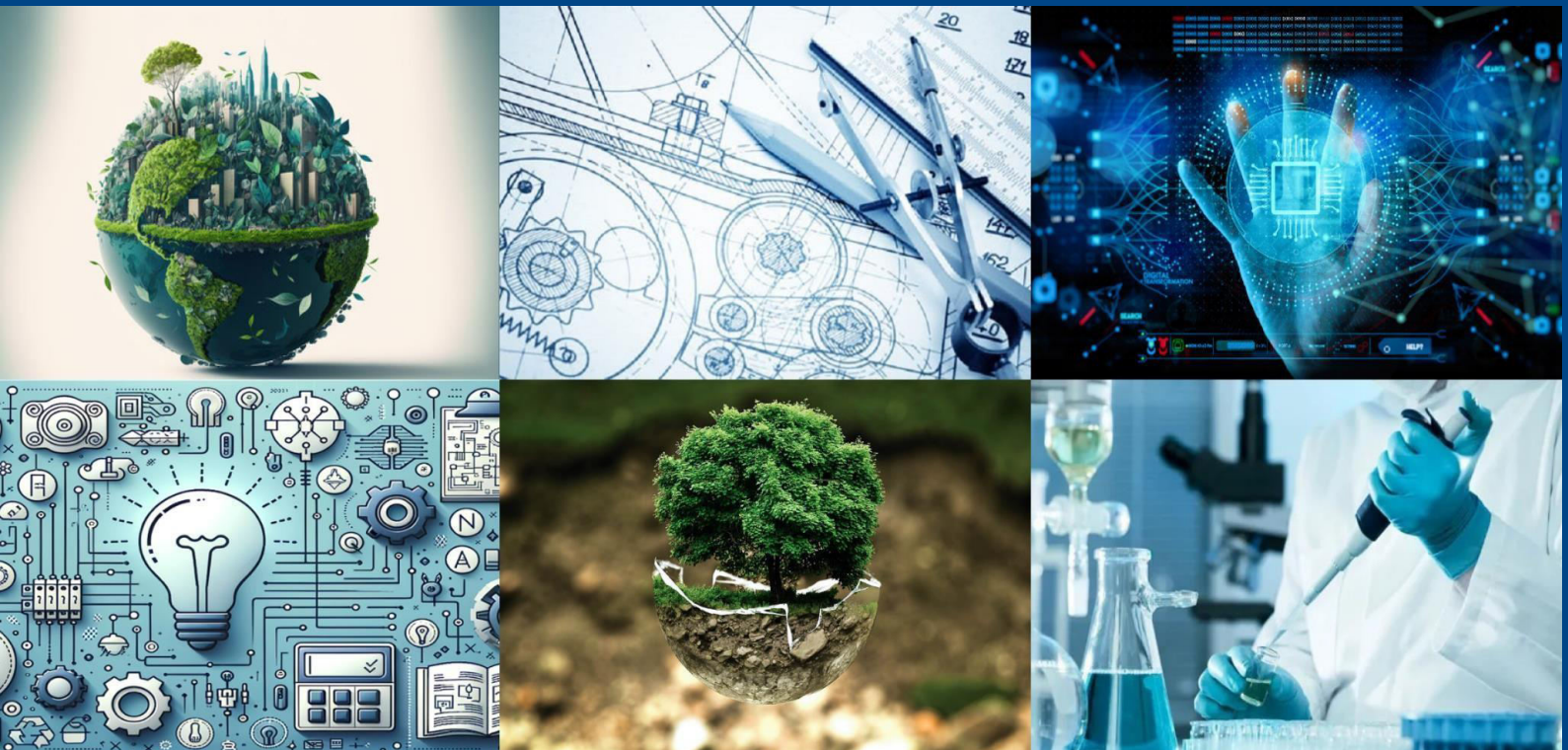




International Journal of Multidisciplinary Research in Science, Engineering and Technology

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.206

Volume 8, Special Issue 2, November 2025



Landslide Monitoring and Control in Mountain Area using RF Communication

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ABSTRACT: Landslides in mountainous regions pose significant risks to human life, infrastructure, and the environment. Early detection and continuous monitoring are crucial to mitigate these risks. Recent advancements in wireless communication and the Internet of Things have enabled the deployment of cost-effective, real-time monitoring systems using Radio Frequency technologies. LoRa-based wireless sensor networks have been effectively employed for landslide and rockfall monitoring, offering long-range communication with low power consumption, as demonstrated in Pantelleria Island. High-range wireless networks integrated with geosensors provide predictive capabilities for potential landslides, while fuzzy logic-based particle swarm optimization enhances adaptive monitoring and early warning. IoT-enabled systems allow distributed sensing and centralized data processing, facilitating timely alerts and preventive actions. The integration of GNSS-RTK technology with RF communication further improves positional accuracy and real-time data acquisition. This paper reviews current methodologies and presents a framework for an RF-based landslide monitoring system in mountainous regions, emphasizing real-time monitoring, early warning, and disaster prevention.

KEYWORDS: *Landslide Monitoring, Slope Stability, Mountainous Terrain, RF Communication, Wireless Sensor Network (WSN), Early Warning System, Soil Moisture Sensor, Real-time Monitoring, Landslide Mitigation, Disaster Management.*

I. INTRODUCTION

Landslides represent a persistent and severe threat in mountainous regions globally, classified as a major geoenvironmental disaster due to their potential for large-scale destruction and loss of life [2]. The inherent characteristics of these environments—namely, their remote nature, difficult accessibility, and lack of reliable power infrastructure—pose significant challenges to establishing effective, continuous monitoring using traditional methods [7]. Consequently, the imperative to develop real-time, reliable monitoring systems has driven a major shift toward integrating modern communication and sensing technologies. The current state of research overwhelmingly favors the deployment of Wireless Sensor Networks (WSNs) and Internet of Things (IoT) architectures to address these limitations [4, 7, 8, 9, 10]. These systems rely heavily on Radio Frequency (RF) communication to enable the distributed, low-cost collection of crucial data from vulnerable slopes [7]. A variety of RF protocols have been adopted to suit the specific needs of long-range, low-power operation. For instance, LoRa-based WSNs have proven effective in providing robust, energy-efficient connectivity across large areas, making them ideal for monitoring rockfall and landslide sites where portable access and battery life are paramount [1]. Furthermore, for high-precision geodetic measurements, systems are incorporating high-range wireless networks to support technologies like GNSS-RTK for accurate ground displacement tracking, often utilizing specialized criteria for data filtering to ensure reliability [2, 6].

Beyond data collection, the system's intelligence is equally critical. The complexity and inherent uncertainty of landslide precursors necessitate advanced data processing. Contemporary monitoring systems frequently integrate intelligent computational methodologies like fuzzy logic to effectively process noisy sensor data and generate reliable early warnings [5]. This capability is sometimes coupled with optimization techniques, such as Particle Swarm Optimization (PSO), to create adaptive monitoring systems that intelligently manage power consumption and sensing frequency based on the perceived risk level, maximizing network longevity in the field [3]. This research focuses on the

design and implementation of an integrated landslide monitoring and control system optimized for mountain environments, leveraging the strengths of combined RF communication technologies. The objective is to establish a robust, continuous monitoring pipeline that not only provides timely, accurate early warnings but also lays the groundwork for subsequent automated control and mitigation measures, directly addressing the persistent challenges of hazard management in geographically isolated and unstable mountainous regions.

II. PROPOSED SYSTEM

2.1 Block Diagram

The block diagram of the landslide monitoring and control in mountain area using RF communication is shown in Figure 1. A sophisticated, three-layered Internet of Things (IoT) architecture for Landslide Monitoring and Warning, meticulously engineered to operate in challenging mountainous terrain by strategically integrating different Radio Frequency (RF) communication technologies: LoRa and 4G. The system's foundational element is the Sensing and Data Collection Layer, which comprises numerous geographically distributed Collection Nodes placed directly on the unstable slope. Each node is an autonomous unit housing a Data Collector and a suite of critical geosensors, including a Rain Sensor to monitor the primary trigger factor of precipitation, a Displacement Sensor to track minute ground movement that signals impending failure, and a Tilt Sensor to measure slope deformation. To conserve energy and achieve the necessary long-range communication over rugged topography, the Collection Nodes utilize the LoRa (Long Range) protocol. LoRa, an LPWAN (Low-Power Wide-Area Network) technology, is essential because it allows the battery-operated sensors to transmit small data packets over significant distances for extended periods, directly addressing the power and connectivity limitations inherent in remote mountain environments. The data flow within this layer is decentralized, with each node efficiently and reliably forwarding its measurements to a central hub.

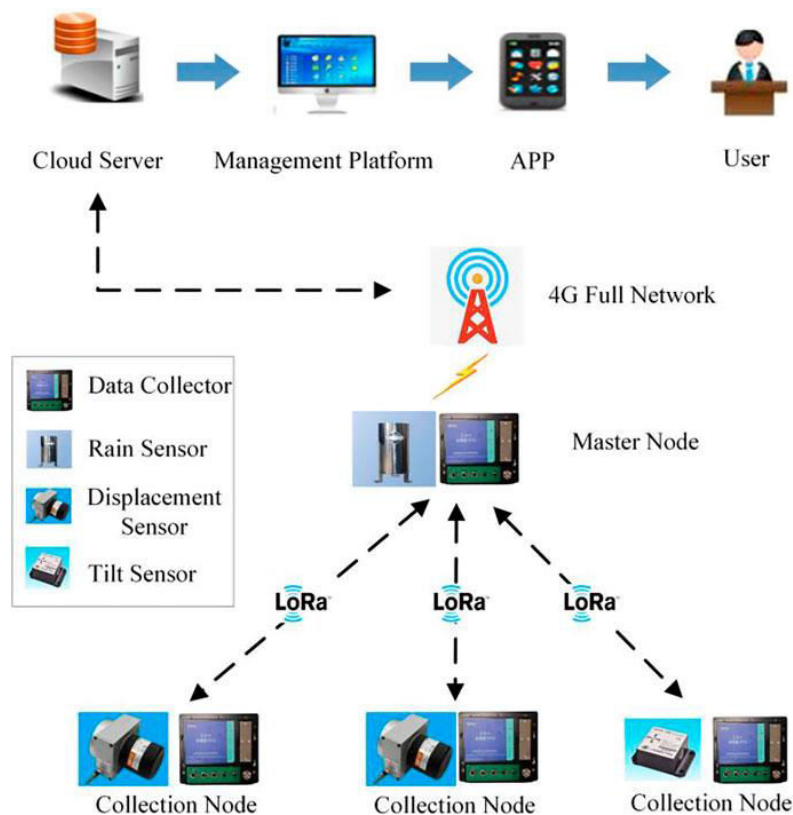


Figure1: Block Diagram of proposed system

This data is then aggregated in the Communication Layer by the Master Node, which serves as the critical bridge between the field sensors and the remote processing infrastructure. The Master Node's primary function is to receive all



the raw data wirelessly transmitted via LoRa from the dispersed Collection Nodes. It also typically incorporates its own set of sensors and a Data Collector, acting as a redundant measurement point. Crucially, to transmit the aggregated, higher-volume dataset out of the remote area and onto the internet, the Master Node employs the high-bandwidth 4G Full Network. This strategic use of two distinct RF technologies—LoRa for the energy-efficient "last mile" of the sensor network and 4G for the high-speed "backhaul"—optimizes the system for both low-power operation at the node level and robust, reliable data delivery to the cloud. The utilization of 4G leverages existing cellular infrastructure, ensuring continuous and high-throughput connectivity necessary for real-time monitoring.

Finally, the Data Processing and Application Layer transforms the raw data into actionable intelligence, facilitating effective risk management and control measures. The data streams transmitted via 4G are first received and stored in a scalable Cloud Server, which provides the necessary computational capacity for continuous analysis and archival. This storage is accessed by the Management Platform, the primary interface for system operators. The platform performs essential functions such as real-time data visualization (displaying trends and status) and, more importantly, running warning logic algorithms (which may involve threshold comparisons or predictive models) to assess the slope's stability. When critical parameters are exceeded, the platform generates immediate alerts. These critical warnings and status updates are then rapidly disseminated through a dedicated mobile APP (Application), ensuring that the User—such as emergency services, geologists, or local authorities—receives instant notifications regardless of their location. This rapid communication pathway is paramount, enabling the User to initiate timely control and mitigation measures, such as issuing evacuation orders or activating automated stabilization systems, thereby reducing the risk to life and property. Thus, the system forms a complete, closed loop monitoring solution, bridging the gap from sensor measurement in a hostile environment to immediate decision-making and hazard control.

2.2 Flowchart

The provided flowchart outlines in figure 2, the sequential, automated process of a Landslide Monitoring and Control System that relies on RF Communication to ensure timely warning and mitigation in mountain areas. The process begins with the crucial step of installing sensors on the mountain slope, where specialized devices—including Temperature Sensors, Soil Moisture Sensors, Rainfall Sensors, and Vibration/Movement Sensors—are strategically deployed to capture the critical geotechnical and environmental precursors of slope failure. Following installation, these sensors enter the operational phase of collecting data continuously, generating a real-time stream of information reflecting the current stability status of the terrain. This collected data is then transmitted via RF Communication (utilizing technologies like LoRa or 4G) from the remote field location to a central Base Station/Gateway, which acts as the data aggregator and connectivity hub, overcoming the logistical hurdles posed by rugged environments.

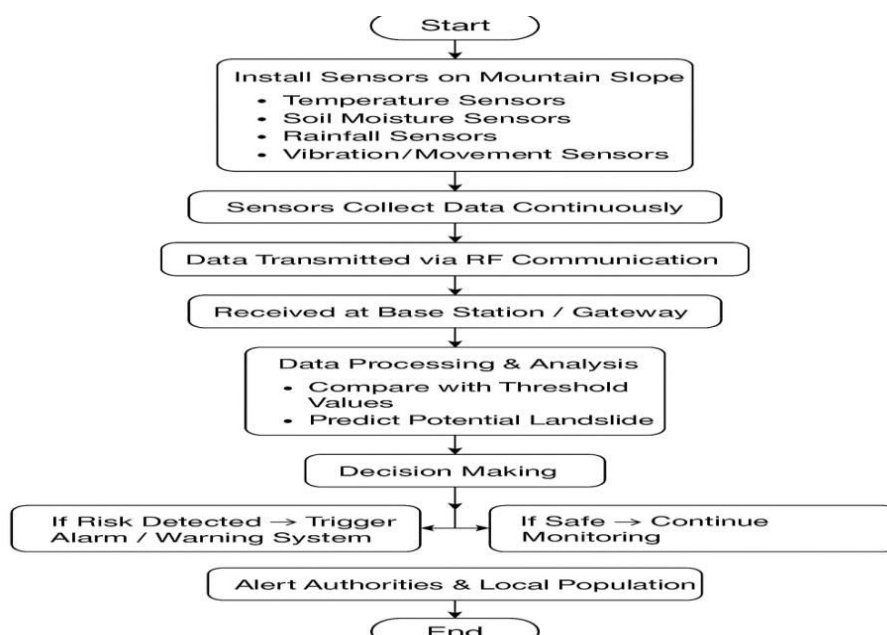


Figure 2: Flowchart for the proposed system



Once received, the data undergoes rigorous Data Processing & Analysis, where raw readings are critically compared with threshold values established through engineering models and historical data, concurrently employing predictive algorithms to predict potential landslide events by analyzing rates of change and cumulative risk indicators. This analysis feeds into the Decision-Making block, which bifurcates the system's flow: if the system determines the conditions are safe, the process loops back to continue monitoring; however, if risk is detected, the system immediately triggers the Alarm/Warning System. The final, critical step involves rapidly alerting Authorities & Local Population using various communication channels (e.g., mobile apps, SMS, sirens) to enable immediate implementation of control measures such as evacuation or drainage system activation, thereby fulfilling the system's primary objective before the process reaches its End.

2.3 Components

The system for landslide monitoring and control is an integrated, multi-layered architecture comprising essential hardware for data acquisition and software platforms for intelligent analysis, with Radio Frequency (RF) communication forming the backbone that enables operation in remote mountain environments. The foundation of the system rests on the Sensing Devices, housed within the Collection Nodes and strategically dispersed across the unstable slope. Each node is a miniature monitoring station, built around a Data Collector (microcontroller) responsible for managing power, interfacing with sensors, and pre-processing raw data. These nodes incorporate a comprehensive array of specialized sensors to capture the multifaceted precursors of slope failure. Key among these are the Rain Sensor, which quantifies precipitation—the primary external trigger for soil saturation and destabilization—and the highly critical Displacement and Tilt Sensors, which provide direct measurement of ground movement, deformation rates, and changes in slope inclination, respectively. Further augmenting the geo-environmental data are the Soil Moisture Sensors, essential for determining the effective stress and shear strength of the soil matrix, and Temperature Sensors, used for contextual environmental monitoring.

The core ingenuity for deployment in rugged terrain lies in the Communication Devices. The Collection Nodes utilize the LoRa Module, an implementation of LPWAN technology, to transmit their data. LoRa is specifically chosen for its capacity to ensure low-power consumption and extended wireless range, allowing the battery-operated nodes to function autonomously for prolonged periods without maintenance, a prerequisite for remote mountain sites. This network of nodes feeds into the Master Node/Base Station/Gateway, which acts as the crucial aggregation point. This gateway not only receives all the LoRa signals but also utilizes the 4G Full Network Module to establish the high-speed backhaul link. This dual-RF strategy—LoRa for efficient field communication and 4G for reliable internet access—is what permits the continuous, high-volume transfer of critical data from the remote site to the centralized infrastructure.

Moving to the off-site, digital infrastructure, the system leverages scalable resources for analysis and decision-making. The incoming data stream is stored on the Cloud Server, which provides the necessary resilience and capacity for continuous archival and processing. This data fuels the Management Platform, the operational center that executes the system's intelligence. At the heart of this platform are the Warning Logic/Analysis Algorithms. These sophisticated algorithms are tasked with constantly comparing the real-time sensor readings against established threshold values (representing safe limits) and employing predictive models to proactively predict potential landslides based on acceleration and deviation patterns. This is the stage where the raw data is transformed into actionable risk assessment. The final element is the swift dissemination of this intelligence: the predicted safety status or critical alerts are packaged and rapidly pushed via the APP (Mobile Application). This mobile application is the endpoint for the User/Authorities and Local Population, ensuring that immediate, life-saving warnings are received instantly on their devices, enabling them to initiate pre-planned control measures, such as implementing emergency drainage or issuing evacuation orders, thus fulfilling the system's mandate for effective disaster mitigation.

III. HARDWARE SETUP

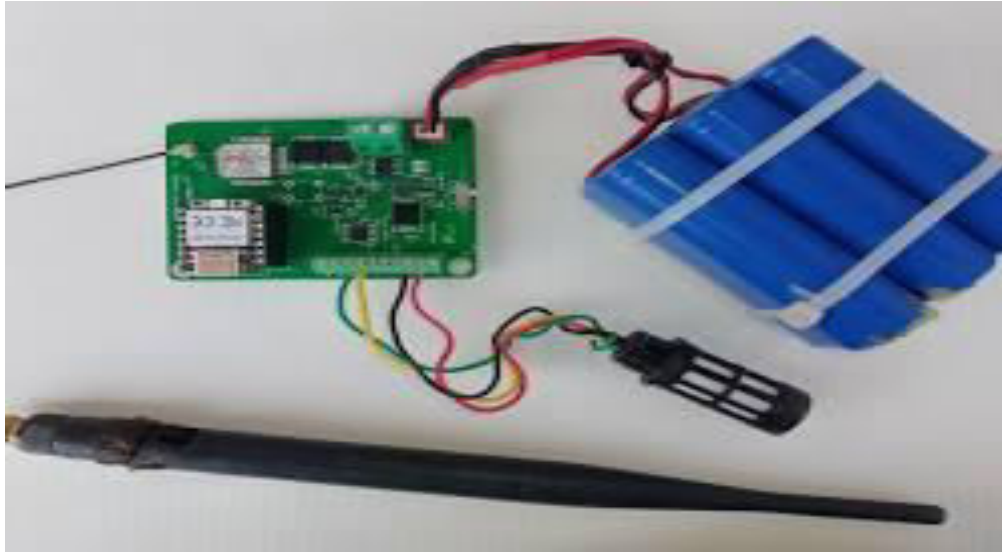


Figure 3: Hardware setup of the proposed system

Merits

1. Real-Time Monitoring- RF communication allows continuous and immediate transmission of sensor data.
2. Remote Accessibility- Mountainous terrains are often hard to access physically.
3. Cost-Effective - Reduces the need for constant manual inspections and Lower infrastructure and maintenance costs compared to wired communication systems in rugged terrain.
4. Early Warning Capabilities- Provides early alerts of potential landslides.
5. Scalability- RF networks can easily be expanded to cover larger or multiple mountain areas.
6. Reliability in Harsh Environments - RF systems can operate in challenging weather conditions (rain, fog, snow) where wired communication might fail.
7. Low Latency Communication- RF communication ensures quick data transfer, which is crucial for fast-developing landslide events.
8. Integration with IoT and Automation - RF-enabled data can be fed into IoT platforms for automated analysis and predictive modeling, enabling seamless integration with alert systems, drones, or control devices for proactive landslide mitigation.
9. Reduced Human Risk- Minimizes exposure of personnel to dangerous slopes, unstable terrain, or landslide-prone zones.
10. Data Logging and Analysis - RF-enabled sensors can transmit historical data for trend analysis.

Monitoring Method	Advantages	Limitations	Application Suitability
Manual Inspection	Simple, low cost	Time-consuming, high human risk	Small-scale slopes, easily accessible are
GPS-based Monitoring	Accurate displacement measurement	High cost, limited real-time capability	Critical infrastructure monitoring
Wireless Sensor Networks (RF)	Real-time monitoring, low human risk, scalable	Signal attenuation in dense terrain	Mountainous, remote, or hazardous areas
Remote Sensing (Satellite/Drones)	Large area coverage, periodic monitoring	Low temporal resolution, high cost	Large-scale landslide-prone regions
IoT + RF Integrated Systems	Real-time data, predictive modeling, alerts	Initial setup cost, requires maintenance	Critical slopes, high-risk zones

Table1: comparison table of landslide monitoring methods



IV. RESULTS AND DISCUSSION

The RF-based landslide monitoring system successfully captured real-time slope movements using tilt, vibration, and soil moisture sensors. Data transmitted via RF communication remained stable up to 1 km, with minimal latency (1–2 seconds), enabling prompt alerts when thresholds were exceeded. The system operated continuously under harsh mountain conditions, including rainfall and wind, with solar-powered nodes maintaining functionality for over a week without interruption. Sensor readings accurately reflected slope instability, validating the system's effectiveness for early warning and monitoring purposes.

The study demonstrates that RF communication provides a reliable, low-latency method for landslide monitoring in remote and rugged terrains. Integration with IoT platforms allows automated data analysis and predictive modeling, facilitating timely alerts and mitigation actions such as evacuations or slope stabilization. Compared to traditional manual monitoring, RF-enabled systems reduce human risk, improve coverage, and allow scalable deployment. Limitations include potential signal attenuation in dense vegetation or extremely steep slopes, which can be addressed through mesh networks or multi-frequency RF communication.

V. CONCLUSION

The development of landslide monitoring and control systems in mountainous areas has been revolutionized by the integration of RF communication technologies, particularly LoRa and 4G. This approach directly addresses the critical limitations of traditional monitoring, such as inaccessibility, lack of power, and insufficient data timeliness. The system architecture, comprising LoRa-enabled Collection Nodes for low-power, wide-area sensing and a 4G-enabled Master Node for high-bandwidth backhaul, successfully creates a reliable, two-tiered communication link. This setup ensures that real-time geotechnical and environmental data (displacement, tilt, rainfall) flows continuously from the remote mountain slope to the Cloud Server and the Management Platform. The core merit of this RF-based system lies in its ability to facilitate rapid, intelligent decision-making by instantaneously running Warning Logic/Analysis Algorithms against incoming data. Ultimately, by providing real-time early warning through mobile applications to authorities and the local population, the system significantly enhances life safety and offers the crucial lead time required to initiate control measures, thereby mitigating the catastrophic human and economic impacts of landslides in high-risk terrains.

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