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On Real-Time Performance Evaluation of Volcano Monitoring Systems with Wireless Sensor Networks

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***Abstract*—Volcanic eruption early warning has to be launched with effectiveness and within the shortest time possible, which imposes the requirement of using real-time (RT) systems. In this setting, volcano monitoring systems using wireless sensor networks (WSN) may play a key role. Previous works did not report detailed enough performance evaluation, in order to identify their main constraints as RT systems, either in simulation tools or in test-bed scenarios. The aim of this work was to identify the optimum number of sensors to be deployed *a posteriori*, based on simulation results considering throughput, packet loss, and end-to-end delay, as metrics to satisfy RT requirements. We corroborated the simulation results obtained by a test-bed deployment within a controlled environment. We determined that optimal scenario for volcano monitoring is random topology, and the results show that twelve nodes should be deployed as maximum to satisfy the RT constraints. To test the system in a real scenario, ten sensors were deployed in a strategic area at Cotopaxi Volcano, and information was collected during three days of continuous monitoring. This information was sent to a remote surveillance laboratory located 45 km away from the station placed at the volcano using WiFi-based long distance technology. Our study shows that the coordinator node is the main bottleneck in the real application scenario, given that its processing rate provokes an excessive time delay near to 3s, which has to be solved to satisfy RT requirements. We conclude that a comprehensive study including simulation, test-bed, and *in-situ* deployment provides valuable information for the specifications to be accounted in permanent WSN RT volcano monitoring.**

***Index Terms*—WSN, 802.15.4, throughput, delay, packet loss, monitoring system, volcano.**

I. Introduction

A volcanic eruption may cause incalculable effects on the health and safety of humans, which has led to volcanoes monitoring systems, for the purpose of understanding their behavior and to provide, if possible, an early warning in case of an imminent volcanic eruption [1], [2]. In the long term, we are interested in developing a Real-Time Volcano Early Warning System (RT-VEWS) to safeguard human lives and resources, and in this setting we will need RT capabilities for monitoring and for decision making in our system. The proposed system can be divided into 3 blocks: the first block performs the volcanic activity monitoring and sensing; since continuous monitoring produces a great amount of daily data; the second block corresponds to the feature extraction and event detection from the raw data; and the third block corresponds to the VEWS itself, in conformance with the Integrated Services Digital Broadcasting (ISDB-T), the standard for digital terrestrial television, to alert people in case of an emergency. In this paper we focus on addressing the requirements of the first block for RT performance.

Several of volcanoes monitoring systems have been deployed around the world in the past fifty years, allowing to understand these volcanoes in a better way [3]. There are several forms of volcanoes surveillance, for instance, visual observation, ground deformation monitoring, chemical analysis, and seismic monitoring [4]. Traditional systems are heavy, bulky, power-hungry, and complex, all of which are limitations in real volcano monitoring deployment scenarios. In the last decade, some works have reported deployments of volcano monitoring systems using wireless sensor networks (WSN), a non traditional monitoring system, as a new alternative to be considered [5]–[7]. WSN, with their low power consumption and ease of deployment, are a promising technology when considering volcano monitoring. As they can form networks independently, they can be provide with environmental information at low operational cost and without periodic maintenance. For these reasons, Cyber-Physical Systems (CPS), Internet of Things (IoT), and Smart Cities, are new research topics based on WSN technologies. All of them are based in a similar infrastructure of heterogeneous networks, where data must be transmitted, processed, and finally enable people to use any application for monitoring or controlling objects [8]–[16].

Volcano monitoring using WSN still requires further research in order to present information in RT and to launch early emergency warnings. For example, South America lacks a sufficient number of monitoring systems, based on WSN, permanently deployed at active volcanoes. In previous works, such systems have been installed just for a couple of weeks, and they have not been reported with enough details about their performance in order to identify the main constraints for using them as RT systems, this issue is discussed in more detail later in Section II. Developing countries, such as Ecuador, can benefit from WSN used for volcano monitoring applications, since the WSN systems are much cheaper and easier to install than bulky and energy-hungry traditional systems.

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The aim of this work was: First, to identify the number of sensors that maximize the capacity of the network by using simulations, taking into account the main indicators to be assessed in a WSN for RT applications; Second, to corroborate the results obtained in the simulation by a test in a controlled environment; And finally, to implement *in-situ* the system at Cotopaxi Volcano, in order to assess its performance and identify the technical considerations to be taken into account for a WSN RT volcano monitoring permanent system. A preliminary version of this work has been presented in [17].

The rest of the paper is organized as follows. Section 2 summarizes previous research on the subject. Section 3 describes the requirements of the WSN in detail. Section 4 presents the simulation and test-bed setup, and it describes the results obtained with simulations and the experimental study performed within a controlled environment. Section 5 presents the results obtained from the real deployment at Cotopaxi Volcano including a comparison between signals obtained by the WSN network and a public permanent network. Finally, Section 6 presents our conclusions and future work.

II. Related Work

Werner et al. [5], [6] demonstrated the applicability of WSN in volcano monitoring, by using seismic and acoustic sensors at Tungurahua and Reventador volcanoes. The major problems encountered were the low reliability of the event detection algorithm, the dependence on climatic conditions, and the excessive number of packet loss (PL). To solve partially these problems, the STA/LTA (short-term-average over long-term-average) trigger algorithm, appropriate protecting boxes, and different kinds of hardware were used, respectively. However, other problems appeared, including that the event detection accuracy was 1% and poor nodes performance. Finally, the system was improved using the so-called LANCE framework, which gave a performance improvement of 11% from previous works [7].

In 2008, a smart solution was proposed to collect reliable data, which was conducted at Mt. St. Helens (USA) [18]. This proposal presented several improvements, such as the efficient use of memory space, the configurable detection attribute, time synchronization for complying sampling requirements through the network with high accuracy, and noise removal process. Other relevant contributions in the same work were the event-trigger mechanism and the priority-label-process for the different types of data, which improved the use of the network bandwidth and allowed reliable data reconstruction on the end user side. This was the first attempt to improve signal processing, since only data considered from real events were analyzed. Five of these sensors were deployed around the crater of Mount St. Helens, where the distance between stations reached up to 2 km [19]. Each sensor station picked up data of earthquakes, infra-sounds, lightnings, and GPS. Despite heavy rain, snow, ice, and wind gusts above 193 km/h, WSN achieved a packet delivery ratio above 99% with an overall system performance of 93.8% of the time during the 1.5 months post-deployment evaluation.

A methodology was later developed in order to minimize the energy consumption of sensors to collect adequate information, which was able to discriminate false alarms from real events. For this purpose, a Bayesian detection algorithm was designed, based on a new statistical model of energy and frequency spectrum of the signal [20].

Although, there are some solutions at network and MAC layer referred to *in-situ* data acquisition, data gathering and data dissemination, these results of WSN performance evaluation are insufficient to determine their possibilities to be used in a RT volcano monitoring systems. For instance, and to our best knowledge, there are no reports about which are the best topology and the main metrics to guarantee Quality of Service (QoS).

III. Requirements and Metrics for Volcano Monitoring

A. Sensors Requirements and Selection

The seismic-volcanic signals are presented in the low frequency range from 1 to 20 Hz [21], therefore accordingly with Nyquist criteria we required to use a sampling frequency (f_s) of at least 40 Hz, which permits to reconstruct the original signal, other parameters to consider were time response, accuracy, processor time, noise presence, and the cut-off frequency response of the sensor to use [22], however we considered that the main limitation in our system was the transmission rate, if we sampled with an unnecessarily high f_s, the system would generate a lot of data saturating the wireless channel capacity and noise would dominate the input signal. For these reasons, we selected a low cost dual-axis accelerometer (Analog Devices ADXL202E) sensor with f_s of 100 Hz having a 0.167 V/g sensitivity with 2g of resolution; these sensors met the minimum requirements for this kind of application.

B. QoS Metrics for RT Volcano Monitoring System

Our main interest consists in determining the network behavior, which can be evaluated by QoS metrics, such as: availability, reliability, time response, time delay, throughput (η), bandwidth capacity, and packet loss ratio. In order to provide RT in WSN with guaranteed QoS metrics, the network must be analyzed in a different way than traditional RT systems, since several challenges must be met to obtain reliability due to its wireless nature, distributed architecture, and dynamic network topology. The state of the art of RT solutions currently developed have been presented with emphasis at MAC level, routing, data processing, and cross layer. Therefore, there is a direct relationship between RT and QoS metrics, as well as new general concepts related to RT WSN systems [23] [24].

RT WSN can be defined as a network capable of ensuring maximum sustained traffic rate, and minimum latency and PL, as main QoS metrics. An ideal development process starts from the theoretical analysis of the protocol to provide bounds and information about its performance [25], [26], then it has to be verified and refined by simulations [27]–[32], and finally confirmed in a test-bed [33], [34]. We found several works which presented a mixed analysis, since in real scenarios it is possible to obtain measures of main metrics (as received signal strength indication, packet error rate, and end-to-end delay

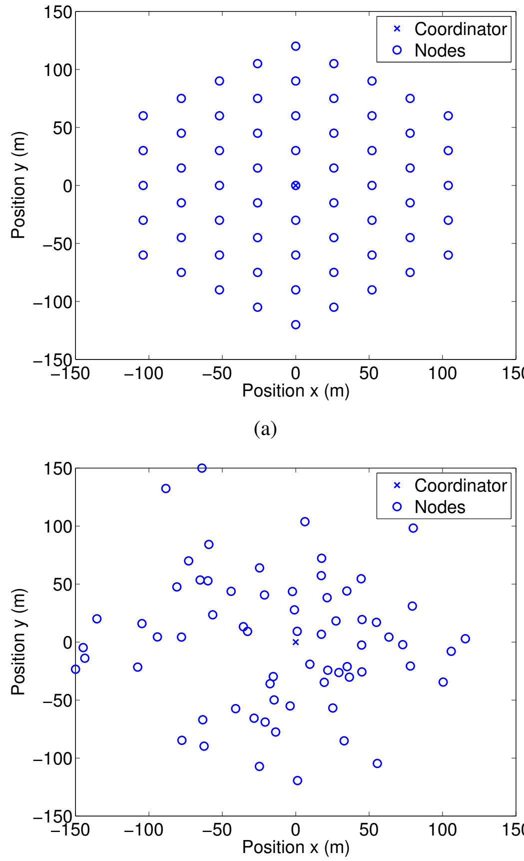
EED), by using tools developed by manufacturers [35]–[37]. However these results of WSN performance evaluation are insufficient in our case, since in this work we are proposing the use of WSN as a new alternative for RT volcano monitoring systems.

C. QoS metrics selected for RT Volcano Monitoring System

For our application we have to consider the environment presented by a volcano –wild terrain and lack of energy supply– to implement a WSN. A mesh topology presents the best way to communicate among sensors in this kind of scenario, while the positions of the nodes have to be defined according to the requirements that an *in-situ* visit could give us according to the variables to be monitored. We wanted to consider also a performance evaluation by taking into account the nodes position.

We selected three main metrics required for RT monitoring [38], namely, normalized throughput (η_N), EED, and PL. As mentioned in previous works, there are other metrics that can also be considered (for example, duty cycle, energy consumption, average jitter, load factor, and traffic type), but most of them have a direct relationship to our selected metrics.

After several meetings with experts in volcanology from *Instituto Geofísico de la Escuela Politécnica Nacional* (IGEPN), we concluded that the system requires a maximum η, PL less than 20%, minimum EED, at least 5 stations should be deployed, and it must be able to work in a permanent way to monitor several variables from the volcano. For the last reason, it is ineffective to set a WSN in a saving power mode, therefore we did not consider the power consumption metric.



(a)

(b)

Fig. 1. Simulation setup: triangular tessellation (a) and random (b) scenarios evaluated in an approximated area of 300×300 m^2.

IV. Simulation and Test-bed Results

In this section, we describe our experiments setup and tasks accomplished, in order to compare simulation data against test-bed data, and from the obtained results we made the following observations.

A. Simulation Setup

There is a wide range of simulators that can be used to test WSN. Following [39], we choose the Network Simulator *ns-2* as simulation tool. In order to obtain the performance of the network using simulations, we analyzed two types of topologies, namely, a regular and a random nodes distribution. The simulation scenarios for both network topologies are shown in Figure 1. For the first one, we choose a triangular tessellation pattern network $\{3,6\}$, that can be specified using the *Schläfli* notation [40], whereas for the second one we defined a random position of sensor nodes placed on the plane at a distance of 30 meters each (typical mean value for connection in practice). The number of nodes n in the triangular tessellation can be obtained as a function of number of layers C, this is, $n = 1 + 3C(C + 1)$.

In both scenarios, we started with 6 nodes growing until 66 nodes in 6 nodes steps. We defined one coordinator node and n full-function devices (FFD), and all the transmissions were directed to the coordinator node. We assumed an event occurring with a duration of 220 s in an approximated area of 300×300 m^2. For our simulation process, it was necessary to specify the number of replications to reduce the mean squared error. Accordingly, we run 6 replications for the tessellation scenario, whereas we run n replications for each random scenario. The main simulation parameters defined were simulation time, topology, routing protocol, and transmission rate. We clustered all of them in three main groups, namely, general parameters, power parameters, and node parameters. The rest of the parameters used to simulate the network model are detailed in Table I.

In order to determine the values of our metrics, we analyzed the information provided in the trace file, by using a suitable tool named *Tracegraph* [41]. We used this information in order to define a suitable expression for η^S in simulation scenario [42], as estimated from these files, which was determined to be as follows,

$$\eta^S = 8\frac{B}{t_{tx}}\left[\frac{bits}{s}\right], \tag{1}$$

where B is the number of transmitted bytes, the factor of 8 is used to convert bytes into bits, and t_{tx} is the time of transmission in seconds. Also a normalized parameter η_N^S is calculated by

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TABLE I
SIMULATION PARAMETERS FOR THE WSN IN TESSELLATION AND RANDOM CONFIGURATIONS

General Parameters	**Value**
Radio Propagation Model	Two-Ray Ground
Routing Protocol	AODV
Raw Bit Rate (kbps)	250
Antenna Type	Omni-directional
Simulation Time (s)	260
Transmission Time (s)	220
Power Parameters	**Value**
Transmission Power (dBm)	0
Sensitivity (dBm)	-94
Antenna gain (dBi)	1.0
Trajectory loss (dB)	1.0
Nodes Parameters	**Value**
Traffic type	FTP
Traffic direction	all to Coordinator
Package size	55 bytes
Number of Coordinators	1 coordinator
Distance between nodes	30 m
Number of nodes	1 to 66
Beacon mode	Beacon enabled Beacon Order:3 Superframe Order:3

$$\eta_N^S = \frac{\eta^S}{RBR}, \tag{2}$$

where *RBR* is the raw bit rate 250 kbps.

B. Test-bed Setup

We developed a test-bed in order to corroborate the simulation results with a real deployment in a controlled scenario. Figure 2 shows the network topology deployed in our Campus. We set all nodes in high power, meaning a current consumption between 15 and 30 mA, because we needed to cover an extension of near 4000 m^2. Our test tried to follow the same criteria as simulations, however, we incremented the number of sensors from 5 to 20 in 5 steps (excluding the coordinator node), accordingly to simulation results with the maximum number of nodes obtained.

With the aim of determining the values of our metrics, we used *Xsniffer* to acquire data and *MoteView* to analyze the trace files [43]. We were able to define the expression to estimate the η^T in the test-bed, yielding

$$\eta^T = 8\frac{I \times P}{100 \times t_{pack}}\left[\frac{bits}{s}\right], \tag{3}$$

where *I* is the percentage of transmitted sensors information, *P* are the sensors data payload (48 bytes), the factor of 8 is used to convert bytes into bits, and t_{pack} is the transmission time needed to send a package in seconds. Also a normalized parameter η_N^T is calculated similarly as in Ec. (2).

C. Simulation Results

Figure 3 shows our main metrics related to the number of nodes obtained in tessellation and random scenarios, where error bars represent one standard deviation around the mean. We observed in Figure 3a that the tessellation scenario showed an irregular decay of η_N^S, where the maximum and minimum

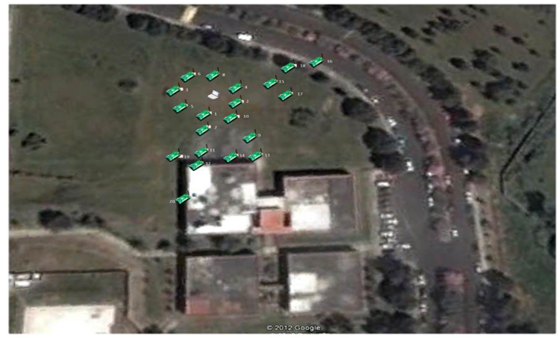

Fig. 2. WSN deployed in an approximated area of 200×160 m^2 at ESPE Campus.

values were 0.58 and 0.28, respectively, and its standard deviation was negligible. Meanwhile, the random scenario showed a direct relationship between η_N^S and *n*. The maximum and minimum values of η_N^S, in this scenario, were 0.57 and 0.41, respectively. A significant standard deviation was observed due to its own random nature. Note that the tessellation scenario presented more irregularity than the random scenario. Both scenarios presented a mean value of EED around 3 ms, but the behavior of EED in tessellation was more irregular than random. Finally, PL presented an increment as an exponential function of *n* in both scenarios. In Figure 3c we can observe that tessellation scenario had irregular PL in the nodes from 36 to 48, whereas in random scenario it increased directly with *n*. The main difference between both was that the random scenario presented lower PL than the tessellation scenario.

Accordingly to the specific requirements gave from IGEPN with respect to PL, which must be less than 20%, we observed that in tessellation scenario this value is reached when *n* = 12, meanwhile in random scenario, this value is reached when *n* = 18. Therefore, a random scenario allows us to use less nodes with same or better characteristics of η_N^S and EED than those presented in tessellation scenario.

D. Test-bed Results

Figure 4 shows our main metrics related to the number of nodes obtained in test-bed and simulations in the range from 1 to 24 nodes, in order to compare the obtained results. We observed that data in simulation and test-bed did not correspond to each other. Figure 4a shows that η_N for test-bed had a near-linear behavior, meanwhile, for simulation it decayed in a smooth way. Note that in Figure 4b, the results obtained for EED in simulation where around 3 ms, whereas the EED obtained in test-bed presented an increment as an exponential function of *n*, and the minimum value was close to 2s, which means almost 1000 times the EDD obtained in simulation. Finally, PL in both, simulation and test-bed, presented an increment as a direct function of *n*.

Accordingly with our requirements, metrics, and with the results obtained in our simulation and test-bed experimentation for volcano monitoring system, we determined that the maximum number of nodes using, *Micaz* motes, should be

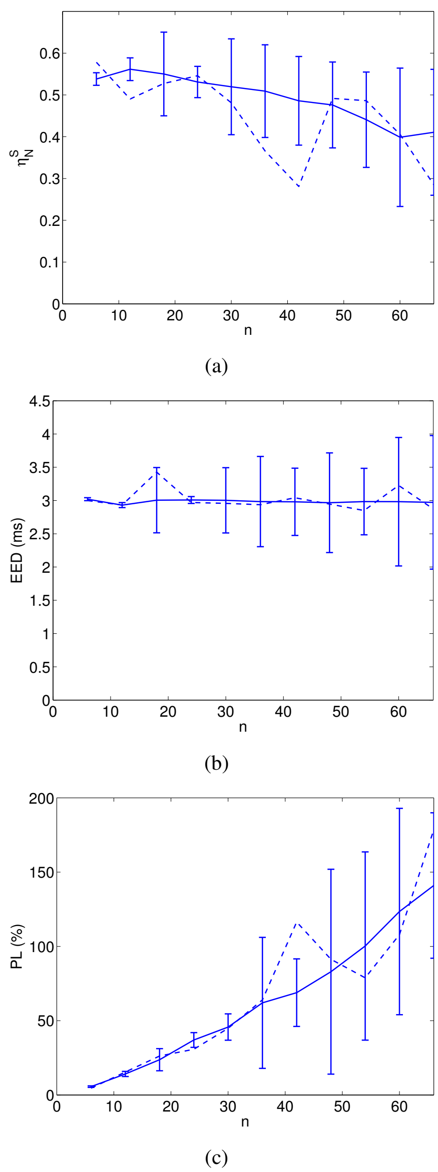

Fig. 3. Simulation results for QoS metrics in tessellation (dotted) and random (continuous) configuration for: η_N^S (a), EED (b), and PL (c), in terms of the number of nodes n in the network.

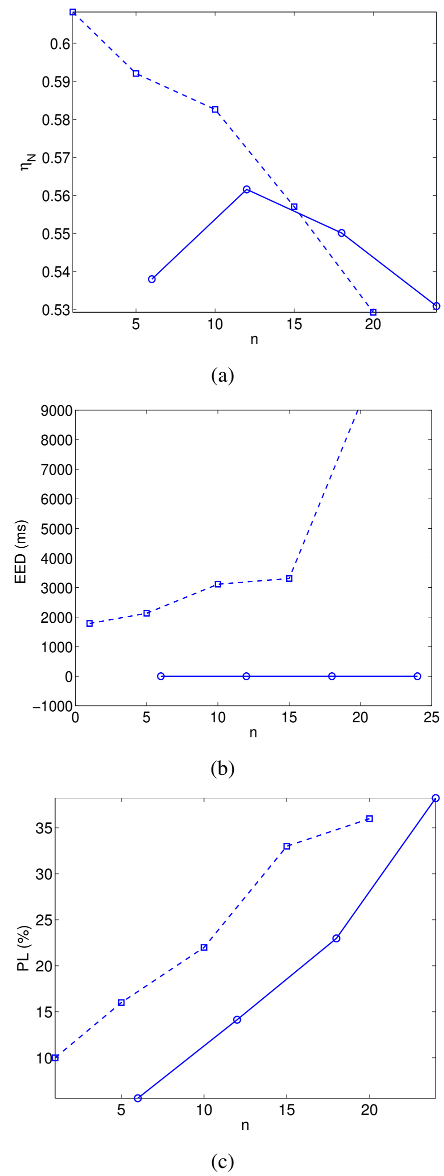

Fig. 4. QoS metrics for random scenario in simulation (dotted) and test-bed (continuous) for: η_N^T (a), EED (b), and PL (c), in terms of the number of nodes n in the network.

less than 12 to ensure a PL less than 20%, as we can observe in Figure 4c. Therefore, we only deployed 10 nodes in the real volcano, mostly due to the difficulty in the installation, as far as Cotopaxi is a snow climb volcano, and deployment of the sensor nodes was not an easy task.

V. Results from Cotopaxi Volcano Deploying

The Wireless Communications Research Group (WiCOM) from Universidad de las Fuerzas Armadas ESPE, developed a first attempt for replicating preceding works by using *Micaz* platform. Thus, Cotopaxi (which is currently the highest active snow-capped volcano in the world) was selected for deploying our WSN. Table II summarizes the comparisons among previous works and our deployment.

Our first visit to the Cotopaxi Volcano was for locating the geographic coordinates for placing the wireless communication systems (0º 39’ 49” S, 78º 26’ 17” W), and to determine the necessary requirements for WSN deployment at the location. In our second visit, we deployed 10 motes *Micaz* with *MTS400* sensor cards using a *MIB520* gateway at 4870 m altitude. *Mote Config* 2.0 was the software used to configure the nodes. Figure 5 shows the location of the deployed motes. Data were collected continuously for three days, the energy problem was solved by using a power generator, and the information was stored in a central station placed *in-situ*. We used a wireless link to transmit data to the surveillance laboratory, which is 45 km away from the station placed on the volcano.

A. WiFi-Based Long Distance Link

As previously mentioned, a wireless link was used for transporting the WSN sensed data, which has proven to be

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TABLE II
DEPLOYMENT COMPARISON FOR ACOUSTIC (A) AND SEISMIC (S) SENSORS AT COTOPAXI VOLCANO.

WSN Deploy.	Variables/ Platform	Number sensors	Operation frequency (MHz)	Sampling frequency (Hz)	Duration (Days)
[5]	A/Micaz	3	2400	100	2
[6]	SA/Tmote	16	2400	100	19
[7]	SA/Imote2	5	900	1000	Abiding
Proposed Work	S/Micaz	10	2400	100	3

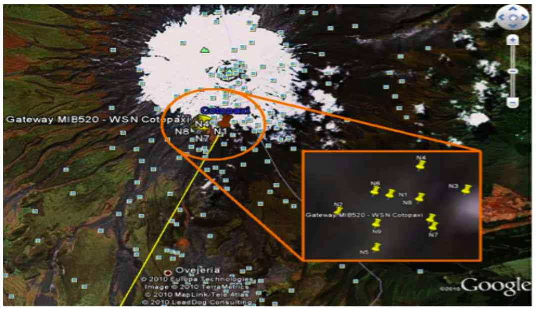

Fig. 5. WSN deployed in an approximated area of 140×120 m^2 at Cotopaxi volcano.

cost effective for long distance applications. The two major limitations for using WiFi over long distances (WiLD) are the requirement for line of sight between the endpoints, and the vulnerability to interference in the unlicensed band. Two further hurdles have to be overcome when applying WiLD technology, namely, power budget and timing limitations. The former was easily solved by using high gain directional antennas, while the later was addressed by modifying the media access mechanism, as proposed in [44].

IEEE 802.11b was selected for our purposes, mainly because the 2.4 GHz ISM band presents less losses that the 5.8 GHz ISM band. We used antennas with 24 dBi gain and 1 W transmission power. In the MAC sublayer, three types of limitations can be pointed out, namely, the timer waiting of ACKs, the RTS/CTS, and the slottime. We used *Alix* boards, in which we embedded a middleware that allows us to modify these parameters, in order to link endpoints. The performance of the link was determined by using *DITG* traffic injector, in which the injection time was 1 min, the mean η obtained was less than 2 Mbps, and the PL was less than 5%. This data rate was enough for transmitting the information sensed by our WSN, but the packet loss still has to be improved.

B. Seismic Signal Analysis

We next include a seismic signal analysis from registers of events captured by our WSN system and the network of the IGEPN, in order to compare qualitatively the main differences between both registers systems, it is important to notice that for this study sensor nodes have been deployed using commercial off-the-shelf and cheap sensor with the aim of only evaluating RT transmission performance of the network topology systems. The seismic volcano monitoring system

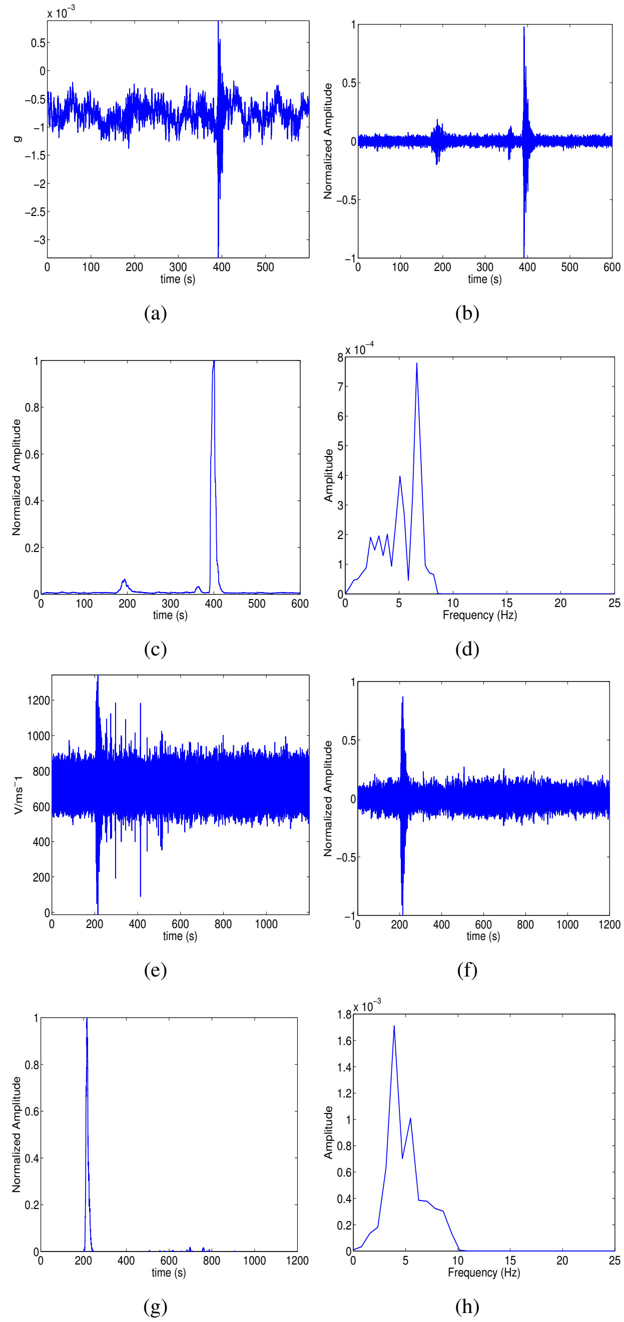

Fig. 6. Event 1 - LP event example from the WSN (a-d) and IGEPN (e-h). (a,e) Original Signal; (b,f) Processed Signal; (c,g) Event detection; (d,h) LP PSD.

of the IGEPN deployed at Cotopaxi volcano is composed by five short-period seismometers, two seismometers of three components, two wideband seismometers and seven stations for lahares [21]. The IGEPN provided us with information from the wideband seismometers, which are characterized by having a flat response speed in the frequency range from 0.01 to 50 Hz. Each station is equipped with a *Guralp CMG-40T* seismometer broadband of three components, they use 100 Hz for f_s, and they have 1600 V/ms^{-1} sensitivity, and as we mentioned before, our system used an ADXL202E accelerometer.

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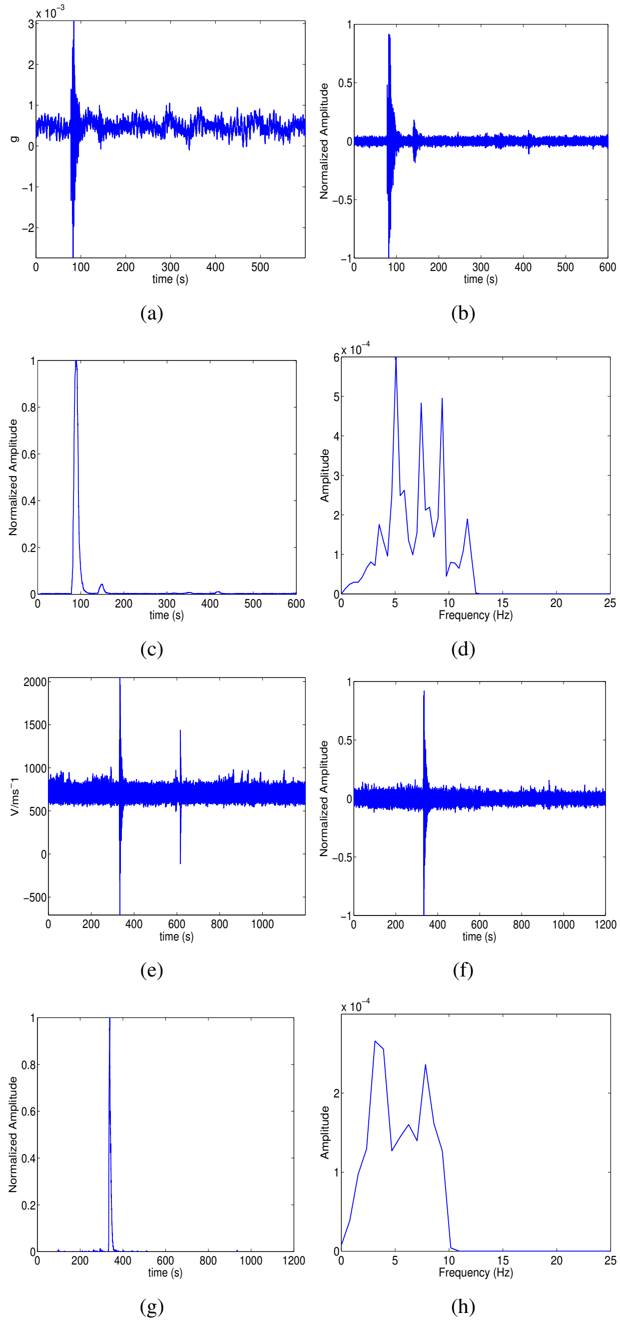

Fig. 7. Event 2 - VT event example from the WSN (a-d) and IGEPN (e-h). (a,e) Original Signal; (b,f) Processed Signal; (c,g) Event detection; (d,h) VT PSD.

Figures 6 and 7 show similar volcanic information registered by the proposed WSN system and by IGEPN network. We observe in panels (a) of Figures 6 and 7 the original signals registered by the WSN system, corresponding to a Long Period event (LP) and a Volcano Tectonic earthquake (VT), meanwhile panels (e) of Figures 6 and 7 show LP and VT registered by IGEPN network, which presented a DC component, that could be attributed to long-term sensor calibration drift. In Figures 6(e) and 7(e) we observed that the Background Noise (BN) is more representative that in Figures 6(a) and 7(a), since the sensors of the IGEPN network are more sensitive than ours, therefore they are able to discriminate better the signal from the noise, becoming indispensable a pre-processing signal stage with these registers. Figure 6(a) shows the presence of one event, since we observe a predominant peak around 400s, meanwhile for the IGEPN system, in Figure 6(e) shows the presence of some consecutive events with a considerable BN, and a possible volcanic event around 200s.

Figures 6b, 6f, 7b, and 7f show the pre-processed signal, from which we removed the mean value, then we applied a normalization process, and a band-pass FIR filter from 1 to 25 Hz, with this processing it is possible to observe the presence of a predominant event in each system, that is confirmed in Figures 6c, 6g, 7c, and 7g, which show the representation of the moving average processing with an overlapping value step of 1 sample, this method helped us to identify the events. Finally, we analyzed the power spectral density (PSD) with Welch method, where the main parameters of the FFT were 50% overlapping in order to have a good resolution in frequency and time, 500 samples window (corresponding to 5s), and 128 points for obtaining the PSD of the event. Figures 6d and 6h show that the most representative spectral components for a LP event corresponds to the frequency range [2 - 7 Hz], and the signal spectral content between [3 - 10 Hz] correspond to a VT earthquake, as shown in Figures 7g and 7h.

In both cases was possible to observe clear differences between these two types of volcanic events, LP are the result of a resonance phenomenon of a magma filled conduit, LP at Cotopaxi Volcano have presented distinct peaks in narrow frequency range from 0.5 and 7 Hz as shown in panels 6(d) and 6(h), they are characterized by a duration between a few seconds to more than one minute and with a very limited to a relatively narrow frequency bands spectral content as it can be observed in panels 6(c) and 6(g). Meanwhile, VT are commonly due to brittle fracture in response to accumulate stress changes associated with magma dynamics and pressure variations in the conduits, they present sharp onsets, dominant high frequencies (in geophysical terms bigger than 5 Hz) as shown in panels 7(d) and 7(h), and short variable durations from seconds to a minute, as is observed in panels 7(c) and 7(g). The beginning of the signal is usually impulsive, corresponding to the arrival of the P wave, it is also possible to identify the arrival of the S wave along the time signal of the seismic event [45]. Further work is required in order to provide a more formal and quantitative evaluation of our WSN and the existing IGEPN network, which will involve adapting sensors with similar seismic characteristics to the ones present in the existing monitoring network of the IGEPN.

The main differences between the records of the IGEPN and ours were the frequency response and the sensitivity. Our network could register events in the range from 1 to 50 Hz, meanwhile data of IGEPN network is able to register events in the range from 0.01 to 50 Hz. For instance, in the signals recorded by IGEPN, we observed a main frequency component in 0.2 Hz attributed to sea micro-seisms [46], for this reason, we used a band-pass FIR filter from 1 Hz, and this network can register other types of non-volcanic events as lightnings. Nevertheless, we checked that our system could loss some events or part of them, due to its sensitivity limitation and its packet loss, which is a relevant information to be accounted for in further developments for RT operation.

VI. Discussion and Conclusions

Previous works focus mainly on the event detection algorithm, and signal pre-processing, rather than a detailed network description and performance analysis. Most of these works did not report the QoS metrics, which make not possible to determine a quantitative analysis between those systems and ours. However, the main differences are the operation frequency and the f_s. Regarding this, the majority of systems operate in the frequency band of 2.4 GHz instead of operating in the frequency band of 900 MHz, due to the RBR in these bands reach 250 kbps and 40 kbps, respectively, this became the main constraint in the 900 MHz band, despite the distance between nodes is improved in low frequencies, and the line of sight among them is not strict. Meanwhile, for the latter if we use a very large f_s an unnecessary amount of data is generated considering that the bandwidth in these systems is our main constraint.

In this work, we addressed the performance evaluation of topologies and the number of sensor nodes to be deployed in a volcano monitoring system. We determined that the optimal scenario for this kind of system using WSN is the random topology, which presented the best performance related to the metrics considered in this work including its η maximization. Data in the simulation stage showed that the maximum η is approximately 145 kbps, the PL is less than 20%, and the EED equal to 3ms, whereas for test-bed experimentation these values were η of 139 kbps, PL of 22%, and EED of 3.1s, and the values measured at Cotopaxi were η of 130 kbps, PL of 25%, and EED of 3.1s. We corroborated that both η and PL were affected mostly by the topography, since at Cotopaxi Volcano the η is smaller and its PL is bigger than test-bed.

In our approach several stages are actually RT, such as data acquisition and data transmission from volcano to surveillance laboratory, but data presentation, data processing, data analyzing, and decision making are not RT. Our results suggested that the processing data and the transmission time from the coordinator node to PC took too much time, near to 3s, and these values had not been considered in the simulation tool. We concluded that the main problem was the coordinator node, due to its delay in presenting new data was significant. This provoked another problem, the sub-sampling leading to loose parts of the signal. Consequently, the maximization of the η in our network was unnecessary, since the rate of the coordinator node is limited to its processing rate, and it is lower than the η of our WSN.

Moreover, it is still not possible to give an early warning with this kind of systems, because data were processed off-line in a far distanced surveillance laboratory. We are interested in feature extraction from volcanic or seismic signals in order to determine the main features that could be transmitted, without the necessity to transmit the entire registers. Data reduction with this information will be able to optimize the performance of the network, reducing time delay in transmitting and processing data. We have to consider another alternative of using a coordinator node or another type of technology to improve the performance of the entire system.

A possible eruption in Cotopaxi Volcano will be directly related to a significant increment of both LP and VT events; however, an increment of the VT earthquakes above some threshold may indicate an imminent eruption, according to experts. As with any natural phenomena there is no guarantee that the system will be able to survive an eruption, however, we hope some relevant information will be captured and sent by the nodes before this happens.

As future work, we will model this system considering the value of EED related to processing data, and we will use machine learning algorithms to evaluate the possibility of improving detection and having an automatic classification of events.

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