



Design, development, and deployment of a wireless sensor network for detection of landslides

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ABSTRACT

Wireless sensor networks are one of the most promising emerging technologies, providing the opportunity for real-time monitoring of geographical regions (remote and hostile) that are prone to disasters. With a focus on landslide detection, this work reaffirms the capability of wireless sensor networks for disaster mitigation. A complete functional system consisting of 50 geological sensors and 20 wireless sensor nodes was deployed in Idukki, a district in the southwestern region of Kerala State, India, a highly landslide prone area. The wireless sensor network system has, for the past three years, gathered vast amounts of data such as correlated sensor data values on rainfall, moisture, pore pressure and movement, along with other geological, hydrological and soil properties, helping to provide a better understanding of the landslide scenario. Using the wireless sensor networks, system was developed an innovative three level landslide warning system (Early, Intermediate and Imminent). This system has proven its validity by delivering a real warning to the local community during heavy rains in the July 2009 monsoon season. The implementation of this system uses novel data aggregation methods for power optimization in the field deployment. A report on unanticipated challenges that were faced in the field deployment of the wireless sensor networks and the novel solutions devised to overcome them are presented here.

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1. Introduction

A landslide is a short-lived yet potentially destructive phenomenon. Its causative factors include a steep slope angle, toe cutting (removal of a portion at the foot of the hill), and saturated soil. These factors are more likely in an area considered unstable because of a previous history of landslides. The triggering factor can be either rainfall or earthquakes. India faces landslides every year with a large threat to human life causing annual loss of US \$400 million [1].

The degree of unpredictability of landslides and the rapid change of contributing parameters greatly impacts the complexity in design of an early warning system.

Technology has to be developed to capture relevant signals with a minimum monitoring delay.

The successful implementation of a landslide detection application requires handling massive amounts of data from the wireless sensor network, maintaining its accuracy and integrity and ensuring low-latency transmission of the sensed data with efficient utilization of energy [2]. Wireless sensors are one of the leading technologies that can record rapid changes in data and transmit the sensed data to a data analysis center from the remote hostile regions. Wireless sensor network technology has the capability to capture quickly, process, and transmit of critical high-resolution data for real-time monitoring. It also has the advantage of deploying sensors that require low maintenance, which is ideal for hostile environments.

However, it should be pointed out that the wireless sensor nodes are constrained in the amount of energy and memory they have available to utilize for the application.

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The effective management of these resource constraints determines the lifetime of the network and the frequency of data collection, as well as the collection processing and transmission [24,25].

We have used wireless sensor networks in the landslide scenario for estimating the probability of landslides and to issue early warnings if needed [15]. This work has improved the ability to save lives by producing India's first real-time wireless sensor network for landslide detection. Equipped with a three-level landslide warning system, it uses the readings of moisture, pore pressure, and movement in the earth that can be supervised over the Internet. The design and deployment has provided a feedback loop to improve the algorithms used as well as the software and hardware architecture for the heterogeneous wireless networks. New algorithms solving the concerns of energy optimization and changing environmental conditions had to be developed. To improve the reliability of the system, fault tolerant clustering, energy optimizing topology, and data aggregating algorithms were included in the system design.

A landslide prone area in Anthoniar Colony, Munnar, Idukki (Dist.), Kerala (State), India has had geological sensors embedded in the earth which were connected to wireless sensor nodes. The implementation consisted of a heterogeneous wireless network that includes a wireless sensor network, a Wi-Fi network, a satellite network, a GPRS network, and the Internet. These deployed geophysical sensors have been producing real-time data for three years allowing for a better understanding of landslides and how wireless networks are integral to emergency management.

This project was part of WINSOC¹ project whose primary objective was to obtain the deployment experience from landslide detection experiments to in situ monitoring and to develop and test innovative algorithms implementing the self-organization capabilities of the low level sensors.

The remainder of the paper is organized as follows. Section 2 describes related work in WSN systems and other methods for landslide prediction. Section 3 delineates the sensors for landslide detection. Section 4 explains the multisensor Deep Earth Probe (DEP), the details of sensor placement, and the design of interfacing circuits. Section 5 presents the wireless network design and its architecture. Section 6 describes the wireless software architecture. Section 7 distinguishes the power considerations that were taken into account for the landslide monitoring system. Field deployment and the ensuing design concerns and experiences are described in Section 8. Section 9 summarizes the validation of the complete system, specifies the data results that led to the landslide warning issued in July 2009, and explains the innovative three-level landslide warning method. Finally, we conclude and outline the future work in Section 10.

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2. Related work

The evolution of wireless sensor networks has fostered development in real-time monitoring of critical and emergency applications. A Drought Forecast and Alert System (DFAS) [3] has been developed that uses mobile communication to alert the users. In contrast, this proposed system uses real-time data collection, transmission using wireless sensor nodes, Wi-Fi, a satellite network and the Internet. The real streaming of data through broadband provides connectivity to a wider audience including scientists to laymen, which can provide a capable pool of experts to analyze the landslide data and provide information to the government. Liu et al. [4] describes a wireless sensor network prototype for environmental monitoring of greenhouses. An experimental soil monitoring network using a wireless sensor network is presented by Musaloiu-E et al. [5].

Research has shown that other than geotechnical sensor deployment and monitoring, other techniques such as remote sensing, automated terrestrial surveys, and GPS technology can be used by themselves or in combination with other technologies to provide information about land deformations. Hill and Sippel [6] delineate a state-of-the-art system that combines multiple types of sensors to provide measurements to perform deformation monitoring. Terzis et al. [7] discusses the topic of slip surface localization in wireless sensor networks, which can be used for landslide prediction. A durable wireless sensor node has been developed, which can be employed in expandable wireless sensor networks for remote monitoring of soil conditions in areas conducive to slope stability failures [8].

The currently available system concentrate on deformation monitoring or monitoring only a few parameters that trigger the landslide. Hence the capability of these systems provide early warning for landslides is low and they provides almost no time to evacuate the humans. However, the proposed system monitors all the landslide triggering parameters using the heterogeneous sensors integrated with wireless sensor nodes. Thus providing the capability to issue early warning and save human lives.

3. Sensors for landslide detection

The essential requirement of this study was to identify the sensors needed to monitor and detect landslide phenomena. Selecting the appropriate geophysical sensors requires a thorough knowledge and understanding of landslide phenomena, the parameters that trigger landslides, and the hydrology of the deployment area. Rainfall-induced landslides commonly occur in landslide prone areas during heavy, high intensity rainfall or prolonged medium intensity rainfall. Under heavy rainfall conditions, rain infiltration on the slope causes instability, a reduction in the factor of safety, transient pore pressure responses, changes in water table height, a reduction in shear strength which holds the soil or rock, an increase in soil weight, and a reduction in the angle of repose [19,20]. When the rainfall intensity is larger than the slope saturated hydraulic conductivity, runoff will occur [9].

The most significant physical phenomena to be monitored for early warning of landslides are the changes in moisture content, pore pressure, rainfall, movement, and vibrations inside the earth. After careful study, the geophysical sensors needed for monitoring these phenomena were selected and used. These are:

- **Dielectric moisture sensors:** Capacitance type soil moisture sensors were selected that measures the dielectric constant or permittivity of the soil in which it is buried.
- **Pore pressure piezometers:** As rainfall increases, rain water accumulates in the pores of the soil, exerting a negative pressure which causes the loosening of soil strength. Thus, it is necessary to measure groundwater pore pressure, using either the vibrating wire piezometer or the strain gauge type piezometer.
- **Strain gauges:** A strain gauge is used to measure the movement of soil layers by attaching itself to a Deep Earth Probe (DEP). Deflections in the Deep Earth Probe (DEP) of 0.5 mm per meter need to be detected. So strain gauges of different resistance such as 100 Ω , 350 Ω , and 1000 Ω have been used for deployment.
- **Tiltmeters:** Tiltmeters are used for measuring the soil layer movements such as very slow creep movements or sudden movements. High accuracy tiltmeters are required for this scenario.
- **Geophones:** The geophone is used for the analysis of vibrations caused during a landslide. The characteristics of landslides demand the measurement of frequencies up to 250 Hz. The resolution should be within 0.1 Hz and these measurements need to be collected real-time.
- **Rain gauges:** The effect of rainfall infiltration on a slope can result in changing soil suction and positive pore pressure, as well as the depth of the main water table or the raising the soil unit weight and reducing the anti-shear strength of rock and soil that may trigger a landslide. Maximum rainfall of 5000 mm per year needs to be measured using the tipping bucket. A tipping bucket type of wireless rain gauge in which the tipping event is counted as .001 in. of rainfall was used for the deployment.
- **Temperature sensors:** The physical properties of soil and water change with temperature. Resolution of 1/10th degree celsius measured every 15 min is sufficient.

All the above mentioned geophysical sensors are attached to wireless sensor nodes which are capable of real-time monitoring with bare minimum maintenance.

4. Multi sensor deep earth probe

The many sensors for landslide monitoring were identified and buried underground to measure the pertinent geological and hydrological properties. A Deep Earth Probe (DEP) was devised to deploy these many sensors as a stack in different locations [10–13]. The ideal depth for the DEP to be deployed would be the same as the depth of the bedrock in that location.

The DEP design uses a heterogeneous structure with different types of geophysical sensors at different positions.

The geological and hydrological properties at the location of each of the DEPs determine the total number of each of the geophysical sensors needed and its corresponding position on the DEP. These geophysical sensors are deployed or attached inside or outside of the DEP according to each of their specific deployment strategies. All these geological sensors of the DEP are connected to the wireless sensor node via a data acquisition board as shown in Fig. 1. This apparatus, including the DEP with its sensors, the data acquisition board, and the wireless sensor node, is conjunctly termed Wireless Probe (WP).

4.1. Sensor placement

The spatial distribution and design of geophysical sensors on the DEP are determined by many factors including: the number of soil layers, layer structure, soil properties and variability, hydraulic conductivity of the soil layers, the presence of impermeable layers, the water table height, the bed rock location, depth of the bore hole for deploying the DEP, and the specific deployment method required for each geophysical sensor.

- let the length of the DEP from surface of the earth be l ,
- the maximum number of soil layers up to a depth of l be n ,
- the thickness of i th soil layer be t_i , where i varies from $i = 1, 2, \dots, n$,
- the soil layer number at water table depth be $i = wt$,
- the maximum number of impermeable layers in the bore hole used for the DEP deployment be m ,

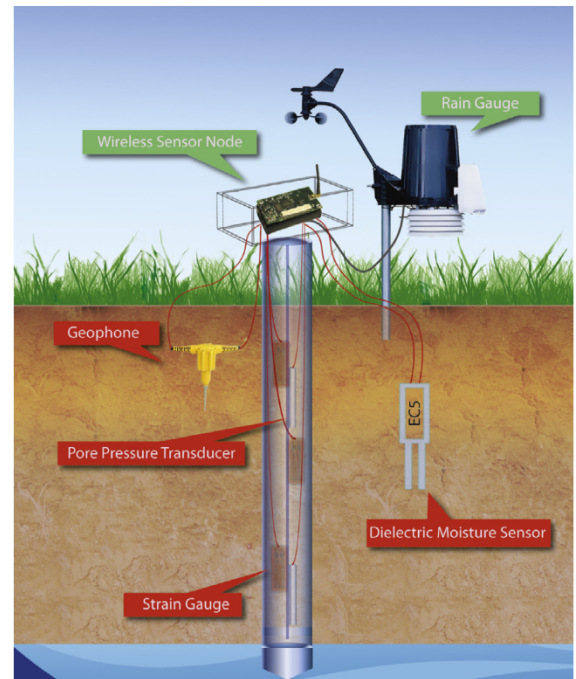


Fig. 1. Multisensor DEP.

- the depth of impermeable layer from the surface of earth can be d_{im} (including the soil layer thickness of the impermeable layer), where im varies from $im = 1, 2, \dots, m$, and
- the thickness of im th impermeable layer be t_{im} , where im varies from $im = 1, 2, \dots, m$.

We developed the formulae for determining the location of each sensor placement and the number of sensors needed for deployment as follows:

4.1.1. Dielectric moisture sensor

Deployment of at least one dielectric moisture sensor (to measure soil moisture) in each of the soil layers is needed. Hence the maximum number of dielectric sensors is given by

$$N_{DMS}(\text{theoretical}) = n \quad (1)$$

However, soil is made up of impermeable and permeable layers. It should be noted that when an impermeable layer is below a permeable layer, the water will infiltrate through the permeable layer and then cannot seep out through the impermeable layer at the same rate, leading to a perched water table that will loosen the soil particles and cause slope instability. Therefore, it is only necessary to insert sensors into the impermeable layers of soil (and not the permeable layers). In addition to the sensors in each impermeable layer, one more sensor is required in the soil above the actual water table to measure the water table's variation in hydrological properties. So, the optimum number of sensors required is given by

$$N_{DMS}(\text{min}) = m + 1 \quad (2)$$

The sensors are placed in the middle of the soil layers since at the boundaries the properties can be quite different.

The sensor positioned in the bottom layer of the borehole, $i = n$ is given by

$$P_{DMS}(n) = l - \frac{1}{2}t_i = l - \frac{1}{2}t_n \quad (3)$$

The sensor positioned in any other soil layer starting from $i = n - 1$ to $i = 1$ is determined using the formula:

$$P_{DMS}(i) = l - \sum_{j=n}^{j=i+1} t_j - \frac{1}{2}t_i \quad (4)$$

The sensor positioned at any impermeable soil layer is determined using the formula

$$P_{DMS}(im) = d_{im} - \frac{1}{2}t_{im} \quad (5)$$

where $im = 1, 2, \dots, m$.

The sensor positioned at the soil layer above the water table height is determined using the formula,

$$P_{DMS}(wt - 1) = l - \sum_{j=n}^{j=wt} t_j - \frac{1}{2}t_{wt-1} \quad (6)$$

Using the Eqs. (5) and (6) the minimum number of dielectric moisture sensors required and their positions can be determined.

4.1.2. Pore pressure piezometer transducer

Deploying at least one pore pressure piezometer (to measure pore pressure) in each of the soil layers is required.

The theoretical number of pore pressure piezometer sensors is given by,

$$N_p(\text{theoretical}) = n \quad (7)$$

For the purpose of pore pressure measurement, piezometers are strategically placed. Similar to dielectric moisture sensor placement, piezometers are placed in each impermeable soil layer and at the water table. Differing from dielectric moisture sensors, additional piezometers are placed in the layers above and below the impermeable layer. In contrast to dielectric moisture sensors piezometers placed at the water table, there are additional piezometers placed in the layers above and below also. These additional piezometers are required to capture varying water levels. Therefore, the minimum number of pore pressure piezometer sensors is given by

$$N_p(\text{min}) = m + 2 * m + 3 \quad (8)$$

The sensor positioned in the bottom layer of the borehole $i = n$, the sensor positioned in any other soil layer starting from $i = n - 1$ to $i = 1$, and also the sensor positioned at any impermeable soil layer is determined by adapting the formula used for dielectric moisture sensor such as Eqs. (3)–(5) respectively. The pore pressure piezometer sensor positioned at the any other soil layer above the impermeable layer is determined using the formula:

$$P_p(im - 1) = l - \sum_{j=n}^{j=im} t_j - \frac{1}{2}t_{im-1}. \quad (9)$$

The pore pressure piezometer sensor positioned at the any other soil layer below the impermeable layer is determined using the formula:

$$P_p(im + 1) = l - \sum_{j=n}^{j=im+2} t_j - \frac{1}{2}t_{im+1} \quad (10)$$

The pore pressure piezometer sensor positioned at the any other soil layer above the water table height is determined by adapting the Eq. (6), and the pore pressure piezometer sensor positioned at any other soil layer below the water table height is determined using the formula:

$$P_p(wt + 1) = l - \sum_{j=n}^{j=wt+2} t_j - \frac{1}{2}t_{wt+1} \quad (11)$$

4.1.3. Strain gauge

Strain gauges are attached on the outside of the DEP. Strain gauges measure the movements induced by sliding soil layers. Water table depth is not relevant to strain gauge sensor placement. To efficiently capture the movements, multiple strain gauges are placed in the middle section of the DEP, and also in impermeable layers that may contribute to slope instability. We adapted the Eqs. (3) and (4) to determine the position of a strain gauge sensor in each layer. The soil layer movement at the landslide prone areas can be in any direction. Therefore to capture

the movement in multiple directions, the strain gauges in are placed in either x , y -direction, or three strain gauges separated by 120° . Hence the theoretical number of strain gauge sensors is given by

$$N_{SG}(\text{theoretical}) = n * 3 + 3 \quad (12)$$

In the field, each vulnerable layer has three sensors placed in the expected direction of movement. Also, three sensors are deployed at the middle of the DEP. Therefore, the minimum number of strain gauge sensors is given by

$$N_{SG}(\text{min}) = 2 * m + 3 \quad (13)$$

4.1.4. Tiltmeter

The purpose of the tiltmeter is to capture the change in angle experienced by the DEP during slope instability. The tiltmeters are placed in each of the soil layers to capture the tilt accurately. We adapt the same equations used for the dielectric moisture sensor such as Eqs. 1, 3 and 4 to determine the theoretical number of tiltmeters, and the position of the tiltmeter at each layer.

Intense rainfall and the presence of impermeable layers contribute to slope instability. Therefore, tiltmeters are deployed in the impermeable layers, and also a tiltmeter is placed inside at the center of the DEP. Therefore, the minimum number of tiltmeters is given by

$$N_T(\text{min}) = m + 1 \quad (14)$$

4.1.5. Geophone

A geophone is used to measure the vibrations experienced during slope instability. Geophones are placed on the surface of the earth. Three geophones are deployed at each region (toe, middle and crown of the hill) of the landslide prone area. The three geophones at each region will perform triangulation techniques providing detection of vibrations. Therefore, the theoretical number of geophones is given by

$$N_G(\text{theoretical}) = r * 3 \quad (15)$$

where r is the number of distinctive regions in the landslide deployment field. The vibrations due to slope instability can be captured using at least one geophone in each of the regions. Our current deployment consists of three regions. Therefore, the optimum number of geophones is given by

$$N_G(\text{min}) = 3 \quad (16)$$

4.1.6. Rain gauge

Rain gauges measure the rainfall intensity. They can be deployed separately from the DEP in different regions. The theoretical number of rain gauges is given by

$$N_{RG}(\text{theoretical}) = r \quad (17)$$

The deployment field should have at least one rain gauge. Therefore, the minimum number of rain gauges is given by

$$N_{RG}(\text{min}) = 1 \quad (18)$$

There are specific deployment methods for each sensor. Dielectric moisture sensors and geophones are deployed outside the deep earth probe (DEP) in the respective soil layers whereas the strain gauges are attached to the outer surface of the DEP, and the tiltmeters are placed inside the DEP. Multiple pore pressure sensors are deployed in the same bore hole at different depths. Each pore pressure sensor is attached to a separate DEP. These pore pressure DEPs have a lesser cross sectional area than the DEPs used for other sensors. Rain gauges are deployed above ground at a predetermined height.

4.2. Spatial distribution of deep earth probes

Different approaches can be used for the deployment of these DEPs. Some of the approaches considered are

- Random approach: DEPs are deployed at non-specific locations of a landslide prone mountain.
- Matrix approach: Sectoring the total area of deployment, A , into a matrix of $N \times N$ size. and one DEP is placed in each cell of the matrix. The cell size of the matrix is found by identifying the maximum range covered by each sensor (sensor coverage) present at the DEP. The sensor covering the smallest range determines the cell size in the matrix ensuring complete coverage of the area.
- Vulnerability index approach: Deploying DEPs in vulnerable regions that have been identified during the site investigation, terrain mapping, and soil testing.
- Hybrid approach: This approach incorporates both the matrix approach and the vulnerability index approach.

The current deployment uses the hybrid approach. The whole deployment area was initially sectoried using a matrix approach. In each cell, the deployment location of the DEP was decided after considering the vulnerability index approach. This combination of approaches helped to maximize the collection of relevant information from the landslide prone area.

5. Wireless network design and architecture

One of the important requirements for any landslide detection system is the efficient delivery of data in a real-time manner. This objective requires seamless connectivity with minimum delay in the network. The architecture we have developed for satisfying the above requirements is shown in Fig. 2.

The complete architecture is developed by integrating different heterogeneous wireless networks such as,

5.1. Probe network

The probe network is developed to capture the prevailing geological and hydrological parameters in a landslide prone area. This probe network has 20 wireless sensor nodes built on different hardware platforms. The first hardware platform, a Crossbow MicaZ follows a three-layer hierarchy with a lower level (wireless probes), a

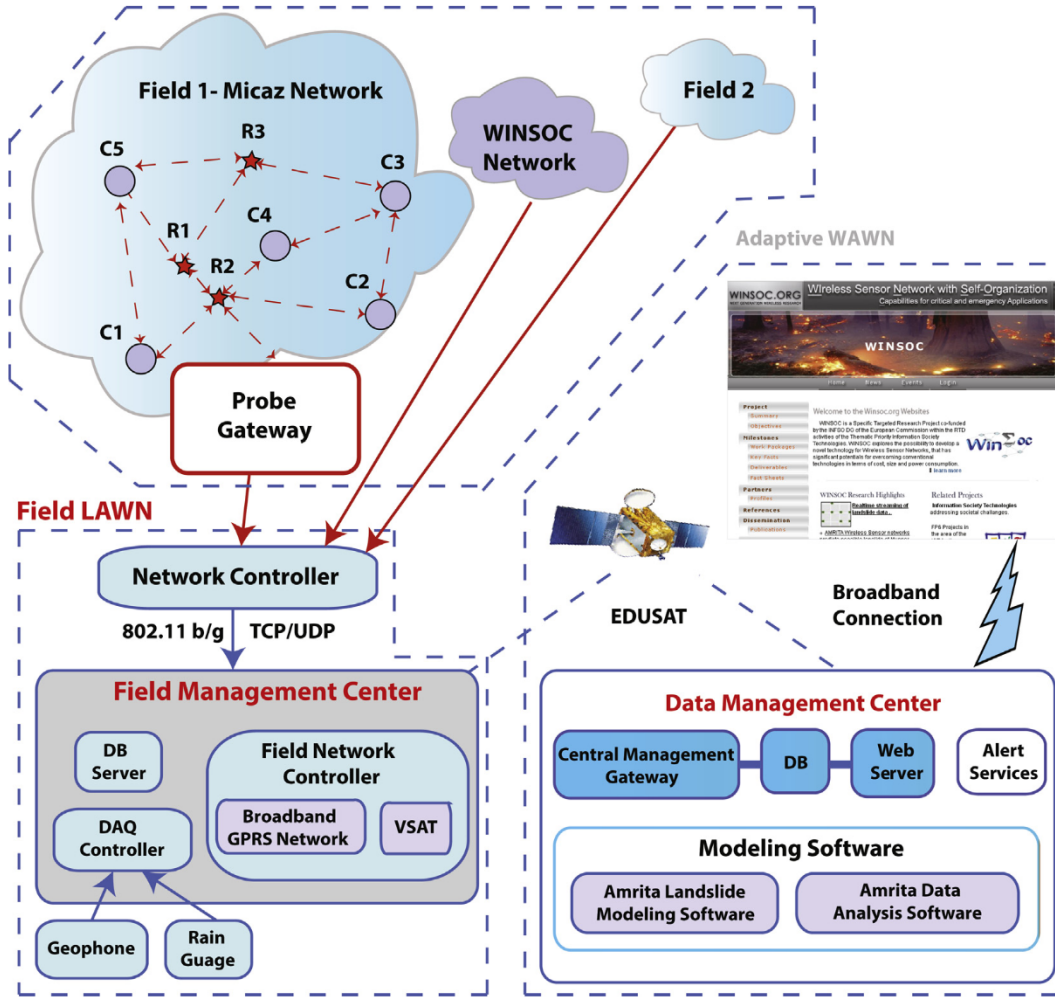


Fig. 2. Wireless sensor network architecture for landslide detection.

middle level (cluster head), and a higher level (sink node). The wireless probes with the lower level nodes sample and collect the heterogeneous data from the DEP, and the data packets are transmitted to the middle level which aggregates the data and forwards it to the probe gateway (sink node) maintained at the deployment site.

To improve the performance, reliability, and energy consumption of the wireless sensor nodes in a landslide scenario, a special purpose WINSOC wireless node, shown in Fig. 3a and b, was developed. The WINSOC network was able to extensively test and validate the wireless sensor nodes using the WINSOC distributed consensus algorithm [16–18].

5.2. Field LAWN

A Field LAWN (local area wireless network) is designed to transmit the data received at the probe gateway to the VSAT earth station at the Field Management Center (FMC), which are separated by approximately 500 m. A Wi-Fi network is used to link the probe gateway to the Field LAWN. The data received from the probe gateway is duplicated and stored in a database server.

5.3. Adaptive WAWN

Adaptive WAWN (Wide Area Wireless Network), which consists of a satellite network, a GSM/GPRS network, and a broadband network, is used to provide wide area connectivity. The data received through the Field LAWN is transmitted to the destination using an Adaptive WAWN (Wide Area Wireless Network). The deployment field is 300 km away from our Data Management Center (DMC) at the university; hence the data is transmitted using the VSAT (Very Small Aperture Terminal) satellite earth station. The DMC consists of the database server and an analysis station, which performs data analysis, landslide modeling and simulation on the field data to determine the landslide probability [28,26]. The real-time data and the results of the data analysis are streamed on the Internet in real-time [27]. Alert services such as e-mail, SMS and MMS are implemented to alert researchers about the probability of landslides, the status of the network, and the monitoring of the system components. Under extreme conditions, the WAWN has the capability to switch to whichever network is available. For example, if the VSAT network is not



Fig. 3. Field deployment of WINSOC node.

available, the broadband or GPRS connectivity at the FMC is used for uploading the real-time data directly to a web page with minimum delay, thus providing fault tolerance.

The entire system is equipped to dynamically monitor the level of battery charge remaining and the rate of solar charging. The system also monitors all wireless sensor nodes and geological sensors to detect faulty nodes or sensors. A feedback loop is used that dynamically changes the sampling rate of the geological sensors, with respect to the real-time climatic variations.

This proposed network architecture is scalable, as any number of nodes and new landslide deployment fields can be incorporated and connected to the same FMC via a Wi-Fi network. In the future, this architecture will provide the capability to monitor many large areas and also to incorporate the different spatio-temporal analysis to provide an even better understanding of landslides.

6. Wireless software architecture

The heterogeneous wireless networks such as the wireless sensor network, Wi-Fi networks, satellite network, and broadband network are used for the landslide detection system. The data collection, processing and transmission techniques in each of these networks are different and each of them demands different requirements to achieve seamless communication with minimum delay. The software architecture we have developed is capable of achieving all the above requirements. Software interfaces and modules for different processes required for these heterogeneous wireless networks have been designed, implemented and tested in the deployment field.

6.1. Sensor network software

The software modules implemented for the wireless sensor network consist of three root modules namely:

1. **Data Acquisition Module:** This module is developed to provide the capability of collecting data from both digital and analog geophysical sensors. It is implemented for data collection from the DEPs. The digital data arriving from the rain gauge is collected using the digital drivers implemented in this module. The analog drivers are utilized for data acquisition from the sensor circuits and excitation circuits.
2. **Data Processing Module:** Large distributed monitoring applications require scheduling the events and managing each node's buffer to avoid loss of events and data. The data processing module is the core component for processing all the incoming and outgoing data from the sensors and transceivers respectively in our wireless sensor network. The main functionalities implemented in this module are scheduling the events and managing the buffers in a distributed environment. The scheduler module implements four basic functionalities:
 - **Sensor sampling:** This module is designed to provide efficient communication between the geophysical sensors and the wireless sensor node attached to it, through the custom developed interfacing circuits. It has the capability to sample and collect geophysical sensor data in the user defined inter-sampling rate. This data is then sent to the buffer manager module.
 - **Health monitoring:** This module is designed and implemented to monitor the health of the network and of the wireless sensor nodes. The node health functionality provides the status of power in the node, the health of the battery, and other required aspects. The network health functionality is used to identify the dead nodes in the network by periodically updating the neighborhood address. These neighborhood addresses will be used for efficient routing of the data to the probe gateway.
 - **Power saving:** This module is designed to provide power saving mechanisms to the wireless sensor nodes. It is implemented by integrating wireless

sensor node state transitions such as 'sleep', 'monitor', 'active', and 'off'. Power saving can be further improved by implementing geophysical sensor state transitions.

- Time synchronization: The module provides time synchronization between the motes and is implemented using a linear regression method between the motes. Time synchronization is currently implemented using the following phases:
 - Synchronization of wireless sensor nodes to a unique (global) clock value.
 - Synchronization of the global clock to the UTC time using GPS receiver.
- 3. Data Communication Module: The main functionalities implemented in this module are the routing and the configuration management. The routing module is used for configuring the routing method by implementing routing algorithms and time synchronization methods [18]. The configuration assistant is used to configure the wireless sensor node to act as a configuration assistant when the need arises.

The Fig. 4 shows the different modules implemented in a wireless sensor node.

6.2. Probe gateway software

The wireless probe gateway consists of one or more sink nodes or base stations. The functionality of the sink node is to listen to the packet transmissions in the wireless sensor network and log and store them if the package transmissions are addressed to that particular sink node. This sensor data is accessed through the Wi-Fi network. During a faulty Wi-Fi network condition, the data can be retrieved using either the GSM network or the Ethernet interface of the sink node.

The wireless probe gateway is also implemented with a client utility that provides the functionality to broadcast any configuration information into the network. The software routines implemented in the wireless probe gateway are divided into four categories:

- Sink node module: This module is designed and implemented to collect and filter the incoming data packets based on their destination id, group id, or broadcast id, and processes them for transmission to the Field Management Center (FMC).
- Packet processing routine: This module is designed and implemented to act as a central point of contact for all sink nodes, data loggers and configuration routines. All data packets to and from the wireless sensor network are received and transmitted respectively, through these processing routines.
- Packet parsers and data loggers: This module is designed and implemented to prevent congestion by prioritizing and queuing the inflow and outflow of the packets. Each of these packets is passed onto the data logger once the CRC (cyclic redundancy check) is verified. It logs all the data from the processing routines based on the address id of each of the packets. It also stores the date, time, node ID, sequence number and the sensor data values in an archive of secondary storage.
- WSN configuration routines: The configuration routines are designed and used to send the configuration packets to the network. The configuration packet includes the different sampling rates, destination id, routing ID, etc.

6.3. Middleware for heterogeneous wireless networks

The middleware is built using a Service Oriented Architecture (SOA) that provides the distributed virtual environment for the heterogeneous wireless networks used for

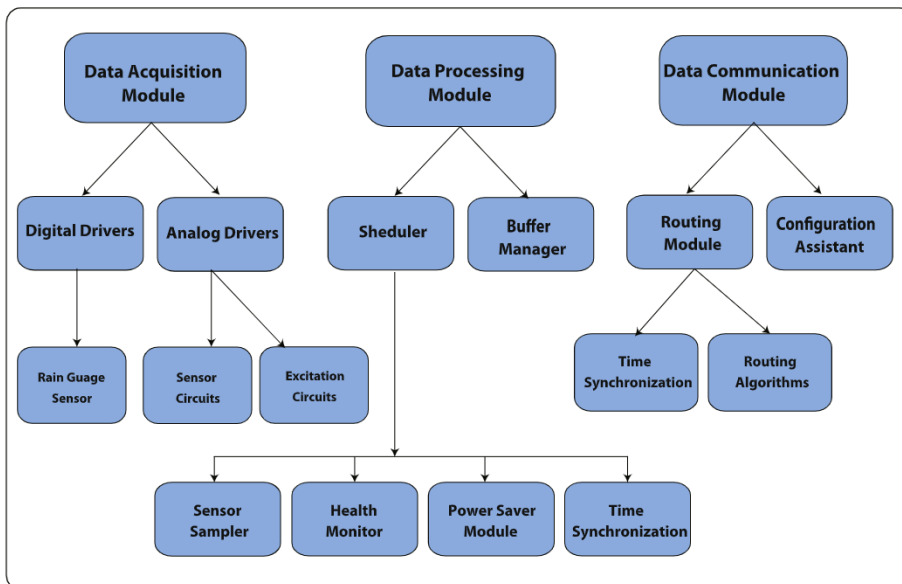


Fig. 4. Wireless sensor network software modules.

this system development. SOA communicates through service brokers such as an Enterprise Service Bus (ESB). ESB provides a number of higher-level services that facilitate service reuse and event driven service initiation. These higher level services are used to implement the required functionalities needed for the different wireless networks such as packet loss handling, bulk data transfer, packet format handling, and remote administration. This architecture abstracts the complications of handling multiple wireless networks and provides a seamless virtual network layer. Since the functionalities are designed under ESB, these services are scalable and follow well-defined interfaces, so that any client (independent of platform) can talk to these services. Also, the different subsystems in the middleware are designed independently so that failure of one system will not affect the other. These systems use a distributed computing architecture that allows them to be controlled remotely. Fig. 5 shows the block diagram of the middleware.

Fig. 6 shows the block diagram of the different modules implemented in the Data Management Center. One of the important requirements of any real-time network is traffic control in the network. This is implemented using the module Bandwidth Utilizer that provides the capability to calculate the amount of traffic in the network and to control the injection of data in accordance with the current traffic. Other than this module, the Congestion Controller module is also implemented. Both the modules are customized to work independently for the connected network e.g. VSAT, Internet. The system logs all the events, and it works both in synchronous and asynchronous modes. These modes provide the capability to connect to any external services such as a database, messaging servers, and http support.

Real Time Data (RTD) services are implemented to collect the real-time data. Depending on bandwidth availability, these services provide the capability to dynamically adjust the frequency with which the real-time data is

collected and acknowledgments are sent. The BDE (Bulk Data Enabled) services are implemented for packet loss handling, bulk data handling, packet error handling, detection of network termination, and for varying acknowledgment levels. The RNC (Real-time Network Configurator) services are implemented for the remote administration of the wireless sensor network from the DMC. Packet tracking performs two functions. Firstly, it monitors the status of the packet transmission. Secondly, it allows access to only one user, for each RNC service, at any given time. The thread pools and load balancing on the shared resources are monitored and analyzed to prevent dead locks. The whole functionality of this architecture provides a virtual, distributed environment for the different wireless networks used in the development of the landslide detection system.

The wireless sensor network system for landslide detection is deployed in a remote, hostile region that experiences extreme climatic conditions, which may cause the network to experience problems such as a non-responding FMC network, system crashes, and depletion of resources. These rare events are also handled using the middleware modules.

Whenever the network is down, the sensor data is cached in the gateway, and once the network is reactivated or reconnected, then the cached data is relayed to the FMC. If the system crashes due to some unexpected rare events, the state of the gateway is logged and reverted back when the system reactivates. Resource allocation is controlled and maintained to prevent the depletion of resources.

The different modules implemented in the heterogeneous wireless networks, using service-oriented architecture, provide a virtual, distributed network for the real-time wireless sensor network for landslides. All these modules together provide a seamless connectivity, with reliable minimum data packet loss and low energy consumption. The complete software architecture provides

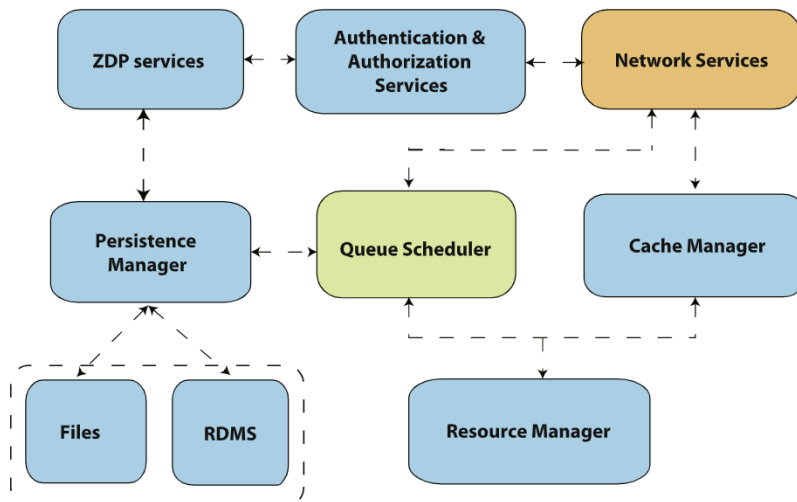


Fig. 5. Middleware.

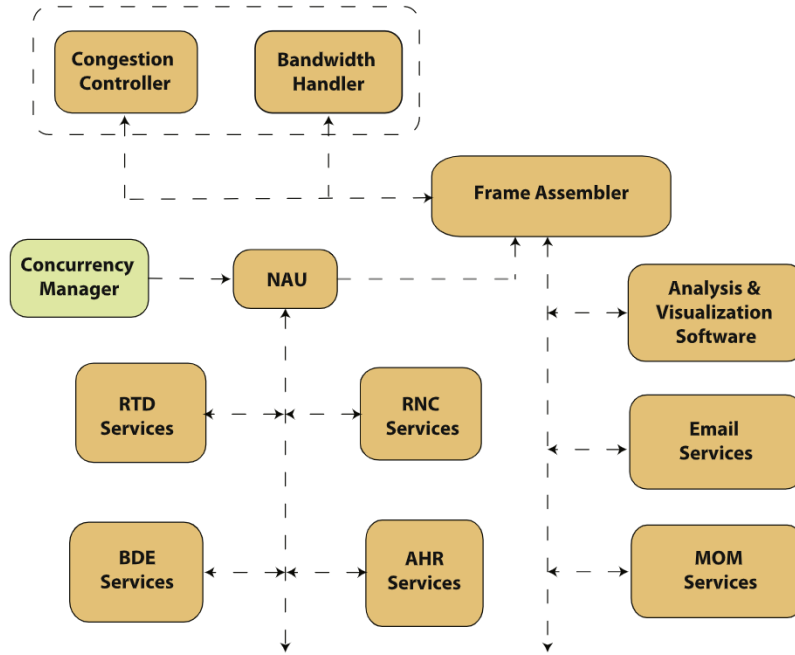


Fig. 6. Block diagram of the modules implemented in the data management center.

a lightweight management framework for the real-time landslide detection system.

7. Power considerations

The wide area monitoring of the wireless sensor network can be performed in a centralized or distributed manner. In this research, the wireless sensor network architecture for landslide detection uses a three-layer hierarchy. The wireless probes (lower level nodes) sample and collect the heterogeneous data from the DEPs, and the data packets are transmitted to the cluster head (middle level node). The cluster head aggregates the data and forwards it to the probe gateway (higher level).

The geological and hydrological properties of each of the locations of the landslide prone area differ with respect to the varying regions they belong to. So the data received from each of the sensors cannot be aggregated together due to the variability in geological and hydrological soil properties. Therefore, the whole landslide-prone area is divided as regions of unique properties. In this particular case, the deployment area is divided into three regions such as crown region, middle region, and toe region as shown in Fig. 7, and numerous wireless probes (wireless sensor nodes attached to the DEPs) are deployed in these regions.

Power constraints are one of the major challenges experienced by researchers wanting to do real-time deployments. Power can be efficiently utilized, using either hardware or software or hybrid solutions. Three different algorithms (fault tolerant hierarchical clustering algorithm [21], energy optimization algorithm [22], and threshold based data aggregation algorithm [14,23]) have been developed and implemented in the wireless sensor net-

work for landslide detection. The main purposes of these algorithms are to reduce the energy consumption of the whole network, reduce packet transmission delay, reduce redundant data collection, transmission and processing, and also to incorporate fault tolerant capabilities throughout the network.

The power requirements of the deployment vary depending on a spatio-temporal basis, taking into account the amount of connected components. The geophysical sensor excitation requires different levels of power (e.g. the dielectric moisture sensors, pore pressure sensors, and strain gauges require 30 mW, 300 mW, and 435 mW respectively.) The geophones are self-excited, so no power is needed. The interfacing circuit and power circuit needs approximately 635 mW, 900 mW respectively. The wireless sensor node and data acquisition board, gateway, Wi-Fi access point, and satellite network requires 81 mW, 6600 mW, 10,000 mW, and 8000 mW respectively. The field management center and the data management center needs approximately 1620 W.

Indigenous power circuits are developed to provide constant power for the excitation of the geophysical sensors, wireless sensor nodes, and interfacing circuits. The power (circuit) board provides multiple outputs from a single power battery input, a non-regulated 6 V DC supplied from rechargeable lead acid batteries. The power board is designed with high efficiency regulator chips to provide multiple outputs such as +2.5 V, -2.5 V, +3 V, +15 V for different requirements. These IC's are loaded to only 5–10% of the rated full load current.

The lifetime of the lead acid battery used for the deployment depends on the rate of power consumption by the geophysical sensors, wireless sensor nodes, and the interfacing circuits. These batteries are automatically recharged by the solar recharging unit using the charge controller.

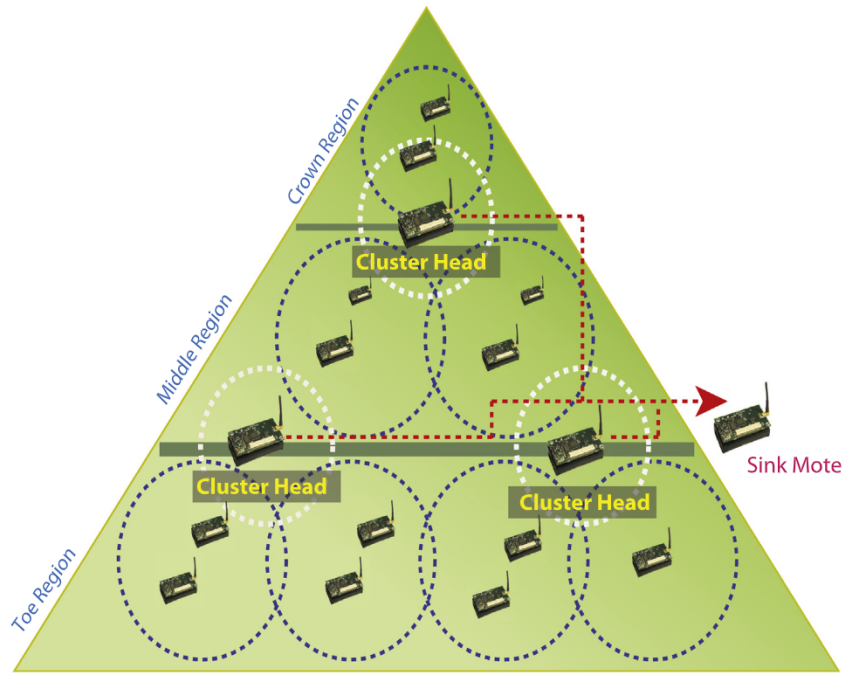


Fig. 7. Regionalized wireless sensor network architecture for landslides.

The function of the charge controller is to provide the correct voltage for charging the battery and to prevent over-charging the battery.

Each solar panel can output 3 W of power at 8 V under maximum sunlight conditions. For each DEP, six panels are connected in parallel for a total of 18 W. This wattage is enough for charging drained batteries in one hour of sunlight which is helpful since the deployment site experiences many months with a high percentage of cloud cover and rain. The batteries used are a rechargeable sealed lead acid type with 36 A-h capacity at 6 V. The charge controllers were also brought inside the waterproof battery to keep them isolated from the electronics circuits.

Software power solutions are implemented by integrating automatic on and off switching of the geological sensors and the different state transitions of wireless sensor nodes as described in the research paper [14]. Efficient use of power and an optimized lifetime has been achieved by these hardware and software solutions.

8. Field deployment

The wireless sensor network for landslide detection system is deployed at Anthoniar colony, Munnar, Idukki (Dist), Kerala (State), India, shown in Fig. 8. The deployment site has historically experienced several landslides, with the latest one occurring in the year 2005, which caused a death toll of 8 people.

The wireless sensor network for landslide detection system is deployed in an area of seven acres of mountain. The whole area consists of approximately 20 wireless sensor nodes and 20 DEPs consisting of approximately 50 geological sensors. Important research focal points included the

determination of the DEP locations, designing and constructing the DEPs, DEP deployment methods, interfacing circuitry, wireless sensor network, Wi-Fi network, satellite network, and power solutions, soil tests, and data analysis.

Extensive field investigations were conducted for identifying the possible landslide prone areas for the deployment of the system and also for identifying the possible locations for DEP deployment. The borehole locations for the DEPs were chosen so as to measure the cumulative effect of geographically specific parameters that cause landslides.

The field deployment was performed in phases: The pilot deployment in January 2008–March 2008 and the main deployment from January 2009 to June 2009. The period in between these phases involved extensive testing and calibration processes.

8.1. Field selection

Extensive field investigations were conducted for identifying the possible landslide prone areas for the deployment of the system in the state of Kerala, India. Approximately areas that had historically experienced landslides were visited and studied. After extensive investigation of the 15 sites, five sites were identified as potential field deployment sites for a wireless sensor network in landslide monitoring applications. Other sites were also visited but were not deemed suitable for the field deployment due to various factors: difficulty of access, uncertainty about the landslide risk, lack of communication facilities, and the size of the potential landslide, among others.

From the shortlisted five landslide prone sites, Anthoniar Colony was selected for deployment, which is located



Fig. 8. Deep earth probe deployment locations at the Anthoniari Colony Site, Munnar, Kerala, India.

700 m Northwest of Munnar town. A first slide had occurred many years earlier. On July 25th, 2005, another landslide also occurred in Munnar at the Anthoniari colony. A torrential rainfall of 460 mm in the middle of the monsoon period was the primary trigger. Three levels of slide area can be observed at the Anthoniari Colony, as shown in the Fig. 8.

There is a high probability of another slide at this location. Some of the factors that indicate a probability of landslide is the seepage flow during the dry season, long vertical and horizontal cracks, the soil material has a large amount of quartz vein, and the soil type is reddish colored sticky clay. Even now when the rain falls, water will flow down onto the top of the houses that are at the foot of the hill, indicating water saturation and higher pore pressure at the toe region, which can indicate a landslide in the future.

8.2. Deployment of deep earth probe

One of the important activities required for deploying the landslide detection system is bore hole drilling. The location and depth of bore holes determines the maximum amount of geological and hydrological properties that can be gathered from the field for the functioning of the landslide detection system. Hence, the most important parameters that determine the bore hole design include the decision of location, depth, and diameter of the planned bore hole, soil sample extraction methods to be adopted, field tests involved, and the bore hole drilling method.

Different types of bore hole drilling are available such as the hand auger method and the rotary drilling method. After the site investigation at Munnar, the pilot deployment on February 2008 was performed at three locations using the hand auger method (maximum depth of 5 m).

These were at location 1, which is at the toe region, and location 2, which is at the middle region of the hill. The rotary drilling with mud circulation method was used for the January 2009 deployment. This method helped to dig bore holes as deep as 23 m, consuming less time and labor compared to the hand auger method. During the drilling operation, both undisturbed and disturbed soil samples were retrieved for the purpose of determining the soil properties. Also, at every 4-m depth and whenever a major soil layer change was experienced, field permeability tests were performed. Drilling continued until bedrock was observed unless the bedrock was too deep. In that case, drilling was continued until the observation of weathered rock unless, that too, was too deep, in which case, drilling was stopped at a major soil layer change after the water table. The decision of the borehole depth was dependent on the location of the hole, vulnerability of the location, sensor deployment requirement, water table height, and location of weathered rock or bedrock.

The deep earth probe (DEP) design was influenced by the local geological and hydrological conditions, the terrain structure, and accessibility of that location. The distribution pattern of different types of geophysical sensors at different depths of the DEP was unique depending on the characteristics of each specific location.

The DEPs were designed in a three-stage process. Initial DEP designs were made for the pilot deployment, which consisted of three DEPs with ten sensors in the field, along with six wireless sensor nodes. These DEPs housed piezometers, dielectric moisture sensors, tiltmeters, strain gauges, and geophones. In the main deployment, the spatial granularity was increased to 20 DEPs and 20 wireless sensor nodes. Multiple DEPs were installed in six locations (labeled henceforth as either C1, C2, ..., C6), shown in Fig. 8. These locations were identified as ideal for the

deployment of the geological sensors, for the following reasons.

- C1: A location at the toe region of the hill with substantial pore-water pressure underneath the ground. Constant seepage flow is observed at this location even during the summer season.
- C2: Another location at the toe region of the hill with substantial pore-water pressure underneath the ground. Constant seepage flow is observed at this location even during the summer season.
- C3: Located at the middle region of the hill.
- C4: A location near the crown of the hill where creep movements are evident.
- C5: Located at the middle region of the hill. This region experiences creep movements and also the most vulnerable region evident with large cracks that separate the land forms.
- C6: A relatively stable location in the upper regions of the hill. Geological sensors have been deployed in this region so as to compare differences in the responses of sensors that are placed in unstable locations with sensors that are placed at relatively stable positions.

The DEPs were redesigned for the main deployment, based on the experiences with the pilot deployment. Main deployment DEPs were placed significantly deeper than the pilot deployment, on average two to five times deeper, with a maximum depth of up to 23 m, penetrating to the weathered rock or bedrock. The geological sensors were attached to the ABS plastic inclinometer casing according to the geological or hydrological parameter that will be measured. The pore pressure sensors are attached to the DEP at different positions (at water table level, at the soil layers above and below the water table level, at impermeable layers, and at the soil layers above and below the impermeable layers). The sensor placement at these positions provides the capability to capture the water table fluctuations and the corresponding pressure generation. The strain gauges were attached at the middle of the DEP (middle of the bore hole), and at the middle position of each of the soil layers, which allows the sensors to capture the movements that may arise at any of the soil layers. The infiltration rate is captured by multiple dielectric moisture sensors. A maximum of three dielectric moisture sensors were placed in each borehole. The first dielectric moisture sensor was always placed in the top soil layer of the

borehole, the others were spaced 1 m consecutively deeper than the previous. The geophone was deployed at approximately 30 cm depth.

Eight external sensors is the maximum number that can be attached to the data acquisition board of Crossbow's wireless sensor nodes. Due to the above-mentioned constraint, even if more external sensors are deployed, only eight of them can be attached to the data acquisition board. In the future, this constraint will be rectified by using a multiplexer. The details of the connected geological sensors as on June 2009, is detailed in Table 1.

External hardware components have three enclosures that are used to protect the data acquisition and transmission equipment for the wireless sensor node – one electronics box and one power box as shown in Fig. 9b) and are attached to poles equipped with solar panels and external antenna. These were designed and then fabricated at the University.

8.3. Network implementation and integration

The network consists of a wireless sensor network, Wi-Fi network, a satellite network, a broadband network, a GPRS network, and a GSM network. The network integration of all the components requires different software and hardware implementations. The design and development of a wireless sensor network for the landslide scenario involves the consideration of different factors such as terrain structure, vegetation index, climate variation, accessibility of the area, location of DEP, transmission range, identification of the communication protocol and radio interface technology, the application specific algorithms for data collection and aggregation, and routing and fault tolerance. The wireless sensor nodes used for the deployment were 2.4 GHz MicaZ motes from Crossbow. The MDA 320 from Xbow was the data acquisition board used to interface the sensors with the MicaZ motes. The MicaZ samples and processes the sensor values from the MDA board that has up to 8 channels of 16-bit analog input, logs it, and sends it to the communication routines for packetizing, framing, check sum generation, etc.

Although the manufacturer specified that the MicaZ nodes could transmit up to 100 m, in ideal field conditions (flat dirt ground, dry weather), the maximum range was only 50 or 60 m even after the motes were placed 2 m above the ground. Due to this shorter transmission range, a number of relay nodes were used to maintain communication

Table 1

Main deployment – details of geological sensor deployment, location and its depth of deployment.

DEP location	Depth (m)									Geophone	Rain gauge height (m)
	Piezometer	Moisture Sensor		Strain Gauge							
		1	2	1	2	3	4	5	6		
C1	5.5	0.8	3.05	1.5x	4x	4x	7x			0.5	
C2	6.8	1.73		3x	3y	6x	6y	9x	9y		
C3	15.4	1		7.5x	7.5y	10.5x	10.5y	16.5x	19.5y		
C4	18	2		3.5x	3.5y	6.5x	9.5x	11.5x	11.5y		
C5	14	1.37		4.25x	4.25y	10.75x	10.5x	10.5y	15x		3
C6	19.75	2		2x	2y	5x	5y	11x	17x		

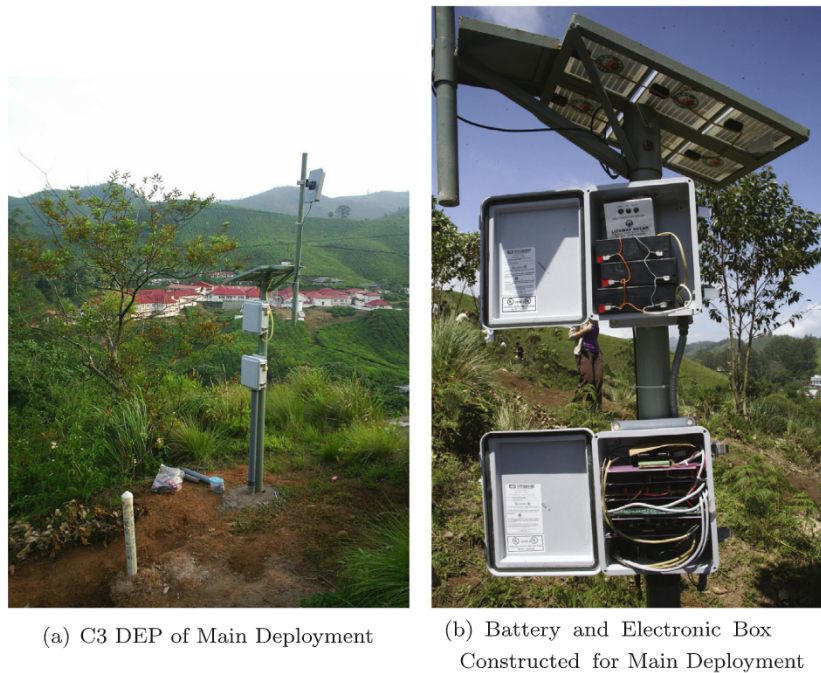


Fig. 9. Deep earth probe deployment.

between the DEPs. These relay nodes required extensive testing for careful placement such that the network connectivity can be maintained even in the worst case weather conditions. External antennas were also used to maintain network connectivity.

The gateway is based on an AMD Geode Mini-ITX Motherboard. The base station listens to the packet transmissions in the sensor network and logs them if they were addressed to it. The sensor data is stored and then accessed through the Wi-Fi network or through the Ethernet interface of the probe gateway.

Data received at the probe gateway is transmitted to the Field Management Center (FMC) using a Wi-Fi network. The Wi-Fi network uses standard off the shelf Wi-Fi components, such as a compact flash Wi-Fi card at the gateway and an Ethernet wireless access point at the Field Management Center. The Wi-Fi network allows us to install the gateway at any scalable distance from the FMC. The FMC incorporates a VSAT (Very Small Aperture Terminal) satellite earth station and a broadband/GPRS network for long distance data transmission.

Data received at the FMC is transmitted to the Data Management Center (DMC) using a satellite network. The data received at the DMC is analyzed using an in-house designed data analysis and visualization software. This software is interfaced with landslide modeling software and data analysis software developed at AMRITA. Landslide modeling software provides the factor of safety of the mountain and the probability of landslide occurrence with respect to the signals received from the deployed sensors. Data analysis software provides the capability to compare and analyze data from different DEPs, different sensors in the same DEP, the same sensors in different DEPs, selective comparison, etc.

The data analysis and visualization software also has the capability of real-time streaming of the data, as well as the results of the data analysis, over the Internet. This system provides an additional capability for the scientists around the world to analyze the data with minimal delay and an effective warning can be issued immediately.

9. Validation of the complete system – landslide warning issued

A novel and innovative decision support system for landslide warning has been developed using a three level warning (Early, Intermediate and Imminent). The decision for each level depends on the moisture (Early), pore pressure (Intermediate), and movement (Imminent) sensor data values correlating with the rainfall intensity.

Each of the sensors reacts to rainfall in a different time frame and intensity, as they monitor different physical processes. During heavy rainfall, the moisture sensor is the first sensor to saturate compared to the other types of sensors, and the data will remain unchanged after the volumetric water content has approached approximately 100%. At this point, the system will issue the early warning or the first level of warning. As time progresses and if the rainfall rate remains the same or if the intensity has increased, change in pore water pressure values can be seen with respect to the infiltration rate. When the system identifies that the pore pressure value also has saturated, the system will issue the intermediate or second level warning. At this point in time, the warning will be issued to the local community and government officials and if the rainfall still persists, the local community will be advised to evacuate the location to save human life from future

disaster. Further, if the system receives a change in movement of the sensor values along with the high pore pressure value, it will issue the imminent or third level of warning. At any time if the pore pressure value reduces heavily, due to a reduction in rainfall, the warning issued will be removed.

Along with the three level warning systems, the results of the landslide modeling software were compared to avoid false alarms. Landslide modeling software incorporates the raw sensor data from the field deployment site along with data from soil tests, lab setup, and other terrain information to determine the Factor of Safety (FS term used to quantify the slope stability). Depending on the results reaching a threshold, each grid point could be pronounced 'unsafe' or 'safe'. This implementation is incorporated into the data

visualization software, and the results are streamed real-time to the website.

In July 2009, high rainfall was experienced at our deployment site, and multiple landslides occurred all over the state of Kerala, India. The data analysis showed an increase in pore pressure and also noticeable soil movements. The pore pressure transducer deployed 14 m deep from the surface at location 5 (which is a vulnerable area) showed a gradual increase in pore pressure. The strain gauges deployed at location 5, at various depths such as 4.25x, 4.25y, 10.75x, 10.5x, 10.5y and 15x, showed noticeable movements of underneath soil. More strain gauge soil movement was shown at position 10.75x, 10.5x and 10.5. Other sensors at six different locations at Anthoniar Colony also showed observable soil movements and increase in pore pressure.

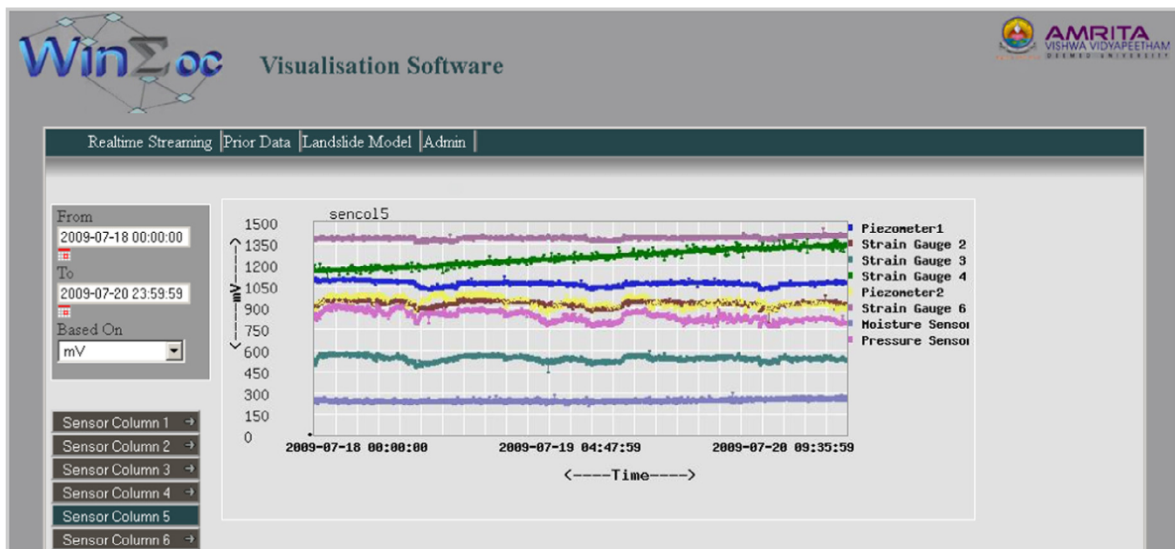


Fig. 10. Snapshot from the real streaming software, for a period of 18 July 2009 (00:00:17)–20 July 2009 (08:09:05) for location 5, the middle position of the hill.

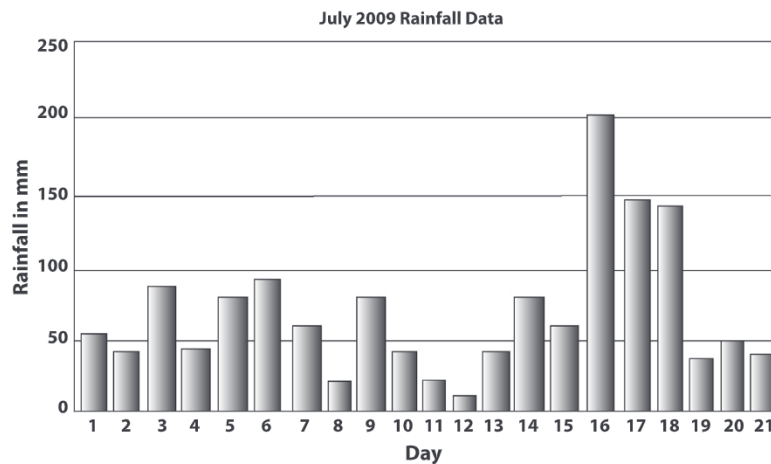


Fig. 11. Rainfall data for July 2009.

Our real streaming software currently incorporated to www.winsoc.org website can be used to view the pattern. Fig. 10 shows the real-time streaming data, for a period of July 18th, 2009–July 20th, 2009 for location 5. It shows an increase in the pore pressure and also soil movements at the middle position of the hill, which is actually a vulnerable area after the previous landslide of July, 2005. Additionally, the soil moisture sensor readings at location 1, the toe region of the hill, were already saturated. The strain gauges at locations 1 and 4 also showed slight soil movements.

The corresponding rainfall data for July 2009 is shown in Fig. 11. The maximum rainfall of 200 mm was experienced on July 16th, 2009. The rainfall remained at, almost the same, 150 mm for the next 2 days. This continuous rainfall along with the antecedent rainfall caused the increase in pore pressure.

All of the above analysis shows the vulnerability of Anthoniar Colony to possible landslides. In this context, we issued a preliminary warning through television channels and the official Kerala State Government authorities were informed. The government authorities considered the warning seriously. Senior officials made visits to the landslide prone area and the people were asked to evacuate. As the rainfall reduced, the real-time streaming software showed a reduction in the pore pressure and stabilization of the same. This situation helped us to validate the complete system. As a result of the successful warning issuance and system validation, the Indian government now wants to extend the network to all possible landslide areas within India.

10. Conclusion and future work

Wireless sensor networks are one of the most efficient techniques for real-time monitoring of areas that are prone to disasters. This work provides the experience of design, development, and deployment of a wireless sensor network for landslide detection. This network has the capability to provide real-time data through the Internet and also to issue warnings ahead of time using the innovative three level warning system that was developed as part of this work. The system incorporates energy efficient data collection methods, fault tolerant clustering approaches, and threshold based data aggregation techniques. For the last three years it has been gathering vast amounts of data, providing a better understanding of landslide scenarios, and is poised to warn of any pertinent landslide disaster in the future. The system has been validated by delivering a real warning to the local community during heavy rains in the July 2009 monsoon season. This system is scalable to other landslide prone areas and also can be used for flood, avalanche, and water quality monitoring with minor modifications.

Our next steps are to study how to further reduce the cost of this system, thus increasing the feasibility of wide area deployment. We plan to determine the optimal number of geophysical sensors and wireless sensor nodes with the hope of reducing the cost and energy consumption and thus increasing the lifetime of the network.

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References

- [1] P.K. Thampi, John, Mathai, G. Sankar, S. Sidharthan, Landslides: Causes, Control and Mitigation. Based on the Investigations Carried Out by the Centre for Earth Science Studies, Trivandrum.
- [2] Fact Sheet, Wireless Sensor Networks with Self-Organization Capabilities for Critical and Emergency Applications. <<http://www.winsoc.org>>.
- [3] H. Kung, J. Hua, C. Chen, Drought forecast model and framework using wireless sensor networks, *Journal of Information Science and Engineering*, 22 (2006) 751–769.
- [4] H. Liu, Z. Meng, S. Cui, A Wireless Sensor Network Prototype for Environmental Monitoring in Greenhouses, *IEEE Xplore*, 2007.
- [5] R. Musaloiu-E, A. Terzis, K. Szlavetz, A. Szalay, J. Cogan, J. Gray, 2006. Life Under Your Feet: A Wireless Soil Ecology Sensor Network.
- [6] C. Hill, K. Sippel, Modern deformation monitoring: a multisensor approach, in: *FIG XXII International Conference*, Washington, DC, 2002.
- [7] A. Terzis, A. Anandarajah, K. Moore, I.-Jeng. Wang, Slip surface localization in wireless sensor networks for landslide prediction, in: *Proceedings of IPSN'06*, 2006.
- [8] E.A. Garich, Wireless, Automated Monitoring For Potential Landslide Hazards. Master thesis, Texas A&M University, 2007.
- [9] Hengxing, Lan, C. Zhou, C.F. Lee, S. Wang, W.U. Faquan, Rainfall-Induced Landslide Stability Analysis in Response to Transient Pore Pressure – A Case Study of Natural Terrain Landslide in Hong Kong.
- [10] M.V. Ramesh, Real-time wireless sensor network for landslide detection, in: *Proceedings of the Third International Conference on Sensor Technologies and Applications, SENSORCOMM 2009*, IEEE Digital Library, 2009.
- [11] M.V. Ramesh, N. Vasudevan, The deep-earth sensor probes for landslide detection, *Landslides*, Springer-Verlag, 2011, ISSN 1612-5118.
- [12] M.V. Ramesh, S. Kumar, P.V. Rangan, Wireless sensor network for landslide detection, in *The Proceedings of the 2009 International Conference on Wireless Networks (ICWN'09)*, 2009, pp. 89–95.
- [13] M.V. Ramesh, K.P. Soman, Wireless sensor network localization with imprecise measurements using only a quadratic solver, in: *The Proceedings of the 2009 International Conference on Wireless Networks (ICWN'09)*, 2009, pp. 109–112.
- [14] M.V. Ramesh, P. Ushakumari, Threshold based data aggregation algorithm to detect rainfall induced landslides, in: *Proceedings of the 2008 International Conference on Wireless Networks (ICWN'08)*, vol. 1, 2008, pp. 255–261.
- [15] S. Barbarossa, G. Scutari, Decentralized maximum-likelihood estimation for sensor networks composed of nonlinearly coupled dynamical systems, *IEEE Trans. Signal Process.* 55 (2007) 7.
- [16] S. Barbarossa, G. Scutari, A. Swami, Achieving Consensus in Self-Organizing Wireless Sensor Networks: The Impact of Network Topology on Energy Consumption, *IEEE*, 2007.
- [17] G. Scutari, S. Barbarossa, Distributed consensus over wireless sensor networks affected by multipath fading, *IEEE Transactions on Signal Processing* 56 (2008) 8.

- [18] M. Maréchal, J. Pierrot, J. Gorce, Fine synchronization for wireless sensor networks using gossip averaging algorithms, in: Proceedings of ICC 2008, 2008.
- [19] R.M. Iverson, Landslide triggering by rain infiltration, *Water Resource Research* 36 (2000) 1897–1910.
- [20] G. Wang, K. Sassa, Pore-pressure generation and movement of rainfall-induced landslide: effect of grain size and fine-particle content, *Eng. Geol.* 69 (2003) 109–125.
- [21] R. Raj, M.V. Ramesh, S. Kumar, Fault tolerant clustering approaches in wireless sensor network for landslide area monitoring, in: Proceedings of the 2008 International Conference on Wireless Networks (ICWN'08), vol. 1, 2008, pp. 107–113.
- [22] M.V. Ramesh, R.T. Raj, J.D. Freeman, S. Kumar, P.V. Rangan, Factors and approaches for energy optimized wireless sensor network to detect rainfall induced landslides, in: International Conference on Wireless Networks, WORLDCOM-07, 2007.
- [23] K. Akkaya, M. Younis, M. Youssef, Efficient Aggregation of Delay-Constrained Data in Wireless Sensor Networks, Department of Computer Science and Electrical Engineering, University of Maryland 2005, 904–909.
- [24] H. Zhang, C.J. Hou, On the upper bound of α -lifetime for large sensor networks, *ACM Trans. Sensor Networks* 1 (2) (2005) 272–300.
- [25] S. Lindsey, C. Raghavendra, K. Sivalingam, Data gathering in sensor networks using the energy \times delay metric, in: Proceedings of the 15th International Parallel and Distributed Processing Symposium, IEEE, 2005.
- [26] J. Medhi, *Stochastic Models in Queuing Theory*, 2nd edition., Academic Press, 2003 (An Imprint of Elsevier).
- [27] A. Iserles, S.P. Norsett, *Linear ODE's in Lie Groups*. Numerical Analysis Report, University of Cambridge, 1997.
- [28] A. Chydzinski, R. Wojcicki, G. Hryn, On the number of losses in an MMPP queue, in: Y. Koucheryavy, J. Harju, A. Sayenko (Eds.), NEW2AN 2007, LNCS 4712, 2007, pp. 38–48.



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Dr. Ramesh's key research areas are wireless networks, wireless sensor networks, body area sensor network, technologies for disaster management, wireless robots for rescue and search operations, wireless robots for assisted living, design and development of real-time systems, algorithm development etc. She has represented and led Amrita in many International collaborations and projects such as WINSOC (www.winsoc.org), Indo-Brazil, and Indo-German projects. Her teaching interests are in different areas such as Wireless Communications, Wireless Sensor Networks, Advanced Wireless Networks, Advanced Computer Networks, Algorithms for Wireless Sensor Networks, and Security in Wireless Networks. Amrita center for wireless networks and applications admits approximately 25 students for M.Tech in Wireless Networks and Applications. Currently Dr. Ramesh is guiding 10 PhD students in various research areas such as wireless underground sensors, remote sensing, wireless sensor networks, landslides, disaster management, haptics, and cognitive networks.

Dr. Ramesh has also served as the Principal Investigator for many research projects taken up by AMRITA. She served as the Editorial Board member & Advisory Committee member, International Conference on Computing ICC 2010. She has also served as the Reviewer for International Journal of Digital Earth, and the Technical Program Committee member in SENSORCOMM 2010, ICCAIE 2010, ICOS 2010, ISCI 2011, and has several international publications in her name. Her paper “**Real-Time Wireless Sensor Network for Landslide Detection**” was awarded a best paper award in the conference SENSORCOMM 2009 held in Athens, Greece and her another paper “**Real-Time Monitoring and Detection of Heart Attack Using Wireless Sensor Networks**”, was also awarded best paper award in SENSORCOMM 2010. She has more than 30 international publications in prestigious IEEE/ACM conferences and journals for the last 5 years (2007–2011).

Maneesha V. Ramesh has been invited to deliver research presentations in more than 30 prestigious international universities such as University of California, Berkeley, San Diego, Los Angeles, Santa Cruz, Harvard, Stanford, MIT, USGS, Purdue University, University of Illinois, etc., in USA, EPFL and ETH in Switzerland, University of Helsinki, Finland, University of Twente, Vrije University, and ITC at Netherlands, UPC in Spain, University of Torenio in Italy, University of Montepilliar II, Eurecom, and University of Grenoble in France, University of Mannheim, and University of Paderborn in Germany.

All her, Dr. Ramesh's, work always caters to societal needs and she is also interested in developing India's upcoming young scientists.