- Streamlined network setup process
- Demonstrated promising alternative to existing comms tech
  - Cheaper than most radio systems
  - Easy to make cheap, rugged, waterproof enclosures

Kit Concept

- Single technician could easily carry 12 nodes in one box
  - <7lbs
  - Fits in 10L backpack
  - Cover roughly 2,000ft of passage
  - Estimated $600
- Bridge nodes can be added in if needed
  - Existing comms wire can be used
  - Expand network through tight passage if needed
- Technicians can wear mobile nodes on their persons
  - Maintain comms when walking through the cave

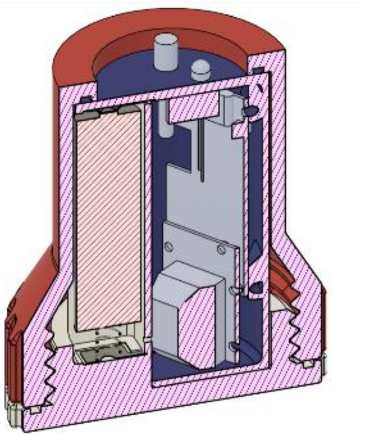
Fieldability

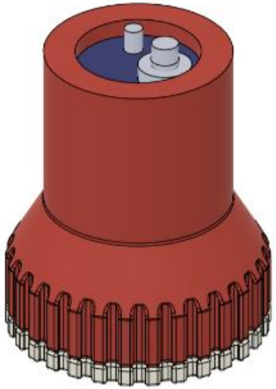
- Mesh radios show promising improvement in size and weight
- Comparable cost for bare minimum configuration
- Comparison:
    - 9x mesh radios in carrying case versus:
    - 2x military phones with standard wire spool

	Comms Wire	Mesh Radios
Packaged Size [in]	14x14x4 (spool) 10x9x4 (phone)	13x10x5 (box)
Est. Kit Volume [in3]	1285	650
Est. Weight [lbs]	34	6
Max. Length [ft]	1,000	2,000
Est. Cost [USD]	$420	$450

Next Steps

- Utilize functional network in mock rescue scenario
    - HCRU Cave Rescue class scheduled for 3 Aug 2025
- Further improve hands-free setup process
    - Improve audio feedback
    - Streamline RSSI testing (reduce setup time)
- Create affordable, rugged enclosures
    - Designing 3D printed rugged cases for both RF and Wired Bridge types
    - Explore better antennas
    - Utilize standard, replaceable **18650 Li-ion batteries**





Conceptual enclosure by Becky Williams

Next Steps

- Investigate MQTT implementation
  - See if it can be combined with existing internet/SMS messaging service
  - Allows users to reach emergency services directly from inside cave
- MORE TESTING!!
- Develop training material

Acknowledgements

Development

- Bob Reese
- Chris Tran
- Daniel Mote
- Phillip Balister (Vangelis)
- Paul Walko (Vangelis)

Mechanical

- Brad Tannehill
- Austin O’Neil
- Becky Williams

Field Testing

- Jimmy Farrar
- Chris Cargal
- Walter King
- Abby Diering
- Andy Sheaff
- Tom Barthal
- Stephen Estevez

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Questions?

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