

Aerial–Ground Mesh Networking System for Wilderness Search and Rescue

Instituto Superior Técnico
ElectroCap (PIC1)

Team (students & advisors)

Students

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Advisors

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Problem definition

- ▶ Terrain and vegetation split ground teams into disconnected mesh partitions.
- ▶ Partitioned teams lose route continuity, voice coordination, and command visibility.
- ▶ Aerial elevation is required to restore connectivity when ground placement cannot bridge obstacles.
- ▶ Required operator workflow: detect partition → guide UAV positioning → verify PTT voice restoration.

Engineering objective

Implement UAV-assisted topology repair in a closed offline tactical mesh with measurable reconnection behavior and operator-visible evidence.

System engineering scope

Novelty is end-to-end implementation and demonstration (UAV-assisted repair, guidance workflow, acceptance evidence), not inventing a new routing protocol.

Solution beneficiaries

Direct beneficiaries

- ▶ Firefighters
- ▶ Police/SAR units
- ▶ Field teams
- ▶ Command post operators

Final beneficiaries

- ▶ Missing persons and casualties
- ▶ Responder safety during operations

Technological solution

- ▶ Ground mesh nodes + UAV relay node for topology repair.
- ▶ Open networking stack (Wi-Fi AP + BATMAN-adv) with local PTT/map/monitoring services.
- ▶ Operator-in-the-loop guidance software suggests UAV move direction and altitude band from live local telemetry.
- ▶ Local services: PTT voice, map/position view, monitoring dashboard.
- ▶ Validated platform: hovering multicopter UAV carrying a self-powered relay payload (no flight-controller integration).
- ▶ Closed offline tactical mesh with no external infrastructure dependency.

Design principle

Simple, robust, repeatable deployment with deterministic operator steps and measurable acceptance tests.

Networking & software stack

Networking stack

- ▶ User access: Wi-Fi AP on Team nodes (SSID + WPA2/WPA3).
- ▶ Mesh backbone: BATMAN-adv (L2) over 2.4 GHz Wi-Fi.
- ▶ Addressing: single L2 domain with per-node roles; fixed service IP on Command.
- ▶ Service discovery: mDNS/DNS (offline).
- ▶ Traffic handling: simple QoS (prioritize voice) using 'tc'/'iptables' on the local mesh.

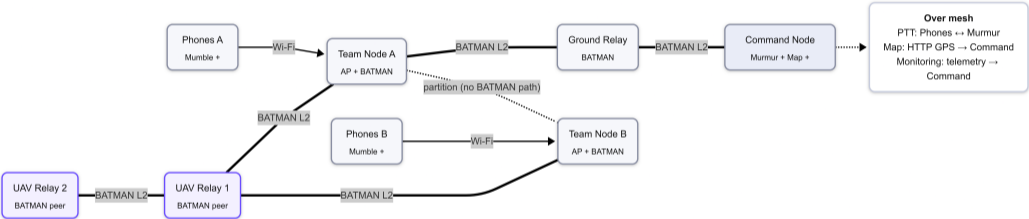
Software/services

- ▶ PTT voice: Murmur (server) on Command + Mumble client on phones.
- ▶ Map/position: local web dashboard (Leaflet or equivalent) with GPS upload endpoint.
- ▶ Monitoring/logging: node/link status, BATMAN originators, RSSI/SNR, uptime, battery logs.
- ▶ Automation: reproducible configs (OpenWrt UCI scripts / Ansible / shell) and one-command bring-up.
- ▶ Data capture: structured logs exported for the test report.

Why this stack

Simple, debuggable, repeatable offline implementation.

System architecture



Component integration

Node role	Network functions	Services & agents
Command	BATMAN-adv peer, fixed service IP, route/health aggregation	Murmur server, web map/dashboard, log collector, Guidance Engine, admin UI
Team node	Wi-Fi AP for users, BATMAN-adv, QoS rules for voice	Telemetry Agent (GPS + link metrics), local AP management scripts
Ground relay	BATMAN-adv forwarding bridge, no user AP	Telemetry Agent, link/uptime telemetry exporter
UAV relay	BATMAN-adv relay bridge, fast boot-to-mesh procedure	Telemetry Agent, boot checklist for hovering multicopter payload

All services are local; closed offline network.

Architecture addendum: guidance and telemetry blocks

- ▶ **Telemetry Agent (all nodes):** publishes GPS position + RSSI/SNR/TQ + node health to Command over the local mesh.
- ▶ **Guidance Engine (Command/laptop):** consumes telemetry, computes recommended UAV move direction and altitude band, and updates link-margin score.
- ▶ **Operator interface output:** arrow/direction, recommended altitude band, and concise “PTT margin” summary for the pilot/operator.
- ▶ **Flight control boundary:** UAV piloting stays manual; no flight-controller integration.

Hardware and telemetry

Telemetry signals collected

- ▶ RSSI/SNR per link and per route segment.
- ▶ BATMAN originators and next-hop changes over time.
- ▶ Packet loss/latency probes between command and team nodes.
- ▶ Battery runtime traces (voltage/current/runtime).
- ▶ GPS tracks from field teams and key relay positions.
- ▶ Reconvergence timestamps (partition detect, UAV join, route restore, PTT restore).

Data products for reports

- ▶ Coverage maps (RSSI/SNR vs location).
- ▶ Route-stability timelines and outage/recovery event tables.
- ▶ KPI plots for reconvergence, latency, and packet delivery.

Prototype hardware stack

Ground node (each)

- ▶ OpenWrt-capable router/SBC with 2.4 GHz Wi-Fi.
- ▶ External antenna: 2.4 GHz omni, vertical polarization.
- ▶ Connector chain: SMA/RP-SMA adapters + pigtailed as needed.
- ▶ Mounting: small mast/clamp/tripod/zip ties.
- ▶ Power: USB power bank ($\geq 20,000$ mAh) + short USB cable.
- ▶ Instrumentation: inline USB power meter or measured current-draw procedure.
- ▶ GPS source: phone GPS upload.
- ▶ Optional altitude source: barometer/altimeter.

UAV payload

- ▶ Validated platform: hovering multirotor UAV carrying a self-powered relay payload (no flight-controller integration).
- ▶ Mesh node + short/lightweight 2.4 GHz antenna.
- ▶ Self-powered battery pack sized for ≥ 30 min.
- ▶ Payload power measurement method: inline voltage/current logger during mission tests.
- ▶ Mounting bracket + vibration isolation + safe antenna clearance.
- ▶ Total payload mass target < 500 g.

Node count

Command (1), Team nodes (2), Ground relay (1), UAV relay (1)

Operational constraints (explicit)

- ▶ Validated UAV platform: hovering multirotor, self-powered payload, no FC integration.
- ▶ Payload mass < 500 g (including mount + power).
- ▶ Boot-to-mesh ≤ 60 s from power-on.
- ▶ UAV mission window ≥ 30 min (battery sized accordingly).
- ▶ 2.4 GHz band initial; external antenna vertical polarization.
- ▶ Safety/operations: defined takeoff/landing procedure + keep-away distance from personnel.
- ▶ No external infrastructure permitted (closed offline network).

Deployment workflow (operator procedure)

1 — Bring up command and services

- ▶ Power command node
- ▶ Confirm PTT/map/monitoring status

3 — Detect partition event

- ▶ Topology table split observed
- ▶ Ping + PTT fail between teams

2 — Deploy ground nodes

- ▶ Position team nodes and ground relay
- ▶ Confirm baseline routes and voice path

4 — Launch UAV repair

- ▶ Follow dashboard guidance (direction + altitude band + link margin score)
- ▶ UAV joins mesh and closes partition
- ▶ Route, ping, and PTT recover; operator verifies voice audibility

UAV Positioning Guidance (Operator-in-the-loop)

- ▶ Ground and relay nodes publish local telemetry: GPS + RSSI/SNR + BATMAN TQ (+ optional RTT/loss probes).
- ▶ Command-side Guidance Engine computes recommended UAV move using weakest-link margin logic for required route segments.
- ▶ Pilot remains fully manual; software does not command the flight controller.
- ▶ Guidance output is intentionally simple for field use:
 - ▶ Arrow/direction to move relative to current UAV position
 - ▶ Recommended altitude band (example: “increase to 35–45 m AGL”)
 - ▶ Link-margin score summary and PTT status (OK/FAIL)
- ▶ Acceptance check: before UAV positioning, PTT fails across partition; after guided positioning, PTT is restored and audible.

Multi-team & multi-UAV operation

- ▶ Scaling model: each team has a Team Node; partitions appear when ground links drop below quality thresholds.
- ▶ UAV relays act as standard BATMAN peers; multiple UAVs extend coverage by forming an aerial chain (UAV-UAV mesh).
- ▶ UAV piloting remains manual; Command provides operator guidance from live telemetry only.
- ▶ Telemetry inputs: RSSI/SNR per UAV link, BATMAN TQ + originator visibility, packet loss/RTT probes.
- ▶ Deterministic rule: define required links, compute link-margin score per candidate position, move UAV to maximize the weakest required link.
- ▶ Spacing emerges from threshold compliance: keep Team↔UAV and UAV↔UAV hops within pass/fail limits shown on the dashboard.
- ▶ Acceptance evidence: thresholds met → routes restored → stable end-to-end PTT.

Competitors / previous work and engineering gaps

Named competitors / references

- ▶ ResponDrone
- ▶ Persistent Systems
- ▶ Rajant
- ▶ goTenna-like off-grid mesh
- ▶ Elsieht-like aggregation

Competitor-specific gaps

- ▶ ResponDrone: focuses on drone support; lacks open repeatable offline PTT+monitoring kit with acceptance tests.
- ▶ Persistent Systems: strong MANET but proprietary/high cost; not reproducible commodity build.
- ▶ Rajant: industrial mesh, proprietary ecosystem; not designed for rapid SAR kit deployment with UAV repair proof.
- ▶ goTenna-like: messaging-centric; lacks live PTT + topology observability + mesh repair with UAV.
- ▶ Elsieht-like: connectivity aggregation oriented; not a closed offline network.

Technical challenges and mitigations

A) Software/networking challenges

- ▶ Reproducible BATMAN/OpenWrt configs; QoS under loss; offline service discovery.
- ▶ Mitigations: scripted configs, bench tests, acceptance harness.

B) Hardware/environment challenges

- ▶ Power autonomy vs performance; enclosure/weather/strain relief; antenna placement.
- ▶ Mitigations: power logging, simple ruggedization, deployment kit.

C) RF/field challenges

- ▶ Vegetation/terrain loss; intermittent links; determining node spacing + UAV hover altitude guidelines.
- ▶ Mitigations: walk tests, RSSI/SNR logs, spacing rules.

Partners, stakeholders, and interview outputs

Partner	Requested contribution
ANEPC	Scenario definition, mission constraints, drill realism feedback
GNR/UEPS	Field usability feedback for mountain SAR workflow
Portuguese Air Force	Airspace coordination and UAV operational constraints
Instituto de Telecomunicações	RF guidance, propagation interpretation, measurement support
UAV industry	Payload integration best practices and mounting reliability checks

Requirements

- ▶ Partition detection procedure ≤ 20 s.
- ▶ UAV boot-to-mesh ≤ 60 s.
- ▶ Reconvergence ≤ 30 s after UAV joins.
- ▶ Deployment ≤ 10 min from transport state.
- ▶ Ground autonomy ≥ 8 h.
- ▶ Payload mass < 500 g.
- ▶ Scalability: supports ≥ 2 teams and ≥ 1 UAV relay; additional UAV relays integrate as standard mesh relays.

Testing and validation metrics: acceptance matrix

Objective proof	Pass criteria
Pre-UAV partition proof	No route; ping fails; PTT fails; topology table split.
Hard link thresholds validation	RSSI \geq -75 dBm, SNR \geq 20 dB, BATMAN TQ \geq 200/255, probe loss \leq 10%, median RTT \leq 50 ms (30 s window).
UAV entry timing	UAV relay joins mesh in \leq 60 s.
Post-UAV recovery proof	Route restored; ping succeeds; PTT succeeds.
Reconvergence timing	Recovery in \leq 30 s after UAV join.
Deployment timing	Full setup in \leq 10 min.
Autonomy run	Ground nodes operate \geq 8 h with logs.

Primary success criterion: fail before UAV, pass after UAV

Operational KPIs (demonstration layer)

- ▶ Time-to-detect partition event (targeted and logged from first route/PTT failure signal).
- ▶ Time-to-restore PTT after UAV reaches guided position.
- ▶ Maximum separation distance where restoration still succeeds under test conditions.
- ▶ Setup time from transport state to working closed offline network.
- ▶ UAV mission time achieved with payload battery under relay operation.

Operational success demonstration

Before UAV positioning: PTT across partition fails. After guided UAV positioning: PTT works and operator confirms audibility.

Work plan

- ▶ **Phase 1 (Late Feb–Early Mar):** refine proposal, stakeholder interviews, requirement freeze.
- ▶ **Phase 2 (Mar):** material procurement and bench setup.
- ▶ **Phase 3 (Early Apr):** integration checkpoint and architecture lock.
- ▶ **Phase 4 (Late Apr–Mid May):** subsystem development and system integration.
- ▶ **Phase 5 (Mid–Late May):** functional prototype tests and defect closure.
- ▶ **Phase 6 (Early Jun):** communication assets and final demonstration package.

Course calendar mapping (deliverables)

Milestone date	Concrete output
3-Mar-2026	Revised proposal deck + clarified subsystem boundaries and responsibilities.
10-Mar-2026	Interview blog report with stakeholder summaries and extracted requirement candidates.
17-Mar-2026	Requirements list baseline (functional, operational, and acceptance criteria).
24-Mar-2026	BOM freeze with selected models or documented candidates and procurement plan.
7-Apr-2026	Mid-program pitch final (architecture, validation plan, risks, schedule).
20-Apr-2026	Prototype development start (branch/repo structure, bring-up scripts, bench rigs).
19-May-2026	First functional prototype (offline mesh + PTT + basic telemetry + UAV relay join).
26-May-2026	Prototype + tests done (acceptance matrix + operational KPI datasets).
2-Jun-2026	Communication materials (user workflow docs, visuals, draft video/poster assets).
9-Jun-2026	Final materials package (report, slides, manuals, reproducibility artifacts).
15-Jun-2026	Discussions and final technical review notes integrated.
27-Jun-2026	ElectroDay live demo package and field-ready deployment checklist.

Member responsibilities (1/3)

Pedro Gonçalves — Networking + integration

- ▶ Offline mesh bring-up (OpenWrt + BATMAN-adv) reproducible configuration package.
- ▶ Partition detection logic + event logging (pre/post UAV evidence).
- ▶ End-to-end system integration (network + services + telemetry agents).
- ▶ Integration test plan + final integration sign-off checklist.

Henrique Ferreira — Voice + User Workflow Lead

- ▶ PTT service deployment (server + clients) packaged for offline operation.
- ▶ User onboarding workflow (phone connect, PTT join, troubleshooting steps).
- ▶ Voice quality test procedure + dataset (before/after UAV recovery).
- ▶ Operator SOP draft → final (deployment steps + safety + pass/fail checks).

Member responsibilities (2/3)

Leonardo Catarino — UAV Payload & Flight Ops Lead

- ▶ UAV payload mechanical integration (mount, vibration isolation, antenna placement).
- ▶ Payload power system + runtime validation (\geq 30 min target).
- ▶ Flight operations checklist + safety procedure (takeoff/landing + keep-away).
- ▶ Air-to-ground link characterization logs for guidance calibration.

Vicente Ferreira — Field Hardware & Deployment Lead

- ▶ Ground node ruggedization/enclosure + mast/tripod mounting kit.
- ▶ Field deployment kit assembly (cabling, antennas, labels, spares).
- ▶ Outdoor setup timing validation (\leq 10 min goal) + reliability notes.
- ▶ Mechanical integration documentation (photos, diagrams, build notes).

Member responsibilities (3/3)

Eduardo Curião — Power & Autonomy Lead

- ▶ Power budget model for ground nodes + payload (spreadsheet + assumptions).
- ▶ Instrumentation harness (voltage/current logging method) for ground + UAV payload.
- ▶ Autonomy run tests (≥ 8 h ground) + plots/tables.
- ▶ Battery safety + charging/handling guidelines for team operations.

Dylan Félix — Monitoring + Guidance Software Lead

- ▶ Node telemetry agent (GPS + link metrics) and collection pipeline (offline).
- ▶ Command dashboard UI (map + status + “PTT OK/FAIL” indicators).
- ▶ UAV positioning guidance engine (recommend direction/altitude using telemetry).
- ▶ Acceptance test harness automation + demo-mode “one-button” bring-up scripts.

Per-member schedule by phase

Member	Late Mar	Feb–Early Mar	Mar	Early Apr	Late Apr–Mid May	Mid–Late May	Early Jun		
Pedro Gonçalves	Routing doc	baseline	Mesh script set v1	Integration plan v1	test	Partition code	pipeline	Reconvergence evidence logs	Network appendix final
Henrique Ferreira	PTT workflow draft		PTT server config pack	Operator SOP v1		QoS tuning scripts		Voice KPI dataset	User guide final
Eduardo Curião	Power model draft		Instrumentation rig build	Telemetry schema v1		Autonomy run scripts		Battery dataset + plots	Power report final
Vicente Ferreira	Enclosure requirements note		Node kit BOM + CAD	Assembly checklist v1		3-node assembly batch		Robustness test logs	Hardware manual final
Leonardo Catarino	Payload constraints sheet		Mount design prototype	Flight checklist v1		UAV relay integration build		Link characterization logs	UAV ops annex final
Dylan Félix	CI/build draft	workflow	Automation scripts v1	Monitoring mockups	UI	Integration release	branch	Acceptance harness logs	Final package manifest

Conclusion

- ▶ We will deliver a deployable, closed offline mesh kit where UAVs are essential for topology repair in partitioned SAR scenarios.
- ▶ The implementation focus is operational: detect partition, guide manual UAV repositioning, and verify restored end-to-end PTT audibility.
- ▶ By June 2026, success is demonstrated with acceptance evidence and operational KPIs, not a new routing protocol.
- ▶ Scope is realistic for a 6-student final-year team through explicit subsystem ownership, milestone mapping, and reproducible test procedures.

Final deliverables

- ▶ Working prototype
- ▶ Test report
- ▶ Deployment manual
- ▶ Website/blog
- ▶ Demo video
- ▶ Poster