# Volcanic Earthquake Timing Using Wireless Sensor Networks

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# Volcano Hazards

**Eruption in Chile, 6/4, 2011**
**$68 M instant damage, $2.4 B future relief.**
**www.boston.com/bigpicture/2011/06/volcano_erupts_in_chile.html**

**Eruptions in Iceland 2010**
**A week-long airspace closure**
**[Wikipedia]**

- 7% world population live near active volcanoes
- 20 - 30 explosive eruptions/year

# Volcano Monitoring

- Seismic activity monitoring
  - Earthquake localization, tomography, early warning etc.
- Traditional seismometer
  - Expensive (~$10K/unit), difficult to install & retrieve
  - Only ~10 nodes installed for most threatening  volcanoes!

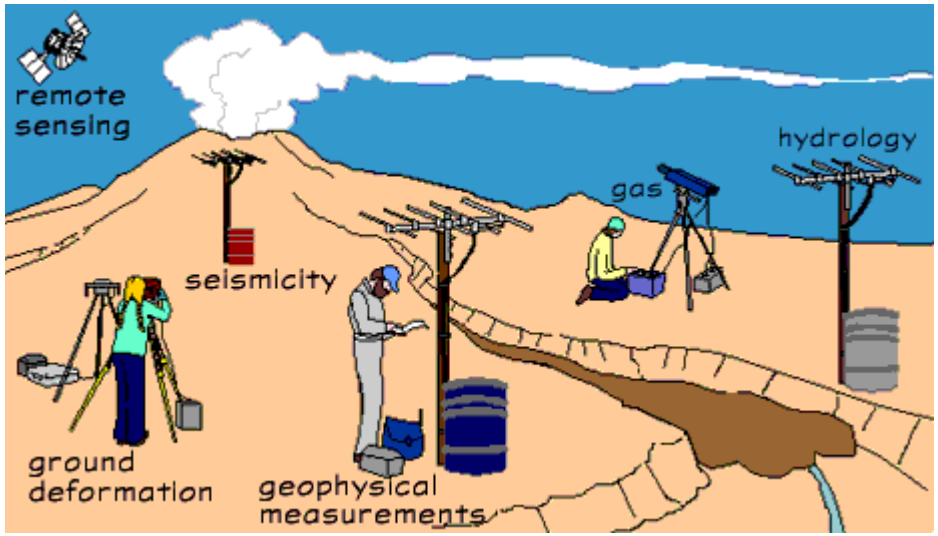
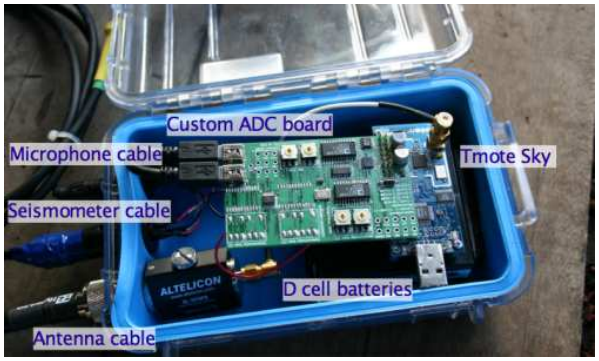



Photo credit: USGS, http://volcanoes.usgs.gov/activity/methods/

# Sensor Networks for Volcano Monitoring

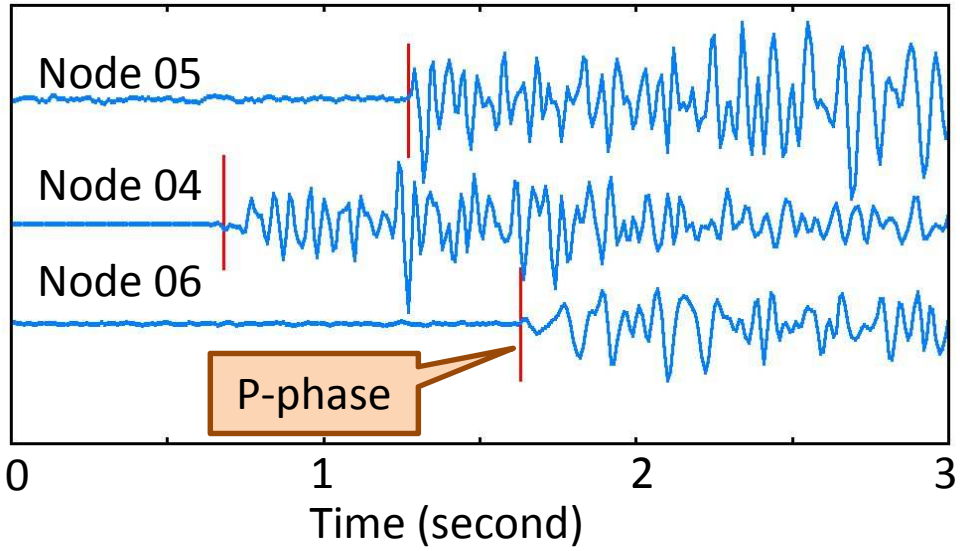
- Sensor systems for volcano monitoring
  - Harvard , OASIS@GSU, VolcanoSRI@GSU/MSU/UNC
  - Raw data collection@100Hz & centralized analysis
  - Short lifetime (~1 week)
- In-network earthquake detection [Tan 2010]
  - Distributed seismic signal processing
  - 83% energy reduction from raw data collection

OASIS node




Harvard node

# Earthquake Timing

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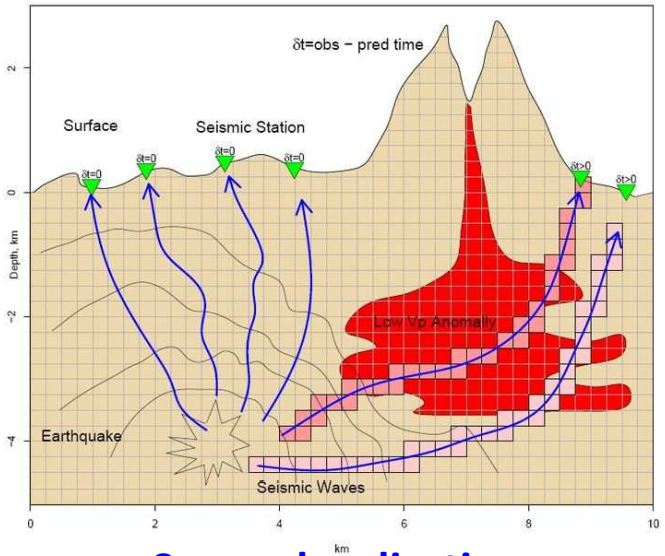


**Source localization**
**Seismic tomography**

- Key to localization, seismic tomography, etc.
  - Usually done manually, automation is expensive

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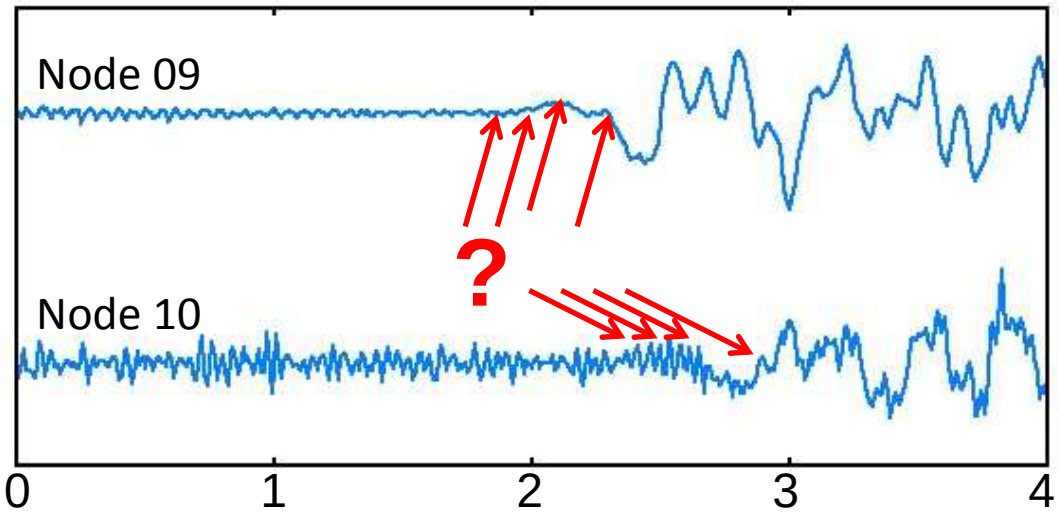
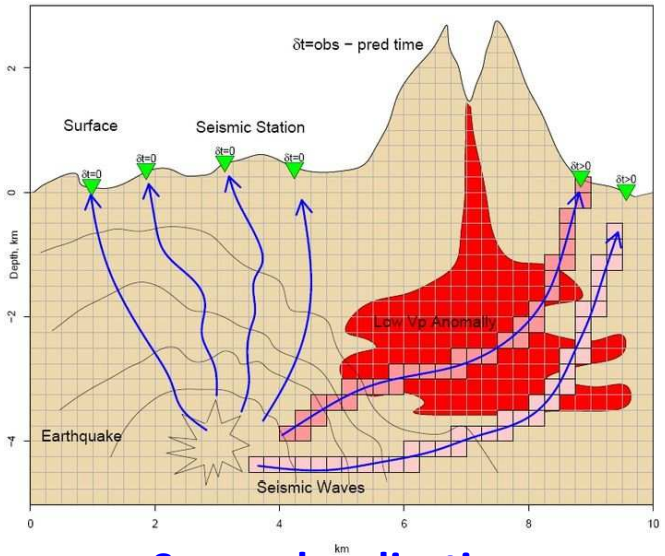


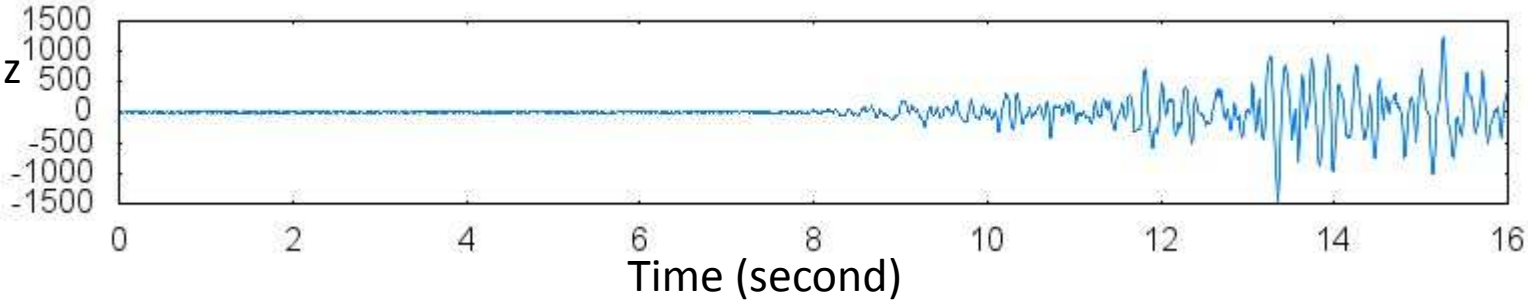




**Source localization**
**Seismic tomography**

- Key to localization, seismic tomography, etc.
  - Usually done manually, automation is expensive
- *In-situ* P-phase picking w/ limited transmission
  - Data intensive
  - Sensors have limited compute & comm. capabilities

# Seismic Signal: Sparsity

Original @ 100Hz



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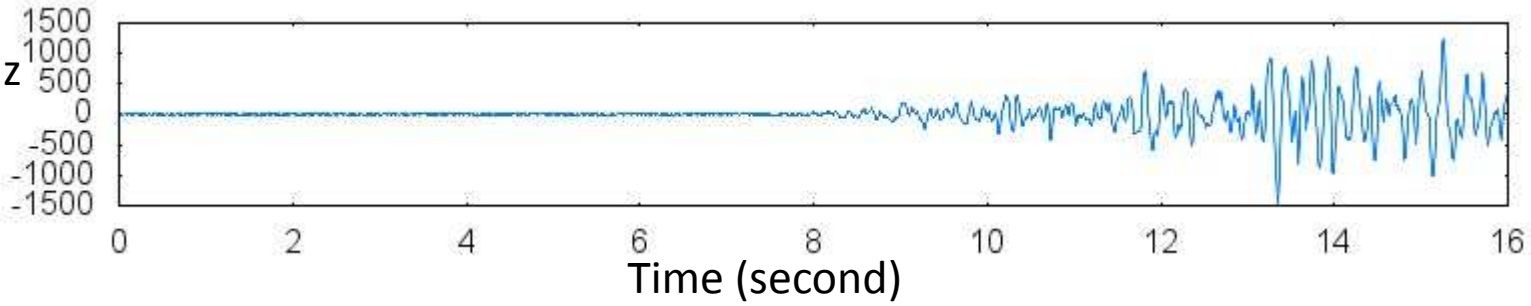
Sparsity=0.57




wavelet

K largest points

K-sparse signal: $\frac{\| s - s_{(k)} \|_2}{\| s \|_2} < 5\%$

$$\text{sparsity} = \frac{k}{\text{signal length}}$$

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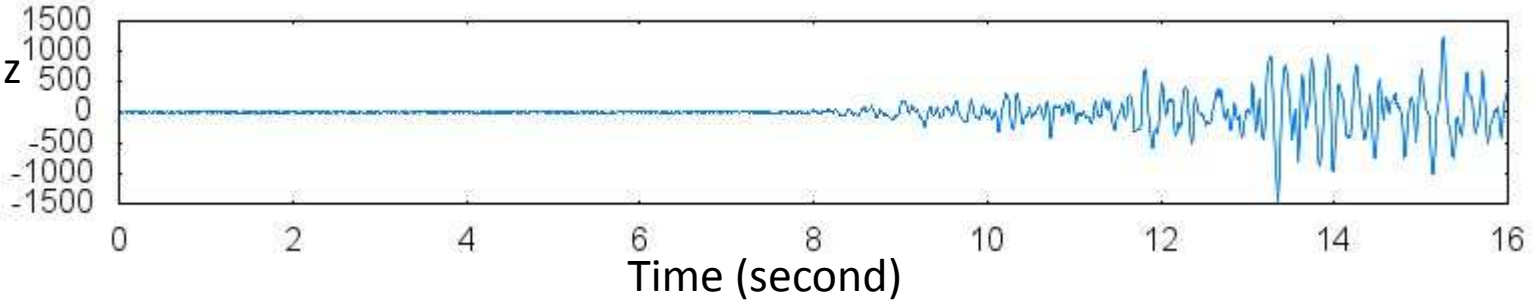
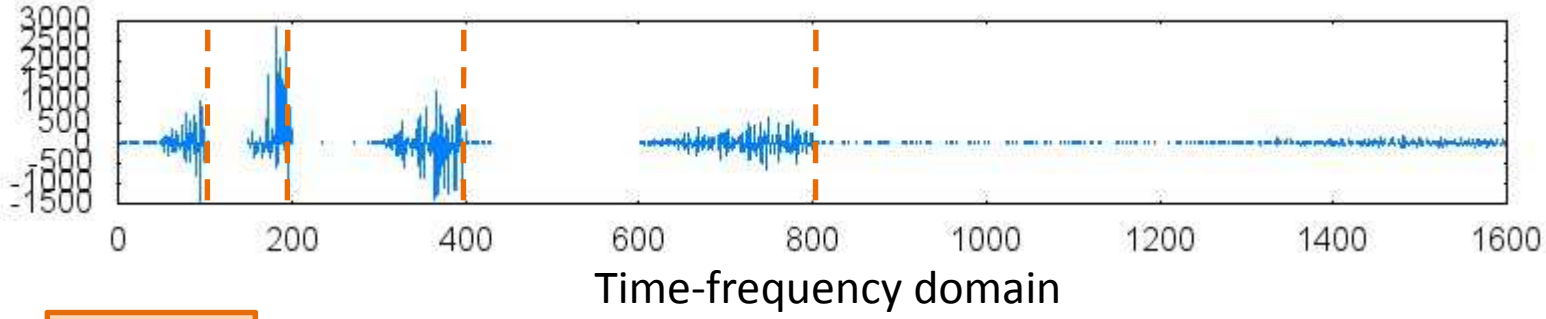



Wavelet

Sparsity=0.14

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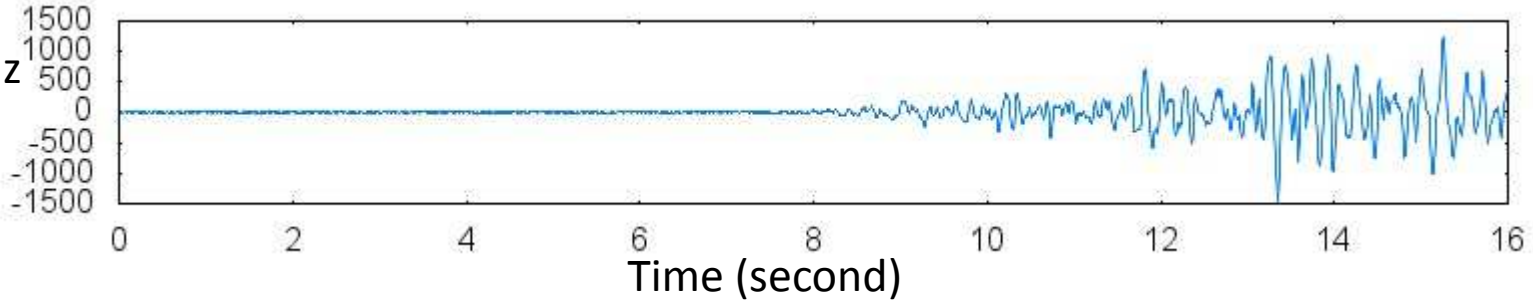


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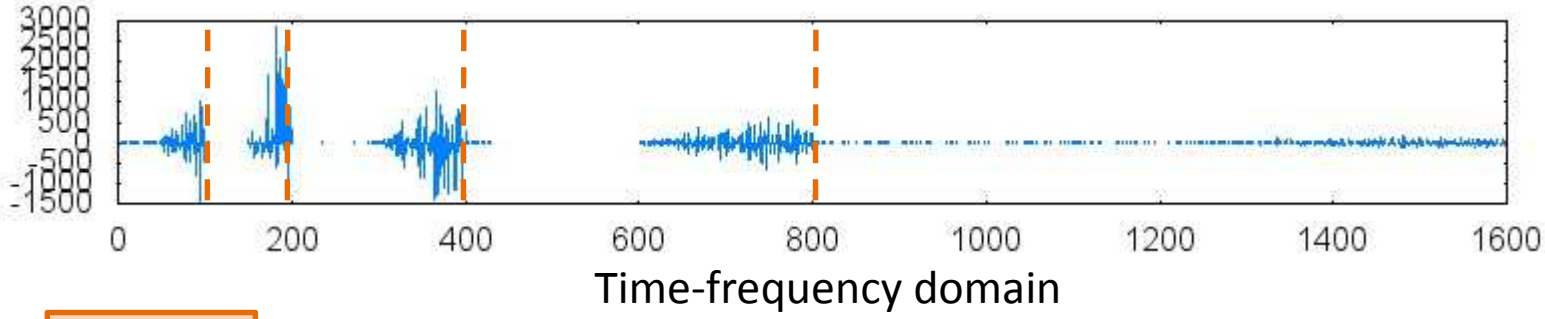


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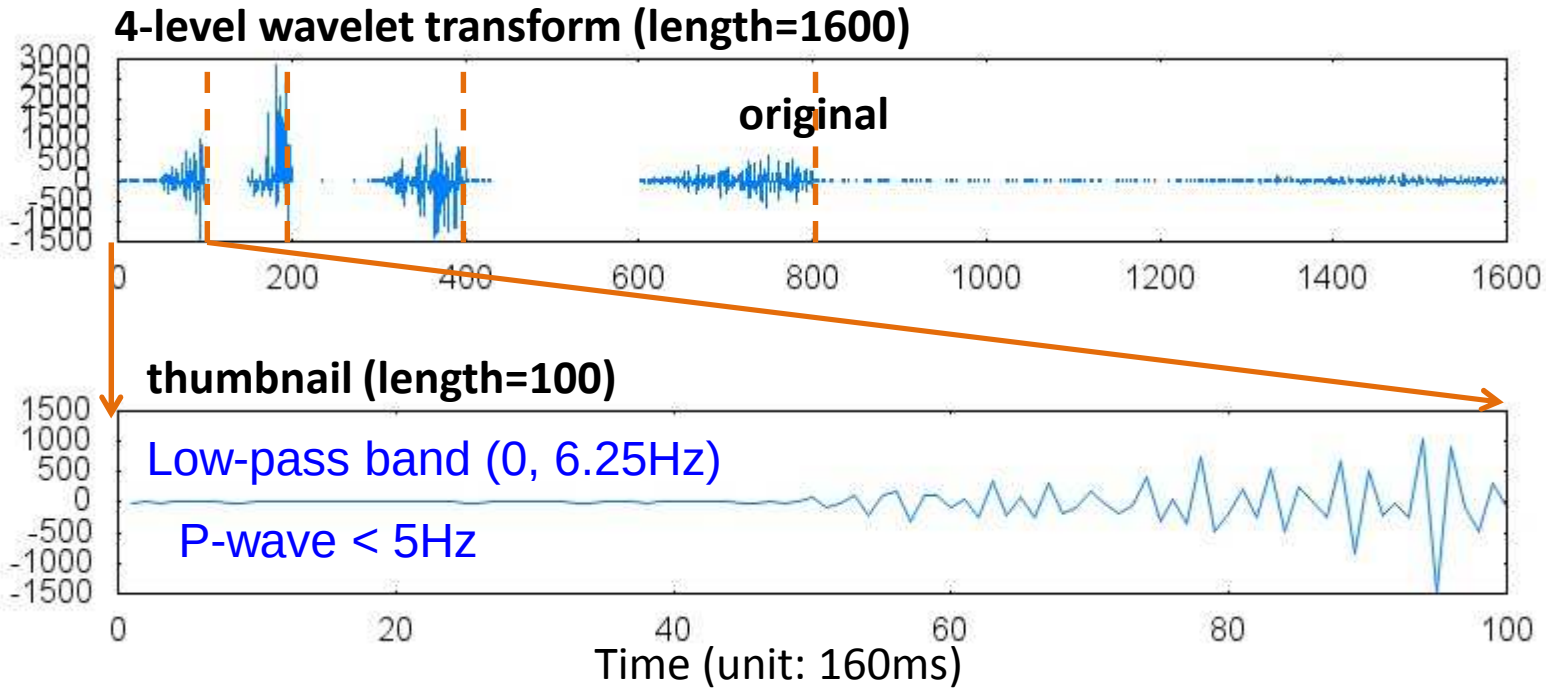
- **Observation 1: wavelet sparsifies signal**

# Seismic Signal: Frequency-Time



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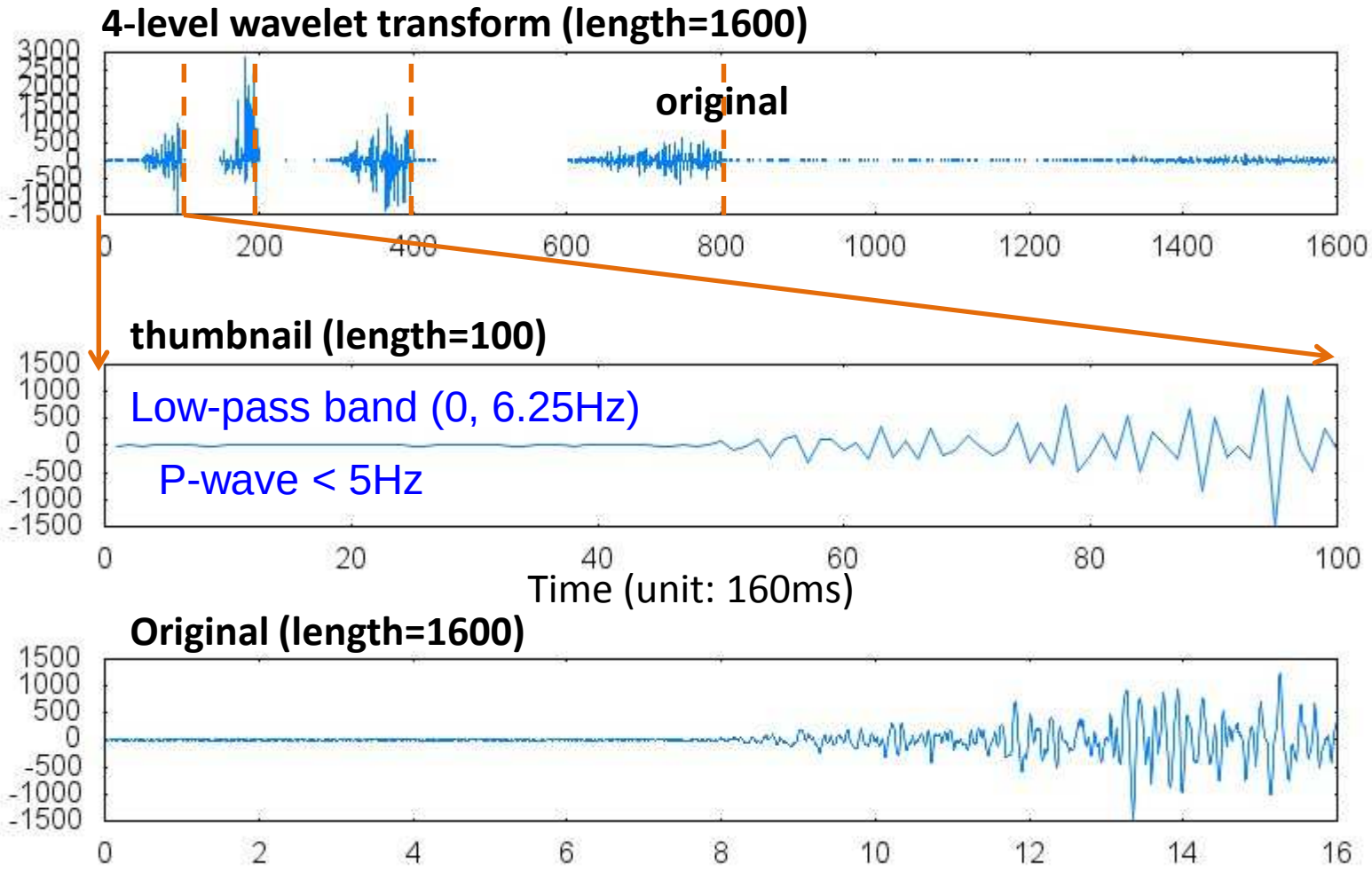

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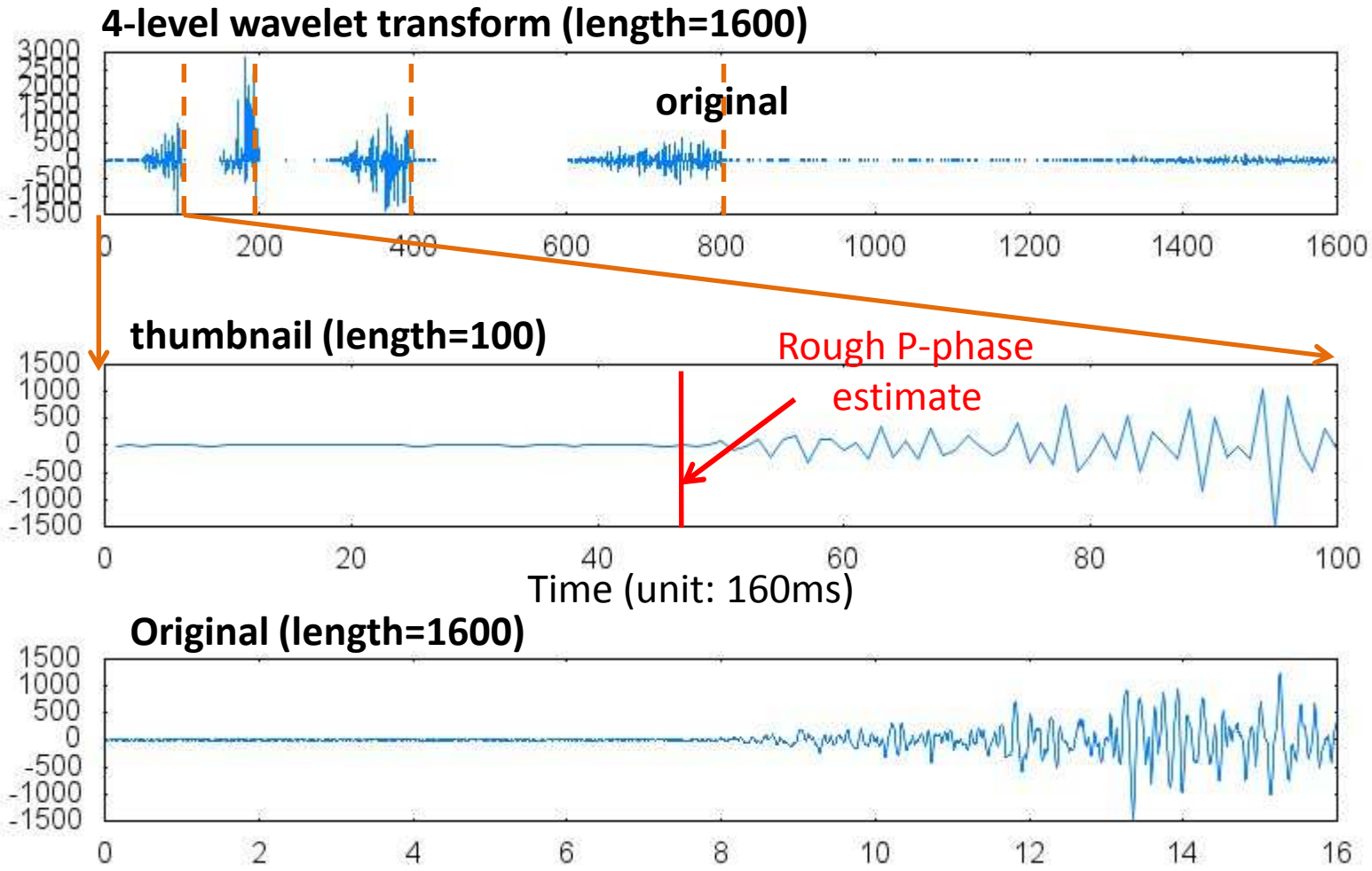

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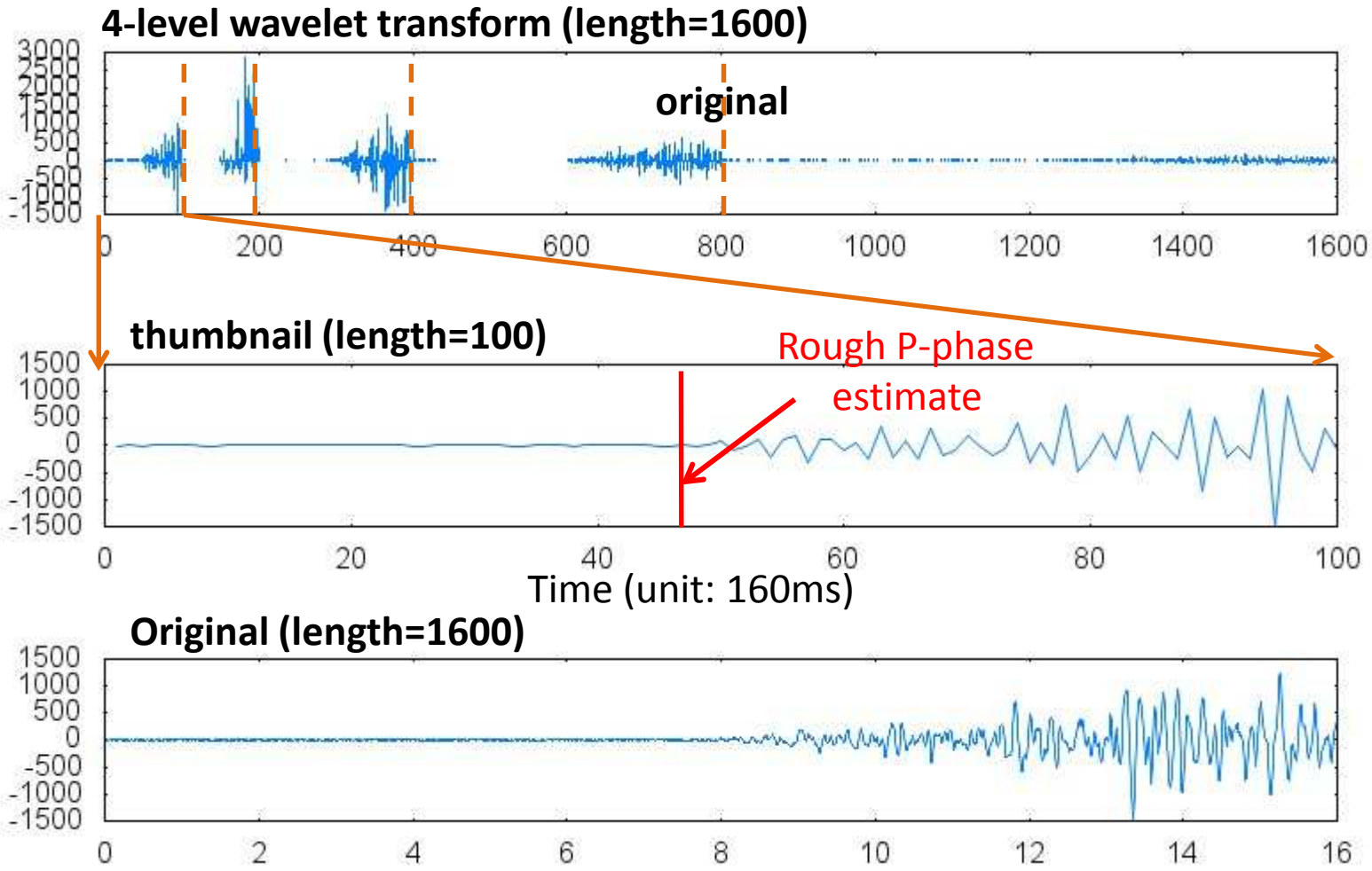
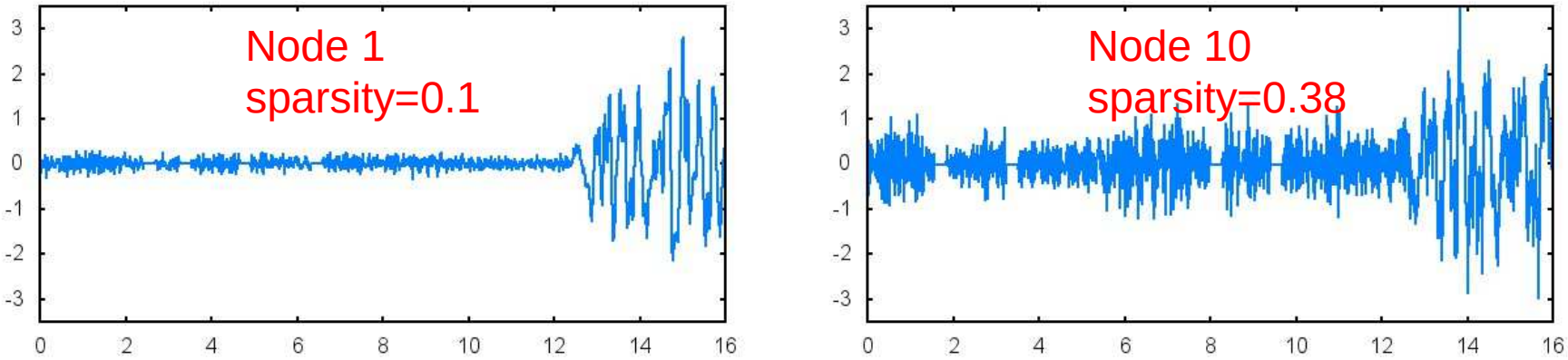


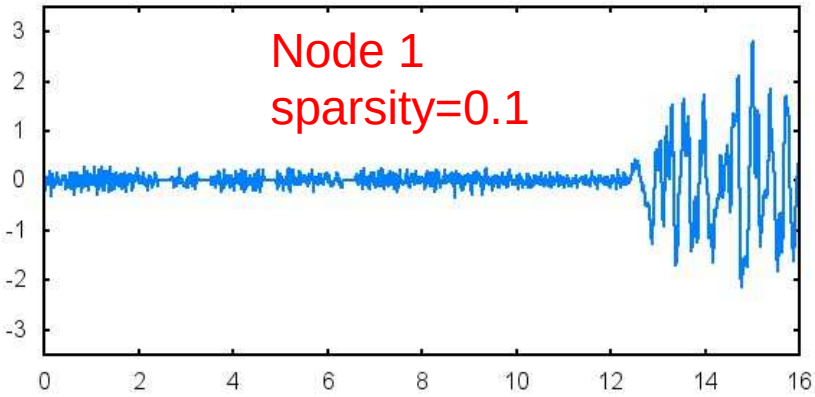

- **Observation 2: P-phase estimate from thumbnail**

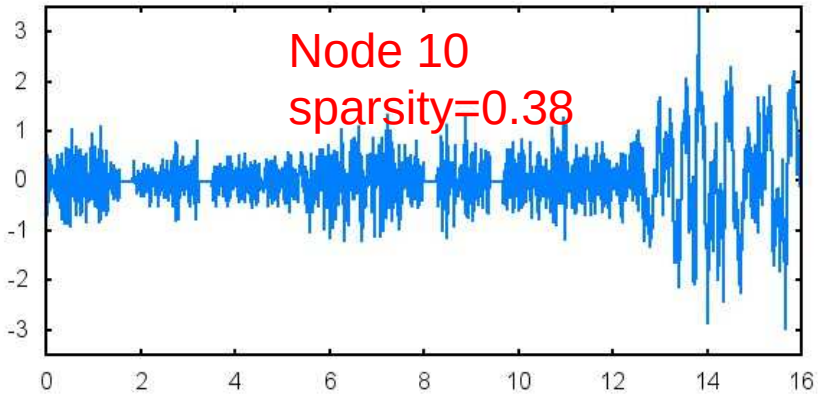
# Seismic Signal: Diversity




Earthquake 1

# Seismic Signal: Diversity

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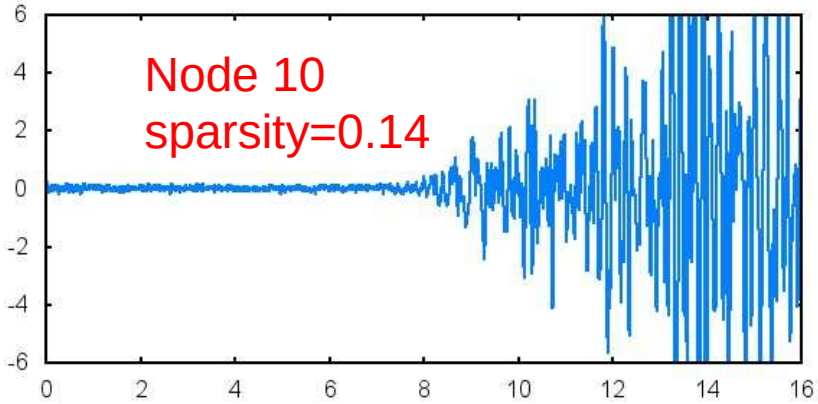
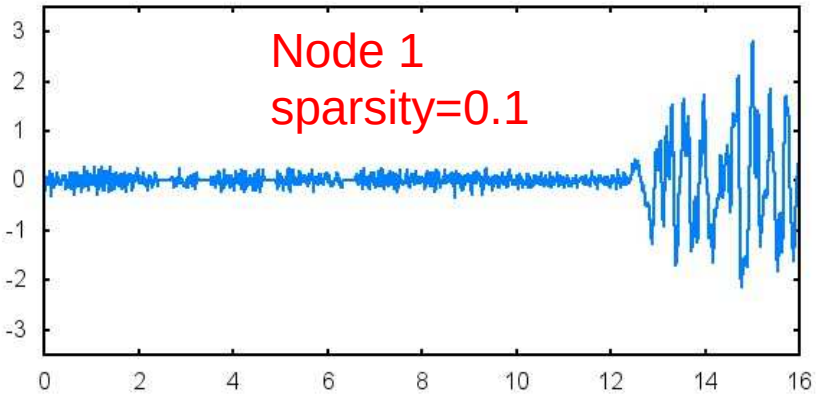
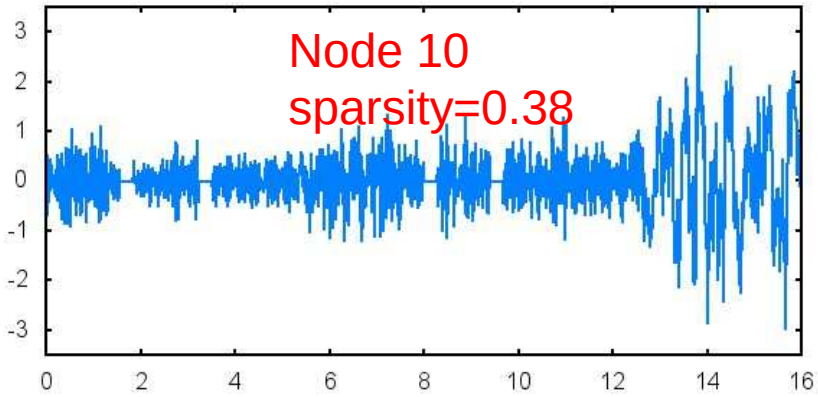



Earthquake 2

# Seismic Signal: Diversity

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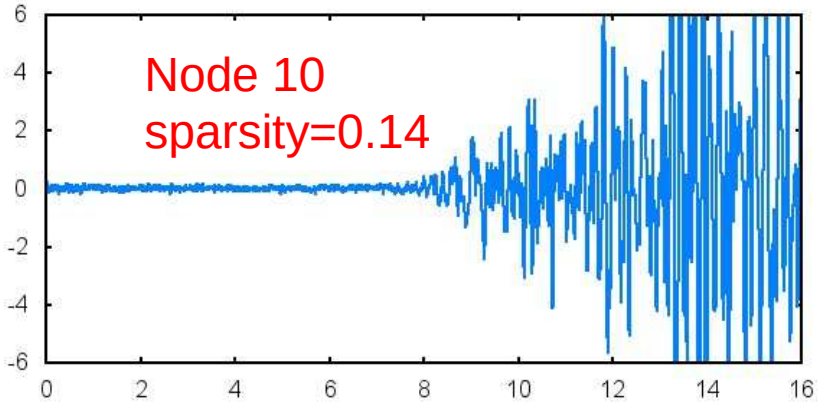


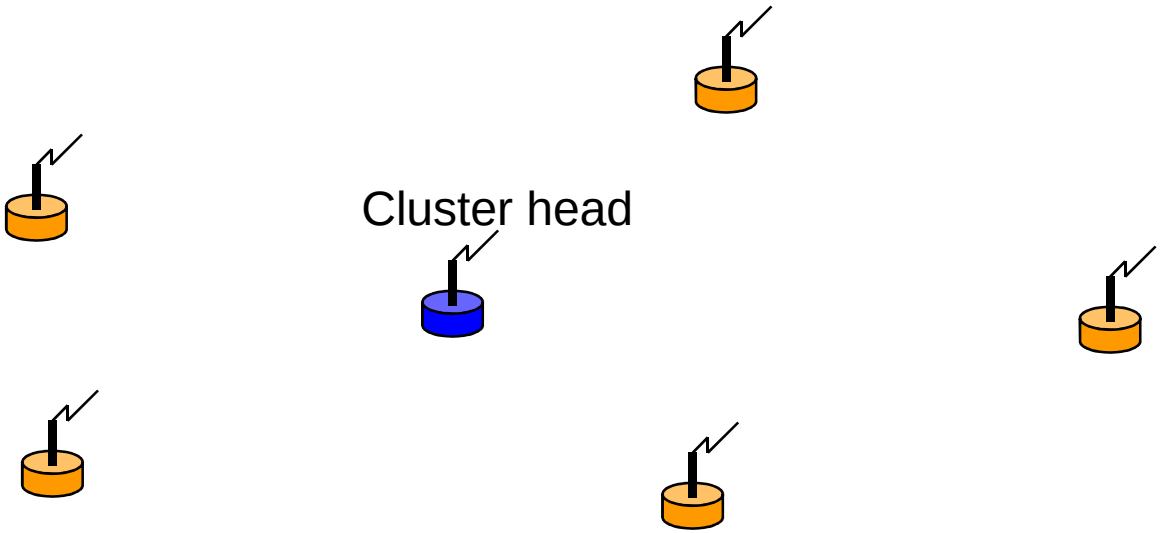

Earthquake 2

- **Observation 3: sensors have different sparsities**

# Outline

- Problem statement
- **Approach overview**
- Earthquake timing algorithms
- Performance evaluation
- Conclusion

# Approach Overview



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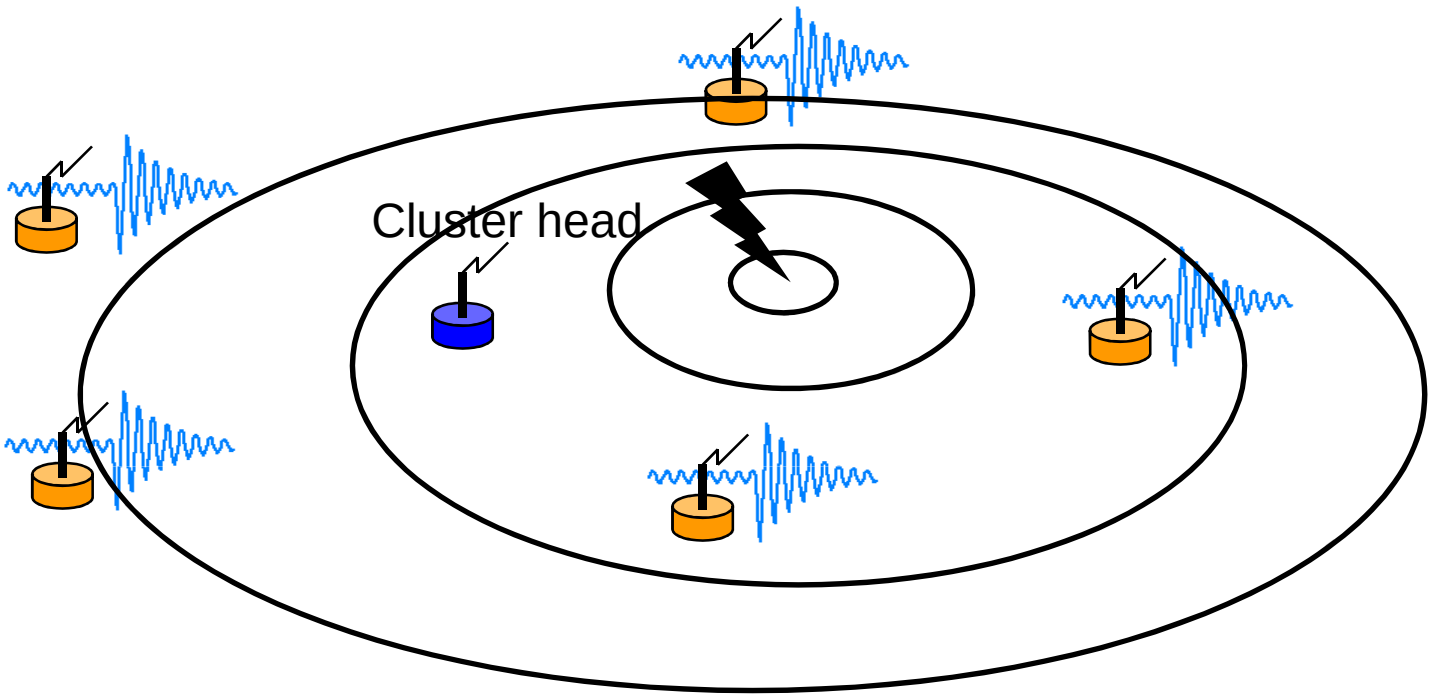

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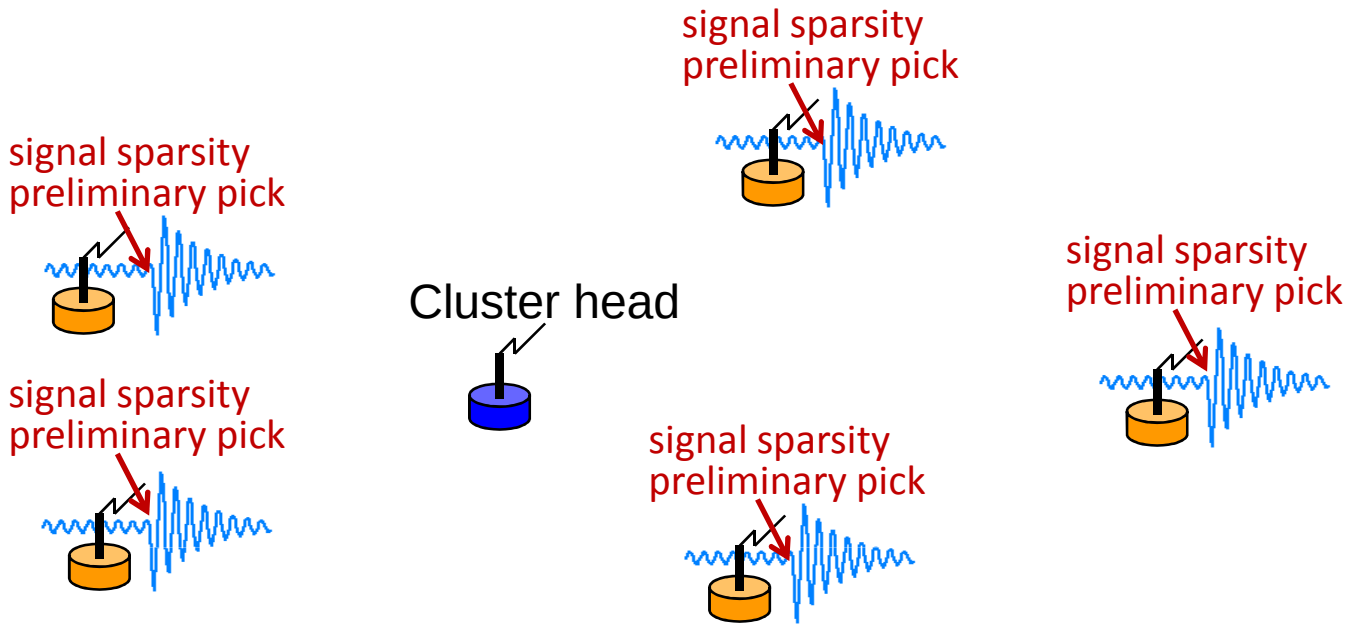


- Lightweight signal processing algorithms
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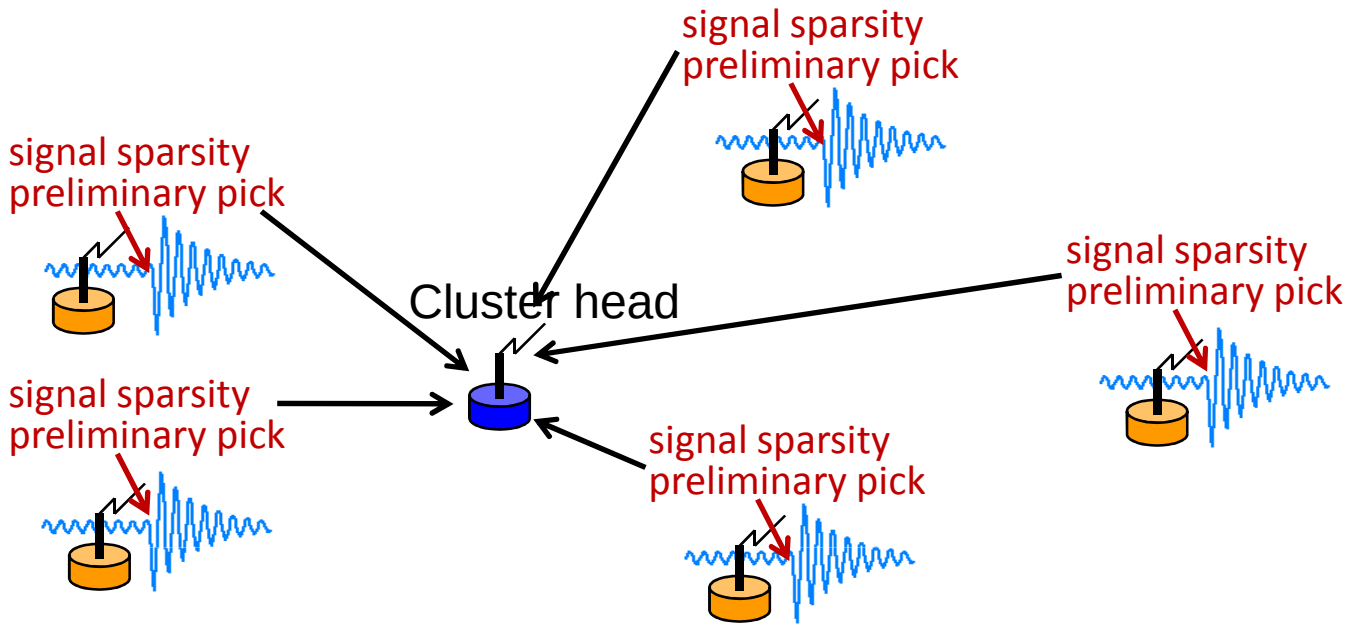


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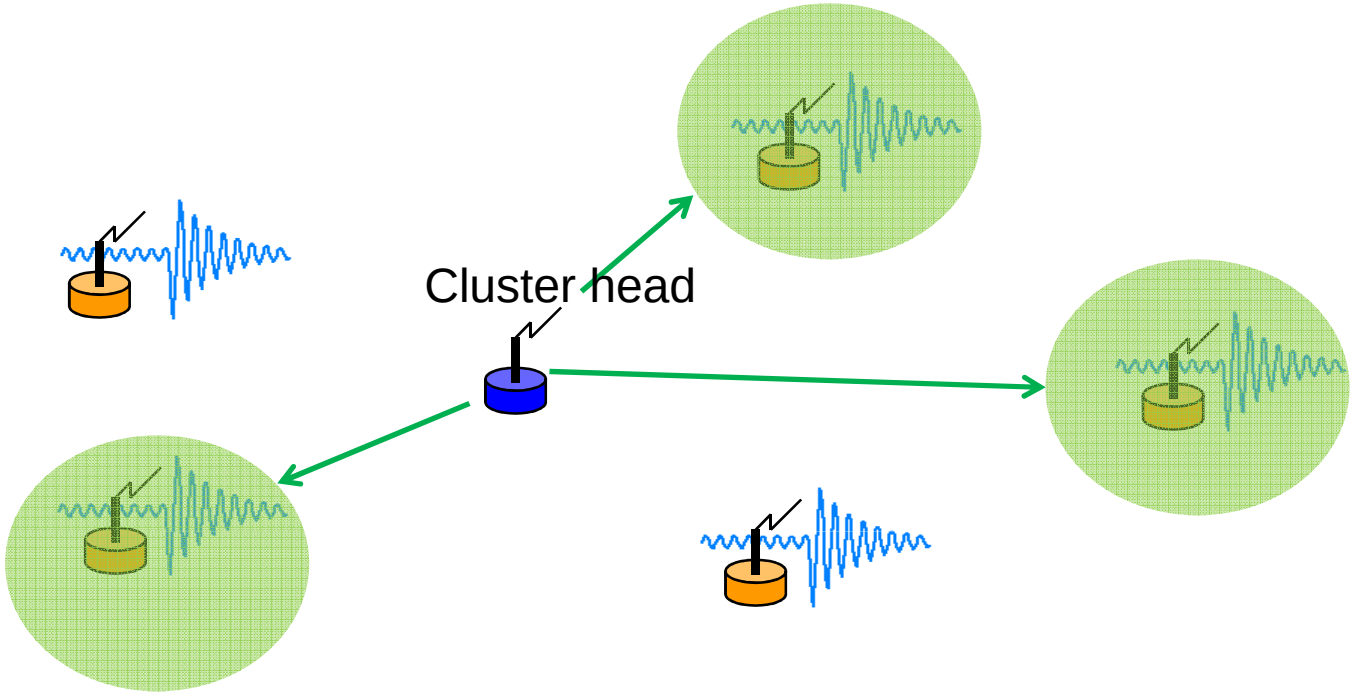


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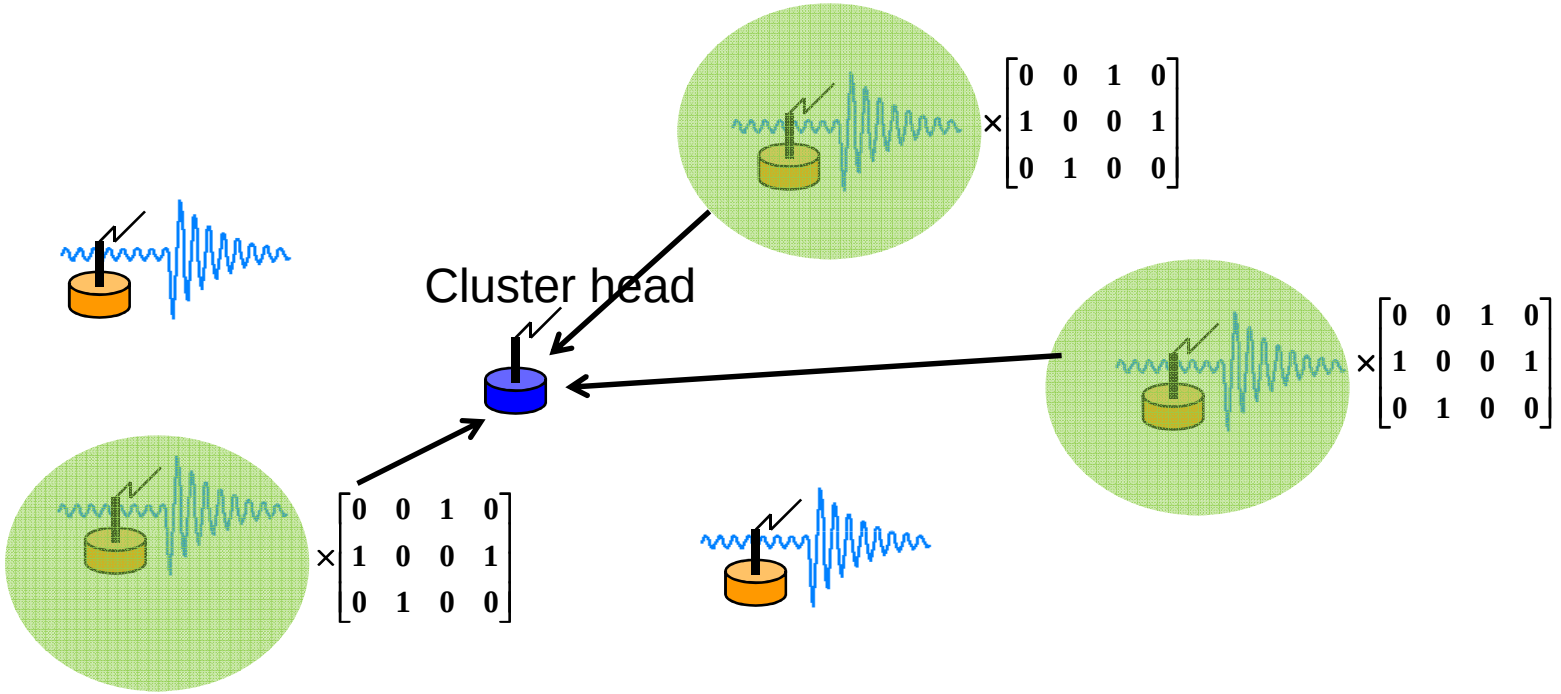


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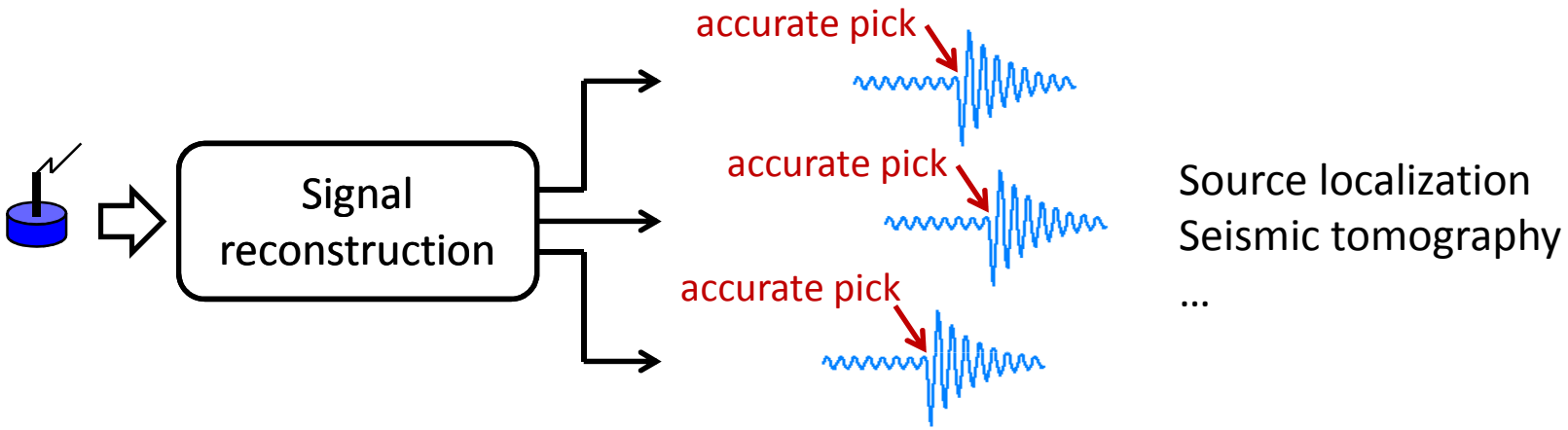


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  - **Pre-processing @ sensors**
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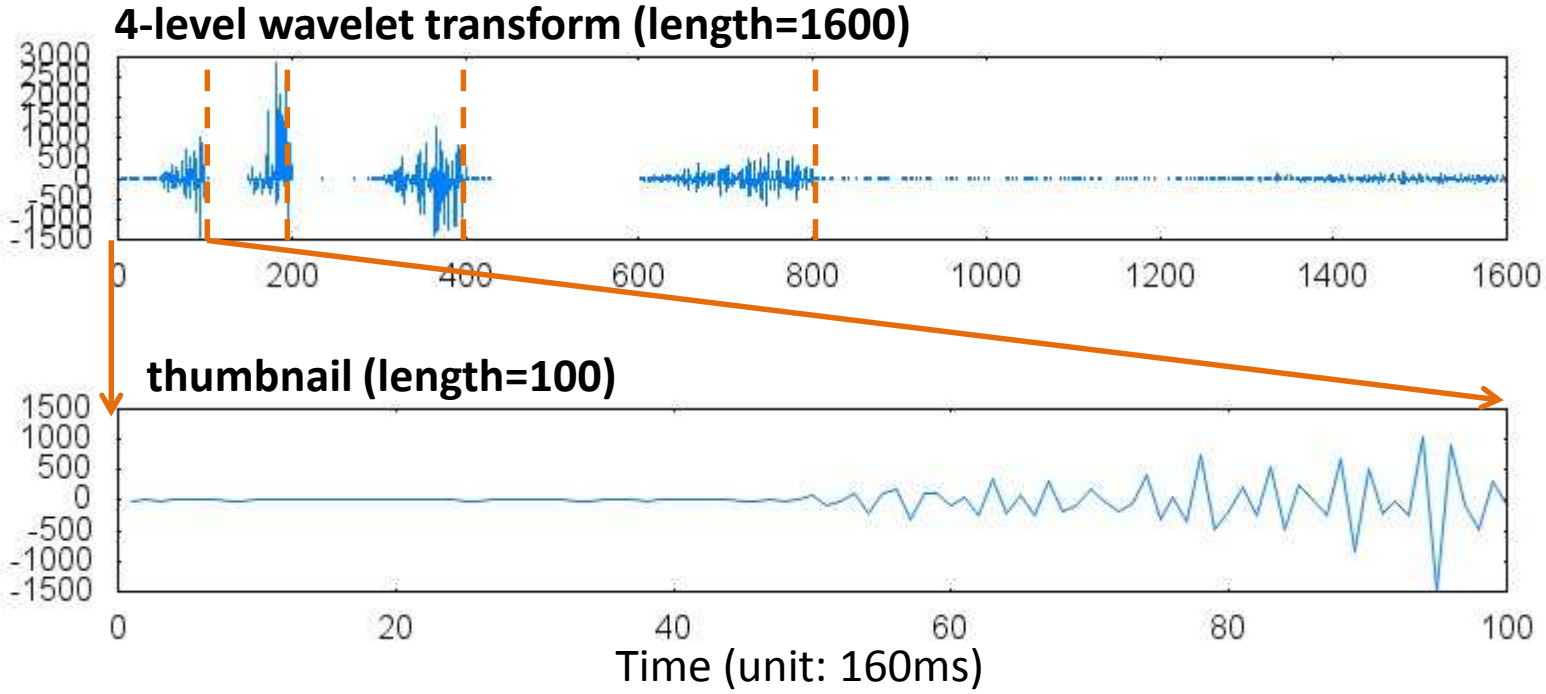
# Preliminary P-phase Pick



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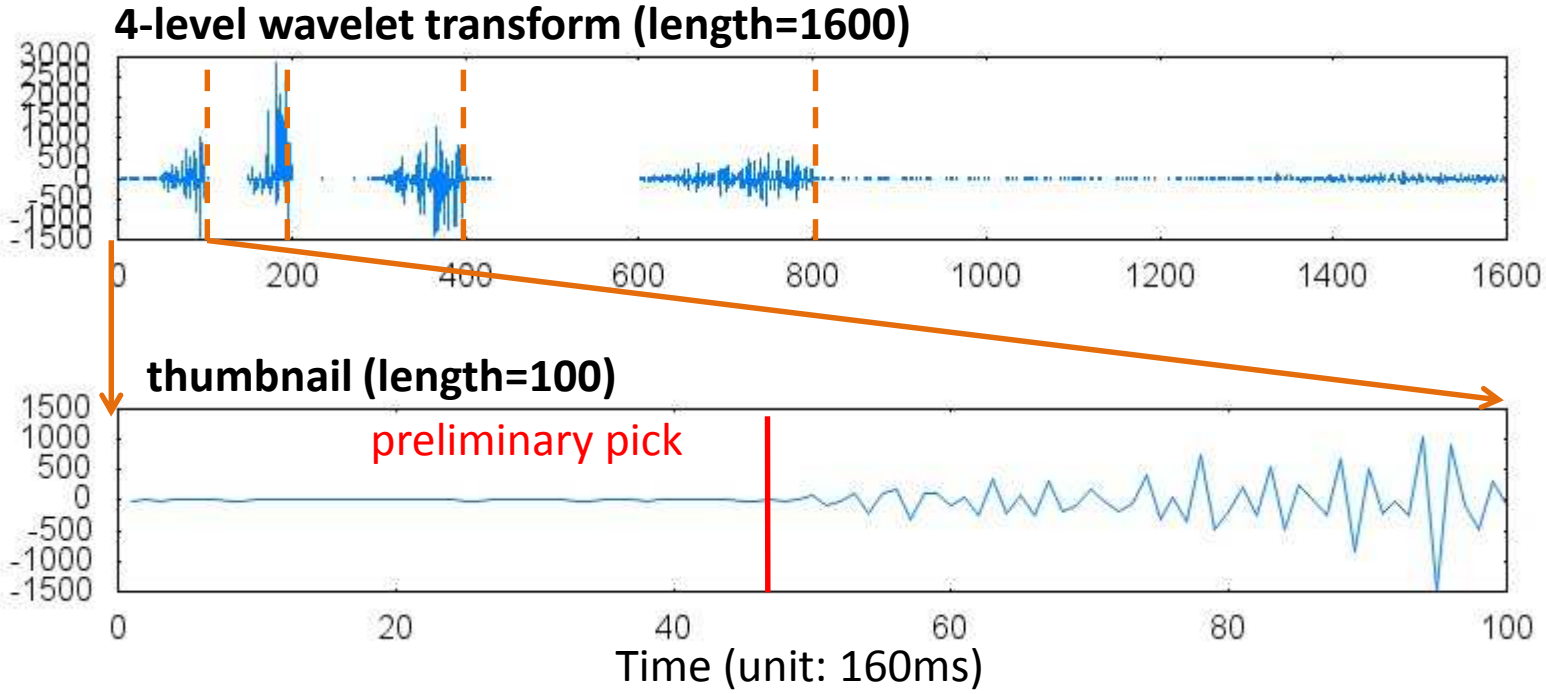


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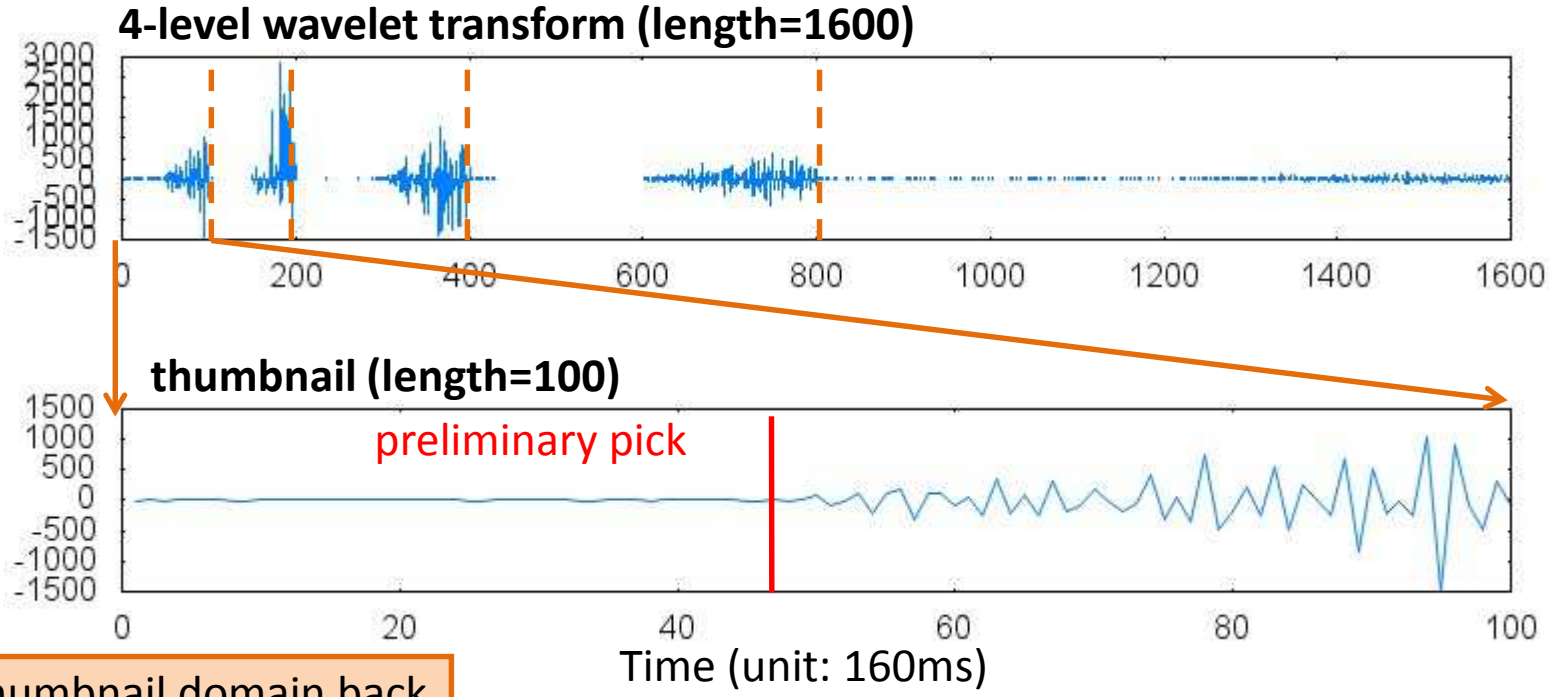


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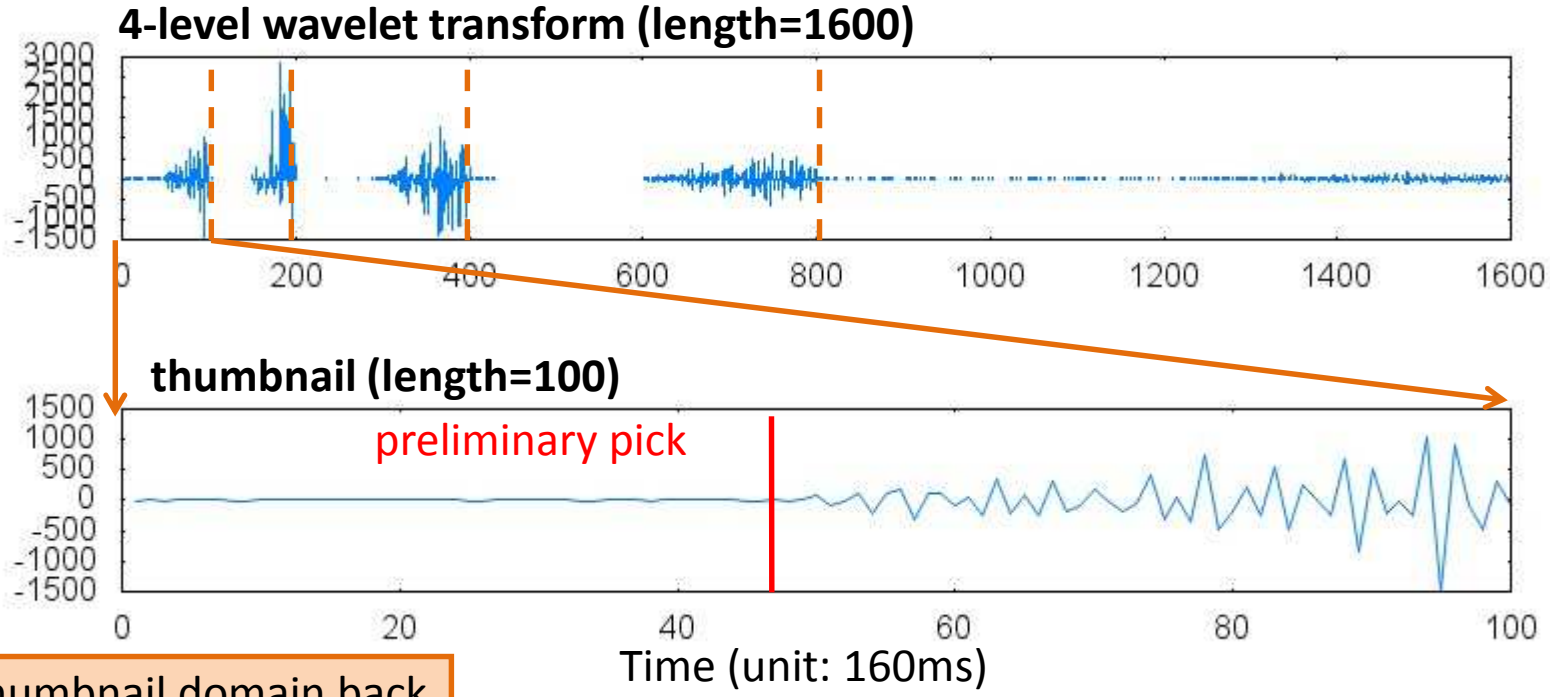


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$$\text{preliminary pick} = 2^4 \times \arg\max_{p \in \text{thumbnail}} \frac{\text{signal energy after } p}{\text{signal energy before } p}$$

- Lightweight: O(signal length)
  - Suitable for resource-constrained sensors

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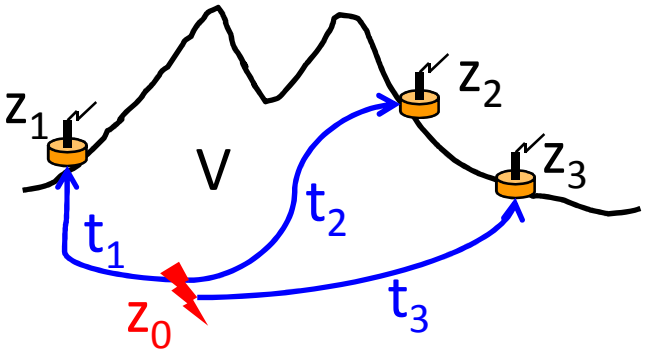
- Source localization
  - Basis for many volcano monitoring applications
  - Complex non-linear inverse problem




$$t_i = \text{ray tracing}(z_i, z_0, V)$$

- Information-theoretic error metric

$$E = \text{tr}\left(\left(\mathbf{G}\mathbf{G}^T\right)^{-1}\right)$$

**scaled Fisher matrix:** $z_i$, $z_0$

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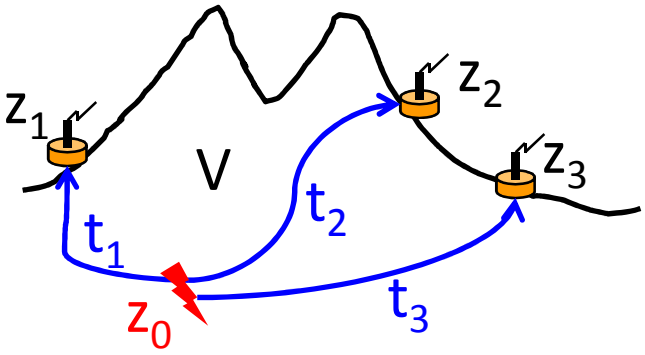


sensor position

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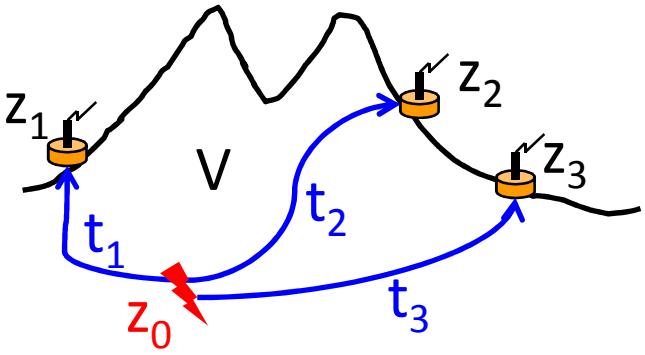


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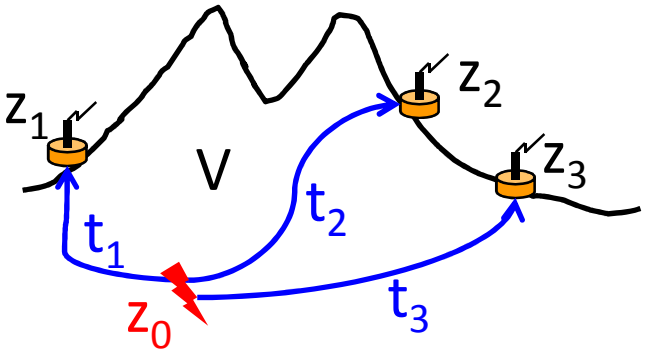


sensor position | source location | volcano model

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**scaled Fisher matrix:** $z_i$, $z_0$

# Dynamic Sensor Selection

- Find a subset of sensors $S$ to minimize $E$ s.t.

$$\sum_{i \in S} c_i \cdot m(\text{sparsity of sensor } i) \leq C$$

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unit TX cost

TX volume

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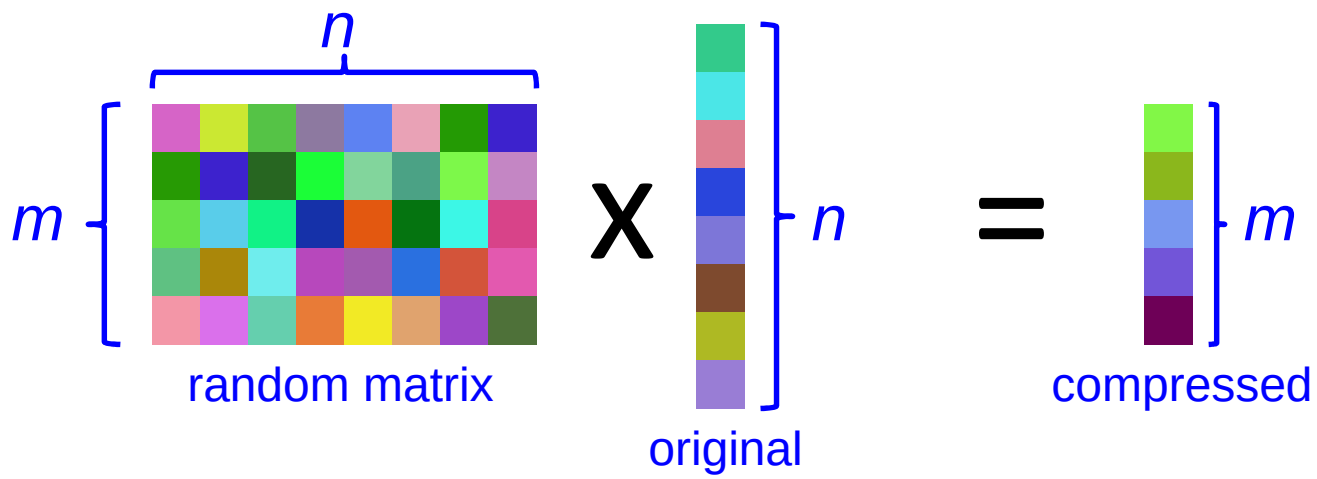
- Brutal-force search
  - 8 seconds on Imote2 for 16 sensors
  - Information gain diminishes for larger clusters

# Compressive Sampling (CS)




- Apply CS to **wavelet coefficients**
  - Known TX volume before compression

$$m = 1.5 \times \text{sparsity} \times n$$

  - Unselected sensors avoid compression overhead

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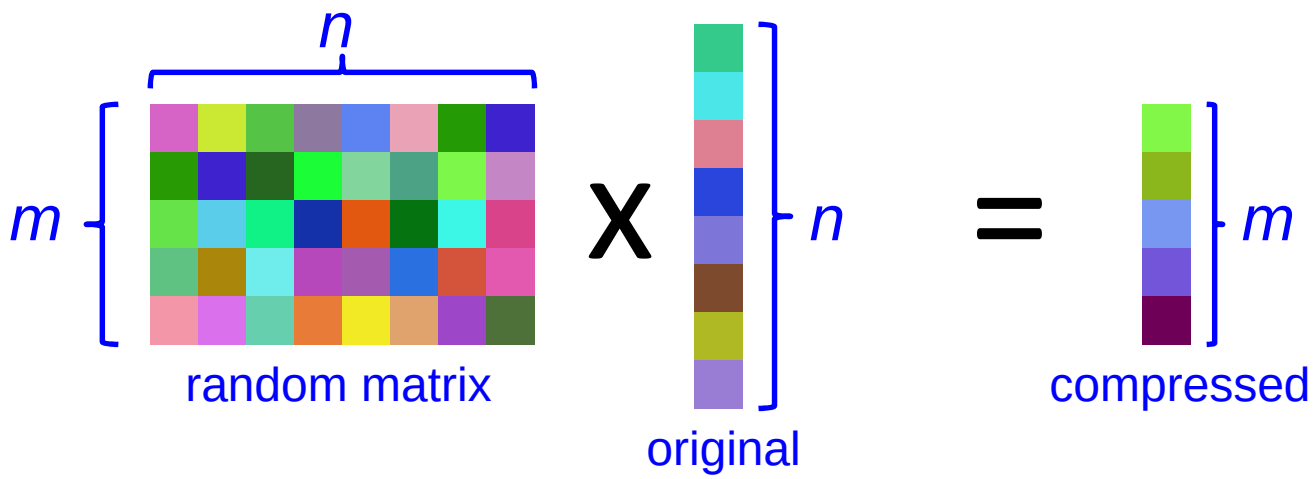


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best trade-off b/w TX volume and signal reconstruction error

  - Unselected sensors avoid compression overhead

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- Problem statement
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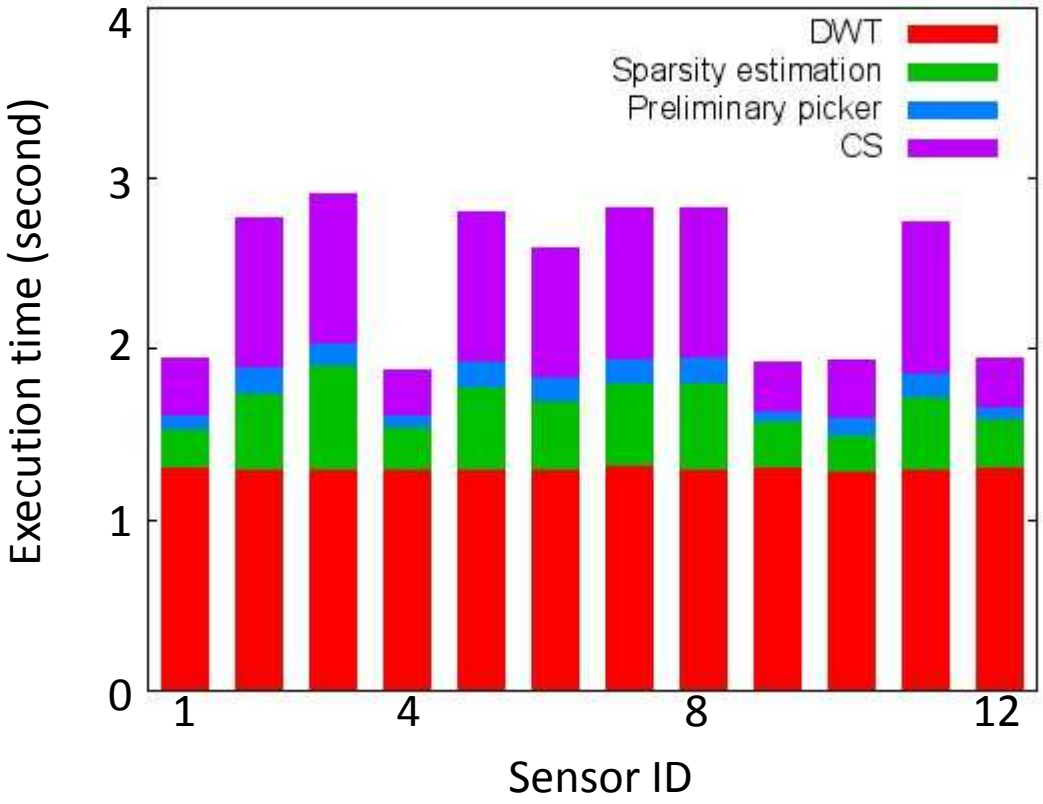
- **Performance evaluation**
  - **Testbed experiments**
  - **Extensive trace-driven simulations**
- Conclusion

# Testbed Experiments

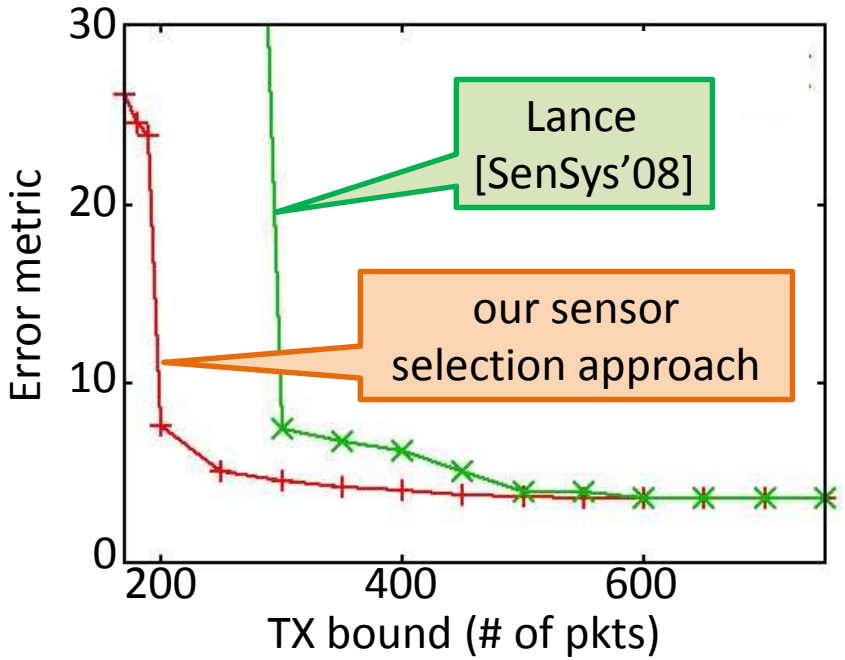
- Implementation on 12 TelosB
  - Seismic data from Mt St Helens -> mote flash
  - Real-time data acquisition @ 100 Hz

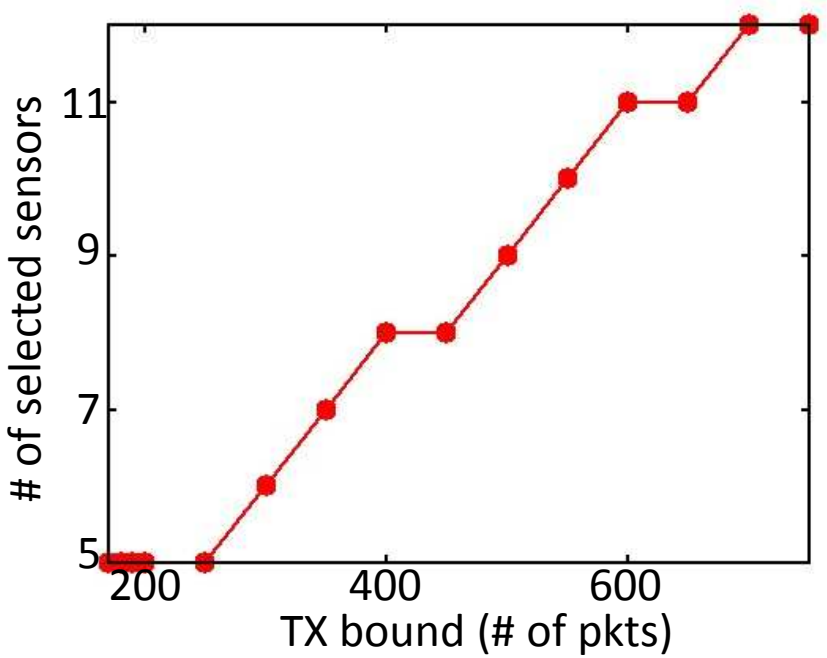



**End-to-end delay**
**< 3 seconds**

# Trace-driven Simulation

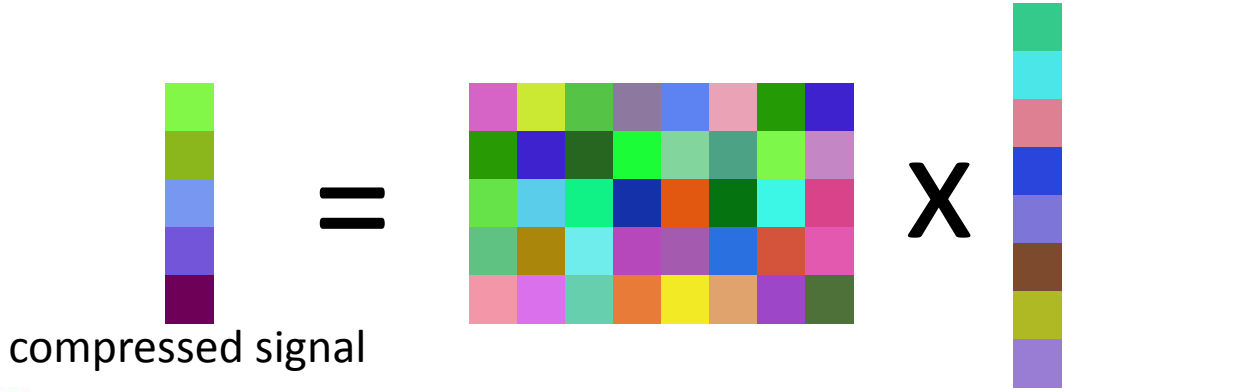
- Data traces from 12 sensors on Mt St Helens
- 30 significant earthquakes in 5.5 months

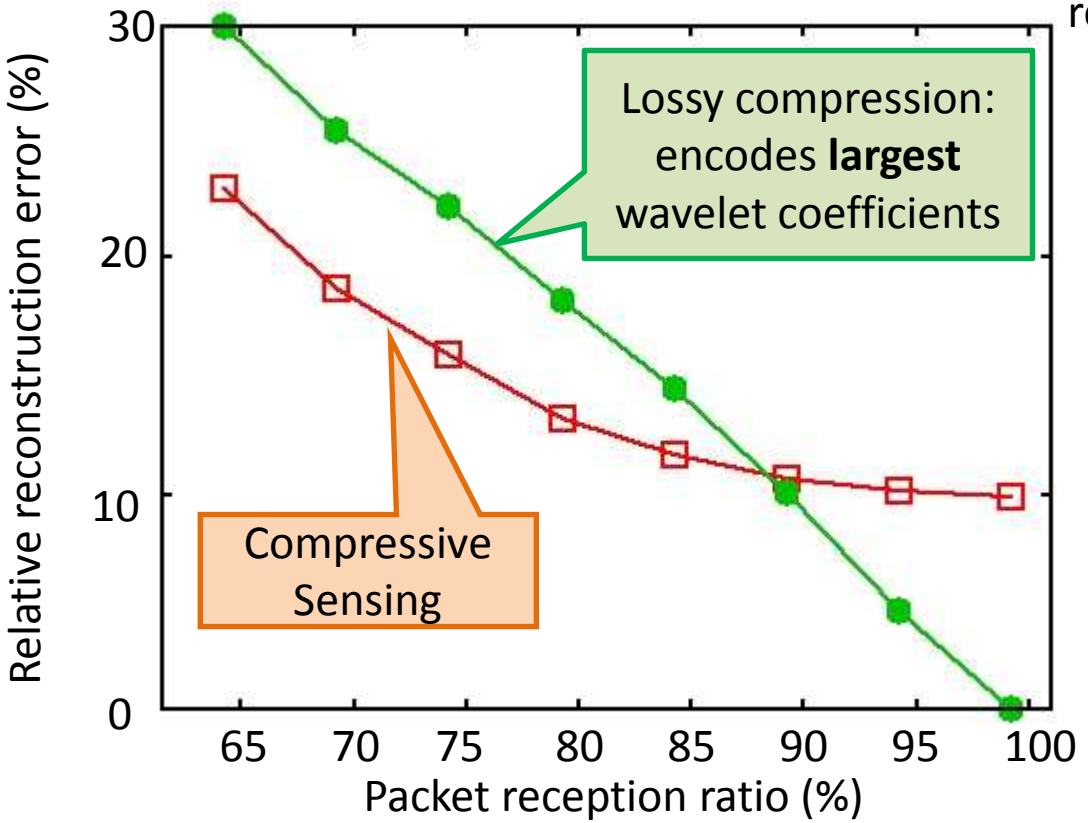



**Configurable trade-off between system performance and energy consumption**

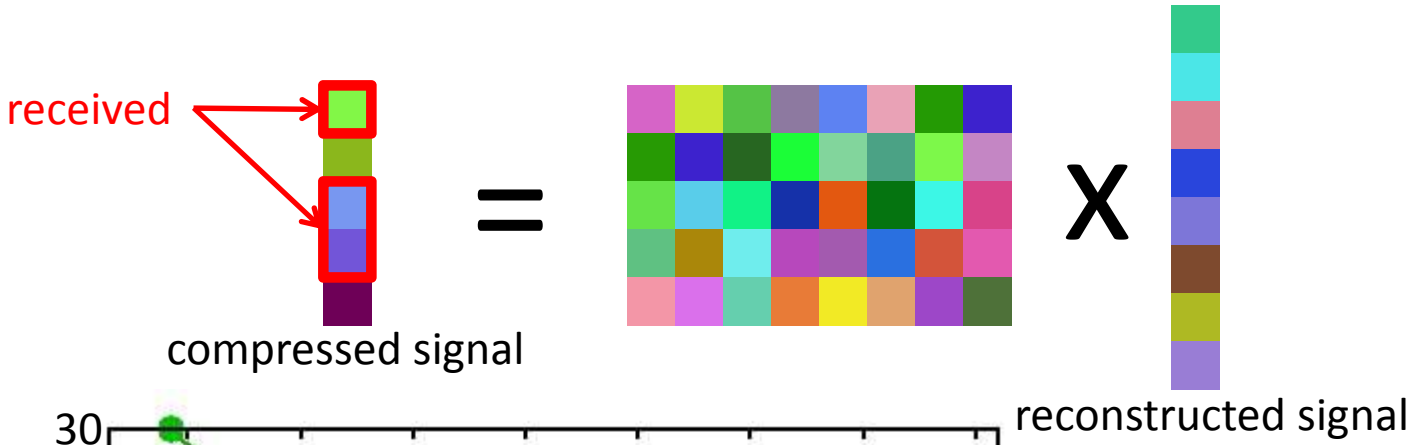
# Impact of Packet Loss

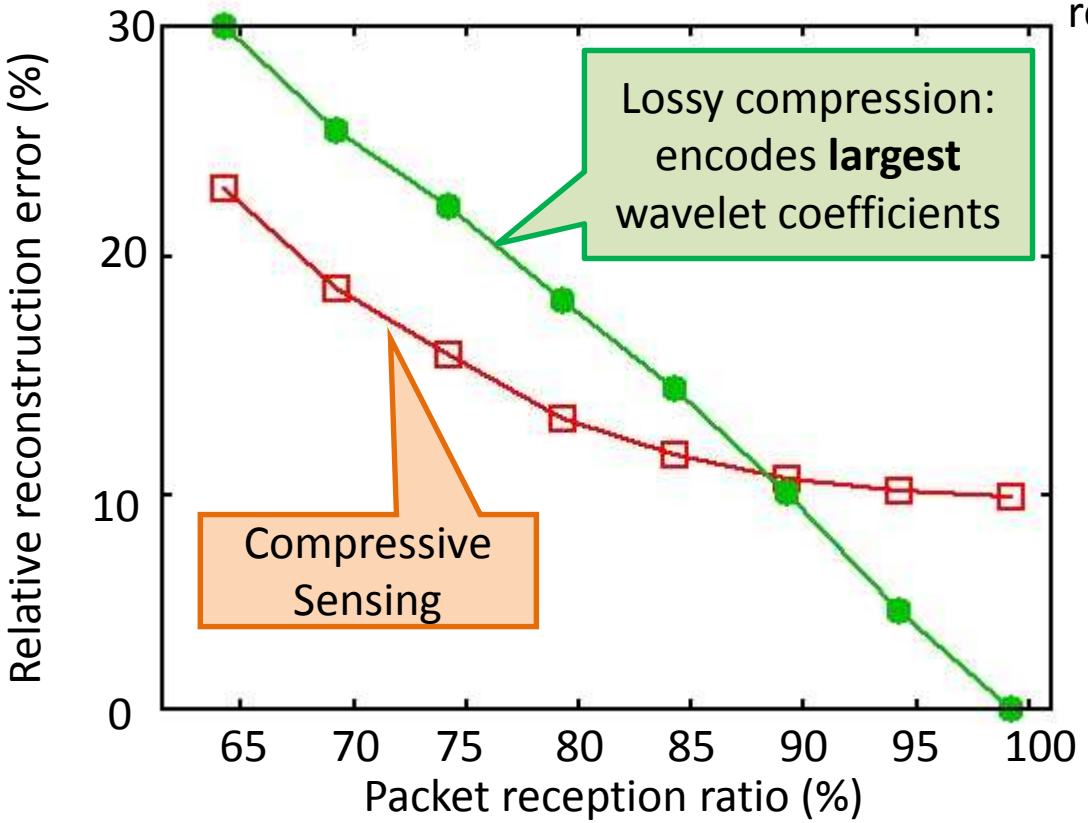



**CS is resilient to packet loss!**

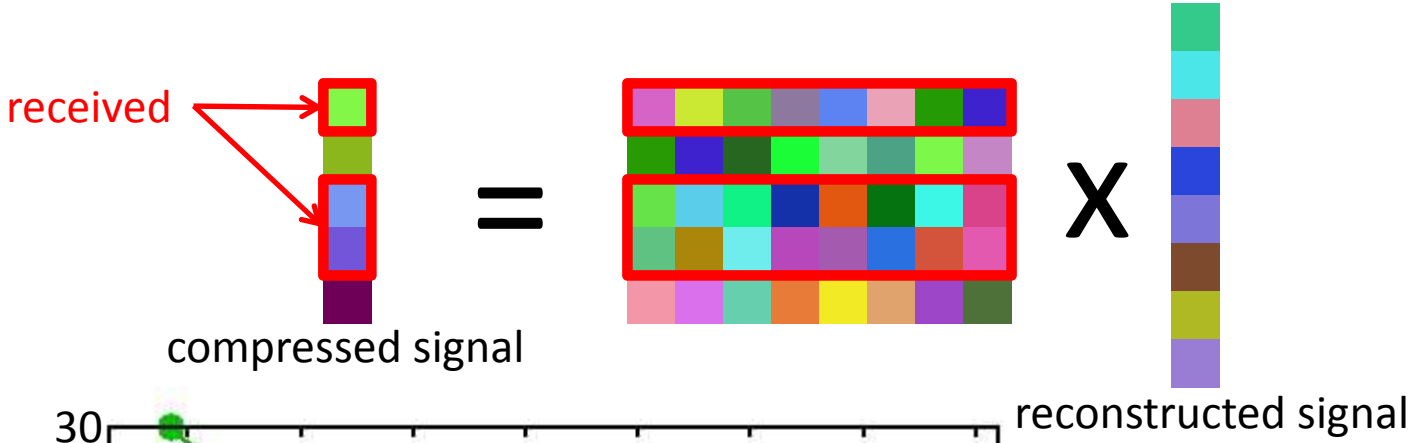
# Impact of Packet Loss

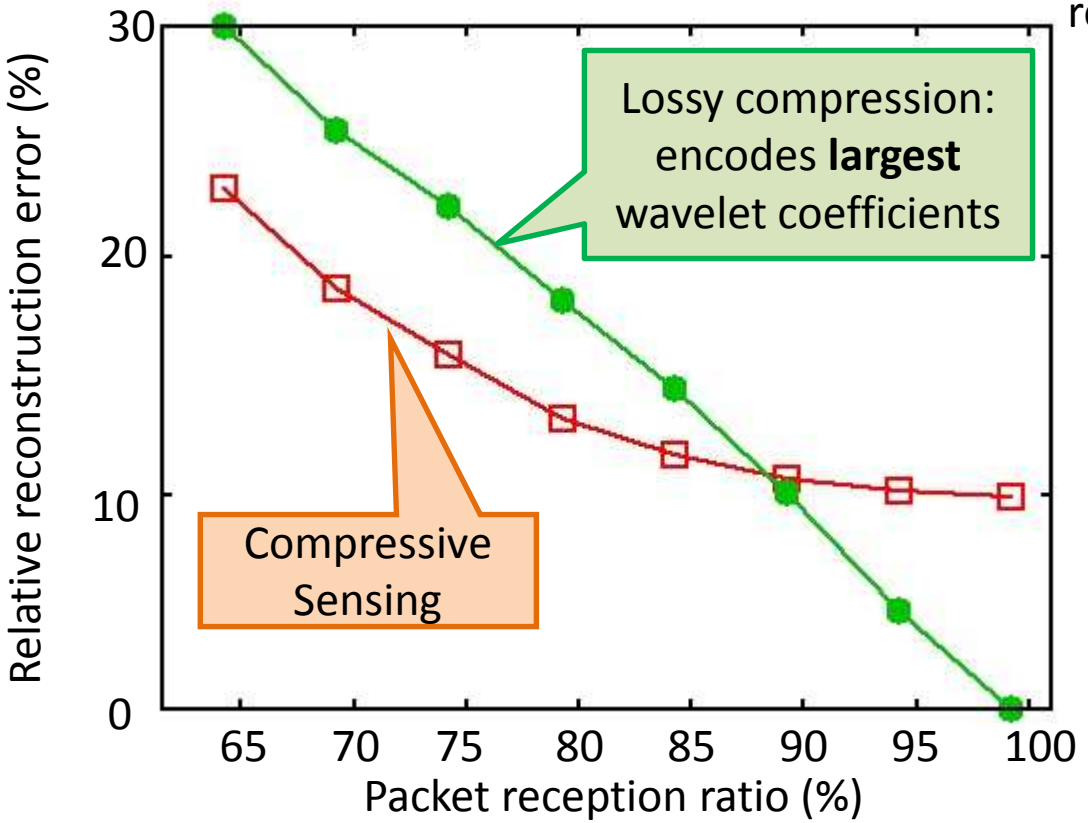



**CS is resilient to packet loss!**

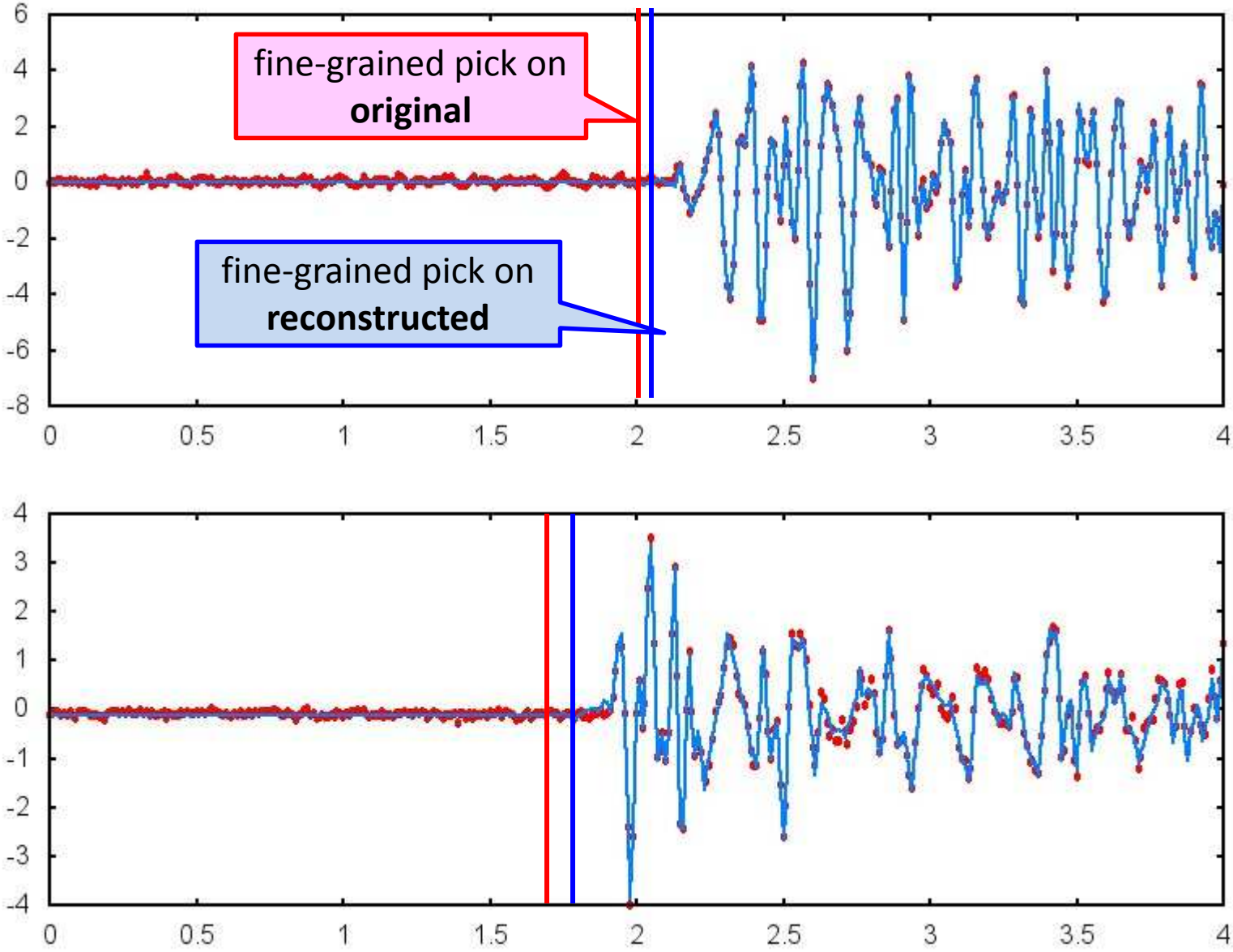
# Impact of Packet Loss



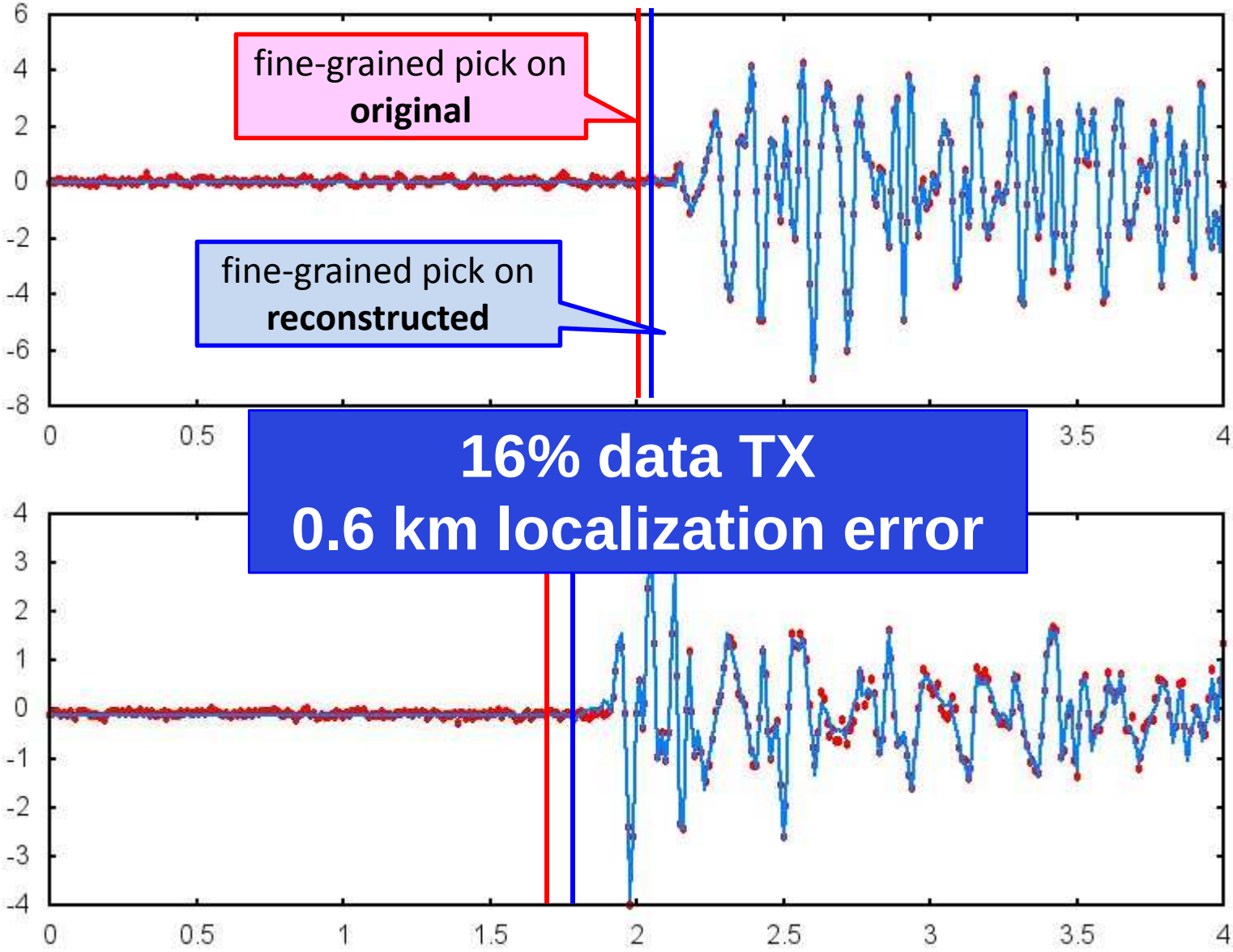




**CS is resilient to packet loss!**

# Accuracy of Timing



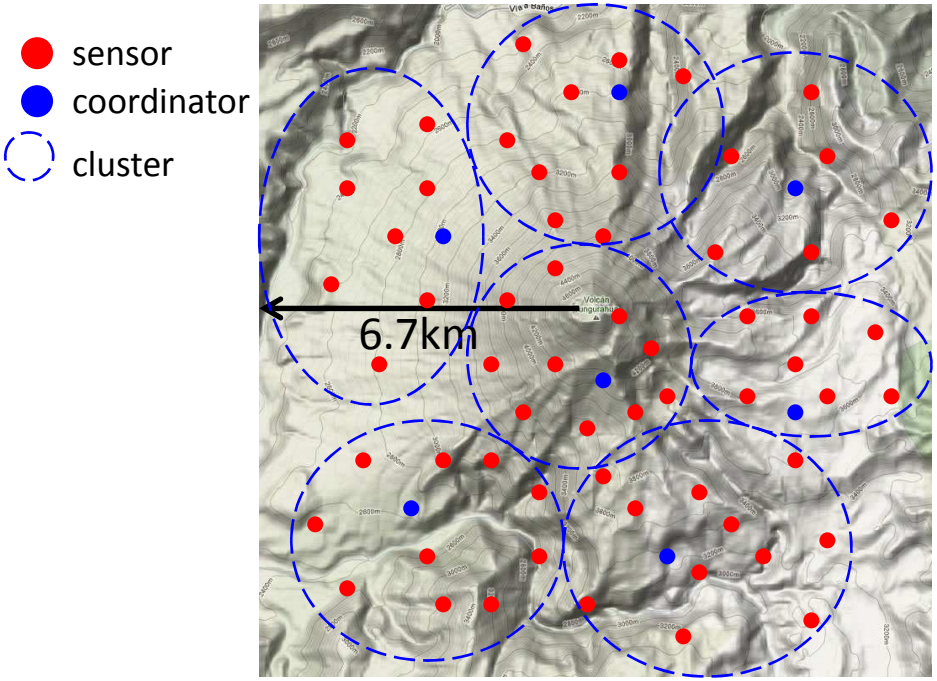
# Accuracy of Timing



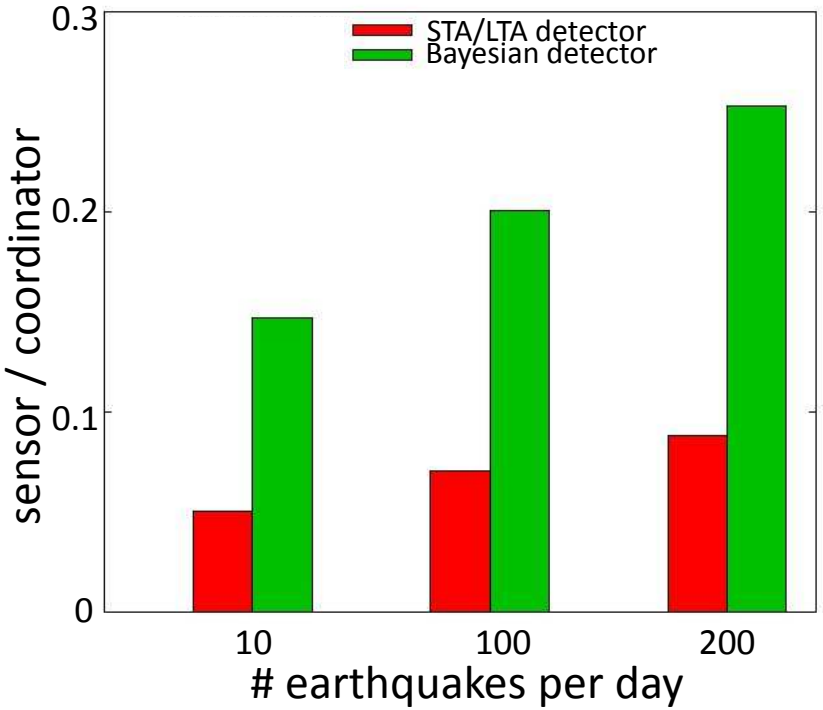
# Conclusions

- Energy-efficient earthquake timing
  - Lightweight algorithms for sensors
  - Dynamic sensor selection
  - Compressive sampling
- Testbed experiments
  - Feasibility of our approach on motes
- Trace-driven simulations
  - Accurate timing with 16% data transmitted

# Hierarchical Network Architecture



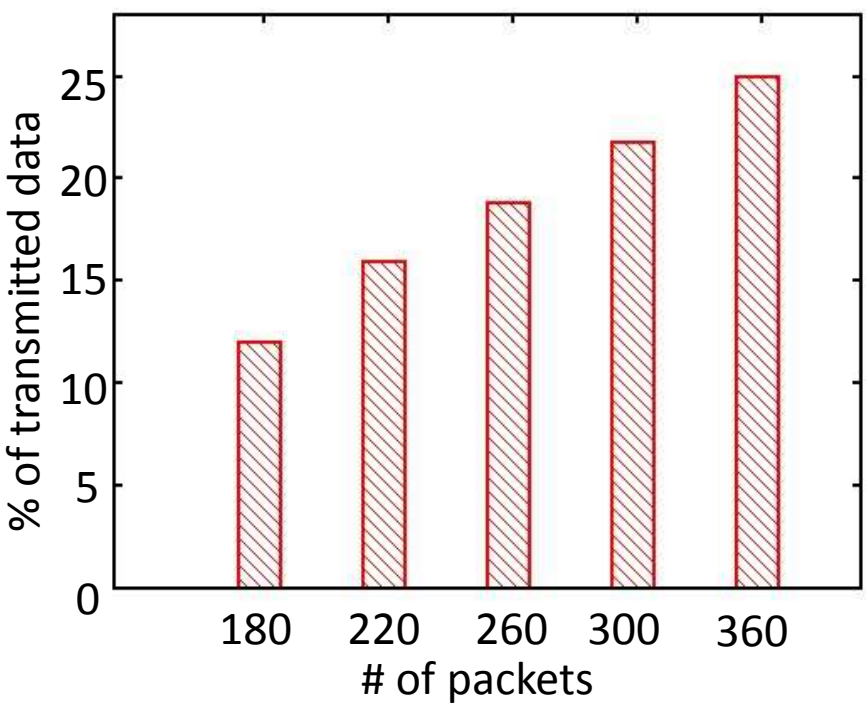

**500 nodes on Tungurahua, Ecuador, 2015**
**[VolcanoSRI project]**

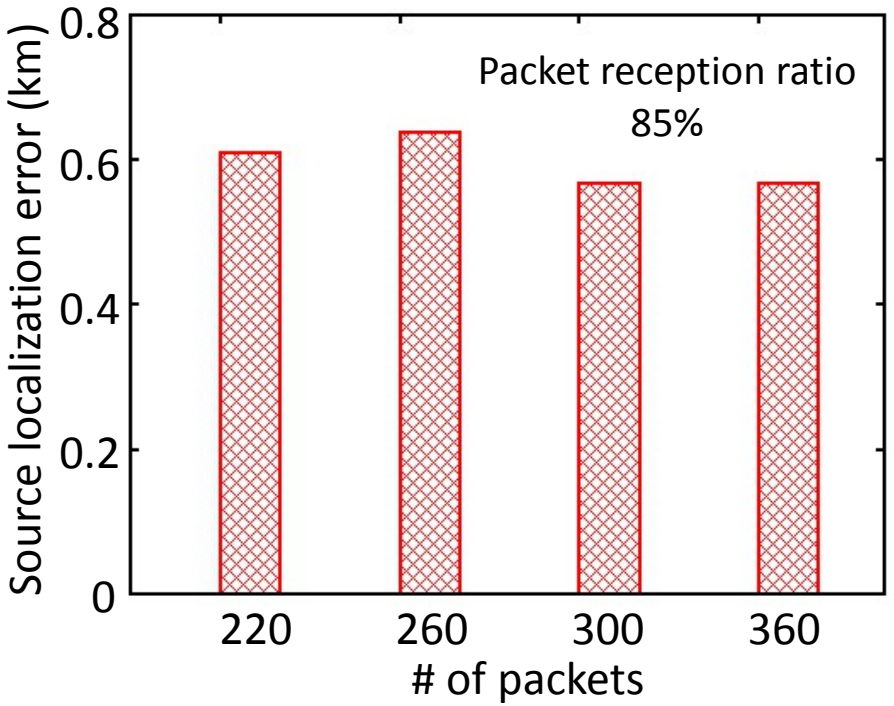



**MCU & radio energy ratio**
**TelosB vs. Imote2**

- Sensors
  - Limited capability, large spatial coverage
- Coordinators
  - Powerful, limited number

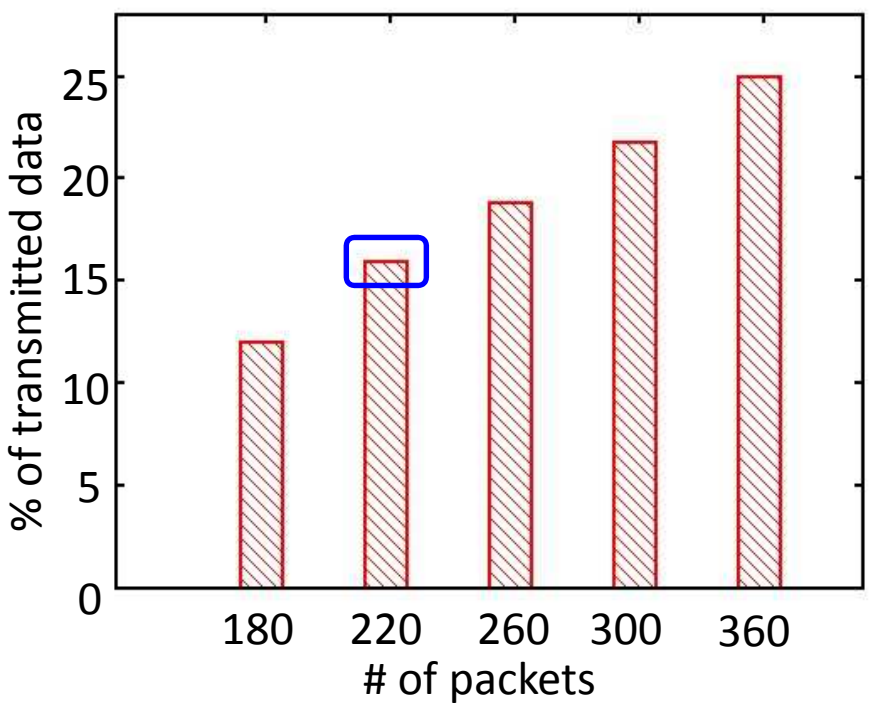
# Earthquake Source Localization

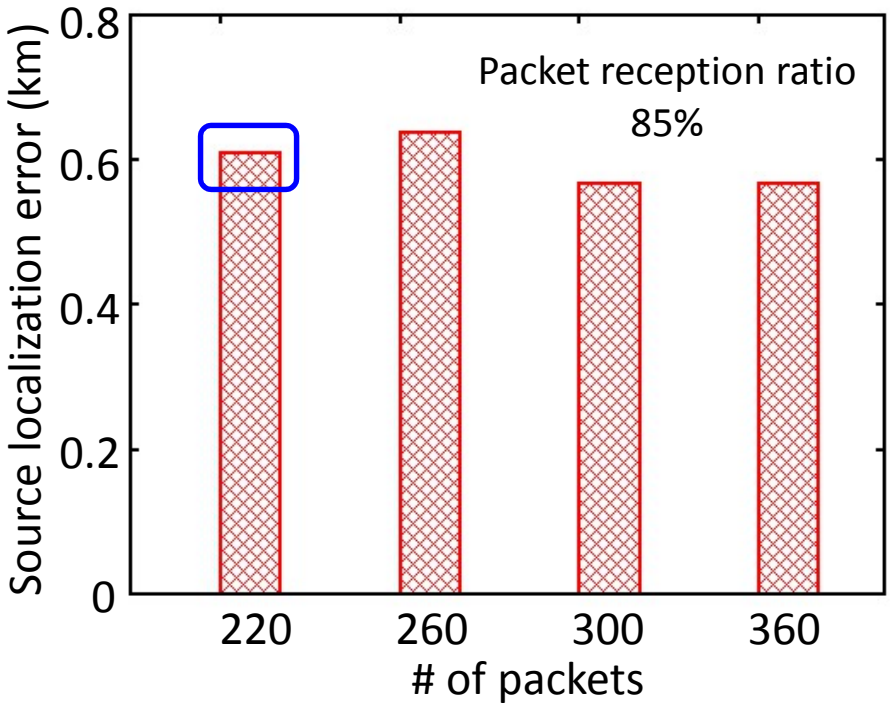



Source localization result for an earthquake
16:56:47 Nov 03 2009 @ Mt St Helens

# Earthquake Source Localization




Source localization result for an earthquake
16:56:47 Nov 03 2009 @ Mt St Helens

**Localization error below 1km, common in volcano seismology**
**Only 16% data transmission**