IROS 2022 Tutorial on Practical Mesh Networking in Field Robotics

Organized By: Harel Biggie and Prof. Steve McGuire

MARBLE CSIRO Australia's National Science Agency COSTAR explorer CTU-CRAS-NORLAB

Speaker Introduction


Dr. Steve McGuire (left)
Harel Biggie (right)


Lillian Clark (left)
Dr. Jeffrey Edlund (right)

Alex Pitt

Ryan Darnley

Dr. Jan Faigl

Tomas Rouček

Time	Talk
9:00 – 9:15	**Panelist Introduction and Problem Motivation**
9:15-9:55	**Physical Layer** *Order of speakers:* Explorer, MARBLE, CTU-CRAS-NORLAB, CSIRO, CoSTAR *Demo:* Lillian Clark, CoSTAR
9:55-10:40	**Mesh Layer** *Order of Speakers:* Explorer, CTU-CRAS-NORLAB, CSIRO, MARBLE, CoSTAR *Demo:* Lillian Clark, CoSTAR
10:40-10:50	**Break**
10:50-11:35	**Logical Layer** *Order of Speakers:* Explorer, CoSTAR, CTU-CRAS-NORLAB, CSIRO, MARBLE *Demo:* Steve McGuire / Harel Biggie, MARBLE
11:35 – 11:50	Panel Discussion
11:50 – 12:00	Closing Remarks

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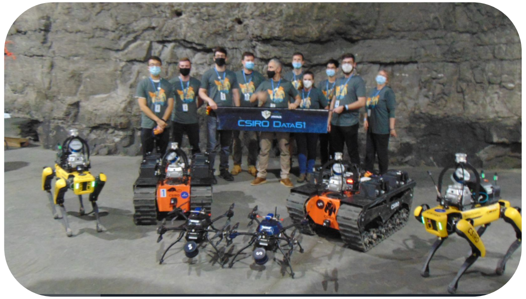

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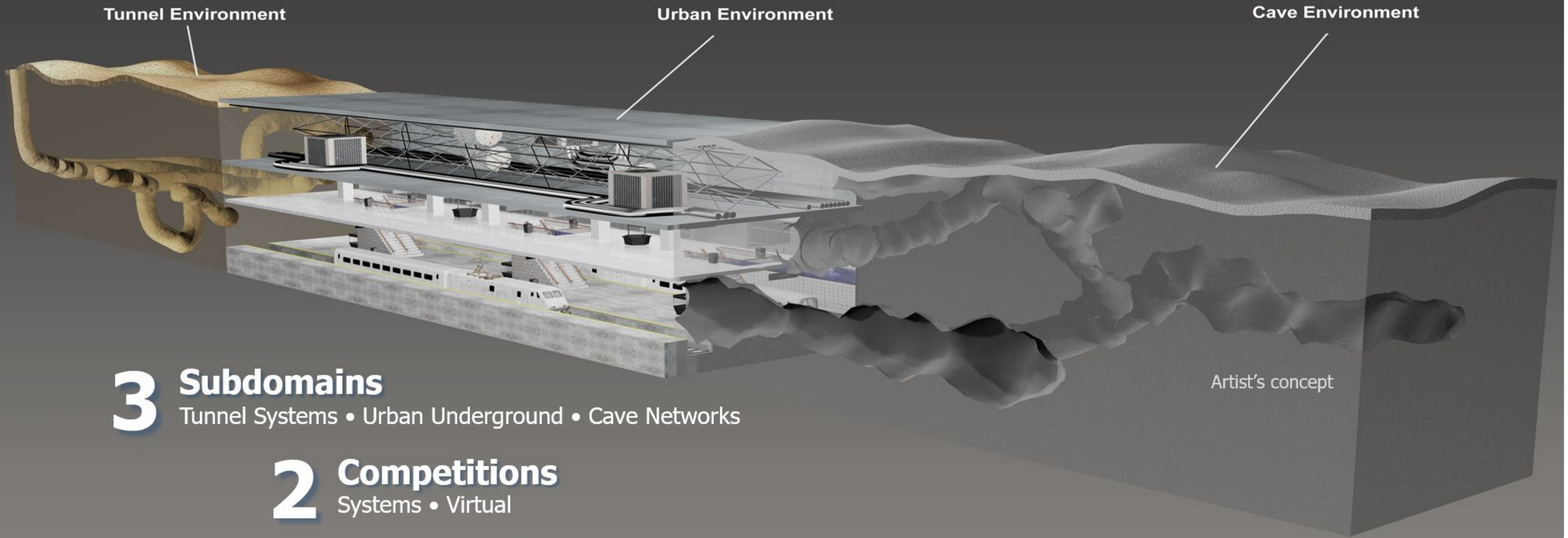
DARPA SUBTERRANEAN CHALLENGE



3 Subdomains
Tunnel Systems • Urban Underground • Cave Networks

2 Competitions
Systems • Virtual

1 Revolutionary Vision
Create breakthrough technologies and capabilities for underground operations

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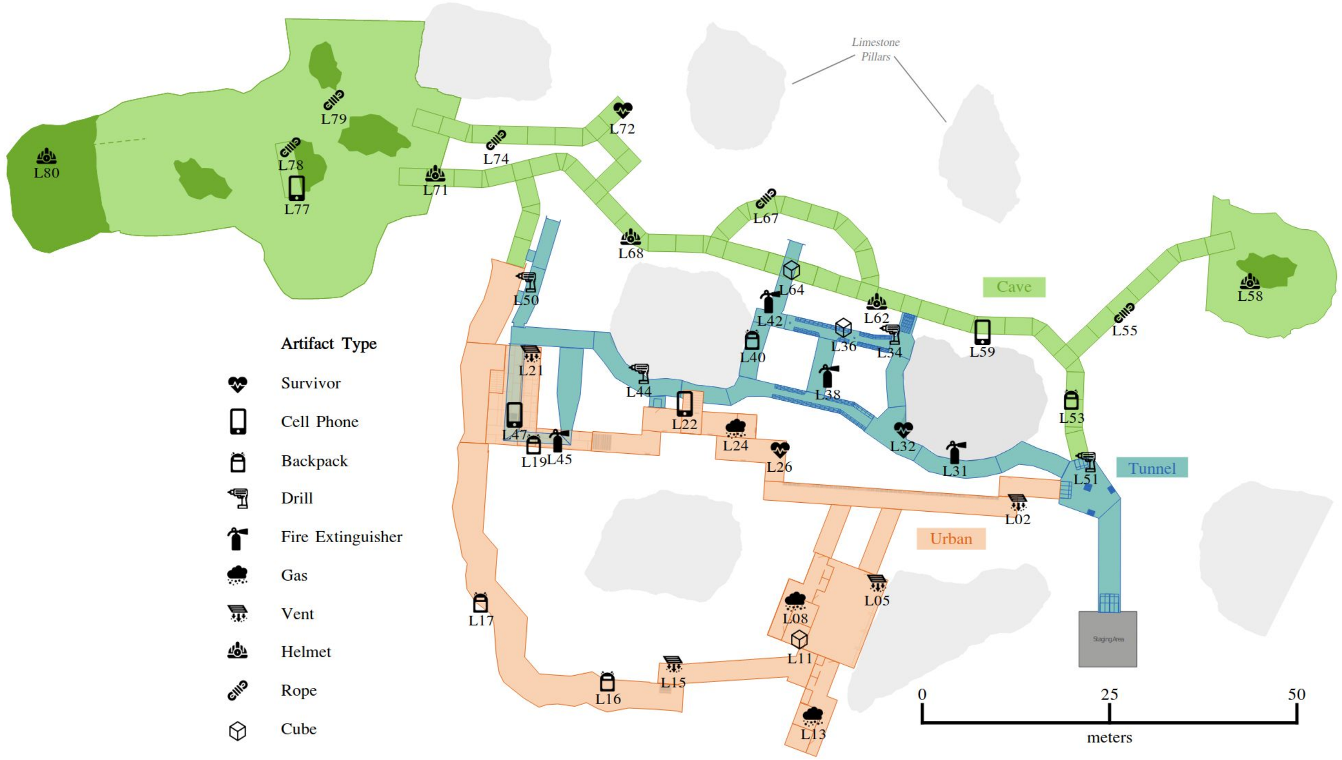
Final Map



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Competition Layout

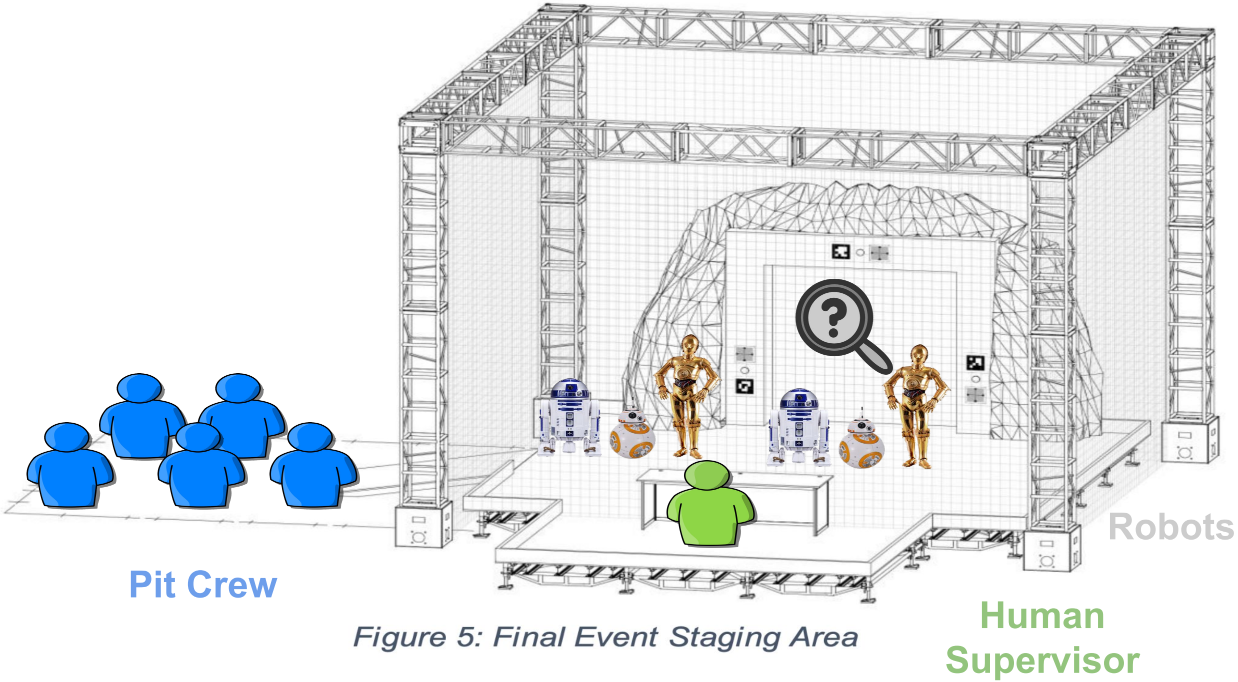

Figure 5: Final Event Staging Area

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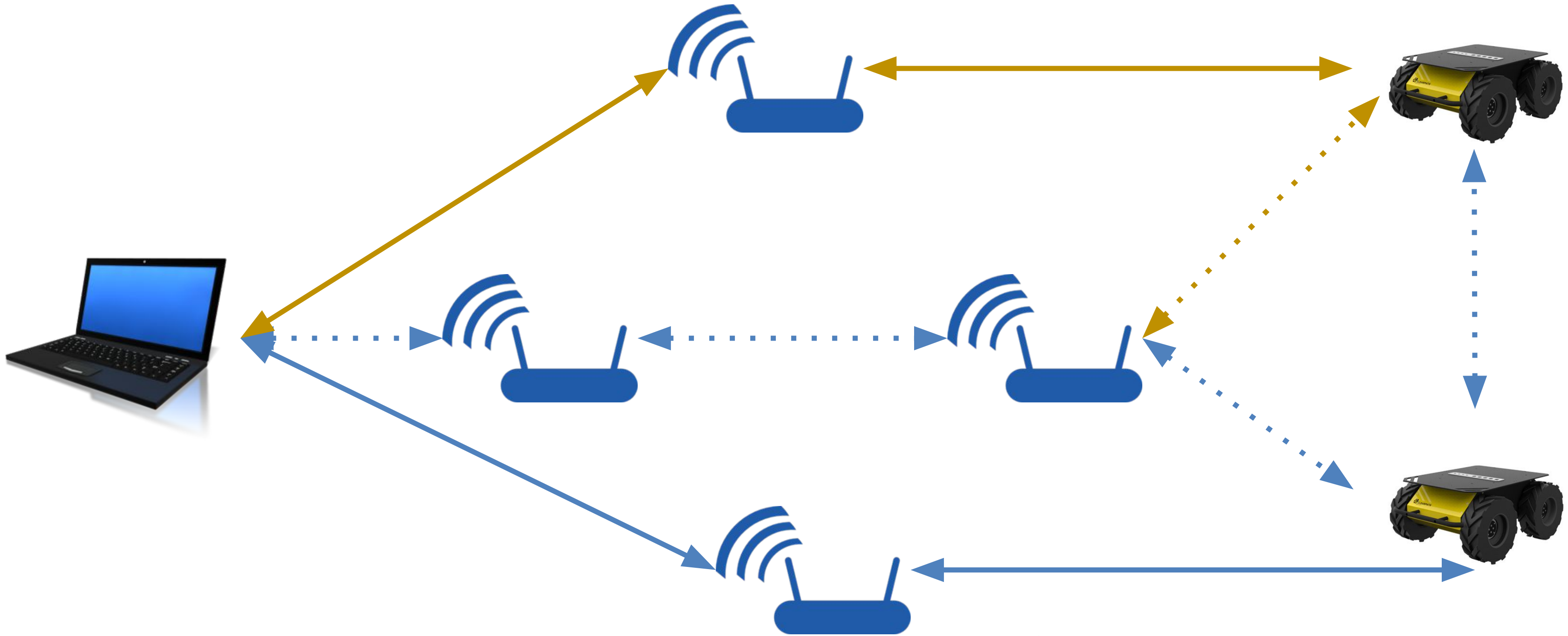
Generic Network Architecture



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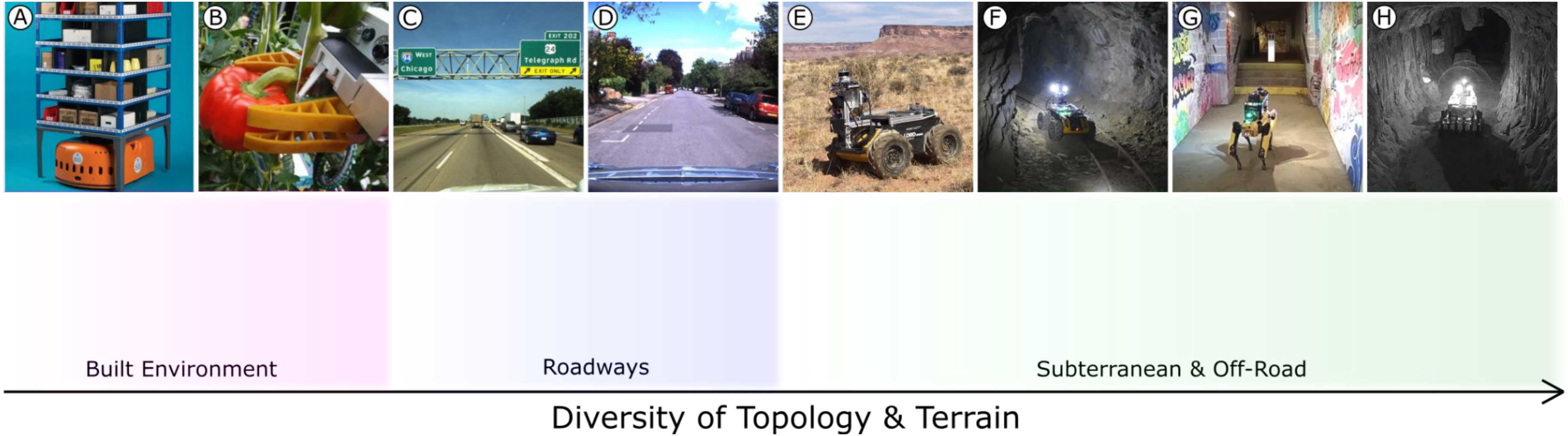
Example Greater Impact Applications



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Physical Layer

Team Explorer

Ryan Darnley

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Team MARBLE

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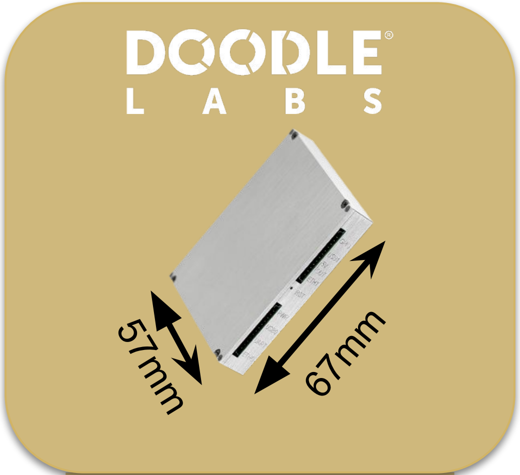
Multiple Form Factors

GL·iNet

100mW

Multiple Form Factors

100mW



1W

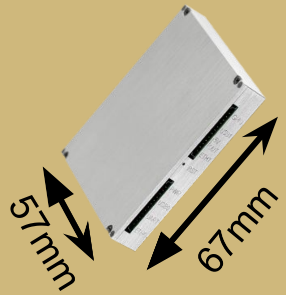
Team MARBLE

Multiple Form Factors

GL·iNet

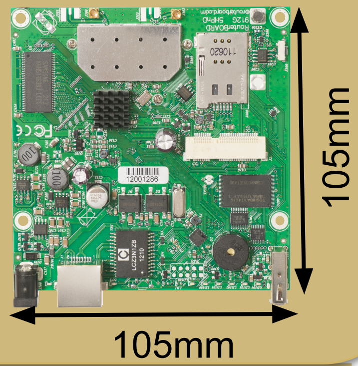
100mW

DOODLE LABS



2W

MIKROTIK



1W

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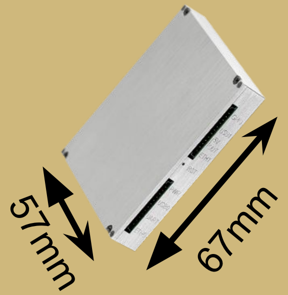
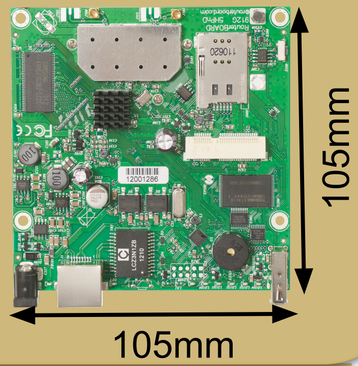
Multiple Form Factors

100mW



2W



1W

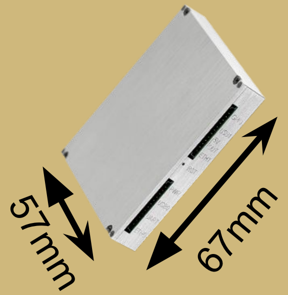
All packages use the 2.4GHz baseband on an *ath9k* based CPU with OpenWRT firmware

Multiple Form Factors

GL·iNet

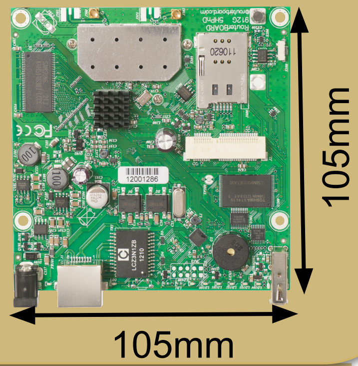
$40

DOODLE LABS



$1500

MIKROTIK



$100

Open source backends combined with a variety of costs enables economical scaling

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Physical Layer Evolution

Tunnel

Urban

Final

Physical Layer Evolution

Tunnel

Disposable

Urban

Final

Physical Layer Evolution

Tunnel

Disposable

Urban

Height Is Might

Final

Physical Layer Evolution

Tunnel

Disposable

Urban

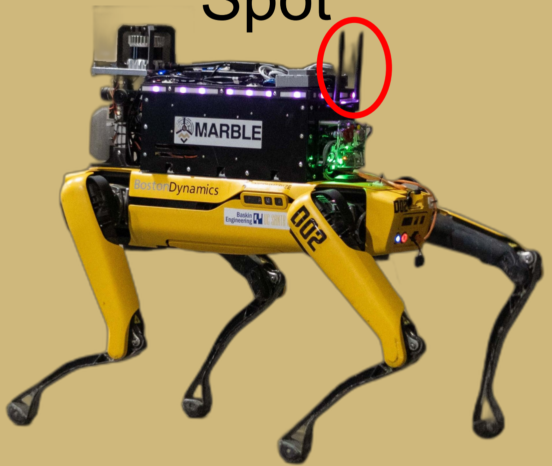
Height Is Might

Final

Balanced

Final Configuration

Spot

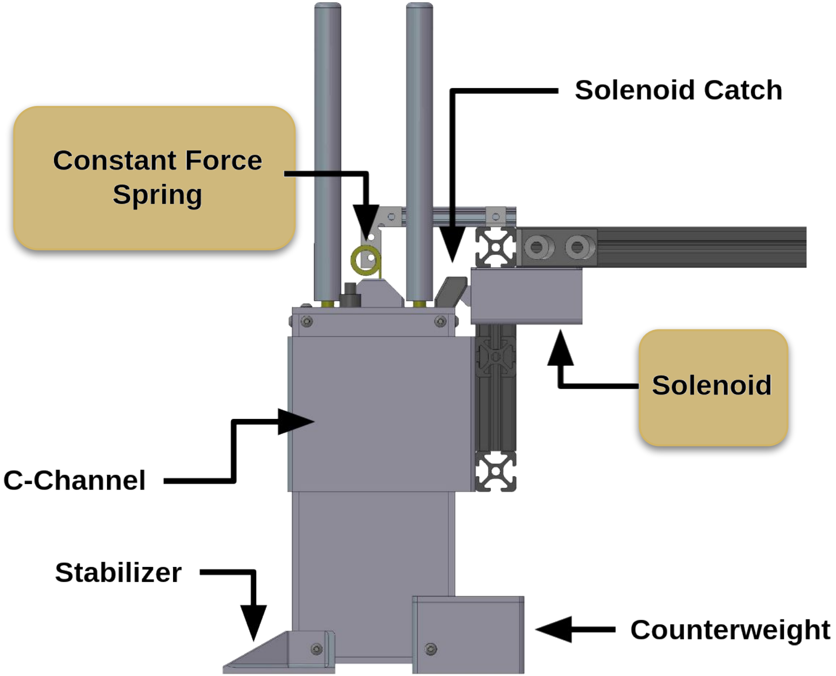


Omnidirectional

Husky

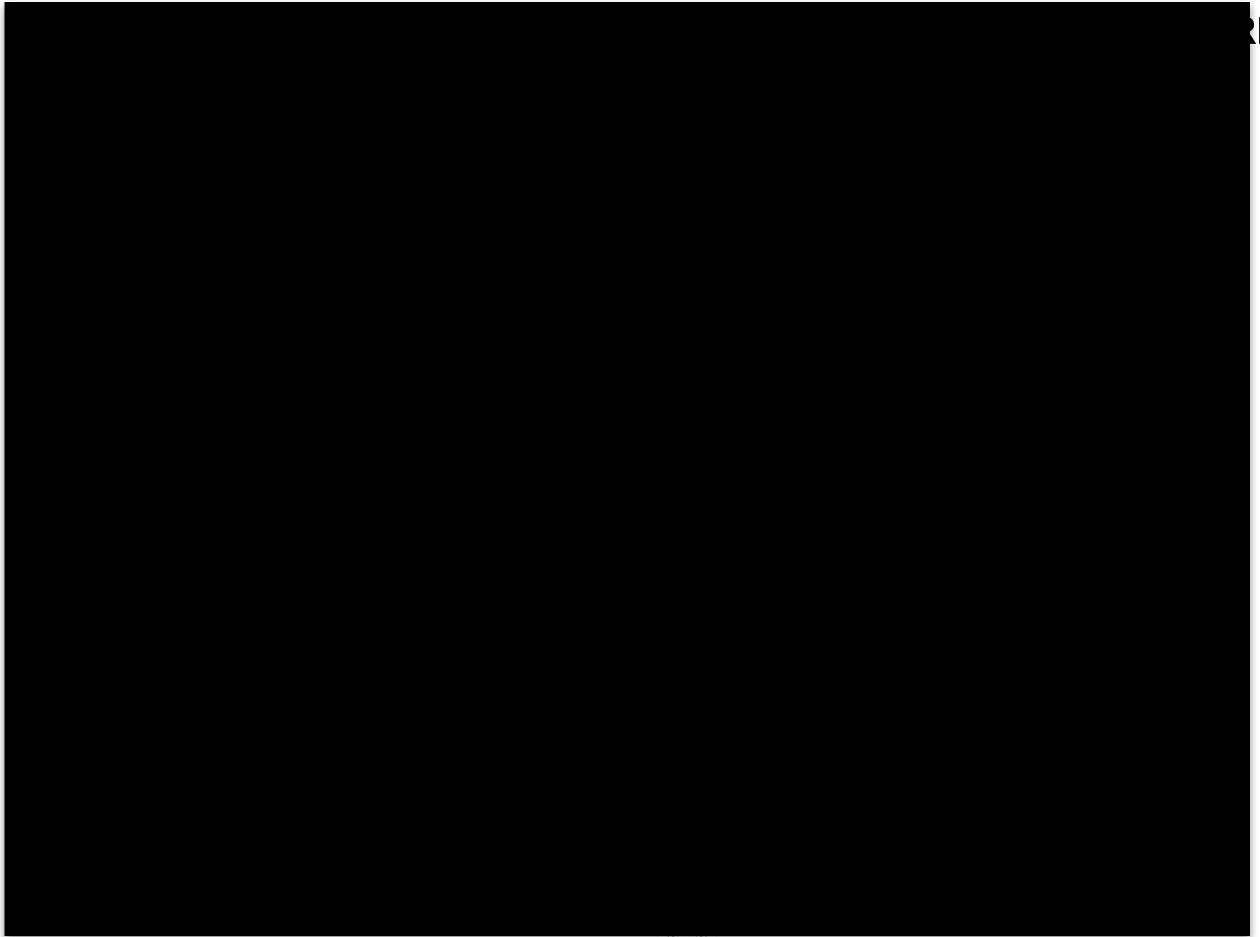
Sector

Beacons and Deployment Mechanism



RBLE

Deployment



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Takeaways

- Open source firmware provides system adaptability
- Multiple form factors enables integration on a variety of platform sizes
- Simple deployment mechanisms

CTU-CRAS-NORLAB

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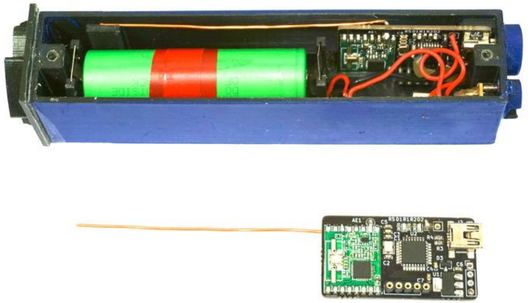
From start 3 different networks

- Redundancy
- Different capabilities

Semi-Custom
Base connection
Orange-box

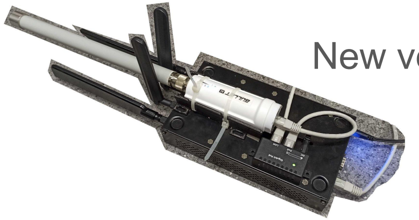
Commercial long range
Mobilicom



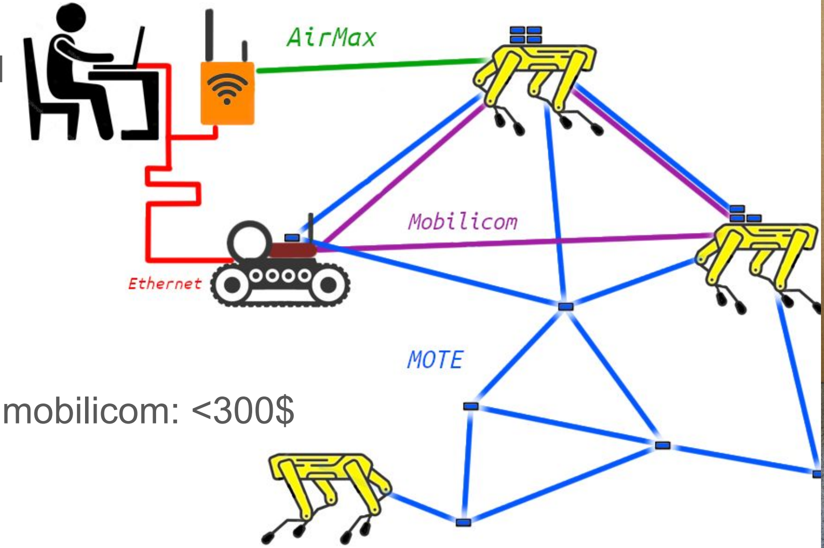
Fully custom breadcrumbs
MOTE

Base station comms - Orangebox

- WiFi for everyone + airMAX to robots
- Built from off the shelf components
- Main platform for experiments
- ~250Mbit/s from robots
- Range up to 200m open field
- Portable internet
- NTP server
- Mian DHCP
- ~500$ + mobilicom
- ~6h battery

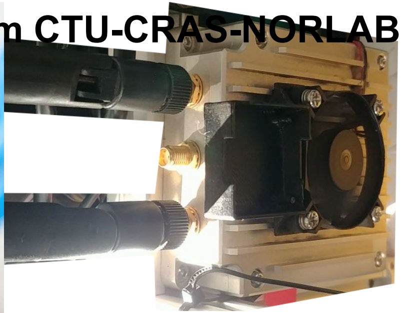


New version w/o mobilicom: <300$

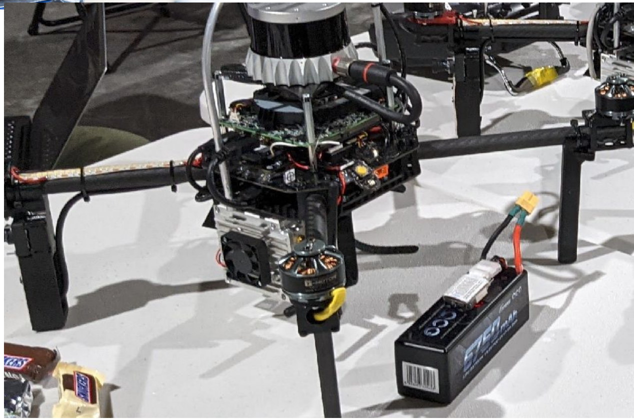


Team CTU-CRAS-NORLAB

Mobilicom



- Prebuilt custom 4g networking at 2.3-2.5Ghz@2W
- Based on time domain multiplex
- 8Mbit/s shared between all nodes
- Up to 2Km on open field
- 140g @ 8 x 8 x 3 cm w/o antennas
- Built in meshing capabilities and GPS
- Behaviour of networking HUB
- Need for additional switch supporting VLAN
- Bigger base version with 10W max output



- Due to low bandwidth usage of Nimbro to translate to UDP nad limit bandwidth of pure ROS

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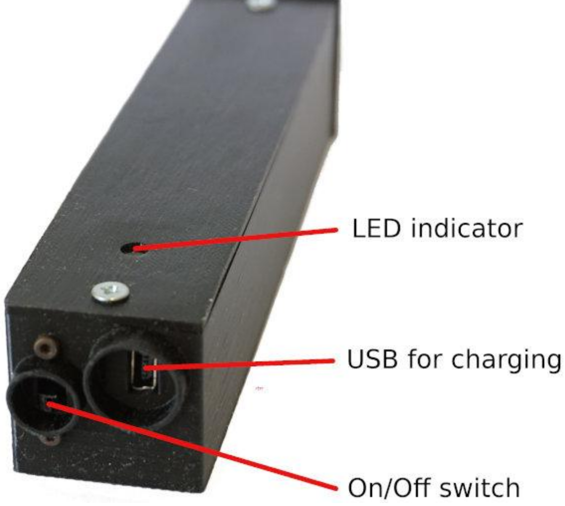
MOTE network (breadcrumbs)

- Custom RFM69HCW-based 400 or 868 or 915Mhz disposable nodes
- 1kbit per network (given by network topology)
- 100s of meters open field, up to 100m underground
- Focus on price and disposability
- Originally <8 USD per unit, due to chip shortage ~15 USD w/ battery
- 6h battery
- 100g @15x3x3cm for droppable node
- 7g @ 2.5x2.5x5 for UAV module
- Flood networking with transmission window for each 64B data packet
- Custom code to translate required ROS topics
- Nodes are sealed by glue ends with silicone caps
- Should float on water

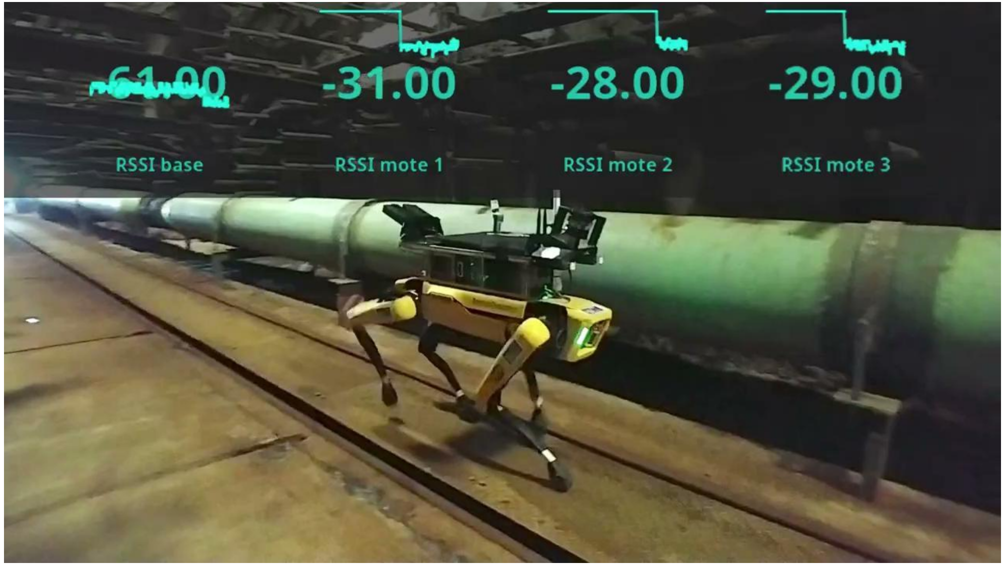


Drop strategy

2 different versions

Second independent on vertical mounting
Dropping strategy:

- Tunnel + Urban: traveled distance (100m)
- Finals: RSSI to closest node to base
  - Not fast enough



Eventual improvements:

- RSSI prediction with interpolation
- Usage of topometric map and treating the environment as waveguide

CSIRO

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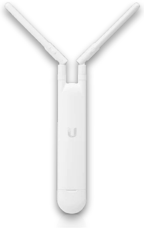
Physical Layer

History:

- Prototypes based on ESP32 SoC
- Development slower than expected
- Pivot to Ubiquiti UniFi mesh
- Drop node design v1
- Slow remeshing with Ubiquiti firmware
- OpenWRT + BATMAN?
- Pivot to Rajant Breadcrumbs



Physical Layer

Nodes:

- Rajant Breadcrumbs
- Multiple form factors
- 802.11 layer 1, proprietary layer 2
- Multi-frequency (FE1, ES1)
- 300Mb/s signal data-rate
- 2x2 MIMO (FE1, ES1, DX2)
- Highly configurable firmware



Model	**FE1-2255B**	**ES1-2450R**	**DX2-50**
Dimensions	265 x 254 x 46 mm	139 x 143 x 57 mm	108 x 43 x 40 mm
Weight	2946 g	440 g	123 g
Frequencies	2.4 + 5.8 GHz	2.4 + 5.8 GHz	5.8 GHz only
Power	10-34 W @ 20-60 VDC	2.8-15 W @ 9-30 VDC	2.8-7.5 W @ 8-60 VDC
Price*	~$10,000 USD	~$3,000 USD	~$4,000 USD

*current prices are based on own market research, units are sold through distribution partners

Physical Layer

Drop-nodes:

- Aluminium housing for node + RPi
- Elastic-strap launcher w/ latch
- Reed switch senses launch
- Self-righting via side panels
- Curved honeycomb TPU bumpers
- Unfolding antennae arms

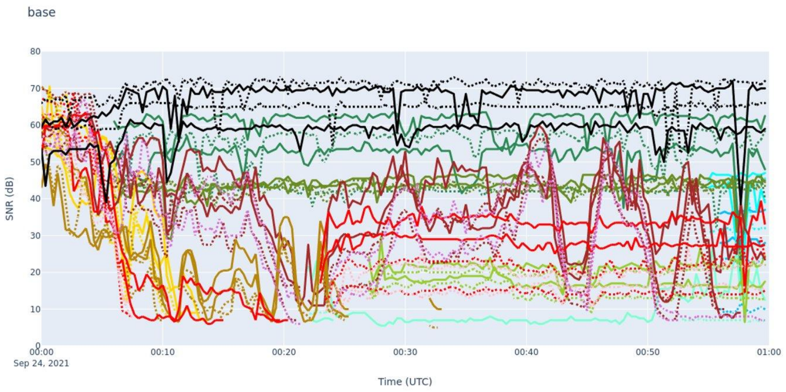
Antennae:

- Sector, omni options at base
- Polarization diversity for non-line-of-sight

Physical Layer

Pros/Cons:

- + Mature COTS
- + Frequency, transmit, polarization diversity
- + Drop nodes worked well…
- – …but too big for Spot and tight paths
- ? Drop-nodes as data-caches



Lessons Learned:

- Bluetooth/RC interference
- Set up logging early

COSTAR

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Thanks to CoSTAR team members

PI: Ali-akbar Agha-mohammadi

Comms: Jeffrey A. Edlund, Lillian Clark

Operations/integration: Kyohei Otsu, Muhammad Fadhil Ginting, Gustavo J. Correa, Angel Santamaria-Navarro

Autonomy: Maira Saboia, Vivek Thangavelu, Vivek Shankar Varasharajan, Tiago Stegun Vaquero

Hardware: Matt Anderson, Thomas Touma, Hovhannes Melikyan, Torkom Pailevanian, Avak Archanian

Planning: Amanda Bouman, Sung-Kyun Kim

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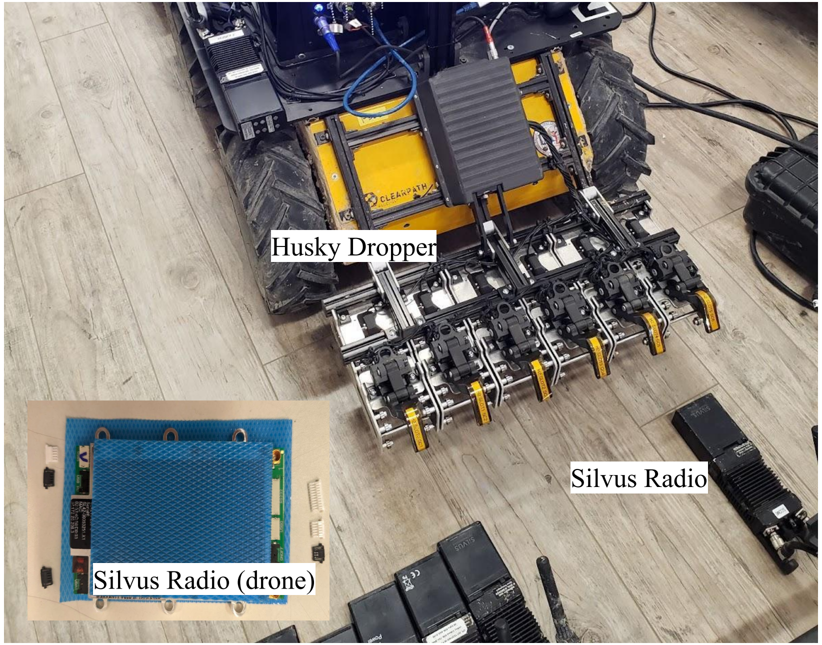
Silvus Radios & Nebula Comm Deployment System



Drone - StreamCaster LITE 4200 (2x2 MIMO Radio)

WAVEFORM	Mobile Networked MIMO (MN-MIMO)	VOLTAGE	8-32 VDC or USB-PD (9V@3A min)
ENCRYPTION	DES56 (Standard) AES256 (Optional)	POWER CONSUMPTION	4.8W-17W @ 1W TX Power
DATA RATE	Up to 20Mbps (Adaptive)	FREQUENCY BANDS MHz	S Band (235) 2200-2500 Federal C-1 (467) 4400-4940
OUTPUT POWER	1mW - 1W variable	RF INTERFACE	2x TNC(f)
LATENCY	28ms average (5MHz BW)	DATA INTERFACES	1x USB 2.0 Host; 1x USB 2.0 OTG; 1xSerial RS-232
SENSITIVITY	-105dBm @ 1.25MHz BW	CONTROL INTERFACE	2-Position ON/OFF Switch Web-Based StreamScape Network Manager
CHANNEL BANDWIDTH	1.25, 2.5, 5, 10, or 20 MHz		

Roughly $6,500

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Drone - StreamCaster LITE 4200 (2x2 MIMO Radio)

RUGGED		OEM (LIGHTWEIGHT)	
DIMENSIONS	140 x 72 x 20 mm (with connectors)	DIMENSIONS	97 x 70 x 11.3 mm
WEIGHT	295 grams	WEIGHT	105 grams
MATERIAL	Black Anodized Aluminum	I/O CONNECTORS	Qty 6, Molex style (Power, data, status, control)
AMBIENT TEMPERATURE	40º to +65º C	RF CONNECTORS	2x SMP (m)
IP RATING	IP67 (Up to 1m for 30min)		

Roughly $6,500

Roughly $6,000

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Robots - StreamCaster 4200 (2x2 MIMO Radio)

WAVEFORM	Mobile Networked MIMO (MN-MIMO)	VOLTAGE	9 - 20 VDC
ENCRYPTION	DES56 (Standard) AES256 (Optional)	POWER CONSUMPTION	5W-48W @ 10W TX Power 5W-24W @ 4W TX Power 5W-16W @ 1W TX Power
DATA RATE	Up to 100Mbps (Adaptive)	FREQUENCY BANDS	From 300MHz to 5.8GHz available
OUTPUT POWER	1mW - 10W variable	RF INTERFACE	2x TNC(f)
LATENCY	7ms average (20MHz BW)	PRIMARY INTERFACES	1x Ethernet, 1x RS232, DC Input
SENSITIVITY	-99dBm @ 5MHz BW	AUXILIARY INTERFACES	1x USB 2.0 Host, 1x USB 2.0 OTG
CHANNEL BANDWIDTH	5, 10, or 20 MHz		

Roughly $8,000

Robots - StreamCaster 4200 (2x2 MIMO Radio)

RUGGED	
DIMENSIONS	101.6 x 66.8 x 38.35 mm (without connectors)
WEIGHT	425 grams
MATERIAL	Black Anodized Aluminum
AMBIENT TEMPERATURE	40º to +65º C
IP RATING	IP68 (submersible up to 20m for 30min)

Basestation - StreamCaster 4400 (4x4 MIMO Radio)

WAVEFORM	Mobile Networked MIMO (MN-MIMO)	VOLTAGE	9 - 20 VDC
ENCRYPTION	DES56 (Standard) AES256 (Optional)	POWER CONSUMPTION	8W-100W @ 20W TX Power 8W-43W @ 8W TX Power 8W-24W @ 1W TX Power
DATA RATE	Up to 100Mbps (Adaptive)	FREQUENCY BANDS	From 300MHz to 6GHz available
OUTPUT POWER	1mW - 20W variable	RF INTERFACE	4x TNC(f)
LATENCY	7ms average (20MHz BW)	PRIMARY INTERFACES	1x Ethernet, 1x RS232, DC Input
SENSITIVITY	-102dBm @ 5MHz BW	AUXILIARY INTERFACES	1x USB 2.0 Host, 1x USB 2.0 OTG
CHANNEL BANDWIDTH	5, 10, or 20 MHz		

Roughly $16,000

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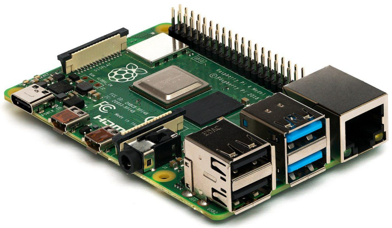
Deciding on Silvus



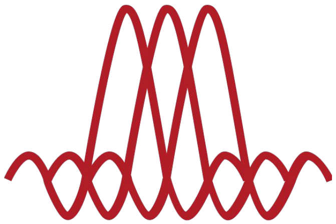
1. 802.11s with Raspberry Pis: power supplies, routing (loops), interoperability
2. Persistent Systems: less info through API
3. Silvus Technologies: preliminary tests seemed better at large quantities of data

Silvus had more radios available to purchase/borrow at the time.

MN-MIMO from Silvus

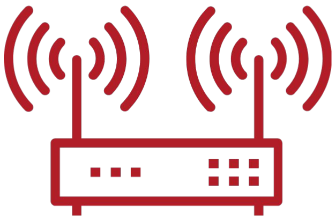
Coded Orthogonal Frequency Division Multiplexing (COFDM)

- Handles multipath
- Handles frequency selective fading
- Handles long delay spread

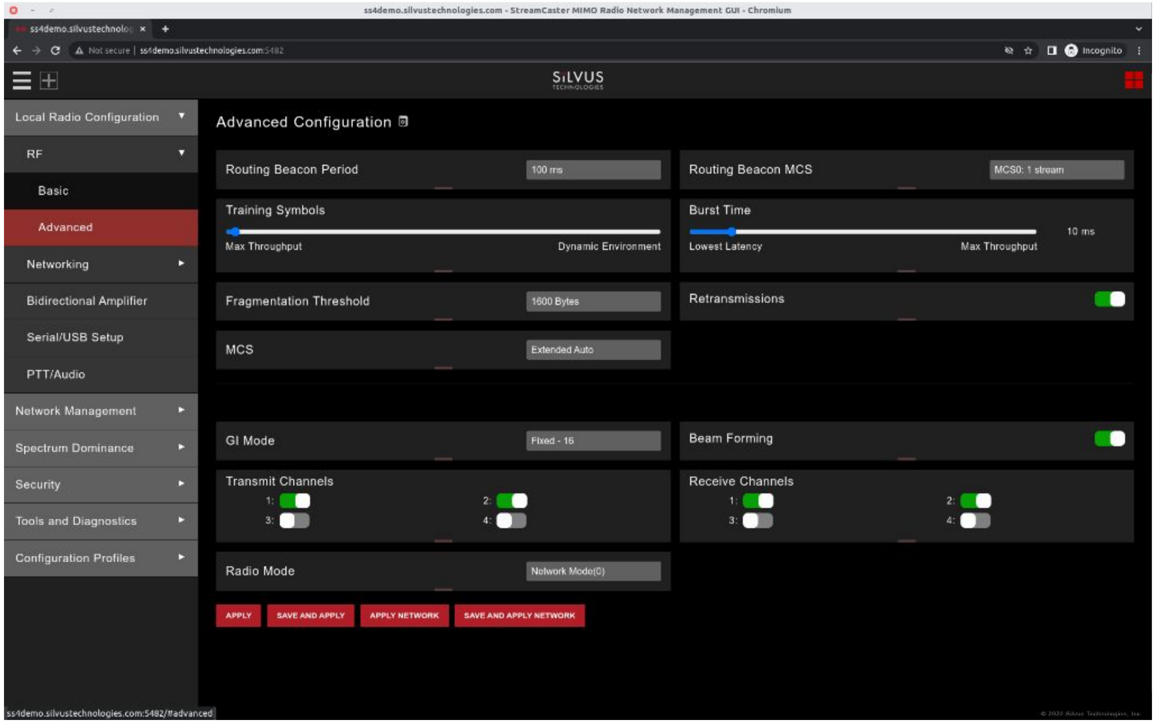


Multiple Input Multiple Output (MIMO) antenna techniques

- Spatial diversity
- Spatial multiplexing



Silvus GUI - local radio configuration open



Easier to use virtual IP's instead of node labels

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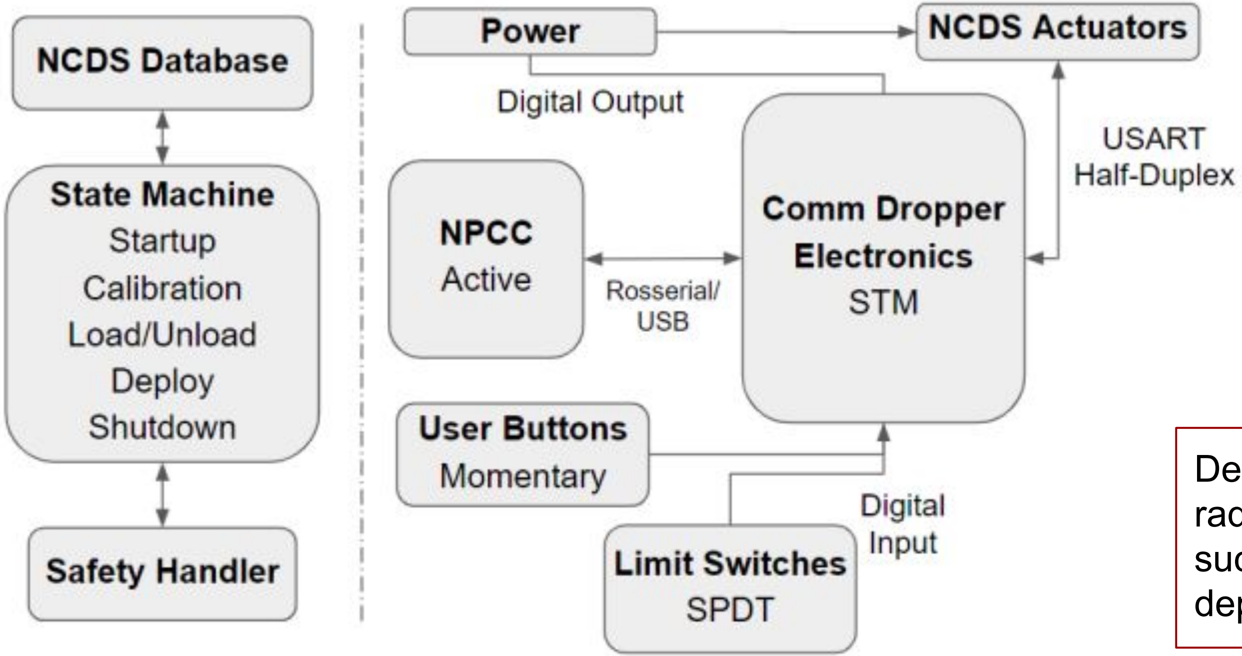
Silvus API (JSON RPC)

```
import jsonrpclib
import requests

rx = jsonrpclib.Server('http://{0}/cgi-bin/streamscape_api'.format(target_radio))
streamscape_data = getattr(rx, “streamscape_data”)
node_labels = requests.get('http://{0}/data/node_labels'.format(target_radio), timeout=1)
```

- target_radio is the virtual IP address
- rx has attributes: `"nodeid", "streamscape_data", "read_current_temperature", "input_voltage_monitoring", "battery_percent"`
- streamscape_data has attributes including: Virtual IP, Bandwidth, Contention Window Minimum, Frequency, GPS status, Link adaptation mode, Modulation and coding scheme, Noise level, Queue size, Tx power requested, Tw power actual

Nebula Comm Deployment System (NCDS)



Detects when radios were successfully deployed.

Lessons learned

- 3D printed braces to keep antennas up
- Ferrite beads to block USB 3.0 from the RealSense interference
- Silvus radius interfering with each other
  - Could have been more clever with changing tx power
- We didn't explore antenna alternatives
- Radio labels were key

Team CoSTAR

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Mesh Layer

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Explorer

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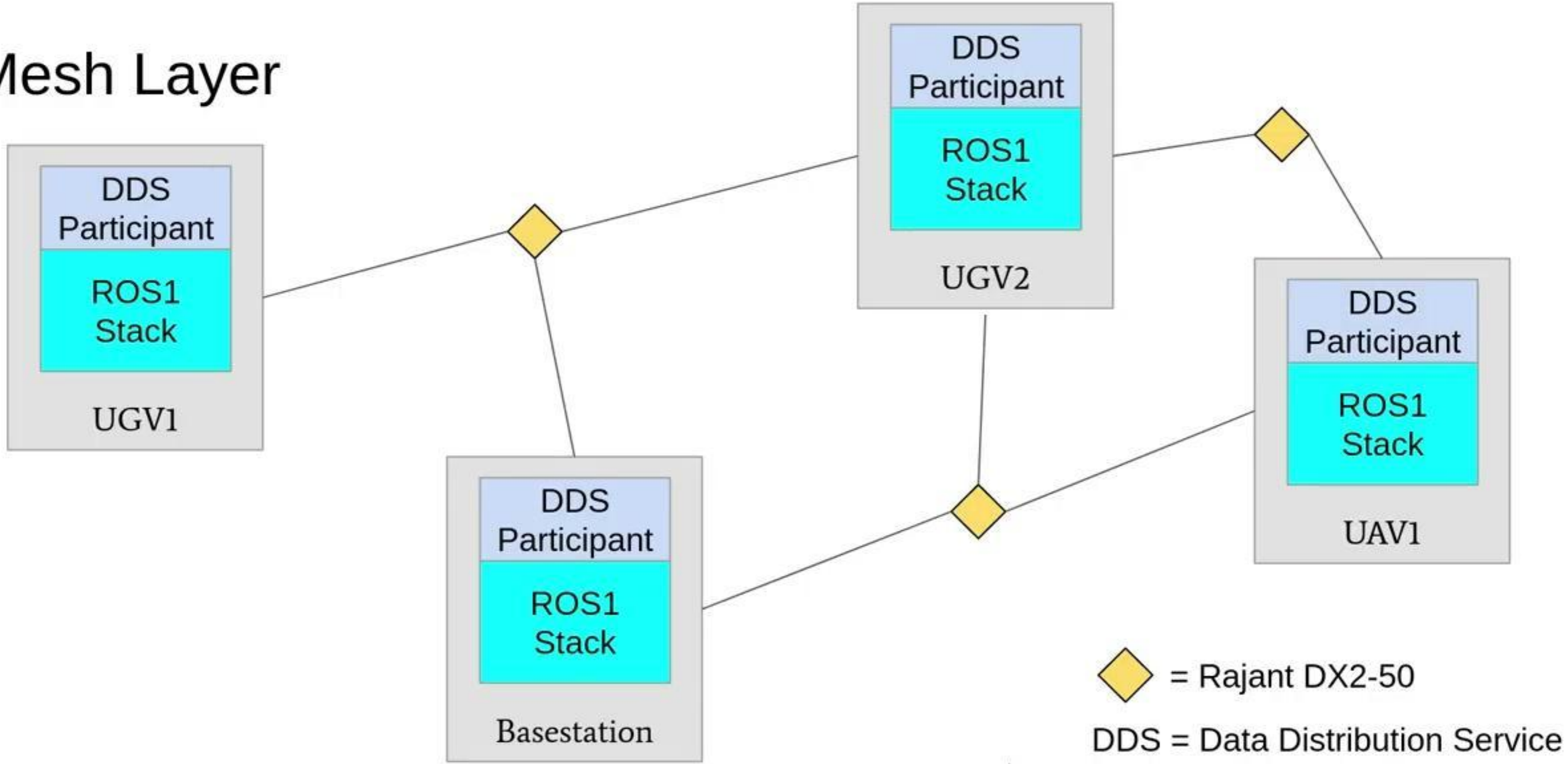
Mesh Layer



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CTU-CRAS-NORLAB

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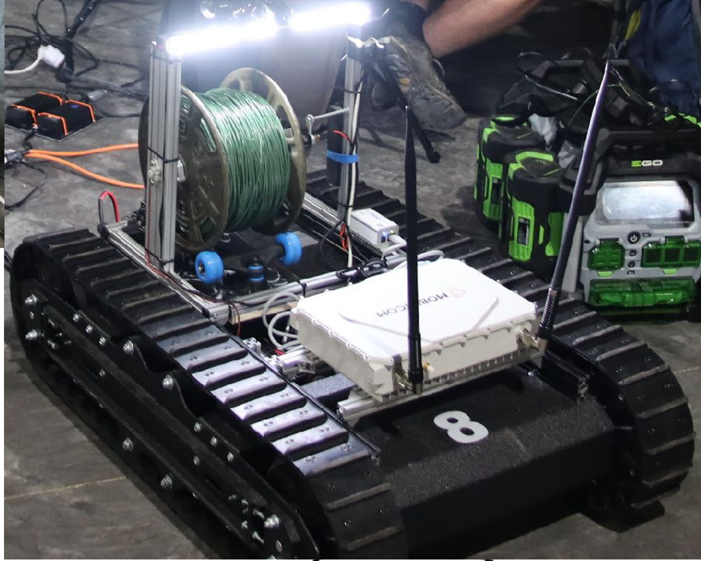
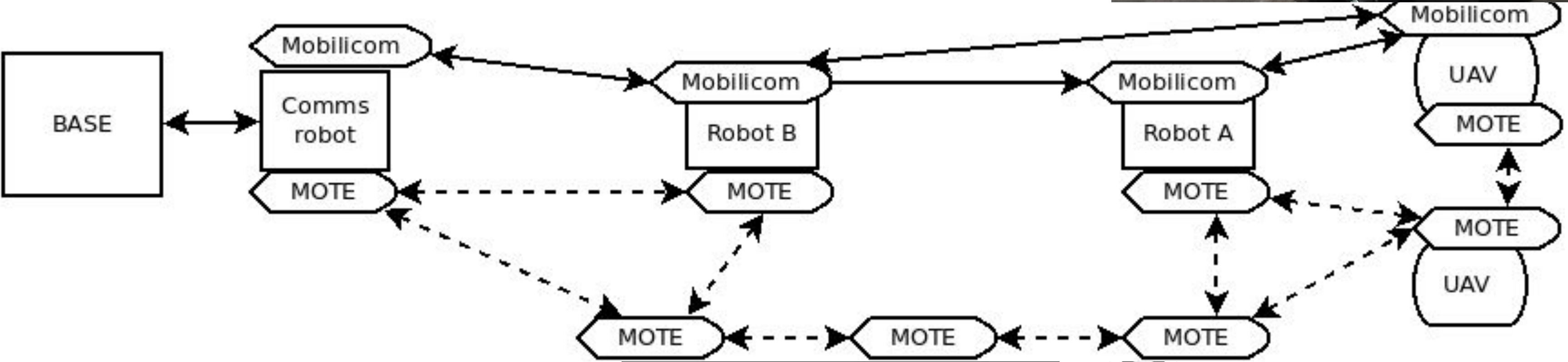
Networking diagram



- Mobilicom present only on UGVs and few UAVs
- MOTE breadcrumbs including 4-8 per robot
- Essentially making two independent networks for redundancy
- Commsbot via 2-wire ethernet (~20Mbit/s) back to base
- Orangebox used only for setup at the beginning
- Issue: the 2-Wire did not work on the stage due to stage lights



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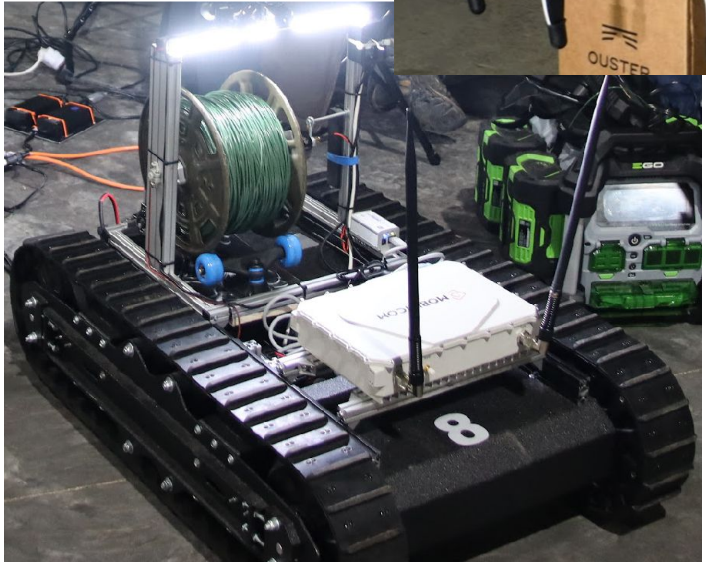
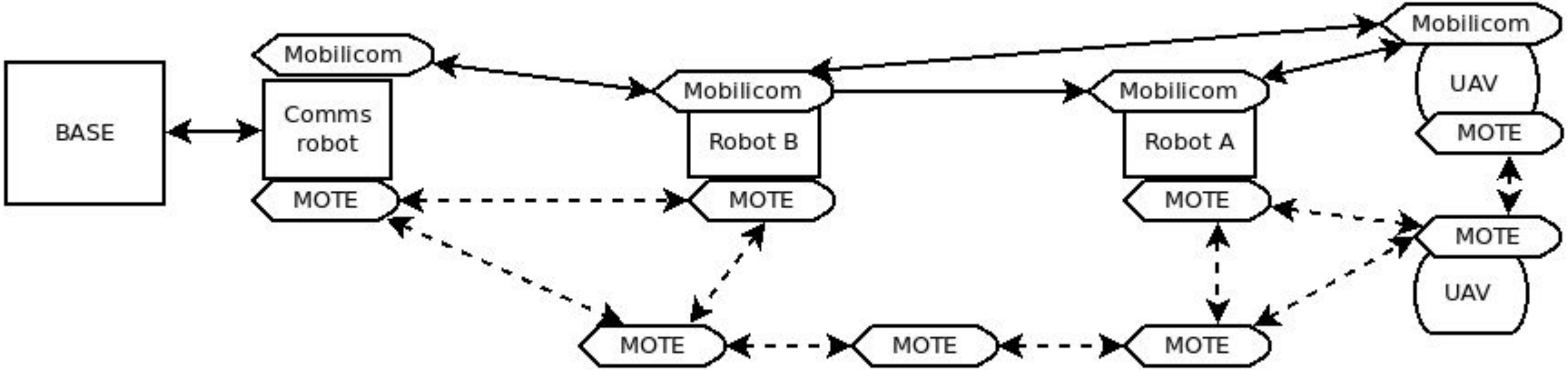
Meshing Layer Mobilicom

- Mobilicom has built in mashing
- Retransmission of a packet everytime it was seen in allotted time slot by others
- Max 5 hops - 10 units deployed at one time
- Lowers the bandwidth (divide by hops)
- Mashing reconnection ~1s then data dump back to base if high enough CINR for all links
- Units can be configured to have maximum outbound traffic with internal buffer
- Data flows through all available connections
- To save a hop one Commsbot connected via 2-wire ethernet (~20Mbit/s) back to base



Meshing Layer MOTE

- MOTE custom flood mashing
- All “packets” have unique ID (timestamp)
- Each packet robot adds specified data in to the packet which is then shared throughout the network
- Each MOTE keeps all data it had received that second for the packet and retransmits it further
- Packet can live up to one second on the network



CSIRO

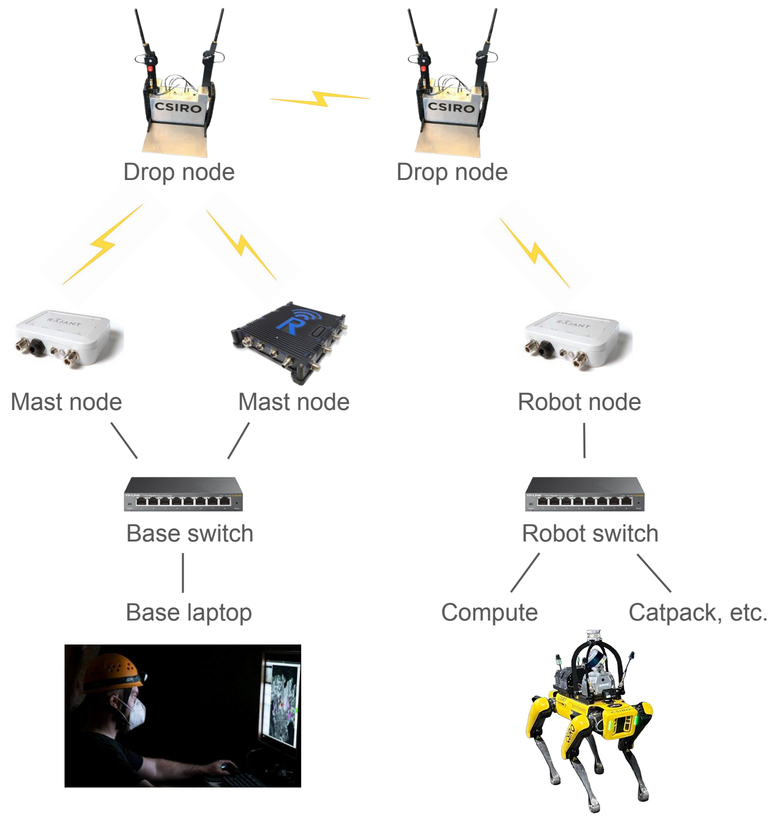
Mesh Layer

Configuration:

- Layer 2 bridging
- Static IP assignment
- Common hosts file
- MAC whitelisting

Protocol:

- Rajant InstaMesh
- Ethernet frame encapsulation
- Alternate next-hops for fast failover
- Opportunistic link selection



Mesh Layer

Performance:

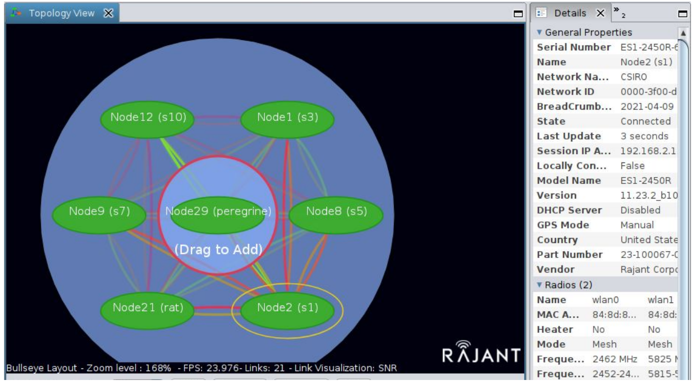
- Convergence <1s (break in small mesh)
- Reconnection <15s (robot return from range)
- Throughput >10Mb/s (10 hop chain)
- Latency <20ms (10 hop chain)

Tools:

- BCCommander (GUI)
- BCAPI (Java library)
- Live: wireshark, nethogs, iftop, iperf3
- Logs: tcpdump w/ rotation, compression

Drop-node Hops	Latency (ms)*	Throughput (Mbps)*
1	3.3	84
3	6.7	45
5	10.1	31

* tested indoors at ground-level, 1 frequency/channel per hop



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Mesh Layer

Pros/Cons:

- + Mature COTS
- – Harder to try alternative protocols
- ? Cross-layer optimization

Lessons Learned:

- Limit shared broadcast domains
- Choosing node placements on the fly is hard

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MARBLE

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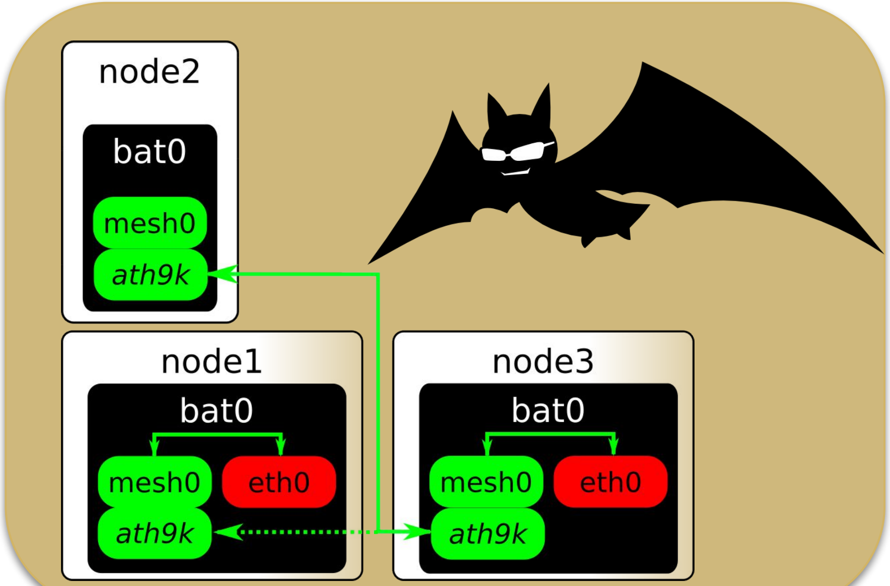
Initial Mesh Solution:

Better Approach To Mobile Ad-hoc Networking (B.A.T.M.A.N)

- Layer 2 meshing
- Open Source
- Designed for optimal routing

Observations:

- 5-10s reconnect times
- Plethora of tuning parameters



https://www.open-mesh.org/projects/open-mesh

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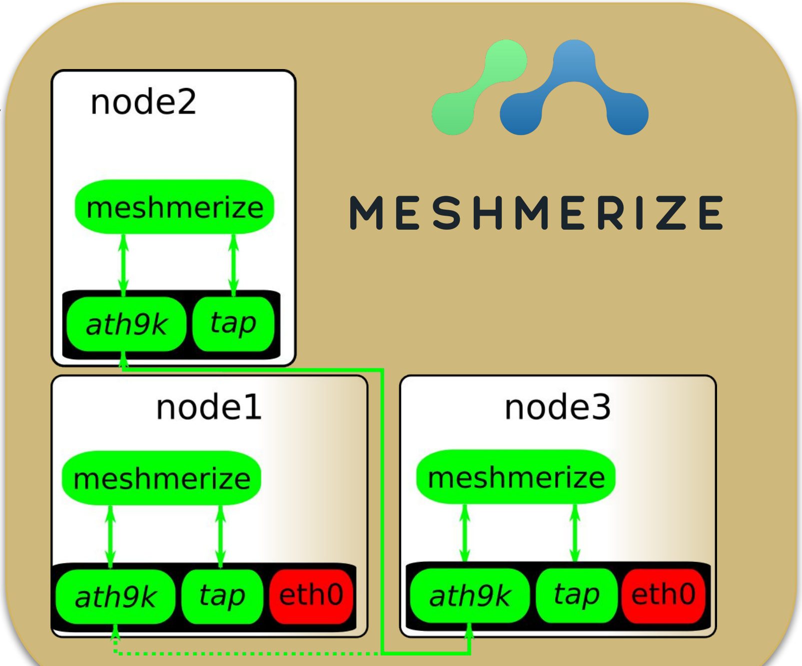
Replacement: *meshmerize*

- Commercial product
- Emphasizes very fast reconnect times over optimal routing or throughput

Observations:

- Max throughput ~12MBit / s , CPU limited
- Expertise is key for debugging

Note: Newer versions of Meshmerize are available that handle 100Mbit/s+ on *ath9k* hardware



https://www.open-mesh.org/projects/open-mesh

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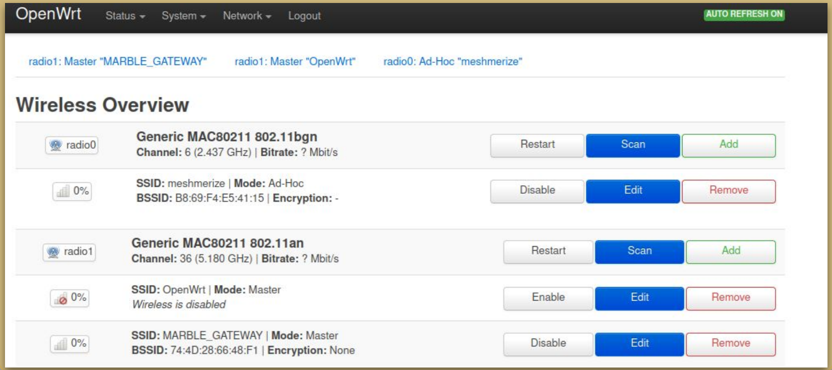
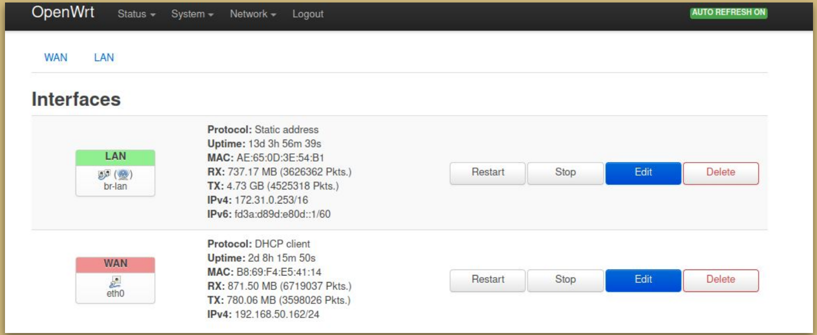
Configuration Management

Problem: 30+ radios to reconfigure with any firmware change

Solution: Layer 2 management tool using custom Ethernet frame types

Impact: One-click firmware upgrades and configuration





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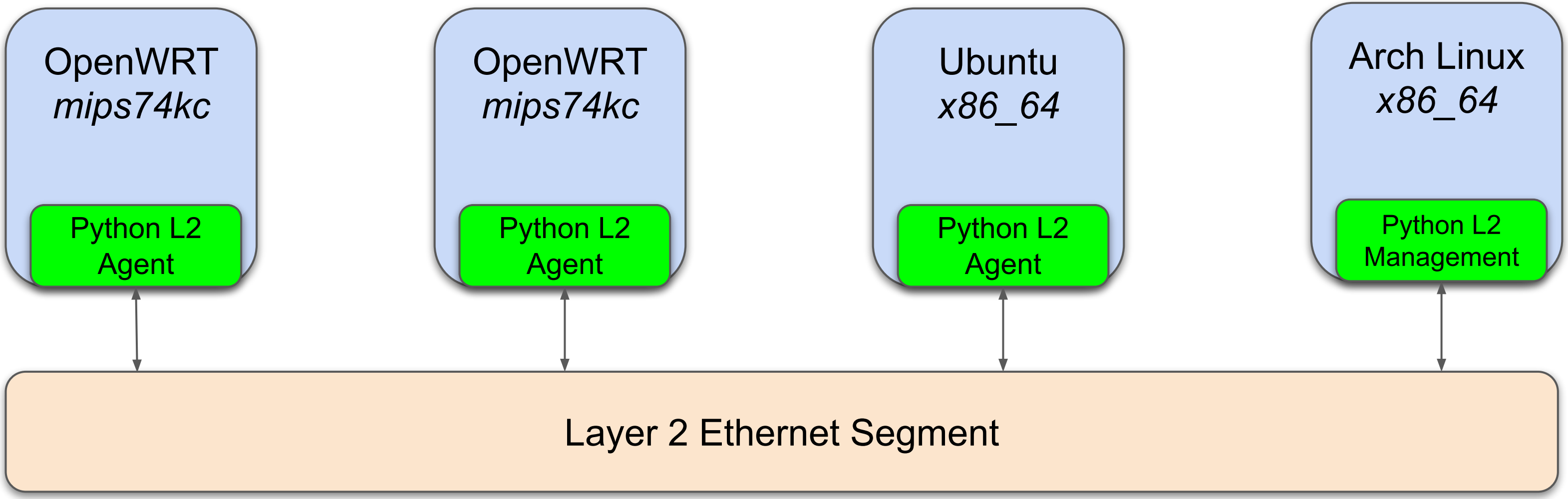
Program Elements



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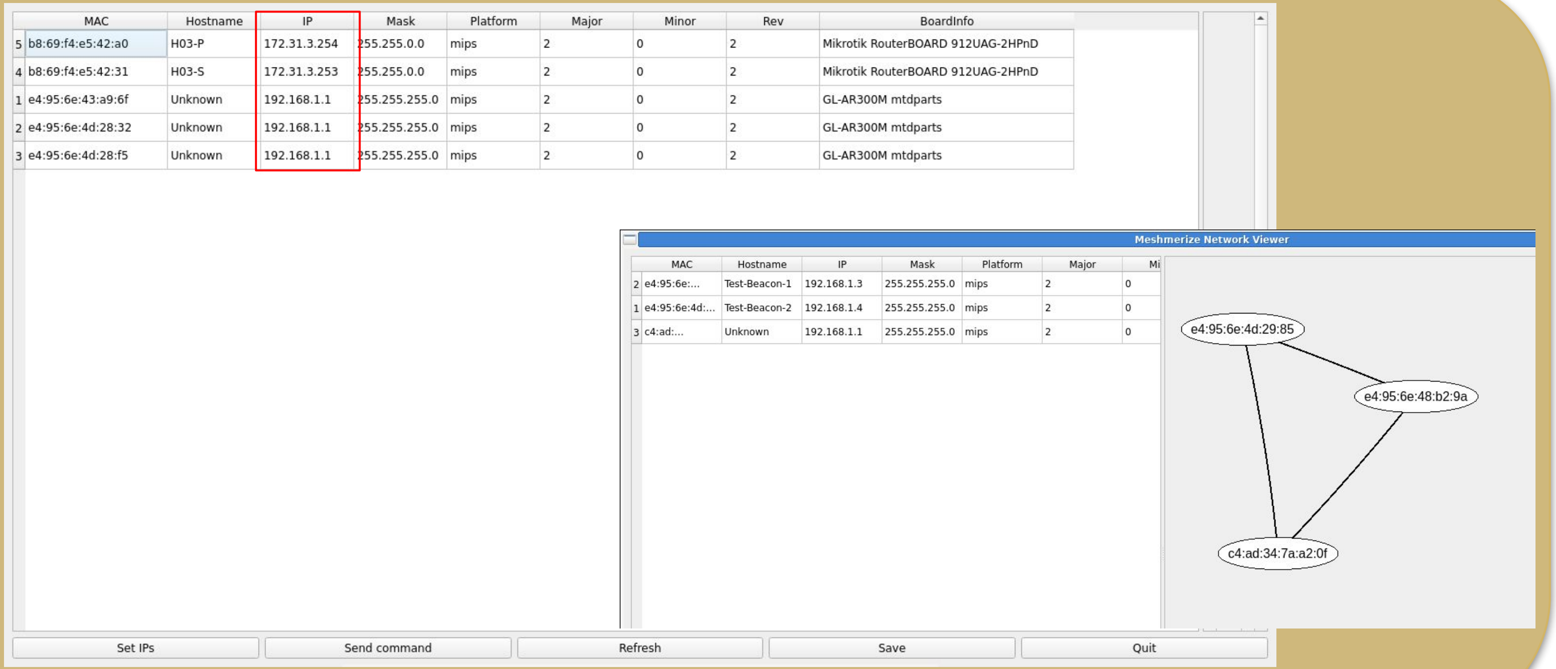
Layer 2 Discovery



	MAC	Hostname	IP	Mask	Platform	Major	Minor	Rev	BoardInfo
5	b8:69:f4:e5:42:a0	H03-P	172.31.3.254	255.255.0.0	mips	2	0	2	Mikrotik RouterBOARD 912UAG-2HPnD
4	b8:69:f4:e5:42:31	H03-S	172.31.3.253	255.255.0.0	mips	2	0	2	Mikrotik RouterBOARD 912UAG-2HPnD
1	e4:95:6e:43:a9:6f	Unknown	192.168.1.1	255.255.255.0	mips	2	0	2	GL-AR300M mtdparts
2	e4:95:6e:4d:28:32	Unknown	192.168.1.1	255.255.255.0	mips	2	0	2	GL-AR300M mtdparts
3	e4:95:6e:4d:28:f5	Unknown	192.168.1.1	255.255.255.0	mips	2	0	2	GL-AR300M mtdparts

Meshmerize Network Viewer

	MAC	Hostname	IP	Mask	Platform	Major	Mi
2	e4:95:6e:...	Test-Beacon-1	192.168.1.3	255.255.255.0	mips	2	0
1	e4:95:6e:4d:...	Test-Beacon-2	192.168.1.4	255.255.255.0	mips	2	0
3	c4:ad:...	Unknown	192.168.1.1	255.255.255.0	mips	2	0

Selecting Subset to Configure

	MAC	Hostname	IP	Mask	Platform	Major	Minor	Rev	BoardInfo
5	b8:69:f4:e5:...	H03-P	172.31.3.254	255.255.0.0	mips	2	0	2	Mikrotik ...
4	b8:69:f4:e5:...	H03-S	172.31.3.253	255.255.0.0	mips	2	0	2	Mikrotik ...
1	e4:95:6e:...	Unknown	192.168.1.1	255.255.255.0	mips	2	0	2	GL-AR300M ...
2	e4:95:6e:4d:...	Unknown	192.168.1.1	255.255.255.0	mips	2	0	2	GL-AR300M ...
3	e4:95:6e:4d:...	Unknown	192.168.1.1	255.255.255.0	mips	2	0	2	GL-AR300M ...

Set IPs | Send command | Refresh | Save

File Edit Options Buffers Tools Help

Save Undo

```
b8:69:f4:e5:42:a4, 172.31.20.254, 255.255.0.0, 172.31.0.253, D01
b8:69:f4:e5:42:39, 172.31.21.254, 255.255.0.0, 172.31.0.253, D02
b8:69:f4:e5:42:21, 172.31.0.1, 255.255.0.0, 172.31.0.253, Base
b8:69:f4:e5:42:aa, 172.31.1.254, 255.255.0.0, 172.31.0.253, H01-P
b8:69:f4:e5:42:a2, 172.31.1.253, 255.255.0.0, 172.31.0.253, H01-S
b8:69:f4:e5:42:3e, 172.31.2.254, 255.255.0.0, 172.31.0.253, H02-P
b8:69:f4:e5:42:33, 172.31.2.253, 255.255.0.0, 172.31.0.253, H02-S
b8:69:f4:e5:42:a8, 172.31.2.254, 255.255.0.0, 172.31.0.253, H02-P
b8:69:f4:e5:42:a0, 172.31.3.254, 255.255.0.0, 172.31.0.253, H03-P
b8:69:f4:e5:42:31, 172.31.3.253, 255.255.0.0, 172.31.0.253, H03-S
b8:69:f4:e5:41:03, 172.31.5.254, 255.255.0.0, 172.31.0.253, T02-P
b8:69:f4:e5:40:cf, 172.31.5.253, 255.255.0.0, 172.31.0.253, T02-P
00:30:1a:4e:85:56, 172.31.9.254, 255.255.0.0, 172.31.0.253, A01
00:30:1a:4e:85:6b, 172.31.10.254, 255.255.0.0, 172.31.0.253, A02
b8:69:f4:e5:41:15, 172.31.0.253, 255.255.0.0, 172.31.0.253, Gateway
00:30:1a:4e:85:6a, 172.31.101.1, 255.255.0.0, 172.31.0.253, Beacon-1
00:30:1a:4e:85:62, 172.31.101.2, 255.255.0.0, 172.31.0.253, Beacon-2
00:30:1a:4e:85:4a, 172.31.101.3, 255.255.0.0, 172.31.0.253, Beacon-3
00:30:1a:4e:85:5c, 172.31.101.4, 255.255.0.0, 172.31.0.253, Beacon-4
00:30:1a:4e:85:41, 172.31.101.5, 255.255.0.0, 172.31.0.253, Beacon-5
00:30:1a:4e:85:47, 172.31.101.6, 255.255.0.0, 172.31.0.253, Beacon-6
00:30:1a:4e:85:50, 172.31.101.7, 255.255.0.0, 172.31.0.253, Beacon-7
00:30:1a:4e:85:5f, 172.31.101.8, 255.255.0.0, 172.31.0.253, Beacon-8
00:30:1a:4e:85:43, 172.31.101.9, 255.255.0.0, 172.31.0.253, Beacon-9
00:30:1a:4e:85:65, 172.31.101.10, 255.255.0.0, 172.31.0.253, Beacon-10
00:30:1a:4e:7e:59, 172.31.101.11, 255.255.0.0, 172.31.0.253, Beacon-11
00:30:1a:4e:85:68, 172.31.101.12, 255.255.0.0, 172.31.0.253, Beacon-12
00:30:1a:4e:85:53, 172.31.101.13, 255.255.0.0, 172.31.0.253, Beacon-13
```

-:--- mac_ip.csv Bot L5 Git:updated_meshmorize (Fundamental)

Success!

	MAC	Hostname	IP	Mask	Platform	Major	Minor	Rev	BoardInfo
5	b8:69:f4:e5:...	H03-P	172.31.3.254	255.255.0.0	mips	2	0	2	Mikrotik ...
4	b8:69:f4:e5:...	H03-S	172.31.3.253	255.255.0.0	mips	2	0	2	Mikrotik ...
1	e4:95:6e:...	Unknown	192.168.1.21	255.255.255.0	mips	2	0	2	GL-AR300M ...
2	e4:95:6e:4d:...	Unknown	192.168.1.22	255.255.255.0	mips	2	0	2	GL-AR300M ...
3	e4:95:6e:4d:...	Unknown	192.168.1.24	255.255.255.0	mips	2	0	2	GL-AR300M ...

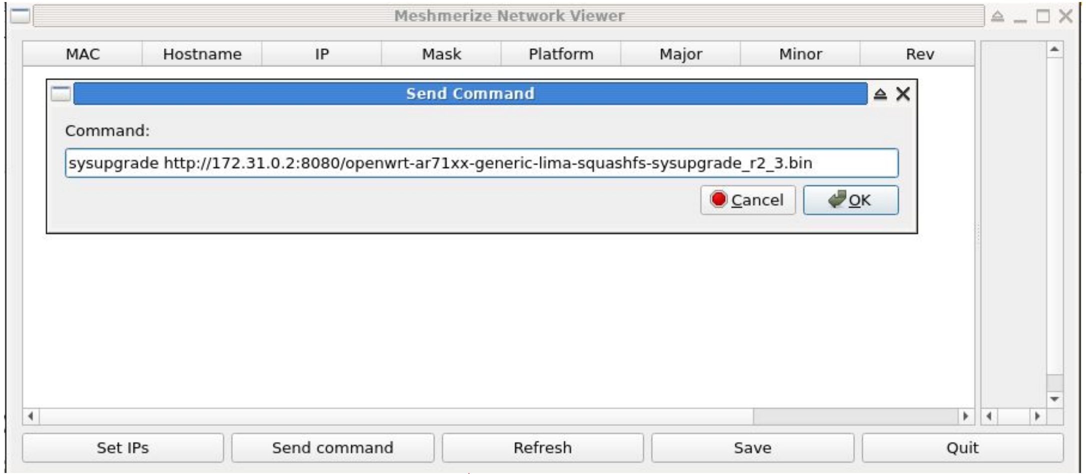
Set IPs | Send command

File Edit View Terminal Tabs Help

```
Setting MACs:
[]
qt.qpa.xcb: QXcbConnection: XCB error: 3 (BadWindow), sequence: 1245, resource id: 10720568, major code
, minor code: 0
Setting MACs:
['e4:95:6e:43:a9:6f', 'e4:95:6e:4d:28:f5', 'e4:95:6e:4d:28:32']
Setting IP for mac e4:95:6e:43:a9:6f
Src:
['e4:95:6e:43:a9:6f', ' 192.168.1.21', ' 255.255.255.0', ' 192.168.1.254', ' Test-Beacon-2']
Setting IP for mac e4:95:6e:4d:28:f5
Src:
['e4:95:6e:4d:28:f5', ' 192.168.1.22', ' 255.255.255.0', ' 192.168.1.254', ' Test-Beacon-3']
Setting IP for mac e4:95:6e:4d:28:32
Src:
['e4:95:6e:4d:28:32', ' 192.168.1.24', ' 255.255.255.0', ' 192.168.1.254', ' Test-Beacon-5']
qt.qpa.xcb: QXcbConnection: XCB error: 3 (BadWindow), sequence: 1468, resource id: 10720779, major code
, minor code: 0
SET_IP_ACK from e4:95:6e:4d:28:f5
e4:95:6e:4d:28:f5 reports IP: 192.168.1.22 Mask: 255.255.255.0 Gateway: 192.168.1.254
SET_IP_ACK from e4:95:6e:43:a9:6f
e4:95:6e:43:a9:6f reports IP: 192.168.1.21 Mask: 255.255.255.0 Gateway: 192.168.1.254
SET_IP_ACK from e4:95:6e:4d:28:32
e4:95:6e:4d:28:32 reports IP: 192.168.1.24 Mask: 255.255.255.0 Gateway: 192.168.1.254
```

Operational Evaluation

- Research-grade tool
- Critical to reducing manual labor when radio firmware / settings change
- Very useful in testing to evaluate network connectivity
- No security considerations



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COSTAR

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Setup from a fresh Ubuntu

Allows all robots to use a single image

Configure host from MAC (python script)

- Sets hostname `subprocess.call(["hostnamectl", "set-hostname", host_name])`
- Writes `/etc/hosts` file
- Exports env variable (e.g. `ROS_MASTER_URI, ROS_HOSTNAME, ROBOT_NAME`)

Configure networking files (`comm_mesh/install.py`)

- Creates symbolic links (e.g. `/etc/network/interfaces` → `../CostarMesh/etc/network/interfaces`, NetworkManager config file, chrony config file, etc)
- Checks driver versions, etc

IP Address Management

Fairly complex to join robot network → no chance of unnecessary traffic

Costar_ip_table.csv - to configure static IP addresses

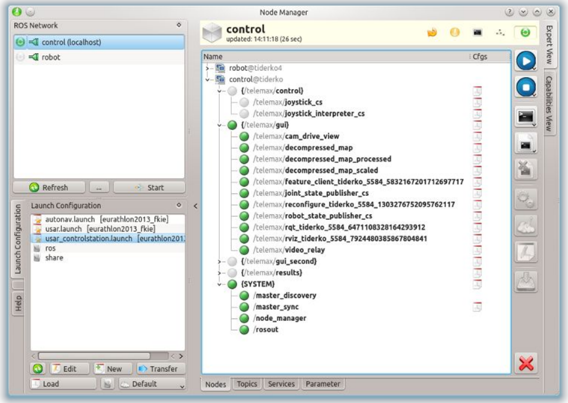
- Maps hostnames to IP addresses (175 entries)

Robot network, radio network

- Different ethernet switch for artifact computer, velodyne, hovermap

Node Manager from multimaster_fkie

- Master discovery node needs external IP



Radio label management lessons learned

Tradeoff between human readable and machine consistent/accurate

Robot's radio determined by hostname & radio node label

- We found node labels difficult to keep consistent

Robot's droppable radios configured manually

- Also configured using node label
- Used for high-level logic
- Needs to be done manually, often forgotten

Base Station Computer

- Gateway to internet
  - Easy SW updates
  - NAT
- Time Synchronization
  - Chrony (NTP implementation)
  - Artifact computer points to Robot
  - Robot points to Base

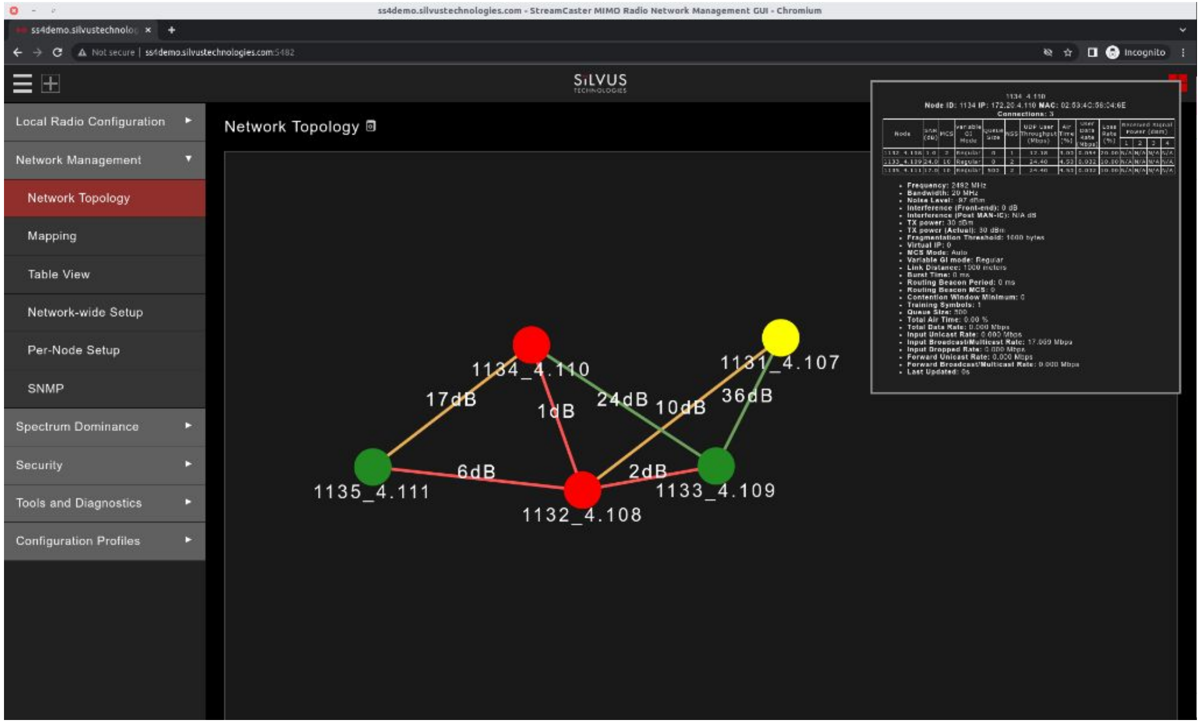
Pointing to base works better than pointing to a pool of Ubuntu NTP servers

Silvus MN-MIMO

No control over routes, but able to inspect them via API

- Self-forming, self-healing
- Adaptive links, adaptive routes
- Transparent IP Networking
  - entire MANET network appears as if it is a single Layer 2 networking switch
  - any number of standard computer, IP video camera or other devices may be connected to each of the mobile radios and communicate through the mesh network just as if all of the devices were in a single office with wired Ethernet

Silvus GUI - Network Management [open]



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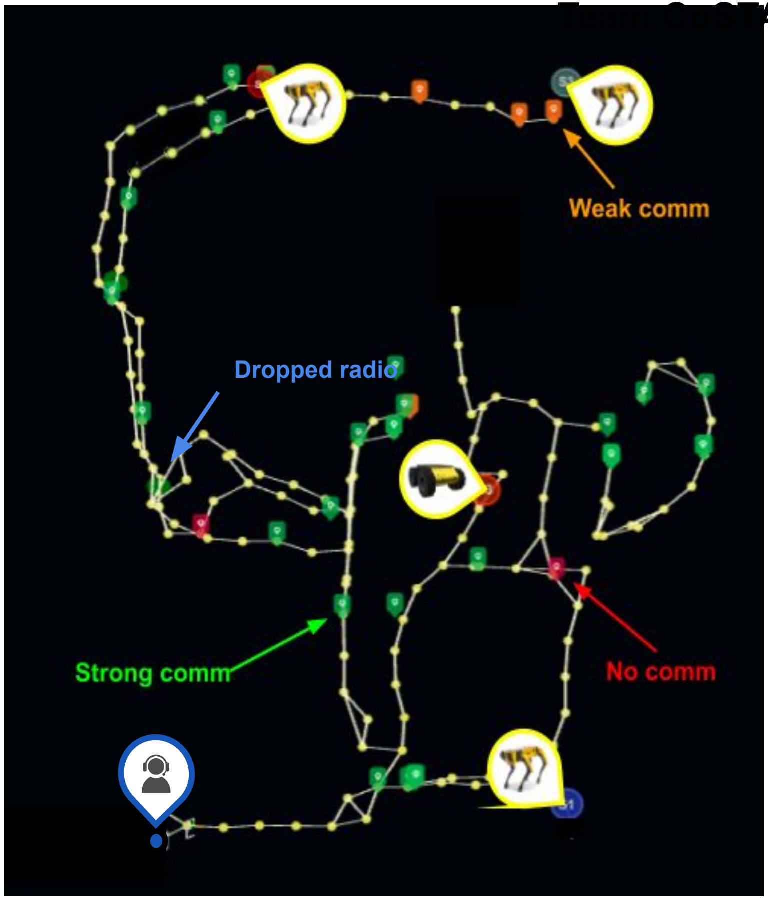
Network modeling & visualization

Network representations (custom ROS messages)

- Node-centric (streamscape roadmap)
- Link-centric (radio link lists)

Information Roadmap →

- Graph of environment
- Radio poses
- Robot poses
- SNR Checkpoints



Kim, Bouman, et al., “PLGRIM: Hierarchical Value Learning for Large-scale Exploration in Unknown Environments,” ICAPS, 2021.

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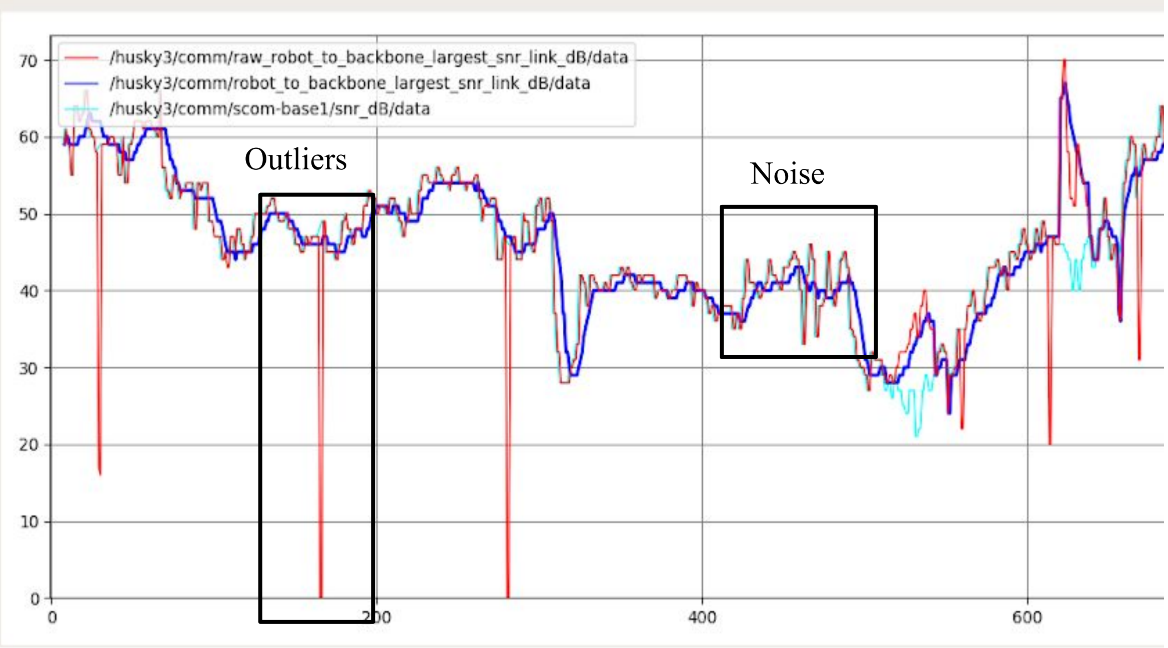
Modeling route to base (multi-hop link)



Smoothing this helped prevent early radio drops.

Simplified route estimates → could have used next-hop info from Silvus instead.

Lessons learned

- Lots of layers of addressing and discovery
  - Node manager discovery separate from ROS2 discovery separate from radio MANET discovery
  - ROS2 also has configurations for IP addressing and leases & throughput control
- Better to avoid manual configuration
  - Or at least automate checks on anything configured manually

Logical Layer

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Explorer

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Logical Layer

Communication Manager :

- DDS-ROS Bridge
- Leveraged in-built DDS Discovery Protocols
- Organized Topics Into Different Namespace Resolutions Depending On Unicast or Multicast
- Applied Different QoS and Reliability Protocols Per Message

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COSTAR

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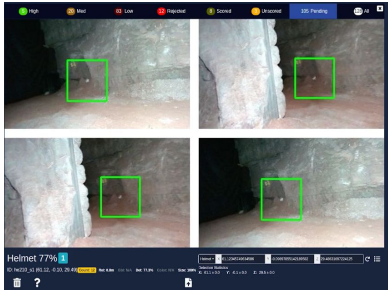
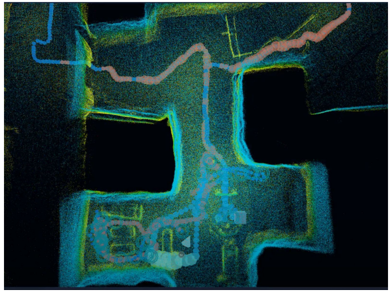
Data classification

<table>
<tr><td>Critical data (e.g. target detection)</td><td>Key data (e.g. partial maps)</td><td>Time sensitive data (e.g. telecommands)</td></tr>
<tr><td>
</td><td></td><td></td></tr>
</table>

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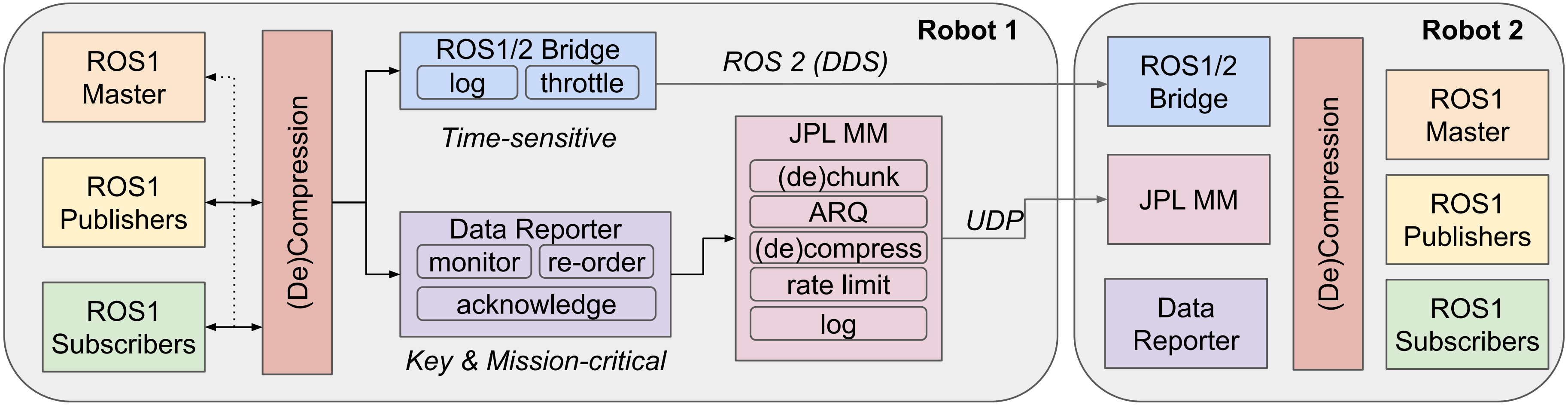
System Diagram



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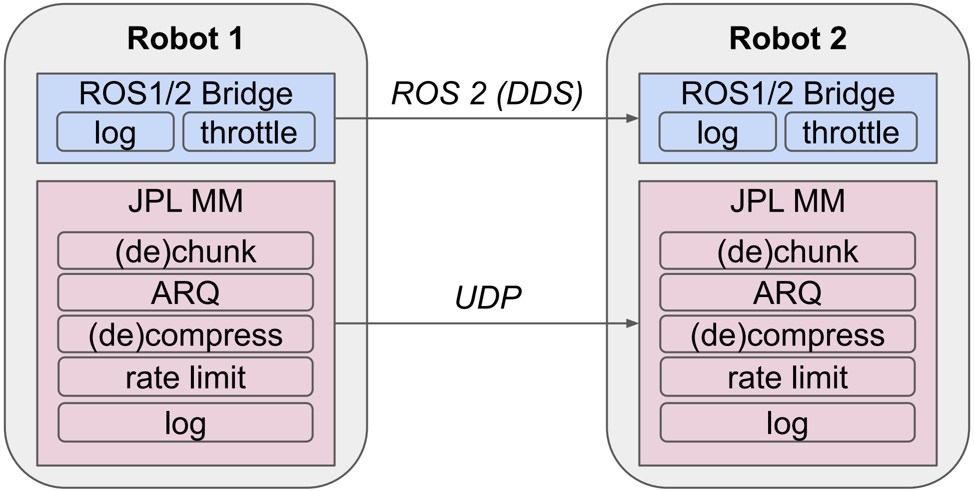
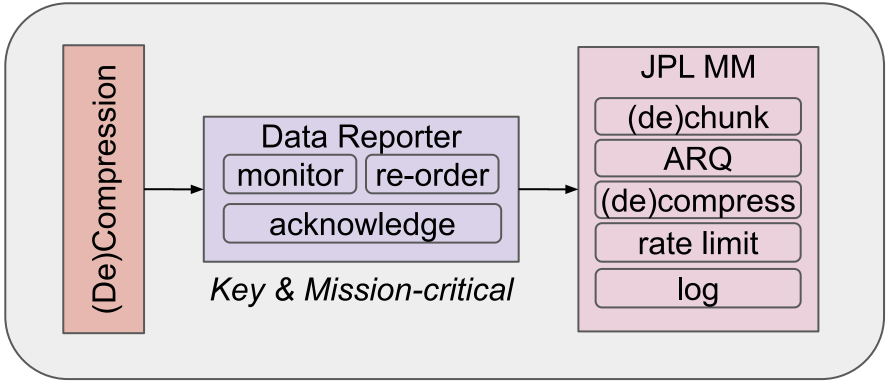
ROS2 and JPL Multi Master (MM) hybrid solution

- ros1_bridge (ROS2)
  - Bridges any matching publisher/subscriber pari
- JPL MM
  - Chunk/reassemble datagrams
  - Selective repeat ARQ
  - Token bucket rate limiting (per-topic)
- JPL MM Sender
  - Subscribe to ROS topic
  - Write to UDP socket
- JPL MM Receiver
  - Read from UDP socket
  - Write to ROS topic



Data reporter



- Sender
  - subscribes to all reliable topics
  - republishes on topic/reliable
- Receiver
  - subscribes to topic/reliable
  - republishes on topic
- Application-layer acknowledgements
  - Allows resending *specific* messages
  - Really useful for intermittent connectivity
- Queue size monitoring
  - Really useful for communication-aware behavior
- Re-ordering
  - Needed for some topics (keyed scans)

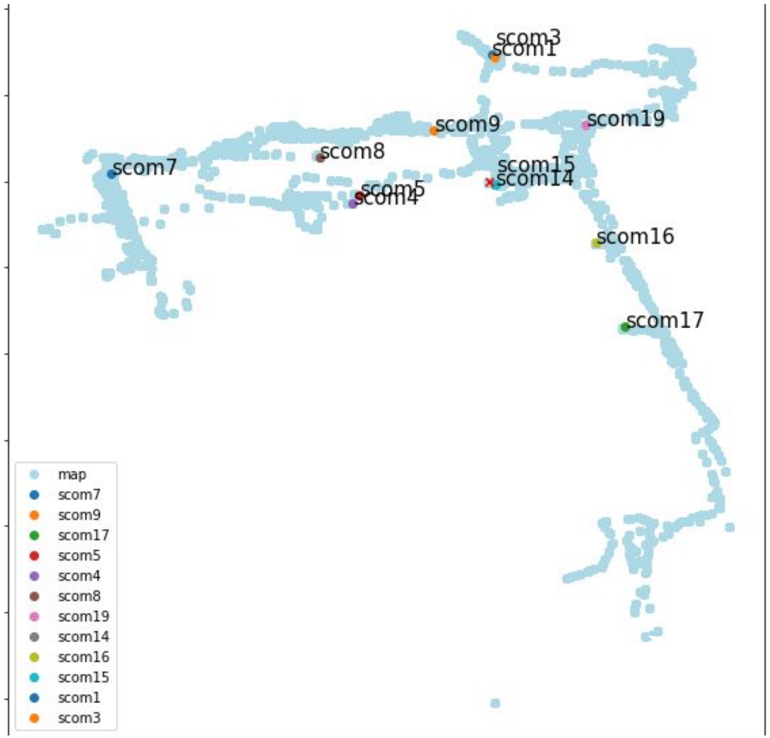
Comm-aware behavior

Autonomous comm drop

- Nominally triggered by drop in bottleneck SNR
- If successful, radio added to Information Roadmap

Return to comms

- Nominally triggered by queue size
- Robot backtracks to checkpoint with high SNR

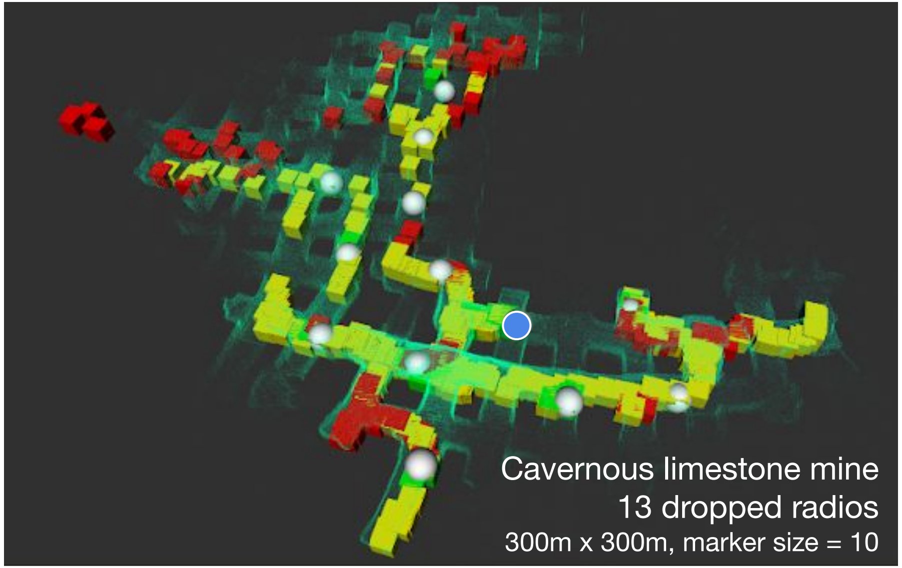


*Vaquero et al. "Traversability-aware signal coverage planning for communication node deployment in planetary cave exploration." i-SAIRAS 2020.

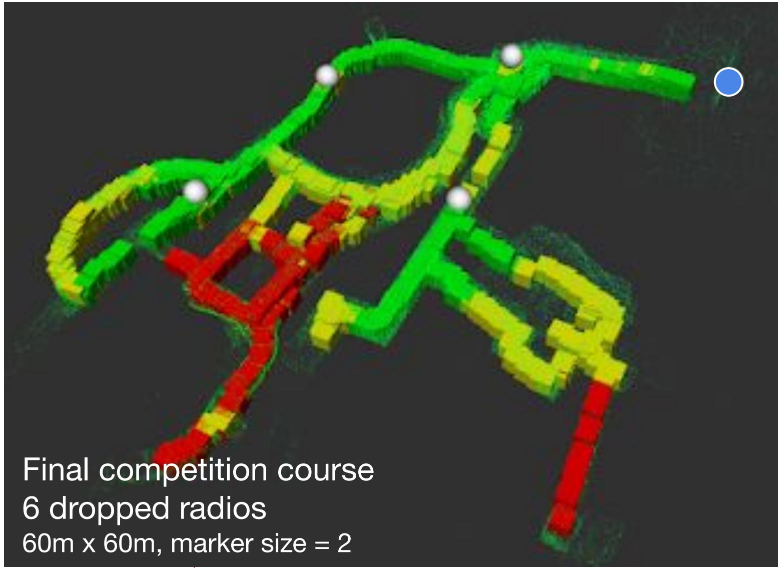
CoSTAR Comms Performance (1)

Measured signal quality and autonomous radio placement during exploration

SNR > 50 SNR > 25 SNR < 25 dropped node base radio

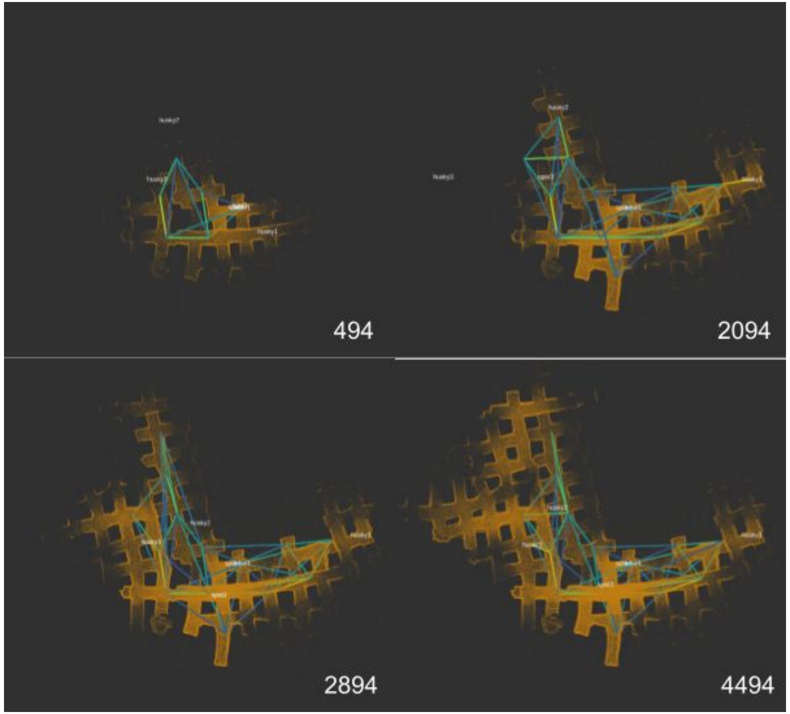


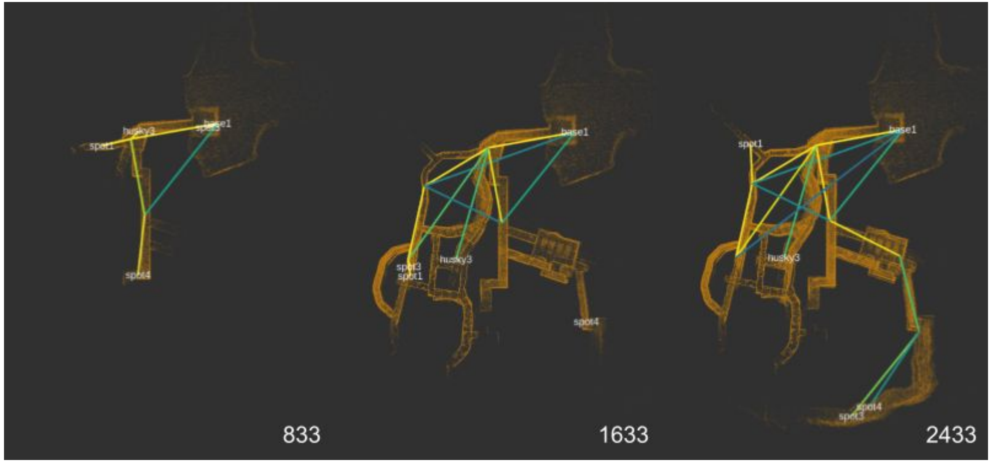
Cavernous limestone mine
13 dropped radios
300m x 300m, marker size = 10



Final competition course
6 dropped radios
60m x 60m, marker size = 2

CoSTAR Comms Performance (2)





Cavernous limestone mine

- 173m effective comm range
  23/12 Mbps data rates at base station

Final competition course

- 86m effective comm range
  35/17 Mbps data rates

Lessons learned

- Scaling the network is non-trivial
- Asking subsystems to transfer less data is useful but hard to enforce
- Debugging over ethernet was useful for determining if issues were logical or physical/mesh
- Important to be careful about resend policies at different layers

Unsolved problems

- A fully ROS2 solution had non-deterministic behavior
- Adaptive bandwidth limits per topic

Acknowledgements

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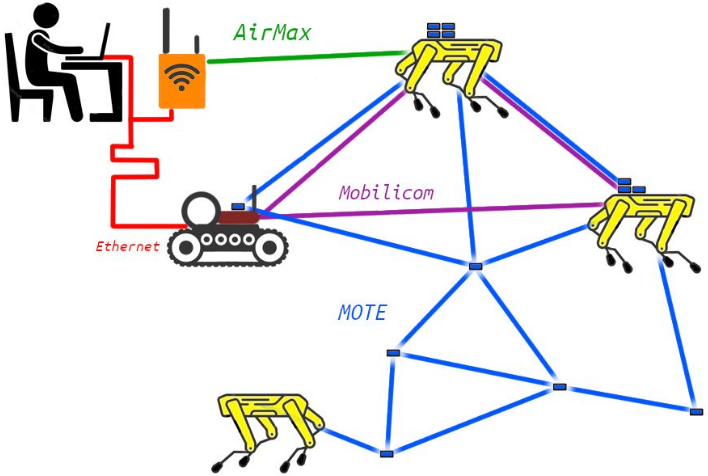
Logic Layer

- ROS Multi-master setup
- Tunnel: only nimbro_network
- Urban: nimbro for cameras and control
  Distributed DB for detections
- Finals: all custom Distributed DB

- Each robot (and base) had its own database synced with others
- Division between live topics (cams) and topics that required history (poses)
- Visibility graph of robots used to send only relevant information (CINR)

- MOTE network independent to DB
- High level commands to robots
- Was adding some information to the DB as well (positions, detections ect..)
  - These would be sent by DB anyway with images if robot reconnected
- DB limited the max bandwidth through Mobilicom network



Lessons learned

- Lots of disposable nodes are hard to manage - requires lot of manpower
- Check if your disposable comms are charged
- 3D print is tougher than one might think
- Most of electronics survives water at least short term
- Test all claim manufacturer makes in the conditions it is going to be used before fully implementing
- VLAN on switches can have different implementations
- Testing is the key, everything works on paper
- Dumping all data to the network saturates it
- Introspection is a key to be as early as possible with warnings and checks (diagnostics)

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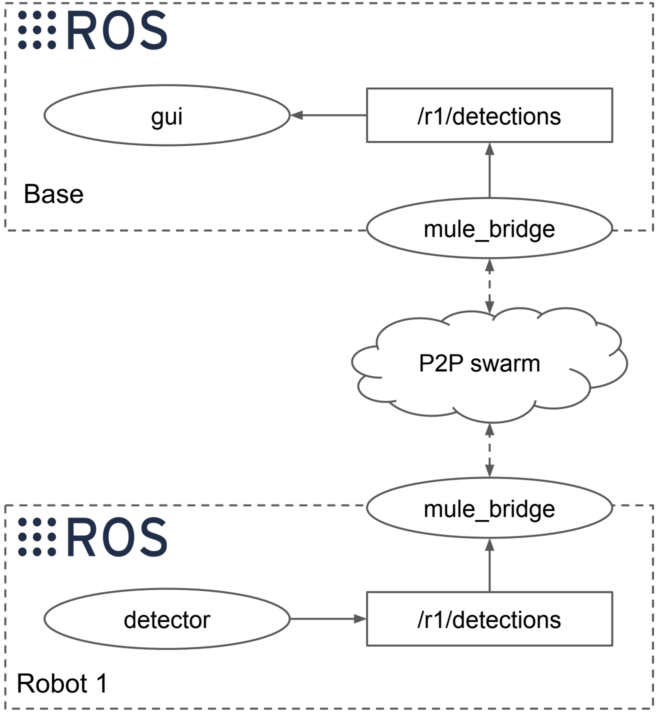
Logical Layer

Design:

- Multi-master, P2P, disruption-tolerant
- Persistent QoS: indirect, fully-reliable
- Volatile QoS: direct, best-effort
- Compression, heartbeats, multiplexing
- Python 3, (Py)ZMQ, Tornado, Sqlite, Zlib
- TCP/IP for congestion, prioritisation, tooling



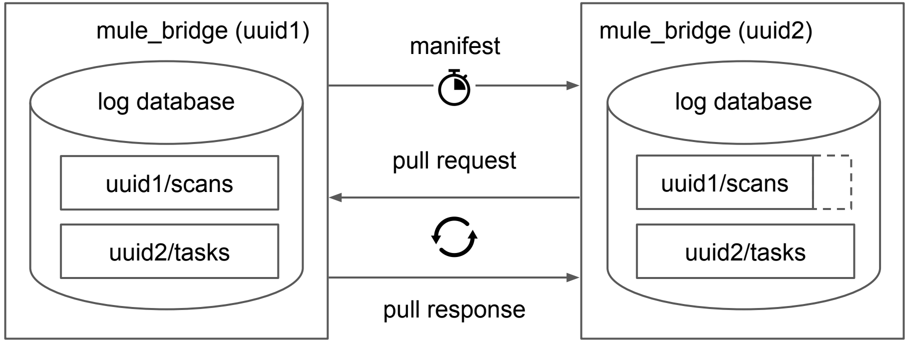
Logical Layer

Persistent:

- Append-only log replication
- Truncation for non-incremental data
- Multicast manifest
- Pull-based sync (w/ response size limit)
- >100Mb/s max throughput
- Used for detections, mapping, tasks

Volatile:

- Thin wrapper around ZMQ PUB/SUB
- Heartbeats, tuned timeouts
- Used for robot status, teleop, video



Manifest

Owner	Log	Trunc	Tail
uuid1	maps	true	25
uuid2	tasks	false	10

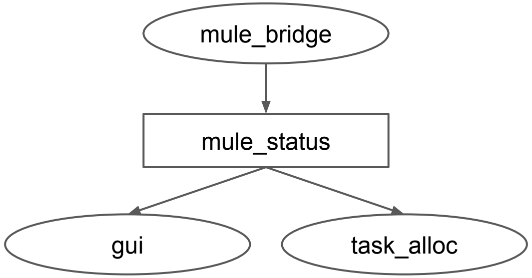
Logical Layer

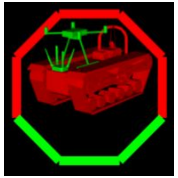
Autonomy:

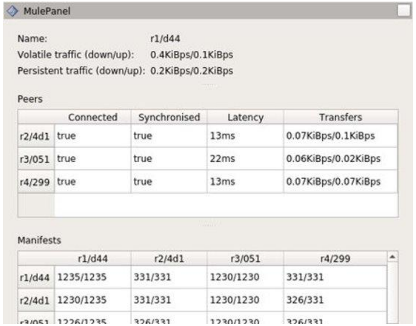
- Live info for autonomy, operator GUI
- Sync "lag" metric per-peer, up/down
- Task-allocation creates sync-tasks
- Homing navigation until sync or "steal"
- Any robot can "steal" sync-tasks and be the data-mule

Overlay:

- Discovery through multicast
- Partition ID (e.g. separate fleets)
- Edge pruning (e.g. sync along MST)







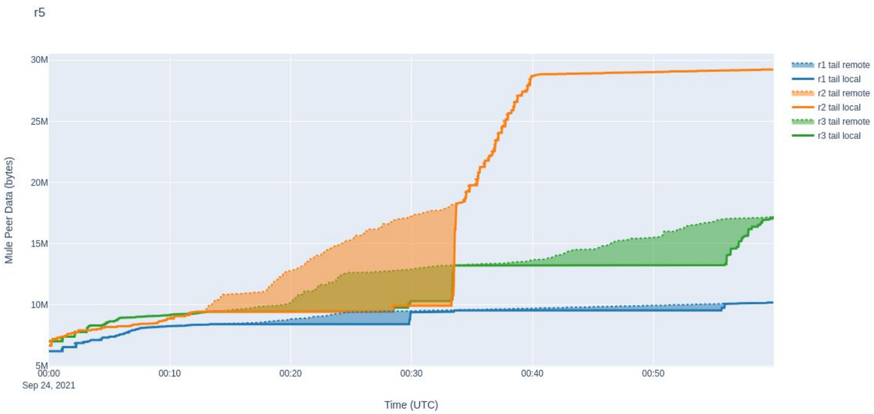
	Connected	Synchronised	Latency	Transfers
r2/4d1	true	true	13ms	0.07KiBps/0.1KiBps
r3/051	true	true	22ms	0.06KiBps/0.02KiBps
r4/299	true	true	13ms	0.07KiBps/0.07KiBps

	r1/d44	r2/4d1	r3/051	r4/299
r1/d44	1235/1235	331/331	1230/1230	331/331
r2/4d1	1230/1235	331/331	1230/1230	326/331

Logical Layer

Pros/Cons:

- + Drops in to existing ROS systems
- + Comms-informed autonomy
- + Open-source release coming soon*
- – Scaling limits



Lessons Learned:

- Hard for operator to use all information
- Libraries/tools outside ROS ecosystem

* github.com/csiro-robotics/mule_bridge

Thanks!

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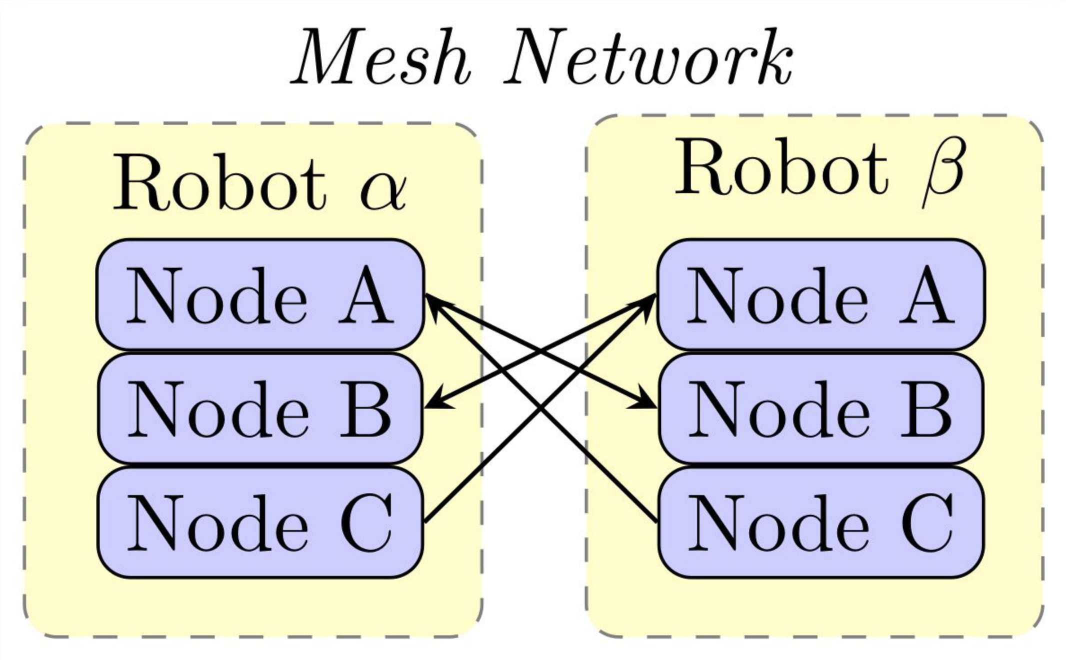
Initial Logical Solution: *fkie_multimaster*

- Discovery via multicast
- Individual nodes unaware of each other
- ROS1 ecosystem

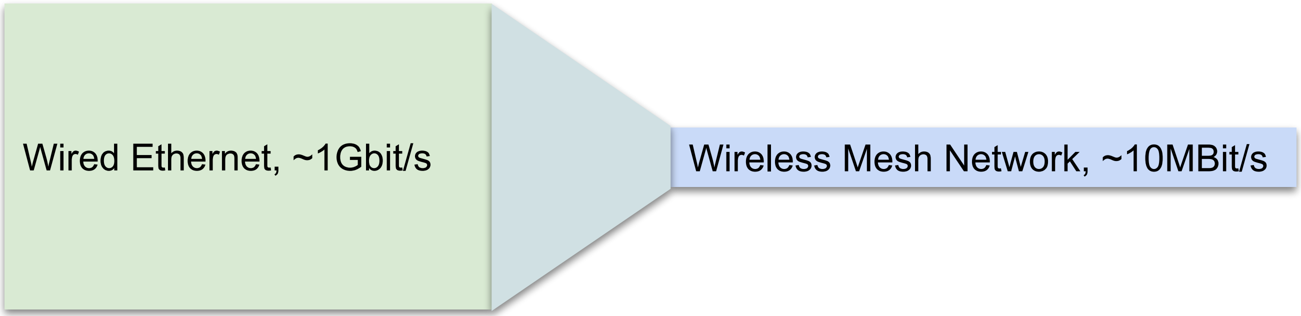


Problems:

- Reliance on TCP transport
- No prioritization

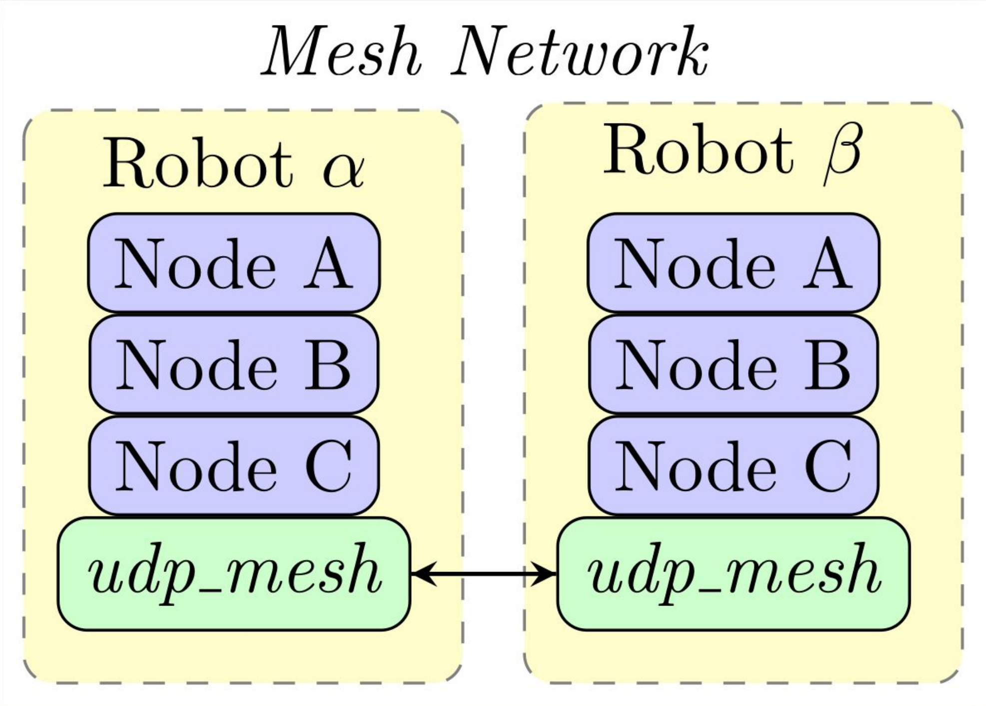
Observed Challenges

- Limited to ROS1 and Python2 as a dev env
- Link saturation with low-priority data
- Research lab mindset (bandwidth-aware software design)

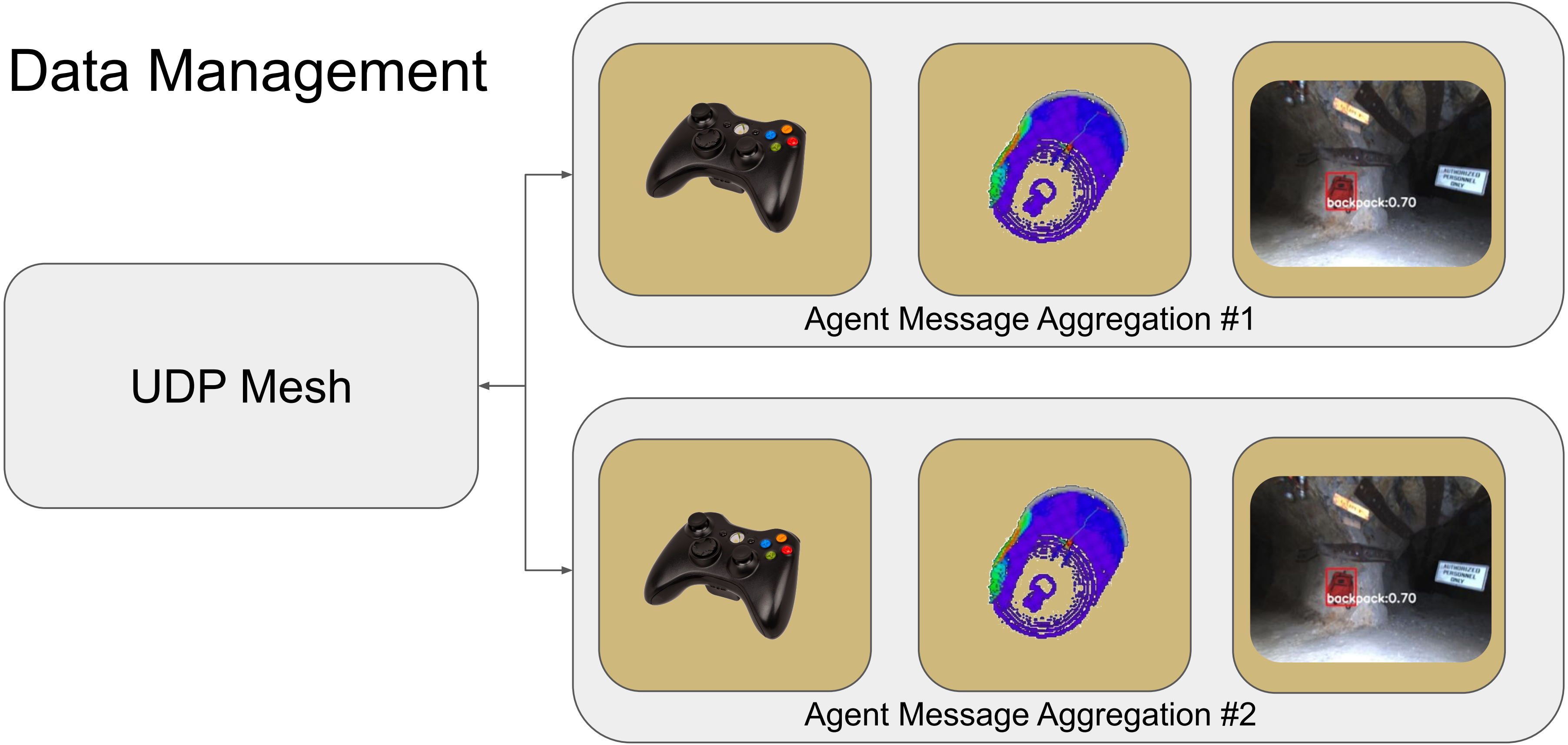


Adding Prioritization Over Unreliable Networks: *udp_mesh*

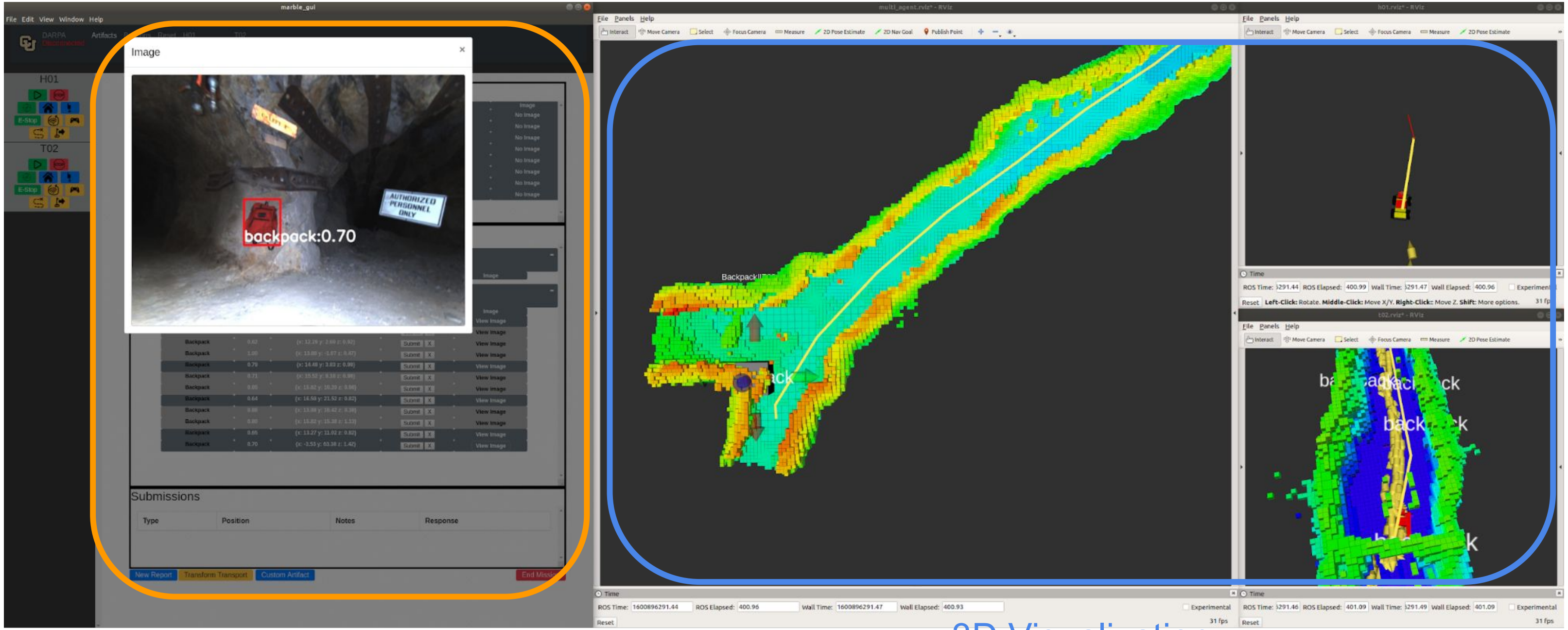
- Python layer 3 node to manage inter-robot data flow
- Provides:
    - Discovery
    - Name Resolution
    - Reliable Transport over UDP
    - Data Prioritization
    - Link Quality Estimate
    - ROS1 Message Encapsulation



Data Management



Human Operator View



Artifact Reports

3D Visualization

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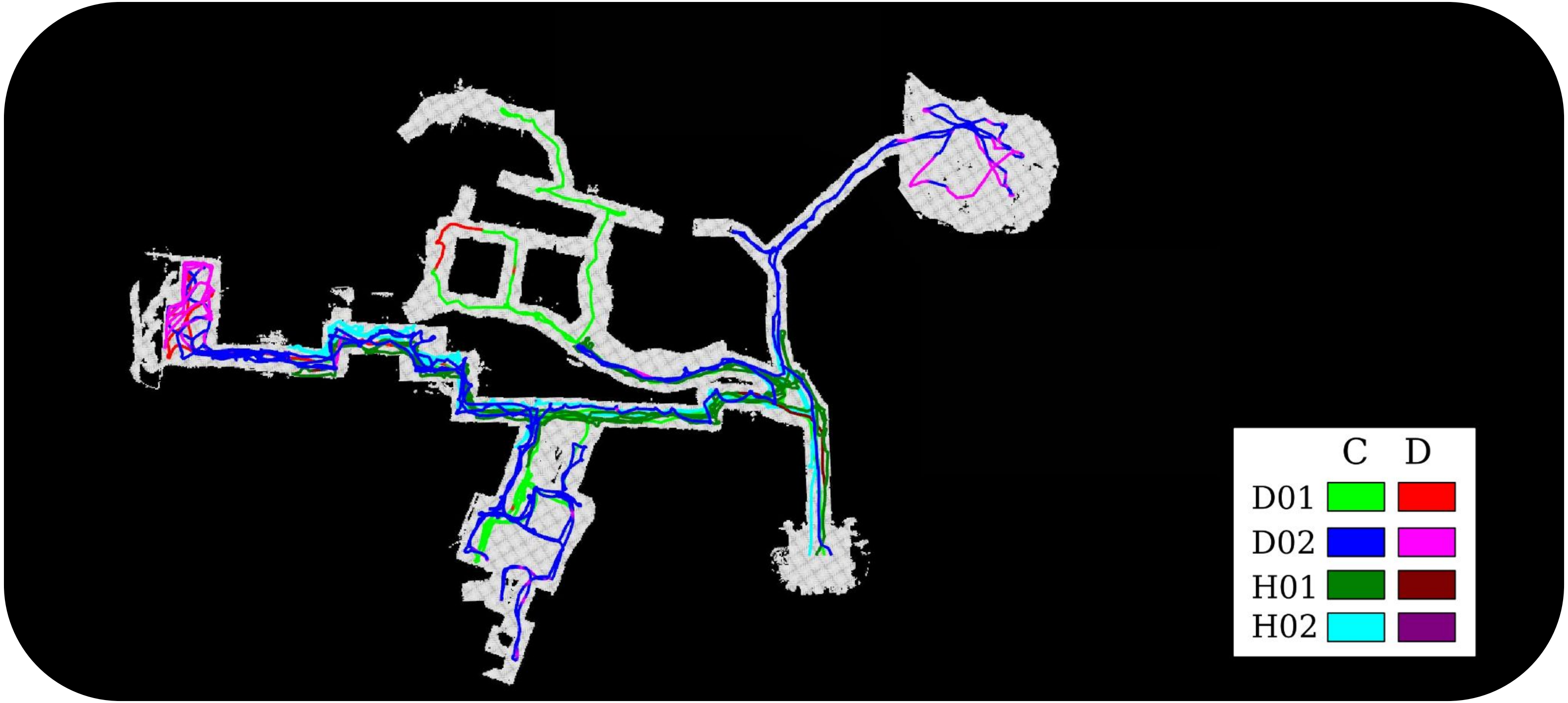
Performance



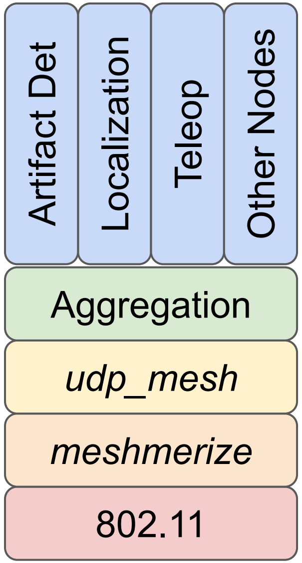
Lessons Learned

Pro:

- Enabled fine-tuning of data flow via priorities
    - Adjusting comm posture by adding FPV for finals

Con:

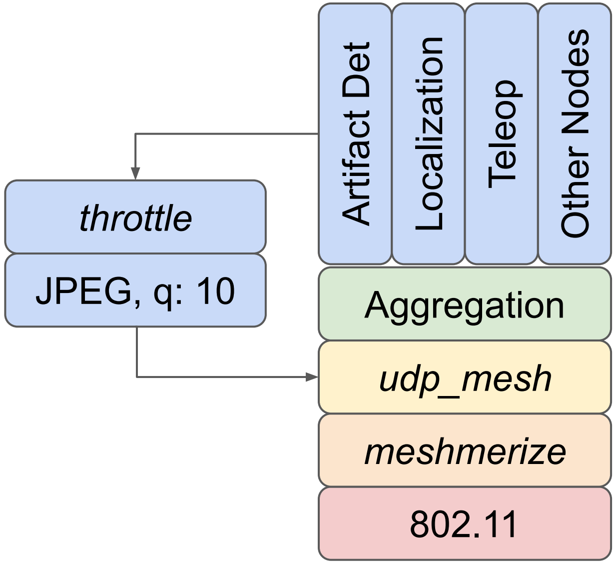
- Lean development team
- Isolation between layers leads to duplication and delays
    - Multiple levels of heartbeat and online detection
- Aggregation is tightly coupled to message definitions



Adding FPV

Wiring camera source imagery to *udp_mesh*

- Throttle to 1Hz
- JPEG compression, quality 10
  - ~10kB/s/robot
- Transmit as lowest priority data



Limitations:

- Only usable when in comm range

Takeaways

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Takeaways: Physical Layer

- Multiple form factors enables flexibility
- Effective management tools are required when scaling networks
- Open source software enables greater form factor flexibility but requires subject matter expertise
- Commercial solutions provide robustness but may also need to be adapted
- Height is might (with limits) for beacon performance

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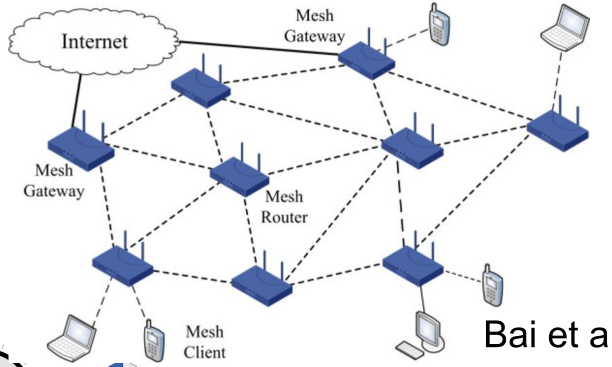
Takeaways: Mesh Layer

- Layer 2 meshing provides configurability and implementation convenience
- Developing custom mesh routing algorithms is resource intensive and purchasing a routing solution is a viable alternative
- Management and visualization tools are key to understanding network characteristics
- Fast reconnect times can take advantage of ephemeral conditions



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Takeaways: Logical Layer

- System data needs to be optimized to fit the communication network (not the other way around)
- Prioritization and rate limiting are required to prevent link saturation
- Multiple options exist for interfacing between ROS1/2 and custom code

ROS

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Considerations for Wider Applications

- RF permeability of environment
- Data needs by throughput and latency
- Radio / integration budget
  - Don’t forget the rest of the system!
- Balance between reconnection speed and optimal mesh routing
- Regulatory limitations (or lack thereof)
- Scalable configuration management

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