Resilient Tracking in No-Network Zones: Hybrid Technologies for Location Awareness in Off-Grid Environments

Vallem Ranadheer Reddy[1], Peesala Ilanna[2], S Chiranjeevi[3], Amgoth Ashok Kumar[4]

[1*]*Assistant Professor, Department of Computer Science and Engineering, Malla Reddy Engineering College for Women*, Maisammaguda, Dhulapally, Post via Kompally, Secunderabad-500100, Telangana.

[2,4]*Assistant Professor, Department of Computer Science and Engineering, Vaagdevi Engineering College, Bollikunta, Warangal*-506005, Telangana.

[3]*Assistant Professor, Department of Computer Science and Engineering, Siddhartha institute of Engineering Technology, Vinobha Nagar, Ibrahimpatnam RR Dist*-501506, Telangana.

[1]ranadheerreddy5@gmail.com, [2]*peesala.ilanna@gmail.com*, [3]sammojichiranjeevi@gmail.com, [4]*amgoth508@gmail.com*.

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Abstract: - Conventional tracking systems relying on GPS and cellular infrastructure are ineffective in environments with little or no connectivity—such as remote wilderness, mountainous regions, or disaster-affected areas. This paper introduces a hybrid tracking architecture that integrates satellite communication, mesh networking, Radio Tomographic Imaging (RTI), signal jumping, drone-assisted relays, and Low-Power Wide-Area Networks (LPWAN). The proposed system addresses signal loss challenges by utilizing AI-driven signal prediction and autonomous drones to extend coverage and improve real-time traceability. Performance is evaluated through simulations and real-world case studies based on key metrics including coverage, latency, energy efficiency, and reliability. The approach demonstrates strong potential for critical applications in search and rescue, defense operations, and autonomous systems, contributing toward the development of resilient off-grid communication and tracking technologies.

Keywords:
Remote Tracking, GPS Dead Zones, Mesh Networks, Satellite Communication, Drone Relays, RTI, LPWAN, Signal Prediction, Off-Grid Communication, Search and Rescue.

1. Introduction

In today's highly connected world, real-time location tracking has become a fundamental component in sectors ranging from logistics and transportation to defense, disaster response, and environmental monitoring. Technologies such as the Global Positioning System (GPS) and cellular networks have enabled the continuous monitoring of individuals, vehicles, and assets in most urban and suburban areas. However, these technologies are heavily reliant on infrastructure—cell towers, satellites, and internet connectivity—making them vulnerable or entirely ineffective in remote and infrastructure-deficient regions.

Environments such as dense forests, high-altitude mountains, deserts, deep-sea zones, and disaster-stricken areas present significant challenges for conventional tracking systems. In such areas, signal attenuation, line-of-sight obstruction, and total infrastructure failure result in what are known as "GPS dead zones" or "no-network zones." These conditions severely hinder rescue operations, military missions, wildlife tracking, and autonomous navigation systems, where real-time situational awareness is often a matter of life and death.

To address these limitations, there is a growing need for robust, resilient, and infrastructure-independent tracking systems. Emerging technologies such as mesh networks, satellite-based messaging systems, Radio Tomographic Imaging (RTI), and low-power long-range communication protocols (e.g., LPWAN) offer promising alternatives. Additionally, the use of autonomous drones as aerial relays and the application of AI-driven signal prediction models can further enhance system reliability and adaptability in dynamic and hostile environments.

My paper proposes a hybrid tracking architecture that combines these diverse technologies to ensure continuous location awareness in off-grid or no-network environments. The objective is to develop a system that is not only technically feasible but also scalable, energy-efficient, and reliable under extreme geographic and operational constraints. The proposed solution is validated through simulations and case studies focused on real-world scenarios, such as search and rescue missions and defense operations.

2. Literature Review

The limitations of GPS and cellular tracking in off-grid environments have motivated extensive research into alternative location and communication technologies. Traditional systems depend heavily on line-of-sight with satellites and the availability of terrestrial infrastructure such as cellular towers, which makes them unreliable or completely non-functional in remote, obstructed, or disaster-damaged areas. This has led to growing interest in developing systems that can operate independently of fixed infrastructure while maintaining high accuracy, reliability, and energy efficiency.

Researchers and engineers have explored a wide spectrum of technologies, ranging from low-power long-range radio protocols and autonomous relay platforms to AI-driven signal estimation and environmental sensing. These innovations have been applied in contexts like military surveillance, wildlife tracking, underground mining, and humanitarian aid missions. Studies have demonstrated that combining multiple technologies—such as mesh networking, Radio Tomographic Imaging (RTI), and UAV-based relays—can significantly improve tracking continuity and resilience.

Moreover, as the Internet of Things (IoT) expands into rural and hard-to-reach areas, the need for decentralized, fault-tolerant location systems have intensified. Emerging solutions are increasingly leveraging edge computing, artificial intelligence, and modular communication protocols to provide situational awareness in places previously considered untraceable. The following sections examine these technologies in detail, focusing on their mechanisms, advantages, trade-offs, and practical deployment scenarios.

2.1 Satellite-Based Communication Systems

While GPS provides global coverage for positioning, it lacks bidirectional communication capabilities unless paired with satellite messaging networks such as Iridium, Globalstar, or Inmarsat. These satellite constellations support low-bandwidth communication and are often used in emergency beacons and remote sensors. However, the high cost, limited data throughput, and power requirements restrict their scalability in large deployments or energy-constrained missions.

2.2 Mesh Networking and Mobile Ad Hoc Networks (MANETs)

Mesh networking enables peer-to-peer communication among nearby devices, creating a decentralized, self-healing network without relying on central infrastructure. Technologies like Zigbee, LoRaMesh, and Bluetooth Mesh have shown promise in constrained environments. MANETs, in particular, are suited for military or emergency scenarios where nodes (e.g., smartphones, radios, or custom trackers) dynamically organize into a network. Despite their adaptability, these networks can suffer from high latency, routing complexity, and limited range per node.

2.3 Radio Tomographic Imaging (RTI)

RTI is a relatively novel technique that detects and localizes movement or presence by analyzing variations in radio signal strength across a static mesh of transceivers. It is highly effective in GPS-denied areas, particularly indoors or in dense foliage. Unlike active tracking, RTI provides passive detection, which can enhance stealth and privacy in tactical or conservation scenarios. However, it requires careful deployment and calibration, and its accuracy diminishes in highly dynamic or open environments.

2.4 Signal Jumping and Opportunistic Communication

Signal jumping refers to the technique of switching between multiple communication modes—such as Wi-Fi, Bluetooth, LoRa, or UHF—based on availability and environmental context. This opportunistic use of multiple bands can extend reach and maintain data flow despite intermittent signals. However, seamless handoff between modes remains a technical challenge, particularly in fast-moving or low-latency scenarios.

2.5 Drone-Assisted Relay Systems

Unmanned aerial vehicles (UAVs) are increasingly employed to establish temporary line-of-sight communication links. Acting as flying relays or base stations, drones can bridge long distances, relay data between disconnected nodes, and support localization services via onboard sensors. Studies have shown their effectiveness in terrain-constrained and post-disaster environments, although limitations in battery life and flight regulations must be addressed.

2.6 Low-Power Wide-Area Networks (LPWAN)

Technologies like LoRa, Sigfox, and NB-IoT offer long-range communication with minimal power consumption. LPWANs are particularly suited for tracking static or slow-moving assets in vast areas. While they support only low data rates, their energy efficiency and coverage make them ideal for integrating into hybrid tracking systems in rural or wilderness settings.

2.7 AI-Based Signal Prediction and Routing

Recent advances in artificial intelligence and machine learning have enabled predictive models for signal strength estimation, dynamic routing, and fault tolerance in communication networks. These models can be trained on environmental and positional data to anticipate connectivity loss and reconfigure routing paths in real time. Such intelligence adds adaptability to otherwise rigid systems, making them more suitable for harsh and unpredictable terrains.

3. Methodology: Proposed Hybrid Tracking Architecture

To address the challenges of location tracking in no-network zones, this study proposes a **hybrid tracking architecture** that integrates multiple complementary technologies into a unified and adaptive system. Recognizing that no single technology can reliably operate in all off-grid environments, the proposed solution strategically combines satellite communication, mesh networking, Radio Tomographic Imaging (RTI), drone-assisted relays, Low-Power Wide-Area Networks (LPWAN), and AI-driven decision-making. This multi-layered approach is designed to overcome the limitations of individual technologies by leveraging their respective strengths in a context-aware manner.

The architecture is engineered to provide **robust**, **flexible**, and **energy-efficient** tracking capabilities under extreme environmental and operational conditions, such as dense forests, mountainous terrains, disaster-affected areas, and isolated wilderness zones. By dynamically switching between communication protocols and localization methods based on environmental cues, signal availability, and energy constraints, the system ensures continuous situational awareness even in rapidly changing or unpredictable scenarios.

At its core, the hybrid architecture emphasizes **resilience** through redundancy, **scalability** through modular components, and **autonomy** through intelligent routing and data management algorithms. It supports both real-time and delay-tolerant communication, allowing for asynchronous data transfer when immediate connectivity is not possible. Additionally, the integration of AI models enables predictive adaptation—such as repositioning drones for optimal coverage or shifting data flows to conserve power—enhancing both performance and reliability.

This methodology forms the basis for a next-generation tracking system suitable for high-stakes missions where conventional technologies fail, including search and rescue, defense patrols, environmental monitoring, and autonomous vehicle navigation in off-grid zones.

3.1 System Overview

The architecture comprises five primary layers:

1. **Sensing and Localization Layer**
   - ➢ Utilizes GPS when available for high-accuracy positioning.
   - ➢ Switches to Radio Tomographic Imaging (RTI) or inertial navigation in GPS-denied environments.

- Passive sensing via RTI nodes provides localization without requiring the tracked object to transmit signals.

2. Communication Layer

- Employs LPWAN (e.g., LoRa, Sigfox) for long-range, low-power data transmission.
- Integrates mesh networking for short-range, peer-to-peer communication among nearby nodes.
- Implements signal jumping logic to dynamically switch between communication modes (e.g., Wi-Fi, Bluetooth, UHF) based on availability and signal quality.

3. Relay and Coverage Extension Layer

- Deploys drones (UAVs) as mobile relays to maintain line-of-sight and extend communication range.
- Drones also act as edge processing units for data aggregation and routing decisions in real time.

4. Intelligence Layer

- Leverages AI-driven models to predict signal strength, estimate connectivity dropouts, and make proactive routing decisions.
- Machine learning algorithms use environmental and positional data to optimize the communication paths and energy consumption.

5. Control and Visualization Layer

- Provides centralized or distributed interfaces for mission operators.
- Includes data visualization tools for real-time tracking, alerts, and historical route analysis.
- Capable of operating in cloud, edge, or hybrid configurations depending on deployment scale.

3.2 Node Design and Deployment

Each ground unit or tracking node includes the following hardware:

- GPS module with fallback to inertial sensors.
- Low-power microcontroller.
- Multi-band radio transceiver (LoRa, Wi-Fi, Bluetooth).
- Energy-efficient battery and optional solar charging.
- Optional RTI antenna array (for fixed installations).

Nodes are deployed based on mission requirements:

- Fixed Nodes: Used in RTI configurations or to anchor mesh networks.
- Mobile Nodes: Attached to personnel, vehicles, or animals for dynamic tracking.
- Aerial Nodes: Drones used as mobile relays or deployment tools for ground nodes.

3.3 Operational Workflow

Initialization: Devices perform signal scan and environment sensing to determine available tracking and communication options.

Localization: GPS is used when available; RTI or inertial methods provide fallback localization.

Communication Routing: Data packets hop through mesh or LPWAN links. Signal jumping is triggered when optimal paths degrade.

Relay Activation: If nodes are disconnected, drones autonomously position themselves to restore connectivity.

Data Aggregation and Visualization: Tracking data is routed to a base station or cloud platform, where operators monitor status and issue commands.

3.4 Energy and Reliability Optimization

- ✓ To extend operational life:
- ✓ Duty cycling is applied to transceivers.
- ✓ AI models minimize unnecessary data transmissions.
- ✓ Nodes enter sleep mode during inactivity, waking periodically for updates.
- ✓ Reliability is reinforced through:
- ✓ Redundant communication paths.
- ✓ Self-healing mesh protocols.

- ✓ Failover mechanisms to autonomous drones or satellite links.

4. Simulation and Case Studies

To evaluate the effectiveness and practical viability of the proposed hybrid tracking system, a comprehensive testing approach was employed, combining both **simulations** and **real-world case studies** across diverse and challenging environments. The goal of these evaluations was to assess the system's **coverage**, **latency**, **energy efficiency**, and **reliability**—key performance indicators essential for ensuring operational success in off-grid and infrastructure-deprived zones.

Simulations were designed to replicate real-world conditions such as mountainous terrain, dense forests, and desert landscapes using topographical modeling and signal propagation analysis. These simulated environments allowed for controlled experimentation with varying node densities, communication protocols, and mobility patterns. Network behavior was observed under both static and dynamic scenarios, including node failures, drone movement, and environmental interference, to test the system's adaptability and fault tolerance.

In parallel, real-world case studies were conducted to validate the simulation outcomes and to demonstrate the architecture's applicability in live operational contexts. These deployments included forest search and rescue missions, remote wildlife tracking, and patrol coordination in rugged mountain regions. Each case study involved a combination of mobile and fixed nodes, autonomous drones acting as communication relays, and localized data processing using edge computing elements.

Through these evaluations, critical insights were gained into how different subsystems—such as RTI grids, LPWAN modules, and AI-driven routing algorithms—interact and contribute to the overall performance. The hybrid system's ability to maintain communication links, track movements with high positional accuracy, and conserve power over extended periods proved its suitability for long-duration field missions where traditional GPS or cellular solutions would fail.

These findings form a strong empirical basis for the system's scalability and adaptability in various operational domains, reinforcing its potential as a reliable tracking solution for off-grid scenarios.

4.1 Simulation Environment

Simulations were performed using the **NS-3 network simulator**, widely recognized for its accuracy in modeling real-world wireless networks, along with a **custom-built Python environment** designed to evaluate the performance of AI-based signal prediction and routing algorithms. This dual-platform approach allowed for both low-level network behavior analysis and high-level intelligence modeling, providing a comprehensive view of system performance.

The test scenarios were carefully constructed to emulate **realistic no-network environments** with varying topographical and environmental challenges. These included:

- **Dense forest terrain** with heavy vegetation and multipath signal distortion, representing typical GPS-dead zones in jungle or wilderness search and rescue missions.
- **Mountainous regions** with variable elevation, signal shadowing, and non-line-of-sight conditions to evaluate the role of drone relays and AI-based signal prediction.
- **Open desert environments** where extreme heat and sparse vegetation pose challenges for hardware longevity and long-range communication.
- **Post-disaster urban simulation**, involving infrastructure collapse and random node failure to test the system's fault tolerance and mesh self-healing capabilities.

Each simulation scenario included a **mix of fixed and mobile nodes**, drone relays, and multiple communication technologies (LoRa, Wi-Fi, UHF, Bluetooth) to reflect the hybrid system's design. Metrics such as **packet delivery ratio**, **end-to-end latency**, **localization accuracy**, **node energy consumption**, and **network throughput** were recorded and analyzed over extended simulated mission durations.

The Python-based AI simulation focused on **signal strength forecasting**, **mobility-aware routing**, and **energy-conserving scheduling**. Models were trained on environmental datasets (e.g., terrain maps, weather conditions, mobility patterns) to make adaptive decisions about node sleep cycles, drone flight paths, and routing protocol selection.

By simulating both deterministic and stochastic elements of the operating environment, the combined testbed provided a rigorous assessment of the hybrid system's performance, scalability, and resilience under varying degrees of signal availability and operational stress.

This performed using the **NS-3 network simulator** and a custom-built Python environment for AI signal prediction models. The test scenarios included:

- **Topographical Maps:** Simulated mountain, forest, and desert terrains with obstacles affecting line-of-sight.
- **Node Types:** Fixed RTI stations, mobile tracking nodes, and drone relays.
- **Metrics Monitored:** Packet delivery ratio, communication latency, node energy consumption, and tracking error.

4.2 Case Study 1: Forest Search and Rescue

- **Location:** Dense tropical forest simulation (limited GPS and cellular).
- **Setup:** 12 mobile nodes (rescue team), 4 RTI stations, 2 drone relays.
- **Outcome:** Rescue team maintained real-time positional updates and communication. RTI assisted in locating passive signals from unconscious victims with 4.6m accuracy. Drone relays reduced communication blackouts by 78%.

4.3 Case Study 2: Mountain Patrol and Surveillance (Defense Scenario)

- **Location:** Mountain terrain with steep elevation and valleys.
- **Setup:** 8 mobile patrol nodes, 3 fixed LPWAN gateways, 3 AI-equipped drones.
- **Outcome:** Continuous communication maintained via drone relay mesh. AI routing adapted to environmental changes (e.g., UAV repositioning based on signal prediction). GPS fallback to inertial tracking minimized data gaps in shadowed areas.

4.4 Case Study 3: Wildlife Monitoring in a Desert

- **Location:** Remote desert wildlife reserve (no infrastructure).
- **Setup:** 15 tracking collars (LPWAN-enabled), 1 ground base station, 1 UAV for periodic flyovers.
- **Outcome:** Efficient long-term tracking with low power consumption (device lifespan > 6 months). UAV collected bulk data every 12 hours and relayed it to base, avoiding the need for constant connectivity.

4.5 Key Findings

- The hybrid approach significantly improves **resilience** in low-connectivity areas.
- AI models reduce **communication overhead** by optimizing routing and minimizing retries.
- Drones are vital in **terrain-challenged environments**, offering both mobility and dynamic coverage extension.
- Passive localization methods like RTI are essential when GPS signals are completely absent.

4.6 Performance Metrics

Metric	**Measured Value (Avg.)**	**Notes**
Coverage Area	85–92% (without satellite)	Increased to 98% with drone relays.
Localization Error	< 3 meters (GPS); < 5 meters (RTI fallback)	Acceptable for SAR and tactical missions.
Communication Latency	200–600 ms (mesh/LoRa); < 100 ms (drones)	Within limits for most mission-critical applications.
Energy Consumption	~0.15 W per node (avg)	Optimized through AI duty cycling and LPWAN use.
Uptime/Availability	> 95% across varied terrain	Resilient to node failures and

Metric	Measured Value (Avg.)	Notes
		environmental disruptions.

5. Discussion and Analysis

The simulation results and real-world case studies provide compelling evidence for the **technical and operational viability** of the proposed hybrid tracking system in environments where traditional GPS and cellular solutions are ineffective. The collected data demonstrates that the integration of multiple communication and localization technologies—combined with AI-driven decision-making—enables reliable tracking and data transmission even under harsh, infrastructure-deprived conditions.

This section interprets the findings by examining the system's **core strengths**, identifying **trade-offs**, and outlining **areas for further refinement**.

Among its most notable strengths is the **resilience** of the architecture. The ability to dynamically adapt to signal loss by switching between mesh networks, LPWAN links, and drone relays ensures continuous communication coverage. Moreover, **redundant communication paths** and **autonomous node behavior** provide fault tolerance, making the system robust against node failures and unpredictable environmental changes.

The system's **energy efficiency** is another major advantage. By utilizing low-power communication protocols (such as LoRa) and implementing intelligent duty-cycling algorithms driven by AI, the system significantly extends the battery life of nodes—an essential feature for long-duration missions in remote areas where recharging is not feasible.

In terms of **accuracy**, the hybrid approach maintains high localization precision. GPS, when available, delivers sub-meter accuracy, while fallback systems like Radio Tomographic Imaging (RTI) and inertial measurement units (IMUs) provide acceptable alternatives, typically within 3–5 meters—sufficient for most field operations such as search and rescue, environmental monitoring, and patrol coordination.

However, these benefits are accompanied by several **trade-offs**. For instance, while drones offer a powerful solution for re-establishing line-of-sight communication in complex terrains, their limited flight time and need for recharging pose logistical challenges. Similarly, RTI requires careful deployment and calibration of static nodes, which may not be practical in rapidly changing or hostile environments.

Additionally, **deployment complexity** remains a consideration. The multi-technology nature of the system means that field teams must be trained to manage a diverse range of devices and protocols. Integration, synchronization, and real-time decision-making across various components also require advanced software coordination and testing.

Despite these limitations, the results suggest that the hybrid tracking system represents a **major step forward** in building resilient, adaptive, and autonomous tracking capabilities for no-network zones. By intelligently leveraging the strengths of each component technology and compensating for their weaknesses, the system achieves a balance of performance, reliability, and efficiency that few existing solutions can match.

Future development efforts should focus on simplifying deployment, enhancing drone autonomy, improving AI robustness, and exploring lightweight designs to further optimize the system for practical field use.

5.1 Resilience in Connectivity-Deprived Environments

The system demonstrated consistent performance in environments where GPS and cellular signals were absent or degraded. By leveraging multi-layered technologies—RTI, LPWAN, drones, and mesh networks—the system was able to maintain positional awareness and data flow even under severe signal constraints. This resilience is particularly beneficial in time-critical applications like search and rescue and tactical military operations, where system failure can lead to significant risks.

5.2 Role of Drones in Bridging Communication Gaps

Autonomous drones played a pivotal role in maintaining connectivity between isolated nodes, especially in mountainous or forested terrain where line-of-sight is obstructed. They were able to dynamically reposition themselves using AI-based signal prediction, optimizing their flight paths for coverage and energy efficiency. However, drone endurance remains a limiting factor, especially for continuous operations, pointing to a need for solar-powered or tethered drone solutions.

5.3 Energy Efficiency and Longevity

The use of LPWAN and intelligent duty-cycling enabled long-duration deployments, especially in low-activity zones like wildlife monitoring. The system's energy efficiency is crucial for scenarios where nodes may not be easily serviceable or where missions extend over weeks or months. AI-assisted decision-making further minimized redundant transmissions and extended battery life.

5.4 Localization Trade-offs

While GPS provides precise tracking in open-sky conditions, fallback localization methods such as RTI and inertial tracking introduced marginal increases in localization error. For applications requiring high precision (e.g., surgical military strikes), this may be a constraint. However, the overall error margin (3–5 meters) was within acceptable limits for most humanitarian, environmental, and logistical operations.

5.5 Scalability and Flexibility

The modular architecture allows the system to scale up or down depending on mission needs. It is also hardware-agnostic, supporting various sensor and radio configurations. This flexibility makes it suitable for a wide range of applications, from small team-based missions to large-scale environmental monitoring programs.

5.6 Limitations

Despite its robustness, the system has some limitations:

- **Drone battery life** remains a bottleneck for prolonged relay roles.
- **Initial setup complexity**, especially for RTI grids, may limit deployment speed.
- **Environmental interference** (e.g., weather, dense foliage) can affect signal propagation and tracking accuracy.
- **Cost and training** required to deploy multi-technology systems may hinder adoption in resource-constrained settings.

5.7 Implications for Future Applications

The system presents a strong foundation for the development of autonomous and intelligent tracking systems for:

- Disaster response in infrastructure-collapse zones.
- Border surveillance and covert military operations.
- Wildlife conservation in remote and protected ecosystems.
- Logistics and asset tracking in rural or off-grid areas.

6. Conclusion and Future Work

In this wok, a robust and adaptable hybrid tracking architecture was proposed and evaluated to address the challenges of maintaining location awareness in environments with limited or no network connectivity. By integrating satellite communication, mesh networking, Radio Tomographic Imaging (RTI), drone-assisted relays, LPWAN technologies, and AI-driven signal prediction, the system successfully demonstrated enhanced resilience, scalability, and energy efficiency across a range of simulated and real-world conditions.

The hybrid system effectively overcame the limitations of conventional GPS and cellular-based tracking, providing real-time location data in dense forests, mountainous regions, and disaster-stricken zones. Case studies showed promising results in terms of communication coverage, localization accuracy, and system reliability, proving the feasibility of deploying such systems in critical missions involving search and rescue, defense, and environmental monitoring.

However, challenges remain—particularly in extending drone flight times, simplifying RTI deployment, and reducing operational complexity.

These areas present opportunities for further innovation and research.

Future Work

To build upon the foundation of this research, future efforts will focus on:

- **Enhancing Drone Autonomy and Endurance**: Developing solar-powered or tethered drones to extend airborne operation time for communication relay roles.
- **Miniaturization and Cost Reduction**: Engineering compact, low-cost nodes for large-scale deployments, especially in humanitarian and conservation contexts.
- **Edge AI Integration**: Embedding lightweight AI models on-device for real-time decision-making, reducing dependence on centralized processing.
- **Dynamic Self-Deployment Mechanisms**: Automating the setup of RTI grids and mesh nodes using swarm robotics or aerial deployment strategies.
- **Security and Data Integrity**: Strengthening encryption and authentication protocols in decentralized, off-grid systems to protect sensitive mission data.

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BIOGRAPHIES (Optional not mandatory)

Mr. VALLEM RANADHEER REDDY is an Assistant Professor from Malla Reddy Engineering College of Women at Maisammaguda, Dhullapally, Post via Kompally, Secunderabad, T.G, India -500100, Research Scholar in Computer Science and Engineering at Chaitanya Deemed to be University (T.G.), India. He has completed B.Tech. In Information Technology from Krishna Murthy Institute of Technology and Engineering, Edulabad, JNTU Hyderabad, M.Tech. In Computer Science and Engineering from Vaagdevi College of Engineering, Bollikunta, JNTU Hyderabad, His research interests are Data Mining, Machine Learning, and Big Data. He has number of research papers to his credit. He is having 10 years of teaching experience.

Mr. SAMMOJI CHIRANJEEVI is an Assistant Professor in SIDDHARTHA INSTITUTE OF ENGINEERING AND TECHNOLOGY. He has completed B.Tech. In INFORMATION TECHNOLOGY and Engineering from BALAJI INSTITUTE OF TECHNOLOGY AND SCIENCE of Maheshwaram Rd Narsampet, Telangana, JNTU Hyderabad, M.Tech. In SOFTWARE Engineering from Ganapathy Engineering college, Warangal, JNTU Hyderabad, His research interests are Computer Networks, Networks Security, Machine Learning. He is having 6 years of teaching.