Monitoring Volcanic Activity at Reventador Volcano, Ecuador with a Wireless Sensor Network

Geoff Werner-Allen, Konrad Lorincz, and Matt Welsh
Harvard University

Omar Marcillo and Jeff Johnson
University of New Hampshire

Mario Ruiz and Jonathan Lees
University of North Carolina

With much assistance from
Instituto Geofísico, EPN, Ecuador
Summary

We deployed a 16-node wireless sensor array on Reventador in July/August 2005
  ● Nodes monitored seismic and infrasonic activity of the erupting volcano
  ● Automatic triggering to download data following seismic events

Tested sophisticated data collection, routing, and time synchronization in the real world
  ● Very challenging environment, remote deployment site
  ● Science goals involve high data fidelity requirements

Many lessons learned
  ● Many challenges involved with deployment at remote site
  ● Software robustness is a major concern
  ● Postprocessing and analysis of data is as difficult as initial acquisition
Sensor Arrays for Volcanic Monitoring

Infrasonic waves propagate out of the vent, then through the atmosphere to the microphone.

Seismic waves may originate from a diffuse zone and may be filtered (scattered and attenuated) within the volcanic edifice.
Existing Volcanic Sensor Station

- Car batteries
- Data Logger
- Mic amplifier
- Power distribution
- Cable to seismometer
- Cables to microphones
Wireless Sensor Mote Technology

Telos “mote” platform
- 8 Hz (TI MSP430) CPU, 10 KB RAM, 40 KB ROM
- 2.4 GHz IEEE 802.15.4 (“Zigbee”) radio (Chipcon CC2420)
- 1 MByte flash for data logging

Designed for low power operation
- 1.8 mA CPU active, 20 mA radio active
- 5 µA current draw in sleep state

Cost: About $75 with no sensors
The Role of Wireless Sensor Networks

Wireless sensors are smaller, lower power, and much easier to deploy than existing data logger systems.

Can provide real time monitoring of volcanic activity
  - ... as opposed to manually collecting a CF disk from each station every week

Can enable studies with a large number of sensors
  - Large numbers of sensors are needed for detailed studies of volcanic processes
  - e.g., tomography -- image interior of volcano using wave arrivals at many locations
Challenges

High data rate sampling
  ● Seismometers and microphones typically sampled at 100 Hz, 24 bits per channel
  ● 1200 Bytes/sec per node, or > 4 MB per hour

Reliable communication
  ● Cannot tolerate dropped packets or samples in recorded data stream

Fine grained time synchronization
  ● Must be able to correlate signals from separate nodes to millisecond resolution

Long telemetry distances between nodes
  ● Sensors typically placed 100's of meters apart in highly variable/rough terrain

Automatic event detection
  ● Radio bandwidth precludes continuous transmission
  ● Must detect interesting events and trigger downloads automatically
Previous Work: Volcán Tungurahua, Ecuador, July 2004

Small-scale network of MicaZ motes with infrasonic microphones

- Proof-of-concept deployment to establish groundwork

MicaZ with custom infrasonic microphone sensor board

Example eruption data
Our Wireless Volcano Monitoring Sensor Node

- Telos mote
- Antenna cable
- Seismometer cable
- Microphone cable
- D cell batteries
- Custom ADC board
Enhancements and Add-Ons

Custom four-channel, 24-bit analog-to-digital conversion board
- Based on AD7710 sigma-delta ADC
- 40 mA current draw for two-channel board
- Multiple gain settings with hardware switch and software

Large external antenna for long telemetry distances
- 8.5 dBi omnidirectional antenna mounted on 1.5 m PVC pipe
- Measured 400+ m range

D-cell batteries for increased lifetime

Pelican weatherproof case
- External milspec connectors to sensors
Sensor Types

Geospace Industrial GS-11 geophone
- 4.5 Hz corner frequency, single-axis, inexpensive ($80)

Geospace Industrial GS-1 geophone
- Triaxial, 1 Hz corner frequency, more sensitive, only on two motes

Microphones (Panasonic electret condenser)
- Very cheap, good frequency response with infrasound (< 20 Hz)
Sensor Network Architecture

Yagi to repeater

GPS receiver for time sync

FreeWave radio modem for long-distance communication to base

200-400m

Sensor nodes each with mic and seismometer
Nodes self-organize into multihop routing tree

Protocol based on existing TinyOS routing code, with many enhancements

- Many bug fixes, revamped buffer management
- Hop-by-hop acknowledgement and retransmission

Nodes select parent with strongest link quality indicator (LQI) on received pkts

- May not work with asymmetric links
- Automatic detection of routing loops

Commands propagated to nodes with efficient flooding protocol

- Ensures high reliability for command distribution
- Variant of “Drip” codebase with various enhancements
Long-distance telemetry

Deployment site is over 4km from observatory
- No line-of-sight visibility; cannot directly communicate via radio

Set of three FreeWave radio modems used to establish connectivity
- One each at sensor site and observatory, another used as a repeater on a tall hill
- Each powered by motorcycle or car battery, recharged by solar panels
Time synchronization is critical for volcanic monitoring
  - Must correlate signals across the sensor array with high precision

We made use of Vanderbilt FTSP multihop time sync protocol
  - Required several changes and fixes
  - Synchronizes nodes with accuracy of up to several microseconds
  - However, highly variable

GPS receiver used to establish global timebase
  - This node also acts as FTSP timesync root
  - Periodically beacons GPS time and corresponding FTSP global time
  - This data is logged at base station for later rectification
Nodes continuously sample each channel @ 100 and store to flash

- 1 MByte flash can store about 29 min. of data for 2-channel nodes
- Flash organized as a series of blocks, each block stores ~ 80 samples

Each block indexed by 32-bit block ID; flash used as circular buffer

- Each block has an associated timestamp from FTSP; corresponds to exact time of first sample in the block

Nodes report status to base every 10 sec. via multihop routing tree

- Status message contains much useful information:
  - Tail and head block IDs of flash
  - Total number of collected samples
  - Routing tree parent, depth, and link quality
  - Global and local time
  - Battery voltage and node temperature
  - Software version number
Nodes locally detect “interesting” events and report them to the base

Simple, robust algorithm for eruption detection:

- Maintain two EWMA filters on the incoming data with different gains
- If ratio between filters is above a threshold, trigger detection
Following an event, must reliably download complete signal

Approach: Download complete blocks from each node in turn
  - Base station floods *Fetch Request* message containing:
    - *node ID, block ID, bitmap of required block chunks*
    - Node replies with requested block chunk (one chunk per radio message)

Laptop issues fetch requests for required blocks following trigger
  - Disable sampling on all nodes prior to fetch cycle (avoid data loss)
  - Caveat: Cannot capture back-to-back eruptions

Default: Download 60 sec. of data from each node following an event
  - Requires about 206 blocks, double that for four-channel nodes
  - Takes between 3-5 minutes per node, depending on depth in routing tree
Other system features

Over-the-air network reprogramming using *Deluge*

- Allowed us to push bug fixes and code updates to live sensors after deployment
- However ... not always safe, and in some instances crashed the network
- Added support to our software to monitor current SW version

Continuous (unreliable) sampling from individual stations

- Node collects samples in radio messages and broadcasts unreliably
- Only used on one node to conserve radio bandwidth
- Provides real-time view of volcanic activity; useful for tuning eruption detector
Deployment Site:
Reventador Volcano, Ecuador
Deployment Site: Reventador Volcano, Ecuador

- Solar panels for charging car battery (used by FreeWave and GPS only)
- Radio modem
- GPS receiver
- Konrad
- Four-channel sensor node
- Next node 163m away
Reventador Volcano

One of several very active volcanoes in Ecuador

- Last large eruption: November 2002
- Resulted in 17 km high eruption column and large pyroclastic flows extending for over 8km
- Ashfall reached Quito (95 km away) and closed down airport

Recent activity (since November 2004)

- Andesitic lava flows extending 4 km from the vent – threat to nearby oil pipeline
- Intermittent ash-rich, ballistic-laden explosions, up to 6km above the vent

Deployment site is on upper flanks of volcano in area decimated by 11/02 eruption

- Extremely remote deployment site
- 3 hour hike from observatory through dense jungle, impassable for horses
- All equipment carried to site by research team with help from porters
Sensor Deployment Map

Vent

Base

Typical node separation
200-400 m

4.6 km to observatory

3 km
Some Representative Events
Monochromatic Tremor
Some Representative Events
Volcano-Tectonic (VT) earthquake

node 201
node 202
node 206
node 207
node 212
node 250

Time (sec)
Some Representative Events

Explosion – Note saturation of node 250's sensor
Future Work and New Challenges

Intelligent and adaptive event detection

- Existing code permits network to capture data from a single event at a time.
- As a result, we may miss a large eruption following a small (but important) VT event.
- Need better techniques for categorizing events and prioritizing data download based on event type, amplitude, and energy release.

Event-specific data aggregation and compression techniques

- Eruptions, VT, tremor, and other events can be compressed or aggregated in very specific ways.
- Example: Extracting dominant frequencies from tremor event can greatly reduce size of reported signal.
- Eruptions can be captured by representative signal trace from a few sensors plus RSAM (a measure of energy release) from other nodes.
  - Distill complex seismoacoustic signal to a very concise event report.
Distributed event localization

- Sensor nodes can coordinate to localize source of eruption based on wave arrival times and intensities

Tomographic inversion

- Recover 3D structure of the interior of the volcano using wave arrivals from many sensors
- Inspired by use of tomography in medicine (e.g., CT scans)
- Requires many sensors to yield many viewpoints on the volcano

Exciting opportunity: Performing eruption localization and tomography in **real time**
Conclusions

Wireless sensor networks have tremendous potential for volcanological studies

- Easy to deploy, lightweight, and relatively inexpensive
- Can provide large telemetry distances (100's of meters) between stations
- Can capture real time data from many sensors simultaneously

This work is the result of a highly interdisciplinary effort:

- Computer Science (Harvard)
- Geophysics (UNH and UNC)
- Ecuadorean volcano monitoring agency (IG-EPN)

Bridging the gap from sensor network technology to real applications has been extremely rewarding!

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