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Wireless Sensor Network for Disaster Monitoring

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1. Introduction

This chapter provides a framework of the methodical steps and considerations required when designing and deploying a Wireless Sensor Network (WSN) to a given application. A real example is used to demonstrate WSN deployment in action.
WSN has many possible applications that have not yet been explored. WSN is a fast growing technology however much written about WSN is still theory. 'How to deploy WSNs,' although having much theory written still currently lacks a practical guide.
Using our research experience and the practical real life solutions found when deploying a WSN for the application of Landslide Detection this chapter outlines the steps required when conducting a real world deployment of a WSN.
In this chapter the application for WSN most focused on is for purpose of detecting natural disasters. WSN can be useful to disaster management in two ways. Firstly, WSN has enabled a more convenient early warning system and secondly, WSN provides a system able to learn about the phenomena of natural disasters.
Natural disasters are increasing world wide due to the global warming and climate change. The losses due to these disasters are increasing in an alarming rate. Hence, it is would be beneficial to detect the pre-cursors of these disasters, early warn the population, evacuate them, and save their life. However, these disasters are largely unpredictable and occur within very short spans of time. Therefore technology has to be developed to capture relevant signals with minimum monitoring delay. Wireless Sensors are one of the cutting edge technologies that can quickly respond to rapid changes of data and send the sensed data to a data analysis center in areas where cabling is inappropriate.
WSN technology has the capability of quick capturing, processing, and transmission of critical data in real-time with high resolution. However, it has its own limitations such as relatively low amounts of battery power and low memory availability compared to many existing technologies. It does, though, have the advantage of deploying sensors in hostile environments with a bare minimum of maintenance. This fulfills a very important need for any real time monitoring, especially in hazardous or remote scenarios.
Our researchers are using WSNs in the landslide scenario for estimating the chance occurrence of landslides. India faces landslides every year with a large threat to human life causing annual loss of US $400 million (27). The main goal of this effort is to detect rainfall induced landslides which occur commonly in India.
Many papers have highlighted the need for a better understanding of landslide phenomena and attempted to create systems that gather and analyse that data (1), (14) & (31).

The capacity of sensors and a WSN to collect and collate and analyse valuable worthwhile data, in an ordered manner, for studying landslide phenomena or other natural disasters and has not fully been explored.

Landslide prone-area are usually situated in terrains that are steep, hostile, difficult to access making monitoring landslides a strenuous activity. The wireless sensor network offers itself as an effective, reliable, low maintenance solution.

Using WSN for real-time continuous monitoring has been proven possible as shown the example of (9) who developed a Drought Forecast and Alert System (DFAS) using a WSN. This success in conjunction with (4) who developed a durable wireless sensor node able to remotely monitor soil conditions and (26) who proposed a design for slip surface localization in WSNs motivated our researchers to the design, develop, and deploy a real-time WSN for landslide detection. This system is deployed to monitor and detect landslides, in a landslide prone area of Kerala, India, and is further supported by laboratory setups.

This landslide detection system using a WSN is the first in India, one of the first in the world of its kind. It is also one of the first landslide field deployments backed up by a laboratory setup and modeling software. This system has been operational and collecting data for the last two years, and has issued landslide warnings in July 2009. The current system can be replicated in other rainfall induced landslide prone areas around the world.

One particular advance was the design of a Deep Earth Probe (DEP) to support the deployment of sensors. Previous landslide monitoring procedures have used sensors yet they have not implemented connecting all the sensors to a single wireless sensor node ((29); (28); (14); (1)). We have designed a sensor placement strategy that can be adapted for any landslide prone area and potentially for placing sensors to detect other natural disasters, in other disaster prone areas.

The chapter is arranged as follows: Requirement Analysis consisting of: Analysis of Scenario, Selection of Geophysical Sensors, Placement of Geophysical Sensors, Spatial Distribution of the Deep Earth Probe (DEP), Wireless Sensor Network Requirements, Algorithm Requirements, Network requirements (data transmission requirements/method), Data Analysis Requirements and Data Visualization Requirements;

Followed by sections on: Wireless Sensor Network Architecture; Wireless Network Design and Architecture; Wireless Sensor Network Algorithms; Wireless Software Architecture; Design of Interfacing Sensors and Power Management Methods; Field Deployment Methods and Experiences; Field Selection; Deployment of Deep Earth Probe (DEP); Network Implementation and Integration; Validation of the Complete System - Landslide Warning Issued; and lastly, Conclusion and Future Work.

2. Requirement Analysis

This section will describe in detail how to design a real-time Wireless Sensor Network (WSN), and what are the considerations/requirements that have to be analyzed for designing the network for any scenario. The different processes that will contribute to a WSN design are:

- *Analysis of Scenario*

  Wireless Sensor Networks (WSN) could be useful in a vast and diverse amount of applications. The chosen target scenario must be understood and investigated thoroughly in order to choose the most appropriate sensors and network. A comprehensive analysis of the scenario is one of the first steps to undertake when considering the design of the system. The constraints found (from the analysis of the scenario) determine and govern the overall size and type of network and sensors required.

Understanding the characteristics of a scenario allows logical links to be made about how to detect the occurrence of land movement. The scenario here is landslides and is then further specified to become 'rainfall induced landslides'. The importance of specialization is that landslides would be too generic and there would be too many other factors to consider.

Each landslide behaves differently. Factors playing strong roles in landslide occurrence include slope subsurface factors such as: the type of soil and its properties, soil layer structure, the depth of the soil to bedrock, the presence of quartz or other mineral veins, and the depth of the water table, among others and slope surface factors such as: the types of foliage and vegetation, the topographical geography, human alterations to the landscape, and the amount, intensity, and duration of rainfall.

Landslides are one of the major catastrophic disasters that happen around the world. Their occurrence can be related to several causes such as geological, morphological and physical effects, as well as human activities (30). Basically, landslides are the down-slope movement of soil, rock and organic materials due to the influence of gravity. These movements are short-lived and suddenly occurring phenomena that cause extraordinary landscape changes and destruction of life and property. Some slopes are susceptible to landslides whereas others are more stable. Many factors contribute to the instability of slopes, but the main controlling factors are the nature of the soil and underlying bedrock, the configuration of the slope, the geometry of the slope, and ground-water conditions.

In India, (27) the main landslide triggers are intense rainfall and earthquakes. Landslides can also be triggered by gradual processes such as weathering, or by external mechanisms including:

- Undercutting of a slope by stream erosion, wave action, glaciers, or human activity such as road building,
- Intense or prolonged rainfall, rapid snowmelt, or sharp fluctuations in ground-water levels,
- Shocks or vibrations caused by earthquakes or construction activity,
- Loading on upper slopes, or
- A combination of these and other factors.

Some of the factors that aggravate the incidence of landslides are environmental degradation on account of the heavy pressure of population, decline in forest cover, change in agricultural practices, and the development of industry and infrastructure on unstable hill slopes, among others.

In India, the main landslide triggers are intense rainfall and earthquakes. 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. When the rainfall intensity is larger than the slope saturated hydraulic conductivity, runoff occurs (12).

The key principal parameters that initiate the rainfall induced landslides are:

1. Rainfall: Rainfall is one of the main triggers for the landslide. The increase in the rainfall rate or its intensity increases the probability of landslide. Hence monitoring rainfall rate is essential for the detection and prediction of landslides. This can be performed by incorporating a rain gauge with the complete system for monitoring landslides.
2. Moisture: The moisture level in the soil will increase as the rainfall increases. Enormous increase in moisture content is considered to be a primary indication for landslide initiation. Hence, it is very important to know the soil moisture at which the soil loses sheer strength and eventually triggers failure.
3. Pore pressure: The pore pressure piezometer is one of the critical sensors needed for the rainfall induced landslide detection. As rainfall increases rainwater accumulates at the pores of the soil. This exerts a negative pressure and also it causes the loosening of soil strength. So the groundwater pore pressure must be measured, as this measurement provides critical information about how much water is in the ground. As the amount of water in the ground is directly related to the soil cohesion strength, this parameter is one of the most important for slope stability and landslide prediction.
4. Tilt: Sliding of soil layers has to be measured for identifying the slope failures. This can be performed by measuring the angular tilt (angular slide) during the slope failure.
5. : Vibrations: Vibrations in the earth can be produced during the initiation of a landslide, as the land mass starts to move, but does not fully slide. These vibrations can be monitored and taken as a precursor to a full landslide.

- *Selection of Geophysical Sensors*

  Landslide detection requires measurement of principal parameters discussed in the above section. The key geophysical sensors such as rain gauge, soil moisture sensors, pore pressure transducers, strain gauges, tiltmeters, and geophones are identified for measuring the principal parameters. These sensors are selected based on their relevance in finding the causative geological factors for inducing landslides under heavy rainfall conditions.

  The details of the selected sensors are:

  - Dielectric moisture sensors: Capacitance-type dielectric moisture sensors are used to monitor the changes experienced in volumetric water content.
  - Pore pressure piezometers: Pore pressure piezometers are used to capture the pore pressure variations, as the rainfall rate varies. Either the vibrating wire piezometer or the strain gauge type piezometer is used for in this deployment.
  - Strain gauges: When attached to a DEP (Deep Earth Probe), a strain gauge can be used to measure the movement of soil layers. Strain gauges of different resistance such as 100Ω, 350Ω, and 1000Ω have been used for deployment, to measure deflections in the DEP of 0.5 mm per meter.
  - 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: Maximum rainfall of 5000 mm per year needs to be measured using the tipping bucket. The tipping bucket type of wireless rain gauge, in which the tipping event is counted as .001 inch of rainfall, has been deployed.
- Temperature sensors: The physical properties of soil and water change with temperature. A resolution of 1/10th degree Celsius, measured every 15 minutes, is sufficient. Temperature measurements are collected using the rain gauge.

Cost-Effective Considerations Cost-effective solutions have been explored, e.g. using strain gauges for monitoring slope movement. Investigation into the sensors is a necessary pursuit. Searching for cost effective, yet reliable sensors and accessing their ability to process that data is an issue. When choosing appropriate sensors for your given application it is necessary to access the usefulness of a sensor and its ability to provide the type of worthwhile data required. Developing the ability of sensors effects the applications currently available.

Another factor when considering the most appropriate sensors is how cost-effective the sensor is, for example our team opted to use strain gauges for monitoring slope movement which are significantly cheaper than tiltmeters. Though in choosing to use strain gauges it took a much longer to develop the signal conditioning and electronics to interface the strain gauge to the wireless sensor nodes. It also took a longer time to learn how to accurately interpret the data resulting from the strain gauges since strain gauges capture more noise (and unwanted signals) than other more expensive sensors. Therefore signal conditioning was required to extract the relevant signals that determine slope movements from the strain gauge's raw data.

Nested Dielectric Moisture Sensor is another cost effective choice made by the researchers for monitoring the infiltration rate.

- *Placement of Geophysical Sensors*

  The chosen, above mentioned, sensors or a combination of them can be used for detecting landslides. The terrain and type of landslide will determine the group of sensors to be used in a particular location for detecting landslides. All the chosen geophysical sensors are capable of real-time monitoring with bare minimum maintenance. A DEP (Deep Earth Probe) was devised to deploy these many sensors as a stack, attached to a vertical pipe, in different locations of the landslide prone site. This generalized design for the DEP, and the sensor placement procedures at the DEP has been developed and implemented to simplify future deployments. This design can be adapted for any landslide prone area and potentially for placing sensors to detect other natural disasters, in other disaster prone areas. Preparation with an 'eye on the future' is an integral part of the development of a practical system, as this design for a DEP proves. Currently replication of this particular system is being requested across much of India by the Government, the design of the DEP will enable each procedure to be much more organised and simplify deployment.

  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 their 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 the geological sensors on the DEP are connected to the wireless sensor node via a data acquisition board as shown in Figure 1. This apparatus, including the DEP with its sensors, the data acquisition board and the wireless sensor node, is conjunctly termed a wireless probe (WP).

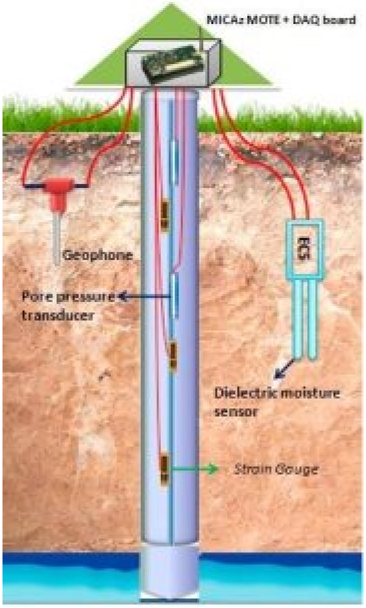

Fig. 1. Multi Sensor Deep Earth Probe

- *Spatial Distribution of the DEP (Deep Earth Probe)*

  Challenges come when wide area monitoring is required. Different approaches can be used for determining the spatial distribution and deployment of Wireless Probes (WPs). The different approaches considered are the Random Approach, the Matrix Approach, the Vulnerability Index Approach, and the Hybrid Approach. In the Random Approach, WPs can be deployed at all possible locations according to the terrain structure of a landslide prone mountain. Whereas in the Matrix Approach, the total area of deployment, A, is sectored into a matrix of NxN size, and one WP is placed in each cell of the matrix. The cell size of the matrix is selected by the smallest value of the maximum range covered by each sensor present with the DEP. In the Vulnerability Index Approach, WPs are deployed in vulnerable regions that have been identified during the site investigation, terrain mapping, and soil testing. The Hybrid Approach incorporates more than one approach stated earlier. After considering these different approaches, a particular approach suitable for the deployment area has to be selected.

- *Wireless Sensor Network Requirements*

  Landslide detection requires wide area monitoring, and real-time, continuous data collection, processing, and aggregation. Wireless Sensor Networks (WSNs) are the key emerging technology that has the capability to real-time, continuous data collection, processing, aggregation with minimum maintenance. Any wide area monitoring must determine the

  – maximum number of wireless sensor nodes,
  – maximum number of relay nodes,
  – maximum frequency of data collection from each node per minute,
  – maximum data rate required,
  – maximum power required for sampling, transmitting, processing, and receiving,
  – maximum tolerance limit of delay,
  – maximum tolerance limit of data packet loss,

- *Algorithm Requirements*

  Wide area monitoring requires efficient algorithm development for data collection, processing, and transmission. The different criteria to be analyzed for designing the algorithms are: the total area of deployment, maximum and minimum transmission range, maximum number of sensor nodes necessary, maximum number of sensor nodes available, maximum amount of power available (in the battery), the corresponding transmission range, data storage capability of each node, availability of constant power source, maximum bandwidth availability, frequency of data collection and transmission specific to the application scenario, and the data aggregation method suitable for the application under consideration.

  Analysis of the above requirements contributes to the development of required algorithms for designing the network topology, data collection algorithm, data aggregation algorithm, data dissemination method, energy optimized network, networks with maximum life time, time synchronized network, localization techniques etc.

- *Network Requirements*

  The design and development of the complete network architecture requires the knowledge and understanding of relevant technologies such as wireless networks, wired networks, cellular networks, satellite networks etc., maximum number of nodes, maximum data rate, available bandwidth, traffic rate, delay, distance between the point of data initiation and its destination, effect of terrain structure, vegetation index, climate variation etc., on data transmission, delay, and data packet loss, accessibility/connectivity of the area, location of DEP (Deep Earth Probe), transmission range, identification of the communication protocol and radio interface technology, integration of the application specific algorithms for data collection and aggregation, routing and fault tolerance etc. These requirements have to be thoroughly analyzed with regard to the conditions of the deployment area, maximum data transmission distance, traffic rate, and the available technologies. Choose the best technologies that can be integrated effectively to achieve minimum data packet loss, delay, minimum power consumption, and fast arrival of data.

- *Data Analysis Requirements* The data received from the deployment area has to be modeled and analyzed according the application scenario requirements. Statistical models and pattern recognition techniques can be used for further data analysis to determine the warning levels. Warning levels are the level of indication (from the sensors) that a landslide maybe becoming possible or about to occur. Along with this data analysis architecture has to be developed for effective and fast data analysis.
- *Data Visualization Requirements* The development of real-time systems requires the design and development of: a data dissemination method, a channel or technology that can be used for data dissemination (within the shortest amount of time), and the data visualization criteria & methods specific to the application scenario. The method of data dissemination, and the allowable delay for data dissemination, and the techniques that should be adopted for data dissemination will depend on the application scenario under consideration. The architecture for data visualization has to be developed with the goal of effective and fast streaming of data.

3. Wireless Sensor Network Architecture

This current deployment used a placement strategy using the Hybrid Approach, by incorporating both the Matrix Approach and the Vulnerability Index Approach. The whole deployment area was initially sectored using Matrix Approach. In each cell, the deployment location of the Wireless Probe (WP) is decided after considering the Vulnerability Index Approach. This has helped to maximize the collection of relevant information from the landslide prone area.
The wide area monitoring using Wireless Sensor Network (WSN) is achieved using a regionalized two-layer hierarchical architecture. Since the geological and hydrological properties of each of the locations, of the landslide prone area, differ with respect to the different regions they belong to they are divided into regions. The data received from each of the sensors cannot be aggregated together due to the variability in soil geological and hydrological properties. So the whole landslide prone area is divided into regions possessing soil geological and hydrological properties unique to their region. In this particular case, the deployment area is divided into three regions such as crown region, middle region, and toe region of the slope as shown in Figure 2, and numerous WPs are deployed in these regions.

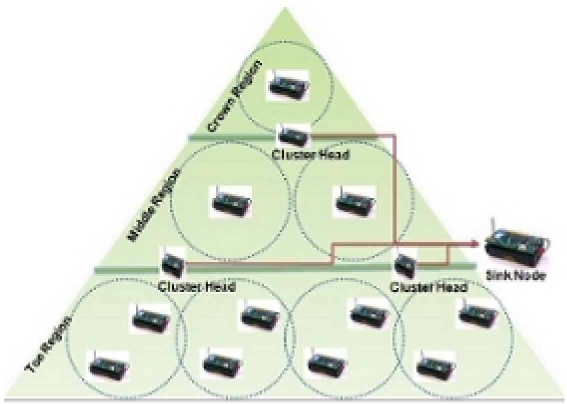

Fig. 2. Regionalized Wireless Sensor Network Architecture for Landslides

4. Wireless Network Design and Architecture

One of the important requirements for any landslide detection system is the efficient delivery of data in near real-time. This requires seamless connectivity with minimum delay in the network. The architecture we have developed for satisfying the above requirements is shown in the Figure 3.

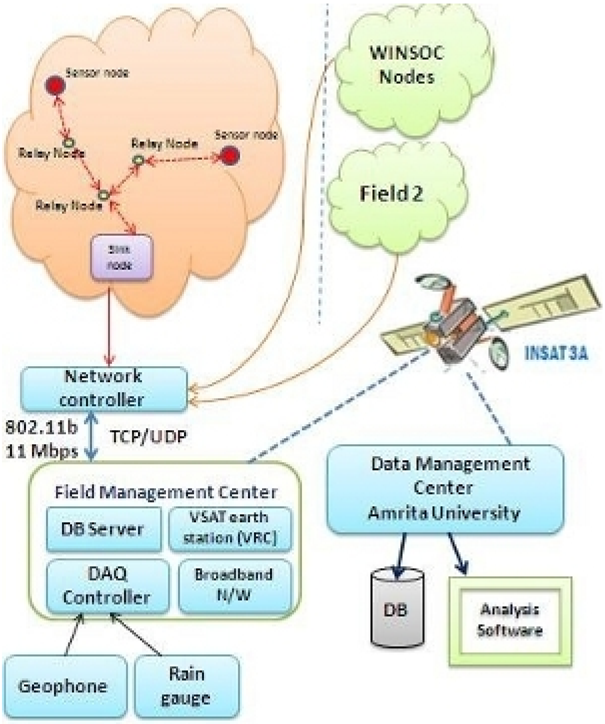

Fig. 3. Wireless Sensor Network Architecture For Landslide Detection

The wireless sensor network follows a two-layer hierarchy, with lower layer wireless sensor nodes, sample and collect the heterogeneous data from the DEP (Deep Earth Probe) and the data packets are transmitted to the upper layer. The upper layer aggregates the data and forwards it to the sink node (gateway) kept at the deployment site.
The current network has 20 wireless sensor nodes spread on two different hardware platforms. The first hardware platform is Crossbow MicaZ. This MicaZ network follows a two-layer hierarchy, with a lower level (wireless probes) and a higher level (cluster head), to reduce the energy consumption in the total network. The wireless probes (lower level nodes) sample and collect the heterogeneous data from the DEP (Deep Earth Probe) and the data packets are transmitted to the higher level. The higher level aggregates the data and forwards it to the probe gateway (sink node) kept at the deployment site.
The second hardware platform, used, is the newly developed WINSOC wireless sensor nodes. One purpose of this WINSOC network is to extensively test and validate the WINSOC nodes, shown in Figure 4, with respect to performance reliability and energy trade-offs between

the two hardware platforms in a landslide scenario. WINSOC nodes are endowed with a WINSOC distributed consensus algorithm. Another purpose of this network is to test and validate the performance and scalability of the WINSOC distributed consensus algorithm in a landslide scenario. This network is scalable as it provides the capability to incorporate any new field networks to the current network.

Fig. 4. Field Deployment of WINSOC Node With MiniatureAntenna

Data received at the gateway has to be transmitted to the Field Management Center (FMC) which is approximately 500m away from the gateway. A Wi-Fi network is used between the gateway and FMC to establish the connection. The FMC incorporates facilities such as a VSAT (Very Small Aperture Terminal) satellite earth station and a broadband network for long distant data transmission. The VSAT satellite earth station is used for data transmission from the field deployment site at Munnar, Kerala, South India to the Data Management Center (DMC), situated at our university campus 300 km away.

The DMC consists of the database server and an analysis station, which performs data analysis and landslide modeling and simulation on the field data to determine the landslide probability. The real-time data and the results of the data analysis are real-time streamed on the Internet. Alert services such as E-Mail, SMS and MMS are implemented to alert about: the probability of landslides, status of the network and for monitoring the system components.

Fault tolerance is achieved even during extreme weather conditions. For example, if the VSAT network becomes unavailable, the WAWN adapts by using the broadband or GPRS connectivity at the FMC for uploading the real-time data directly to a web page with minimum delay and thus providing fault tolerance.

The entire system is equipped to remotely monitor the level of battery charges and the level of solar charging rate, and indicate faulty wireless sensor nodes or geological sensors. A feedback loop is used that remotely 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 via a Wi-Fi network to the same FMC. In future, this will

provide the capability to monitor many very large areas and also to incorporate the different spatio-temporal analysis to provide an even better understanding of landslides.
The Munnar region experiences frequent landslides and has several landslide prone areas within every 1 sq km, which can be utilized as future extension sites for landslide detection systems. The different deployment sites can connect to the FMC via a Wi-Fi network.

5. Wireless Sensor Network Algorithms

The wireless sensor network designed and deployed for wide area landslide monitoring requires efficient data collection, data aggregation, energy management, and fault tolerant methods.
Regionalized dynamic clustering method is designed and implemented for effective geological and hydrological data collection using the wireless sensor network.
Threshold based temporal data collection and data aggregation method (19)is designed and implemented for effective data aggregation. This algorithm combined with the newly designed state transition algorithm (18) contributes optimum energy consumption by each node and in increasing the life time of the whole network, avoiding unnecessary collection, processing and transmission of redundant data thus achieving increased energy efficiency and the simplification of the data analysis & visualization process.
Fault tolerant methods are designed and integrated in the wireless sensor network for effective handling of node failure, reduced signal strength, high data packet loss, and low balance energy per node.

6. Wireless Software Architecture

Real-time monitoring and detection of landslides require seamless connectivity together with minimum delay for data transmission. The existing Wireless Sensor Network (WSN) system for landslide detection incorporates various heterogeneous wireless networks such as the WSN, Wi-Fi, satellite network, and broadband network. Each of these networks perform at different frequency range, that contributes to different traffic rate, congestion, data packet loss, buffering methods, delay, and different data collection, transmission, and processing methods. Hence to reduce the complexity in dealing with different types of wireless network, generic software architecture was designed and implemented for achieving all the requirements of each of the wireless network. This wireless software architecture includes wireless sensor network software, wireless sensor gateway software, and a middleware for heterogeneous wireless networks.

7. Design of Interfacing Sensors and Power Management Methods

We designed special purpose interfacing circuits, since the commercially available wireless sensor nodes do not include implanted geophysical sensors necessary for landslide monitoring, and also the geophysical sensors cannot be connected directly to the data acquisition board, integrated with the wireless sensor node. The special purpose interfacing circuit act as an intermediary to remove the variance experienced between the required input voltage for a data acquisition board and the output voltage received from the geophysical sensors. Thus design requirements of the interfacing board are described in (17), and the output from the interfacing board is directly fed into the data acquisition board inputs. Later, the signals were software adjusted to obtain the original sensor outputs, and hence the sensor data. The details of the interfacing circuit requirements are shown in Figure 5.

Sensor	Output type	Signal pre-processing
Strain gauge piezometer	Dual wire analog	Level shifting, Amplification
Vibrating wire piezometer	RS-232 from the data logger	None
Dielectric Moisture Sensor	Single wire analog	None
Tiltmeter	Single wire analog	Voltage reduction, Amplification
Geophone	Dual wire analog	Level shifting, Amplification

Fig. 5. Interfacing Circuit Requirements (17)

For any Wireless Sensor Network (WSN), power constraints are one of the major problems faced by wide area deployments, for real-time monitoring and detection. In the current deployment, maximum power is consumed for excitation of geophysical sensors than that of transmission, processing, or reception by a wireless sensor node. Indigenous power circuits are developed to provide constant power for the excitation of the geophysical sensors, wireless sensor nodes, and interfacing circuits, since each of them requires different levels of power. This power circuit board is designed with high efficiency regulator chips to provide multiple outputs from a single power battery input, a non-regulated 6 Volts DC supplied from rechargeable lead acid batteries. To increase the lifetime of the lead acid batteries, they are automatically recharged by the solar recharging unit using the charge controller.
Along with hardware power management methods, software methods are also incorporated. Software power solutions are implemented in the wireless sensor network by integrating switching on-off of geological sensors and by the dynamic adjustment of frequency of sensor measurements, according to the different state transitions of wireless sensor nodes as described in the research paper (18). Efficient use of power and an optimized lifetime has been achieved by these hardware and software solutions.

8. Field Deployment Methods and Experiences

The Wireless Sensor Network (WSN) for landslide detection system is deployed at Anthoniar colony, Munnar, Idukki (Dist), Kerala (State), India, shown in Figure 6. 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 WSN for landslide detection system is deployed in an area of 7 acres of mountain. The whole area consists of approximately 20 wireless sensor nodes, 20 DEPs consisting of approximately 50 geological sensors. Important research focal points were deciding the DEP locations, designing and constructing the DEPs, DEP deployment methods, interfacing circuitry, WSN, 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 two phases. The pilot deployment in January 2008 to 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 15 landslide prone areas have been visited and studied, that had historically experienced landslides. After extensive investigation of the 15 sites, five sites were identified as potential field deployment sites for a Wireless Sensor Network (WSN) in landslide monitoring applications. Other sites were also visited but were not deemed suitable for the field deployment due to various factors, including: difficulty of access, uncertainty about the landslide risk, lack of communication facilities, and the size of the potential landslide, among others.

Fig. 6. Deep Earth Probe Deployment Locations at the Anthoniar Colony Site, Munnar, Kerala, India

From the shortlisted five landslide prone sites, Anthoniar Colony was selected for deployment, which is located 700 meters Northwest of Munnar town. A first slide had occurred many years earlier. On July 25th, 2005, another landslide also occurred in Munnar at the Anthoniar colony. A torrential rainfall of 460mm in the middle of the monsoon period was the primary trigger. Two levels of slide area can be observed at the Anthoniar Colony, as shown in the Figure 6.
There is a high probability for 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, soil material has large amount of quartz vein, and the soil type is reddish colored sticky clay. Even now when the rain falls, water will flow down on to 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 future.

8.2 Deployment of DEP (Deep Earth Probe)

One of the important activities required for deploying the landslide detection system is bore hole drilling. Bore hole location and its depth, 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. The pilot deployment the hand auger method was used. In the main deployment the rotary drilling method was used to drill deeper holes as deep as 23 meters as it consumed less time and labor compared to the hand auger method. Soil sample extraction and field permeability tests were performed to collect the relevant soil properties, geologic and hydrologic properties from each of the locations. Drilling was continued until the bed rock was observed. If bedrock was too deep, drilling was continued until the observation of weathered rock. If even weathered rock was too deep, drilling was stopped at a major soil layer change after the water table. The decision of the bore hole depth was chosen to be dependent on the location of the hole, vulnerability of the location, sensor deployment requirement, water table height, and location of weathered rock or bed rock.

The DEP (Deep Earth Probe) design is 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 is unique depending on the characteristics of the specific location.

The DEPs were designed in a two stage process. Initial DEP designs were made for the pilot deployment, which consists of two DEPs, and 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 $C1, C2, \cdots, C6$), shown in Figure 6.

In the main deployment DEPs are placed significantly deeper into the ground than in the pilot deployment, on average 2 to 5 times deeper, with a maximum depth of up to 23 meters, penetrating to the weathered rock or bed rock. The geological sensors are attached to the ABS plastic inclinometer casing according to the geological or hydrological parameter that will be measured. The maximum number of eight external sensors can be attached to the data acquisition board of Crossbow's wireless sensor nodes. The details of the connected geological sensors as on June 2009, is detailed in the Figure 7.

External hardware components have been put in two enclosures that are used to protect the data acquisition and transmission equipment for the wireless sensor node - one electronics box and one power box and are attached to poles equipped with solar panels and external antenna. These were designed and then fabricated at the University as shown in Figure 8.

8.3 Network Implementation and Integration

The network consists of a Wireless Sensor Network (WSN), Wi-Fi, a satellite network, a broadband network, a GPRS and GSM network. The network integration of all the components required different software and hardware implementations. The design and development of a WSN 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 (Deep Earth Probe), transmission range, identification of the communication protocol and radio interface technology, the application specific algorithms for data collection and aggregation,

DEP Location	Piezometer Depth (m)	Moisture Sensor Depth (m)		Strain Gauge Depth(m)						Geophone (m)	Rain Gauge Height (m)
		1	2	1	2	3	4	5	6		
C1	5.5	0.8	3.05	1.5x	4x	4alpha	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	19.5x		
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	10.5 alpha	10.5 beta	15x		3
C6	19.75	2		2x	2y	5x	5y	11x	17x		

Fig. 7. Main Deployment - Details of Geological Sensor Deployment, Location and its Depth of Deployment

routing and fault tolerance etc. The wireless sensor nodes used for the deployment are 2.4 GHz MicaZ motes from Crossbow. The MDA 320 from Xbow is 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 meters, in ideal field conditions (flat dirt ground, dry weather) the maximum range was around 50 or 60 meters even when the motes were being placed 2 meters above the ground. Due to this shorter transmission range, a number of relay nodes are used to maintain communication 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 hardware of the original probe gateway is from Crossbow and is named as Stargate. Later Stargate became unavailable and out of production thereby forcing the use of a new gateway. The new gateway is based on an AMD Geode Mini-ITX Motherboard. The base station listens to the packet transmissions, in the sensor network, and logs the packet transmissions if they are addressed to the base station. After this, the sensor data is stored either 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 distant 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 University. 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

Fig. 8. C3 Sensor Column of Main Deployment

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.
This data analysis and visualization software is also capable of real streaming the data and the results of the data analysis, over the Internet. Which makes it possible for the scientists around the world to analyze the data with very minimal delay and effective warning can be issued on time.

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 (for an Early warning), pore pressure (for an Intermediate warning), and movement (for an Imminent warning) sensor data values correlating with the rainfall intensity. Along with the three level warning system, the results of the landslide modeling software is 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

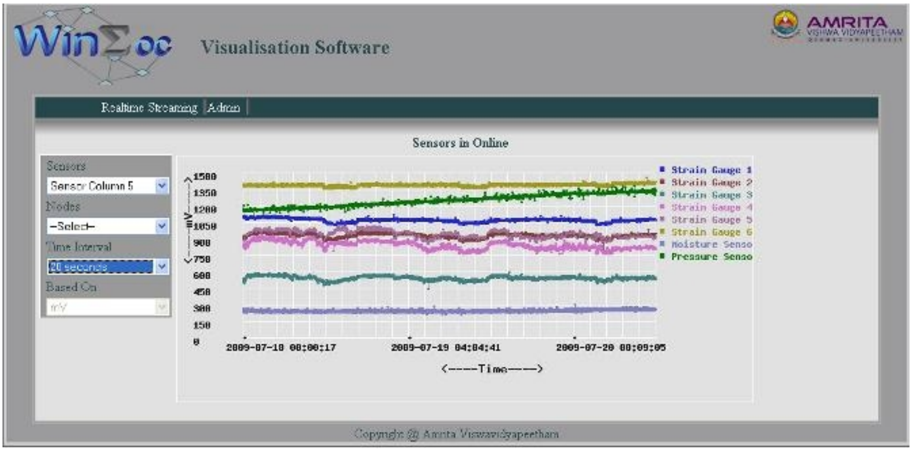

Fig. 9. Snapshot from the real streaming software, for a period of 18 July 2009 (00: 00:17) to 20 July 2009 (08:09:05) for location 5, the middle position of the hill

the slope stability). Dependent on the results reaching a threshold (that is, if $FS \leq 1$), each grid point could be pronounced 'unsafe' or 'safe'. This implementation is incorporated into the data visualization software and the results are real-time streamed to the website.
In July 2009, high rain fall 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 meter 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 4.25 x, 4.25 y, 10.75 x, 10.5 alpha, 10.5 beta and 15 x show noticeable movements of underneath soil. More strain gauge soil movement is shown at position 10.75 x, 10.5 alpha and 10.5. Other sensors at 6 different locations at Anthoniar Colony also showed observable soil movements and increase in pore pressure.
Our real streaming software currently incorporated to www.winsoc.org website can be used to view the pattern.
Figure 9 shows the real-time streaming data, for a period of July 18th, 2009 to July 20th, 2009 for location 5. The figure 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 location 1 and location 4 also showed slight soil movements.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. Higher officials made visits to the landslide prone area and the people were asked to evacuate with the warning given below.
We would like to inform you that in case the torrential rainfall prevails, it would be wiser to alert the people of this region and advise them to relocate to another area till the region comes back to normalcy in terms of pore pressure and underneath soil movements.

As the rainfall reduced, the real-time streaming software showed the pore pressure reducing and then stabilizing. 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 extent the network to all possible landslide areas.

10. Conclusion

Wireless Sensor Networks (WSNs) are still an emerging technology and much literature available is still theoretical, therefore practical deployment guides using actual experience are few if any. Using real practical experience, this overview of operations is one such guide providing the methodical steps and outlining the basic requirements when designing and deploying a WSN into any given application.

This chapter discusses the design and deployment of a landslide detection system using a WSN system at Anthoniar Colony, Munnar, Idukki (Dist), Kerala (State), India, a highly landslide prone area The deployment site had historically experienced several landslides, with the latest one occurring in the year 2005, which caused a death toll of 10 (people).

Our researchers, at Amrita University, designed and deployed a Wireless Sensor Network for the purpose of landslide detection. The complete functional system consists of 50 geological sensors and 20 wireless sensor nodes. 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 developed as part of this work. The system incorporates energy efficient data collection methods, fault tolerant clustering approaches, and threshold based data aggregation techniques. This wireless sensor network system is in place. For two years it has been gathering vast amounts of data, providing better understanding of landslide scenario and has been poised to warn of any pertinent landslide disaster in future. The system has proved its validity by delivering real warning to the local community during heavy rains in the last monsoon season (July 2009). This system is scalable to other landslide prone areas and also it can be used for flood, avalanche, and water quality monitoring with minor modifications.

This development describes a real experience and makes apparent the significant advantages of using Wireless Sensor Networks in Disaster Management. The knowledge gained from this actual experience is useful in the development of other systems for continuous monitoring and detection of critical and emergency applications.

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