Performance Evaluation of a Volcano Monitoring System Using Wireless Sensor Networks

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***Abstract*—A volcano monitoring system plays a key role for launching emergency early warning, and the use of alternative technologies have proven their effectiveness in this setting, which is the case of wireless sensor networks. For surveillance systems, the real-time requirement is mandatory due to the need for immediate access to the signals derived from a natural disaster where the goal is safeguarding lives. Previous works did not report detailed enough performance evaluation of this kind of systems, either by means of using simulation tools or in a test-bed related to real-time metrics. Our aim was to identify the optimum number of sensors to be deployed in a Volcano Monitoring System based on simulation results and corroborated with an *in-situ* testbed. We used *ns-2* as simulation tool, where Random and Tessellation scenarios were evaluated. Our study identified that the optimal scenario in volcano monitoring is Random, with maximum eighteen nodes to satisfy metrics such as throughput, time delay, and packet loss. We deployed sixteen sensors in a strategic area at Cotopaxi Volcano, where 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 at the volcano, and WiFi-based long distance technology was used for this purpose. The data obtained with our system allowed to distinguish long period events and volcano tectonic earthquakes.**

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

I. Introduction to WSN

Wireless Sensor Network (WSN) have become critical in the evolution of Telecommunications, and their constant evolution makes possible to implement devices with low cost and energy autonomy, without periodic maintenance for obtaining environmental information. 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 every heterogeneous networks, where data must be transmitted and processed, for finally enabling people using any application to monitor or to control objects [1]–[6].

Ecuador has a special interest in the use of WSN for volcano monitoring applications, as it is located in the Pacific Ring of Fire –a place with high seismic activity. WSN systems are much cheaper and reliable than bulky and energy-hungry traditional systems. Currently, South America lacks of enough permanent monitoring WSN-based systems deployed in active volcanoes, in previous works such systems have been installed just for a couple of weeks. Volcano monitoring using WSN still requires further research in order to present information in real-time and to launch early emergency warnings. The main constraint to be considered as real-time systems is the time delay in data processing. There are some solutions at Network and MAC layer referred to data acquisition *in-situ*, data gathering and data dissemination, which significantly reduce the time delay. However, it is not possible yet to give an early warning with this kind of systems, because data are processed off-line in a far distanced surveillance laboratory. The time delay related to digital signal processing and signal propagation must be solved using appropriate processing and telecommunication techniques [7]–[11].

Previous works did not report detailed enough performance evaluation of this kind of systems, neither by means of using simulation tools, or in a test-bed, related to metrics for considering a system as a real-time one. Our aim was two-fold: first, we identified the number of sensors that maximize the network capacity, considering the main metrics to evaluate a WSN for real-time applications; and second, we corroborated the simulation results by an *in-situ* testbed deployed at Cotopaxi volcano.

The rest of the paper is organized as follows. Section 2 summarizes previous research on the subject. Section 3 describes the performance evaluation of the WSN in detail. Sections 4 and 5 describe the simulation results obtained and the experimental study performed, respectively. Finally, Section 6 presents our conclusions and future work.

II. Related Work

Our interest consists in determining the network behavior, which can be evaluated by Quality of Service (QoS) metrics, such as: availability, reliability, time response, time delay, throughput, bandwidth capacity, and packet loss ratio. In order to offer real-time in WSN with guaranteed QoS metrics, the network must be analyzed in a different way than traditional real-time systems.

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WSN requires to meet certain severe challenges due to its wireless nature, distributed architecture and dynamic network topology. The state of the art of real-time solutions currently developed have been presented with emphasis at MAC level, routing, data processing, and cross layer. This denotes a direct relationship between real-time and QoS metrics, as well as new general concepts related to real-time WSN systems [12] [13].

Real-time WSN can be defined as a network capable of ensuring maximum sustained traffic rate (throughput), and minimum latency and packet loss (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 [14], [15], then it has to be verified and refined by simulations [16]–[21], and finally confirmed in a testbed [22], [23]. 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), using tools developed by manufactures [24]–[26]. However these results of WSN performance evaluation are insufficient for our case, since in this work we are proposing the use of WSN as a new alternative for volcano monitoring systems.

III. Performance Evaluation

A. Real-Time WSN Requirements for Volcano Monitoring

For our application we have to consider the environment presented by a Volcano –a 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 is quite true 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 a real-time monitoring: normalized throughput (η), EED, and PL. As mentioned in previous works, there are other metrics that can also be considered, but all of them have a direct relation to our main metrics, for example: duty cycle, energy consumption, average jitter, load factor, and traffic type.

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

B. Simulation Environment

There is wide range of simulators that can be used to test WSN in order to obtain several results to be analyzed. Following [27], we have chosen *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 distribution topology. For the first one we have chosen a triangular tessellation pattern network $\{3,\ 6\}$, 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,

$$n = 1 + 3C(C+1). \tag{1}$$

TABLE I
Simulation parameters

General Parameters	Value
Radio Propagation Model	Two-Ray Ground
Routing Protocol	AODV
Raw Bit Rate (kbps)	250
Antenna Type	Directional
Simulation Time (s)	260
Transmission Time (s)	220
Power Parameters	**Value**
Transmission Power (dBm)	0 (1mW)
Sensitivity (dBm)	-94
Transmission antenna gain Gt (dB)	1.0
Reception antenna gain Gr (dB)	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 nodes
Beacon mode	Enabled Beacon Order:3 Superframe Order:3

In both scenarios, we started with 6 nodes growing until 66 nodes in 6 nodes steps. We defined one coordinator and n full-function devices (FDD), and all the transmissions were directed to the coordinator. We assumed an event occurring with a duration equal to 220 seconds in an approximated area of 300×300 m^2.

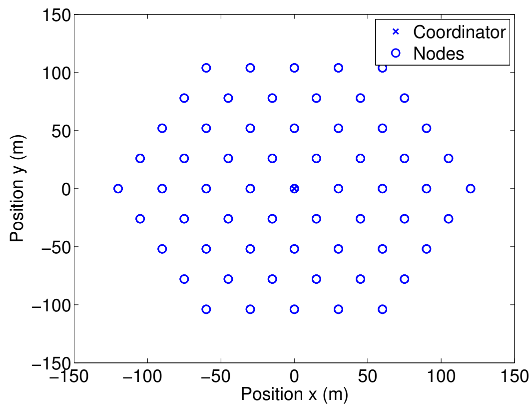
For our simulation process, it was necessary to specify the number of replications to reduce the mean square error. Accordingly, we run 6 replications for Tessellation scenario, whereas we run n replications for each Random scenario.

The main simulation parameters that we defined were simulation time, topology, routing protocol, and transmission rate. We clustered all of them in three main groups: general parameters, power parameters, and node parameters. The rest of the parameters used to simulate the network model are detailed in Table I. The simulation scenarios for both network topologies are shown in Figure 1.

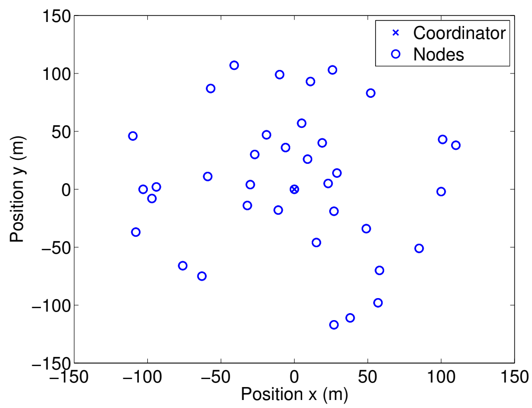
For throughput we used the information that allowed us to define Eq.(2), and we calculated η defined in Eq.(3) [28], [29], meanwhile for EED and PL we used the information obtained in the trace file. We used a tool developed by Jaroslaw Malek, named *tracegraph* [30], to analyze the trace file, yielding

$$Throughput = 8\frac{B}{t_{tx}}\left[\frac{bits}{s}\right], \tag{2}$$

where B is the number of transmitted bytes, and t_{tx} is the time of transmission in seconds. Also, the parameter η represents



(a)



(b)

Fig. 1. (a) Tessellation and (b) Random scenarios evaluated.

the normalized throughput, and it is calculated by

$$\eta = \frac{Throughput}{RBR}, \tag{3}$$

where *RBR* is the theoretical bite rate = 250 kbps.

IV. Simulation Results

Figures 2 and 3 show our main metrics related to the number of nodes obtained in Tessellation and Random scenarios. Figure 2a shows an irregular decay of η in Tessellation scenario, where the maximum and minimum values were 0.58 and 0.28, respectively. Their boxplots corresponded a line because its standard deviation was negligible. Meanwhile, Figure 3a shows a direct relationship between η and n in Random scenario, its maximum and minimum values were 0.57 and 0.41, respectively. Their boxplots showed a significant standard deviation due to its own random nature.

Note that in Figure 2b, Tessellation scenario presented more irregularity than Random scenario. Related to this metric, both scenarios presented a mean value around 3 ms.

Finally, data suggest that PL in both scenarios presented an increment as an exponential function of n. In Figure 2c we can observe that Tessellation scenario had irregular PL in the nodes from 36 to 48, whereas in Figure 3c we observed that Random scenario increased its PL directly with n. The

TABLE II
Comparison deployments, [1]Acoustic, [2]Seismo-Acoustic, [3]Seismo

WSN Deploy.	Variables/ Platform	Number sensors	Operation frequency (MHz)	Frequency Sampling (Hz)	Duration (Days)
[7]	A[1]/Micaz	3	2400	100	2
[8]	SA[2]/Tmote	16	2400	100	19
[9]	SA/Imote2	5	900	1000	Abiding
Proposed Work	S[3]/Micaz and Iris	16	2400	60	3

main difference between both scenarios was that the Random scenario had less 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 more nodes with same or better characteristics of η and EED than those presented in Tessellation scenario.

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 and Iris platforms. Thus, Cotopaxi, which is currently the highest active snow-capped volcano in the world, was selected for deploying a WSN. This system was deployed at an altitude of 4870 meters, where 16 sensor nodes were implemented. Table. II summarizes the comparison 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, WSN were deployed, at an altitude of 4870 meters. Two different kinds of motes were deployed –10 motes MICAz and 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. Figure 4 shows the location of the two motes networks deployed. Data were collected continuously for three days. The energy problem was solved with the use of a generator. 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. In this laboratory, signal processing was off-line in order to define whether or not the events are false alarms.

A. WiFi-Based Long Distance Link

A wireless link was used for transporting data sensed by WSN, and it was proven to be 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

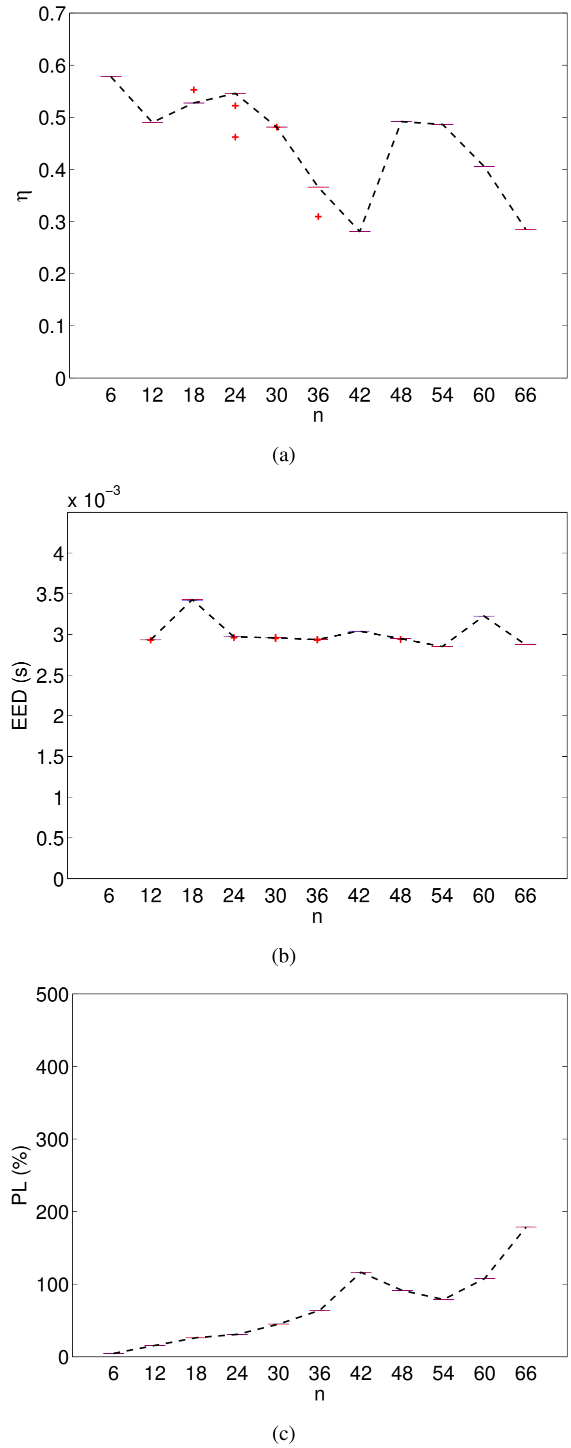


Fig. 2. Metrics of QoS for Tessellation Scenario. (a) η, (b) EED, and (c) PL.

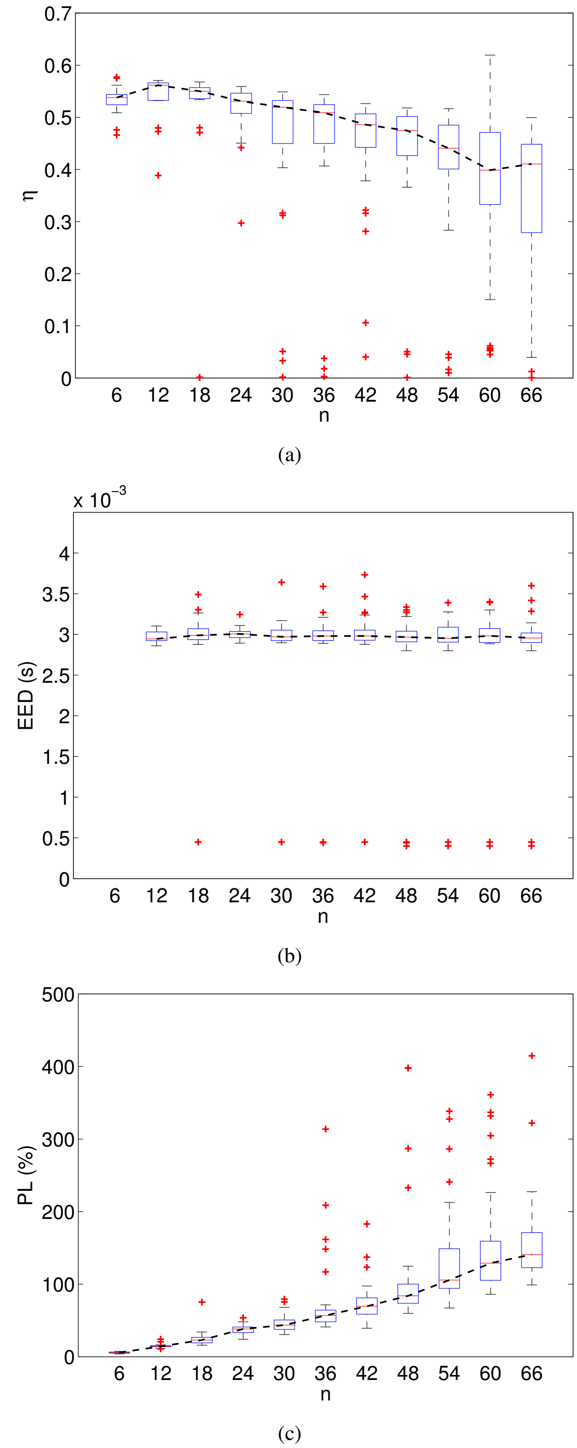
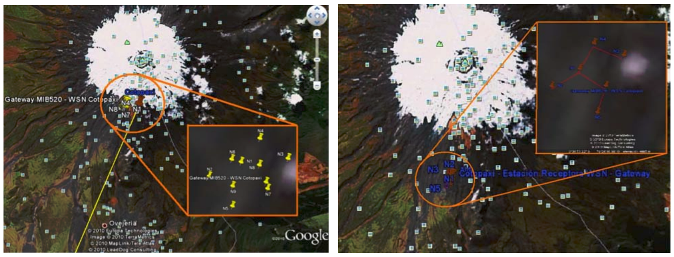


Fig. 3. Metrics of QoS for Random Scenario. (a) η, (b) EED, and (c) PL.

when applying WiLD Technology, namely, power budget and timing limitations. The first was easily solved by using high gain directional antennas, while the timing issue was addressed by modifying the media access mechanism, as proposed in [31].

IEEE 802.11b was selected for our purposes, mainly, because the 2,4 GHz ISM band presents less losses that 5,8 GHz ISM band. We used antennas with gain of 24 dBi and the transmission power of 1 W. In the MAC sublayer, three types of limitations can be extracted, namely, the timer waiting of ACKs, 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 using DITG traffic injector, in which the injection time was 1 minute, the mean throughput obtained was less than 2 Mbps, and the PL was less than



(a) (b)

Fig. 4. Wireless Sensor Networks deployed on Cotopaxi Volcano. (a) Micaz motes and (b) Iris motes.

5%. This data rate is enough for transmitting the information sensed by our WSN, but the packet loss must still be improved.

B. Seismic Signal Analysis

Figures 5a and 6a show the original volcanic information obtained by our system. Figures 5b and 6b show the processed signal after we used z-score technique, the normalized process to encode the distribution and remove the dependence on the size of the seismic register, and a band-pass FIR filter from 1 to 25 Hz. Figures 5c and 6c show the representation of the autoregressive model order zero, this used a moving average concept with an overlapping value equal to 1, this method help us to identify the events. Finally, we used power spectral density (PSD) with Welch method, where the main parameters of the FFT were an overlapping of 50% in order to have a good resolution in frequency and time, a 500 samples window (corresponding to 5 s), and the number of points were 128.

Figures 5d and 6d show that spectral components presented in the frequency range [0 - 8 Hz] corresponds to a long period event, and the signal spectral content between [0 - 13 Hz] correspond to a volcano tectonic event.

VI. Conclusion and Future Works

We determined that the optimal scenario for volcano monitoring system using WSN is Random, it presents the best performance related to the metrics considered in this work with its consequent maximization of the throughput. Data showed that the maximum throughput is approximately equal to 145 kbps, the PL is less than 20%, and the EED equal to 3 ms. These results were corroborated with an *in-situ* deployment, where we obtained a maximum throughput equal to 130 kbps, PL of 25%, and mean value of EED of 3,1 s. The main difference between simulation and testbed was referred to EED, data suggested that the processing data took to much time and this value is not considered in the simulation tool.

As future work, we will model this system considering the value of EED related to processing data. We are also interested in feature extraction from volcanic or seismic signals in order to automatically classify events.

VII. Acknowledgments

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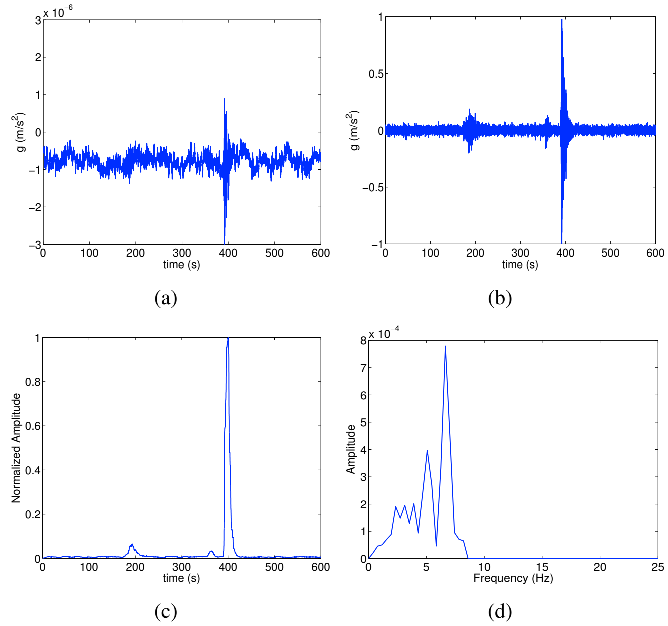

Fig. 5. Event 1 - Long Period. (a) Original Signal, (b) Processed Signal, (c) Event Detection, and (d) Power Spectral Density.

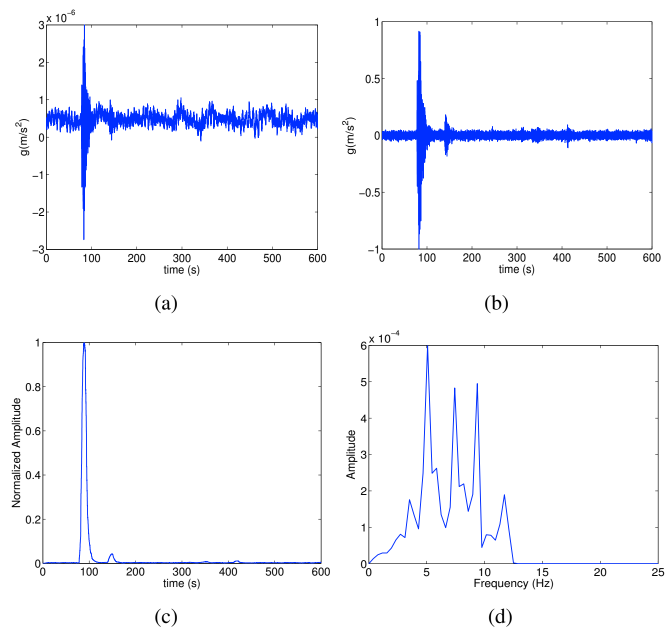

Fig. 6. Event 2 - Volcano Tectonic Earthquake. (a) Original Signal, (b) Processed Signal, (c) Event Detection, and (d) Power Spectral Density.

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