CoughLoc: Location-Aware Indoor Acoustic Sensing for Non-Intrusive Cough Detection

[1]Zheng Sun, [1]Aveek Purohit, [2]Kathleen Yang, [1]Neha Pattan,
[1]Dan Siewiorek, [1]Asim Smailagic, [1]Ian Lane, and [1]Pei Zhang

[1]Carnegie Mellon University, Pittsburgh, PA
[2]Samsung Communication Lab, San Jose, CA

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Motivation

- Cough is common and associated with multiple diseases[1]

- Subjective monitoring of cough count is inaccurate[1, 2]
  - Loosely related to real cough counts
  - Affected by mood and expectations
  - Hard to report nocturnal coughs

- Continuous objective cough monitoring is necessary[1, 2]

[1] Smith J. , “Cough: assessment and equipment”. *The Buyers Guide to Respiratory Care Products*, 2008
[2] K.F.Chung,“The clinical and pathophysiological challenge of cough,” *Cough: Causes, Mechanisms and Therapy*, 2003.

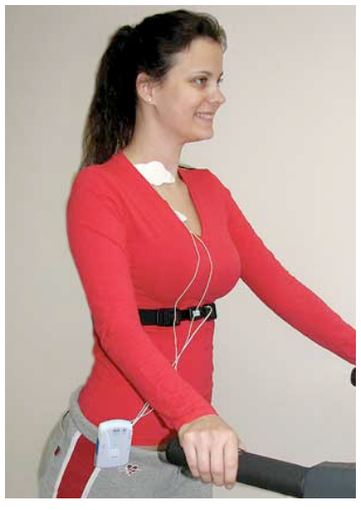
Related Work: Cough Assessment and Monitoring

Cough score questionnaire[1]

Low cost, but inaccurate, obtrusive, not continuous

Manual cough counting[2]

Accurate, but expensive, obtrusive, not support mobility



Ambulatory cough monitors[3]

Accurate, but expensive and obtrusive, partial support of mobility

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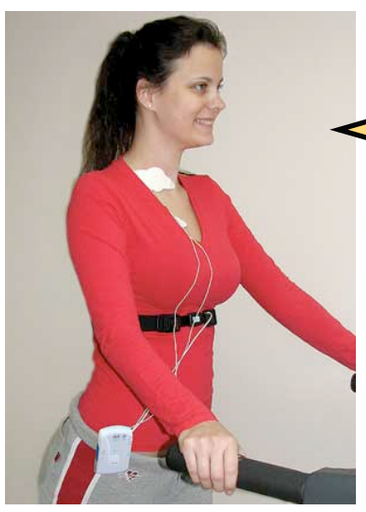
[1] K.F.Chung,"The clinical and pathophysiological challenge of cough," *Cough: Causes, Mechanisms and Therapy*, 2003.
[2] Smith J. , Cough: assessment and equipment. *The Buyers Guide to Respiratory Care Products*, 2008.
[3] S. Matos et al., An automated system for 24-h monitoring of cough frequency: the leicester cough monitor. *IEEE Transactions on BioEngineering*, 2007.

Related Work: Cough Assessment and Monitoring



State-of-the-art Ambulatory Cough Monitors

Ideas:

1) Microphones attached near chest
2) Wearable audio recorders
3) Machine learning-based cough detection

Performance:

1) ~90% accuracy under quiet backgrounds
2) No results reported under noisy backgrounds

Downside:

Intrusive when patients move due to on-body sensors

"The ideal cough monitoring system should be small, inexpensive and unobtrusive for the subject"[2]

[1] K.F.Chung,"The clinical and pathophysiological challenge of cough," *Cough: Causes, Mechanisms and Therapy*, 2003.
[2] Smith J. , Cough: assessment and equipment. *The Buyers Guide to Respiratory Care Products*, 2008.
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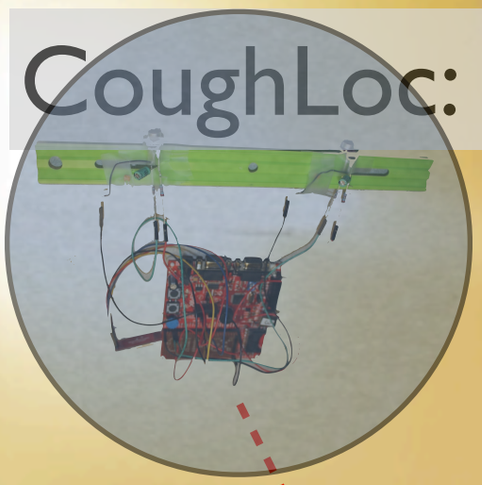
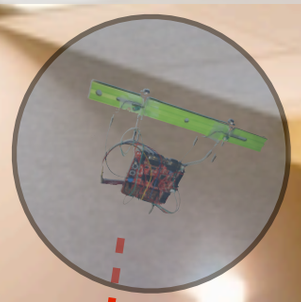
Research Problem

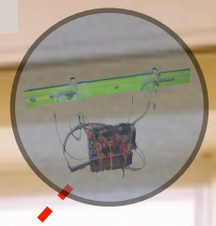
How to continuously detect coughs while achieving two goals?

- Unobtrusiveness to patients & support patient mobility
- High cough detection accuracy (> 90%) under various background noises

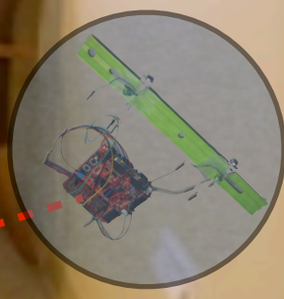
CoughLoc: Non-intrusive Acoustic Sensing







COUGH



Outline

Motivation

CoughLoc System & Challenges

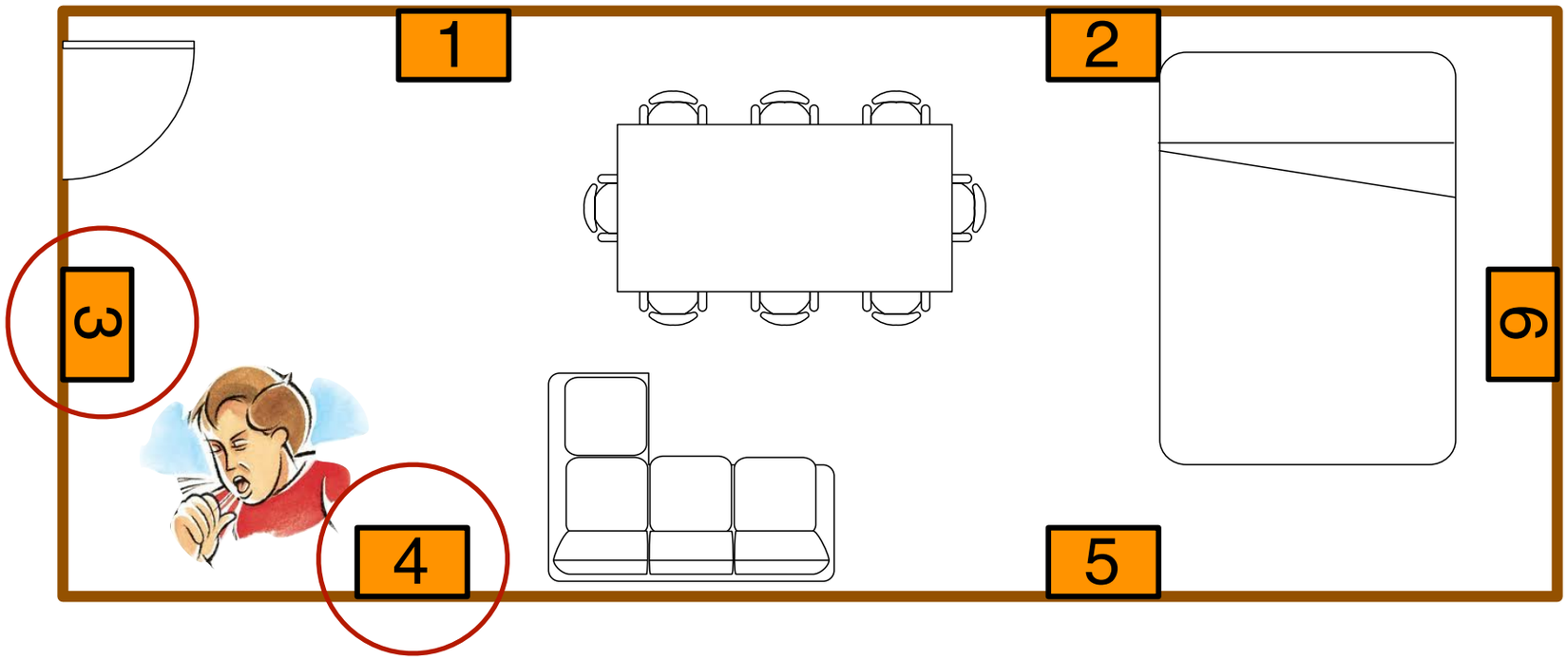
Approach

Results

Summary

Challenges

- Low sensing performance due to patient mobility
  - Cough SNR < 10dB (1m), compared to 55dB using a headset
  - Computing SNR directly is not easy - what is the signal?



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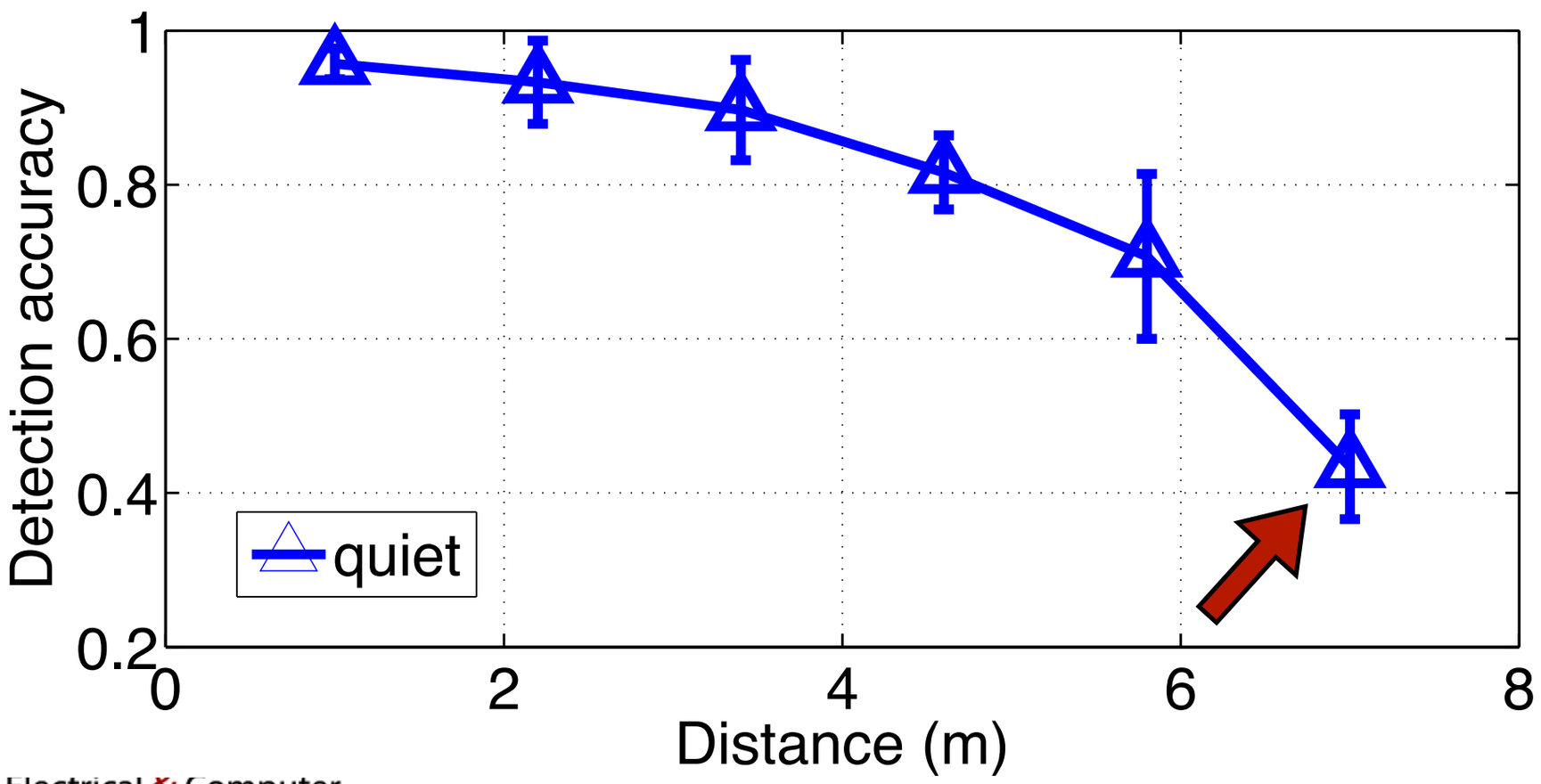

Experiments show 60% performance decrease from 1m to 7m

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Challenges

- Low sensing performance due to patient mobility
  - Cough SNR < 10dB (1m), compared to 55dB using a headset
  - Computing SNR directly is not possible - what is the signal?
- Low system cost
  - Targeted per-node cost < $50
  - Compared to $5000 commercial ambulatory cough monitors[1]
- Low hardware resources
  - Computation & Bandwidth

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[1] KarmelSonix CoughCOUNT™, www.karmelsonix.com/coughcount.html

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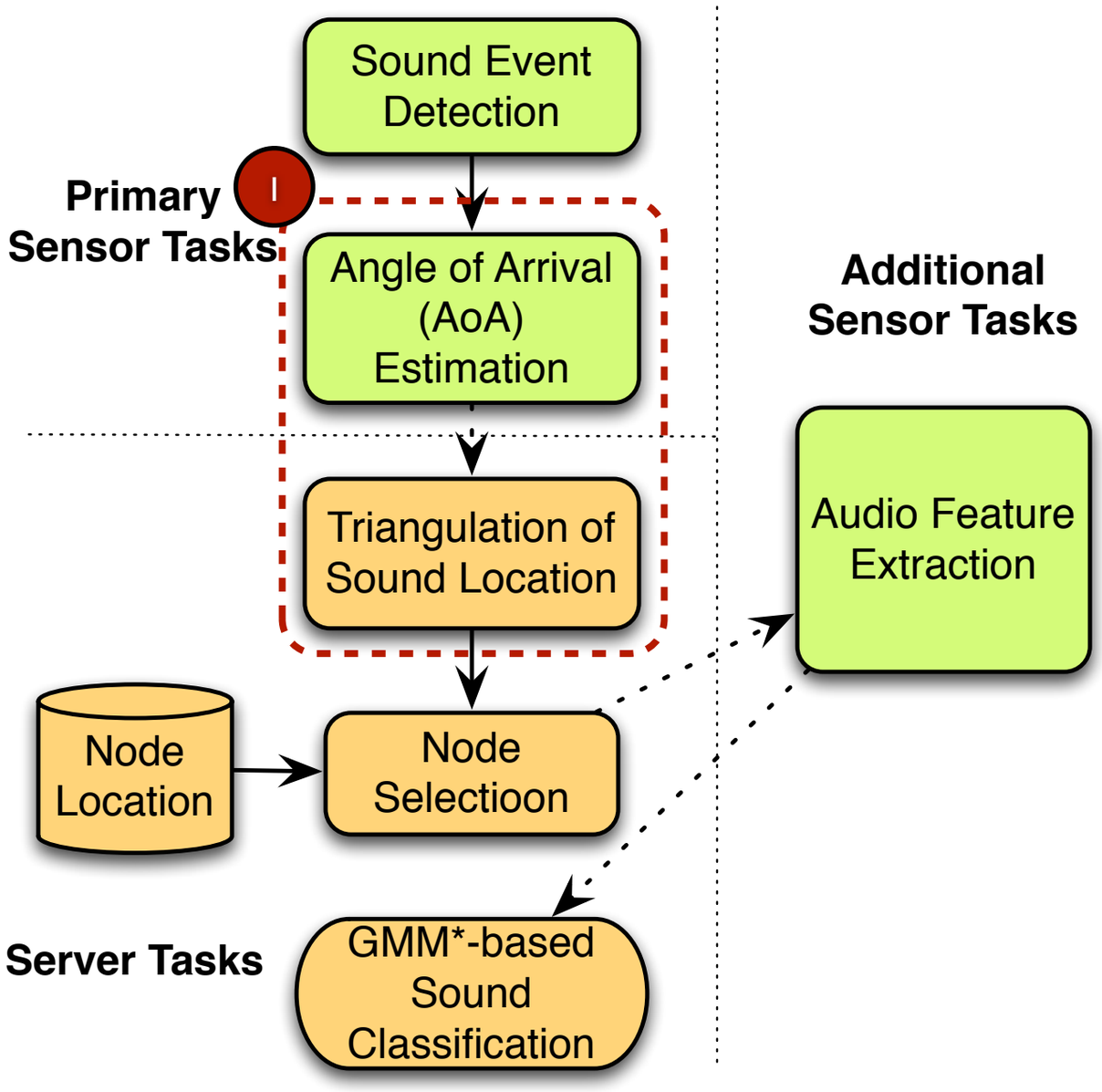
System Overview



✓Step 1: Sound source localization

✓Step 2: Select nodes closest to the sound source

✓Step 3: Compute audio features on selected nodes

✓Step 4: Use the audio features to detect coughs on the server

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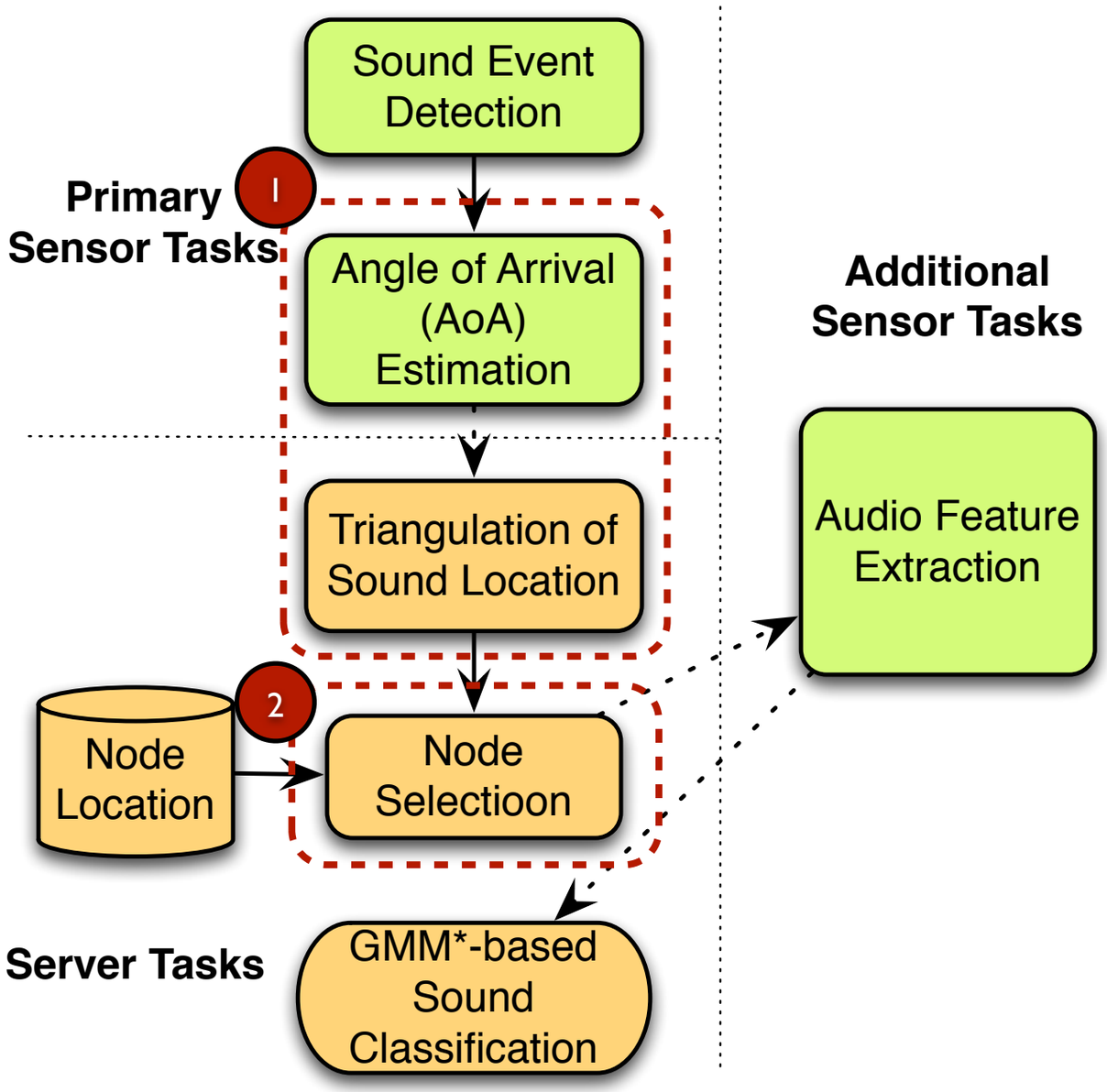
*GMM - Gaussian Mixture Model

System Overview



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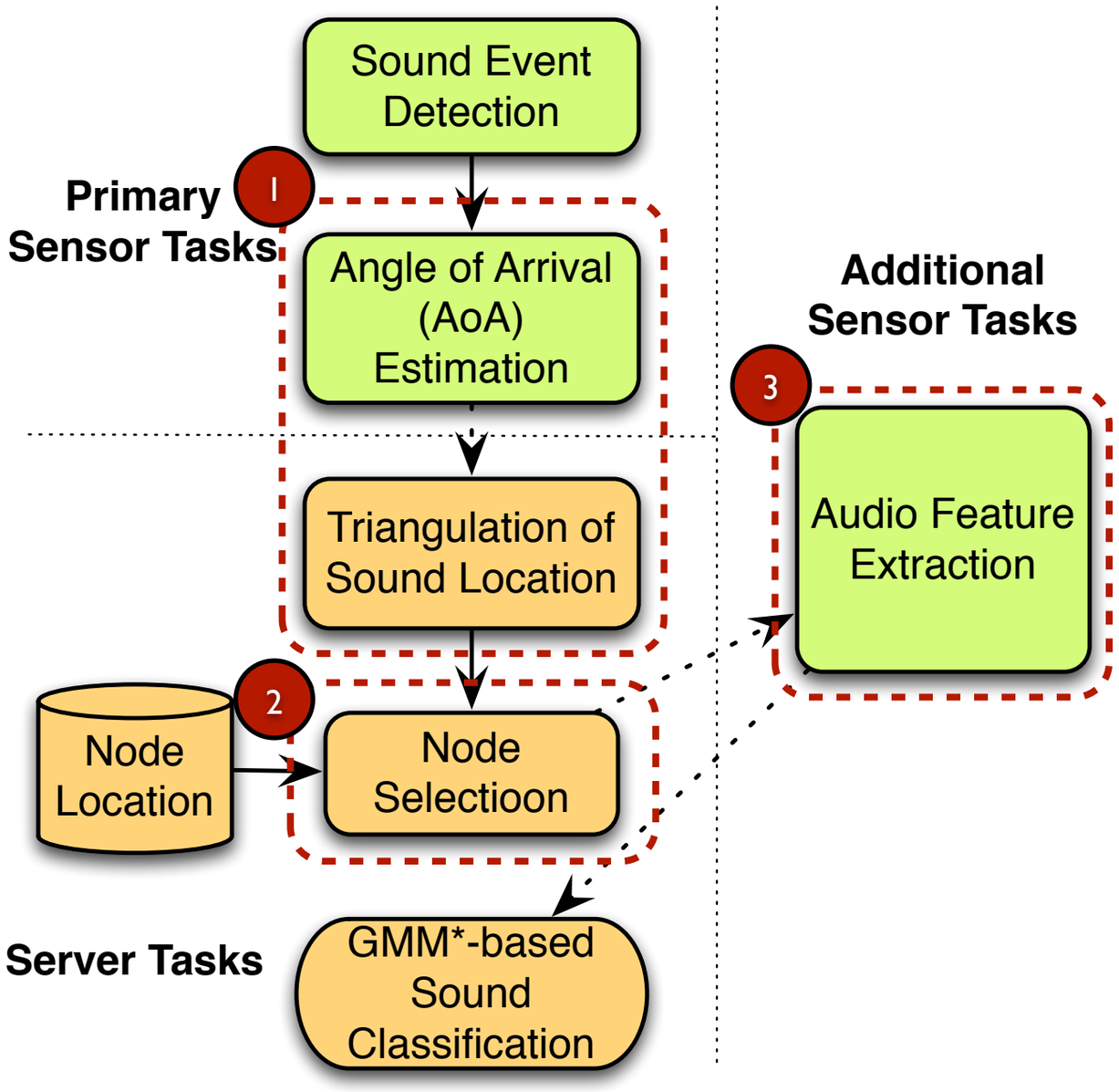

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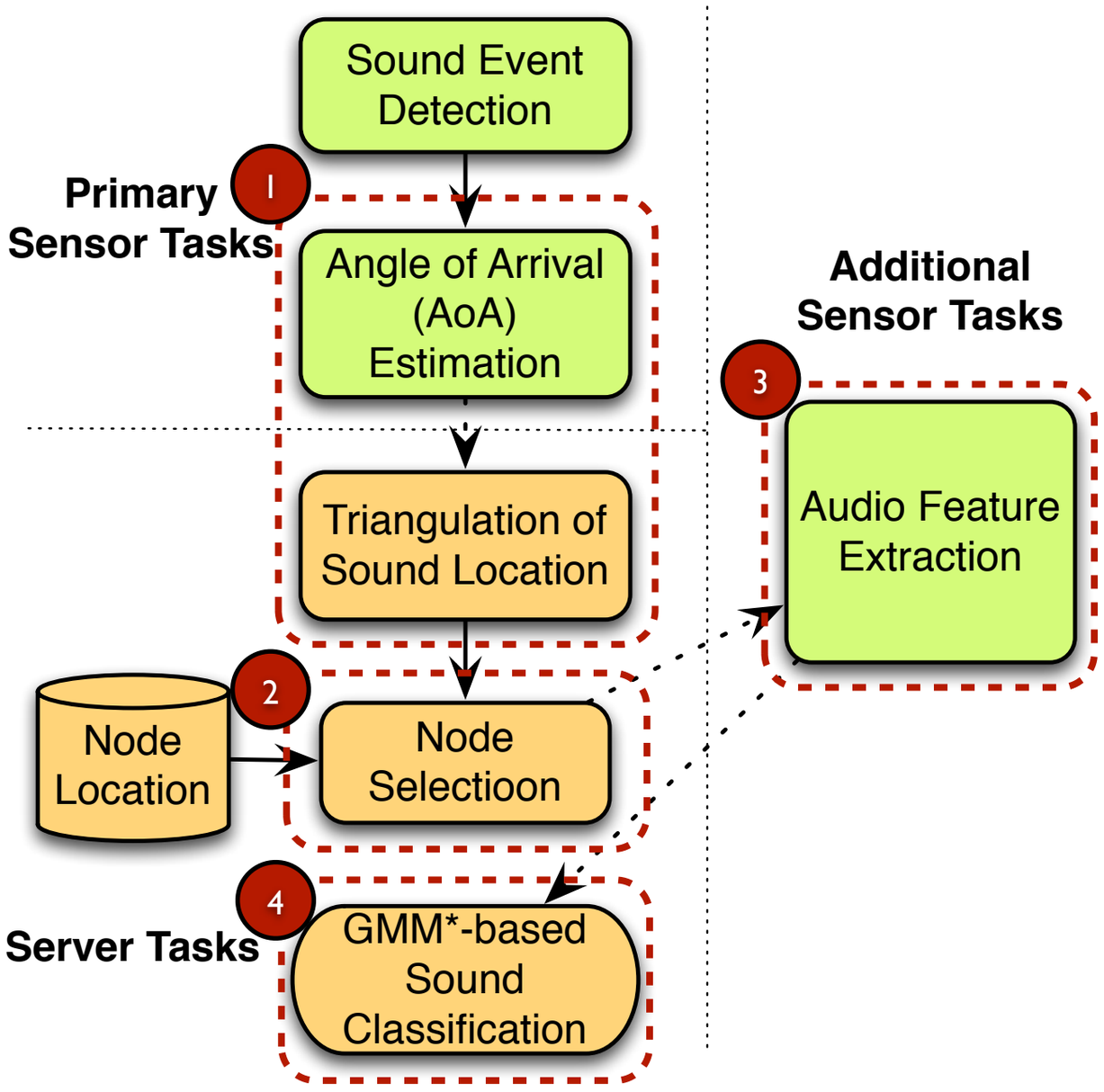

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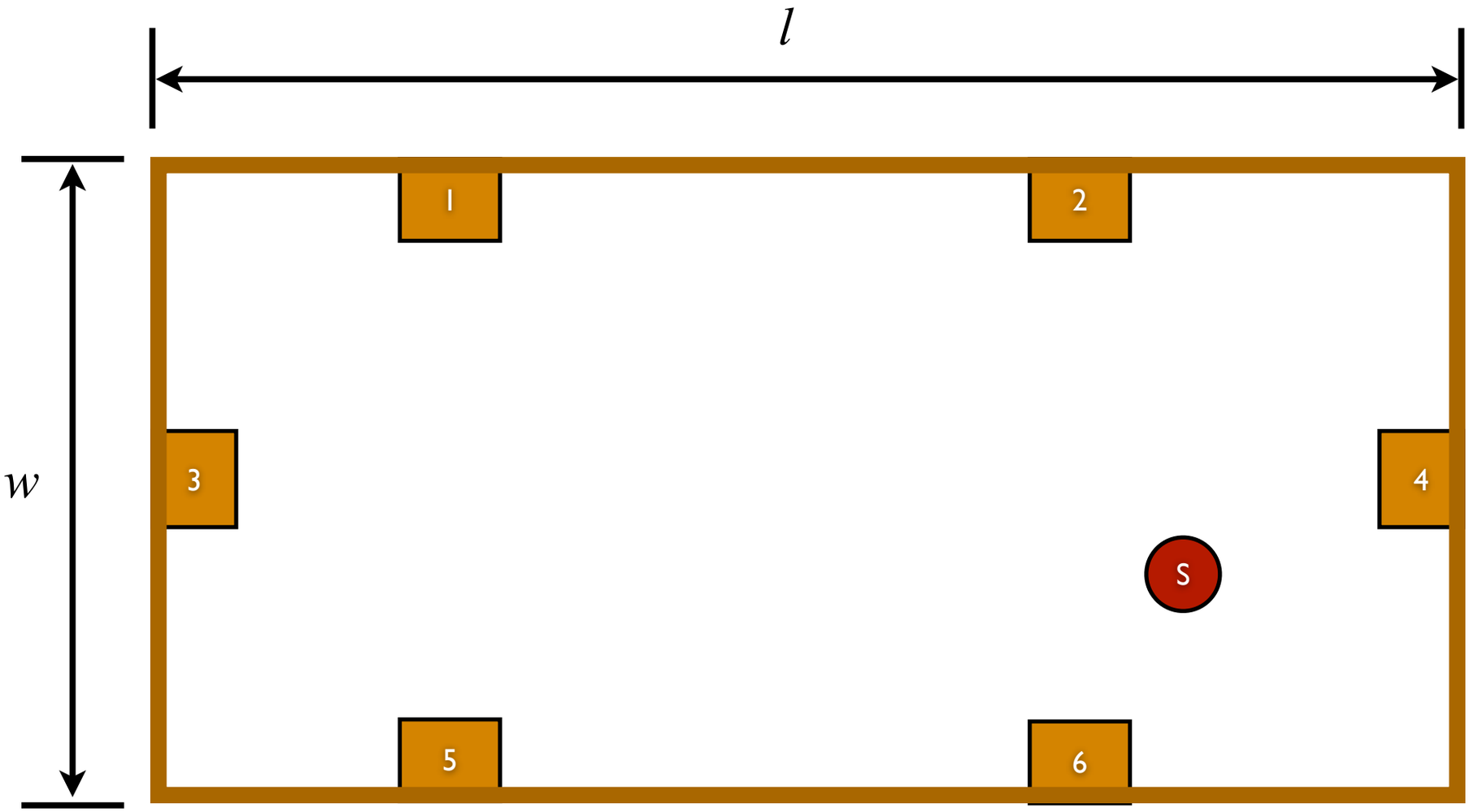
*GMM - Gaussian Mixture Model

Triangulation*

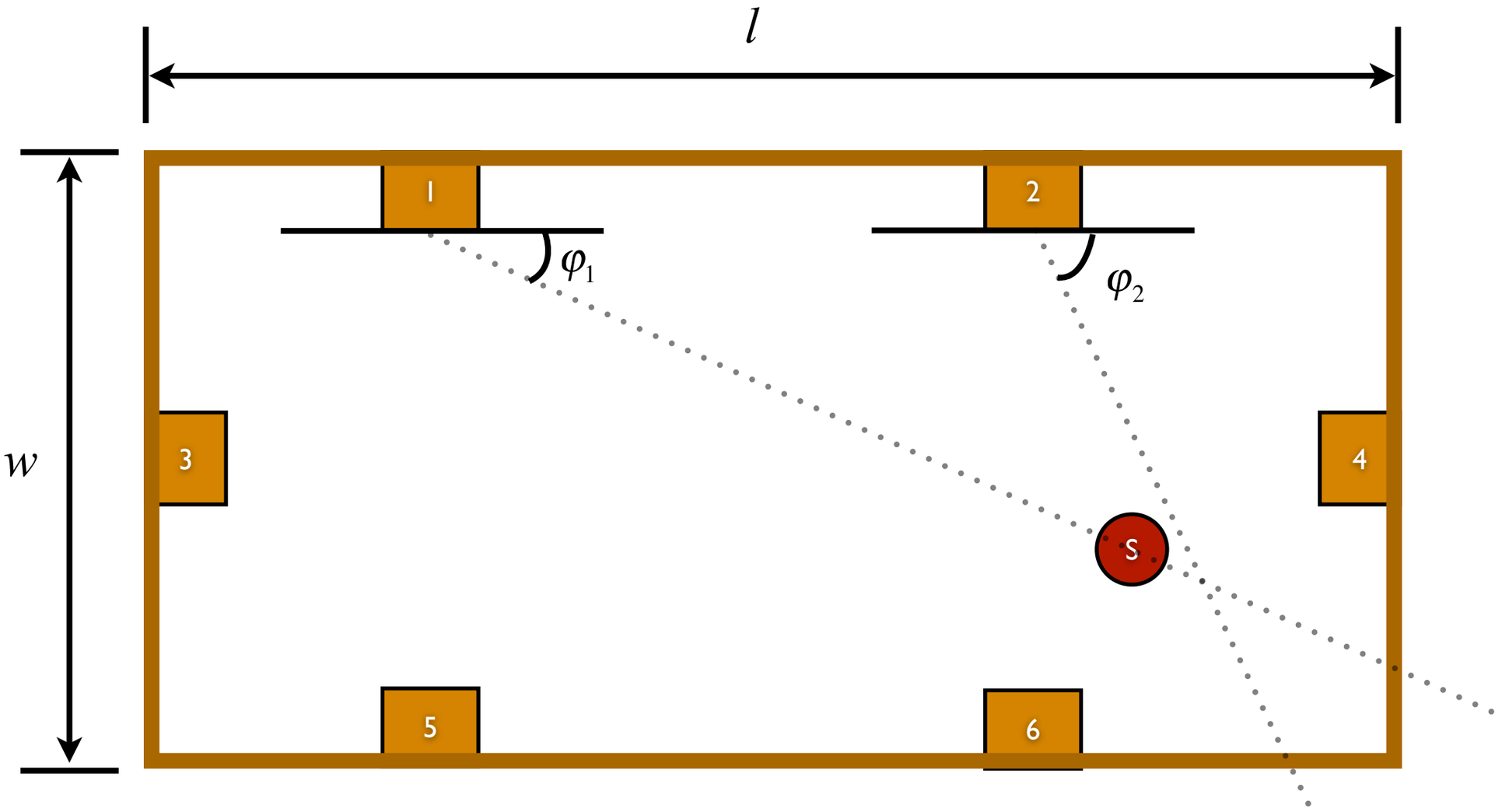


S Sound Source

i CoughLoc Sensor Node

* Commonly used in applications of ship navigation and surveying.

Triangulation*



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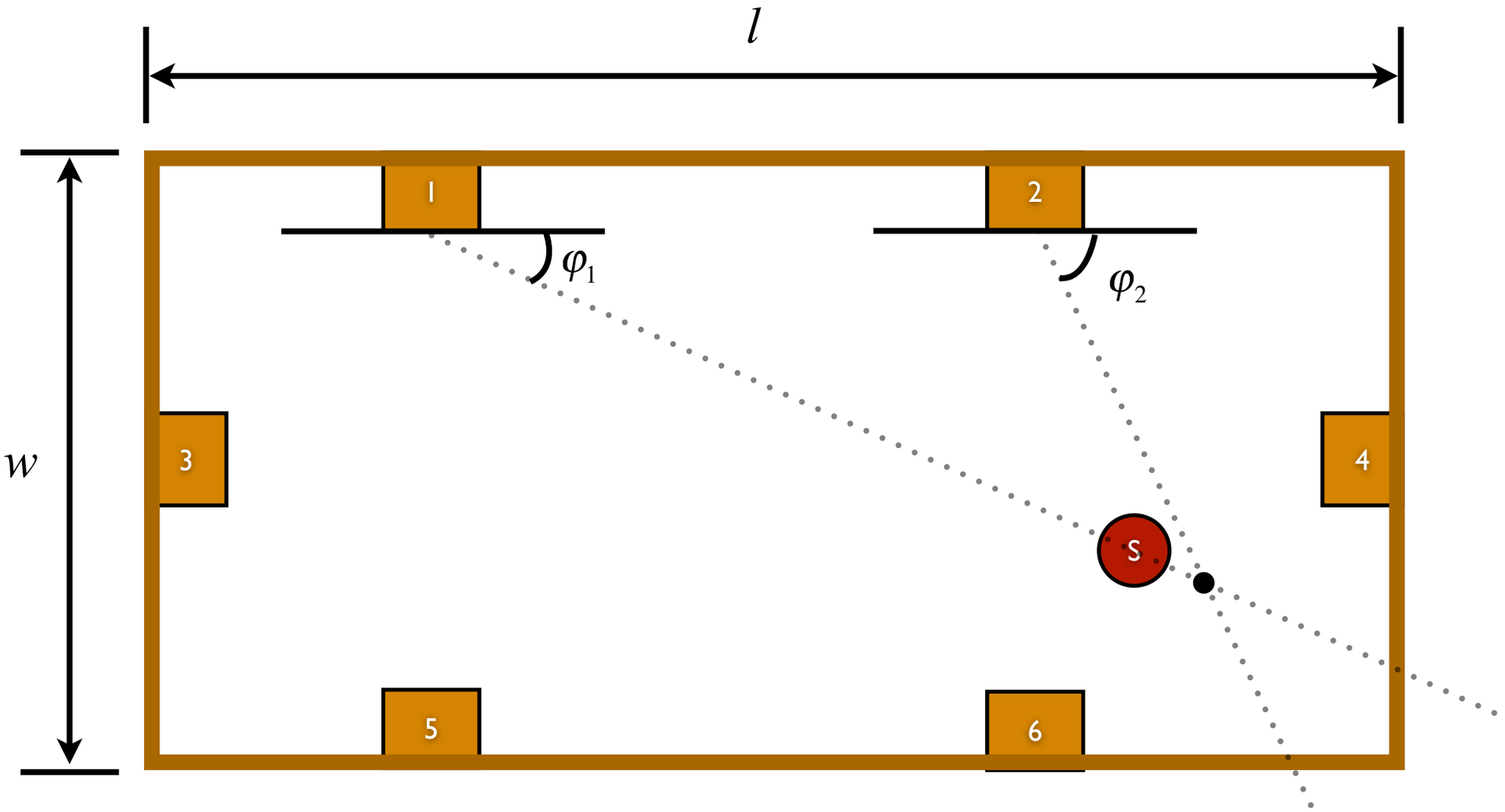

S Sound Source

i CoughLoc Sensor Node

- Candidate Estimates

* Commonly used in applications of ship navigation and surveying.

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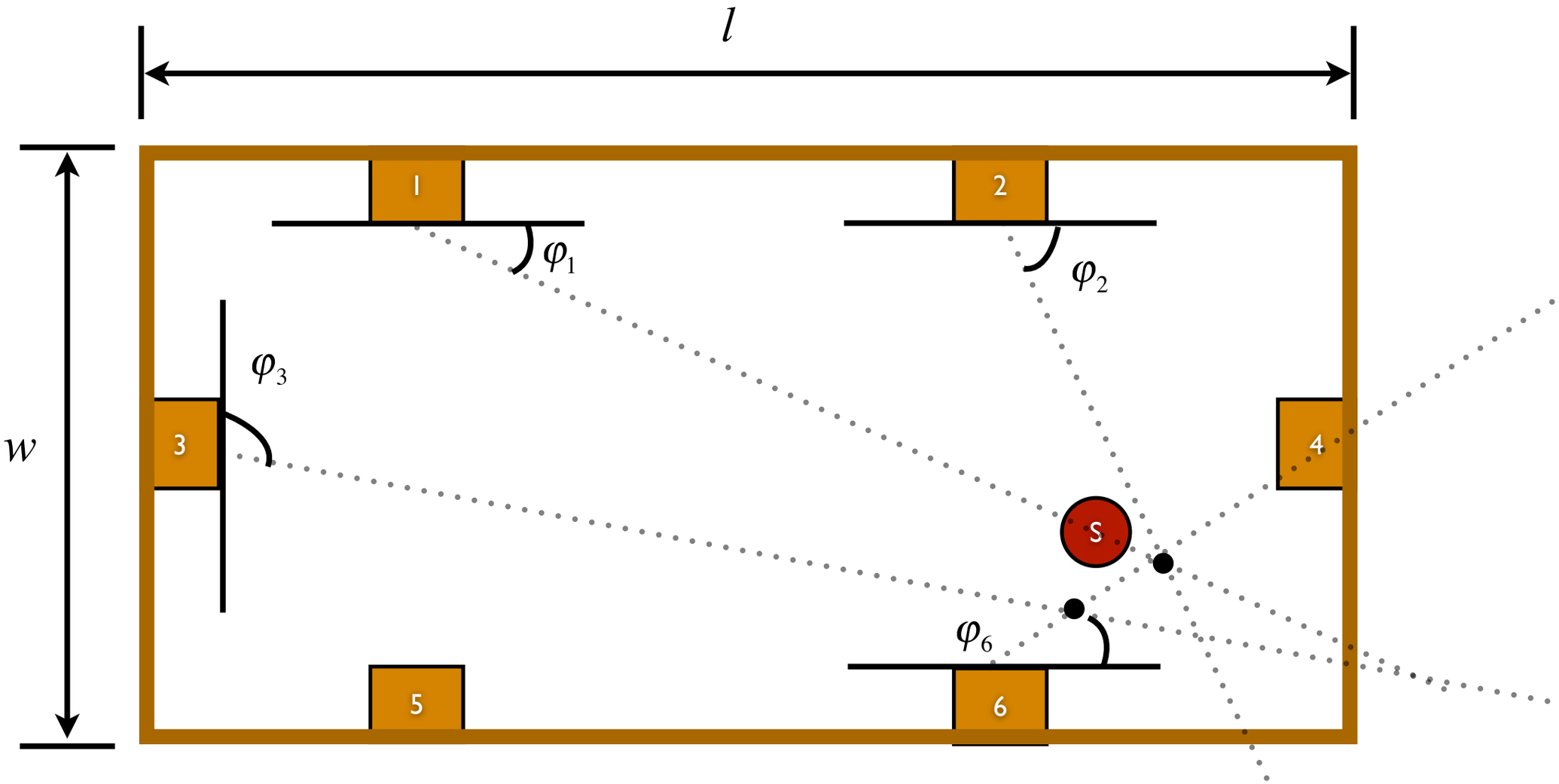

S Sound Source

i CoughLoc Sensor Node

- Candidate Estimates

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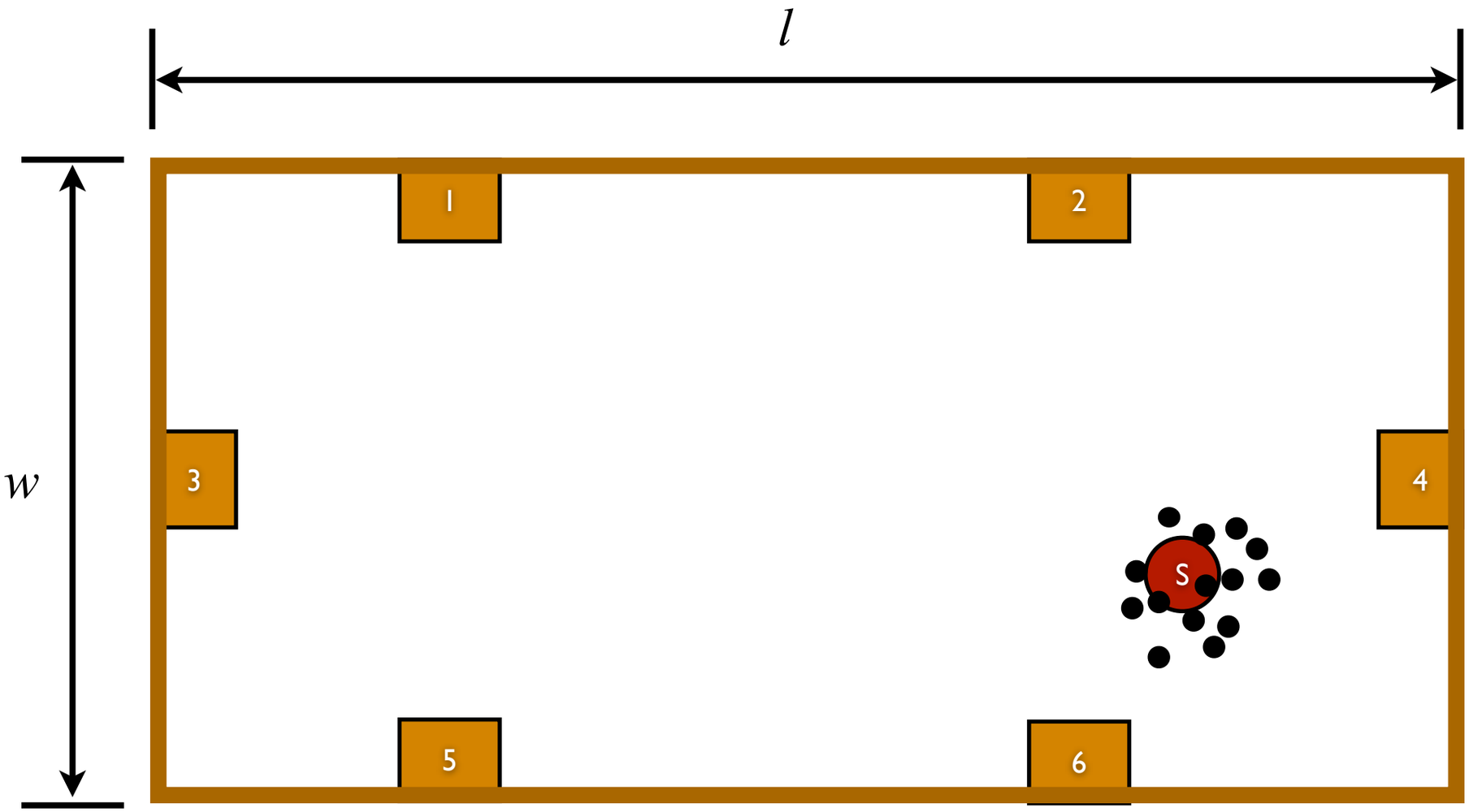
Triangulation*

Localization | Node Selection | Feature Extraction | Classification



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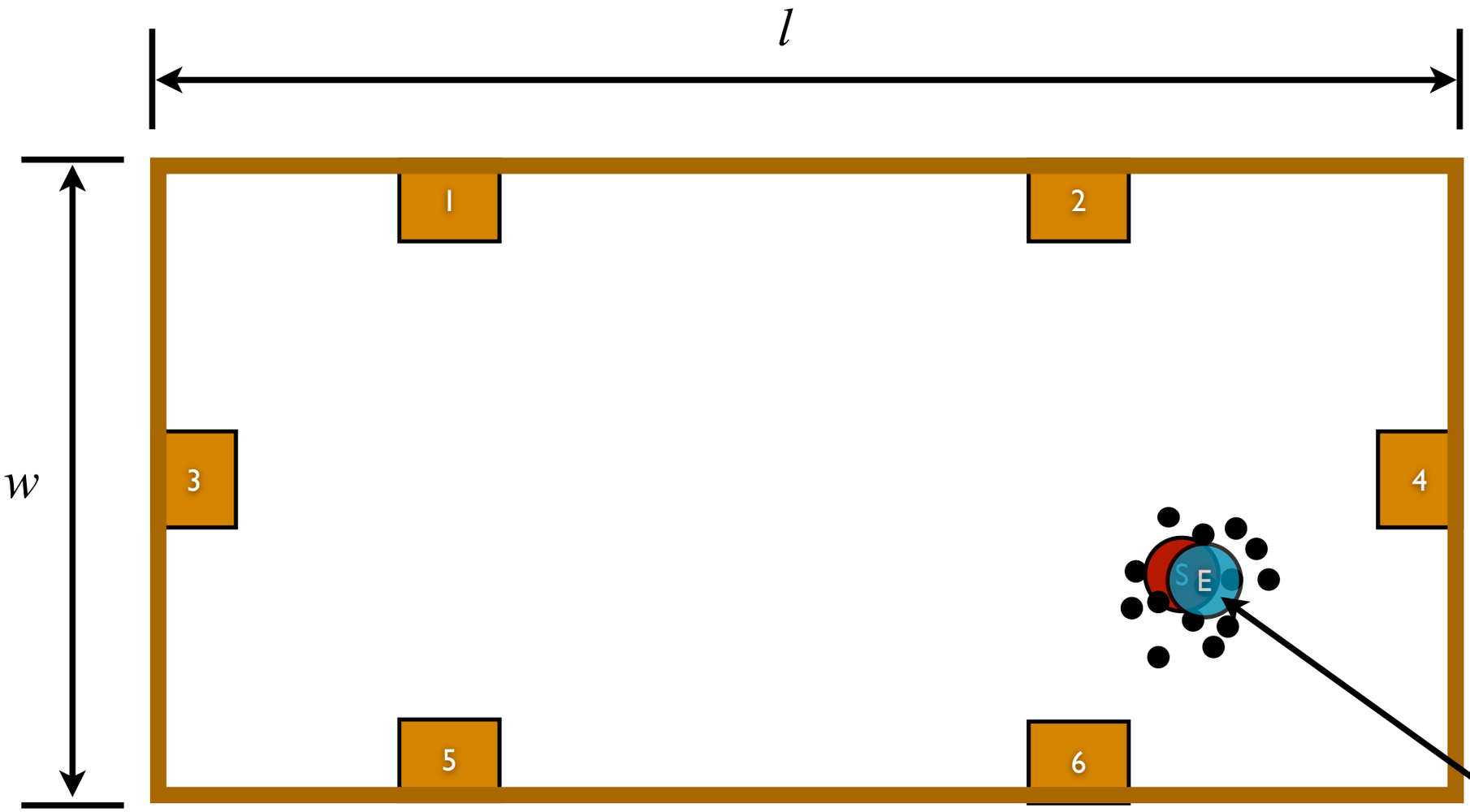

S Sound Source

i CoughLoc Sensor Node

- Candidate Estimates

E Final Estimate

Consider skewness of error distribution
Take median of candidates

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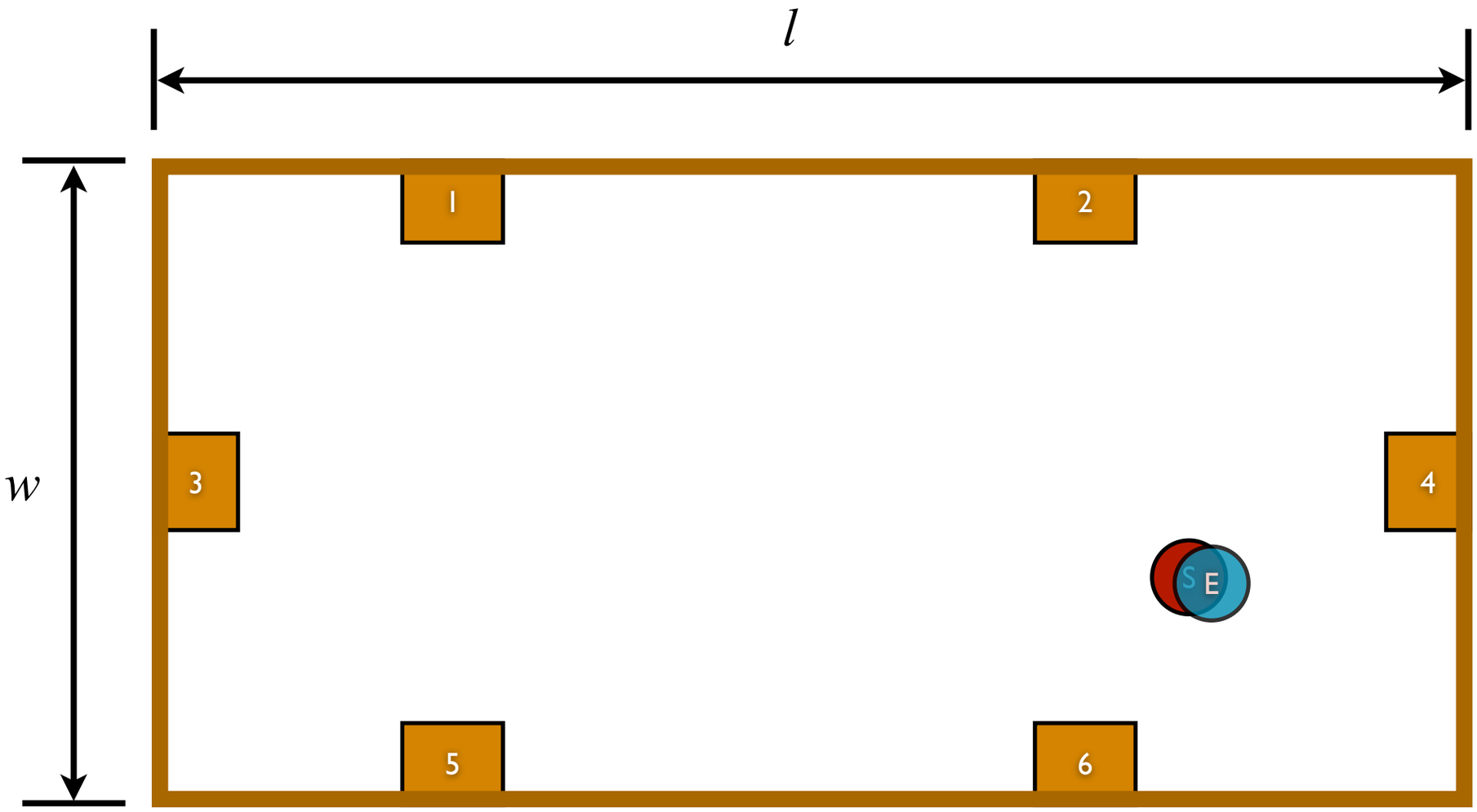
* Commonly used in applications of ship navigation and surveying.

Node Selection



S Sound Source

i CoughLoc Sensor Node

E Estimated Location

Node selection range - Accuracy vs. #node selected

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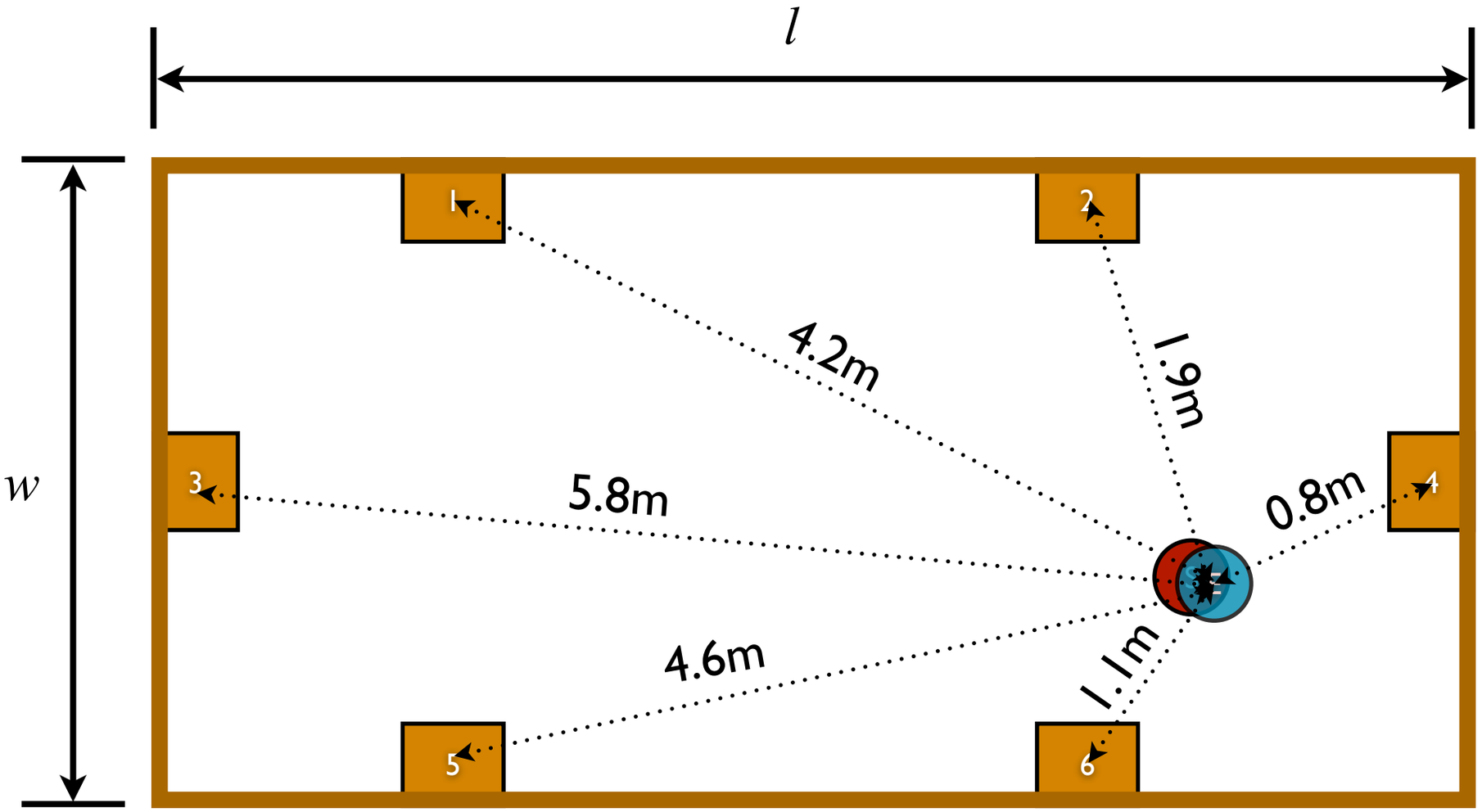
Node Selection



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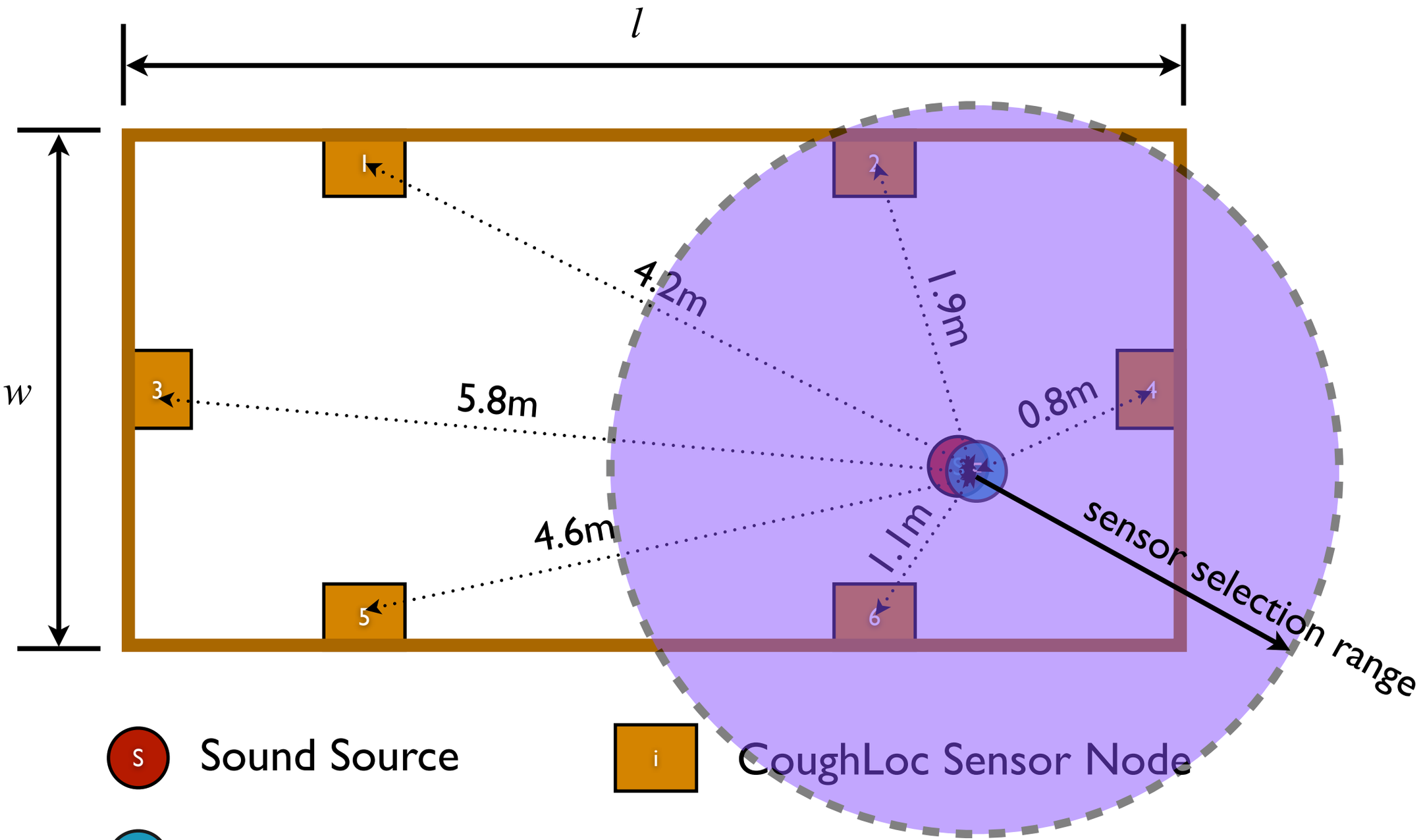

Node selection range - Accuracy vs. #node selected

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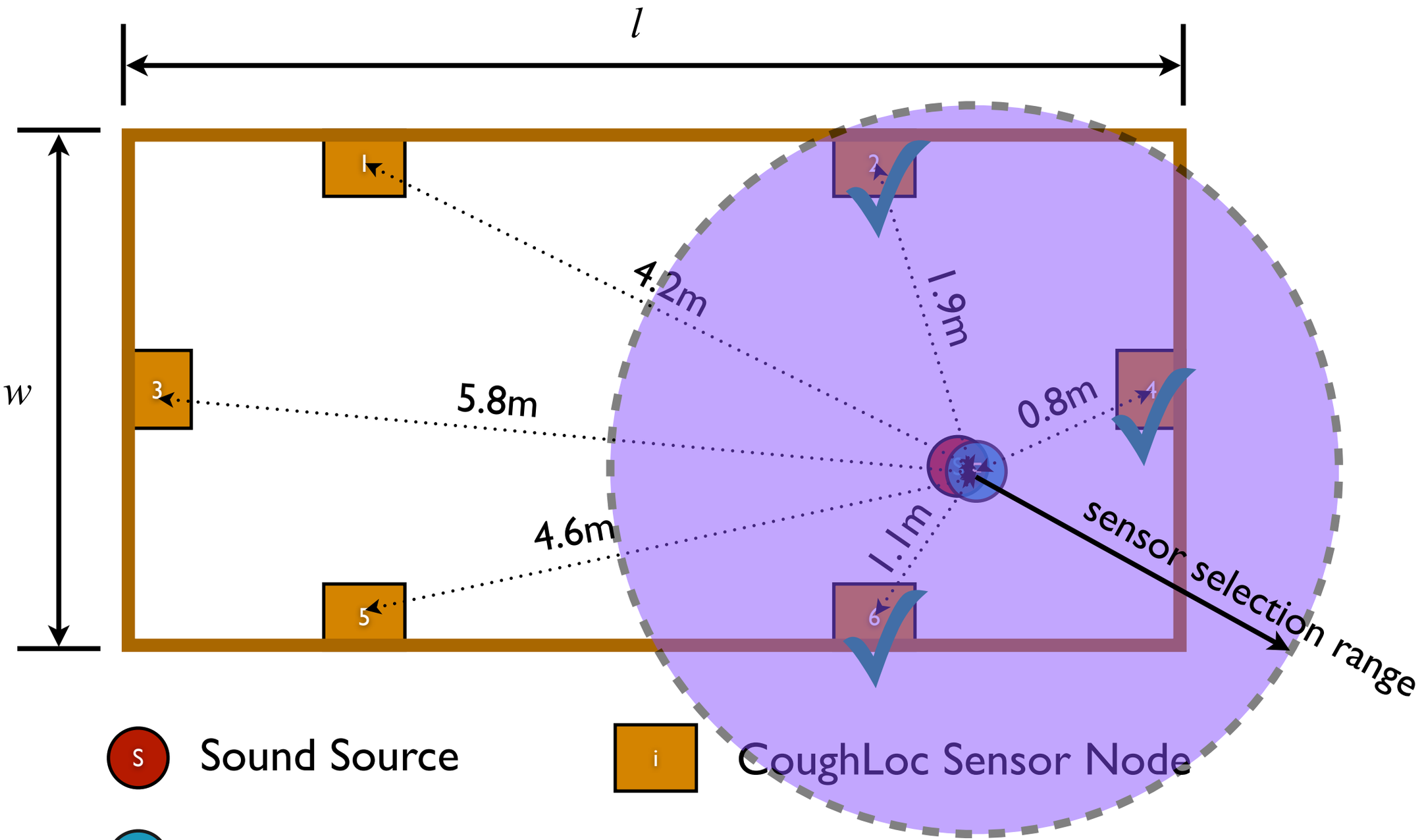

Node selection range - Accuracy vs. #node selected

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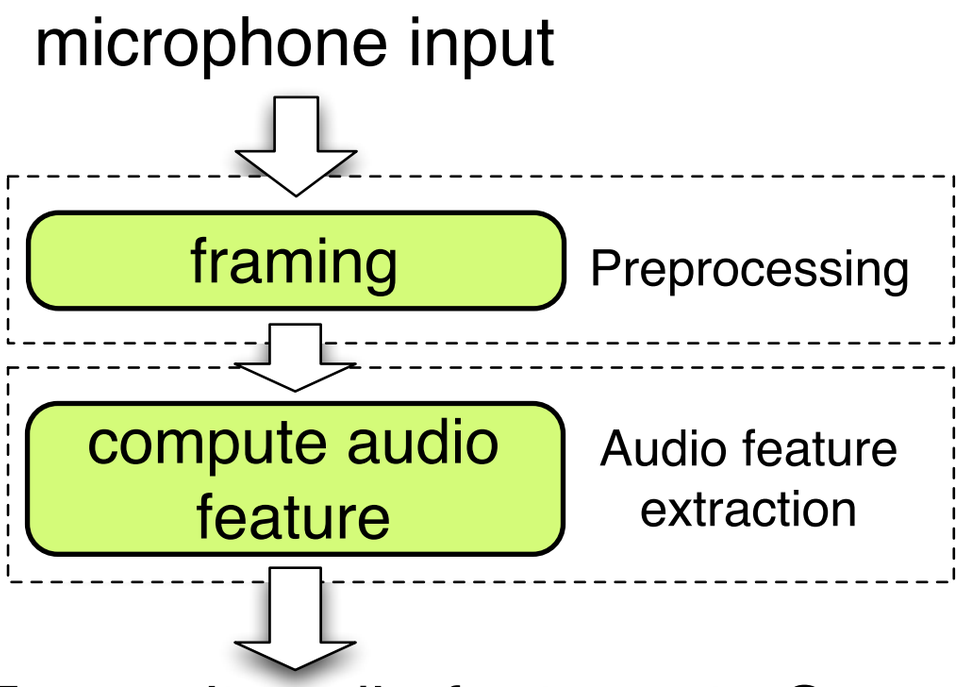
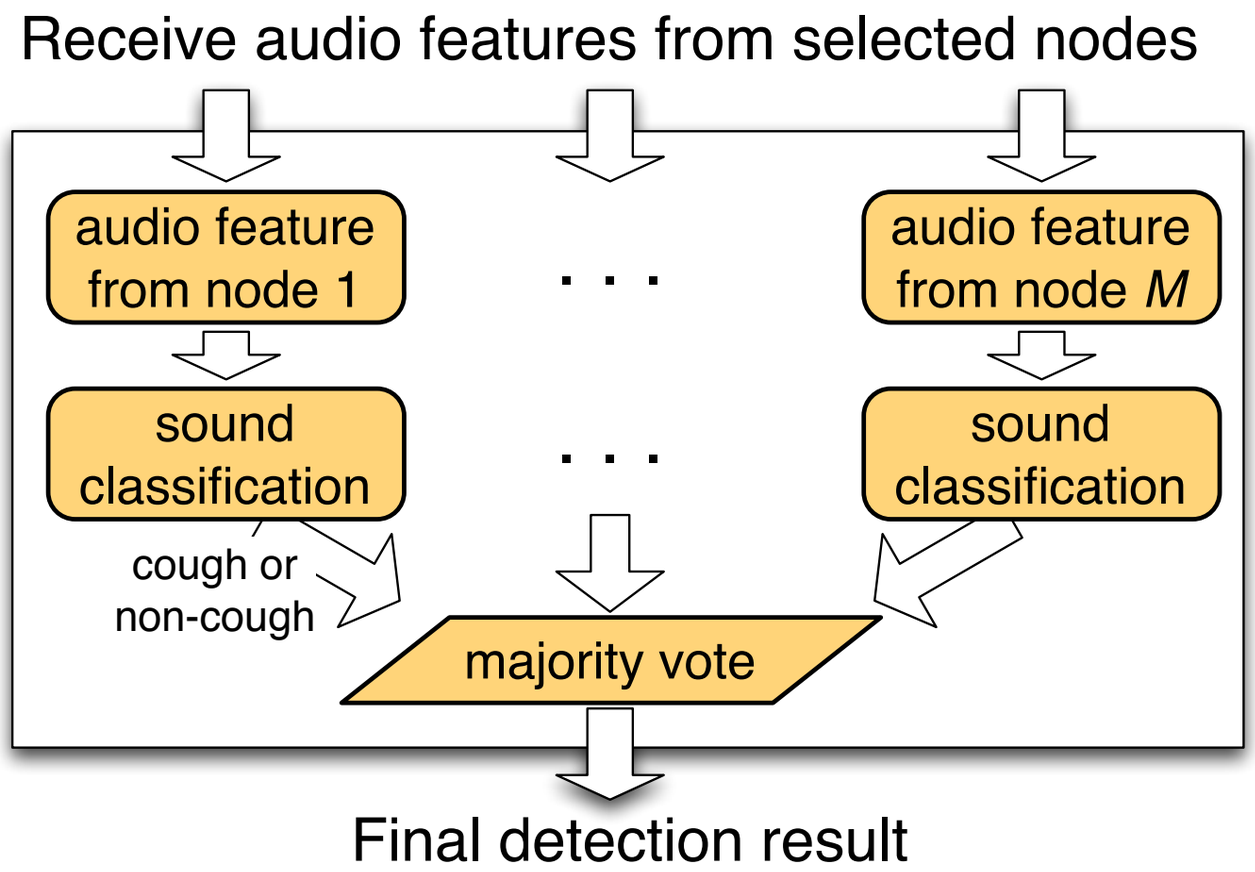
Audio Feature Extraction

- Formulate the cough detection problem as a binary sound (i.e. cough or non-cough) classification problem



Selected Nodes



CoughLoc Server

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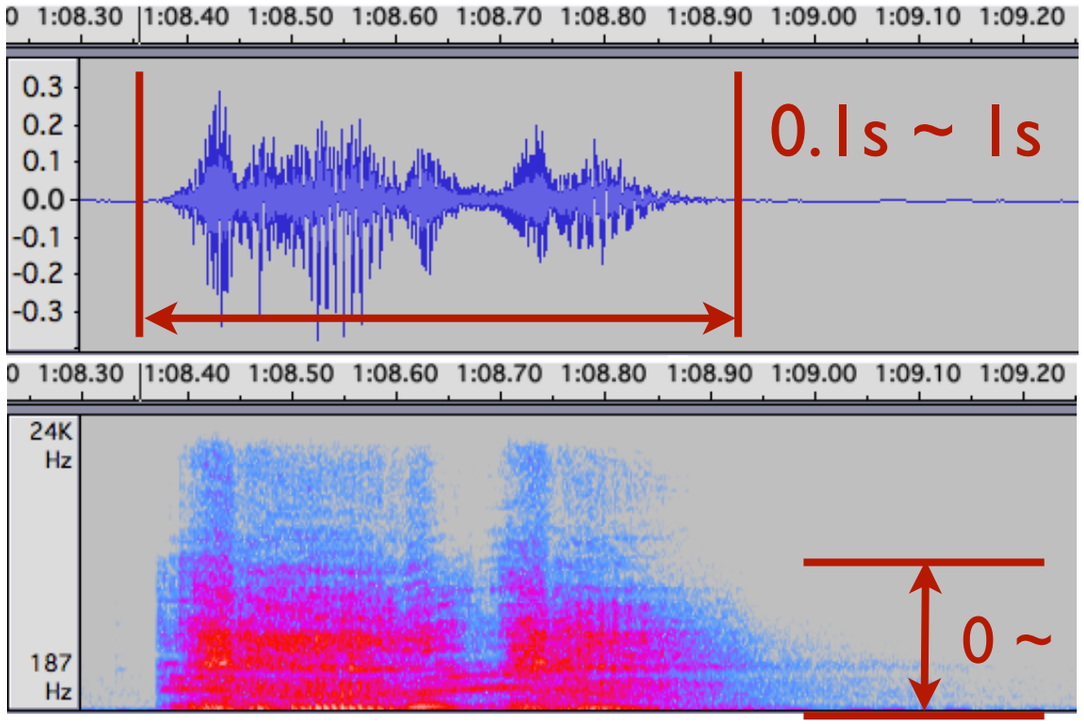
Audio Feature Extraction

- Mel Frequency Cepstral Coefficients (MFCC)
  - Discriminative to represent cough characteristics
  - Short-time power spectrum, ranging 0 ~ 20KHz
  - Widely used in cough detection researches



(real cough audio collected in my experiments)

- Cough Characteristics
  - Main energy
  - Duration
  - Loudness varies

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Matos S, et al. An automated system for 24-h monitoring of cough frequency: the leicester cough monitor. *IEEE Trans. on Biomedical Engnr.*. 2007.

Sound Classification

On the server

- Gaussian mixture models (GMM)-based classifier
  - 2 GMMs to represent "cough" and "non-cough", respectively
  - Empirically, each GMM contains 4 Gaussian distributions
- Final Classification based on weighted majority vote

K : number of selected sensors

ai : per-node GMM classification result

$$S = K \cdot \sum_{i=1}^{K} w_i \frac{a_i}{\sum_{i=1}^{K} w_i},$$

wi : corresponding likelihood of the ith node

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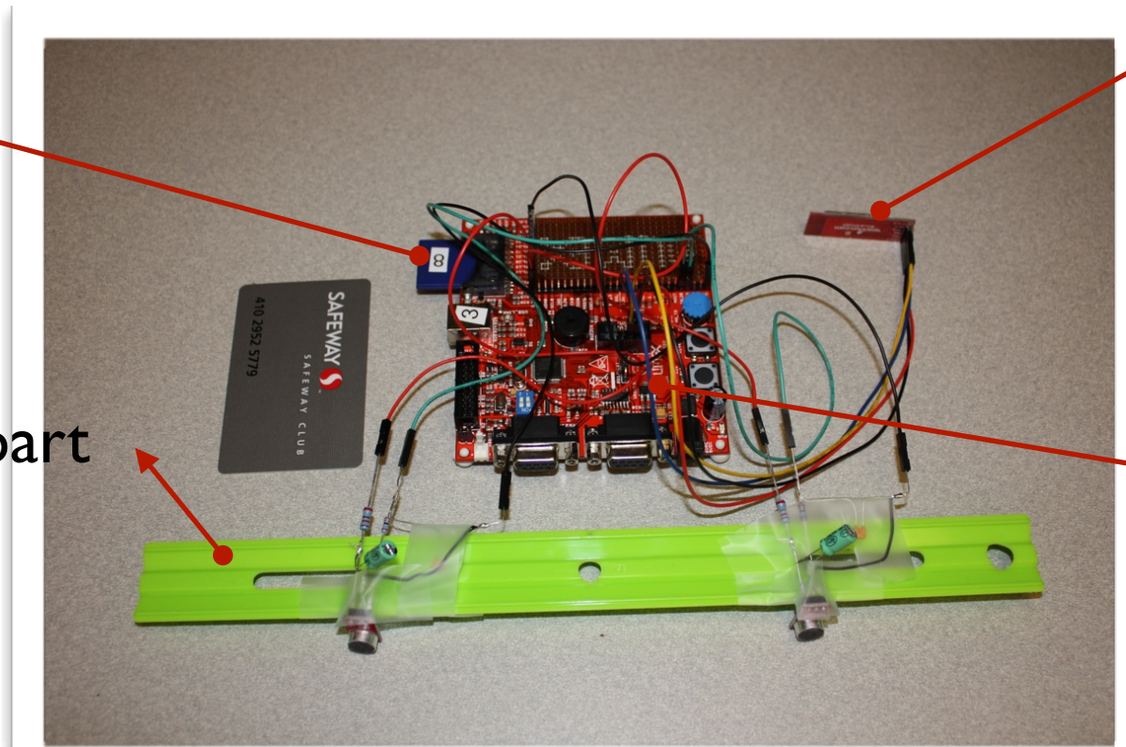
Implementation

- Hardware

SD card storage

Bluetooth



Microphone x 2, 15cm apart

ARM7 60MHz CPU
256KB flash
42KB RAM
Wall power supply

Experiment Process

- **Before**
  - Record clear human coughs (12min, 179 individual coughs)
- **During**
  - Replay back under quiet and noisy backgrounds, changing loudspeaker locations
  - Collect audio using acoustic sensor nodes
- **After**
  - Save audio in database; analyze audio offline using the proposed approach

Dataset

- 8 x 6m^2 classroom; 8 acoustic sensor nodes; midnight
- Four representative noise types

Human voice-like sound
(ABC World News program)

Continuous low-freq and steady hums
(microwave oven)

Loud and high-freq sound
(vacuum cleaner)

Cough Only

Quiet

- 40 hours training (~35,400 coughs) and 5 hours test data (~4,700 coughs)

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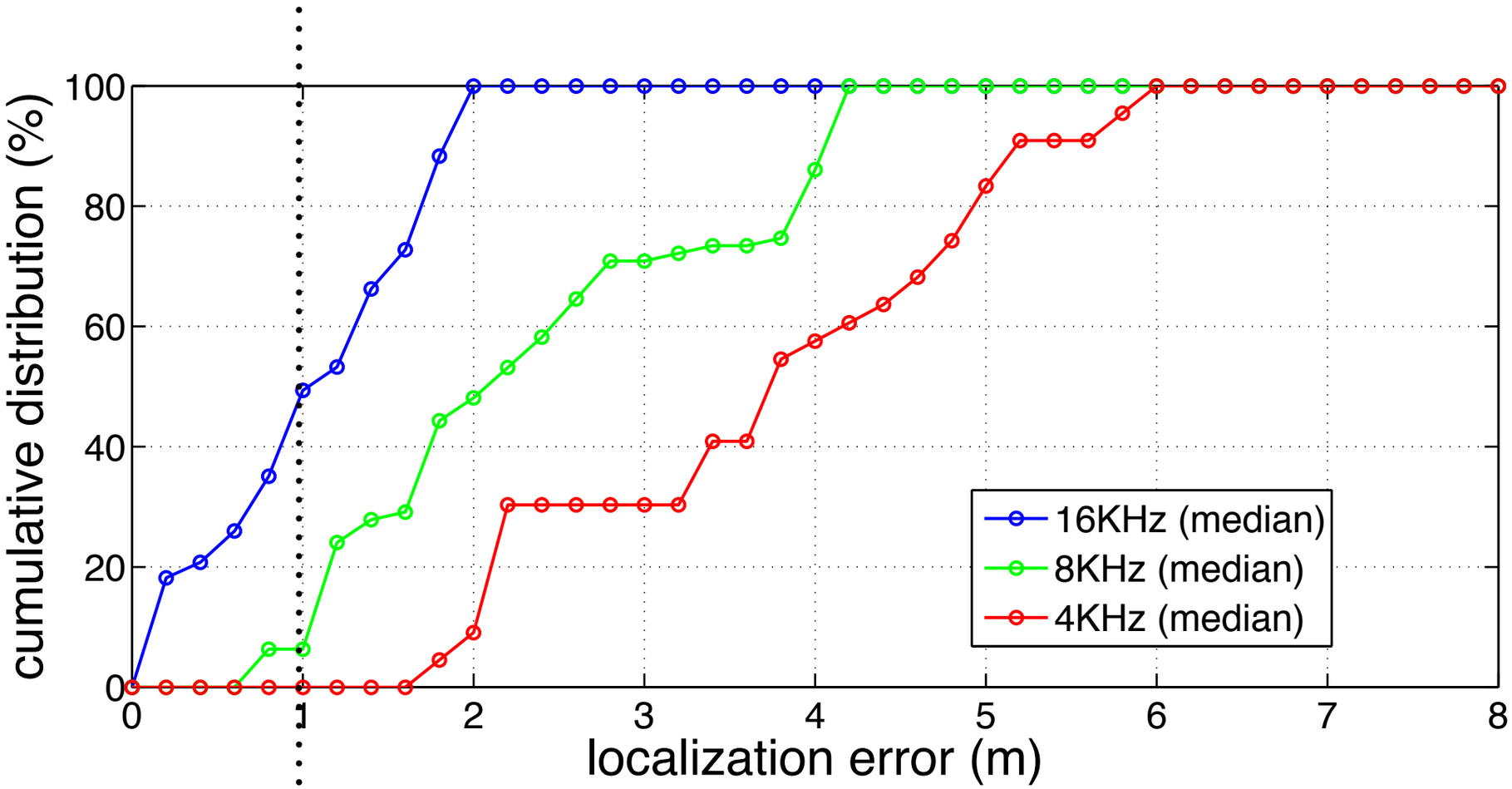
* cough × mic × node × loudspeaker location
$158 \times 2 \times 8 \times 14 = 35392$
$21 \times 2 \times 8 \times 14 = 4704$

How well can we localize a coughing sound source?



- Audio signals down-sampled from 16KHz to 8KHz, 4KHz
- The higher the sampling rate, the smaller the average errors
- The system can localize within 1.0m

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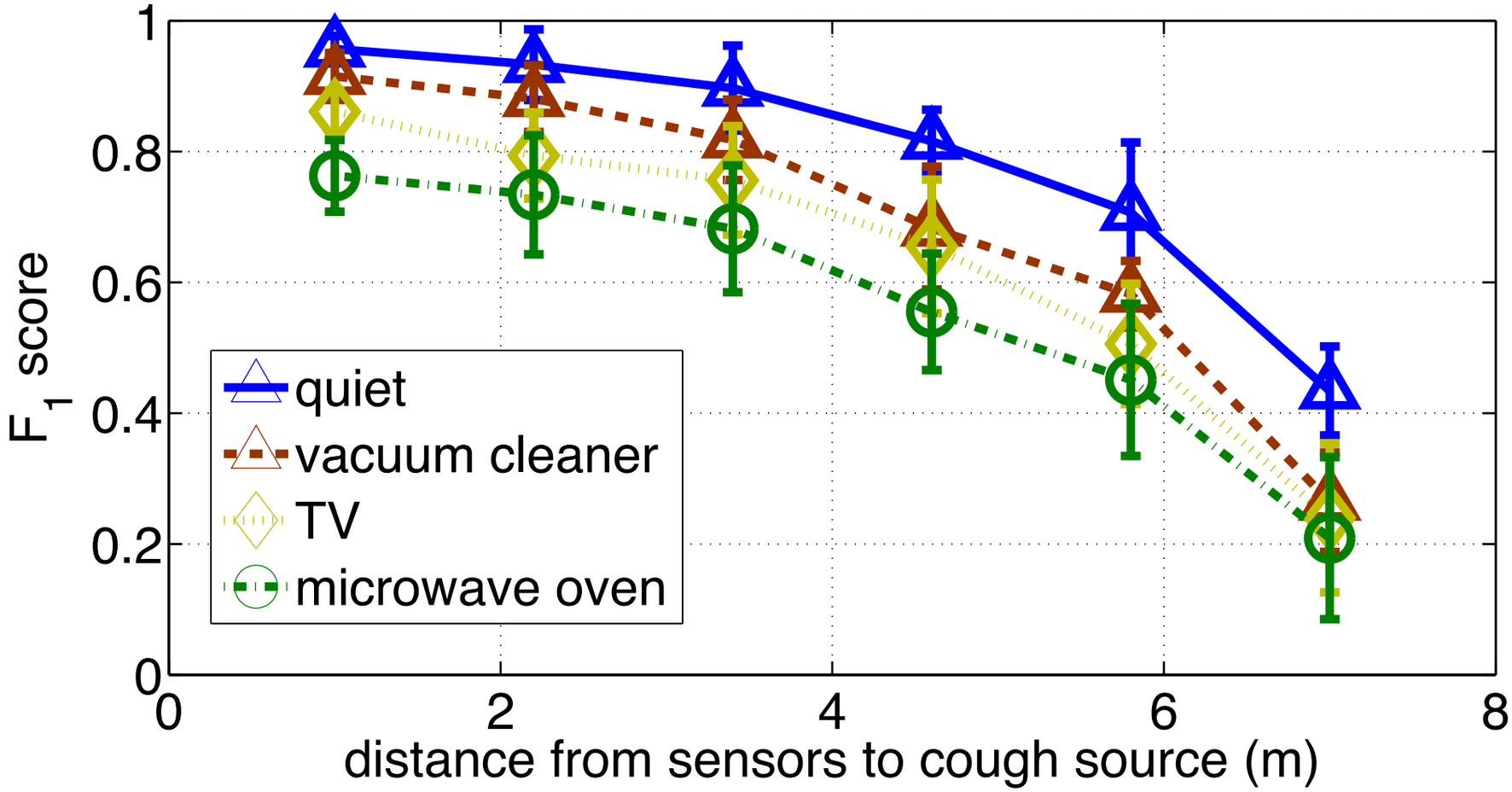
Cough Detection vs. Distance to Loudspeaker (Single Node)



$$precision = \frac{\#\text{true positives}}{\#\text{true positives} + \#\text{false positives}} \qquad recall = \frac{\#\text{true positives}}{\#\text{true positives} + \#\text{false negatives}}$$

$$F_1 = \frac{2 \cdot precision \cdot recall}{precision + recall}$$

- The higher the F1, the better the performance

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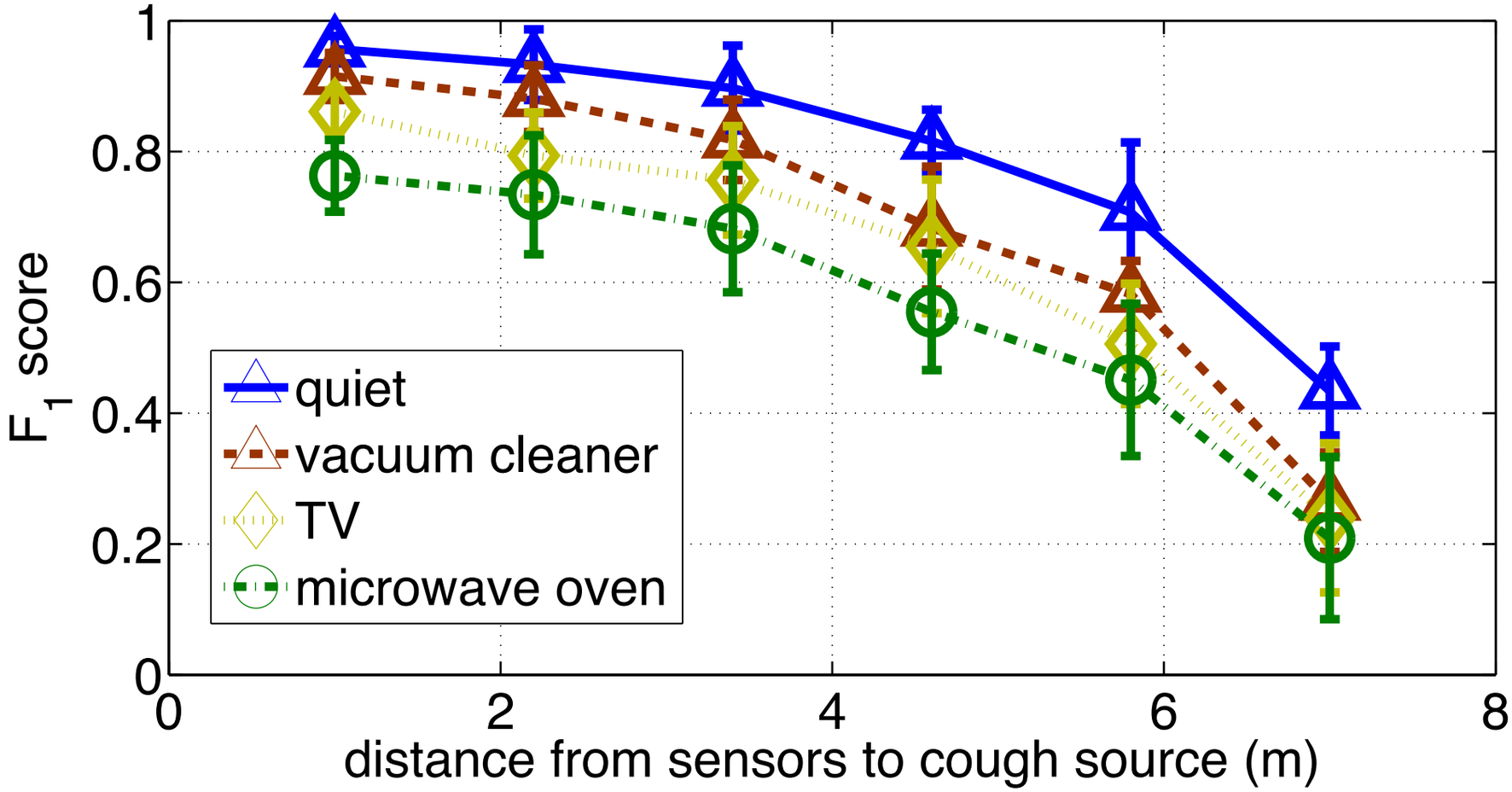
Cough Detection vs. Distance to Loudspeaker (Single Node)



- Nodes with longer distance make worse detection
- Single-node detection is greatly affected by distance

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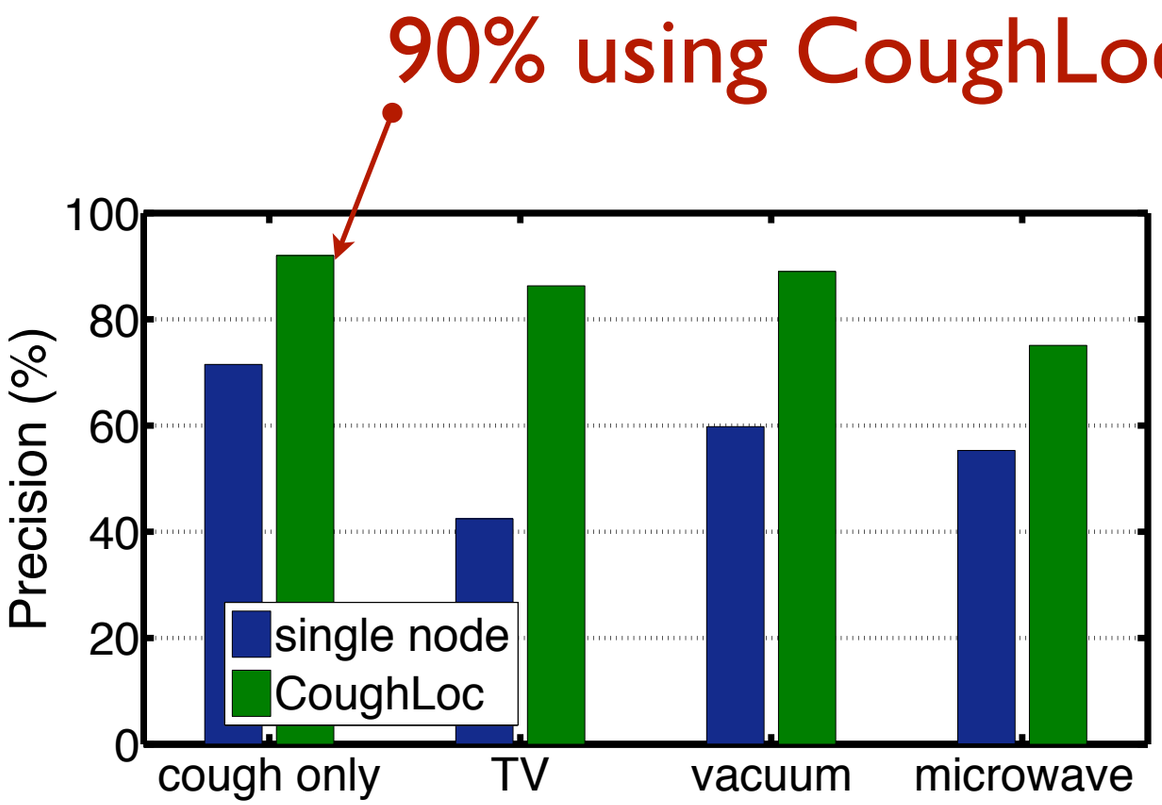
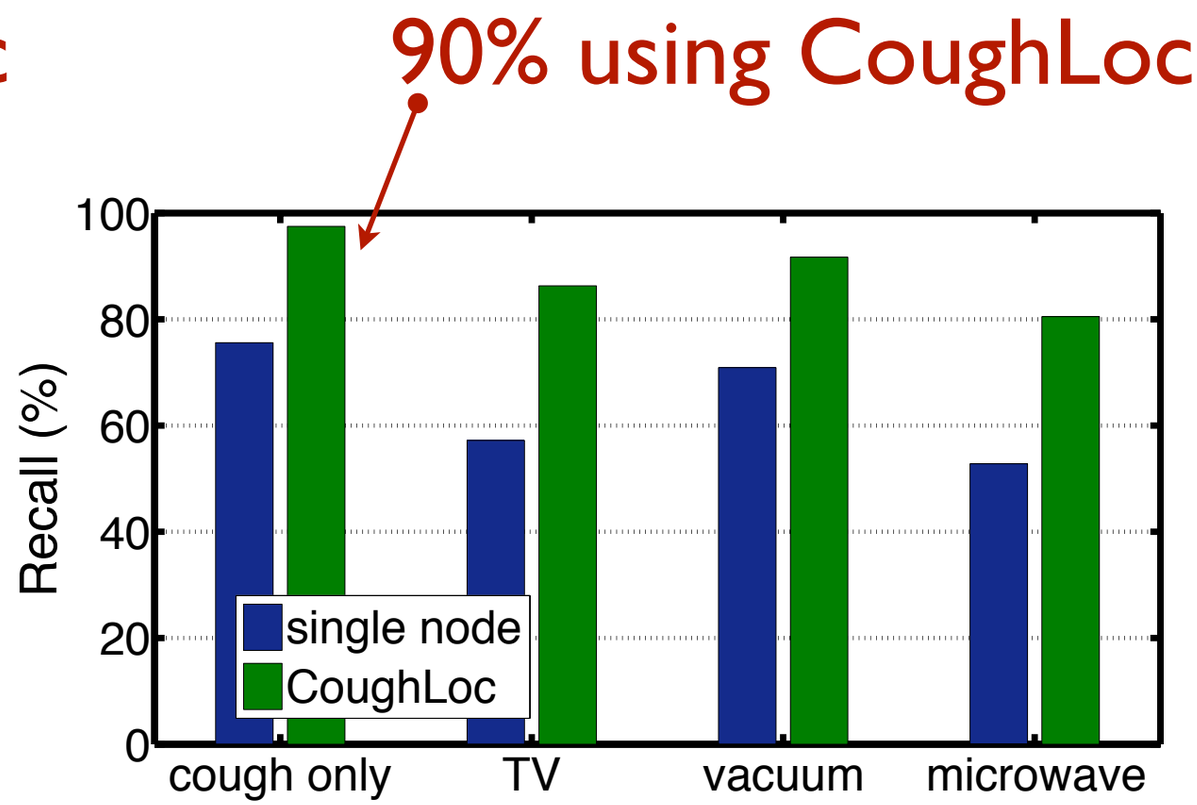
Cough Detection (Single Node vs. CoughLoc)





- 90% precision/recall under quiet condition
- Competitive with state-of-the-art with less intrusiveness[1]

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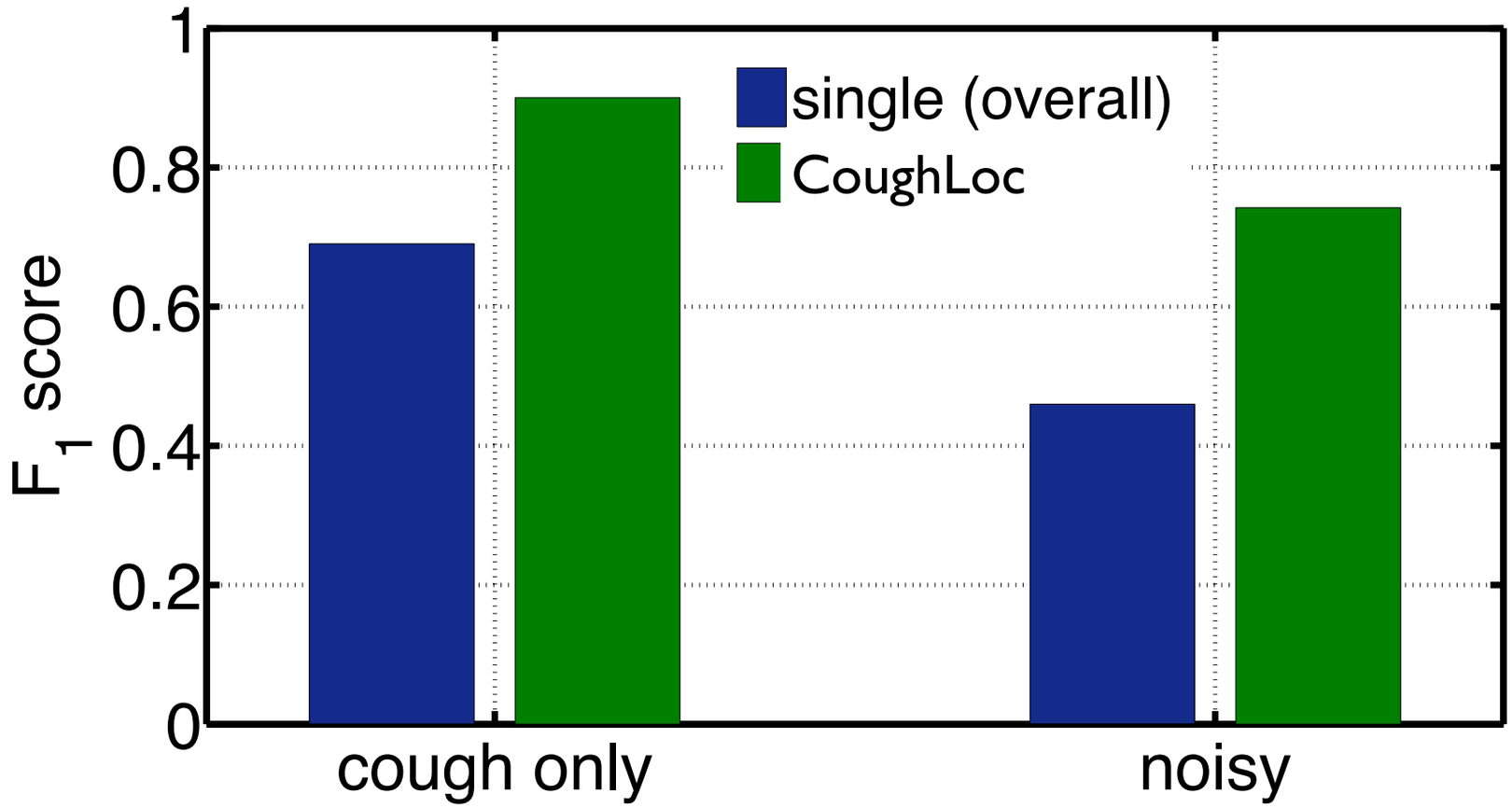
[1] S. Matos et al., An automated system for 24-h monitoring of cough frequency: the leicester cough monitor. *IEEE Transactions on Biomedical Engineering*, 2007.

Cough Detection (Overall Performance)



30% and 60% higher F_1 than baseline under quiet and noisy conditions

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Conclusions

- Location-aware acoustic sensing deals with patient mobility
  - Unobtrusiveness
  - 90% and 80% accuracy under quiet and noisy conditions; 60% higher accuracy than using the single-node baseline
- Low-end hardware keeps system cost low (<$50)
- Task partitioning compensate for hardware limitations

CoughLoc: Non-Intrusive Cough Monitoring

Questions?