Towards a New Volcano Monitoring System Using Wireless Sensor Networks

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***Abstract*—This paper presents a seismic signal analysis on data sensed by a wireless sensor network deployed on Cotopaxi volcano. According to the environmental signals measured in the volcano and the use of mathematical tools, it is possible to find a signal classification to interpret the behaviour of the volcano. Sixteen sensors have been used and deployed in a strategy area, the information was obtained during three days of continuous monitoring. This information was sent to a surveillance laboratory located 45 km away from the station placed in the volcano, a WiFi for long distance technology was used to this purpose. Volcanic information was processed using wavelet transform, a spectral pattern of seismic events determined four kinds of events, corresponding to a volcanic tremor, hybrid seisms, long period seisms and tectonic seisms.**

***Index Terms*—*WSN*, IEEE 802.15, *Zigbee*, spectral analysis, wavelet transform, volcanic analysis.**

I. Introduction

Ecuador is one of the South America countries being crossed by the so-called *Cordillera de los Andes* mountain range. It is located in the Pacific Ring of Fire, which is one of the most world-wide complex volcanic intensity locations, due to the tectonic plate collision of Nazca, and South America, which today still continue to generate high seismic activity. Ecuador has four natural regions, which are clearly defined, namely, Mountain Region, Amazonic Region, Coastal Region, and Insular Region. Each of these regions have their own natural risks, including seismic activity, some activation of its volcanoes, tsunamis, and many others. Additionally, the Intertropical Convergence Zone is often the scenario for threats of hydrometeorological nature (floods, droughts, storms, frost, *El Niño* phenomenon), and geomorphological origin (landslides, mud flows, and erosion), which may have negative, and dangerous impacts on society [1].

Natural risks are attributed to geological, hydrometereological, and antropics phenomena. Hydrometereological and geological phenomena are the most important natural risks in Ecuador, they have caused a vast amount of human lives and material losses [1][2]. Meanwhile eruptions, and earthquakes have been the main problem in the last ten years [1], nowadays, there are two kinds of volcanoes, namely, active, and inactive, including, Guagua Pichincha, Cotopaxi, Tungurahua, Sangay, Reventador. Some of them have caused terrible catastrophes when they have reached activity. There are a lot of volcanological vestiges of volcanic eruptions, which stand as examples of the effects that they can produce. The principal effects have been caused by Cotopaxi, Tungurahua, and Reventador Volcanoes [3][4], however, their sequels have not been the subject of deep analysis and study by the Ecuadorian institutions. These kind of natural risks are unavoidable, but we can monitor them in order to know their activity, in such a way that, when volcanoes have reached their rising activity, early warning could be given to safeguard human lives. The requirement of real-time monitoring is a necessary one, and in this setting, these kind of system could help us to determine early warnings to be dictated by the authorities in charge and minimize the human, and material losses.

Volcanic monitoring (surveillance) could be held either by visual or instrumental methods. The first one is a monitoring method based on the detection of changes in the activity of a volcano, and for that purposes, it employs only the human senses, therefore, changes can be discovered by the population. Visual monitoring is systematically conducted by observations to determine the formation of fractures, landslides or swelling of the volcano's summit, the active crater or one of its flanks, the detection of changes in fumaroles emissions, as the height of gas column, color, odour, and intensity, or changes in flow, smell of hot springs, detection of injury or death of vegetation, the perception of changes in animal behaviour, among others. This method includes the perception of subterranean noises, and earthquakes of volcanic origin.

Instrumental monitoring consists in sensing by using highly sensitive scientific instruments capable of detecting changes in the physic-chemical behaviour of the volcano magmatic system. Usually, these changes are imperceptible to humans, and the most common ones are the detection of seismic activity, the measurement of ground deformation, the study of chemical changes in emissions of gases in the fumaroles, and hot springs.

II. Related Works

The first volcanic monitoring work using WSN was developed in July 2004 [5], by a group of researchers from the Universities of Harvard, New Hampshire, North Carolina, and the Geophysical Institute of the National Polytechnic School at Tungurahua Volcano in Ecuador. The network was composed by 3 acoustic sensor nodes, which

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collected infrasonic signals continuously, and sensed data were subsequently transmitted to an aggregator at 102 Hz. Finally, data were transmitted over a wireless link toward a surveillance laboratory located 9 km away. Data collection was performed with continuous monitoring during 54-hours. Nodes were time synchronized using GPS receivers, and the information collected was correlated with data from a nearby wired network. A distributed event detector was developed, automatically cutting up data transmission when a signal was well correlated and received by multiple nodes. This feature was evaluated in terms of energy reduction, and bandwidth efficiency of use.

The second volcanic monitoring work was developed in 2005 [6][7], by the same group of researchers which carried out their work in Tungurahua volcano. The network was composed by 16 seismo-acustic sensor nodes using multihop communication. The array of nodes was linear, and it was deployed over a total distance of 3 km at the Reventador volcano located in Ecuador. These sensor nodes were equipped with seismometers, and microphones in order to collect seismo-acoustic data from the volcano. This information was collected by an aggregator during 19 days, then it was transmitted to the base station about 9 km away using radio equipments. An event detection algorithm in the network was present triggered when there was significant volcanic activity, therefore reliable data transfer to the base station. During this deployment, the network detected 230 events, including, earthquakes, eruptions, and other seismo-acustic events. The short-term average/long-term average (STA/LTA) algorithm [8] was implemented in this network, in which sensor nodes were activated only when an event existed. Time synchronization was performed through the use of GPS, and The Flooding Time Synchronization Protocol (FTSP) [9] which unfortunately exhibited unexpected behaviour because nodes have reported an inaccurate time synchronization. Sensor nodes had an inappropriate mark of time in data. It was determined that the accuracy of event detection was only 1%, so that the reliability of its network and working time were relatively low, and the working time of the node was only 69%. In order to improve network reliability, the same research tem created LANCE.

LANCE is a framework supporting high data rate sensor networks for optimizing high-resolution signal collection that it is able of managing data collection in order to direct energy, and bandwidth resources towards the most interesting signals. In July 2007, LANCE [10] was tested in Tungurahua volcano, where 8 sensors were deployed, and the network collected data continuously for 71 hours. LANCE successfully downloaded 77 MB of raw data. An additional 308 MB download failed due to timeout or stale summary information, for an overall success rate of 80%.

Currently, there is a satellite system (EO1) able to receive information from a sensor monitoring system, essentially provided by thermic sensors. This satellite system has an advanced software that is responsible for processing all the information on volcanic activities, giving priority in the following order: a possible eruption, the presence of magma, and the presence of pyroclastic flows. The information processing has a time delay of 2 hours until arriving to the management center. This system was tested at various events, and it has obtained very good results. This is a NASA project, and it is performed for research purposes [11].

In 2008, a smart solution was proposed for collecting reliable information aiming to improve the detection of real-time information. This scientific monitoring was conducted in an active volcano, called Mt. St. Helens [14]. The STA/LTA algorithm was also used, whereby priority is given to seismic data sensed from the volcano to locate earthquake events. This design solution has been applied to test sixteen prototype sensor nodes in the OASIS project [15]. For this purpose, a prototype was designed with better characteristics than the ones in the works described above, the most important features are the improvement of 7.37 MHz processor present in Micaz [5] and improvement TMote Sky [6][7] for a processing capacity that may be chosen from a range of 13 MHz to 416 MHz present in Imote2, also provides 256K SRAM and 32M SDRAM memory space, three SPI interfaces, three UART interfaces, and multiple GPIO interfaces that allow flexible extension. In the OASIS project, a hybrid mode is used for time synchronization, where each node is equipped with a GPS receiver, and the node is synchronized by default by the GPS, if the GPS signal disappears, the system it switch to FTSP mode. Once this system has retrieved the GPS signal and it has again the right characteristics will switch to GPS.

In [16] the experience in the deployment of a WSN air-dropped for volcano monitoring was presented. For this purpose, five sensor stations were designed in [14] and were deployed in the rough crater of Mount St. Helens, where the distance present between stations is up to 2 km. Each sensor station picks up and delivers real-time continuous data of earthquakes, infrasound, lightning, and GPS raw data to a node *sink*. The main contribution of this work is the design and evaluation of a sensor network to replace data recorders in long term real-time volcanic monitoring. This system supports synchronized data acquisition (UTC) time with 1 ms accuracy, and is configurable on-line. It has been tested in laboratory environment, the area outside the campus, and in the crater of the volcano. Despite heavy rain, snow, ice, and wind gusts above 193 km/h, the sensor network has achieved an extraordinary packet delivery ratio of above 99% with a time of overall system performance of 93.8% of the time in 1.5 months post-deployment evaluation.

In [17] a methodology was developed to minimize the energy consumption of sensors to collect adequate information to discriminate false alarms from a real event at Mount St. Helens. For this purpose, a Bayesian detection algorithm based on a new statistical model of energy and frequency spectrum of the signal was used. Additionally, an algorithm for selecting the number of sensors that allows the optimization of the data collected was developed, the experimental results show that it reaches a number close to zero false alarms and less than a second delay in the detection, while it has achieved an energy reduction of up to 6 times compared with the data collection methods available today.

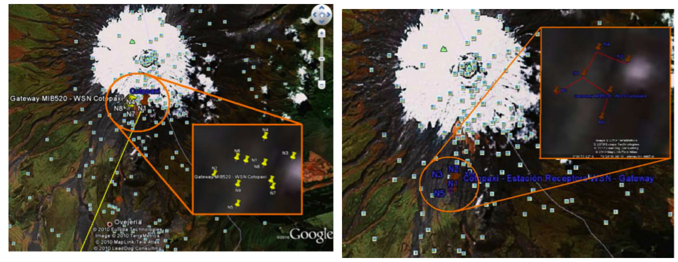
Processing information is one of the main issues that can limit the performance of the system to be considered a real-time system. For this reason, it is required a minimum time delay for all the system. For this kind of applications, the meaning of real time is totally different to other applications, like the transmission of voice, and video. In this case, a real time monitoring system is the one allowing us to launch an early warning in order to safeguard the maximum number of human lifes.

III. Results from Cotopaxi Volcano Deploying

The Wireless Communications Group (WiCOM) from the Army Polytechnic School (ESPE), developed a first attempt for replicating the predecessors' work. Thus, Cotopaxi, which is currently the highest snowcapped volcano on Earth, was selected for deploying a WSN. This volcano has presented its last eruption in the fifteenth century [3]. ESPE Campus is located at the parish of Sangolquí, located 40 km from the volcano. During its last eruption can be found around the campus huge rocks were threw by the volcano. This work was deployed at an altitude of 4870 meters, where 16 sensor nodes were implemented, and data were collected continuously for three days. The main problem of this network was their dependence on an aggregator, added to the information that must be stored before being transmitted to the surveillance laboratory through a wireless link of 40 km of distance where information is processed in order to determine whether or not the events are false alarms. The signal processing takes too long to get the results, because of that, it is not possible to guarantee a real-time monitoring data [12][13].

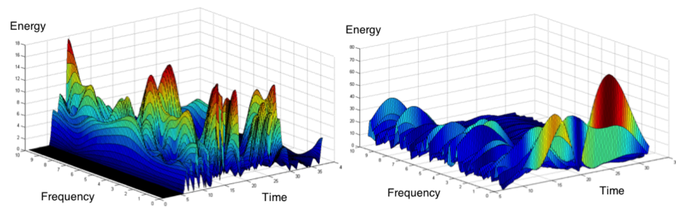
Our first visit to the Cotopaxi Volcano was for locating the geographic coordinates for placing the wireless communications system (0º 39' 49" S, 78º 26' 17" W), and to determine the necessary requirements for WSN deployment on Cotopaxi Volcano. In our second visit WSN were deployed, at an altitude of 4870 meters, two differents WSNs, one of them consisted of 10 motes MICAz, and another with 6 motes IRIS with MTS400 and MTS310 sensor cards using two gateways MIB520 each. Mote Config 2.0 was the software used to configure nodes. FTSP was implemented for time synchronization. In Fig. 1 is shown the location of the two networks deployed. Data were collected continuously for three days. The energy problem was solved with a generator placed in situ. The information should be stored in a central station placed *in situ*, then it should be transmitted to the surveillance laboratory, located at a distance of 40 km from volcano to ESPE, through a wireless link.

Many physical phenomena are described in time domain, however, this representation not necessarily have to be the most appropriate. The signal could be observed more clearly in frequency domain, by detailing the frequency spectrum as part of the signal. Therefore, for a better representation of the signal is necessary to have a representation in the time and frequency domain. Using Fourier Transform, it is possible to detect the presence of a certain frequency but it does not provide information about the evolution over time of the spectral characteristics, for this reason it is important to note that a spectrogram was constructed using the Short Time Fourier Transform (STFT) with a sampling frequency of 20 Hz, which represents the signals in time and frequency domain, since it provides some information about when and how often a specific event occurs, however, it can only obtain such information with limited accuracy, which is bounded by the size of the window, it means the problem arises when choosing a certain size for the window although it is the same for all frequencies.



a) MICAz motes deployed on Volcano *b) IRIS motes deployed on Volcano*

Fig. 1. Wireless Sensor Networks deployed on Cotopaxi Volcano



a) Window width = 32 *b) Window width = 256*

Fig. 2. Seismic signal spectrogram of WSN deployed on Cotopaxi Volcano

Two variables were sensed by WSNs, seismic signals (accelerometer in axis x, and y), and temperature. Many physical phenomena are described by a seismic signals. The seismic spectrogram is shown in Fig. 2a, a small width of window causes the resolution achieved in time domain is enough but it is not enough in frequency domain, on the contrary in Fig. 2b if the window's width is increased, frequency resolution is enough, because it shows more detailed the spectral components, but it is impossible to know when they will occur, that means both figures present the resolution problem and it is the main reason to consider the uncertainty principle if we apply this to the signal analysis.

The information in time and frequency domain of seismic signals on a determined time often cannot be known, therefore, we cannot define if the spectral component exists at any instant of time, the only thing that can be distinguished

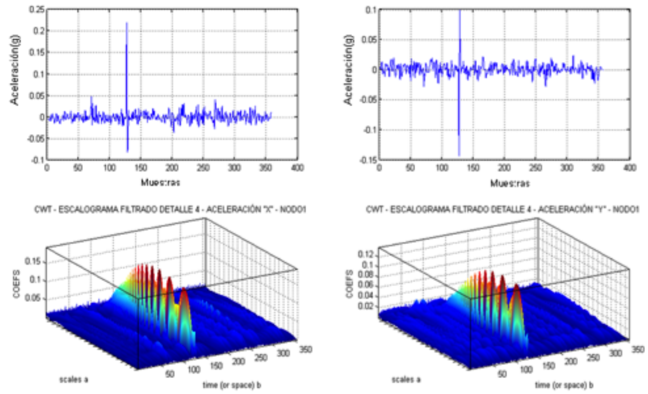


Fig. 3. Noise seismic event determined after digital processing signal

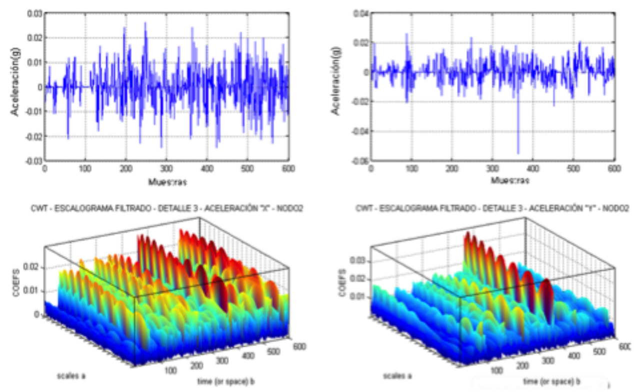


Fig. 4. Short period noise seismic determined after digital processing signal

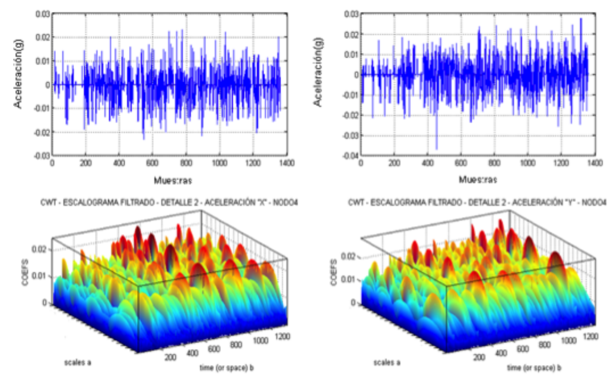


Fig. 5. Volcanic tremor event determined after digital processing signal

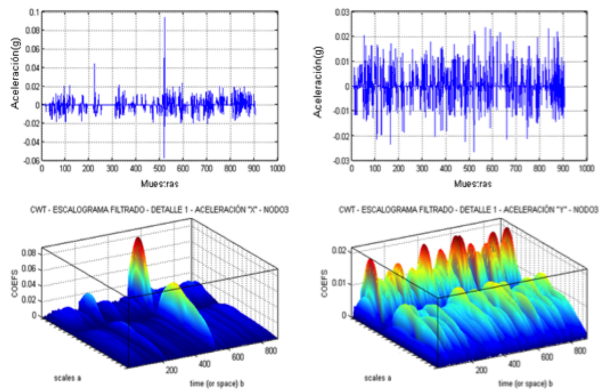


Fig. 6. High frequency volcanic tremor event determined after digital processing signal

are the time intervals at certain frequency bands where we can find spectral components.

Since seismic signals are non-stationary, it is necessary to vary the size of the window, for this reason, wavelet analysis was used. The seismic signals recorded was processed using discrete and continuous wavelet transform, in order to discriminate the occurrence of a particular seismic event. The sampling frequency is 20 Hz, considering the signals decomposition where more detailed information exists, no approximations are accepted. The mother wavelet employed is DB6 (Daubechies 6), in the project were used decomposition levels 2 and 4 for the records of MICAz motes and IRIS motes deployed respectively due to the amount of data they hold. We must define if the event belongs to a volcanic tremor, hybrid seisms, long period seisms or tectonic seisms that permit us to determine an abnormal behaviour.

In Fig. 3, it was determined that the spectral components present in the frequency range [1,25 - 2,5 Hz] are stable and present a low energy, this signal corresponds to a noise seismic event. Meanwhile, in Fig. 4, the signal spectral content between [2,5 - 5 Hz] shows a seismic noise in a short period, this is due to sudden temperature changes. In Fig. 5, the signal between [5 - 10 Hz] is equally distributed in energy, its acceleration remains constant during all time, this event correspond to a volcanic tremor, this event is associated to gas outlet due to high pressures. Finally Fig. 6 shows another case, a high frequency volcanic tremor, signal between [10 - 20 Hz] it is related to strong gas outlet inside of the crater.

IV. Future Works

WSN are presented as an effective and affordable alternative to be implemented in many applications. Developing Countries, like Ecuador, have an special interest for using WSN in a volcano monitoring applications. This case is very interesting because WSN presents confidence in this kind of applications added to its low cost compared with traditional volcano monitoring systems, furthermore at this time this kind of system is not implemented in South America, all projects developed in this region have been deployed for a maximum of a pair of weeks [5][6][7], meanwhile in United States of America a project has been implemented in a permanent way [16].

Volcano monitoring using WSN still requires further research in order to present information in real-time. Previous works show very interesting solutions at Network, and MAC layer level, all of this added with a good real-time data acquisition in-situ. Therefore, at this moment is not possible to give a timely early warning with this kind of systems, because, even if data is real-time acquired, data is post-processed mainly due to that information must be transmitted to a surveillance laboratory located a tens km of distance for processing. A new problem appears, a representative time delay related to digital signal processing and the signal propagation. This problem must be solved with an appropriate telecommunication system, it should permit data travel with confidence, and to assure certain QoS features.

Previous works refered to use WSN are related to seismic, and infrasonic signals analysis, at this moment there is not an analysis of correlation with other variables such as CO, SO_2, and SH_2 in conjunction with seismical and infrasonic signals at the same time.

Volcanic recording stations use sensors to collect data related to variables as seismic activity, infrasonic and several gases. Seismic information describes motion observed at the station, typically, two data channels are used to represent earth motion in the horizontal, and vertical plane (i.e. X, and Y). Meanwhile infrasonic signals are collected through a microphone, and lately signals referred to gases like CO, SO_2, and SH_2 are also possible to acquire using WSN.

Once data are collected and transmitted to a surveillance laboratory, tens of km away, they have to be processed. The challenge is to find a viable solution for collecting data, and to show their respective analysis in real-time. It is necessary to identify all the mechanisms to obtain a system of this nature, in order to submit a volcanic monitoring system in real-time capable of warning the population against a possible eruption or any phenomenon inherent to Volcanology.

V. Conclusions

In this work, Wavelet Transform was the most effective tool to analyze signals acquired by the WSN deployed on Cotopaxi Volcano, through this signal processing, a spectral pattern of seismic events was determined.

A volcanic eruption is a natural event in which monitoring should consider technical, scientific and social aspects. By this purpose we emphasise just in designing a network platform and signal processing issues.

A reliable transmission system is required, it must be robust and remotely managed, therefore, we used WiFi for long distance technology, obtaining a throughput close to 1 Mbps.

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