Quality-driven Volcanic Earthquake Detection using Wireless Sensor Networks

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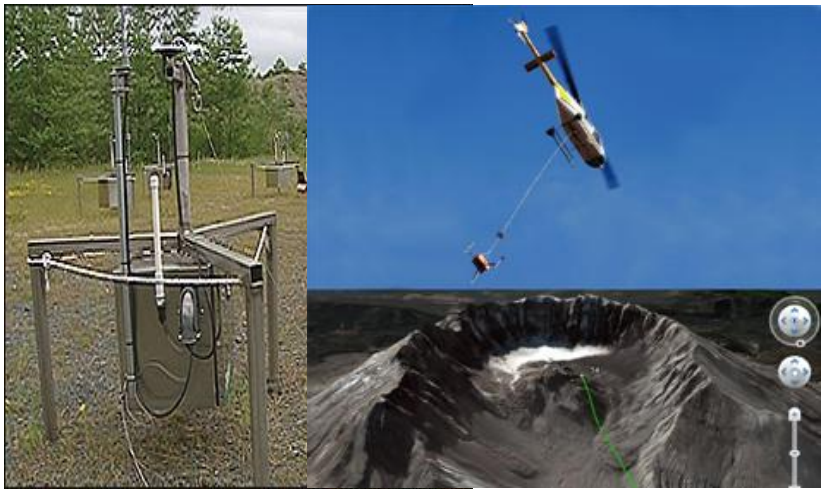
Active Volcano Monitoring

Eruptions in Iceland, 2010 [Wikipedia]



OASIS system on Mt St Helens [Song 2009]

- Traditional broadband seismometers
  - Expensive (~ $10K), difficult to install, small-scale
- Wireless sensor networks on volcanoes
  - Low cost (< $200), easy deployment, large-scale

State-of-the-Art WSN Solutions

- Centralized earthquake detection
  - Energy-consuming data collection
  - Long latency

    6 mins to transmit 1 min seismic data

    [Werner-Allen 2006]

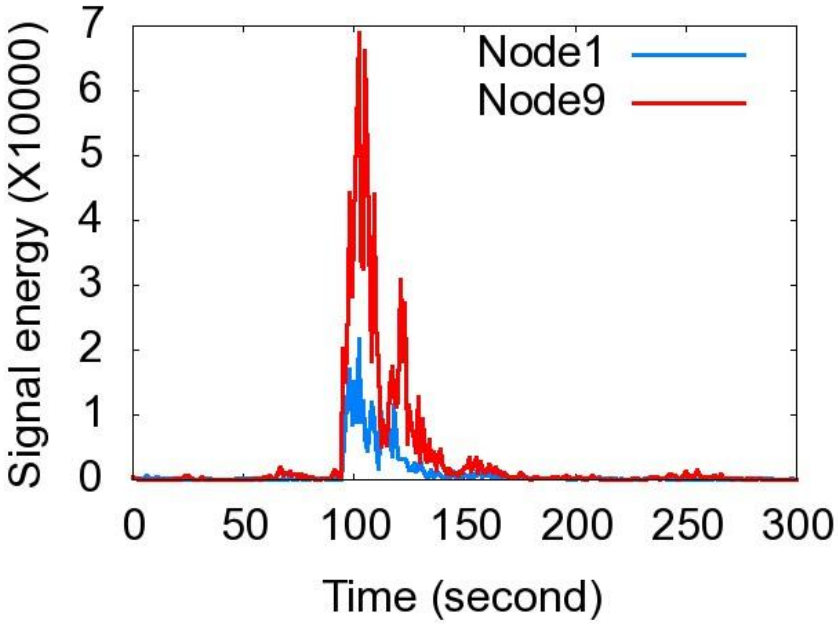
- Heuristic event-triggered data collection
  - Low detection probability

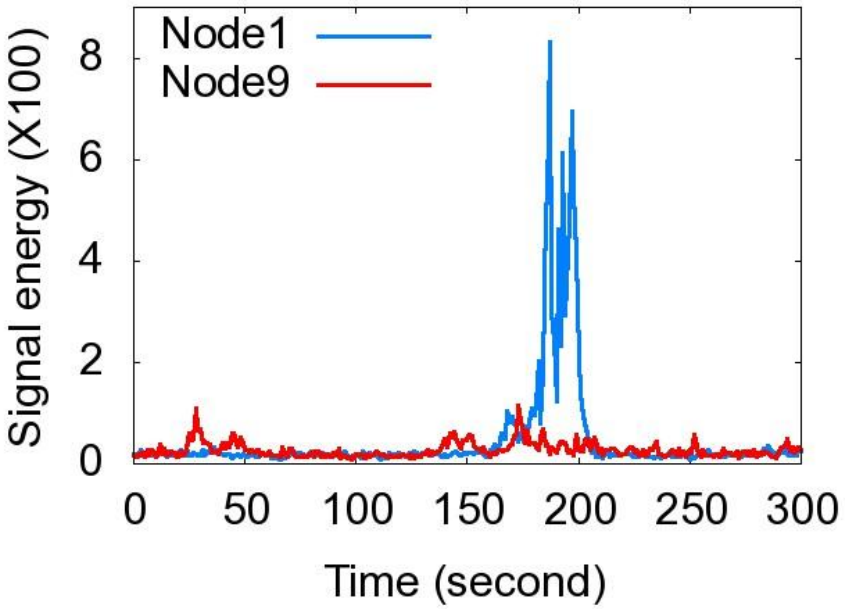
    Only 5% [Werner-Allen 2006]

Goals

- Quality-driven earthquake monitoring
  - Assured false alarm rate & detection prob.
- Real-time detection
  - Temporal resolution: 1s
- Long network lifetime
  - Avoid raw data transmission

Challenge 1: Spatial Diversity





Two earthquakes on Mt St Helens

- Complicated physical process

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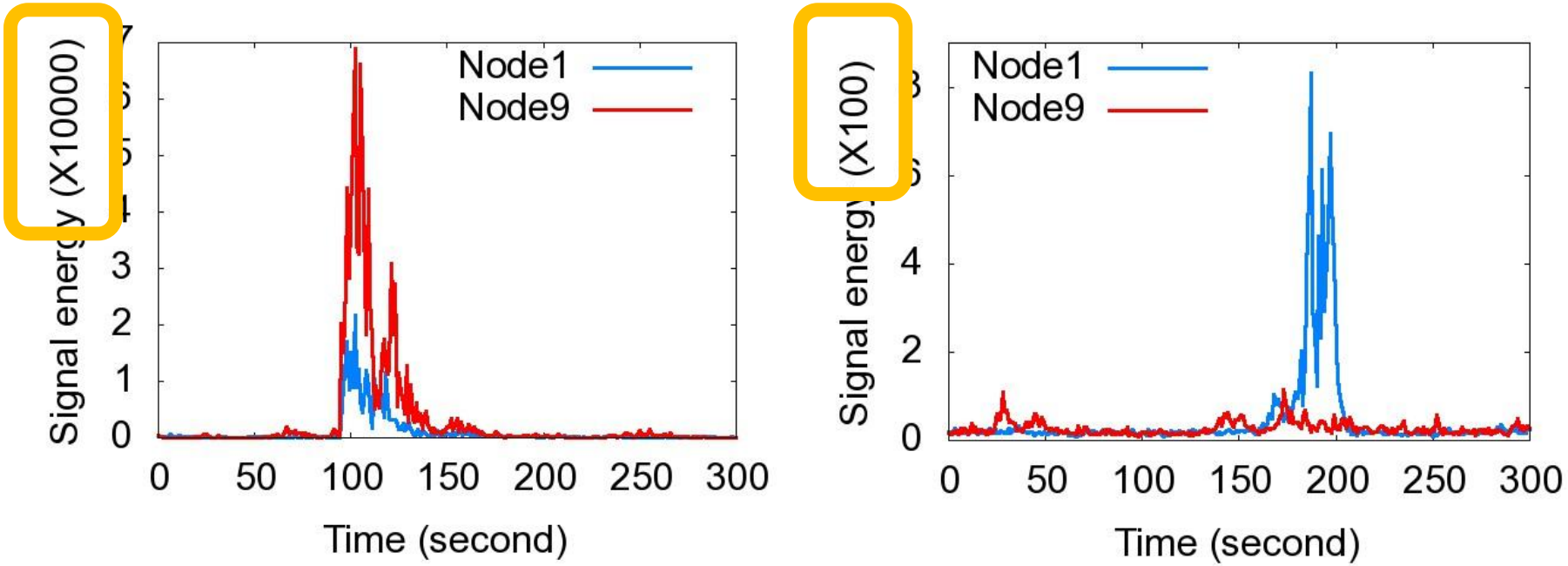

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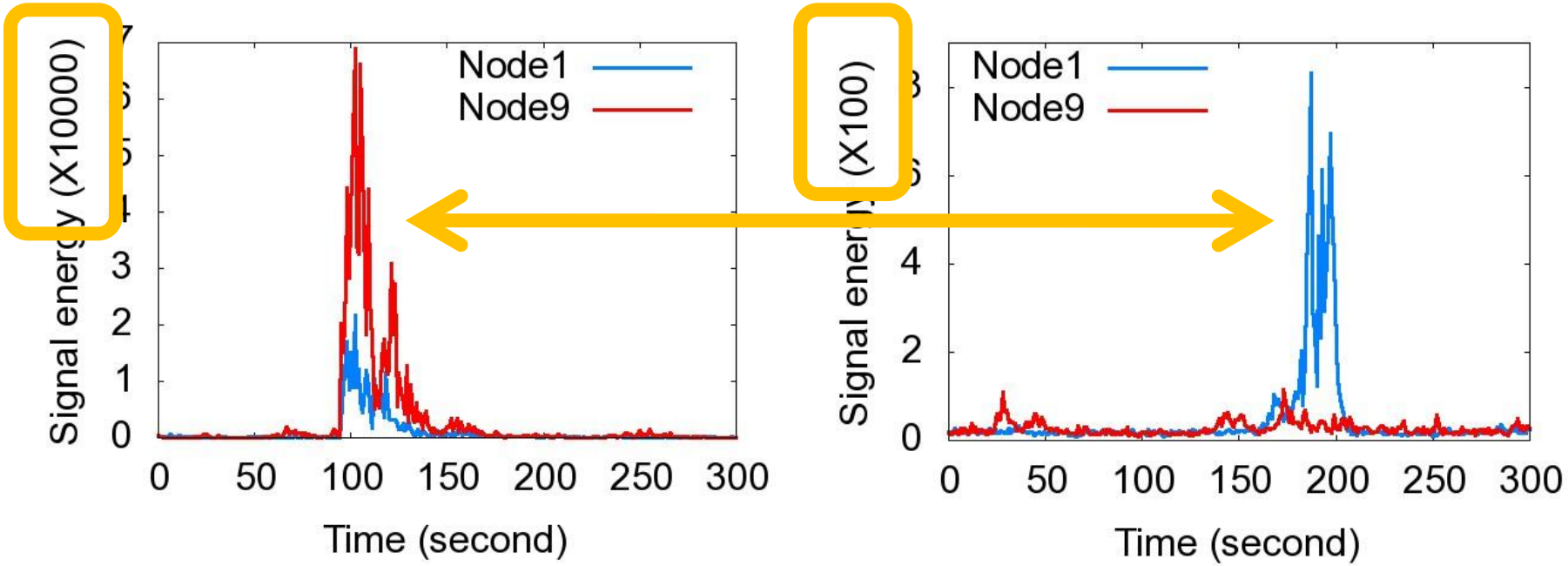
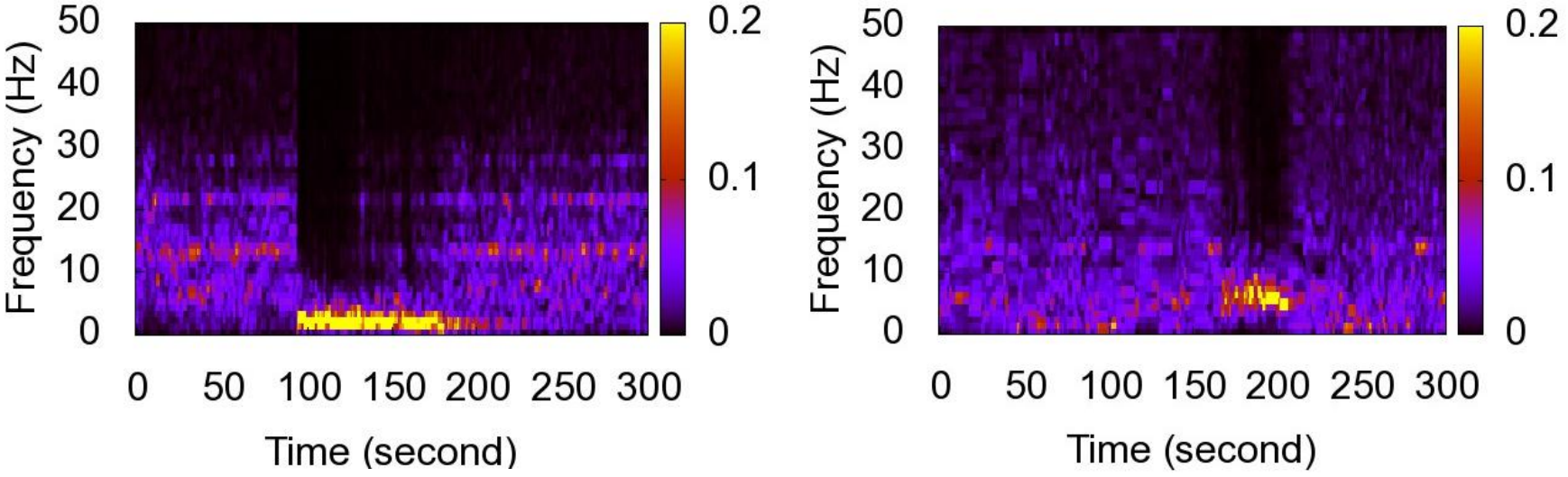


Two earthquakes on Mt St Helens

- Complicated physical process
  - Highly dynamic magnitude
  - Dynamic source location

Challenge 2: Frequency Diversity



- Responsive to *P-wave* within [1 Hz, 10 Hz]

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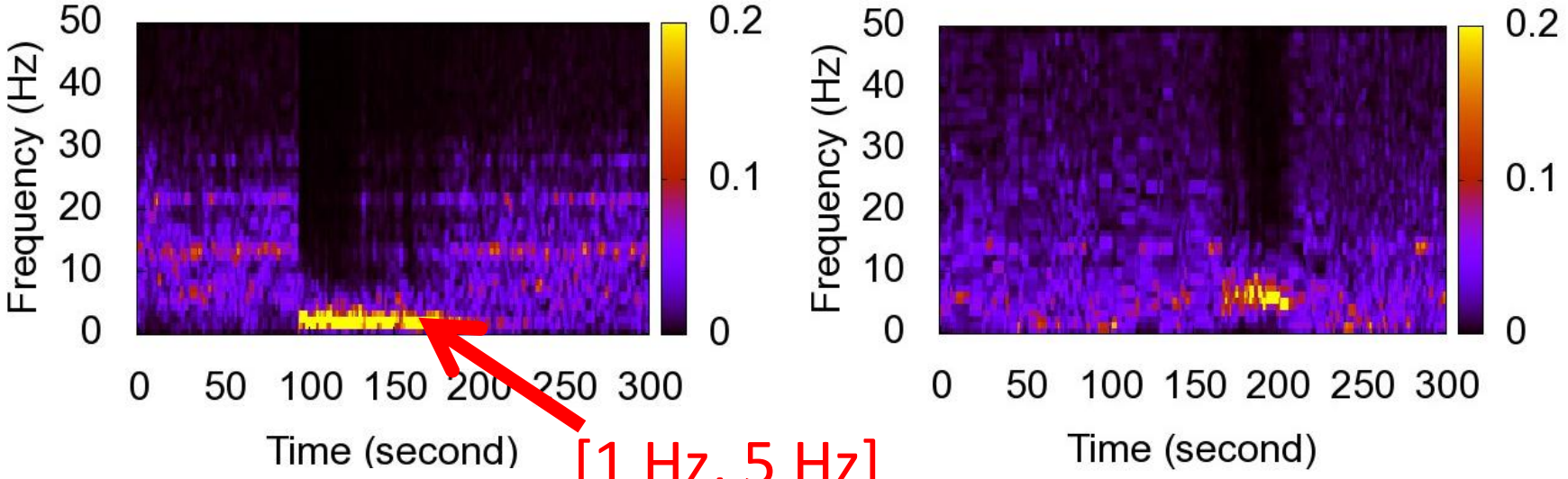

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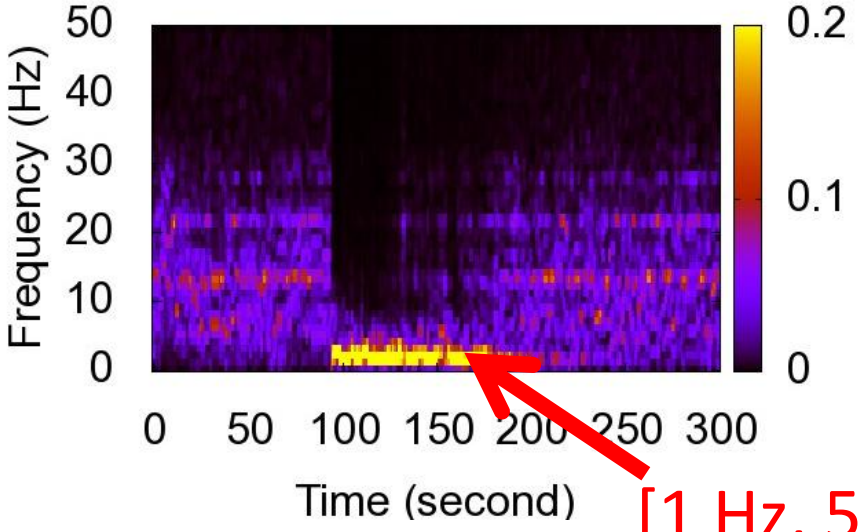

[1 Hz, 5 Hz]

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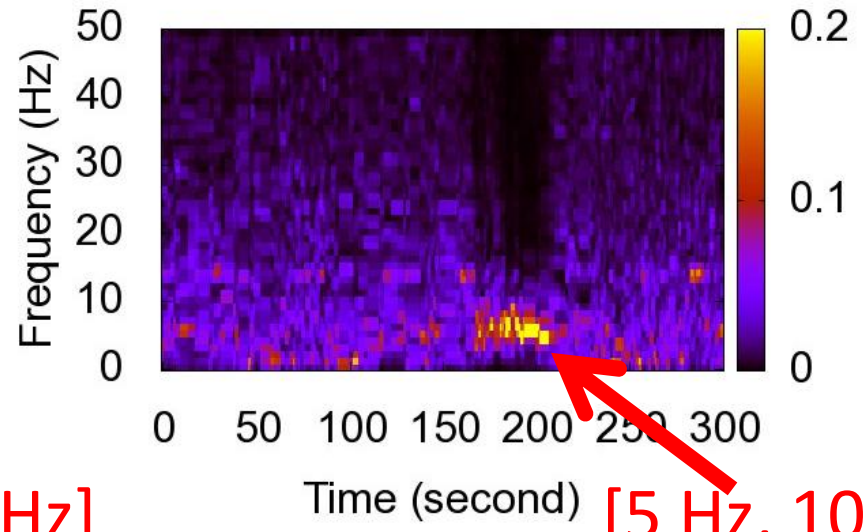

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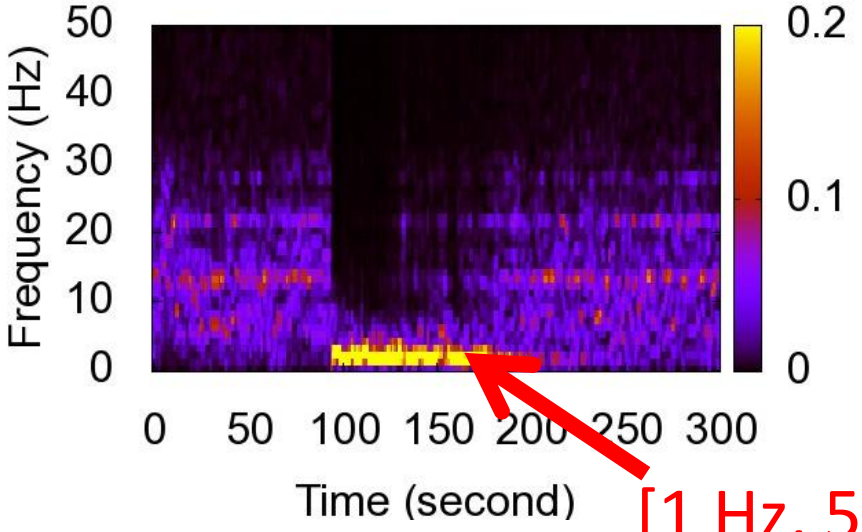

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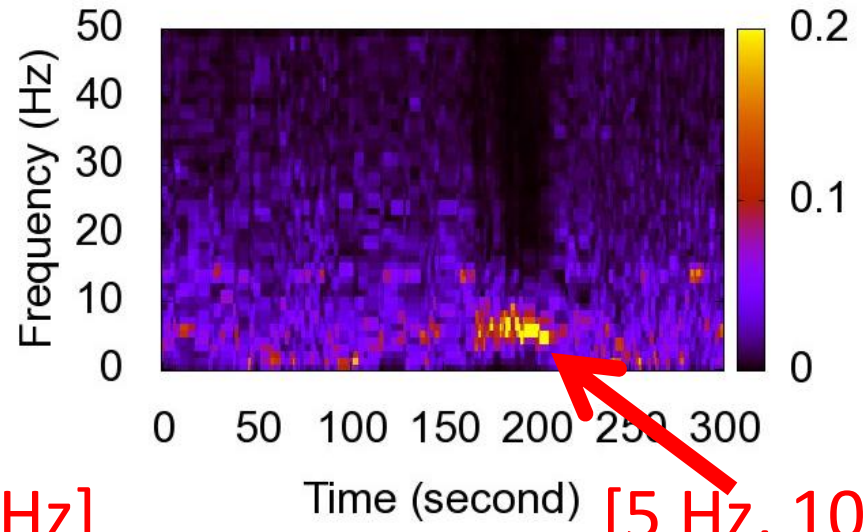
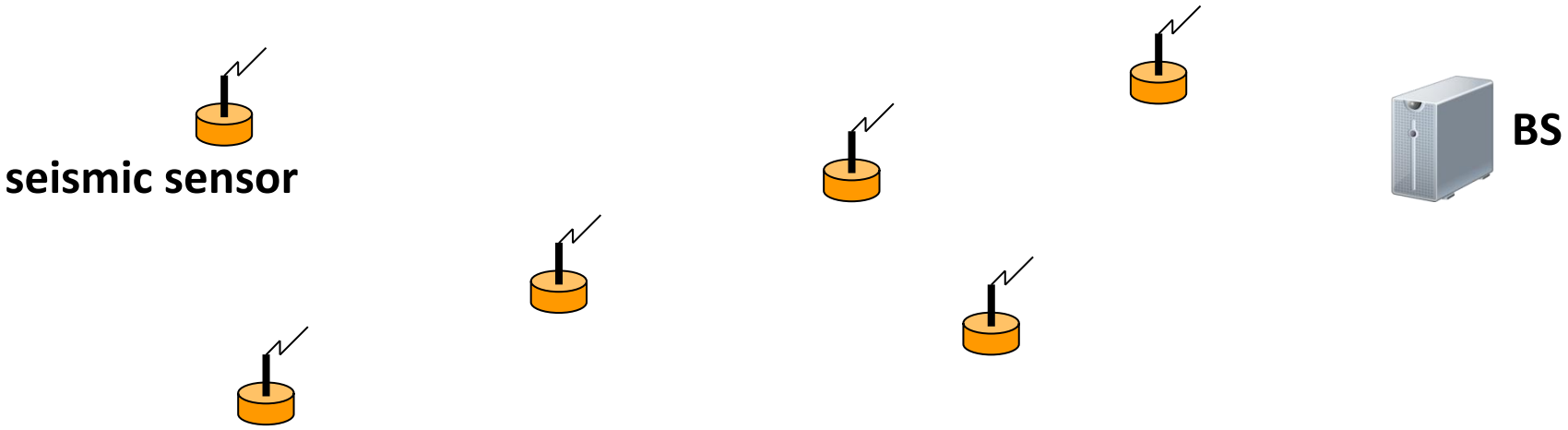


[5 Hz, 10 Hz]

X 100

- Responsive to *P-wave* within [1 Hz, 10 Hz]
- Freq. spectrum changes with signal magnitude

Approach Overview



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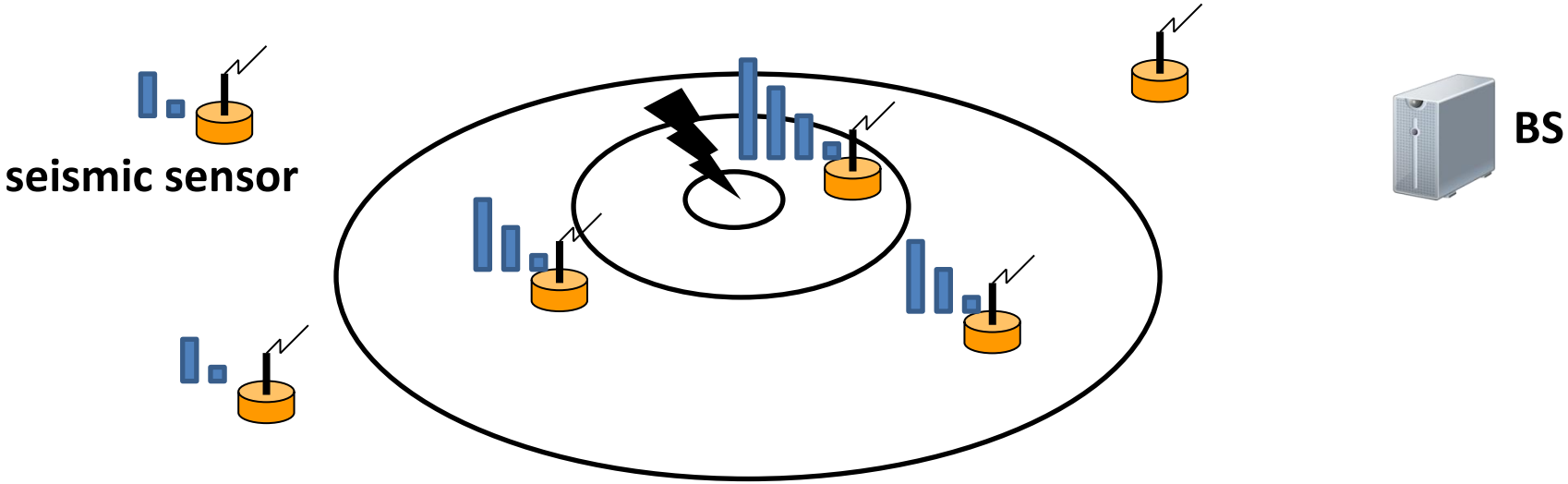

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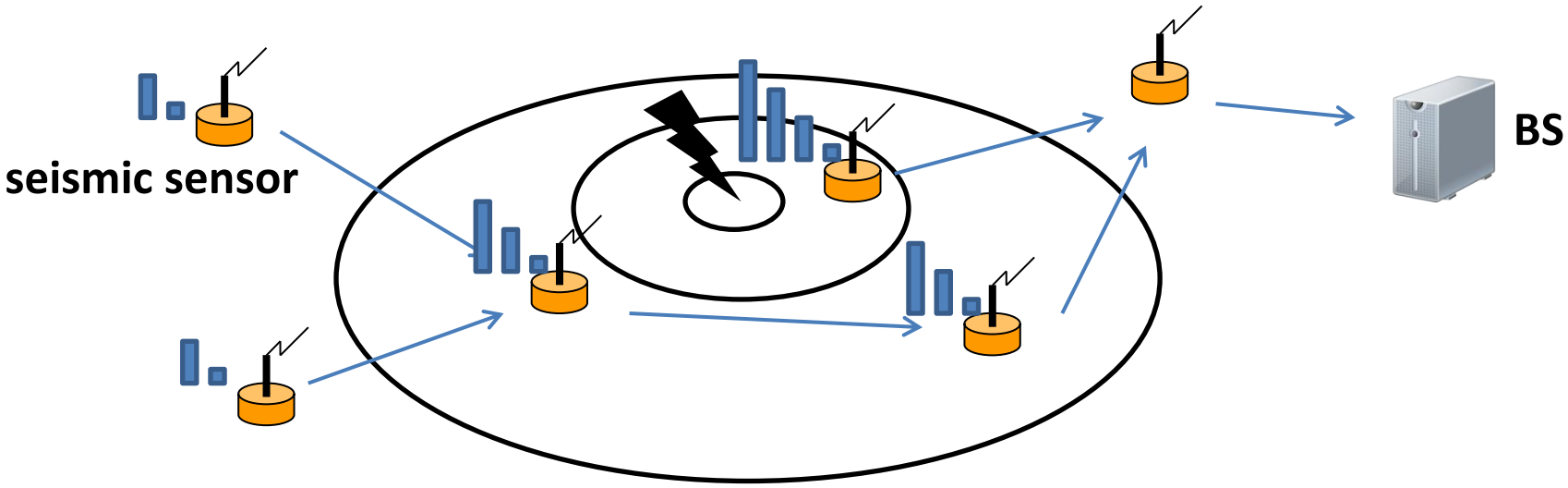

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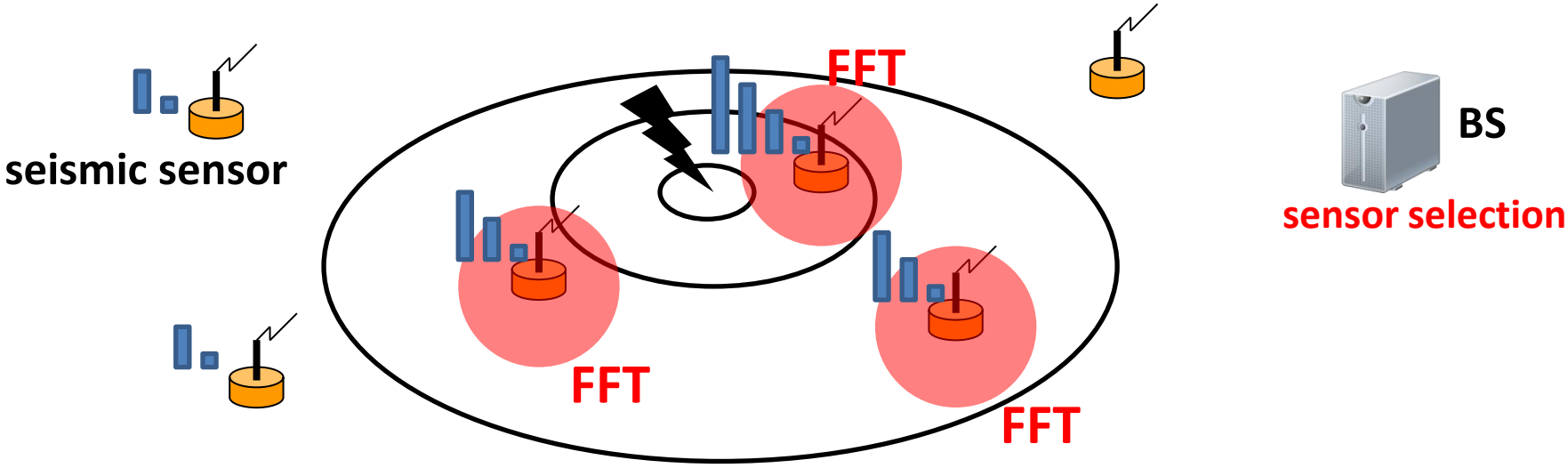

- Select sensors with best signal qualities
  - FFT (computation-intensive)

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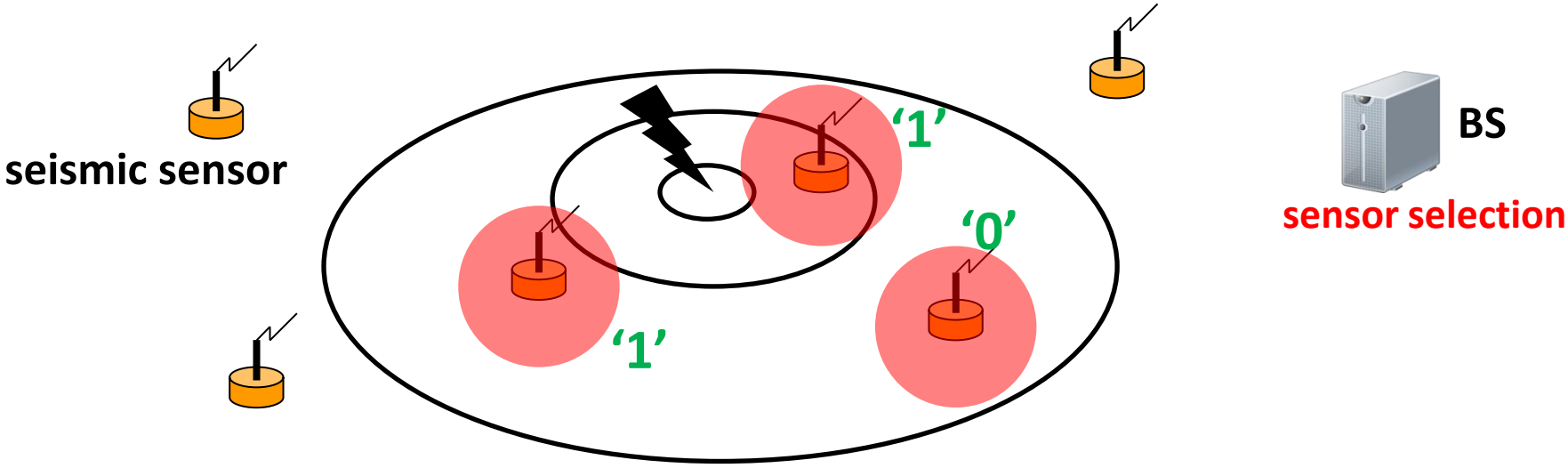

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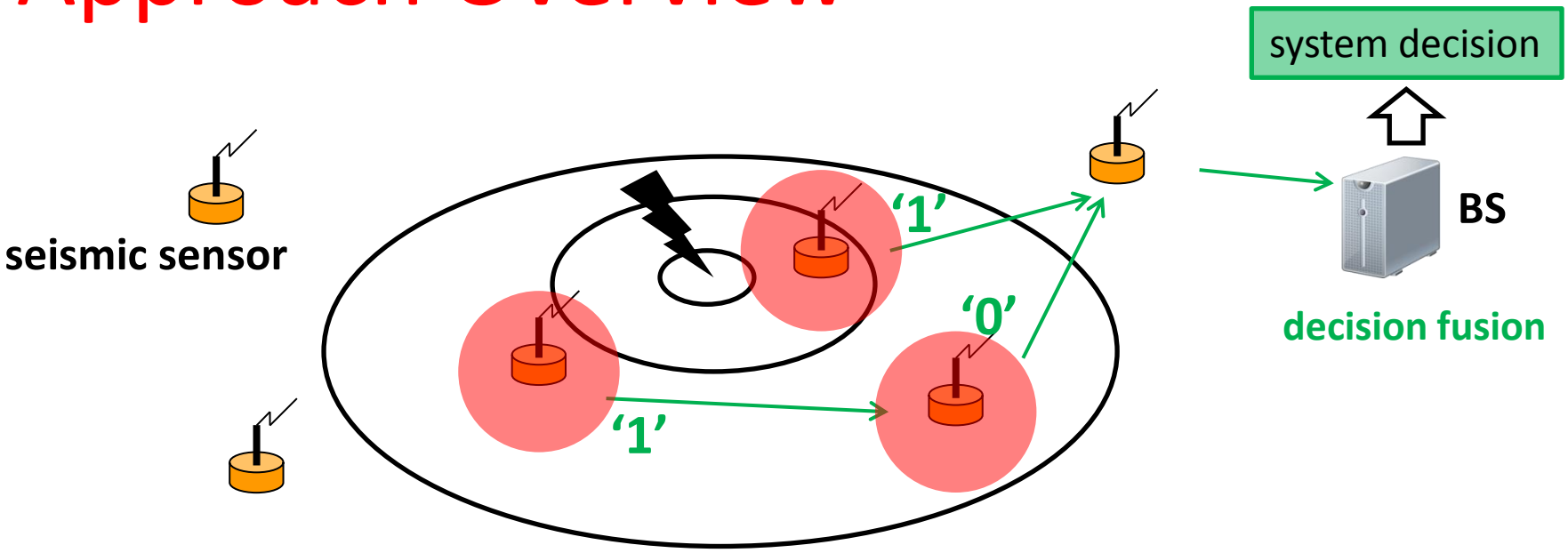

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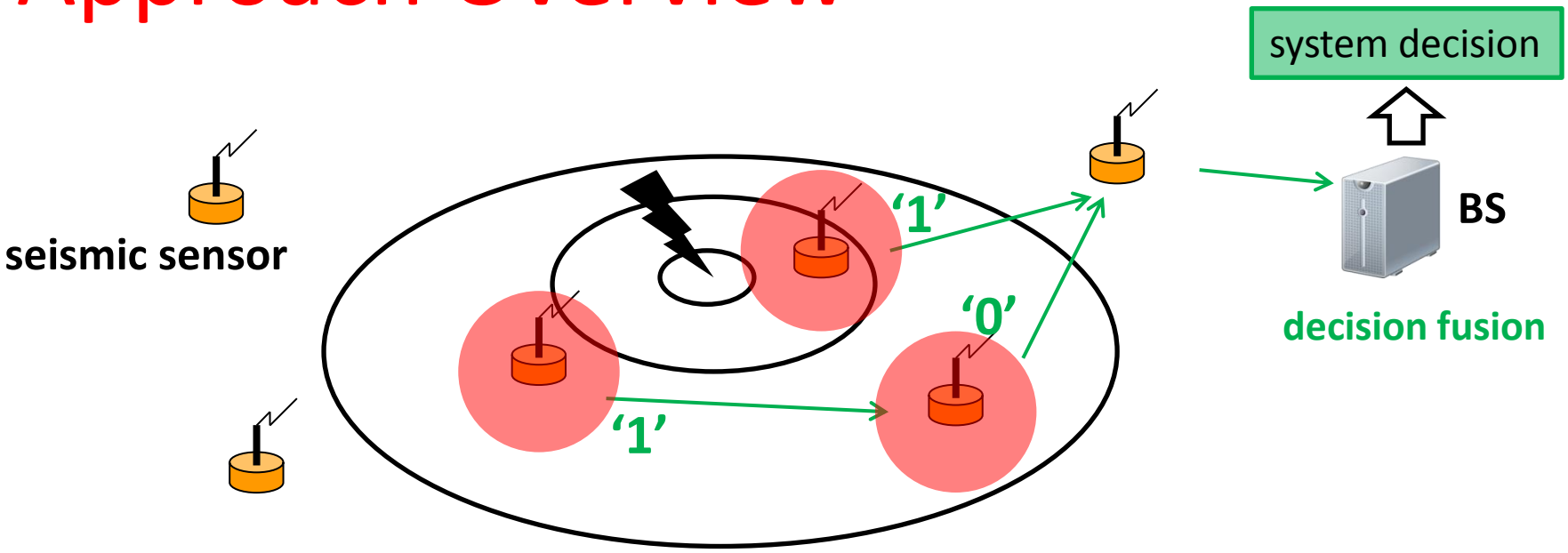

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- Local detection
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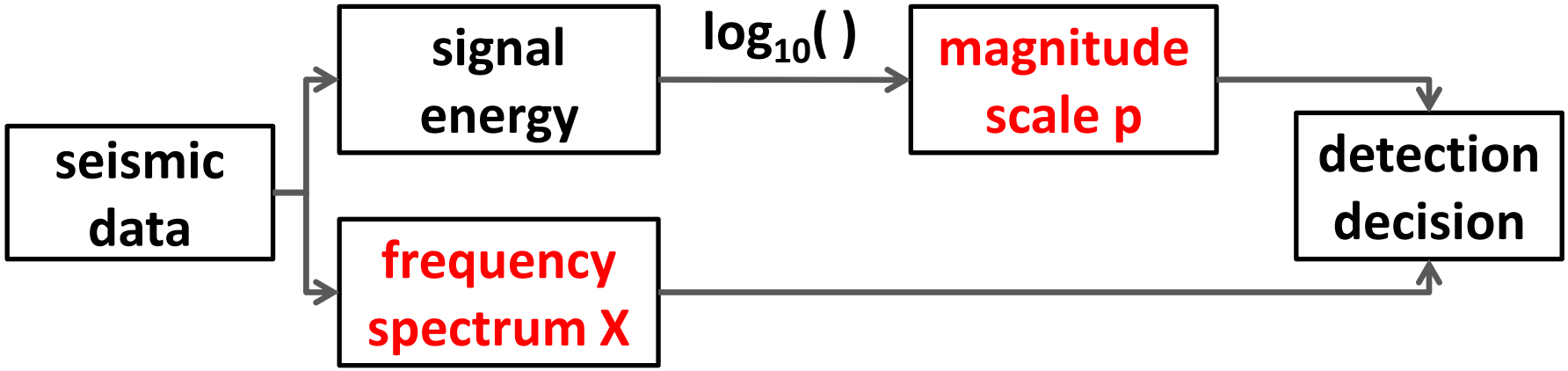
avoid raw data transmission

Outline

- Motivation
- Frequency-based local detection model
  - Preserve essential features
  - Accurately detect earthquakes
- Sensor selection for decision fusion
- Evaluation
- Conclusion

Multi-scale Frequency Model



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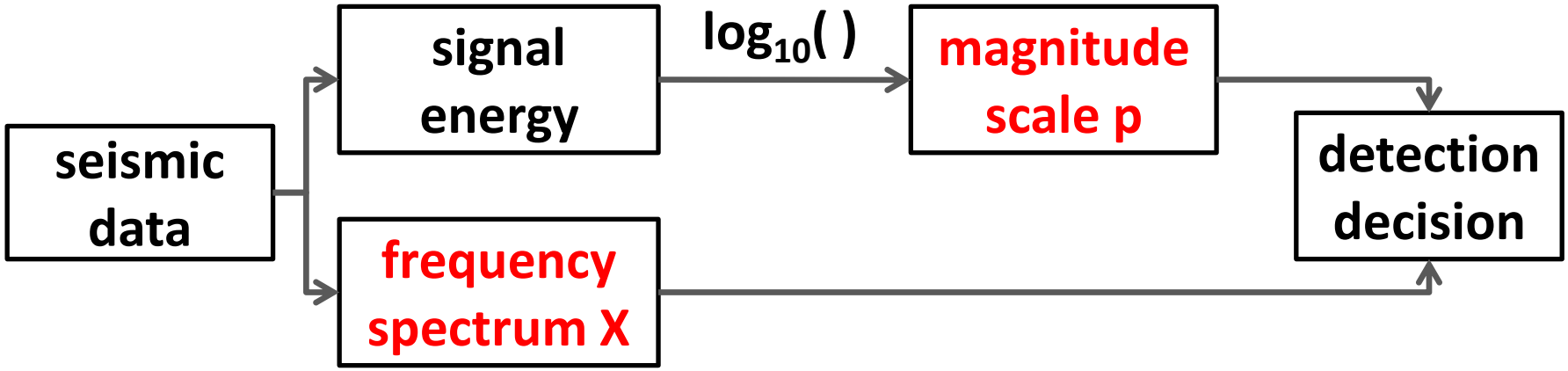

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  - Earthquake happens

$$X \sim N_p(m_p, C_p), \quad p = 1, 2, \ldots$$

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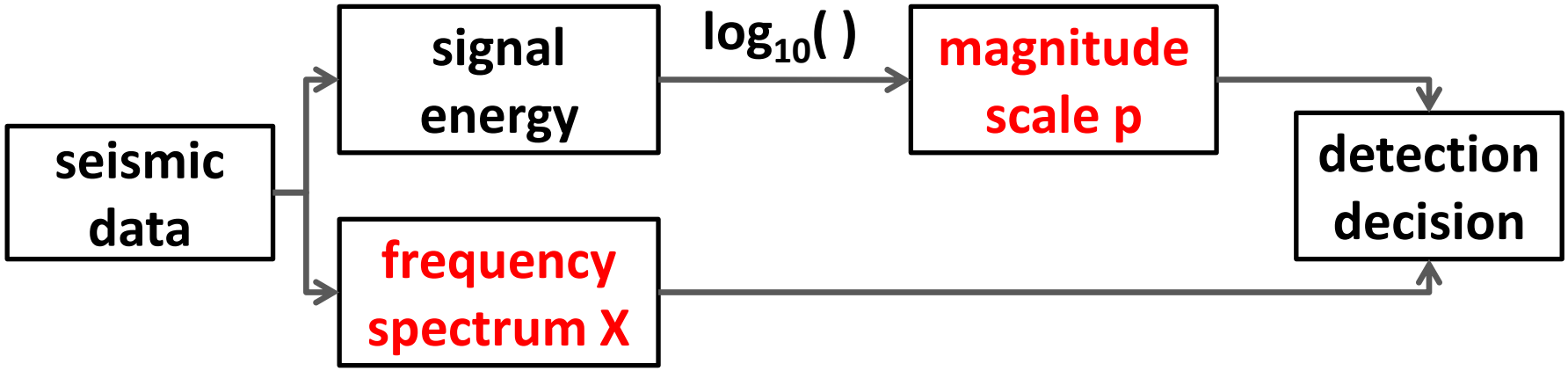

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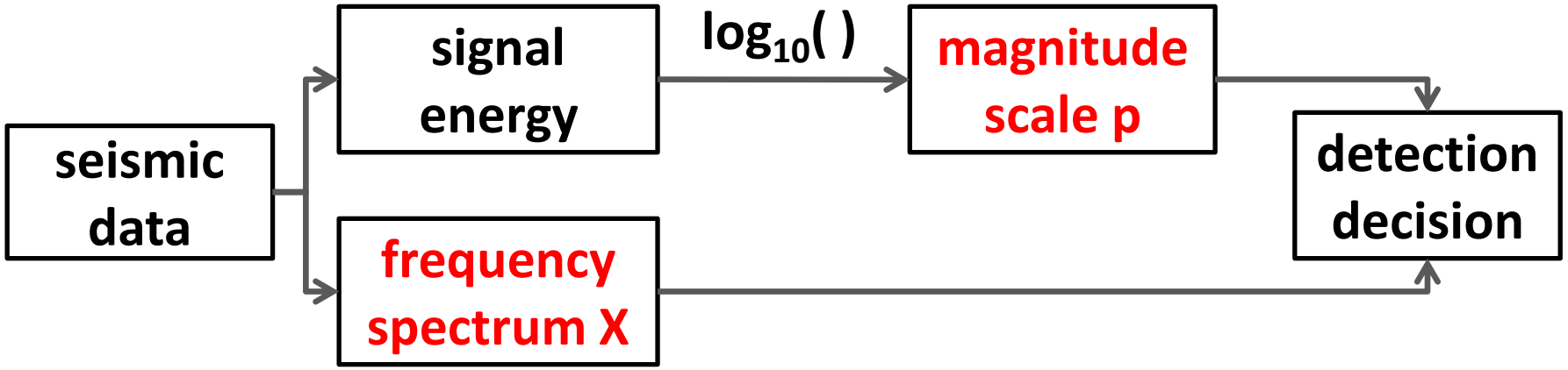

- Gaussian models
  - Earthquake happens

mean vector

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$$X \sim N_p(m_p, C_p), \quad p = 1, 2, \ldots$$

  - No earthquake

$$X \sim N_0(m_0, C_0)$$

Local Detection at Sensor

- Minimum error rate detection

  decision function $g_i(X|m_i, C_i)$

  – If $g_p(X) > g_0(x)$, decide 1; otherwise, decide 0

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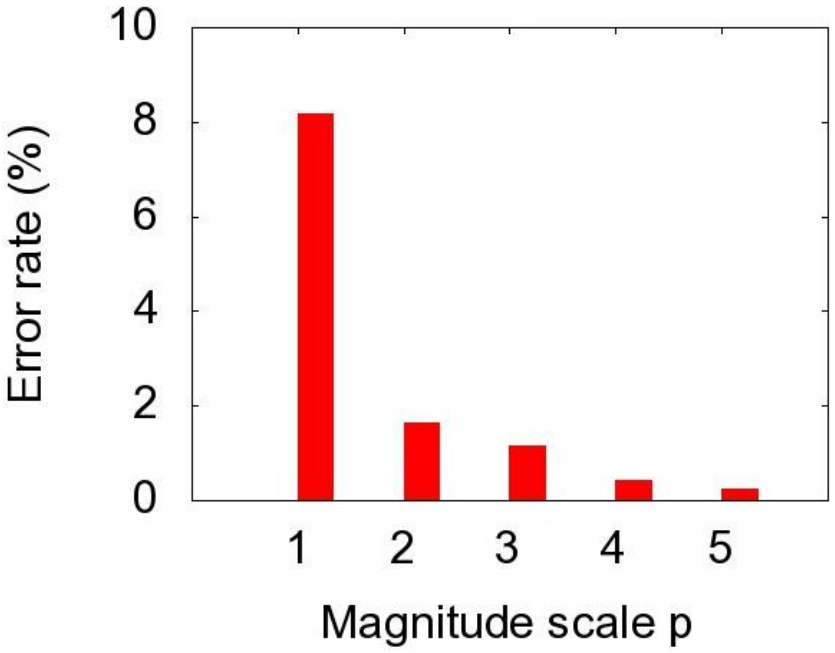

- Error rate decreases with p
- Sensors receive different p's

spatial/frequency diversities

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- Frequency-based local detection model
- Sensor selection for decision fusion
  - Avoid unnecessary FFT
- Evaluation
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Decision Fusion at BS

- Extended majority rule

$$\frac{\text{\# of positive local decisions}}{\text{total \# of sensors}} > \text{threshold}, \quad \text{decide 1}$$

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- Closed-form detection performance

$$P_F = f\left(P_{F1}, P_{F2}, \ldots, P_{FN} \right)$$
$$P_D = f\left(P_{D1}, P_{D2}, \ldots, P_{DN} \right)$$

P_{Fi} / P_{Di} : false alarm rate / detection prob. of sensor i

Sensor Selection For Decision Fusion

Given $\{P_{Fi}, P_{Di} \mid i=1, \ldots, N\}$, find a sensor subset S

$$\text{minimize} \quad \|S\|$$

$$\text{s.t.} \quad P_F \leq \alpha \quad P_D \geq \beta$$

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- Exclude sensors w/ low signal qualities
  - Avoid unnecessary FFT
- Configurable system detection performance

Sensor Selection Algorithm

- Select sensor every detection period
- Brutal-force search: $O(2^N)$
  - Long latency

A fast *near-optimal* algorithm?

Sensor Selection Algorithm

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$$P_D \approx Q\left(\frac{Q^{-1}(\alpha)\sqrt{\sum_i P_{Fi} - P_{Fi}^2} - \sum_i (P_{Di} - P_{Fi})}{\sqrt{\sum_i P_{Di} - P_{Di}^2}} \right)$$

P_D increases with $\Sigma_i(P_{Di}-P_{Fi})$ w.h.p.

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- Sort sensors by $(P_{Di}-P_{Fi})$, include one by one

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- Motivation
- Frequency-based local detection model
- Dynamic sensor selection for decision fusion
- Evaluation
  - Testbed experiments
  - Trace-driven simulations
- Conclusion

Implementation

- Testbed experiments in lab
  - 24 TelosB motes

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  - Seismic data from Mt St Helens -> mote flash
  - Real-time data acquisition @ 100 Hz
- On-mote seismic processing
  - FFT: < 250 ms over 100 data points

Baseline Approaches

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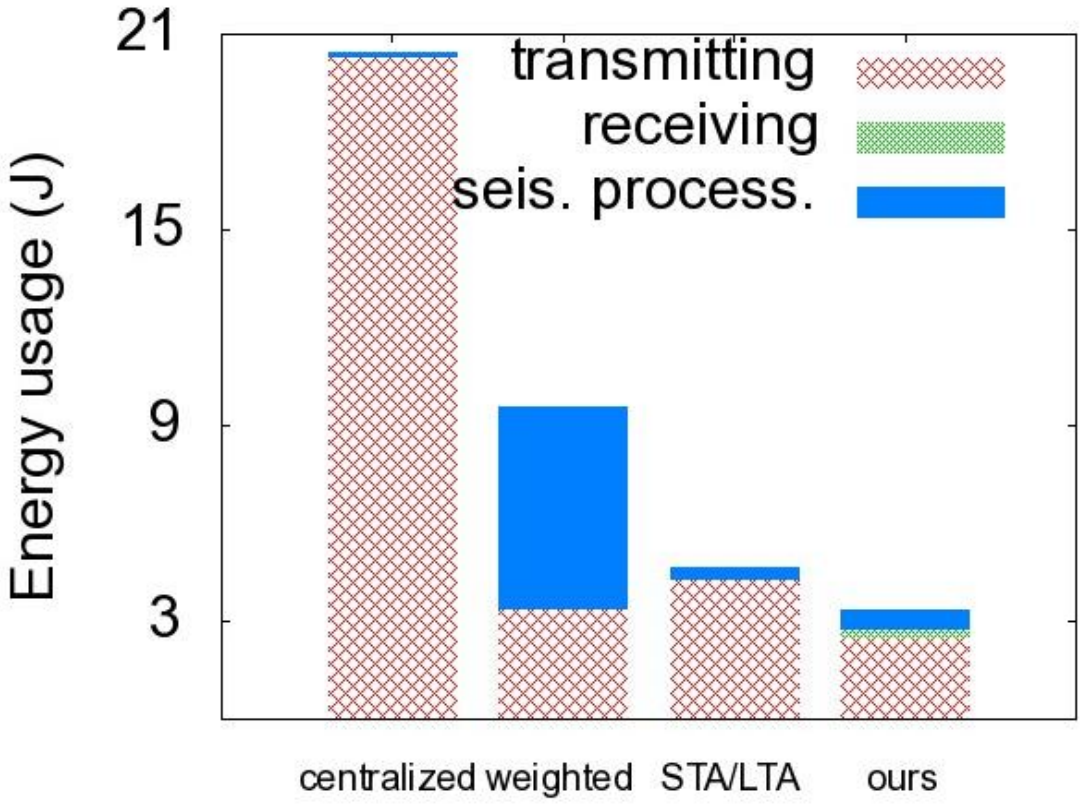
- Weighted decision fusion [Chair&Varshney 1990]
  - Account for signal qualities
  - Sensor selection is not necessary

Energy Usage



Total energy consumption
12 motes
10 minutes

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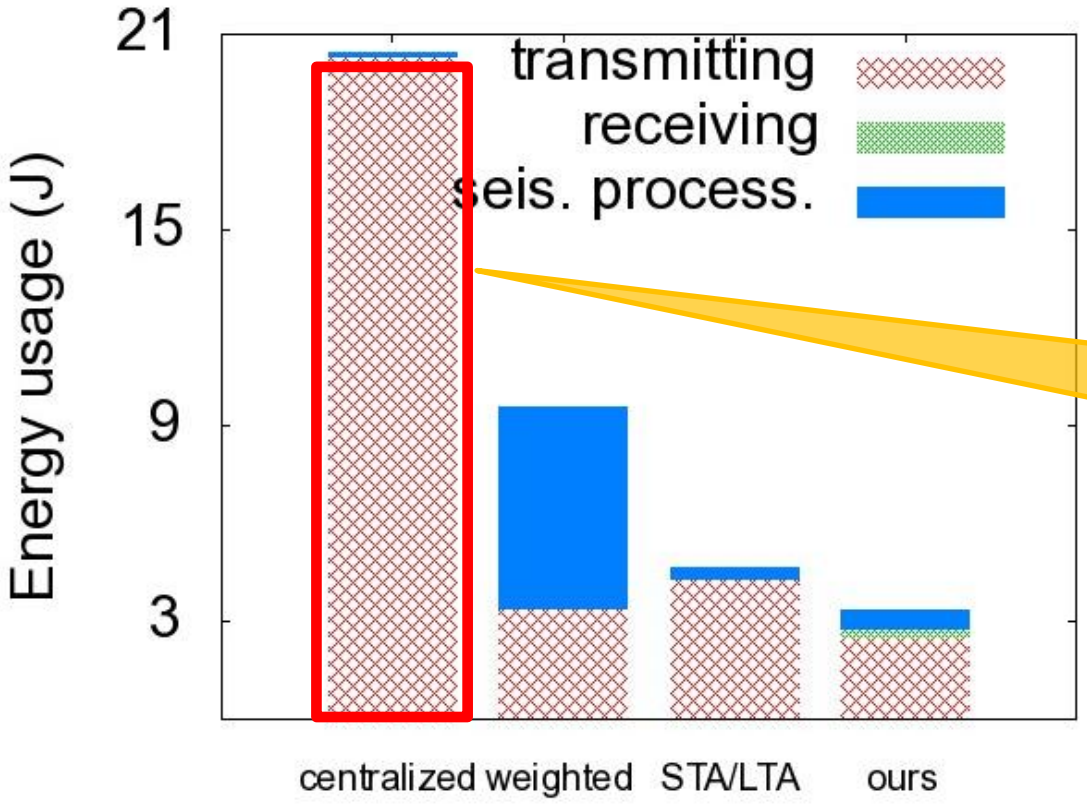

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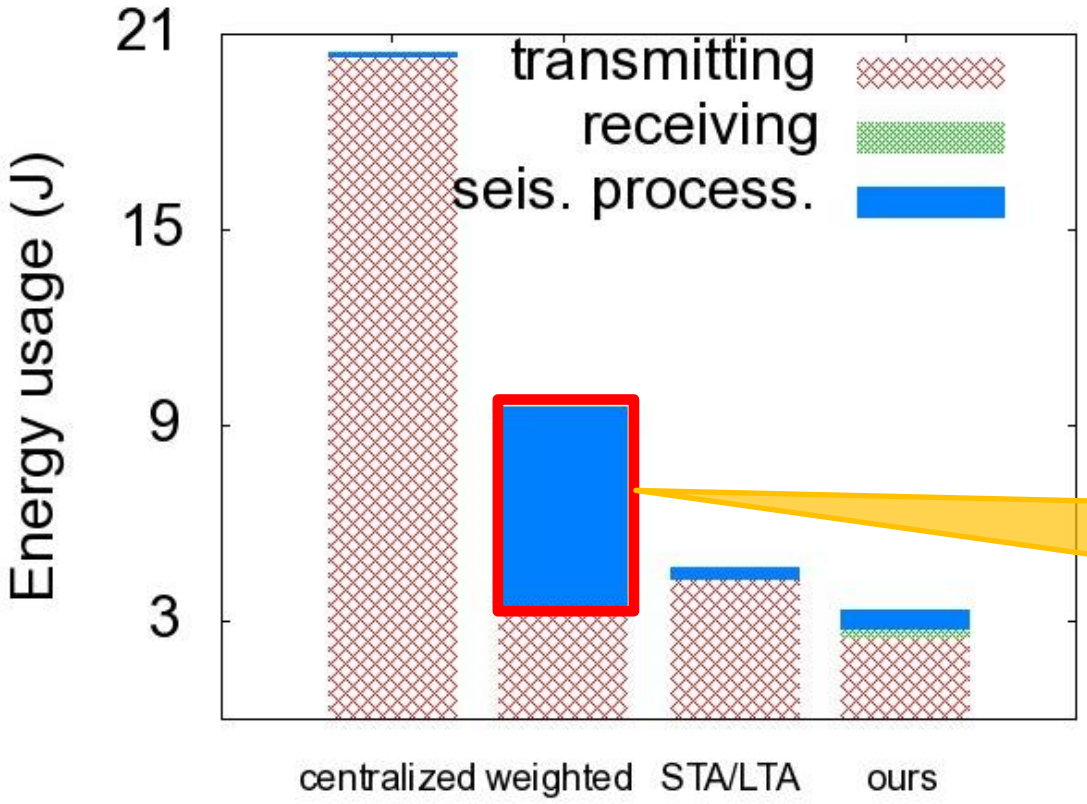
Centralized process.: transmit seismic data

Energy Usage



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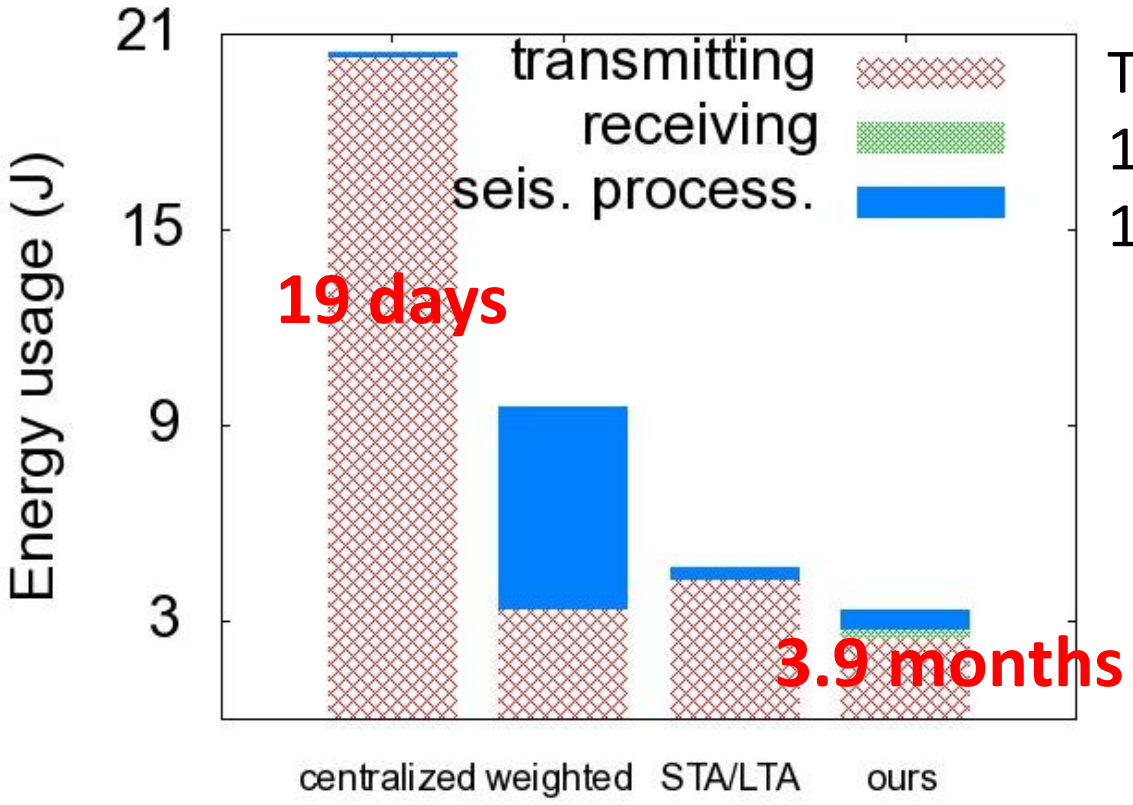
Weighted fusion: always do FFT

Energy Usage



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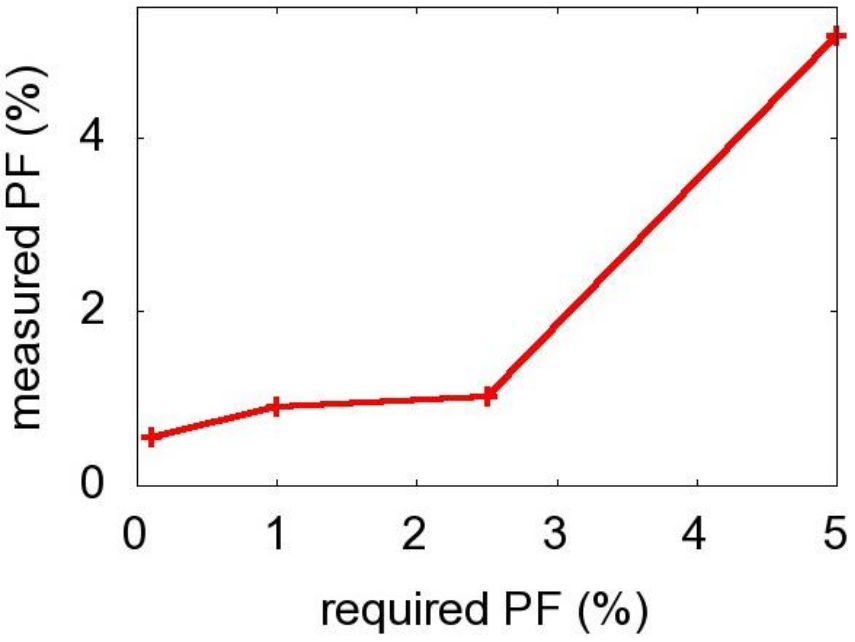
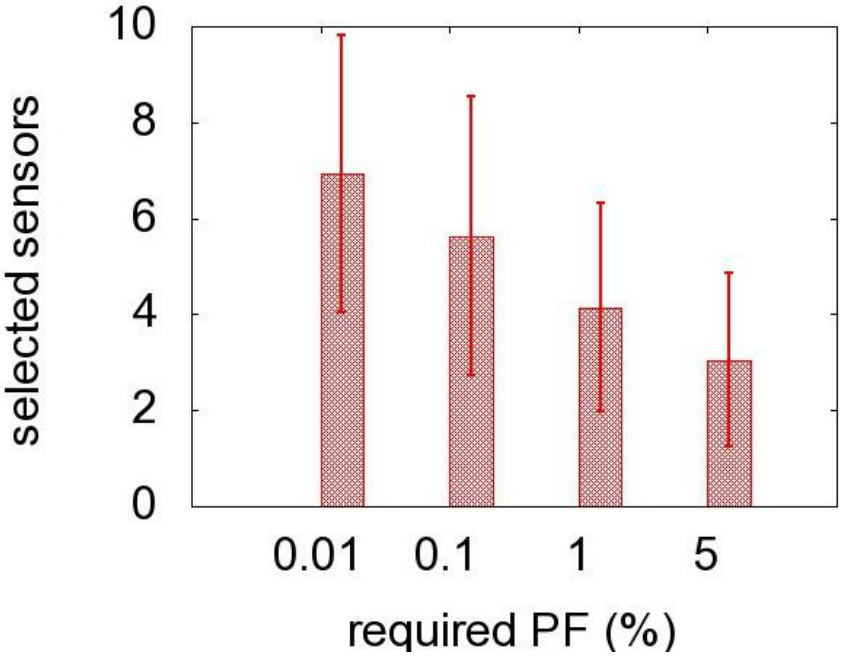
- 6-fold reduction in energy consumption

Trace-driven Simulations

- Data traces from 12 sensors on Mt St Helens
- More than 128 earthquakes in 6 months





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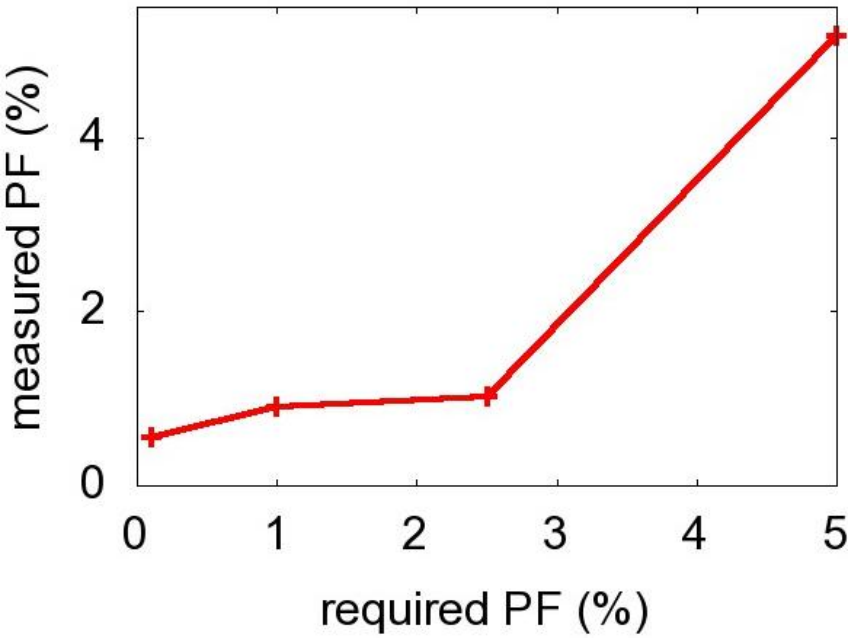

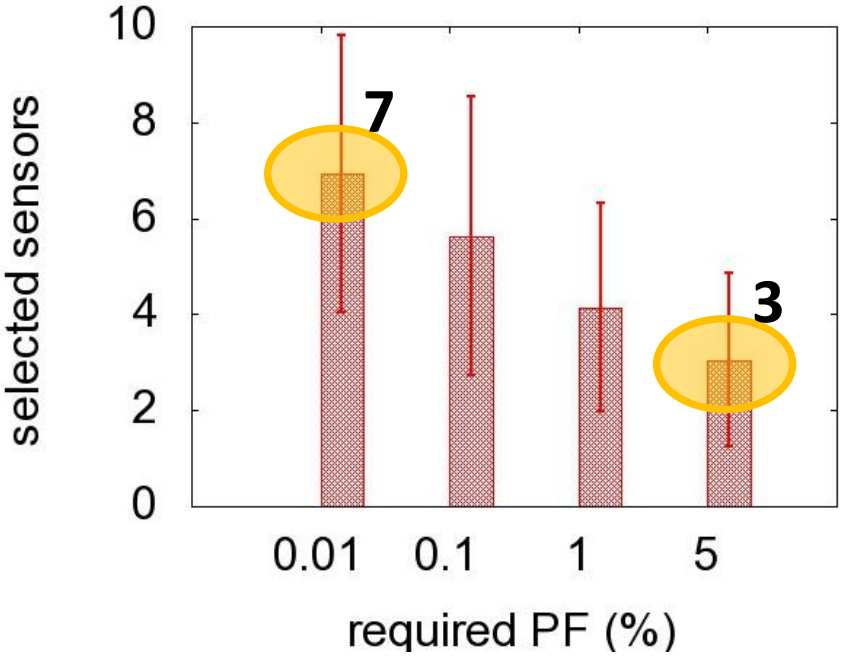

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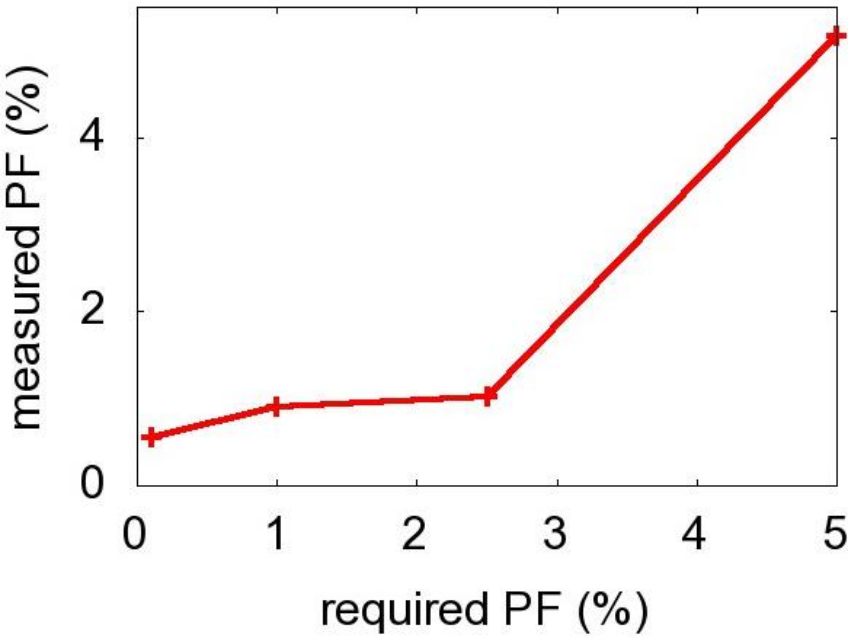
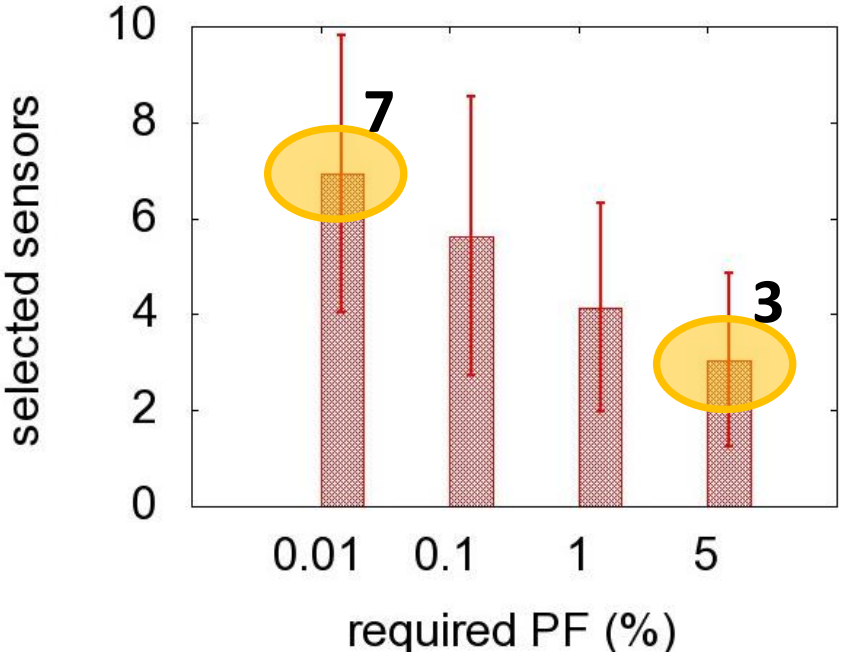




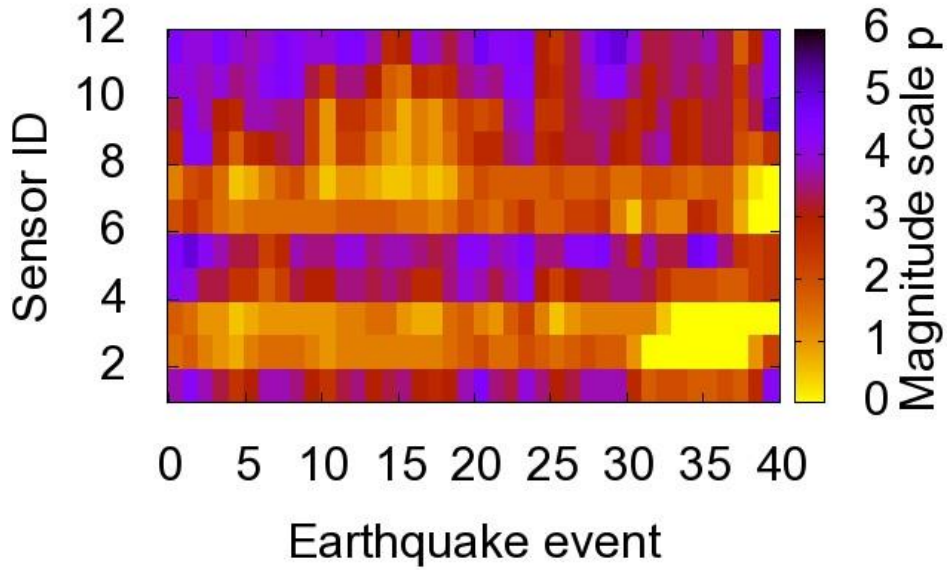
Configurable trade-off btw detection performance and energy consumption

Conclusions

- Quality-driven earthquake detection
  - In-network collaborative signal processing
  - No raw data transmission
- Near-optimal sensor selection algorithm
  - Handle earthquake dynamics
  - Minimize energy consumption
- Extensive evaluation
  - 6-fold energy reduction
  - Comparable sensing performance

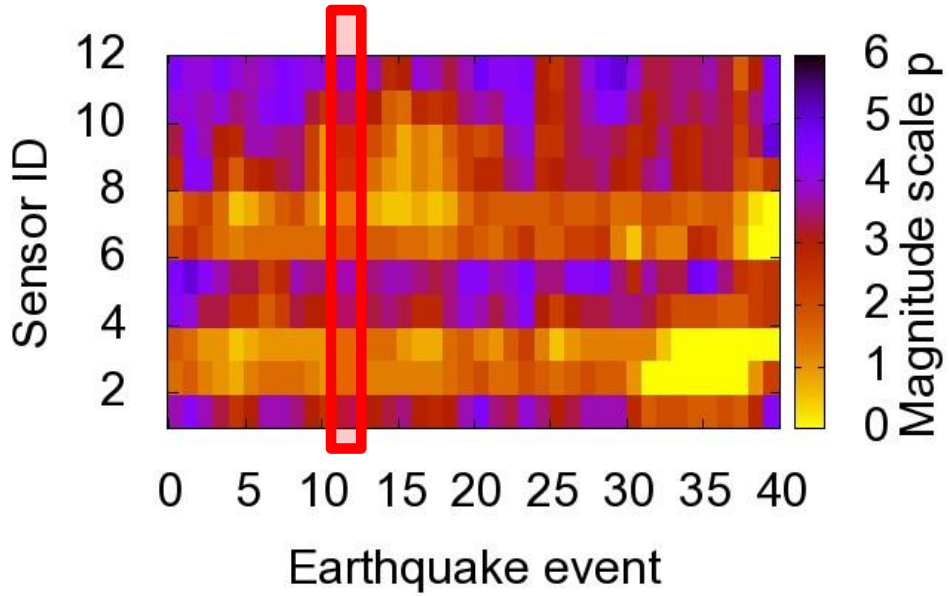
Thank you!

Dynamic Detection Performance



- Spatial-temporal variation

Dynamic Detection Performance



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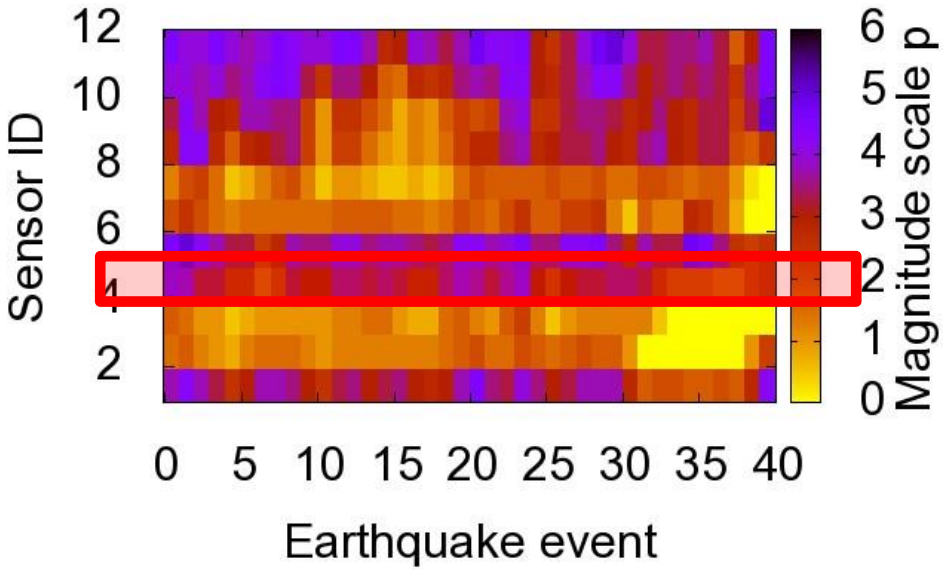
  - Sensors have diverse magnitude scales

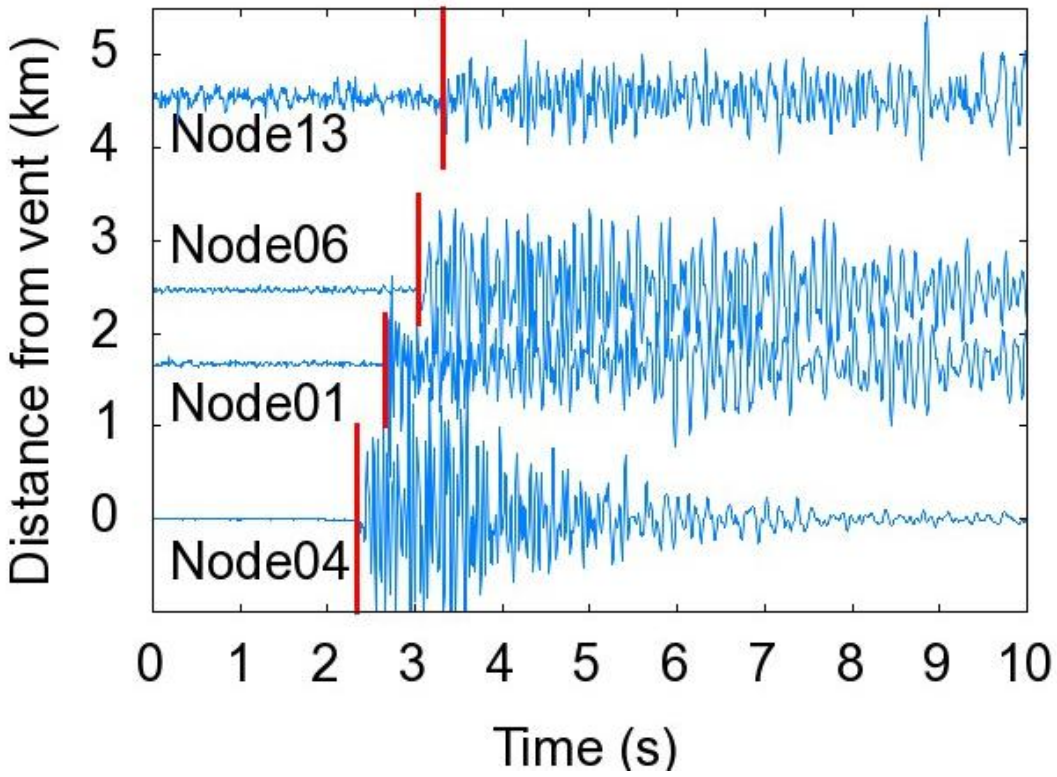
Dynamic Detection Performance



- Spatial-temporal variation
  - Sensors have diverse magnitude scales
  - Each sensor has unpredictable pattern of p

Ongoing Work

- Earthquake source localization
  - Accurate node-level onset time



Onset times of an explosive event

An existing p-wave front picking algorithm

- millisec accuracy
- 7KB ROM + 13KB RAM (unavailable on TelosB)