Design of a Persistent Aerial Relay Node (PARN)

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ABSTRACT

This paper presents a focused investigation into advanced computational and architectural strategies that enable Unmanned Aerial Vehicles (UAVs) to function as Persistent Relay Nodes (PRNs) in disaster-affected regions where terrestrial communication networks often fail. During large-scale emergencies, long-endurance aerial communication relays become essential; however, conventional battery-powered UAVs are unable to meet these endurance requirements. To address this gap, the study introduces the Persistent Aerial Relay Node (PARN), a Tethered UAV (T-UAV) platform designed to provide uninterrupted communication capability through a hybrid power architecture. The system integrates continuous high-voltage tethered power with a 6S 8000 mAh LiPo emergency battery, ensuring operational resilience during unexpected tether failures.

Comprehensive modelling of the 4.98 kg UAV platform indicates a hover power requirement of 900 W, with the onboard battery supporting 11.84 minutes of emergency autonomous flight. To ensure secure, interference-resistant data transmission, the PARN incorporates a fiber-optic uplink, providing jam-immune communication suitable for high-risk environments. The system further enhances positional stability by integrating Real-Time Kinematic (RTK) GPS with Visual Inertial Odometry (VIO), achieving centimetre-level station-keeping accuracy that compensates for the limitations of standard UAV avionics.

The proposed architecture strengthens emergency response infrastructures by enabling persistent, high-reliability aerial communication relays. In alignment with India's National Disaster Management Plan (NDMP) and Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure), this work offers a practical, technology-driven solution capable of supporting critical communication networks during disaster relief operations. Overall, the PARN system demonstrates a powerful approach for enhancing emergency communication resilience through robust UAV-based relay technology.

Keywords: Persistent Relay Node, Unmanned Aerial Vehicle, Disaster Communication, Trajectory Optimization, IoT Networks.

INTRODUCTION

The operational effectiveness of disaster response including comm&, control, & coordination efforts is inextricably linked to the availability of robust communication infrastructure. Across global disaster zones, including areas affected by earthquakes, hurricanes, & severe snowstorms, terrestrial telecommunication systems are frequently among the first critical systems to fail. These communications blackouts severely impede the flow of real-time data to first responders, directly influencing mortality rates during the crucial search & recovery phases. [1-3]

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Traditional communication networks, built upon stationary ground-based towers & complex power grids, are inherently inflexible & lack the resilience required to operate effectively in dynamic, compromised environments. The growing demand for public safety communications mandates a rapidly deployable, high-capacity, & long-endurance solution capable of maintaining connectivity over large, affected geographical areas.[5]

Unmanned Aerial Vehicles (UAVs), particularly multirotor platforms, have been widely recognized as a promising technology for temporary connectivity solutions, offering utility in situational awareness through aerial mapping & in search & rescue operations. However, the intrinsic limitation of conventional battery-powered multirotor lies in their severely restricted flight autonomy, typically offering only 20 to 40 minutes of operational time. This constraint necessitates frequent battery replacement or recharging, rendering standard UAVs unsuitable for missions that require sustained, continuous communication service over hours or days, which is often essential in prolonged disaster scenarios. [5-7]

The Persistent Solution: T-UAV Architecture & Advantages

To overcome this intrinsic endurance problem, the Persistent Aerial Relay Node (PARN) utilizes a Tethered UAV (T-UAV) architecture, defining it as a fixed-position aerial platform dedicated to continuous communication relay. The T-UAV configuration provides three distinct, critical advantages for persistent operation:

1. **Extended Autonomy:** The tether serves as a lifeline, delivering stable, continuous power from a ground station, fundamentally eliminating the battery-imposed endurance constraint. This enables persistent operation for hours or days, far surpassing battery-only platforms.

2. **Robust & Secure Data Link:** The tether integrates a high-bandwidth fiber optic link, which is immune to electromagnetic interference (EMI), signal degradation, & interception. This capability transforms the PARN into a strategic asset for transmitting sensitive comm&-&-control (C2) or reconnaissance data, fulfilling paramount security requirements.

3. **High-Altitude Coverage:** Continuous power enables sustained high altitude (e.g., 100 meters), maximizing the Line-of-Sight (LoS) probability to ground users. This effectively extends geographical coverage & allows the PARN to function as a rapidly deployable, temporary cellular site over affected terrain.

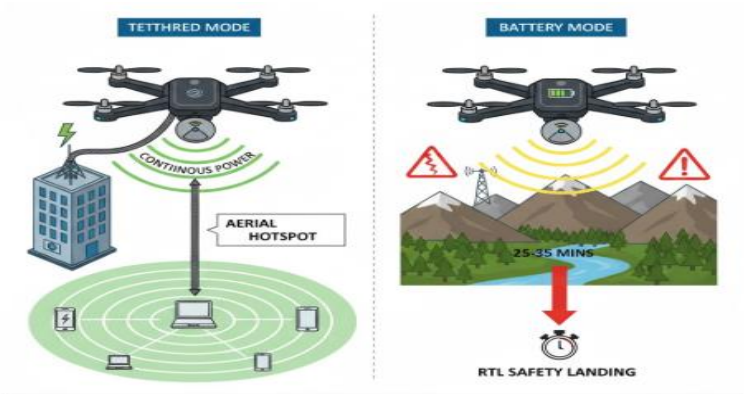

Figure 1.1: Design of a Persistent Aerial Relay Node

Strategic Alignment: SDG 9 & India's NDMP Framework

The development of the PARN directly addresses the global mandate to develop resilient infrastructure, aligning with the United Nations Sustainable Development Goal 9 (SDG 9): Build resilient infrastructure, promote sustainable industrialization & foster innovation. By providing a resilient, temporary communication network secure against both physical & electronic failure, the PARN fulfils the requirement for reliable infrastructure during crises (Goal 9.1). Furthermore, this system supports India's National Disaster Management Plan (NDMP), directly addressing the policy's explicit call for secure & wireless satellite-based communication equipment for technological enhancement in disaster response & risk reduction (DRR).

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LITRATURE SURVEY

Tran, D., Nguyen, V., Gautam, S., Chatzinotas, S., Vu, T., & Ottersten, B. (2020). UAV Relay-Assisted Emergency Communications in IoT Networks: Resource Allocation & Trajectory Optimization.

This paper proposes a UAV relay-assisted IoT communication system using full-duplex (FD) technology to improve data collection efficiency & reduce latency in time-sensitive & emergency scenarios. It jointly optimizes UAV trajectory, power, bandwidth, & storage under latency & power constraints to maximize the number of served IoT devices. An iterative algorithm based on the inner approximation (IA) framework is developed to solve the complex optimization problem efficiently. Simulation results show that the proposed FD-based design outperforms existing benchmark methods in terms of throughput, latency, & number of served devices, while half-duplex (HD) operation is more practical in simple scenarios.[1]

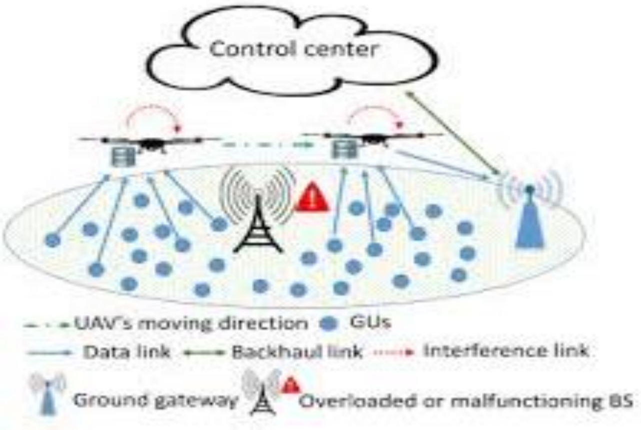

Figure 2.1: UAV Relay-Assisted Emergency Communications in IoT Networks

Tran, D., Nguyen, V., Gautam, S., Chatzinotas, S., Vu, T., & Ottersten, B. (2020). Resource Allocation for UAV Relay-Assisted IoT Communication Networks.

The literature on UAV relay-assisted IoT communication networks highlight the growing role of UAVs as aerial relays & data collectors to enhance coverage, reduce latency, & improve energy efficiency for IoT devices. Early studies focused on UAV deployment, trajectory design, & resource allocation to optimize data collection & energy consumption. Recent works have explored latency & Age of Information (AoI) optimization, emphasizing the importance of timely data delivery for emergency & real-time applications. Full-duplex (FD) technology has been introduced to increase spectral efficiency, though it brings challenges like self-interference management. However, most existing research focuses on either uplink or downlink optimization, neglecting joint latency & storage constraints. This approach significantly improves throughput & device coverage, providing a foundation for future research in multi-UAV & machine learning–based resource optimization systems.[2]

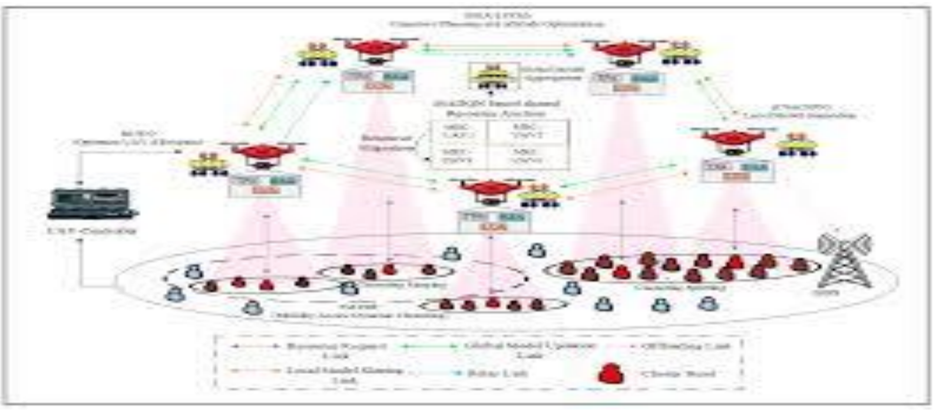

Figure 2.2: Resource Allocation for UAV Relay-Assisted

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Samir, M., Sharafeddine, S., Assi, C., Nguyen, T., & Ghrayeb, A. (2020). UAV Trajectory Planning for Data Collection from Time-Constrained IoT Devices.

UAV trajectory planning plays a key role in efficient & timely data collection from IoT devices, especially when devices have strict time or latency constraints. Earlier studies focused on optimizing UAV placement & coverage but often ignored real-time deadlines. Samir et al. (2020) addressed this by proposing an optimization framework that maximizes the number of IoT devices served within their time limits through efficient UAV trajectory & scheduling design. Using heuristic & dynamic programming approaches, the study showed that adaptive trajectory planning significantly improves data freshness & reliability compared to static or delay-unaware methods, making it highly relevant for time-critical IoT applications.[3]

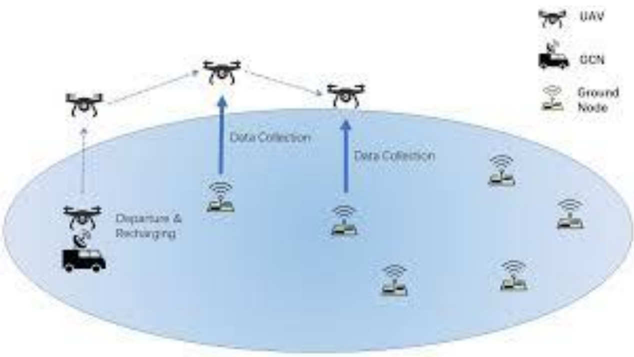

Figure 2.3: UAV Trajectory Planning for Data Collection from Time-Constrained IoT Devices

Nguyen, V., Sharma, S., Vu, T., Chatzinotas, S., & Ottersten, B. (2021). Efficient Federated Learning Algorithm for Resource Allocation in Wireless IoT Networks.

Nguyen et al. (2021) introduced an efficient federated learning (FL) algorithm for resource allocation in wireless IoT networks to enhance performance while reducing communication overhead & preserving data privacy. Unlike centralized methods, their decentralized FL approach allows IoT devices to collaboratively optimize bandwidth & power allocation without sharing raw data. The proposed framework achieves near-optimal resource management with lower latency & energy consumption, demonstrating the potential of FL for intelligent & scalable IoT network optimization.[4]

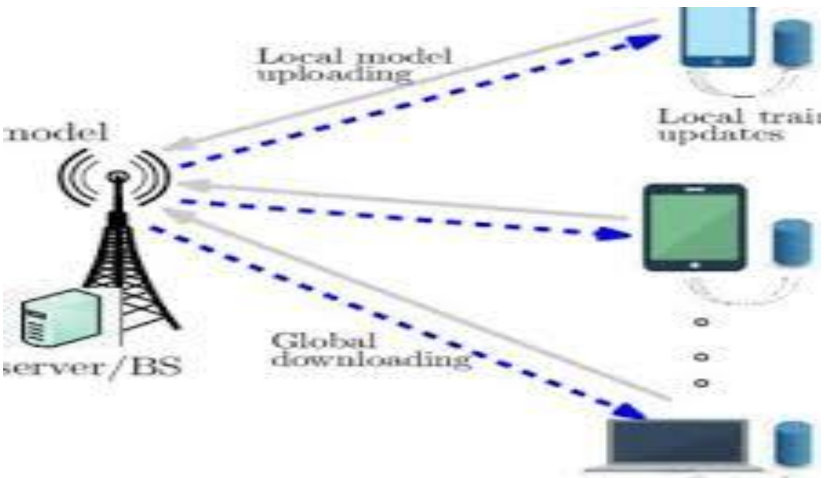

Figure 2.4: Resource Allocation in Wireless IoT Networks.

Do-Duy, T., Nguyen, L., Duong, T., Khosravirad, S., & Claussen, H. (2021). Joint Optimisation of Real-Time Deployment & Resource Allocation for UAV-Aided Disaster Emergency Communications.

They focused on enhancing communication reliability during disaster & emergency scenarios using UAV-assisted wireless networks. The study proposed a joint optimization framework for real-time UAV deployment & resource allocation to maintain network connectivity when terrestrial infrastructure is damaged or unavailable.

The authors formulated a dynamic optimization problem that considers UAV positioning, power control, & spectrum allocation to maximize network throughput & coverage under limited energy & time constraints. Using advanced algorithms, the proposed approach adapts UAV trajectories & resources in real time to changing network conditions. Simulation results showed that this joint optimization method significantly improves communication reliability, coverage, & resource utilization compared to static or single-objective strategies, making it highly effective for disaster recovery & emergency IoT communication systems. [5]

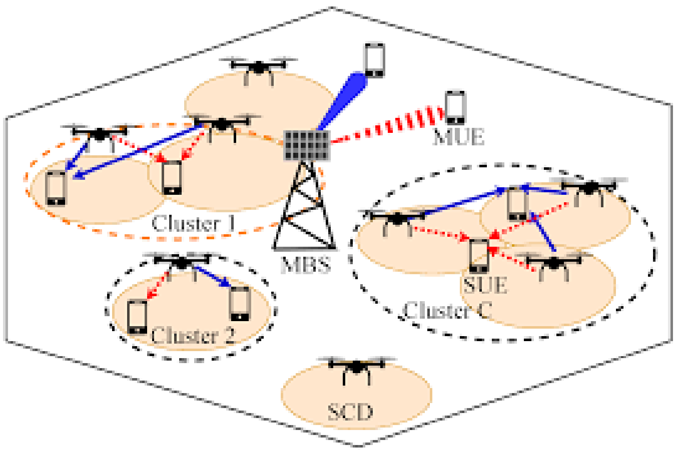

Figure 2.5: UAV-Aided Disaster Emergency Communications

Table 1: Comparison of Existing Research Works

Author & Year	**Focus Area**	**Method Used**	**Main Constraint**
Tran et al. (2020)	UAV relay-assisted IoT communication	Full-Duplex (FD) optimization	Latency, power, bandwidth, storage
Samir et al. (2020)	UAV trajectory for time-limited IoT data	Heuristic & dynamic programming	Time & deadline limits
Nguyen et al. (2021)	Resource allocation in IoT using Federated Learning	Federated Learning algorithm	Energy & communication cost
Do-Duy et al. (2021)	UAV-based disaster communication	Joint optimization of UAV deployment & resources	Energy, time, coverage

System Architecture & High-Voltage Power Strategy

Overview of the Tri-Segment Architecture

The Persistent Aerial Relay Node utilizes a robust tri-segment architecture engineered for high reliability & persistence.[1] This architecture comprises the Airborne Platform, the Tether Link, & the Ground Power Unit/Tether Management System (GPU/TMS).[15]

1. **Airborne Platform:** This is a heavy-lift quadcopter designed to stabilize the communication payload. Its core functions include propulsion, flight control, high-efficiency power conditioning (step-down conversion), & wireless data distribution via an onboard access point.[30]

2. **Tether Link:** The tether acts as the system's lifeline, integrating high-voltage (HV) electrical conductors & a high-bandwidth fiber optic cable. This dual-purpose link manages both the constant energy supply & the robust data uplink.

3. **Ground Power Unit (GPU) / Tether Management System (TMS):** The GPU includes the main power supply (converting grid or generator power to HV DC), battery charger, & data terminal (fibre-to-Ethernet conversion).[19] The TMS component controls the reeling, anchoring, & crucial tension management of the cable, which is critical for mitigating mechanical drag & preventing entanglement.[20]

Propulsion System Design & Static Modelling

3.2.1 Configuration & Mass Estimation

A quadcopter configuration (four rotors) was selected primarily for its mechanical simplicity & inherent weight efficiency.[16] However, this configuration introduces a significant design constraint: the absence of mechanical redundancy, meaning the failure of a single motor or Electronic Speed Controller (ESC) results in immediate flight termination.[17] This constraint mandates an extremely robust power system & rapid safety failover logic, partially addressed by the hybrid power architecture.[18]

The total static airborne mass (M_{drone}) was meticulously estimated based on component selection & payload requirements, totalling approximately 4.98 kg.[1]

Table 2: Estimated Mass & Static Power Budget for PARN Airborne Platform

Component/ Subsystem	Unit Mass (g)	Total Mass (g)	Average Power Draw (W)
BLDC Motor 5060 360kv	470 x 4	1880	N/A
ESC 60 Amps	60 x 4	240	N/A
Flight Controller (Pixhawk 2.4.8)	38 x 1	38	≈ 5
GPS (NEO M8N) + RX (FS+iA6B/10B)	100 x 1	100	≈ 3
Battery (6S 8000mAh)	520 x 1	520	0 (Stand by)
Onboard Power Conversion (DC-DC Converter + Failover Switch)	300 x 1 (Estimated)	300	≈ 20 (Conversion Loss)
Comm Payload	400 x 1 (Estimated)	400	≈ 25
Airframe	1500 x 1	1500	0
Total Airborne Mass (M_{drone})		4978 g (4.98 kg)	$P_{AV} + P_{PL} \approx 33$W

Thrust Requirements & Thrust-to-Weight Ratio (TWR) Modelling

The platform's primary performance constraint is its ability to maintain a stable, persistent hover while compensating for the combined forces of its own mass, the payload, & the dynamic contribution of the suspended tether mass M_{tether}.

The static thrust required to lift the drone airframe is:

$$F_{\text{static}} = M_{\text{drone}} \cdot g = 4.98\ \text{kg} \times 9.81\ \text{m/s}^2 \approx 48.85\ \text{N}$$

However, during operation, the propulsion system must also overcome the weight of the tether & any additional forces introduced by wind loading & tether drag, collectively represented as F_w. Therefore, the total thrust requirement is dynamic:

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$$F_{\text{total}} = F_{\text{static}} + M_{\text{tether}} g + F_w$$

To ensure stable control authority—particularly during high-altitude operation where wind disturbances are both significant & unpredictable—a conservative Thrust-to-Weight Ratio (TWR) of at least 1.5:1 is required.

Given a total hover mass of 5.48 kg (including tether load), the propulsion system must deliver:

$$T_{\text{required}} > 5.48\ \text{kg} \cdot 9.81\ \text{m/s}^2 \times 1.5 = 80.64\ \text{N}$$

With a quad-rotor configuration, each motor must reliably generate at least:

$$\frac{80.64\ \text{N}}{4} = 20.16\ \text{N}$$

This thrust margin is essential for precise control, sustained hover, & safe manoeuvring under adverse atmospheric conditions.

High-Voltage DC Transmission Rationale

A critical enabler of the Persistent Aerial Relay Node (PARN) architecture is the ability to transmit electrical power efficiently through the tether. Because the tether mass directly constrains both attainable altitude & available lift, minimizing conductor size is essential.

Quantitative Justification for HVDC

Transmission losses in the tether are governed by resistive heating:

$$P_{\text{loss}} = I^2 R$$

For a fixed power requirement, increasing the transmission voltage reduces current according to:

$$I = \frac{P}{V}$$

Thus, using High-Voltage Direct Current (HVDC) typically in the 400–800 V range reduces current dramatically, enabling the use of thinner, lighter-gauge conductors & minimizing tether mass.

For the predicted PARN hover power requirement of:

$$P_{\text{PARN}} = 900\ \text{W}$$

If the ground supply voltage is set to:

$$V_G = 400\ \text{V}$$

then the current drawn through the tether is:

$$I_G = \frac{900}{400} = 2.25\ \text{A}$$

For comparison, transmitting the same power at the drone battery's nominal voltage of 22.2 V would require:

$$I = \frac{900}{22.2} \approx 40.54\ \text{A}$$

This 18× reduction in current drastically decreases resistive losses & enables the tether to remain lightweight enough for high-altitude operation. The resulting efficiency improvements are a foundational requirement for long-endurance, 60–100 m persistent flight, where every gram of parasitic weight significantly degrades performance.

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Table 3: Tethered Power Transmission Strategy & Current Reduction

Parameter	HVDC (400V)	LVDC (22.2V)	Significance
Power Needed $\boldsymbol{P}_{\text{PARN}}$	900W	900W	Same power required for hover.
Transmission Voltage $\boldsymbol{V_G}$	400V	22.2V	Higher voltage reduces current.
Current Draw $\boldsymbol{I_G}$	2.25A	40.54A	Lower current → lighter cable.
Power Loss $\boldsymbol{P}_{\text{loss}} \propto \boldsymbol{I^2 R}$	Low	High	Less heat loss at high voltage.

Onboard DC-DC Conversion

Since the airborne platform operates at a 6S battery voltage (≈ 22.2 V), the incoming high-voltage power must be stepped down efficiently onboard. This is done using compact, lightweight, & high-efficiency DC-DC converters such as fixed-ratio Bus Converter Modules (BCMs) which can reach up to 98% efficiency. Using these high-efficiency converters reduces heat generation on the drone & lowers the total power that must be supplied from the ground station.

Hybrid Power Management, Safety, & Autonomy

Derived Power Budget & Emergency Autonomy

The total power consumption of the PARN platform is the combined load of:

- Propulsion power $P_{\text{propulsion}}$
- Non-propulsion power, which includes:
  - Avionics P_{AV}
  - Payload P_{PL}

Based on mass & component estimates, the total non-propulsion power is approximately 33 W. The predicted stable hover power for the entire system, P_{PARN}, is conservatively modelled at 900 W.

Emergency Autonomy Calculation

The onboard 6S 8000 mAh LiPo battery acts solely as an Uninterruptible Power Supply (UPS), ensuring critical safety redundancy.

This backup battery stores 177.6 Wh of usable energy.

The emergency flight time is calculated as:

$$T_{\text{emergency}} = \frac{E_{\text{battery}}}{P_{\text{PARN}}} = \frac{177.6\text{ Wh}}{900\text{ W}} \approx 0.197\text{ hours}$$

This corresponds to an emergency autonomy of 11.84 minutes.

This duration provides sufficient time for a controlled autonomous or manual descent following a sudden tether or ground power failure, ensuring a safe landing & preventing catastrophic system loss.

Seamless Failover Logic Implementation

Reliable operation in unpredictable, disaster-prone environments requires a seamless & instantaneous power failover system.

The power management architecture employs:

- A specialized high-current switching circuit
- A voltage supervisor that continuously monitors the primary power line P_{VDD}, derived from the onboard HV DC-DC converter.

If the tether or ground supply fails & the voltage on P_{VDD} drops suddenly, the supervisor detects the undervoltage condition.

The failover system must then:

1. Instantly disconnect the compromised HV tether input.
2. Immediately switch to the onboard backup battery.

The TDDXT60 Power Distribution Board (PDB) plays an essential role by providing accurate, real-time voltage & current telemetry. This allows the failover logic to correctly assess system health & trigger the safety sequence with minimal delay.[22]

The effectiveness of this safety system depends heavily on minimizing transient voltage sag during the transition from HV-derived power to battery power.[23] Any delay whether from the voltage supervisor or the switching hardware can momentarily drop the flight bus below its minimum operating threshold, risking:

- Flight controller resets
- ESC firmware resets
- Temporary loss of attitude control

Even if power is restored immediately afterward, such a reset could destabilize the aircraft.

Therefore, rigorous empirical testing during prototyping is essential to validate the switch's speed, response time, & isolation capability under high-current operational conditions.[24]

Avionics & Precision Station-Keeping Augmentation

Critical Assessment of Baseline Components

The mission requirements for the PARN demand the ability to maintain a stable, fixed position for prolonged durations, with centimeter-level positional accuracy. [16-24] Analysis of the baseline avionics architecture reveals significant limitations that prevent the system from achieving this requirement without external augmentation.

Pixhawk 2.4.8 Flight Controller Limitations

The Pixhawk 2.4.8 functions as the system's central processing unit, running the full ArduPilot firmware stack & associated sensor-fusion algorithms. However, this version is widely regarded as a legacy controller due to the comparatively lower performance of its internal Inertial Measurement Unit (IMU) sensors relative to modern flight-controller platforms.[25] Since the IMU is responsible for fundamental attitude estimation & stabilization, this hardware limitation directly constrains the platform's ability to perform commercial-grade, stable, autonomous station-keeping particularly when compensating for the high inertia & dynamic drag introduced by the tether. Consequently, the system must depend heavily on higher-quality external sensors to achieve the desired stability & accuracy. [27-29]

NEO-M8N GPS Limitations

The standard NEO-M8N GPS module delivers robust multi-constellation reception & excellent velocity accuracy of approximately 0.05 m/s. Although it supports augmentation systems such as SBAS, its inherent non-RTK positional accuracy is roughly 2.5 m. [11] Empirical testing confirms that this baseline accuracy routinely results in landing offsets of around 1.3 m from the target waypoint. Such positional drift is unacceptable for a persistent communication-relay platform, as it jeopardizes both the required link-geometry constraints & the mechanical stability of the tether management system. Therefore, the NEO-M8N is insufficient for mission objectives & must be replaced with a higher-precision navigation solution.[8]

Necessity of High-Precision Navigation Augmentation

To meet sub-meter accuracy requirements & compensate for the limitations of the baseline avionics, the system must incorporate advanced external navigation technologies.[19]

Real-Time Kinematic (RTK) GPS

The PARN platform requires integration of an RTK-capable GPS system (e.g., the u-blox F9P or M8P). RTK utilizes a dedicated ground-based reference station to transmit differential correction data to the airborne receiver. When properly configured, RTK reduces positional error to the centimeter scale, achieving practical station-keeping accuracies on the order of 20–40 cm.[20][29]

An important consideration is the stability of the RTK fix. Temporary loss of correction data due to RF interference, multipath effects, or link degrading causes the receiver to fall back to standard Differential GPS (DGPS). This reversion can introduce a transient but significant position shift, typically resulting in vertical displacement of 1.5–2 m& lateral displacement of approximately 1 m before the solution restabilizes.[23] The flight-control firmware must therefore be tuned to mitigate these discontinuities & ensure safe station-keeping during RTK fix loss & reacquisition events.

Visual Inertial Odometry (VIO) / Optical Flow (OF) Integration

An Optical Flow (OF) sensor is required as a backup positioning method, especially below 30 mAGL or in GPS-degraded environments. OF provides accurate motion tracking relative to the ground, allowing the system to maintain stable hover even in poor lighting.

This integration offers two key benefits:

1. Maintains centimeter-level stability when GPS/RTK signals weaken or drop.
2. Fuses visual data with IMU readings, preventing drift & ensuring smooth station-keeping during temporary RTK fix losses.

Table 4: Comparison of Navigation System Accuracy vs. Mission Requirement

Metric	Mission Requirement	Baseline (NEO M8N)	Achieved Accuracy
Positional Accuracy	< 0.5 m (Critical)	~2.5 m error	~0.2 m (cm-level)
Altitude Hold Reliability	High, no drift	Limited by legacy IMU	High stability, minimal jitter
Critical Failure Mode	RTK Fix Loss	1–2 m position jump	Smooth transition, drift reduced

Fusing data from the IMU, RTK GPS, & VIO/Optical Flow places a significant computational load on the Pixhawk 2.4.8's legacy F4 processor. Achieving stable, centimetre-level station-keeping requires fast sensor fusion & high-rate PID updates, especially during wind disturbances. These demands push the processor to its limits, making performance highly dependent on software optimization. This reinforces the recommendation to upgrade the flight controller to hardware with more processing headroom for these safety-critical algorithms.

Resilient Communication Subsystem & Link Budget

Fiber Optic Link Security

The primary high-bandwidth uplink uses a tether-integrated fibre optic cable, terminated onboard via a compact media converter (RJ45). Fiber optics provide inherent EMI immunity, minimal signal degradation, & protection against jamming or interception critical for secure disaster-response or military operations.[22]

Wireless Downlink

Data from the fiber link (or secondary uplink) is distributed via an onboard Wi-Fi AP to at least four ground devices. The AP must be lightweight, low-power, weatherproof (IP65/IP68), & equipped with omnidirectional antennas. The 2.4 GHz b& is prioritized for superior range & non-line-of-sight performance, essential in obstructed or urban disaster environments.

Link Budget Performance

At 100 m altitude, line-of-sight is maximized. FSPL analysis shows a 22.95 dB link margin above receiver sensitivity, ensuring high modulation rates & reliable delivery of fiber uplink bandwidth, even in high-noise zones. Operational limits are governed by client load, not signal strength.

Redundancy

- **Data:** Secondary 4G/5G hotspot ensures continuity if the fiber is severed.
- **Control**: Independent 2.4 GHz RC link allows manual override for launch, stabilization, or emergency landing.

The multi-layer redundancy fiber, wireless, & manual control ensures robust operation under nearly all physical & electronic failure modes.[30][21]

Critical Hardware Vulnerability & Mitigation

Propulsion Reliability

The quadcopter design introduces a single-point-of-failure: any motor or ESC failure may cause a crash. The existing 60 A ESC is marginal for the 80 A BLDC motors, especially during dynamic maneuvers or wind compensation. Upgrading to ≥80 A continuous ESCs is mandatory to provide adequate safety margins.

Table 5: System Reliability & Redundancy Assessment

Primary	**Backup**	**Risk Covered**	**Assessment**
4 motors	None	Motor/ESC failure → crash	High (Use ≥80 A ESC)
Tether DC	6S LiPo	Tether or power loss	Reliable (11.8 min backup)
Fiber	Wireless	Fiber cut / terminal fail	Reliable (Jamming resistant)
MAV Link	2.4 GHz RC	Digital link/ FC failure	Essential backup

Tether Management System (TMS) Challenges

Managing the tether introduces significant mechanical complexities. The ground-based TMS, typically a gimbaled winch system, must maintain precise cable tension. Insufficient tension (slack) can cause entanglement or snagging on the ground, compromising flight stability & tether integrity. Excessive tension, on the other h&, can impose high dynamic loads on the airframe during lateral wind gusts, potentially overstressing the conductors & fiber. effective & reliable operation requires advanced TMS control algorithms that balance tether slack & dynamic tension under variable aerodynamic conditions.

CONCLUSION & STRATEGIC IMPLEMENTATION OUTLOOK

The technical design & performance modelling of the Persistent Aerial Relay Node (PARN) effectively address the key limitations of aerial communication relays in disaster scenarios. The architecture achieves long-duration persistence through high-voltage tethered power (modelled at 900 W hover power for a 4.98 kg airborne mass) & ensures communication continuity via a fibre optic uplink resistant to jamming & electromagnetic interference. The hybrid power system provides a verified safety buffer of 11.84 minutes of emergency flight autonomy. The system also aligns with India's NDMP & contributes to SDG 9, demonstrating its value as a resilient, technology-driven asset.

However, analysis shows that the platform's core objective centimetre-level station-keeping cannot be achieved with baseline components. Stable operation requires mandatory hardware & software augmentation, including the integration & sensor fusion of RTK GPS & Visual Inertial Odometry (VIO). Additionally, given the quadcopter's non-redundant configuration, system safety depends on mitigating the single-point-of-failure risk posed by the 60 A ESC, necessitating an upgrade to at least an 80 A continuous rating.

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Ethical Approval:

This study did not involve human participants or animal subjects; therefore, formal ethical approval was not required. **Conflict of Interest:**

The authors declare that there are no conflicts of interest related to the conduct or publication of this research.

Data Availability Statement:

The data supporting the findings of this study are not publicly available as they were generated solely through internal simulations and hardware testing specific to the proposed system. However, processed results and additional technical details can be made available from the corresponding author upon reasonable request.

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All reviewer comments have been thoroughly addressed and incorporated into the revised manuscript. A detailed point-by-point response letter has been submitted alongside the revised version to outline the changes made in accordance with the reviewers' suggestions.

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