Wireless sensor network for volcano monitoring

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Abstract

The monitoring of volcanoes for risk assessment has deployed single sensors for years. This kind of system requires manual supervision to monitor each sensor, which makes the monitoring work not flexible and efficient enough to adapt to variable volcano environments. With the development of wireless sensor networks, the accuracy and coverage of volcano observations can be improved by deploying networked sensors. This paper proposes a wireless sensor network prototype for volcano remote monitoring, which was built and tested in a field campaign in volcano Etna, Italy in September of 2004.Hardware design of sensors, in-depth sensor network design and software module architecture will be introduced in this paper. The experience gained from the practical work in volcano Etna will be used in an upcoming volcano monitoring project.

Key words: wireless sensor network, volcano, remote, sensing

Abstract in Swedish

Vulkaner har, i syfte för riskuppskattning, under en lång tid observerats med enkel sensorteknik. Det systemet behöver dock manuell övervakning av varje sensor, vilket gör att övervakningssystemet inte blir nog flexibelt eller effektivt för att kunna anpassas till en variabel vulkanmiljö.Med utvecklingen av trådlösa sensornätverk kan noggrannheten och täckningen av vulkanövervakning förbättras. I denna rapport föreslås en prototyp för ett trådlöst sensornätverk avsett för övervakning av vulkaner.Denna prototyp byggdes och provades i en fältkampanj på vulkanen Etna i september 2004.I denna rapport presenteras även hårdvarudesign av sensorer, fördjupad design av sensornätverket och arkitektur av mjukvarumoduler.Erfarenheten från det praktiska arbetet på Etna kommer att användas i ett kommande vulkanprojekt.

Nyckelord : trådlös sensor nätverk, vulkan, fjärranalys

Abstract in Chinese

数年来, 火山险情预测工作中普遍采用的是单传感器系统。这种系统需要人工监控每个传感器，由于其不够灵活高效，不能适应多变的火山环境。随着无线传感器网络的发展，采用网络互连的传感器能够提高火山监测的准确性和覆盖范围。本文提出了一种用于火山远程监控的无线传感器网络原型，在 2004 年 9 月意大利埃特那火山的科学考察活动中，该网络被搭建并测试应用。本文将介绍该网络中的传感器的硬件设计，传感器网络设计以及软件模块结构。在埃特那火山的实地考察工作中获得的宝贵经验将做为下一阶段火山监测项目的指南。

关键词: 无线传感器网络， 火山， 远程， 传感

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List of Abbreviations

ARQ	Automatic Repeat Requests
CRC	Cyclic Redundancy Check
DOAS	Differential Optical Absorption Spectroscopy
FEC	Forward Error Correction
FTIR	Fourier Transform InfraRed
GUI	Graphic User Interface
MAC	Medium Access Control
MEM	Micro-Electro-Mechanical-Machines
SNR	Signal-to-Noise Ratio
USB	Universal Serial Bus

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Chapter 1 Introduction

In recent years, Micro-Electro-Mechanical-Machines (MEM) technology and wireless communication technology have been developed at an extraordinary speed. As a result, the field of wireless sensor networks has emerged and we have begun to instrument the world with a large number of intelligent sensors, which are equipped with a sensor module (e.g., acoustic, seismic, image sensor) capable of sensing some quantity about the environment, a digital processor for processing the signals from the sensor and performing network protocol functions, a radio module for communication, and a battery to provide energy for operation.

Smart sensors are designed to be able to work in different kinds of environments. There are many types of sensors that have been developed and deployed in the field. For example, the SmartDust project [19] at Berkeley pushes the size limit of sensors to an extreme - a cubic millimeter, such that these sensors can float in the air like dust; the Wireless Integrated Wireless Sensors (WINS) project at UCLA [20] and the Wireless Sensing Network (WSN) project at Rockwell Science Center [21] integrate multi-modality sensing devices and low-level signal processing on the microsensor, making it more intelligent and powerful; and the Odyssey developed by the MIT SeaGrant Office is a low cost autonomous underwater vehicle (AUV) [22] with a length less than two meters. The current and potential applications of sensor networks include: military sensing, physical security, air traffic control, traffic surveillance, video surveillance, industrial and manufacturing automation, distributed robotics, environment monitoring, and building and structure monitoring.

This thesis concerns the design and evaluation of a wireless sensor network for volcano monitoring. It was tested during a field campaign at the Etna volcano.

1.1 Background

1.1.1 Remote Sensing of Volcano Monitoring

In volcano monitoring, the amount of gas released is related with the magma tank, which is the key to estimate the risk of eruption. The traditional approach is to take gas samples at the crater. It is a very dangerous method, in which people lose their lives each year. Volcanologists have found out a better and safer way –remote spectroscopic sensing. From a spectrum taken far away from the crater, the concentration of SO_2 and HCl can be calculated. Hence the activity inside the volcano can be estimated by means of studying the two most emitted gases from a volcano.

1.1.2 Etna

Etna, located at 37.75 N, 14.98W, is an active volcano in the east coast of Sicily, Italy. It covers an area of 600 square miles [2]. This basaltic volcano is well known for its sustained and prodigious emission of gases. Being one of the ten biggest SO_2 sources in the world, it is particularly suitable for remote spectroscopy. It is also widely recognized as a "laboratory volcano" conducive to trials of new monitoring techniques. It is routinely monitored by Fourier Transform InfraRed (FTIR) spectroscopy by the *Istituto Nazionale di Geofisica e Vulcanologia* (INGV).

1.1.3 DORSIVA Project

To demonstrate the use of remote sensing techniques applied to volcanology, a European project has been launched, DORSIVA, standing for Development of Optical Remote Sensing for Volcanic Application. One milestone of this project is the Etna field campaign, taking place in September 2004. This measurement campaign is the largest concerning remote sensing for volcanology ever realized, with several research groups participating: Chalmers Institute of Technology, Heidelberg University, Centro de Estudios Ambientales del Mediterraneo (CEAM) in Valencia, Spain, Cambridge University, the environment group at University of the Basque Country (ETSII&T), and Gothenburg University.

A major goal of the project is to provide a monitoring capability for remote and automated measurement of volcanic gas ratios and fluxes of SO_2 with high temporal resolution (1-5 minutes). It will also be highly significant to link volcanic degassing to geophysical signals since it has never been possible before to obtain volcanic gas fluxes at comparable temporal resolution to seismic and geodetic data streams [1].

Since the solubility of the species differ in the magma the gas ratios are indicators of processes in the magma and can be used as first alert indicators of eruptions, but they also improve the understanding of geological processes. The interpretation of the above-mentioned ratios is rather empirical and the conclusion from other groups is that long-term measurements at several locations are needed for a better qualitative understanding of processes in the magma.

1.2 Wireless Sensor Network

The current technology in electronics and embedded computer systems has enabled the development of tiny, low-cost, low-power, multifunctional sensor nodes. These tiny sensor nodes, which consist of sensing, data processing, and communicating components, leverage the ideas of sensor networks. Given the development of wireless communication technology, sensors are not separately deployed any longer. Instead sensors are connected forming wireless sensor networks, which makes it easier and more efficient to collect and process information from the monitored field.

Wireless sensor networks are widely used in many fields. The sensors might be deployed in the sea, in the air, or on the ground where temperature, humidity, and other environmental parameters are unstable. The working environment of a wireless sensor network is dynamic. In these environments, communication bandwidth and energy are significantly more limited than in a tethered network environment. Furthermore, dynamic environmental conditions require the system to adapt over time to changing connectivity and system stimuli. In most envisioned sensor network applications, the operation of the network is unattended in harsh natural environments. For example, in the habit monitoring project [14] for plants and animals anthropogenic disturbance can seriously reduce, destroy, or stress a breeding species. These restrictions require innovative design techniques and protocols to use available energy efficiently. After the sensor network is set up, it should operate without human maintenance. The sensor nodes could be prone to failures, thus the sensor network should be able to configure and reconfigure automatically (i.e., self-configurable). Additionally, the nodes are limited in power, computational capacities, and memory.

Communication protocols must be designed to adapt to current conditions instead of simply being designed for worst-case conditions, as worst case may consume much more power than the average case. Wireless microsensor network protocols should be:

- Self-configuring, to enable easy deployment of the networks,
- Energy-efficient and robust, to extend system lifetime,
- Latency-aware, to get the information to the end-user as quickly as necessary
- Cognitive of the application-specific nature of sensor network quality [9].

1.3 The Scanning DOAS System

The scanning Differential Optical Absorption Spectroscopy (DOAS) system was designed and developed by professor Bo Galle and a doctoral student Manne Kihlman from Chalmers University (see figure 1-3). The Scanning DOAS is composed of an Ocean Optics USB2000 Fiber Optic Spectrometer, a fiber, a telescope, a motor, an electronic compass, a GPS receiver, and micro controller.

- The Fiber Optic Spectrometer detects ultraviolet light and converts it to digital signals, which are transmitted over a Universal Serial Bus (USB) link. The signals are the spectra for subsequent gas evaluation.

Figure 1-1 Ocean optics USB 2000 spectrometer [30]

- The telescope collects the ultraviolet light scattered from aerosols and molecules in the atmosphere. Controlled by the motor, it is able to turn 360 degrees.
- The optical fiber transfers light from the telescope to the spectrometer.
- The motor controls the orientation of the telescope. It moves the telescope according to commands from the control circuit.
- The electronic compass records the direction, tilt, and temperature of the system.
- The GPS receiver records the position of the system and provides universal standard time stamps.
- The micro controller receives commands from radio modem via an RS232 serial cable, and controls the motor to move the telescope so that the spectrometer collects spectra at each

position. It also controls the tilt meter, compass, and GPS receiver through additional RS232 serial cables.

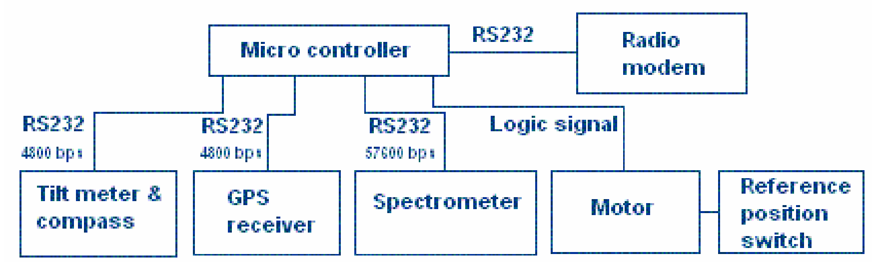

Figure 1-2 System diagram

The micro controller is PIC16F84 by Microchip Technology Inc. The hardware driver running in the controller was developed by Manne Kihlman.

Parameter name	**Value**
Program Memory Type	Standard Flash
Program Memory Size (bytes)	1k
RAM Size (bytes)	68
Data EEPROM Size (bytes)	64
I/O pins	13
Packages	18/PDIP,18/SOIC 300mil
Total power dissipation (mW)	800

Table 1-1 PIC16F84 micro controller parameters [25]

Figure 1-3 Scanning DOAS system

The spectrometer uses scattered sunlight and scans the sky over 180°, from horizon to horizon, at an angle approximately perpendicular to the gas plume, from a location several kilometers downwind of the volcano. From the recorded spectra, integrated trace gas densities per unit length of plume are derived by using the well-established Differential Optical Absorption Spectroscopy (DOAS) approach [18].

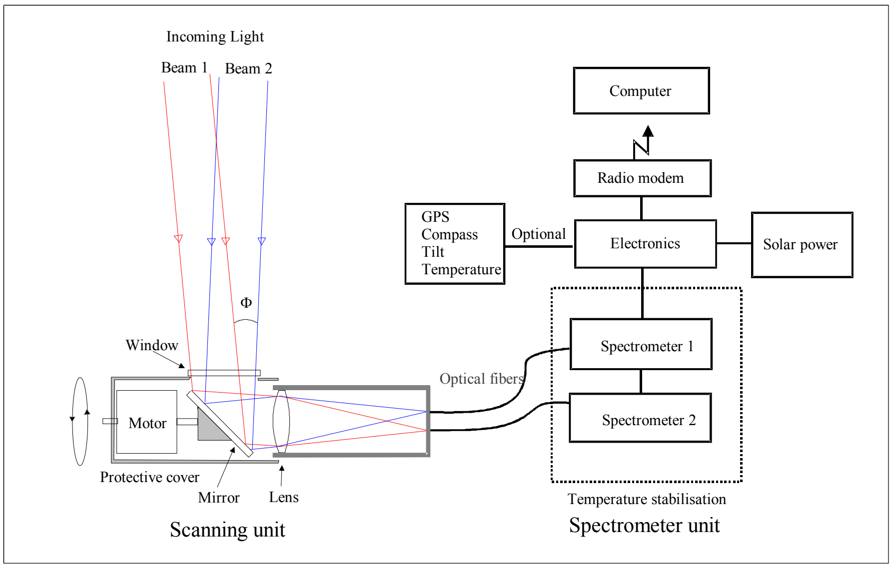

Figure 1-4 Schematic view of the Double Beam Scanning mini-DOAS instrument [18]

1.4 Monitoring Requirements

As explained in previous section, the prediction of volcano eruption is related to gas emission. The important gas to be measured is SO_2. The monitoring goal is to collect spectra and record the SO_2 concentration variation with time. Volcano monitoring has special requirements compared with industrial pollution monitoring due to the more variable environment that generates additional requirements for the monitoring network.

The first requirement is that the system must not need human monitoring during its operation. The basestation controls the nodes remotely. All nodes work simultaneously so that tomogram of gas concentration can be calculated later.

Measurement results should be accurate. The sensor nodes should be well calibrated *before* the measurement. The transmitted data should be examined to make sure that the data is not lost or corrupted during transmission.

The direction of the plume is not constant. It is mainly effected by the wind direction. The worst case is that wind direction changes every hour. So the duration of data collection should be limited to several minutes at each orientation.

The location of the sensor nodes is important. Since the volcano environment is variable, this effects the location of nodes. A node cannot stay in a position where the plume is out of sight or where the plume covers the whole field of view of the system (i.e., 180 degrees). To get a good view of the plume, the sensor nodes should be located in paralleled well-separated sites where the plume can be seen in a section of the scanning scope. Moreover, two sites cannot be located very close to each other or they simply retrieve information from nearly the same part of the plume.

Frequently changes of plume direction means that the sensor nodes may be under plume in the morning, but out of the cover of the plume in the afternoon. Therefore it is necessary to set up sensor nodes in suitable areas according to wind conditions, so that in at least one period a node should be able to observe the plume.

The sensor nodes might lose connectivity sometimes. The system must be able to tolerate disconnects and prevent data loss. However, operation problems are not always possible to prevent. The system must be able to record the errors. An error log is necessary to record errors during operations.

1.5 Thesis Layout

The next chapter describes the complete system architecture. The system is divided into five layers. The network topology is introduced first. Error control will be proposed in two layers. Routing protocols of wireless sensor networks will be reviewed. The routing mechanism proposed for this system will be presented.

In chapter three, the software modules of the system will be described.

Chapter four introduces the implementation of the network architecture. Comparison of different technologies and equipment to build the network will be presented. Then the design choices will be evaluated. Finally practical issues of remote sensing will be discussed.

Chapter five presents the conclusions of the thesis work.

References and an appendix are at the end of the thesis.

Chapter 2 System Architecture

This chapter proposes a system architecture from a hierarchical point of view. First the network topology will be described. Then error control schemes in both the data link layer and application layer will be discussed. Routing protocols of wireless sensor network will be reviewed. Finally a simple routing protocol will be proposed.

2.1 Overview

The system is a tiered cluster-based architecture. It is composed of sensor nodes, basestations, and a remote server. The sensor nodes are organized in a cluster, which is controlled by a cluster head or basestation. The remote server controls all the basestations. The *cluster* feature should make the network easy to expand and organize.

- A sensor node is composed of a scanning DOAS system, a communication module for communicating with the basestation, and a battery to provide energy for its operation. The sensor nodes are distributed around the volcano and collect spectra data. The distance between nodes is approximately 3km.
- The basestation is a computer that controls the connected sensor nodes and gathers data from them. The basestation is connected to the sensor nodes via a communication module. The basestation is also connected to the central server through Internet, which depends on Internet connection available in the observatory, such as ADSL or satellite link. The distance between the sensor nodes and the basestation is around 10km.
- A remote server monitors the working status of all the basestations in its area. It also collects data from each basestation, analyses the data and stores the data. It communicates with the basestation via Internet.
- The central server is located at Chalmers University in Sweden. It monitors all the remote servers via the Internet and stores all the data collected from them.

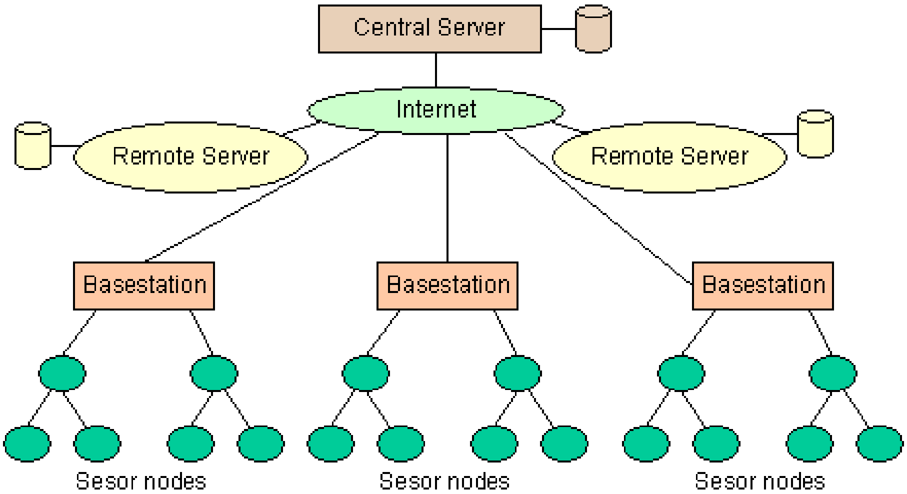

Figure 2-1 Network architecture

ISO OSI model for a protocol stack is widely used to describe conventional computer networks and has become a mature industrial and academic standard. It is not clear whether a strictly layered protocol stack should be deployed in a wireless sensor network. Here we have referred an application-specific protocol architecture LEACH [8], which uses a cross-layer design. In [4] it is claimed that modularity can be preserved by cross-layer design while information can be shared between layers. However, sharing between layers can also be achieved by expanding more interfaces. Clear layer separation is good for modularity. In this paper, the protocol stack for the wireless sensor network utilizes the OSI model. The system structure will be discussed according to the following layers:

Remote server	Base station	Sensor nodes
Application layer		Application layer
Presentation layer		
Session layer		
Transport layer		
Network layer		Network layer
Data link layer		Data link layer
Physical layer		Physical layer

Figure 2-2 Layer details

2.2 Sensor Network Topology

A sensor network is influenced a lot by its environment, the transmission media used and each node's power consumption. The topology is specific to the specific sensor network application. In *A Survey on Sensor Networks* [4], the issues related to topology maintenance and change are divided into three phases:

- Predeployment and deployment phase – Sensor nodes can be either scattered or placed one by one in the sensor field.

- Post-deployment phase – After deployment, topology changes are due to changes in sensor node positions.
- Redeployment of additional nodes phase – Additional sensor nodes can be redeployed at any time to replace malfunctioning nodes or due to changes in task dynamics.

Due to the limited number of sensor nodes and special geographical environment the topology designed for volcano sensor network can be determined on predeployment. The goal of a good volcano sensor network topology is to retrieve as much information as easily as possible and to deploy nodes in safe areas.

Traditional computer network use several classic topologies. They are star, ring, tree, complete, intersecting rings, and irregular.

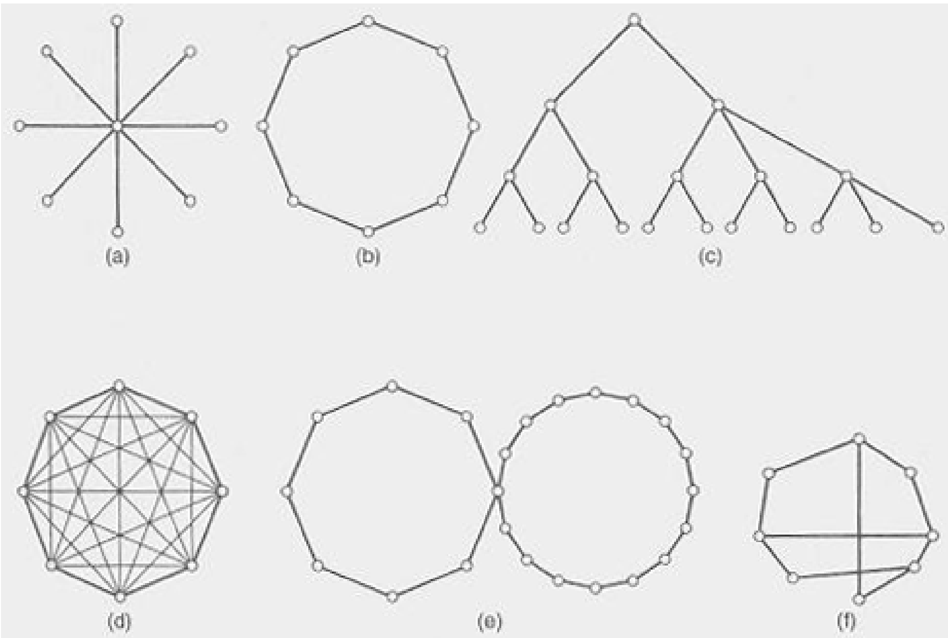

Figure 2-3 Traditional topologies for a point-to-point network

(a) Star. (b) Ring. (c) Tree. (d) Complete. (e) Intersecting rings. (f) Irregular. [5]

Traditional local area networks were mostly built with transmission lines. Thus there is little influence from the physical environment. However, a wireless network is highly affected by its surroundings. Most transmitter antennas need a line-of-sight path to send and receive signals. The main influences of the environment are obstacles or interference along the radio transmission path. The effect of surroundings affects the topology selected for a volcano sensor network a lot.

The research object of volcano sensor network is the plume from the volcano. The scanning requirements of the sensor nodes determine their locations. Considering the case of two nodes, it is desirable to scan the plume from two separate sites symmetrically located on the each side of the plume (as shown in the Figure 2-4). The two sites should be located at the same altitude and their scanning volumes should be the same part of the plume. They should also be located on one line that is perpendicular to the plume direction. The distance between them should be about twice of the plume height at this altitude. Hence, when all the information is gathered, the data can be combined tomographically to reconstruct an image of the plume.

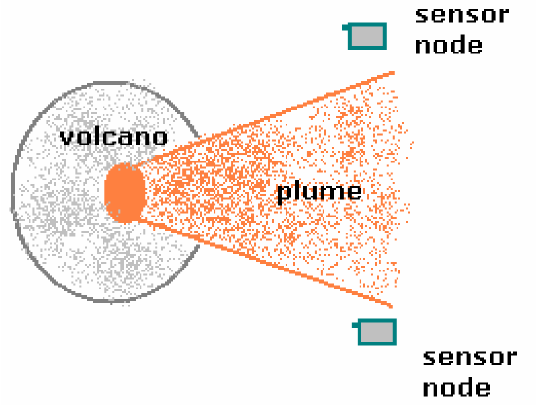

Figure 2-4 Demonstration of the positions of two sites (view from sky)

Because the plume direction is affected by the wind direction, using only two sensor nodes is not enough to enclose the plume when the wind direction changes a lot or the wind direction is not as predicted. In order to retrieve data in all conditions, the sensor nodes should be dispersed around the volcano at a certain radius. Then whatever the plume direction is, the plume can be seen by at least pair of sensor nodes.

Figure 2-5 shows one topology that combines both the star and the ring topologies. This topology has point-to-point and point-to-multipoint connections. Only one basestation is deployed in this topology. Relays are added where there are obstacles between the basestation and the sensor node. The placement of relay nodes can be decided according to the actual geographical situation. Redundant paths are needed to maintain data flows when some relay nodes fail.

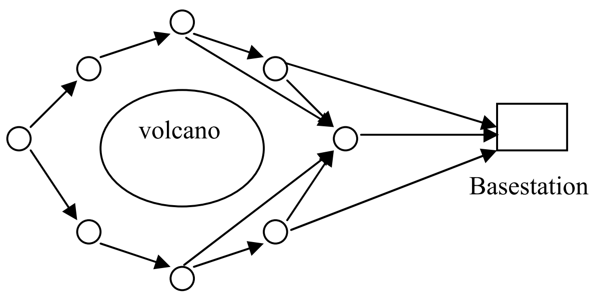

Figure 2-5 An example topology for a volcano sensor network

Figure 2-6 shows another tree topology. In this topology there can be one or more basestations, which can be deployed when the dispersing area is too large for direct radio communication.

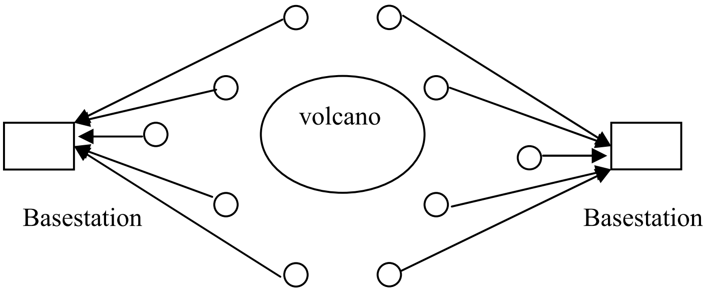

Figure 2-6 A tree topology volcano sensor network

2.3 Physical Layer

The physical layer is the lowest layer of the sensor network. It is concerned with power consumption, signal propagation, and modulation, which are vital to the lifetime of the sensor network and important to select or design suitable equipment. In the volcano sensor network, the geographical environment requires that sensor nodes be separated by a long distance (~ 3km). Hence transmission distance between sensor nodes and the basestation will be many kilometers. Over such a long transmission path, there will be a path loss, which cannot be ignored. Thus it is necessary to explicitly consider the link budget, which is composed of path loss, transmit power, signal-to-noise ratio (SNR), and transmit distance. The calculation will be discussed using three models.

In a wireless channel, under ideal propagation condition, we use the free space propagation model, which assumes that there is only one clear line-of-sight path between the transmitter and receiver. However, if there is no direct line-of-sight path between transmitter and the receiver, then the electromagnetic wave will bounce off objects in the environment and arrive at the receiver from different paths at different times, which causes multipath fading [8]. In this case, the two-ray ground reflection model should be applied.

1. Path loss

Free space model

The path loss between a pair of antennas is the ratio of the transmitted power to the received power, usually expressed in decibels [6]. In the free space model, the path loss L can be calculated as the following formula:

$$L = \frac{P_T G_T G_R}{P_R L_T L_R} \qquad (2.1)$$

where

P_T is the transmit power,

P_R is the receive power,

G_T is the gain of the transmitting antenna,

G_R is the gain of the receiving antenna,

L_T is the feeder loss at transmitting part,

L_R is the feeder loss at receiving part.

The *inverse-square law* for electromagnetic radiation implies a free space *path loss* proportional to the square of the distance.

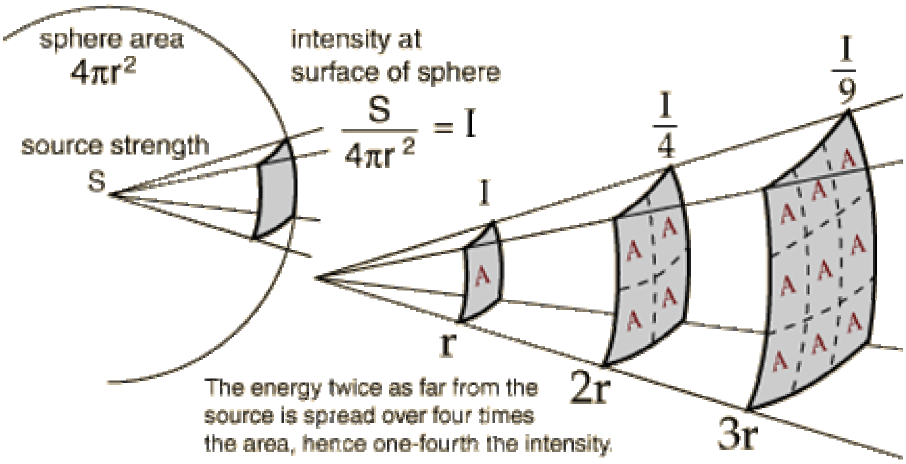

Figure 2-7 inverse-square laws [7]

The loss is given by the following equation:
PathLoss (dB) = 32.4 + 20 * Log (Frequency) + 20 * Log (Distance) (2.2)
where Frequency is in MHz and Distance is in km [6].

Plane earth loss

In practice some factors will reduce the range substantially, so more practical models should be considered. Propagation takes place via both a direct path between the antennas and via a reflection from the ground. The plane earth loss can be calculated as [6]:

$$L_{PEL} = 40\log r - 20\log h_r - 20\log h_t \qquad (2.3)$$

2. Received signal power calculation

In [7], the received signal power calculation is discussed as follows:

If the distance between the transmitter and receiver is less than a certain cross-over distance ($d_{crossover}$), the Friis free space model is used, and if the distance is greater than $d_{crossover}$, then the two-ray ground propagation model is used. The crossover point is defined as follows:

$$d_{crossover} = 4\pi \frac{\sqrt{L} h_r h_t}{\lambda} \qquad (2.4)$$

where

L >= 1 is the system loss factor not related to propagation,

h_r is the height of the receiving antenna above ground,

h_t is the height of the transmitting antenna above ground,

λ is the wavelength of the carrier signal.

If the distance is less than $d_{crossover}$, the transmit power is attenuated according to the Friis free space equation as follows:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 L} \qquad (2.5)$$

where

P_r (d) is the receive power given a transmitter-receiver separation of d,

P_t is the transmit power,

G_t is the gain of the transmitting antenna,

G_r is the gain of the receiving antenna,

λ is the wavelength of the carrier signal,

d is the distance between the transmitter and the receiver, and

L >= 1 is the system loss factor not related to propagation.

If the distance is greater than $d_{crossover}$, the transmit power is attenuated according to the two-ray ground propagation equation as follows:

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4} \qquad (2.6)$$

where

$P_r(d)$ is the receive power given a transmitter-receiver separation of d,

P_t is the transmit power,

G_t is the gain of the transmitting antenna,

G_r is the gain of the receiving antenna,

h_r is the height of the receiving antenna above ground,

h_t is the height of the transmitting antenna above ground,

d is the distance between the transmitter and the receiver.

Before selecting hardware and setting up the system, it is necessary to calculate path loss and to predict the possible range of the network. For the network as deployed for the Etna field trial the above calculations are:

Before antennas are chosen, we suppose that gains of antennas are zero. Assume that the feeder losses are 2dB and system loss factor is 1. The quantities needed for calculation are shown in the following table:

Quantity	Value in original units	Value in consistent units
P_T	1W	0dBW
P_R	-110dBm	-140dBW
G_T	0	0
G_R	0	0
L_T	2dB	2dB
L_R	2dB	2dB
h_t	1m	N/A
h_r	1m	N/A
Frequency	410MHz	N/A

Table 2-1 System parameters

From equation (2.1) the path loss in free-space is

$L = P_T + G_T + G_R - P_R - L_T - L_R = 0 + 0 + 0 - (-140) - 2 - 2 = 136\text{dB}$

Before we find the sites to set up the systems, we do not know altitude difference of the sites. Hence heights of antennas are unknown. Therefore in the calculation for selecting hardware we assume that the heights of both transmitting and receiving antennas are 1m. From equation (2.3) the maximum range of the communication system is

$\log r = (L+20\log h_r +20\log h_t)/40 = 136/40 = 3.4$

Hence r = 2512 m

Here 2.5km does not fulfil the requirement of the system.

When $h_r = h_t = 1\text{m}$, from equation (2.3) we have

$r = 10^{L/40}$

In this system, we need at least 5km communication distance,

$r >= 5000$

$10^{L/40} >= 5000$

$L >= 40\log 5000$

$136 + G_T + G_R >= 40\log 5000$

$G_T + G_R >= 12dBi$

Therefore, the minimum average gain of transmitting antenna and receiving antenna needed is 6dBi. Considering the plane earth loss is rarely an accurate model for real-world propagation and other factors from the environment, we choose 12dBi antenna to ensure a steady communication system.

When $G_T = G_R = 12dBi$,

$L = 12+12-(-140)-2-2 = 160dB$

$\log r = (L+20\log h_r + 20\log h_t)/40 = 160/40 = 4$

$r = 10000m$

Here, 10km can fulfil the requirement of the system communication.

This leads to the hardware choices described in Chapter 4.

3. Error rate of the links

Error rates are usually quoted as bit error rates (BER). The conversion from error probability to BER is numerically simple: BER =P {error}. However, this conversion assumes that the probabilities of errors from bit-to-bit are independent [26]. The probability of bit error occurring in one packet is as the following equation:

$P_{packet} = 1-(1-P_b)^M$,

where,

P_b is bit error rate,

P_{packet} is packet error rate,

M is the bit number of a packet in the link.

In the radio link, the maximum size of one packet is 4kByte. If the packet error rate, P_{packet}, should be below 1%, the BER should be below $2.4*10^{-6}$. We will examine how to achieve this next.

2.4 Data Link Layer

The data link layer is responsible for bits and framing, this enables the multiplexing of data streams. Coding could be used to ensure correct packets can be delivered to the next layer.

In our environment, the wireless sensor nodes face a lot of noise sources and impairments, such as unreliable communication channels, node failures, lack of energy, malicious tampering with nodes. The source of errors can be classified into two categories: (1) faults that change behaviour permanently and (2) failures that lead to transient deviations from normal behaviours [9].

In wireless sensor networks, error control has a different focus from that for traditional wired networks. Most times errors are caused by the wireless link rather than by network congestion. Wireless sensor network are application-specific, i.e., do not use standard network protocols. Error control is still an open research question in the context of wireless sensor network. Additionally, error control can be implemented in the Medium Access Control (MAC) layer, transport layer, application layer, or a combination of these layers.

At the transport layer, there are two main error control protocols - PSFQ and RMST presented in [10,11]. At the application layer, [9] describes a technique to correct for transient errors in sensed data.

2.4.1 Error Detection

Link designers have developed two basic strategies for dealing with errors: Forward Error Correction (FEC) and Automatic Repeat Requests (ARQ). FEC is accomplished by adding redundancy to the transmitted information using a predetermined algorithm [12]. ARQ includes only enough redundancy to allow the receiver to deduce that an error occurred, but not which error, but this indication is used to request retransmission [5]. ARQ includes three common protocols: Stop-and Wait ARQ, Go-Back-N ARQ, and Selective Repeat ARQ.

When designing an error control scheme, the limited energy budget in the wireless sensor network should be taken into consideration. The usefulness of ARQ in multihop sensor network environments is further limited by the additional retransmission energy cost and overhead. On the other hand, the decoding complexity is greater in FEC since error correction capabilities need to be built in. Considering this, simple error control codes with low-complexity encoding and decoding are often the best solutions for sensor networks [4].

2.4.2 Error Detection Methods

There are four error detection methods* [13], which can be applied in wireless sensor network. The selection of error detection method(s) should consider their energy-efficiency and the nodes energy constraints.

(1) Single parity check code

The single parity check code takes *k* information bits and appends a single *check bit* to form a *codeword*. The parity check ensures that the total number of 1s in the code word is even. The linear code calculation is as follows:

$b_{k+1} = b_1 + b_2 + \ldots + b_k$, modulo 2

where $b_1, b_2, \ldots, b_k$ are the information bits.

This method is simple to realize but doesn't detect errors when an even number of transmission errors occur, as one valid codeword is converted to another valid codeword.

(2) Two-Dimensional parity checks

This is a method to improve the error-detection capability of a single parity check code. It generates parity code for a matrix of information bits. Rows and columns generate parity codes. So if one, two, or three errors occur anywhere in the matrix of bits during transmission, at least one row or

* The four methods are combined into three methods in this paper.

parity check will fail. However, this method does not significantly improve error detection of a single parity check code. Some patterns with four errors are not detectable.

(3) Polynomial codes

The polynomial codes use polynomial arithmetic to calculate the code word corresponding to the information polynomial. Polynomial codes are readily implemented using shift-register circuits and are widely deployed in error detection and correction. Check bits are generated in the form of a cyclic redundancy check (CRC).

The following table gives generator polynomials that have been endorsed in a number of standards.

Name	Polynomial	Used in
CRC-8	x^8+x^2+x+1	ATM header error check
CRC-10	$x^{10}+x^9+x^5+x^4+x+1$	ATM AAL CRC
CRC-12	$x^{12}+x^{11}+x^3+x^2+x+1$	Bisync
CRC-16	$x^{16}+x^{15}+x^2+x+1$	Bisync
CCITT-16	$x^{16}+x^{12}+x^5+1$	HDLC,XMODEM,V.41
CCITT-32	$x^{32}+x^{26}+x^{23}+x^{22}+x^{16}+x^{12}+$ $x^{11}+x^{10}+x^8+x^7+x^5+x^4+x^2+x+1$	IEEE 802, DoD, V.42, AAL5

Table 2-2 Standard generator polynomials [13]

For our links we will use CCITT-8 as a CRC.

2.4.3 A Simple Error Control Scheme

In order to ensure the correct point-to-point data communication, an error control scheme can be added into each sensor node. Considering FEC, it needs error correction capabilities built in each sensor. We simply do error control to detect errors by Cyclic Redundancy Check (CRC). When a packet arrives at a sensor node, it checks the CRC control field and the CRC computed over content. The format of a link frame is:

Header	Address	Type	Data	CRC

Table 2-3 Frame format

The communication scenarios are shown in Figure 2-8.

(a) Normal communication

- Node A sends DATA to node B;
- Node A starts a timer;
- Node B checks CRC;

- If the DATA is undamaged, node B sends ACK to node A.

(b) DATA lost

- Node A sends DATA to node B;
- Node A starts a timer;
- Timeout occurs before receiving an ACK. Node A resends DATA at most n times (n is predetermined).

(c) ACK lost

- Node A sends DATA to node B;
- Node A starts a timer;
- Node B checks CRC;
- If the DATA is undamaged, node B sends ACK to node A;
- Timeout. Node A resends DATA at most n times (n is predetermined).

(d) DATA is wrong

- Node A sends DATA to node B;
- Node A starts a timer;
- Node B checks CRC;
- DATA is not correct;
- Node B informs the node A to retransmit the message with NACK.

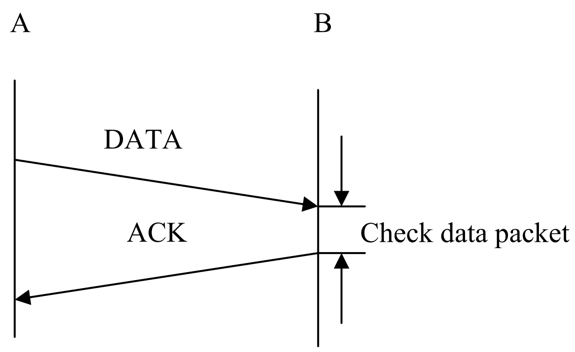

Figure 2-8 (a) Error control in data link layer - normal communication

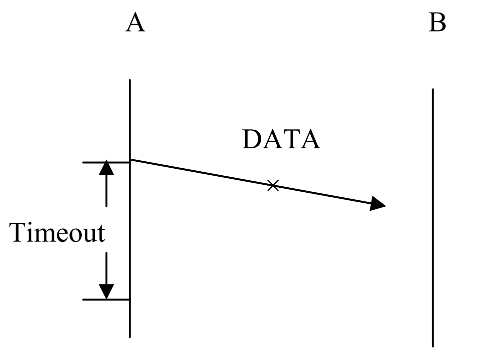

Figure 2-8 (b) Error control in data link layer - DATA lost

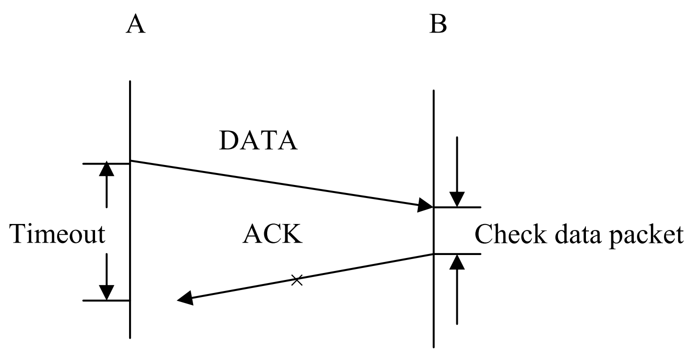

Figure 2-8 (c) Error control in data link layer - ACK lost

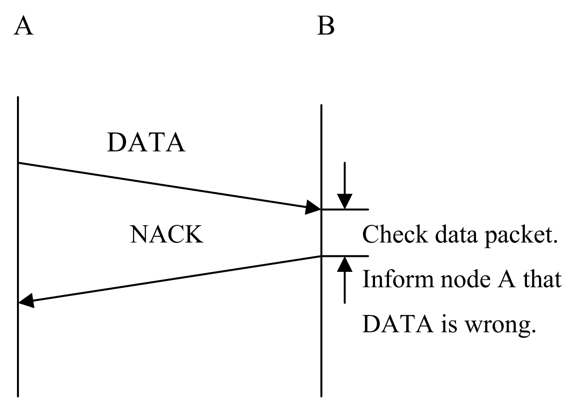

Figure 2-8 (d) Error control in data link layer - DATA is wrong

2.5 Network Layer

Because the sensors have limitations of the following resources: power, computation, communication range, and memory, when considering the characteristic and requirements of a wireless sensor network, the selection criteria for a routing protocol are:

- Energy-efficiency - Routing protocols should be designed to save nodes' power consumption so as to maximize the nodes' lifetime.
- Robust and fault tolerant – The wireless sensor network is mostly deployed in remote wild terrain without human attendance. The network should be able to recover from errors or reconfigure itself when some disturbances to the communication happen.
- Scalability - Because the number of sensors may be large, the routing protocols should also take scalability into consideration.
- Local address- Wireless sensor networks do not use global address, thus the routing protocol should utilize local addresses.

2.5.1 Conventional Routing Protocols

In traditional computer networks there exist nine types of routing protocols. They are shortest path routing, flooding, gossiping, flow-based routing, distance-vector routing, hierarchical routing, routing for mobile hosts, broadcast routing, and multicast routing. Of these only flooding and gossiping are scalable for a large sensor network.

Flooding is a static routing algorithm, in which every incoming packet is sent out on every outgoing port except the one it arrived on, until a maximum number of hops for the packet is reached or the destination of the packet is the node itself. Flooding has proven to be useful in networks whose topology changes frequently. However, it has several deficiencies [15]: implosion, overlap, and resource blindness. Flooding generates duplicate messages which may be sent to the same node. In the flooding the amount of energy available is not considered. So the flooding protocol is not an energy-aware protocol.

Gossiping is a derivation of flooding in which nodes do not broadcast, but send the incoming packets to a randomly selected neighbor [4]. This approach avoids the implosion problem by only having one copy of a message at any node, but it takes a long time to propagate the message to all sensor nodes. Next we will consider routing protocols designed explicitly for wireless sensor networks.

2.5.2 Routing Protocols for Wireless Sensor Network

Routing protocols for wireless sensor network can be classified into three types: direction connection, multi-hop routing, and cluster-based routing.

2.5.2.1 Direct Connection

Direct connection is applicable when there are few nodes and the coverage of the network is not too large for each node to reach the basestation (or sink). While direct connection consumes more power when the number of sensors is large and the coverage of the network is large enough that usually nodes quickly deplete their energy sending data all the way to the basestation. Thus direct connection cannot achieve the scalability requirements of a wireless sensor network.

2.5.2.2 Multi-hop Routing

Multi-hop routing is utilized by several routing protocols, examples include: SPIN [15], direct diffusion [16], and GEAR [17].

2.5.2.3 Cluster-based Routing

Cluster-based routing is hierarchical. It divides the network into cluster layers. A cluster is composed of cluster head and cluster nodes. In each cluster, cluster nodes send data to cluster head. The cluster head takes the responsibility for routing among cluster heads and basestation. LEACH is a typical cluster-base routing protocol.

Energy-efficient and Cluster-based Protocol – LEACH

Wendi Beth Heinzelman built an application-specific protocol architecture LEACH (Low-Energy Adaptive Clustering Hierarchy) [8]. LEACH is a self-organizing, adaptive clustering protocol that uses randomization to distribute the energy load evenly among the sensors in the network. In LEACH, the nodes organize themselves into local clusters, with one node acting as the local basestation or *cluster-head*. Cluster-head position rotates among the sensors in a randomized way in order to avoid draining the battery of any one sensor in the network. In this way, the energy load associated with being a cluster-head is evenly distributed among the nodes. In addition, LEACH performs local data fusion to "compress" the amount of data being sent from the clusters to the sink, further reducing energy dissipation and enhancing system lifetime.

The clustering infrastructure allows all data from nodes within the cluster to be processed locally, reducing the data set that needs to be transmitted to the end-user. It is also possible to save considerable energy by locally aggregating a large amount of data into a smaller set of data before transmission to the basestation, if the cost in terms of energy dissipation of communicating data is greater than the cost of computing on the data.

The proposed routing protocol to be introduced in the next section gets inspirations from LEACH.

2.5.3 Proposed Routing Protocol

The cluster-based model is efficient in energy dissipation. It organizes the nodes in a cluster so that the cluster of nodes can save energy and need not care about routing. As routing protocols are application-specific in wireless sensor network, thus for the volcano sensor network, the routing protocol should meet its special requirements. In the volcano sensor network, there are small number of sensor nodes and the network is a static network. However, the network should be scalable and fault-tolerant. Therefore the routing protocol can apply some routing algorithms used in conventional networks with energy consideration. The basestation is the main controller of routing. The routing procedure is as follows:

1. The basestation broadcasts a routing table to all sensor nodes. The broadcast happens only when the basestation is sure that there is no data being transmitted.
2. Each node extracts the node's neighbors and its cluster head from the table. Thus each node has its own routing table in its cache.
3. The basestation sends data to a cluster node - At first the data is routed to the cluster head in the same cluster with the cluster node, then the cluster head sends data directly to the node.
4. When the cluster node sends data to the basestation – The data is sent directly to the cluster head, then the cluster head routes the data to the basestation according to its routing table.
5. The cluster head might receive several packets in a very short time. In order to prevent collisions, the cluster head handles the packets in arrival order. Thus the first packet to arrive is sent first. If it happens that two packets come in at the same time, the cluster head randomly choose one to be the first.
6. The cluster nodes also have a sleep function. The basestation can put the cluster nodes into sleep status to save energy.
7. To prevent a single cluster head from excessive energy dissipation, the cluster head position is rotated within the nodes in a cluster. The basestation broadcasts newly created routing table after a certain period.

This routing protocol creates a routing table, which enables energy control. It can scale up to handle a lot of sensor nodes. The intensive calculations are only located at the basestation as the basestation is a computer with sufficient power and calculation ability.

2.6 Application Layer

The data link layer only handles error control for each point-to-point link. However, end-to-end communication is not necessarily reliable, thus it is necessary to check data correctness at the application layer before the data is accepted. In [9] a technique of correcting transient errors in sensed data is presented, which is realized at the application layer. The motivation is to use data-aware error correction to reduce the cost of reliability. The framework has three processes: (1) construct a model of the data generation process off-line according to samples of sensor data; (2) use the data model during data acquisition for online prediction of data; and (3) correct the errors using an application-aware predictive correction block with prediction history. The error control in the application layer handles the data received without consideration of channel condition or packet loss. It removes most error control efforts from the sensor nodes, which saves energy in the resource-constrained sensor nodes. It is applicable to real-time demands situation and when the sensed data follow a predictable pattern. When the surrounding environment varies out of the scope of the data model's prediction the deviation of prediction and modification of the model from the real data should be obvious and the data must not be "corrected". As most sensor projects are application-specific, the model can only be deployed when sensed data have a predictable pattern. Constructing such a model for various applications require effect and time.

In the volcano monitoring sensor network, the accuracy of spectrum is important. So the error correction in [9] is not applicable. However, error control in application layer can save energy at the sensor nodes. In the volcano monitoring network we use a retransmission mechanism (ARQ) address the variable and time-varying channel conditions. We can also adapt the transmission rate to the capability of the channel, which enables the system to operate even when the channel characteristics are unpredictable, however it can increase the delay to receive sensor data.

In this network, serial radio link is the final communication choice for this system. In RS 232 protocol, the error control scheme is parity check. When there are an odd number of incorrect bits in one byte, this error can be found by parity check. However, when an even number of bits are not correct, parity check is failed. Hence, in data link layer, this error is ignored. Although this type of error rarely happens, it will ruin the whole data packet which error bits belong to. To prevent from failure of error detection in data link layer, this network deploys error control scheme in application layer. If data is detected to be incorrect in application layer, it will be required to be retransferred on a byte-by-byte basis. Hence, error control applied in two layers can guarantee the quality of data communication in this system.

Transport scenarios

(a) Correct communication

The normal procedure of the data communication in uninterfered channel is as the Figure 2-9(a). The basestation sends CR (connection request) to a sensor node. If the node receives the CR, it sends back ACK (acknowledgement) to the basestation. Then the basestation receives ACK in a period shorter than timeout. It supposes that the channel is good. It continues to send other commands (CMD) to the node. When the node receives the CMD, it sends back DATA to the basestation.

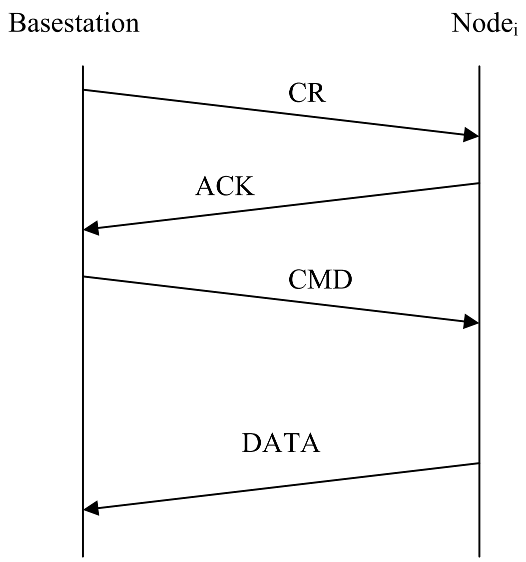

Figure 2-9 (a) Transmission scenarios - Correct communication

(b) ACK lost

The basestation sends the sensor node CR. The node replied ACK. On the halfway of the transmission, the channel could be noisy so that ACK is lost. The basestation waits until time out. It does not proceed to the further step. It resends CR to the node. If it gets the ACK from the node within determined timeout, it continues the other steps. If it still cannot get ACK, it continues to send a certain amount of CRs until the amount exceeds the predetermined limit. The communication is supposed to be broken. The communication is terminated. After a period of time, the communication can be restarted. The procedure is shown as Figure 2-9(b).

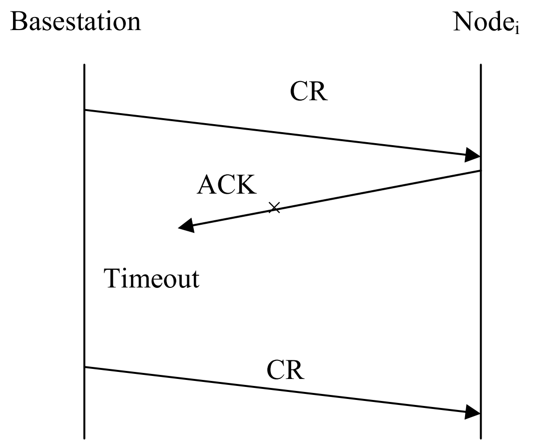

Figure 2-9 (b) Transmission scenarios - ACK lost

(c) CMD lost

In this scenario, the CMD from the basestation to the node is lost on the way. The node cannot get and command from the basestation. So it does nothing. The basestation waits the data from the node until timeout. It knows that the CMD is lost. Then it resends the CMD to the node during the predetermined time. If it gets reply, the communication continues. If it still cannot get reply until timeout, the communication is terminated. After a period of time, the communication can be restarted. The procedure is shown as Figure 2-9 (c).

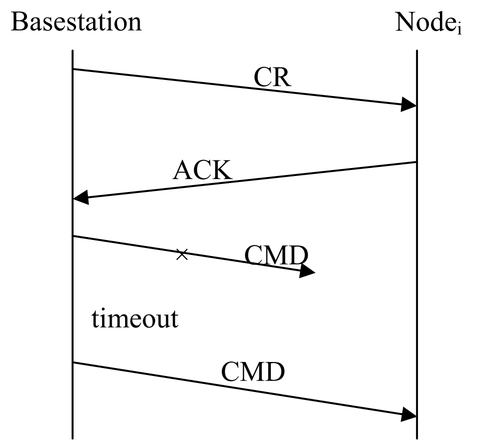

Figure 2-9 (c) Transmission scenarios - CMD lost

(d) Data lost

The basestation and the sensor node have set up communication. The data is lost on the way. There are two possibilities: (1) all the data is lost; (2) a part of the data is lost. If all the data is lost, the basestation cannot receive any data until timeout. If a part of data is lost, the basestation will find out the number of bytes is incorrect since the format of the data is fixed. In both situations, the basestation will resend the command in a predetermined period. If it gets reply, it can continue to communicate with the node. If it still cannot get reply, the communication between them is terminated. The basestation waits for a period of time and then restarts the communication. The procedure is shown as Figure 2-9(d).

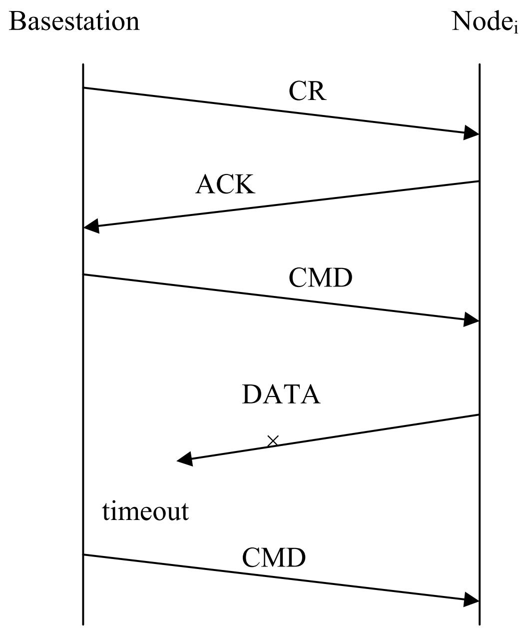

Figure 2-9 (d) Transmission scenarios - Data lost

(e) Data is incorrect

The basestation and the sensor node have set up communication. When the basestation receives a data packet, it will check the whole data packet according to the format of the data packet. If the data is not correct, the basestation will request the node to restart and transmit another data packet. The procedure is shown as Figure 2-9(e).

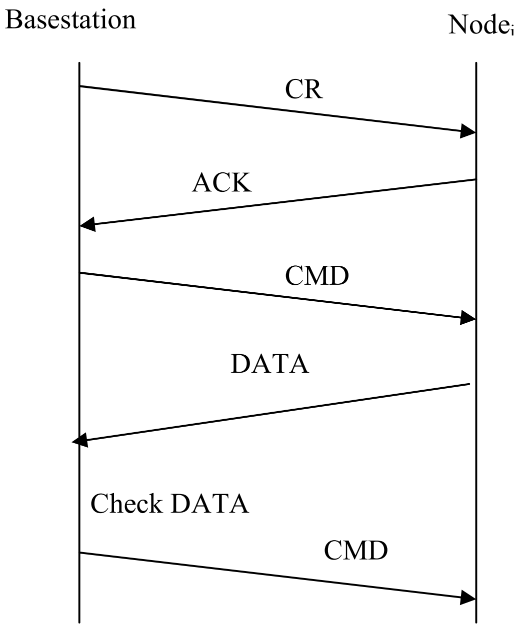

Figure 2-9 (e) Transmission scenarios - Data is incorrect

Chapter 3 Software Design

Chapter 2 described the network architecture. This chapter will propose software modules that realize the functions described in chapter 2. The modules are divided into three types according to the layer.

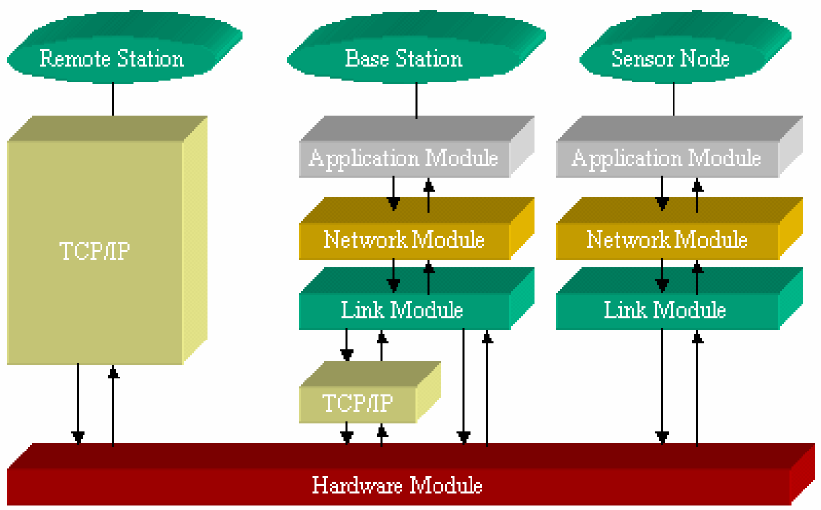

Figure 3-1 Module structure

3.1 Basestation Modules

The basestation software is composed of three modules specific to the sensor network – application module, network module, and link module; additionally it has a standard TCP/IP stack.

3.1.1 Application Module

(1) Function:

- Provides the user interface;
- Receives user requests from the interface;
- Shows plots of data via a Graphic User Interface (GUI);
- Controls the sensor nodes;
- Manages the energy consumption on the sensor nodes;
- Evaluates the data from nodes;
- Manages node clusters.

(2) Module structure

In the application module, there are five classes:

GUI	a class for the user interface. It receives user's request on the interface and displays graphical information on the interface.
ClusterManager	a class for managing clusters. It organizes the sensor nodes into clusters and chooses a cluster head in each cluster.
NodeOperator	a class for handling nodes operations such as resetting nodes, starting nodes, and requesting a node's information, etc. It sends commands to the nodes through the network module.
Evaluator	a class for evaluating the data sent from the sensor nodes. It is application-specific. In this project it includes algorithm to calculate gas concentration.
ErrorLogger	a class for recording the errors. It gets the error messages and sends them to the GUI.

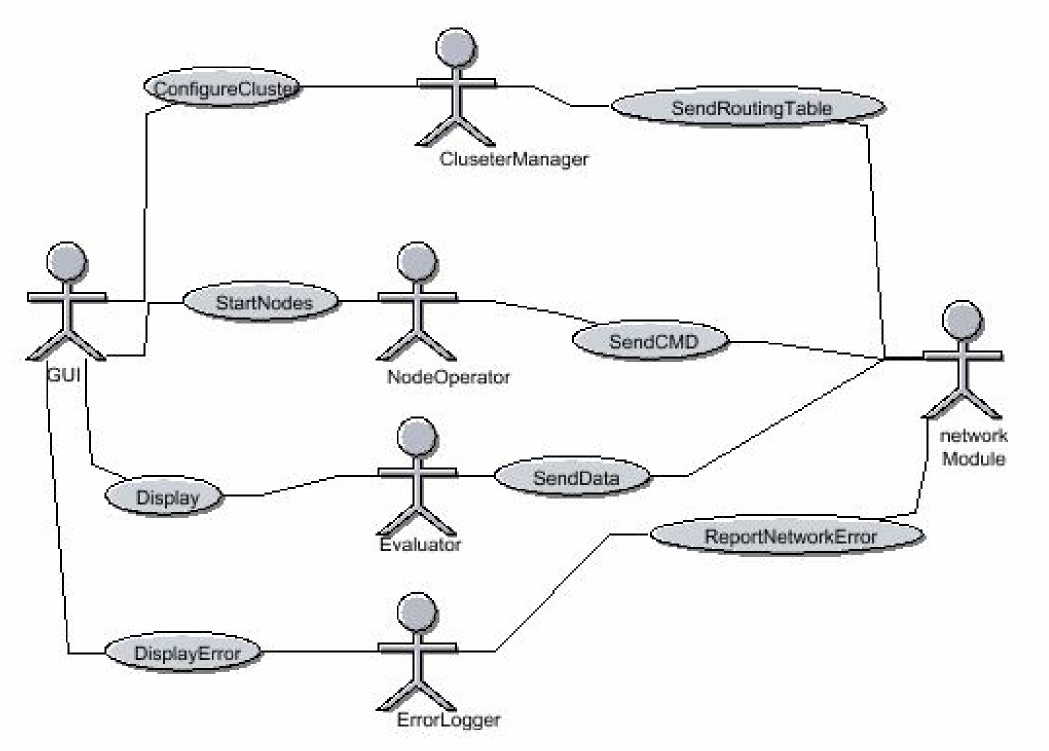

Figure 3-2 Application module of basestation

3.1.2 Network Module

(1) Functions:

- Implements the routing algorithm;
- Encapsulates commands from the application module into packets;
- Unpacks data packets.

(2) Module structure

- RoutingManager a class to run the routing algorithm and store routing tables;
- Packager a class to pack and unpack data;
- ErrorLogger a class to receive error message and send error message to application module.

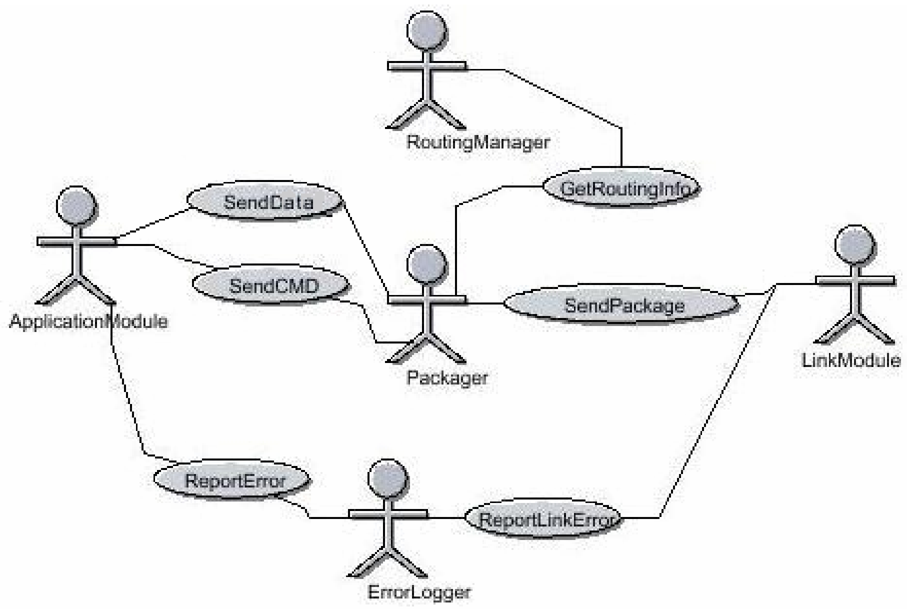

Figure 3-3 Network module of basestation

3.1.3 Link Module

(1) Functions:

- Checks whether the point-to-point communication is correct;
- Stores the received data until new data arrives;
- Performs the data communication.

(2) Module structure

- DataChecker — a class to check data correctness;
- Errorhandler — a class to handle the errors happen during communication;
- Communicator — a class to handle the communication.

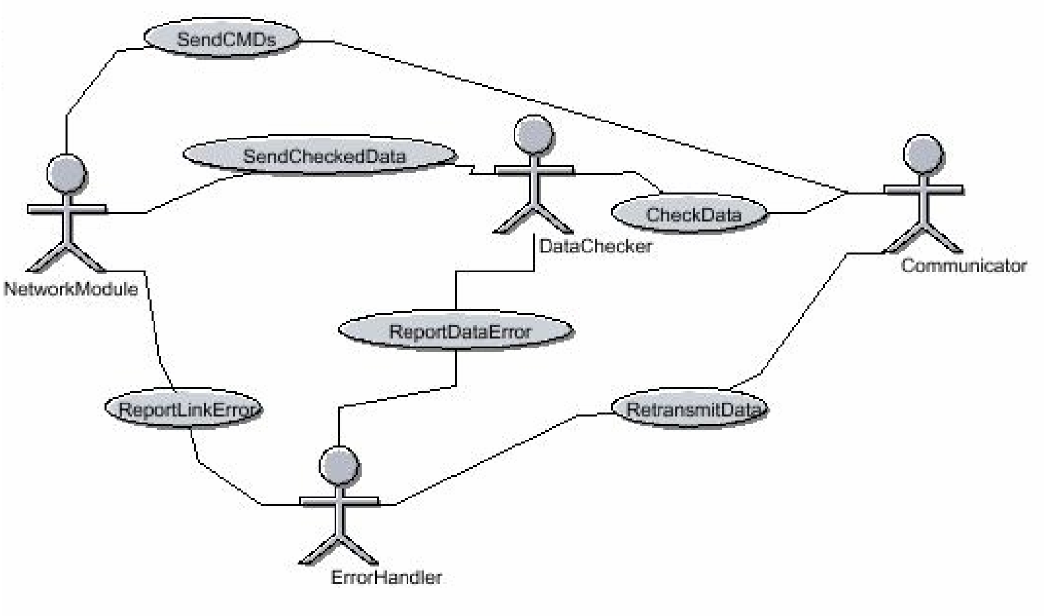

Figure 3-4 Link module of basestation

3.2 Module of Sensor Node

The sensor node modules include: application module, network module, and link module.

3.2.1 Application Module

(1) Functions

- Controls the sensor equipments;
- Stores error logs.

(2) Module structure

- EquipmentController — a module to control the sensors. It receives commands from the basestation via network module. It sends data out through the network module.
- ErrorLogger — a module to store the errors in the local cache.

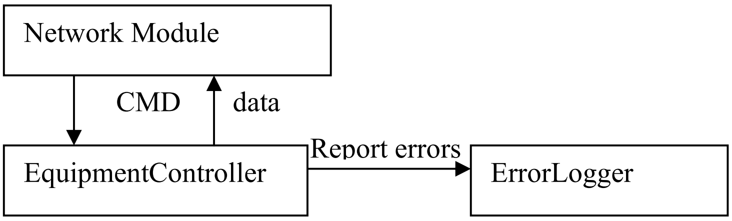

Figure 3-5 Application module in sensor node

3.2.2 Network Module

(1) Functions

- Store routing table and route according to this table.

(2) Module structure

- RoutingTable a table to store the routing information;
- RoutingSelector a module to select the next hop.

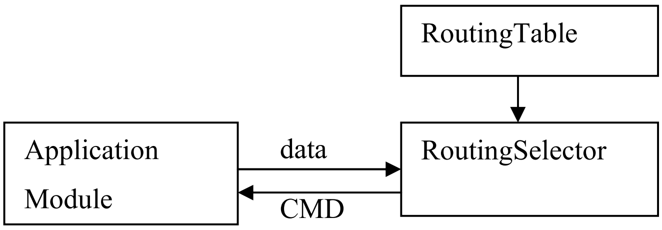

Figure 3-6 Network module in sensor node

3.2.3 Link Module

(1) Functions

- Check data validity and communicate.

(2) Module structure

- DataChecker a module to check whether the data is valid;
- Communicator a module to fulfill communication tasks.

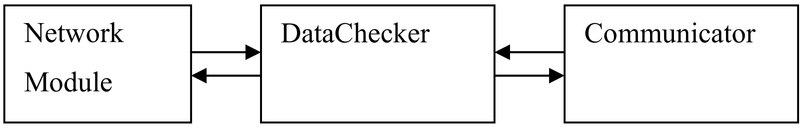

Figure 3-7 Link module in sensor node

Chapter 4 Implementation and Results

This chapter introduces the implementation of the proposed network architecture. The comparison of different scenarios will be described. From the field campaign, fieldwork showed that there is some distance between theory and practice. Some practical issues of remote sensing will be discussed here.

4.1 Goals of the Implementation

The goal of the implementation was to build an effective robust wireless sensor network for volcano monitoring and operate it in a real volcano environment. The feasibility and functions of the system were evaluated and examined in the field. Practical issues and problems were identified.

4.2 Hardware Implementation

Because of the volcano environment, there was no possibility to utilize a wired network. Therefore we need to select a wireless solution. The observation sites are about 3km away from each other. Both wireless LAN (WLAN) and longer distance radio links were candidates.

Type	Communication protocol	Range	Frequency band	Data Rates
WLAN	IEEE 802.11a	91m@6Mbps	5GHz	54, 48, 36, 24, 18, 12, 8, and 6 Mbps
	IEEE 802.11b	91m@1Mbps	2.4GHz	11, 5.5, 2 and 1 Mbps
	IEEE 802.11g	91m@1Mbps	2.4GHz	54, 48, 36, 24, 18, 12, 9, and 6 Mbps
Point-to-point radio link	Frequency hopping, direct FM, spread spectrum, etc.	>5km	380-470MHz, 400-512 MHz, 400-480 MHz, 820-960 MHz, 902-928 MHz, 2.4-2.4835 GHz	2400 bps, 4800 bps, 9600 bps, 19.2 Kbps, 56 Kbps, 115.2 Kbps

Table 4-1 Comparison of WLAN and radio network

Wireless LAN solution

A wireless local area network (WLAN) uses radio frequency (RF) technology to transmit and receive data over the air [25]. The predominant standard for wireless LANs is the IEEE 802.11 standard. WLAN transmits on unlicensed spectrum as listed in table4-1. A wireless access point can be used to connect wireless communication devices together to build the wireless network. The data rates are all above 1 Mbps. However, the transmission range of WLAN is below 1km as shown in the table. If a longer distance is necessary, more equipment will be needed. There are several ways to extend the access point's range.

- One way is to replace a removable antenna of the access point with a high gain antenna. This is as described in the formulas (2.1) and (2.2). The improvement the gain of transmitting antenna overcomes the path loss. The cost is both an antenna and effort to align the sender and receiver antennas. However, the transmission range is increased.
- The second way is to add RF amplifiers. The amplifiers, which cost a few hundred dollars each, can add 20dB of gain to the RF signal. However, when adding amplification (and antennas) we should make sure that the system configurations comply with effective isotropic radiated power (EIRP) rules. In addition, most regulatory agencies, such as the Federal Communications Commission (FCC) in the U.S., require certification beyond what the access point manufacturer receives when the wireless LAN includes additional components such as amplifiers. This certification would increase costs.
- The third way is to install a repeater. A wireless LAN repeater is a stand-alone device. The repeater must be within range of the AP and set to the same channel. It listens to the selected channel and retransmits traffic on the same channel. For example, the repeater may receive a data frame sent by the AP, and then retransmit the data frame, thus expanding the range. However, because repeaters duplicate the traffic sent over a common channel, they reduce the overall throughput by fifty percent. Also, a repeater requires electrical power, which might be costly to install [26]. In our case this makes the use of repeaters impractical (or expensive).

Because the Scanning DOAS has only a RS 232 port, it cannot directly communicate with the access point. A wireless RS232 serial adapter for RS232 devices is needed to connect the Scanning DOAS system and the wireless access point. The architecture for the system is shown in the following figure. The sensor node includes a scanning DOAS, a wireless serial adapter, and an access point. The access point communicates with the scanning DOAS via the wireless serial adapter. The basestation is connected to an access point, which acts as a bridge to connect additional access points.

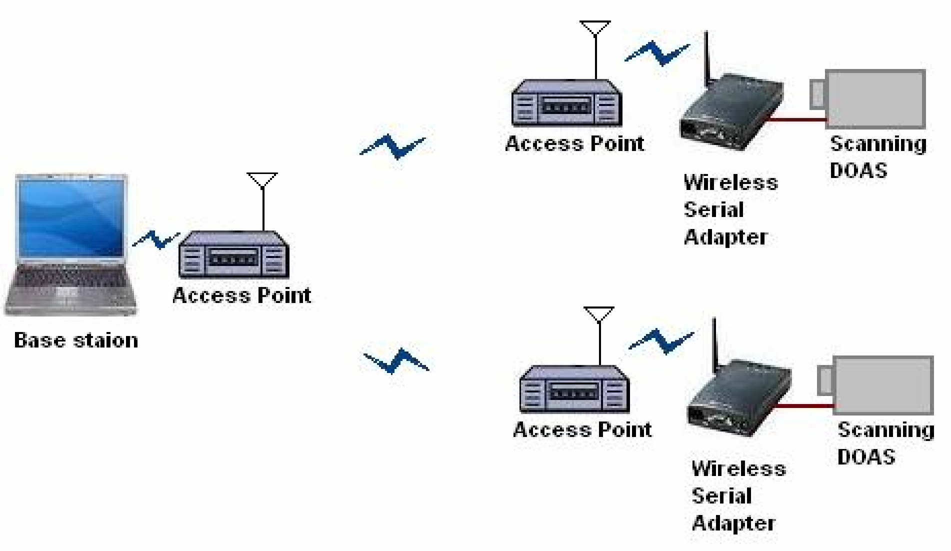

Figure 4-1 WLAN solution for volcano monitoring sensor network

Point-to-point & point-to-multipoint radio network solution

A radio network is a collection of nodes communicating together via radio link, i.e. using radio waves to carry the information. There are many types of radio modems. The main communication protocols are frequency hopping, direct FM, spread spectrum, etc. The transmission range can be more than 5km. However, the data rate is much lower than wireless LAN. A common maximum data rate is 115.2kbps.

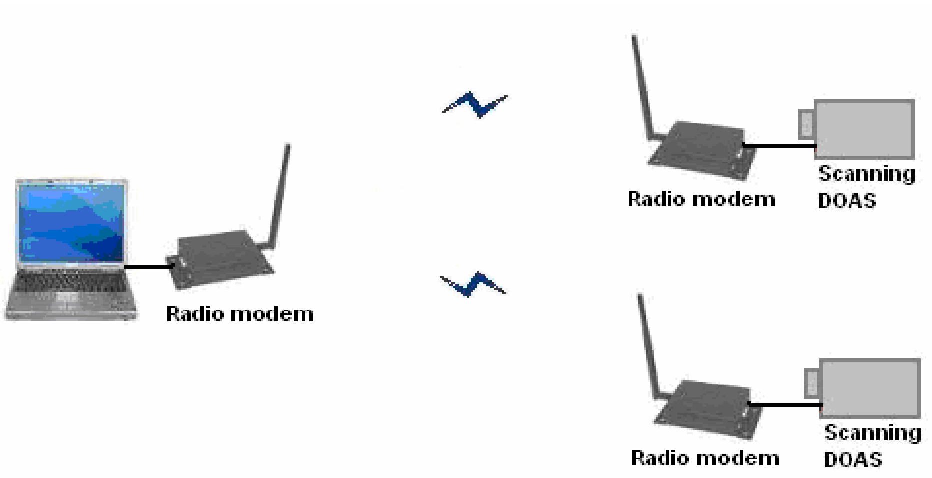

Figure 4-2 Radio network solution for volcano monitoring sensor network

Both the radio network and WLAN methods can achieve a sufficiently long distance. Because the Scanning DOAS has an RS232 port, the WLAN solution needs one wireless RS232 serial adapter in addition to the wireless access points and high-gain antennas. The WLAN method requires deploying more equipment, but adds more control and error checking. To save time money and to simplify the network configuration, the final choice was to utilize a radio network.

In the field campaign, three sensor nodes were deployed in three places. One node was close to the basestation. This node was directly connected to the basestation via serial cable. The other two nodes were ~ 3km away from the basestation. Three Satelline 3AS radio modems provided the radio links. In order to achieve sufficient long-distance communication, 12dBi Yagi antennas were deployed at each site. The three sites were set up in line-of-sight. The routing in the network is a single-hop direct connection.

Exposed in wild environment with limited power, the power budget of a system is necessary when designing a wireless sensor network. The following table is the power consumption of each module of the system.

<table>
<tr><th>Equipment</th><th>Product name</th><th>Voltage
(V)</th><th>Current
(mA)</th><th>Resistance
(Ω)</th><th>Power
(mW)</th></tr>
<tr><td>Spectrometer [31]</td><td>USB 2000 miniature fiber optic spectrometer</td><td>5</td><td>90</td><td>N/A</td><td>450</td></tr>
<tr><td>GPS receiver [28]</td><td>RS 232 GPS receiver BR-304</td><td>5</td><td>90</td><td>N/A</td><td>450</td></tr>
<tr><td>Stepping motor [29]</td><td>RS stock no. 440-436</td><td>12</td><td>160</td><td>N/A</td><td>1920</td></tr>
<tr><td>Tilt meter& compass [27]</td><td>TCM2-20</td><td>5</td><td>15~20</td><td>N/A</td><td>75~100</td></tr>
<tr><td rowspan="2">Radio modem [32]</td><td rowspan="2">Satelline-3AS radio modem</td><td>3 (receive)</td><td rowspan="2">N/A</td><td rowspan="2">50</td><td>180</td></tr>
<tr><td>25 (transmit)</td><td>12500</td></tr>
</table>

Table 4-2 Power consumption of each module of the system

From this table we can compare the total system power vs. the power required to transmit and receive. When the system is at receiving status, the total power consumption is 3100mW and the communication module consumes 5.8% of the total power for receiving signals. When the system is at transmitting status, the total power consumption is 15420mW and the communication module consumes 81% of the total power for transmitting signals.

4.3 Software Implementation

The software modules were described in chapter 3. Because of the direct connection, the routing part was simplified. The routing part of basestation simply adds the destination address to each packet. Since the two remote sites share one radio modem in the basestation, therefore, the basestation's radio link must be multiplexed.

The procedure is as follows:

- Configure all the nodes, such as COM port, baud rate, etc;
- Start the node closest to the basestation and one remote node;
- In order to read the compass information, turn off power of the sensor nodes;
- Get compass information and display them on screen;
- Turn on power of the sensor nodes;
- Move motors to the home position;
- Move motors to collect spectra of sky and darkness and calculate exposure time for the spectrometers inside Scanning DOAS;
- Move motors to positions according to their experimental configuration;
- Initiate spectrometers and collect spectrum;
- Evaluate spectrum and show them on screen;
- The remote node suspends itself and starts the other remote node;
- Motors move until they reach the last position;
- The procedure goes on cyclically until the basestation stops the nodes.

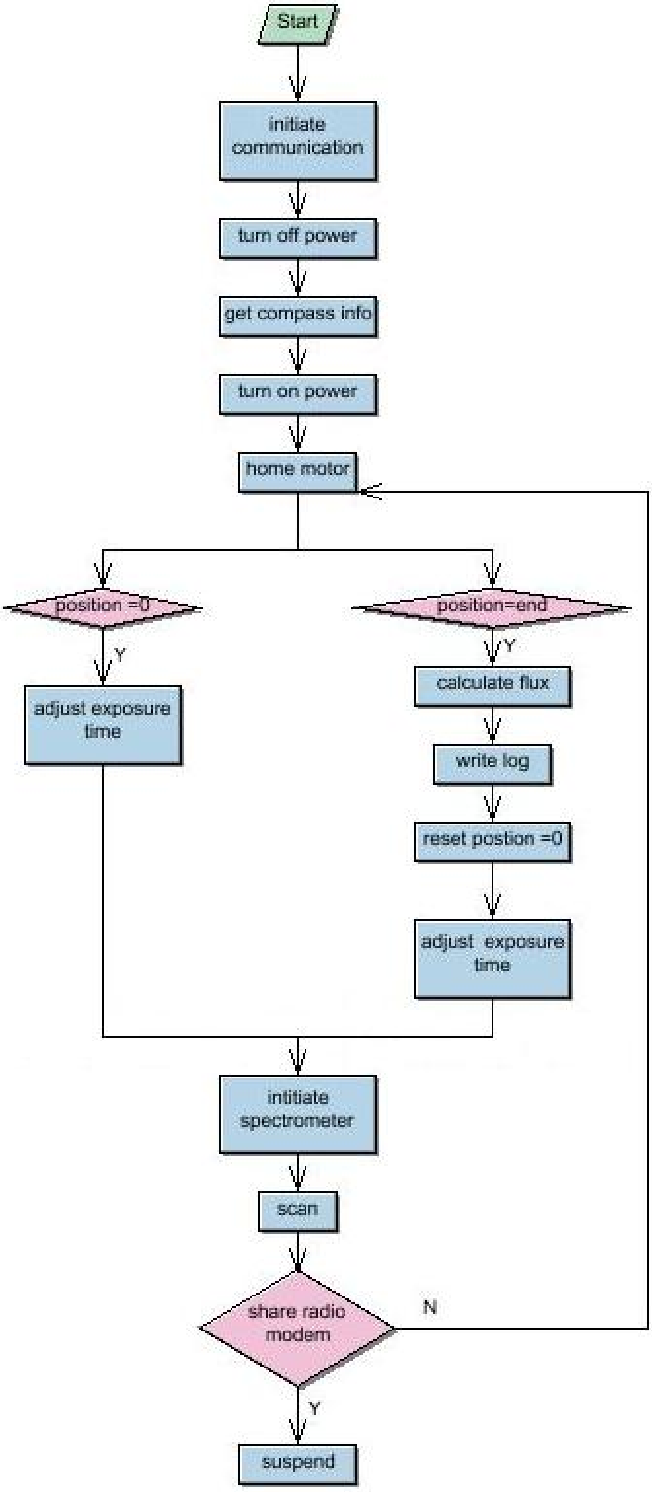

Figure 4-3 Flow chart of the remote control program

4.4 Evaluation of the System Design

The system design of volcano monitoring sensor network covers the hardware design, network design, and software development. The main focus of this thesis were network and software design.

The hardware design had to comply with requirements of the wild environment. The temperature range of hardware should include the temperature range of the environment. This should be considered when designing the sensor nodes and choosing the communication module. The system should be well enclosed so that humidity and dust do not adversely effect on the system. A lightning conductor is also necessary for protecting the system.

One of the important aspects of the system is the range, which is related to a lot of factors, including transmit power, receive power, antenna gain at both transmitting part and receiving part, and so on. Sensor nodes must be located within the range of the radio signal. In order to improve the range of the system, a high-gain antenna and RF amplifier must be deployed. The sensitivity of the receiver is another important factor to effect the range.

Another important aspect is the system capacity, i.e., how many nodes the system can control at the same time. This concerns the bandwidth of the communication module, the size of data packets, and the number of such packets per node. The wireless LAN method provides much high data rates, which enables the system to support more nodes. As the radio network cannot support as high data rate as wireless LAN, because the serial communication interface limits the data rates, the system cannot support as many nodes as a wireless LAN could. However, the radio net solution was cheaper in this field trial, due to the limited number of nodes.

4.5 Practical Issues Regarding Remote Sensing

The environment of a volcano is hilly terrain with moderate-to-heavy tree densities. The physical environment is dynamic. Dynamic operating conditions and dynamic availability of resources make fieldwork very different from lab work. The environmental conditions are unpredictable, so devices must adapt to the environment. Devices should be robust and stable. Complex and extensive manual configuration may delay the observation of important information. Hence the set-up of equipment should be as simple as possible.

Paper [3] mentioned that vulnerabilities specific to sensor networks result from their capabilities to self-configure and from the wireless communication facilities embedded with the nodes. An attacker may deploy counterfeit sensors or take over sensors, even cluster heads. The worst scenario could be that an attacker gains control of the basestation and compromise the entire network. However, in this field trial we only had to face natural impairments.

The volcano sensor network has its own vulnerabilities. The spectrometer sends data in its own special format. If the data doesn't follow the correct format, the control program will request retransmission. A more secure method to protect sensor network is to use checksum for the compressed data. Because of the features of the scanning DOAS equipment, the vulnerabilities are due to the following:

- Unattended– the sensor nodes are in the field with no one guarding the equipment. There could be some physical damage to the equipments from curious human or other wild animals. The data collection procedure can also be disturbed. For example, if the telescope is blocked, there is only dark spectrum that is of no use for gas concentration analysis.
- Protection from weather– the electronics part of the sensor node is the most vulnerable and sensitive part in the whole system. If there is a heavy shower, the water can destroy both the electronics and interface with the link as well as make the system work in a strange manner. Although our instruments were enclosed in water-resistance boxes, one RS232 connector out of the box got wet in the rain, so did not work well.

Chapter 5 Conclusions and Future Work

5.1 Conclusions

A volcano monitoring sensor network is an important branch among many kinds of sensor network applications. It gives valuable risk estimation data, which is very important for the life of inhabitants near the volcano. The thesis work proposes a prototype for a volcano monitoring sensor network. A wireless network was proposed and evaluated. The software modules to fulfill the necessary system functions were described. In the DORSIVA field campaign the network application was tested in a real environment. The volcano monitoring sensor network provided data for risk assessment, gas emission estimates, and geophysical research on a local scale. From the fieldwork, we gained practical experience about remote sensing in volcano environment.

5.2 Future Work

In the field campaign, the prototype of the volcano monitoring sensor network was set up with limited resources and experience. The functions and features of the system were not fully researched. Because of limited memory in microcontroller, the error control protocol in link layer and the routing protocol have not been realized in this system. Those protocols will be added in future work. The scalability of the volcano monitoring sensor network is one aspect to study in future work.

The ultimate goal of volcano monitoring sensor network application is to offer an easy-to-use toolkit for volcanologists. The network must not be hard to deploy for non-network technicians. The software must be user-friendly without complex configuration. Reliable data needs to be retrieved from many distributed locations in real-time without human monitoring. The final network application will be part of the Network for Observation of Volcanic and Atmospheric Change (NOVAC) project, which is to establish a global network for measurement of gas emissions from volcanoes [18].

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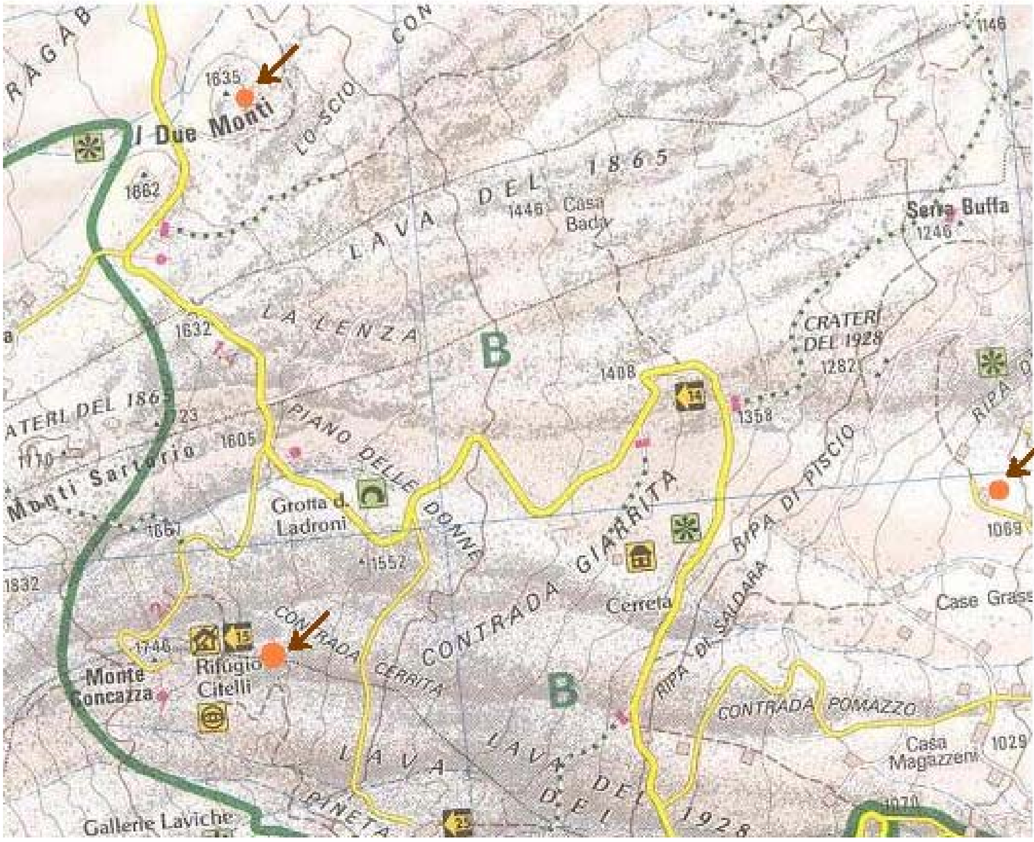
Appendix A - Map of Sensor Nodes in Etna

In this figure, the three sensor nodes are noted by orange circles.



Appendix B - Radio Modems Comparison

<table>
<tr><th>Company</th><th>Range</th><th>Frequency</th><th colspan="2">Power Requirement</th><th>Data through-put (bps)</th><th>Sensitivity (dBm)</th></tr>
<tr><td rowspan="5">FreeWave</td><td rowspan="5">96km</td><td rowspan="5">902~ 928 MHz</td><td colspan="2">6~30 VDC</td><td rowspan="5">Max 115.2k</td><td rowspan="5">-108</td></tr>
<tr><td>T</td><td>500mA</td></tr>
<tr><td>R</td><td>86mA</td></tr>
<tr><td>I</td><td>21mA</td></tr>
<tr><td>S</td><td>6mA</td></tr>
<tr><td rowspan="6">WarWick
S8200</td><td rowspan="6">10km ~20km</td><td rowspan="6">400~480 MHz</td><td colspan="2">10~26VDC</td><td rowspan="6">Max 115.2k</td><td rowspan="6"></td></tr>
<tr><td>T</td><td>330mA</td></tr>
<tr><td>R</td><td>95mA</td></tr>
<tr><td>St</td><td>0.1mA</td></tr>
<tr><td>12V</td><td>50mA</td></tr>
<tr><td>24V</td><td>30mA</td></tr>
<tr><td>WaveNet 1000 System</td><td>50km</td><td>400~512,
820~960
MHz</td><td>90~264
220
VAC</td><td>115/230 VAC</td><td>1.2k~19.2k,
1.2k~4.8k</td><td>-105</td></tr>
<tr><td>RAN Radio Data Modems</td><td>50km</td><td>820~960 MHz or 400~512 MHz</td><td colspan="2">90~264VAC, 50/60Hz ± 24 VDC or
-48VDC optional</td><td>128k (50kHz channel),
64k (25kHz)</td><td>-95</td></tr>
<tr><td>CDR-915M,
9150M
Spread Spectrum Data Radio Modem</td><td>16km,
48km</td><td>902~928MHz</td><td colspan="2">CDR-915M: 8~14VDC

CDR-9150M: 9~28VDC</td><td>2400,
4800,
9600,
19.2K,
56k</td><td>-101</td></tr>
</table>

MaxStream X24-009PKC-RA	5km/dipole, 16km/high-gain	2.4~2.4835 GHz	7~18VDC	9600, 19.2k	-101,-104
GINA 6000N-5	19km	902 ~ 928 MHz	10.5 ~ 13.8 VDC	0.3 to 38.4 Kbps Duplex TDD - RS232 (DB9F)	-100
Satelline-3AS	30km	380 ~ 470MHz	9 ~ 30VDC	300~38400	-110

When choosing radio modems, an important parameter is the sensitivity of a radio modem. According to the formula (2.1), a radio modem with high sensitivity get a big free space loss and long communication range. The Satelline- 3AS radio modem was selected later because of its high sensitivity.

Comments:

In 'power requirement' column, the abbreviations for radio modem modes are as following:

T – Transmit

R – Receive

I – Idle

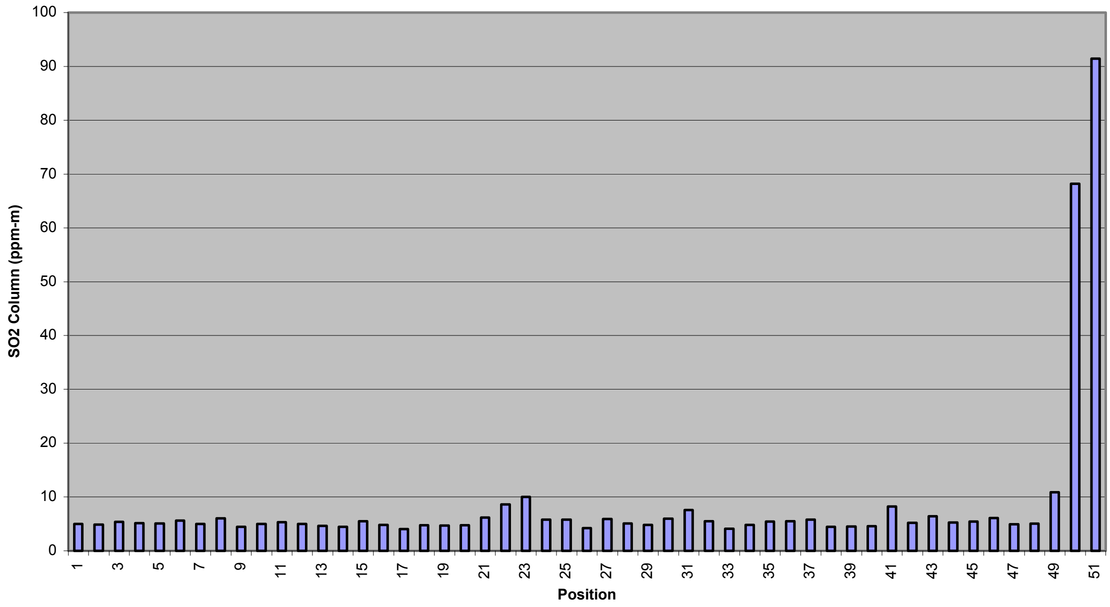
S – Sleep

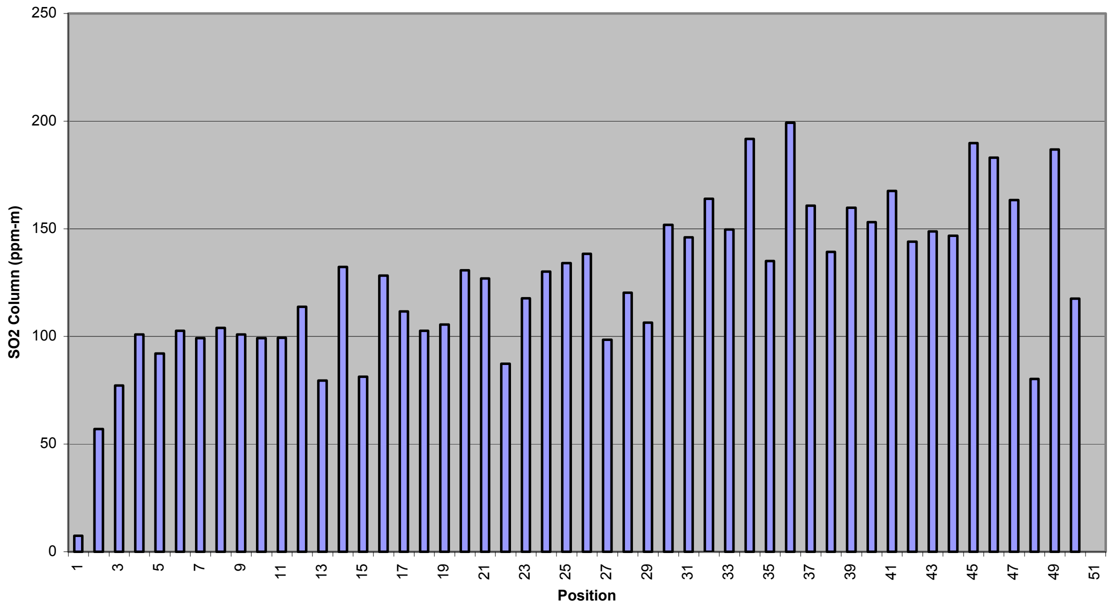
St – Standby

The current drains are the parameters under 12 VDC.

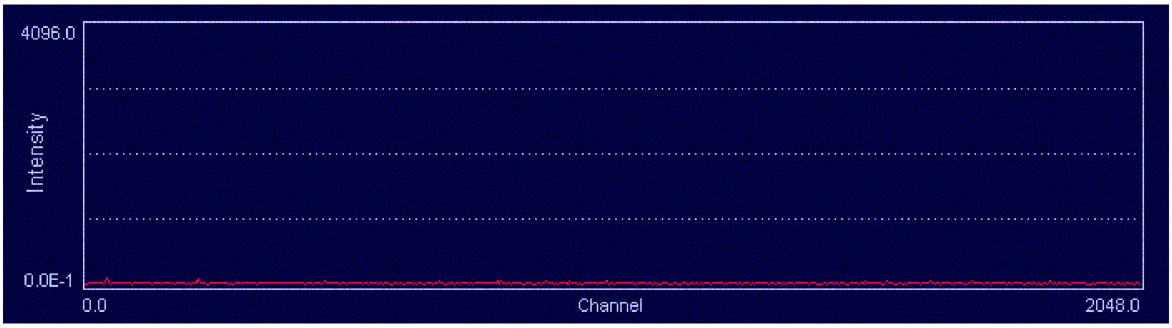
Appendix C - Data samples

The following two plots are SO_2 columns in different positions observed at two parallel sites at 11AM on September 28, 2004.

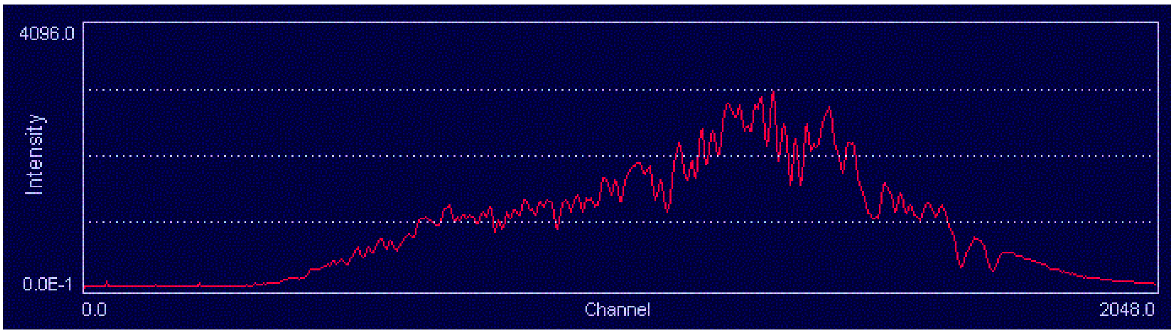




The following figures are screen shots of the remote control program.



This plot shows a spectrum collected at darkness position by Scanning DOAS.



This plot shows a spectrum collected at non-darkness position by Scanning DOAS.

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