PANDAA:
Physical Arrangement Detection of Networked Devices through Ambient-Sound Awareness

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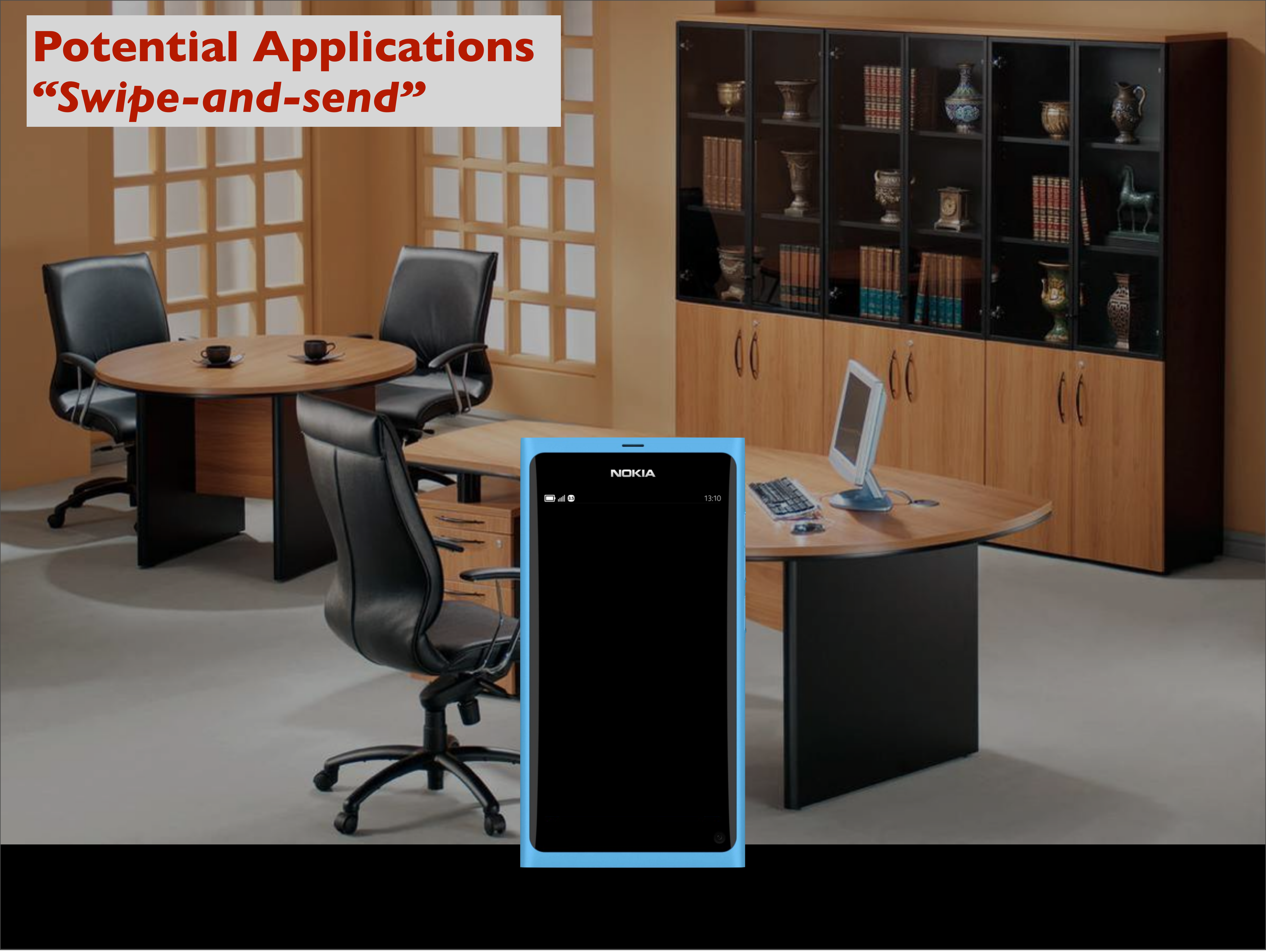
Ubicomp full paper, Sept 21st 2011 (Best Demo Award, too)

The Problem

Potential Applications
"Swipe-and-send"



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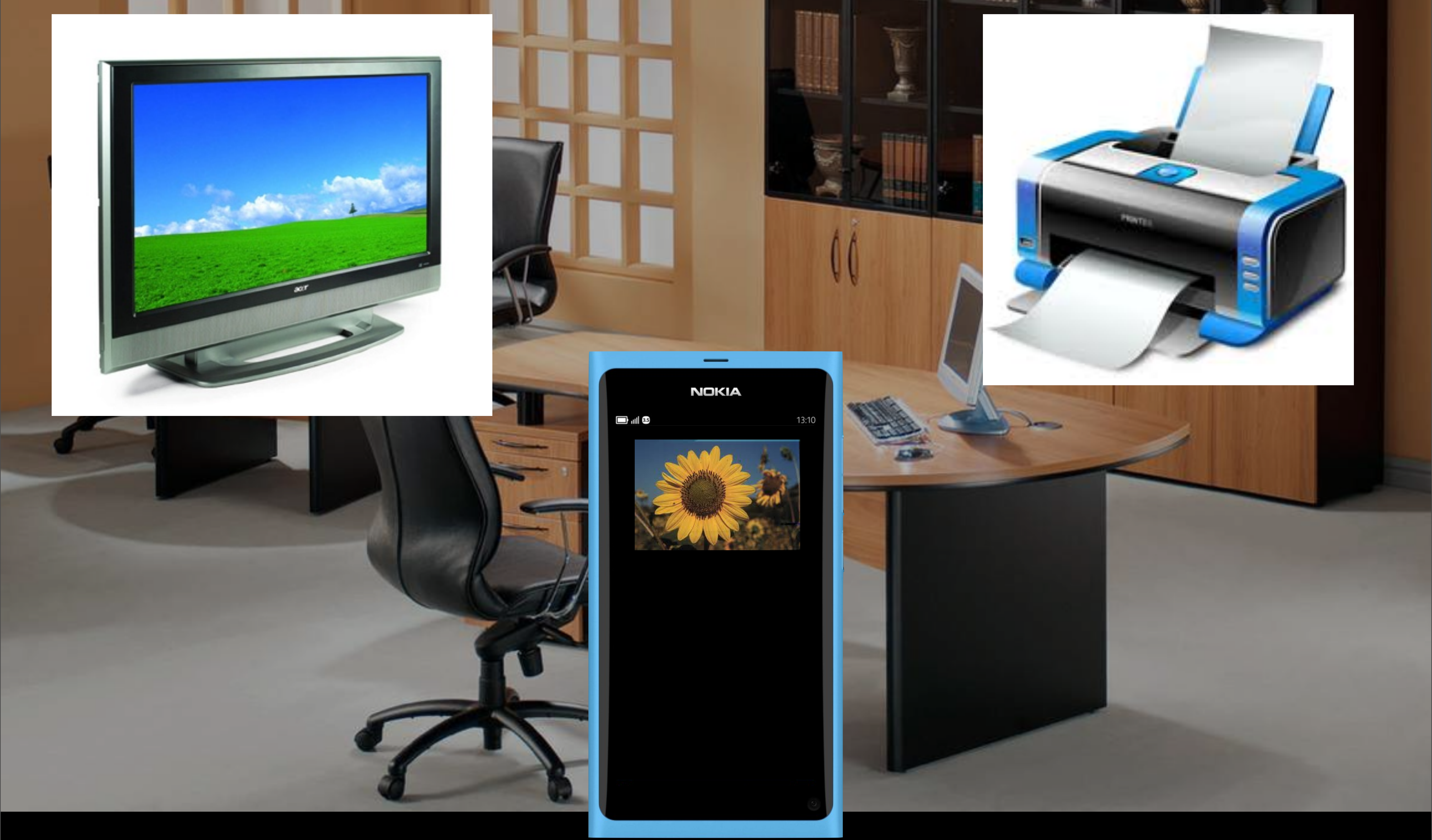

Potential Applications
“Swipe-and-send”

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“Swipe-and-send”

“Smart Offices”

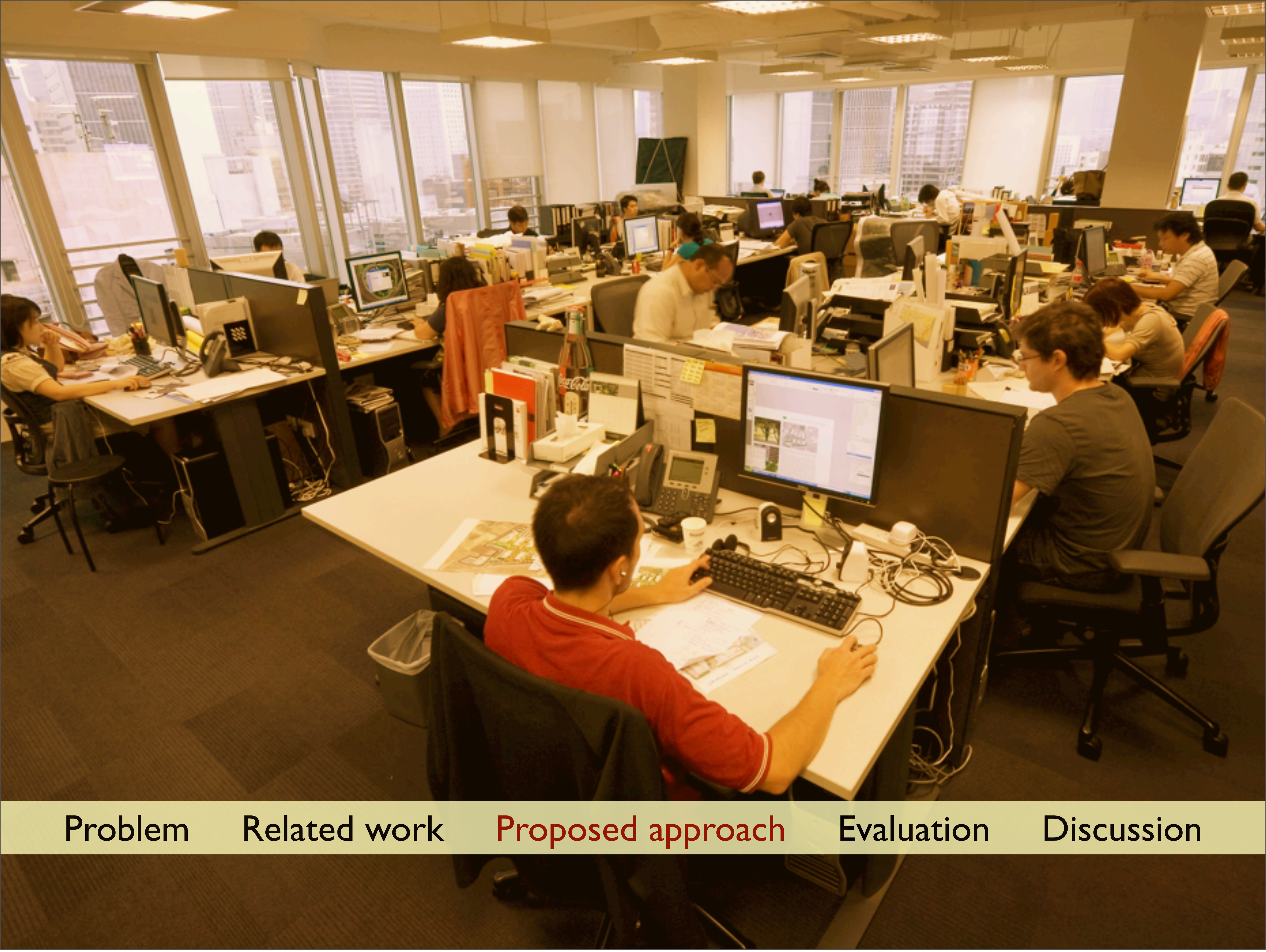
Meetings - Intuitive Content Sharing

Requirements

- Must be accurate (sub-meter).
- Work on off-the-shelf devices, minimal requirement of specialized hardware.
- Non-intrusive, automated operation and maintenance.

Related Work (Indoor Localization)

	Desired Sub-meter Accuracy	Requirement of Specialized Hardware	Non-intrusive
WiFi signal strength range/ fingerprint	✗	Low	✓
Ultrasound-RF	✓	High	✓
Audible chirp ranging	✓	Low	✗
Ambient sound ranging (PANDAA)	✓	Low	✓



Problem Related work Proposed approach Evaluation Discussion

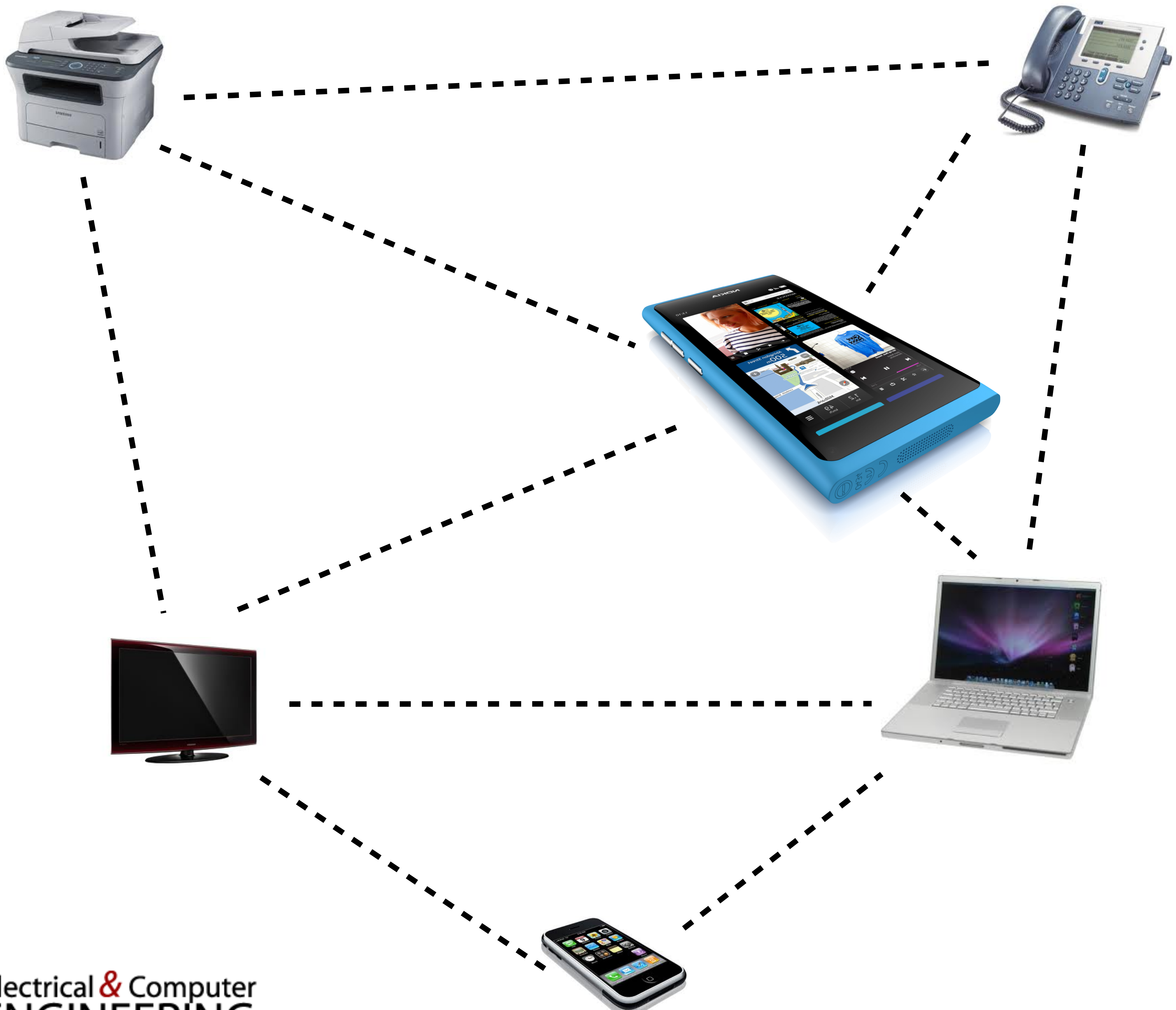
PANDAA

A microphone

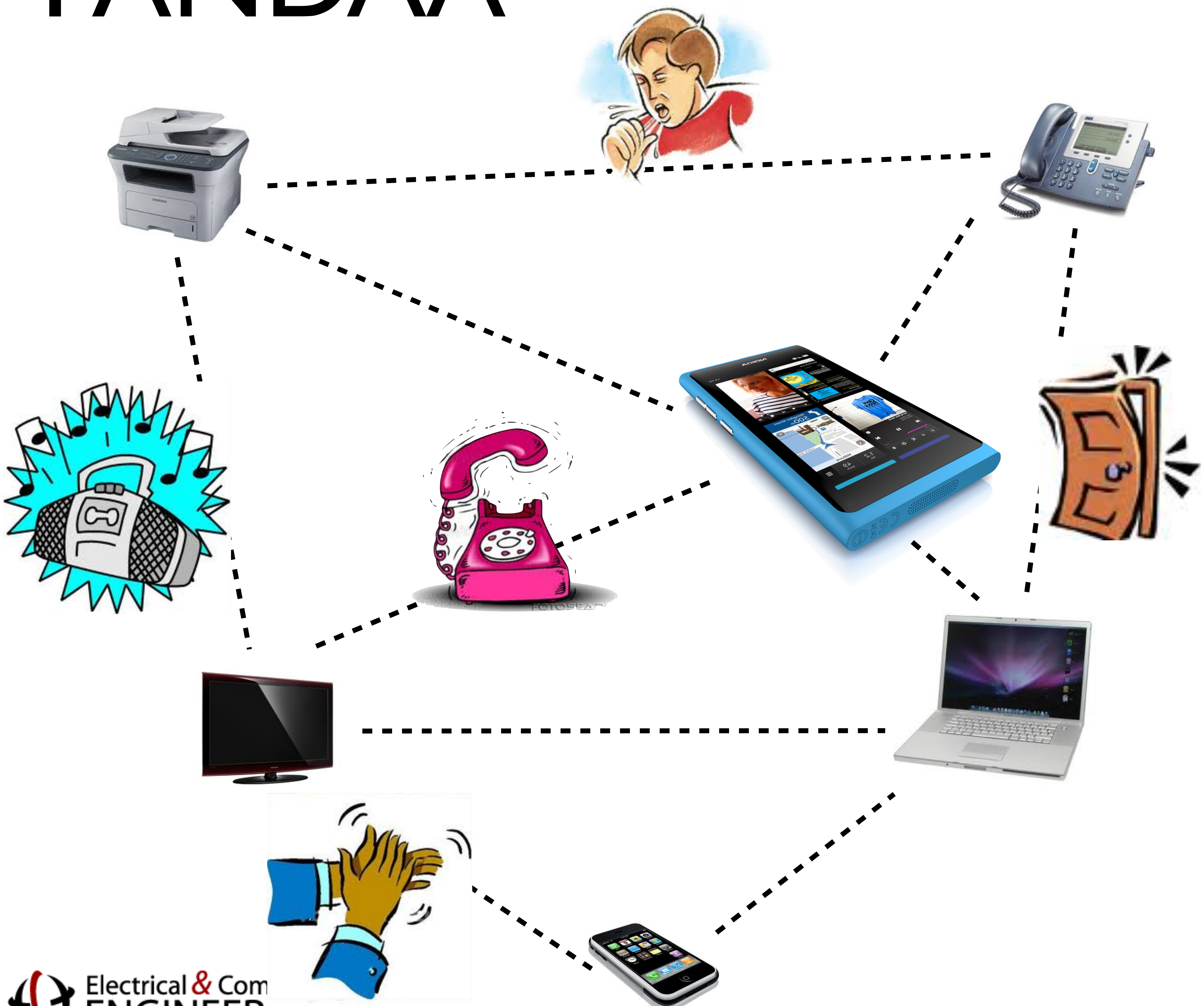
Wireless connection

PANDAA

PANDAA



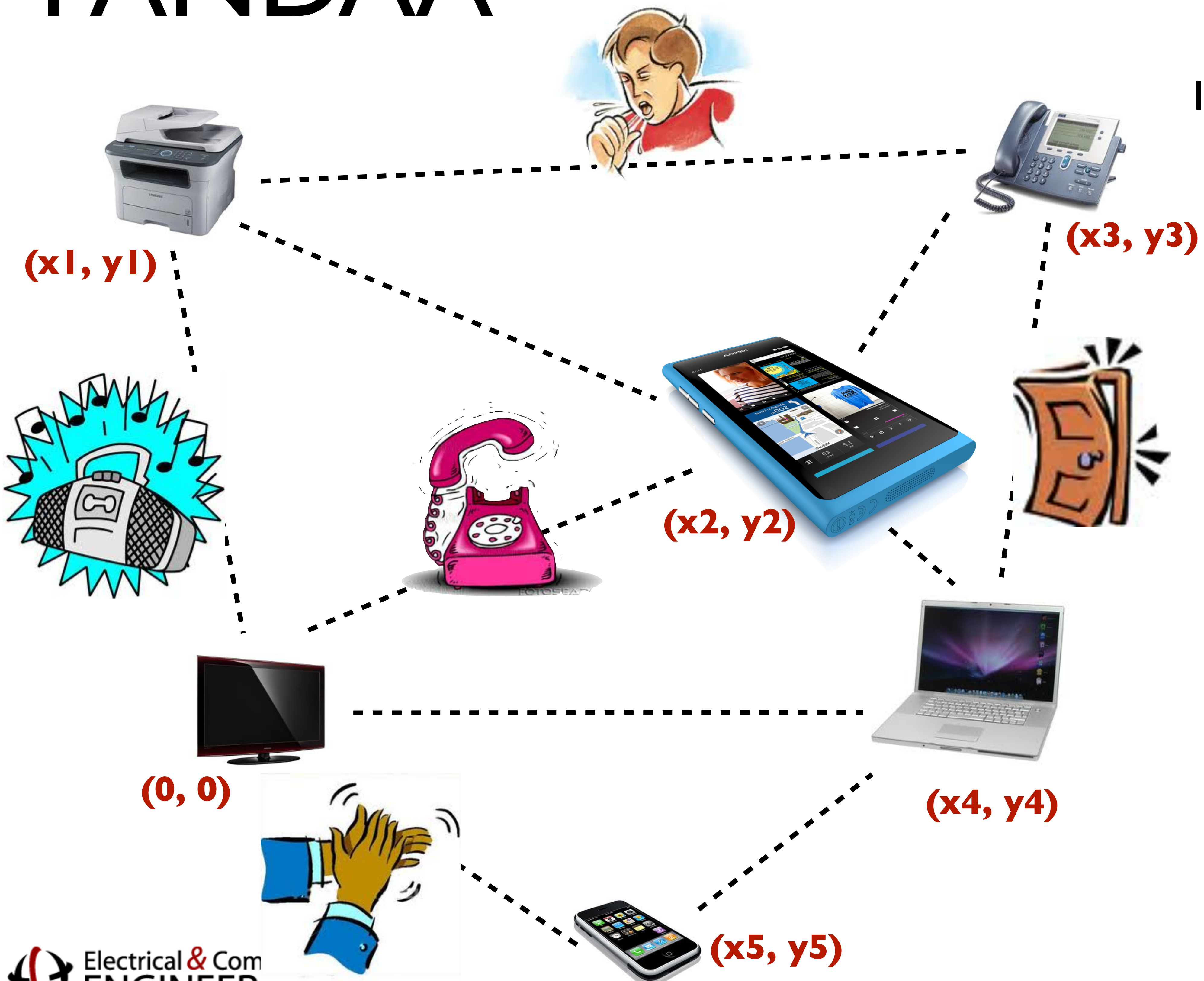
PANDAA



Indoor ambient sounds:

- a door closing
- a barking dog
- human talk
- coughs
- hand claps
- a ringing phone
- finger snaps
- ......

PANDAA



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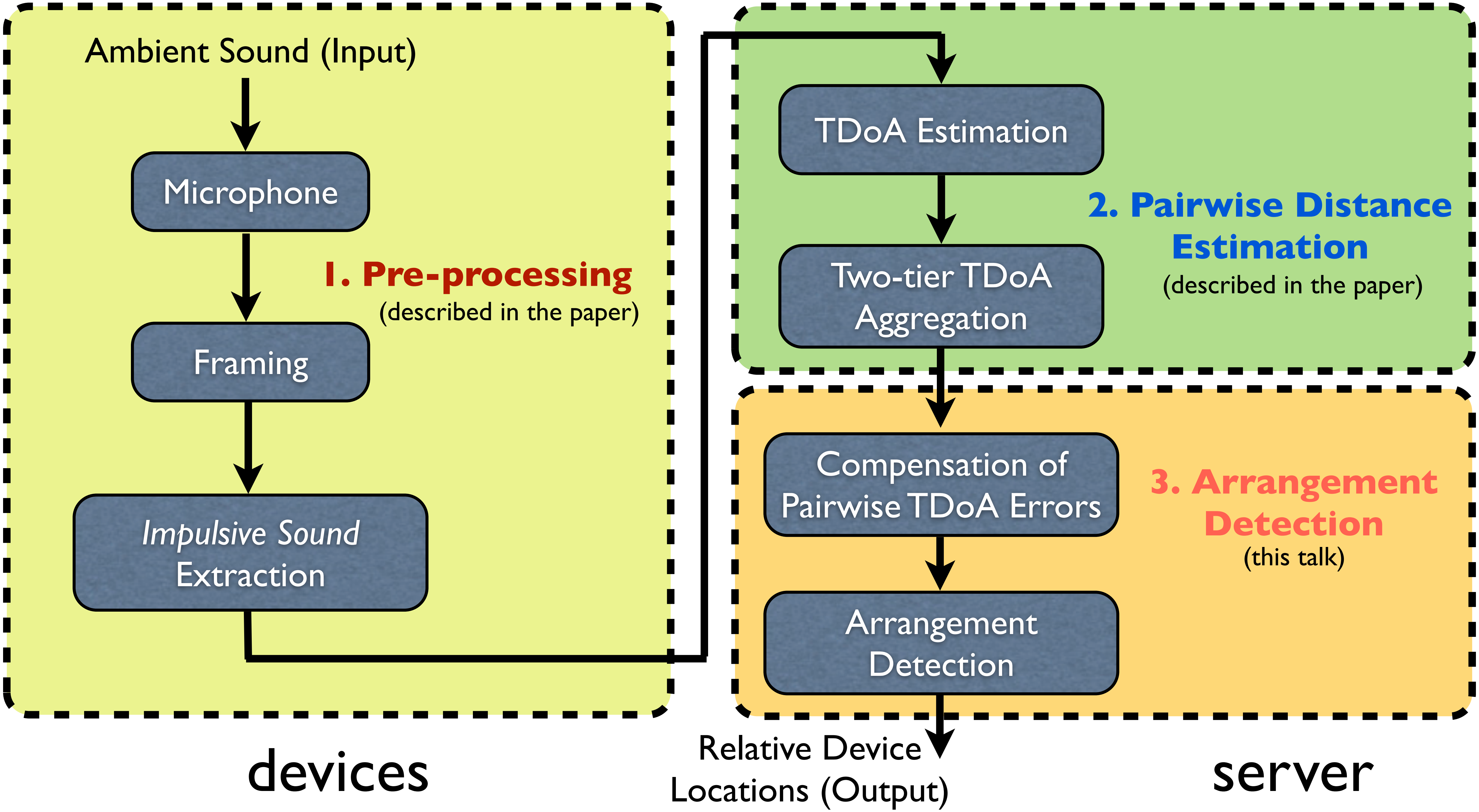
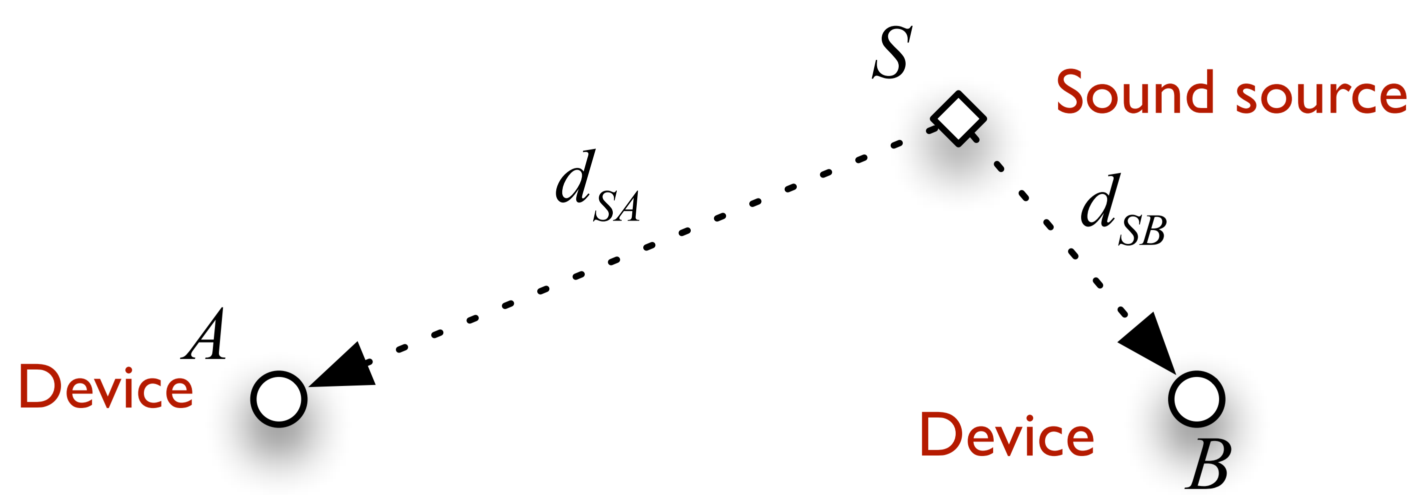
Ambient Sound Processing Pipeline



TDoA: Time Difference of Arrival

Get Pairwise Distances Using TDoA



Time difference of sound arrivals (TDoA) can be expressed as

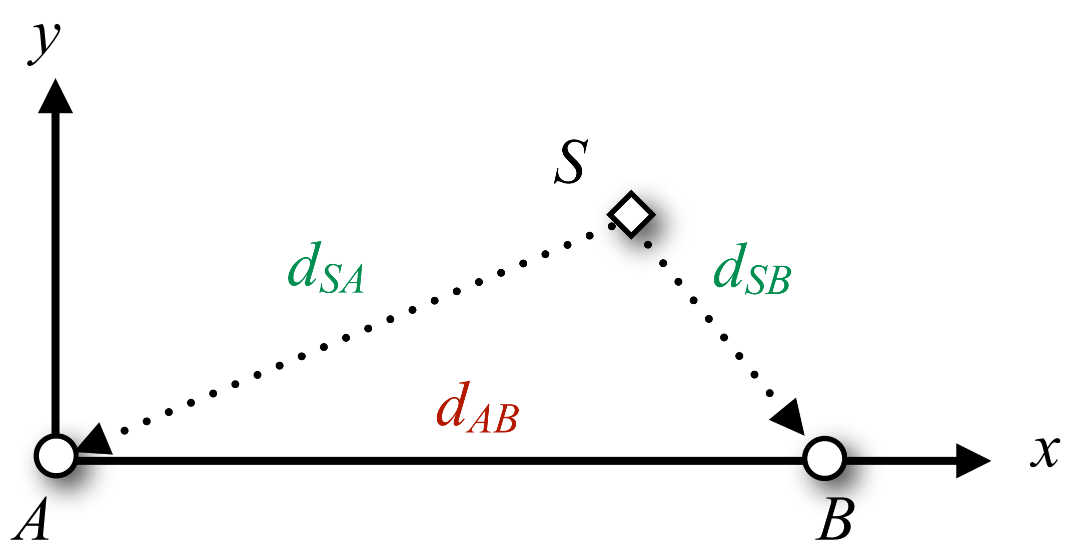
$$\Delta t_{BA} = \frac{(d_{SB} - d_{SA})}{\text{speed of sound}}$$

computable through matching of impulsive peaks

what we want !

a constant

Estimate Distances Between Devices

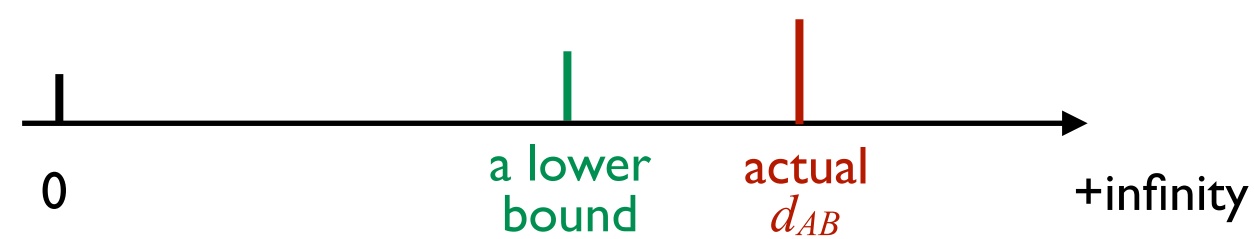


unknown value
estimated value

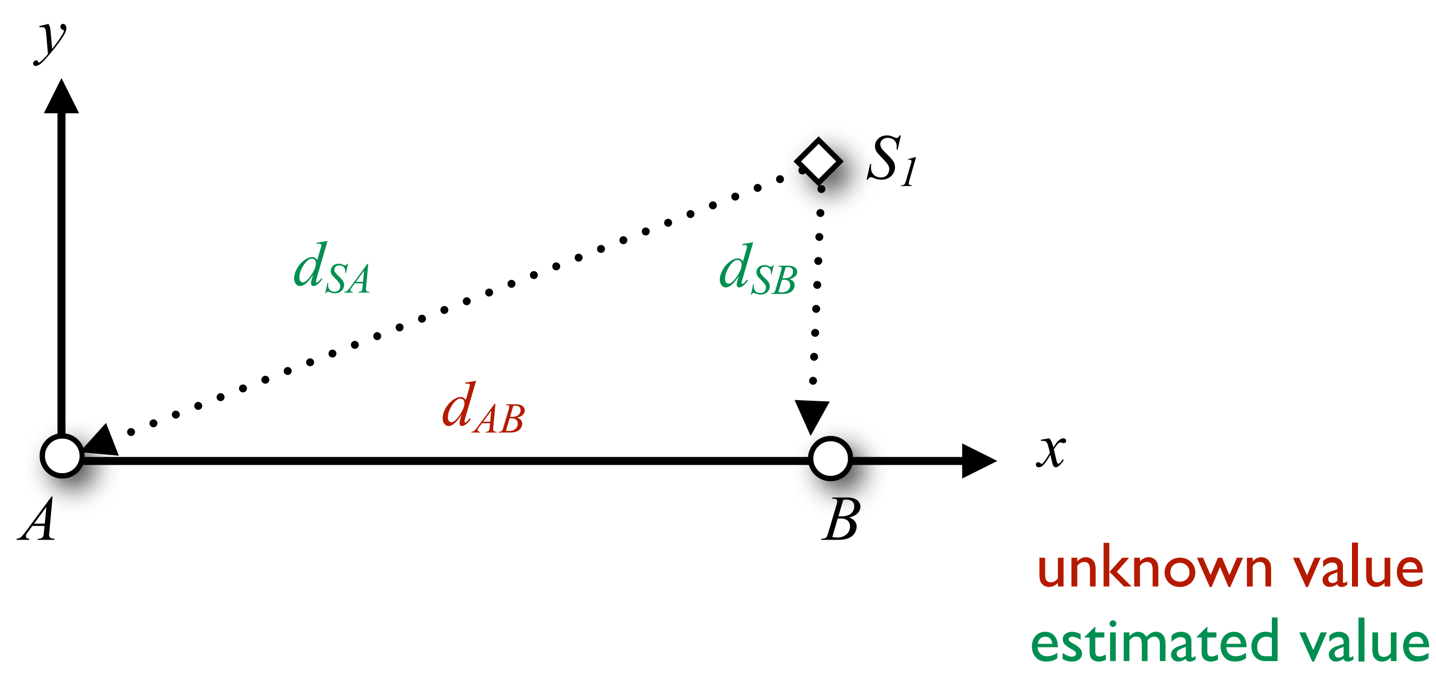
Given one source *S*, we have one lower bound of d_{AB}

$$\underline{\left| d_{SB} - d_{SA} \right|} \le d_{AB}$$

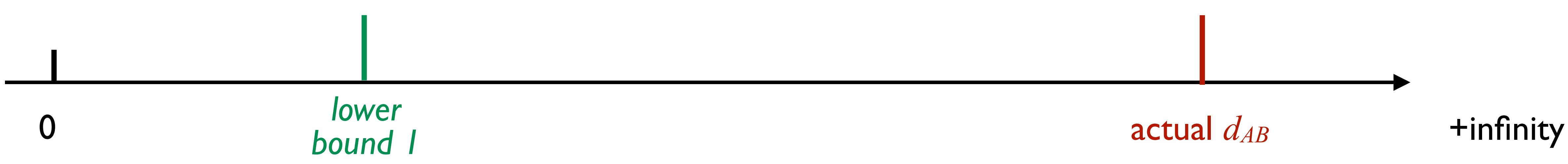
a lower bound of d_{AB}



Successive Estimation of d_{AB}



Given multiple sources, we have overlapped bounds of d_{AB}



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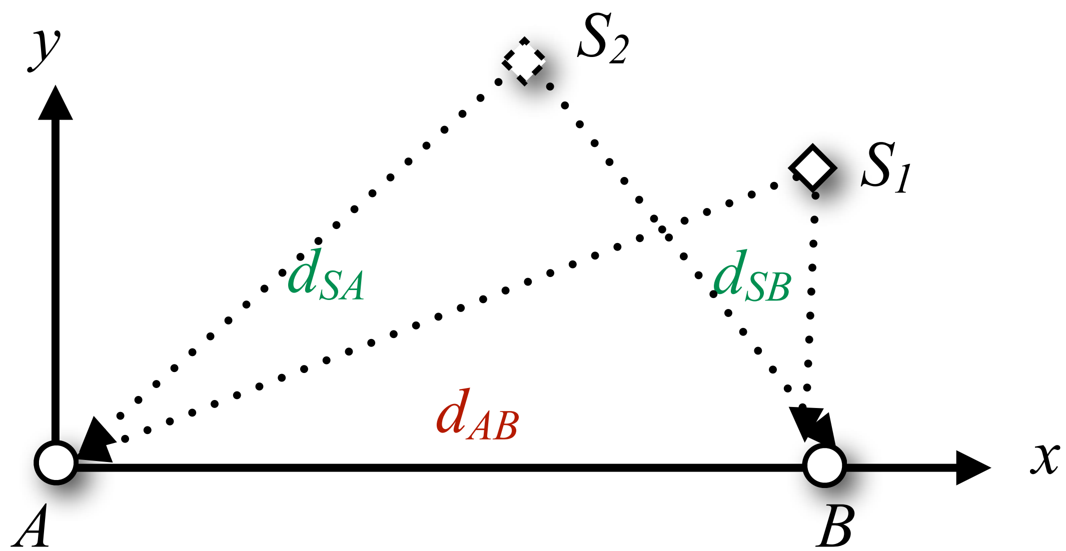

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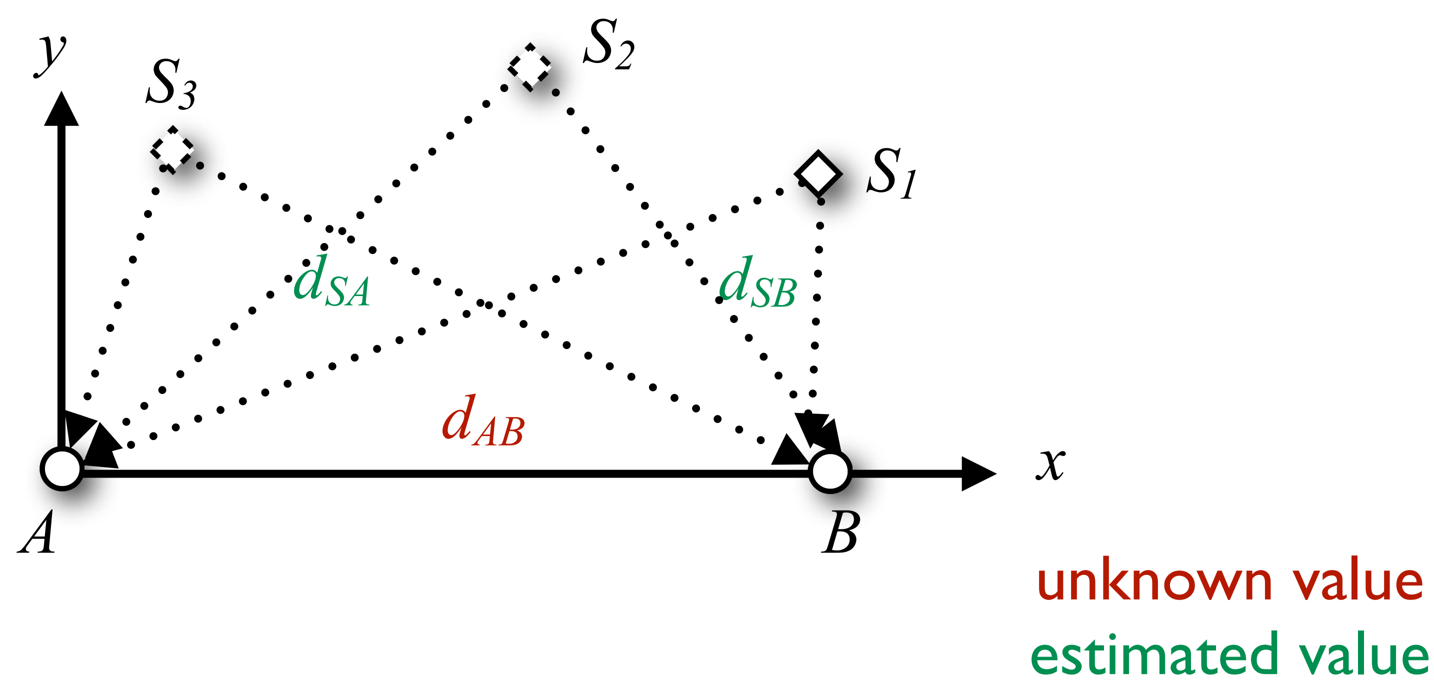

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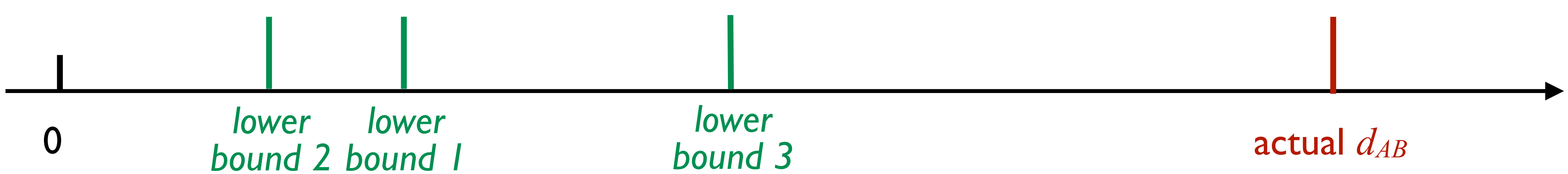

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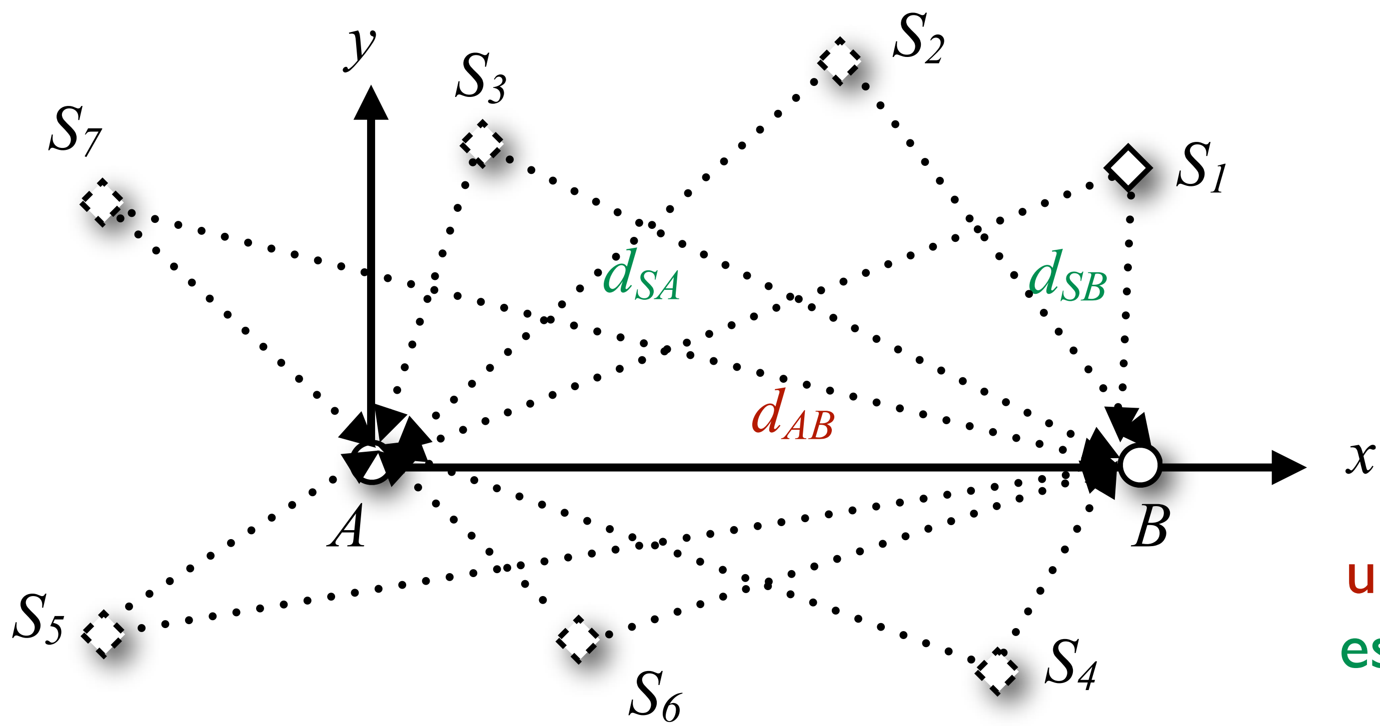

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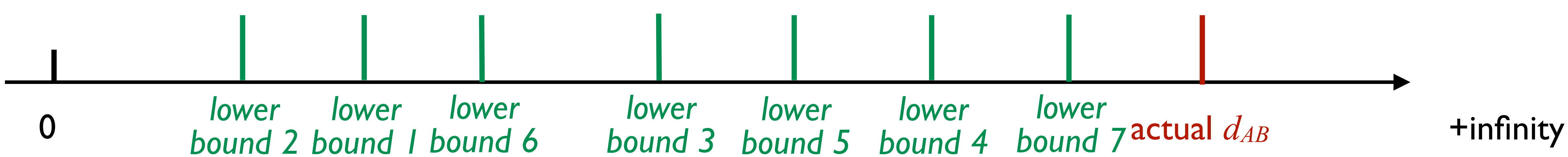

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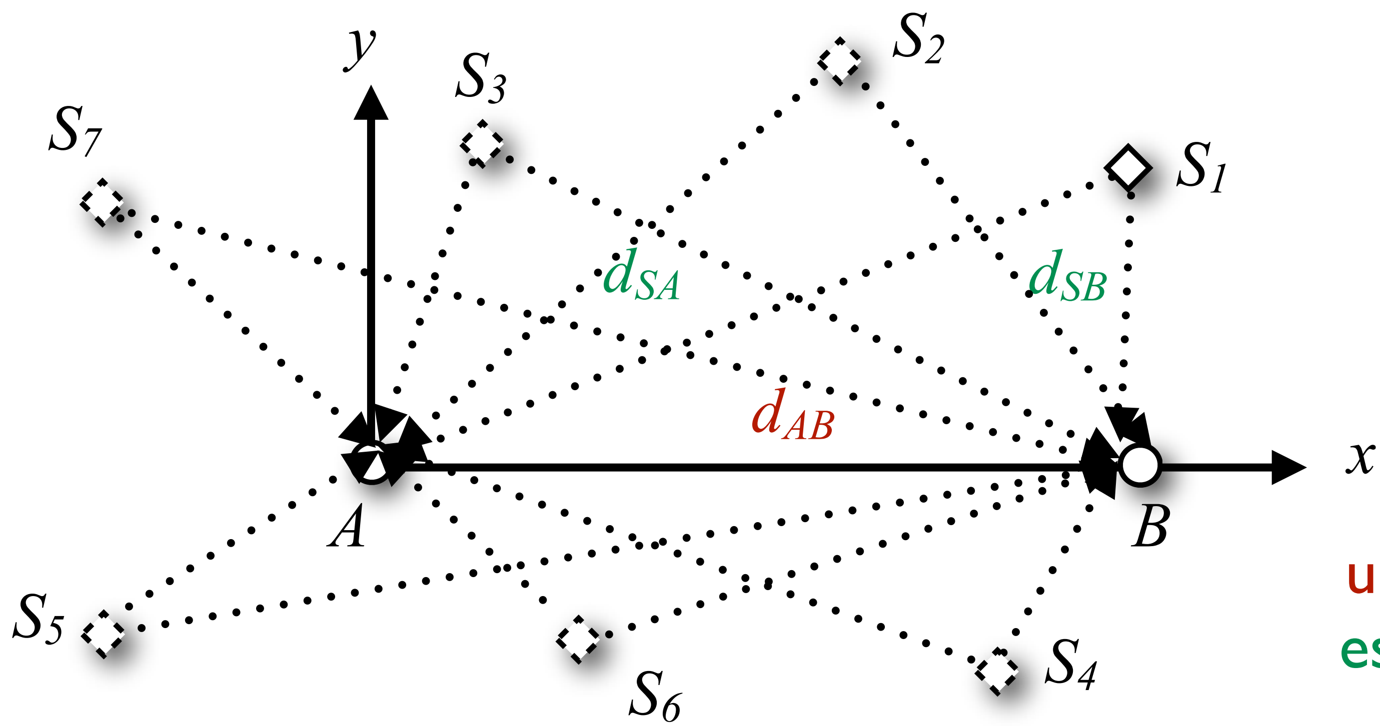

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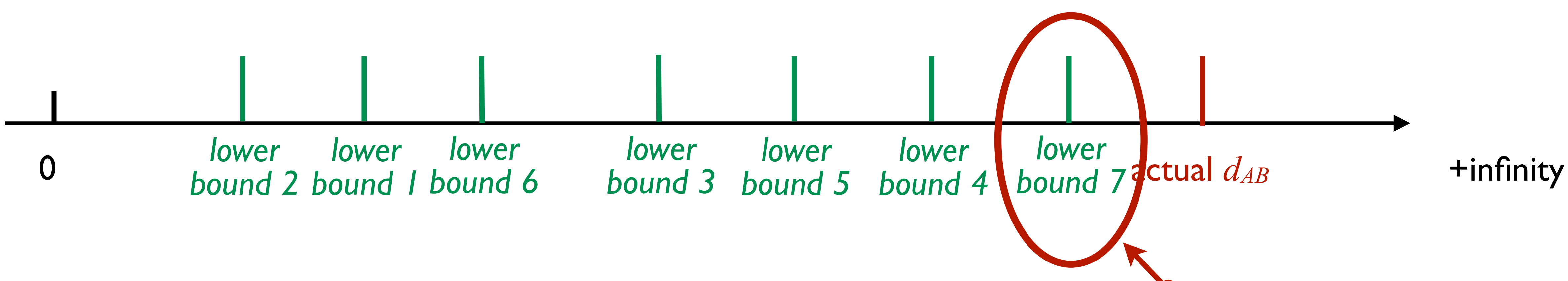

The maximal lower bound will get closer and closer to the actual d_{AB}.

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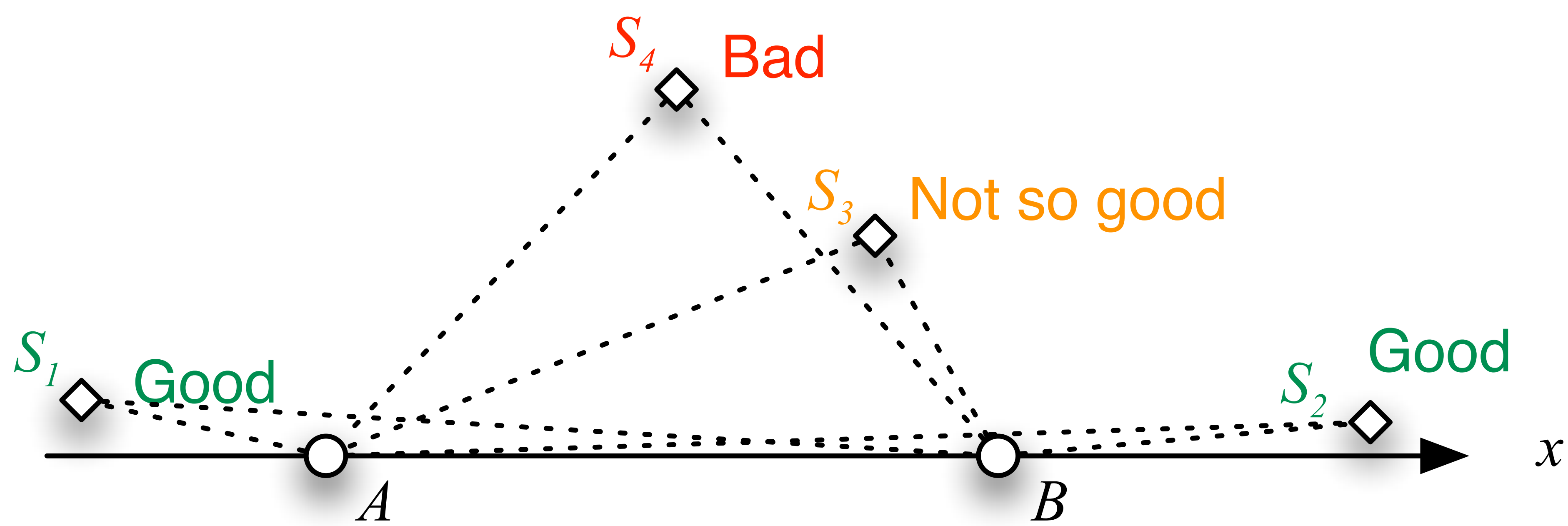
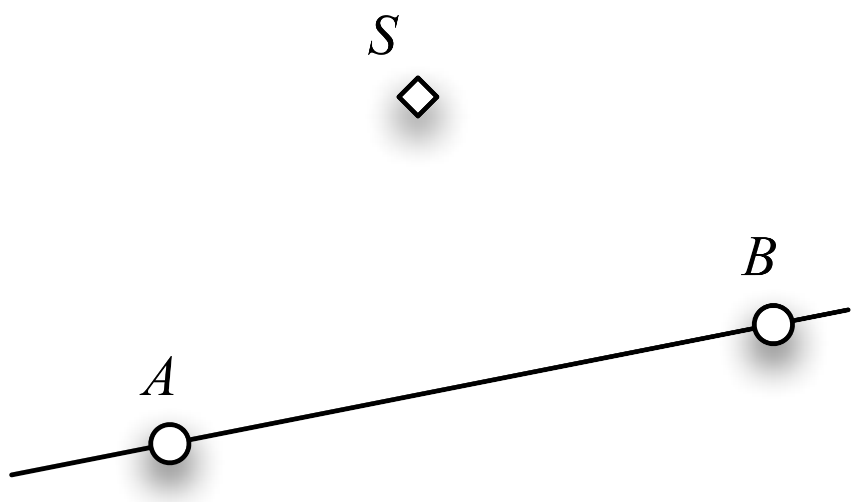
A Problem!

Different Sound Source Locations



Compensate for Pairwise Errors



Only two devices A, B
S is not good for estimating the distance between A and B

- As #devices increases, estimation accuracy can be improved
  - A sound source may be bad for one particular device pair, but good for others.

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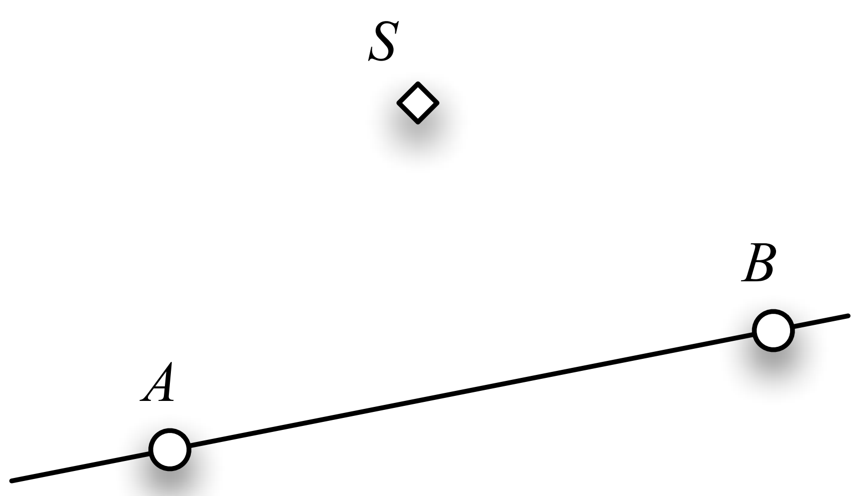

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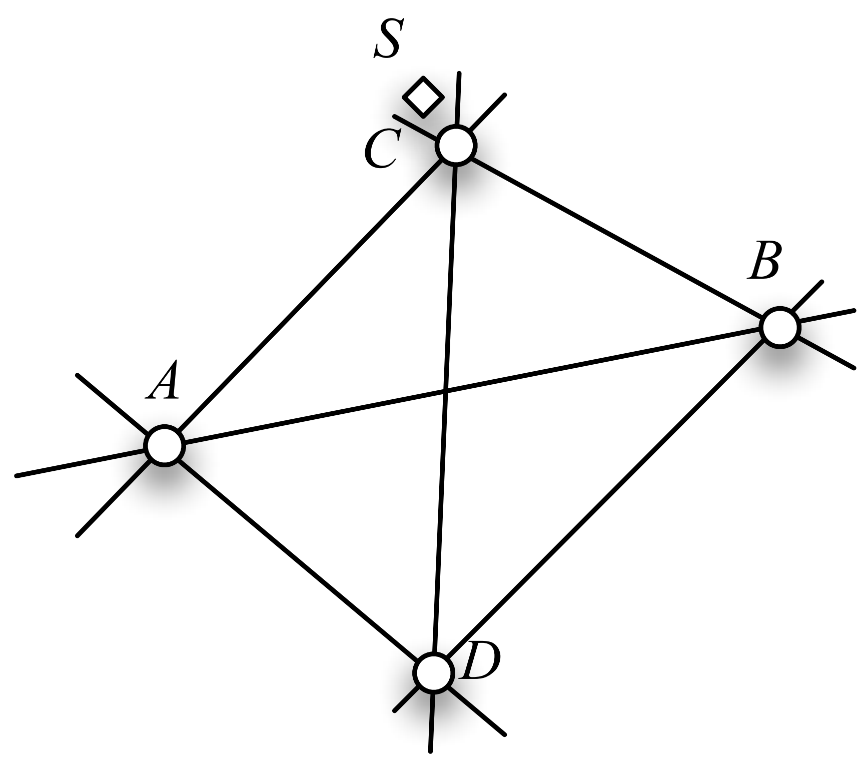
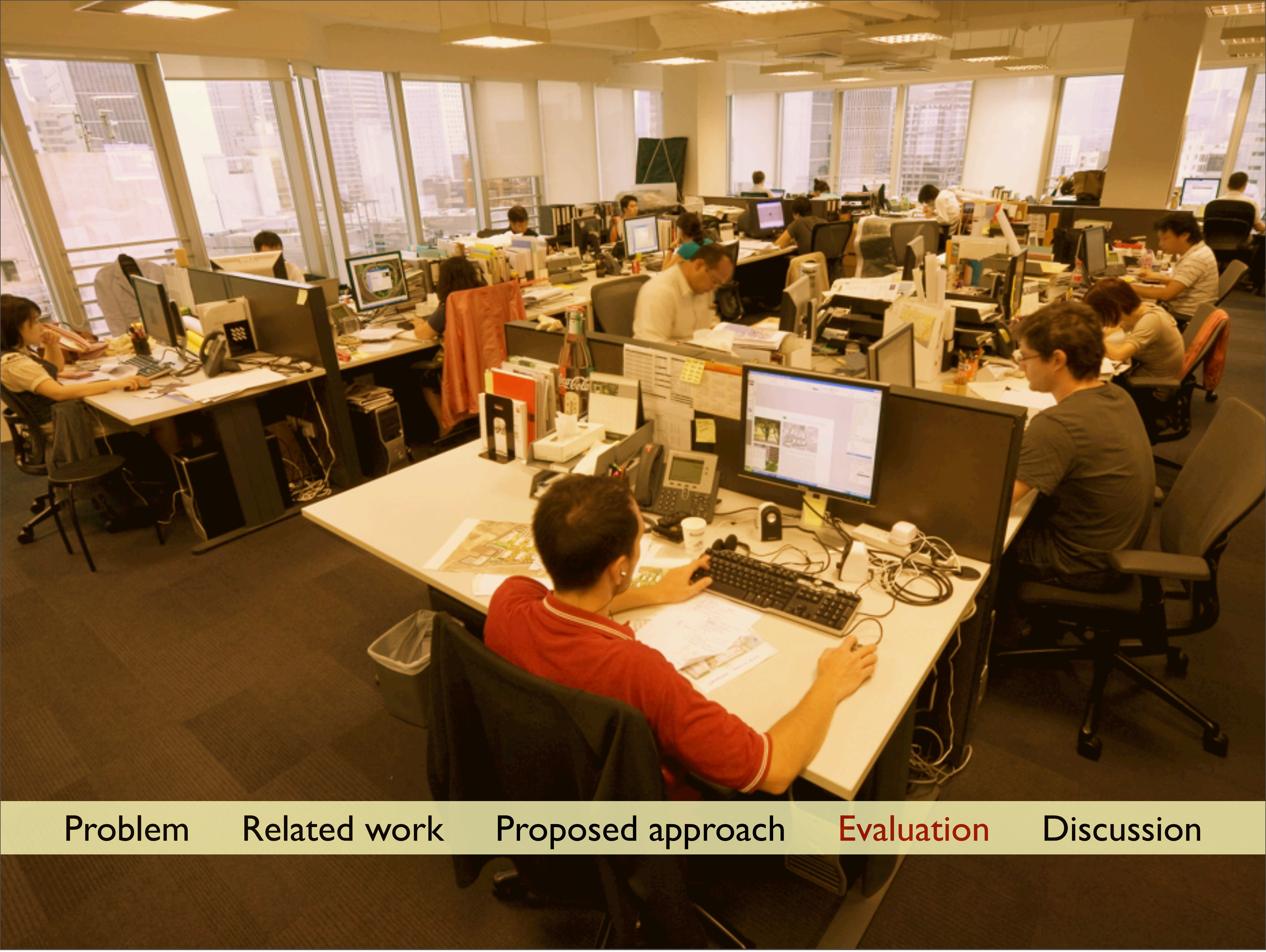


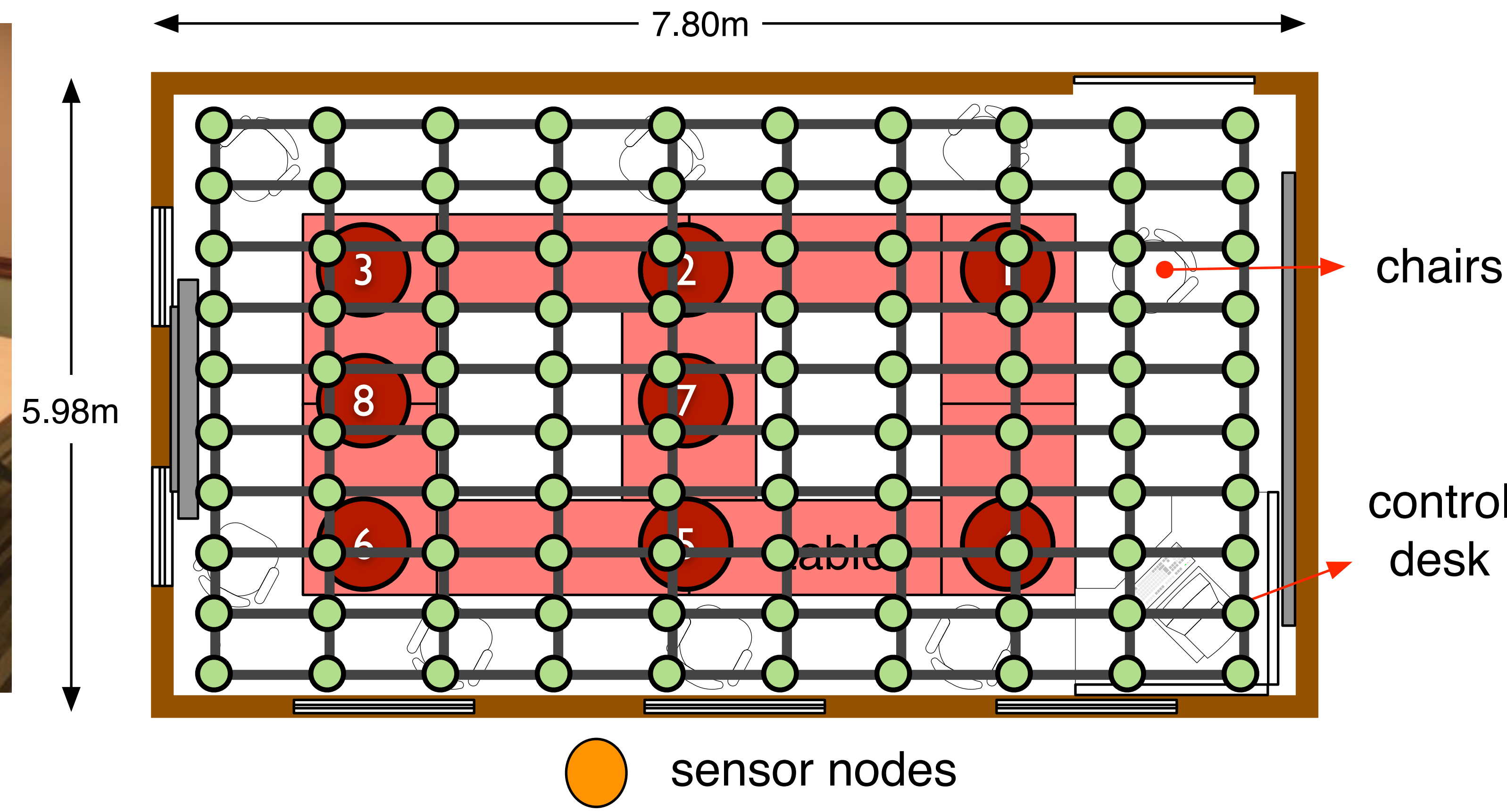
If we have 2 more devices in the network
S is not good for estimating the distance between A-B, but is good for A-C, B-C, and C-D

- As #devices increases, estimation accuracy can be improved
  - A sound source may be bad for one particular device pair, but good for others.



Meeting-room Experiments

photo



floor plan

- $8 \times 6 m^2$ meeting room
- Eight nodes (orange dots on the floor plan)
- 100 locations to generate ambient sound (grid intersections)

Ambient Sound Used In Experiments

95-second audio at each source location (the "grid") using loudspeaker

Types	Durations (s)	Notes
Cough	32	12 coughs from 6 individuals (2 males and 4 females)
Conversation	21	Between a male and a female
Music #1	21	"*Billie Jean*"
Music #2	21	"*The Sound of Silence*"

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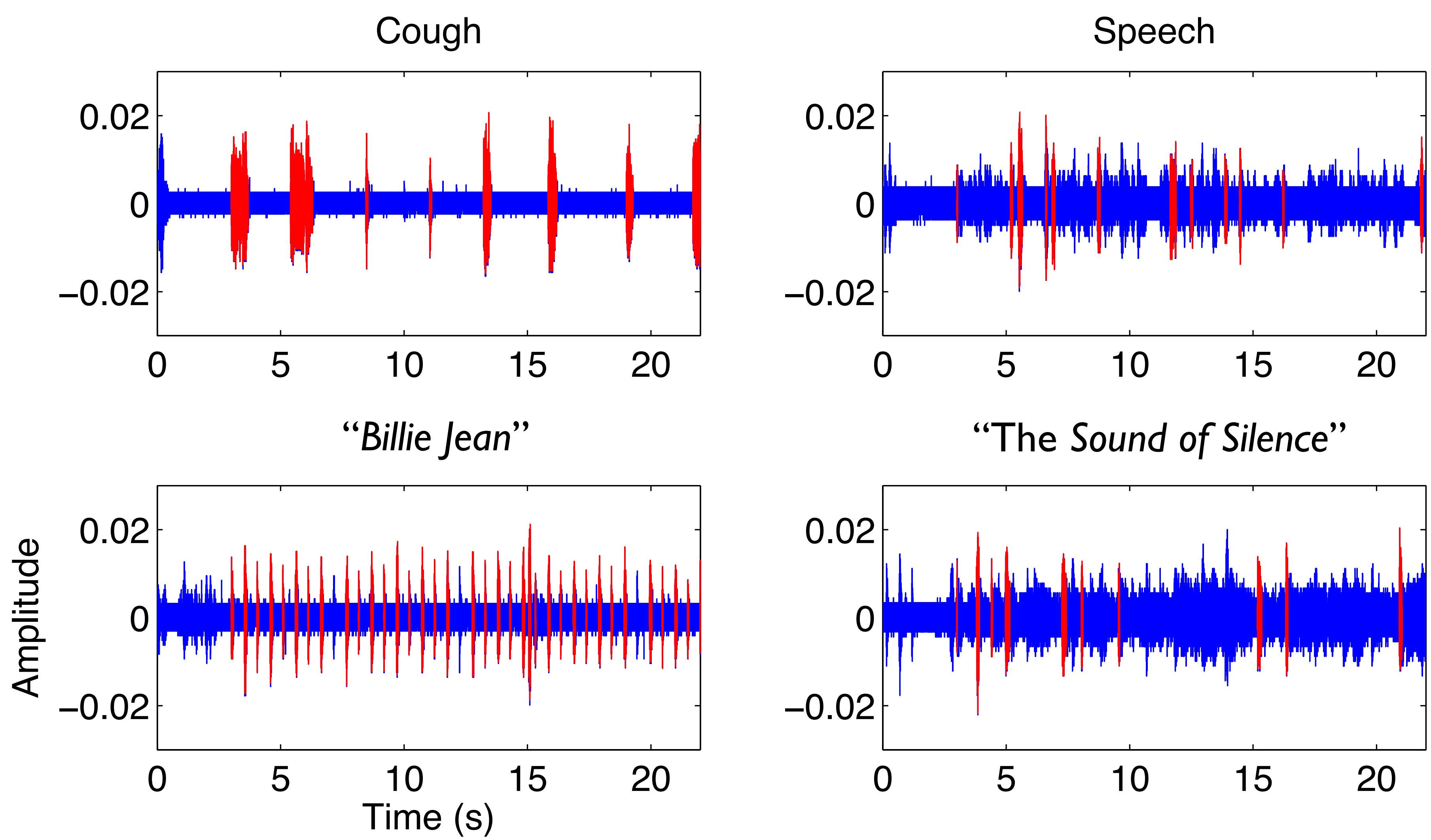
Impulsive Sound Event Detection



- Averagely 1 event/cough; for other types, 1 event/sec.
- Effective to extract impulsive sound from all four sound types.
- Detection rate is high to generate sufficient events for arrangement detection.

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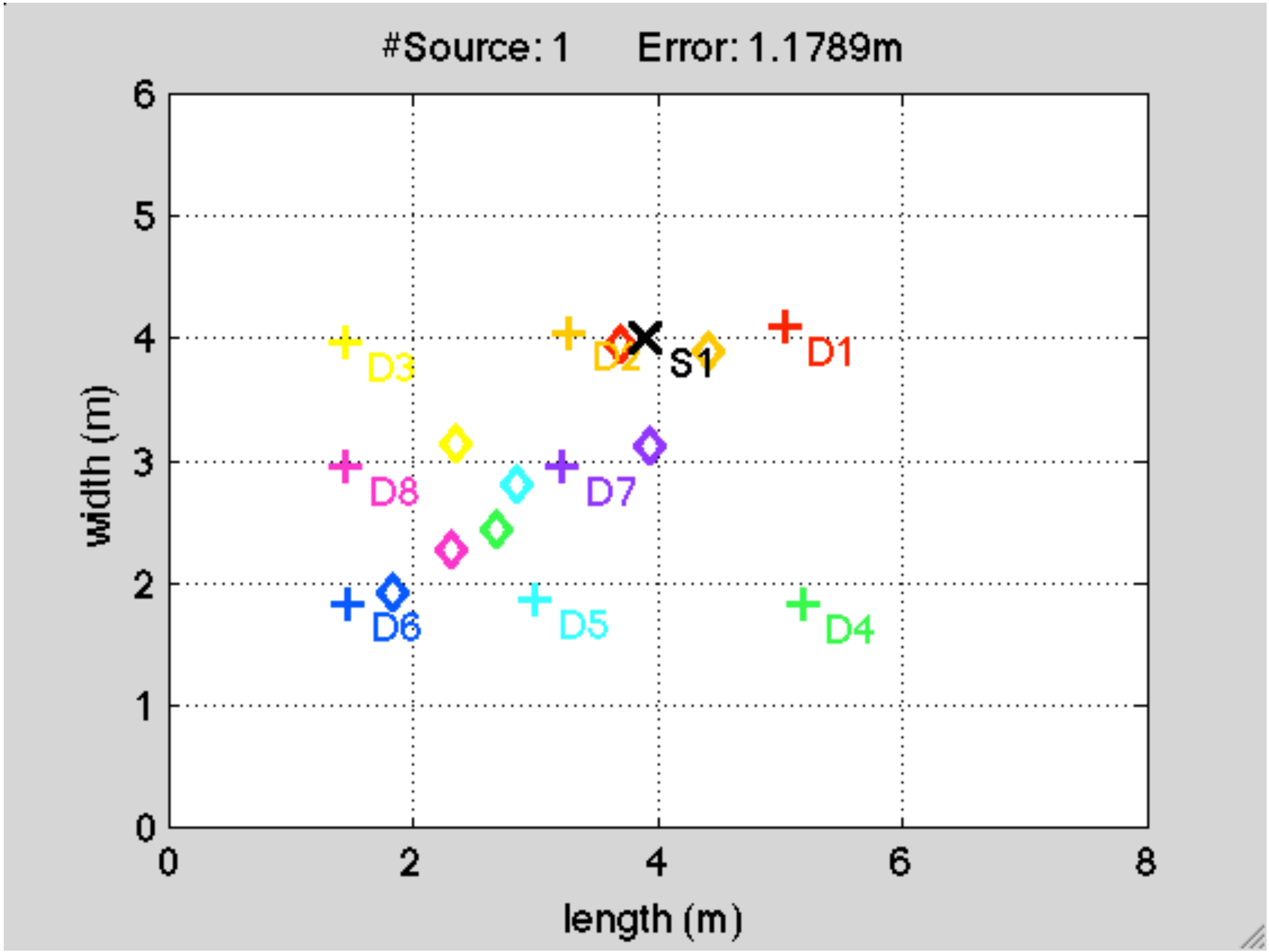
Estimated Locations vs. Ground-truths



x: Sound sources **+**: Ground truths ◇: Estimated locations

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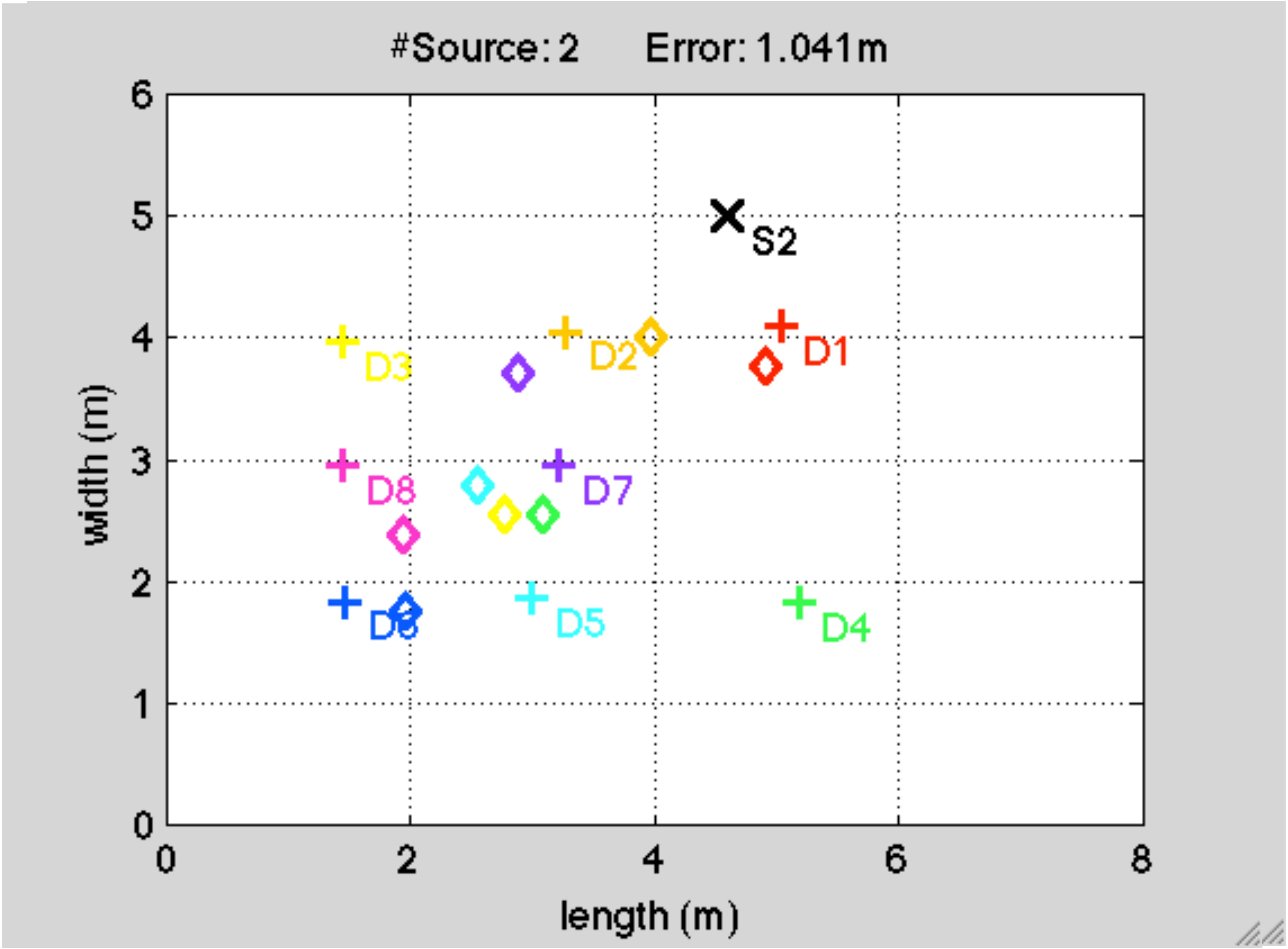

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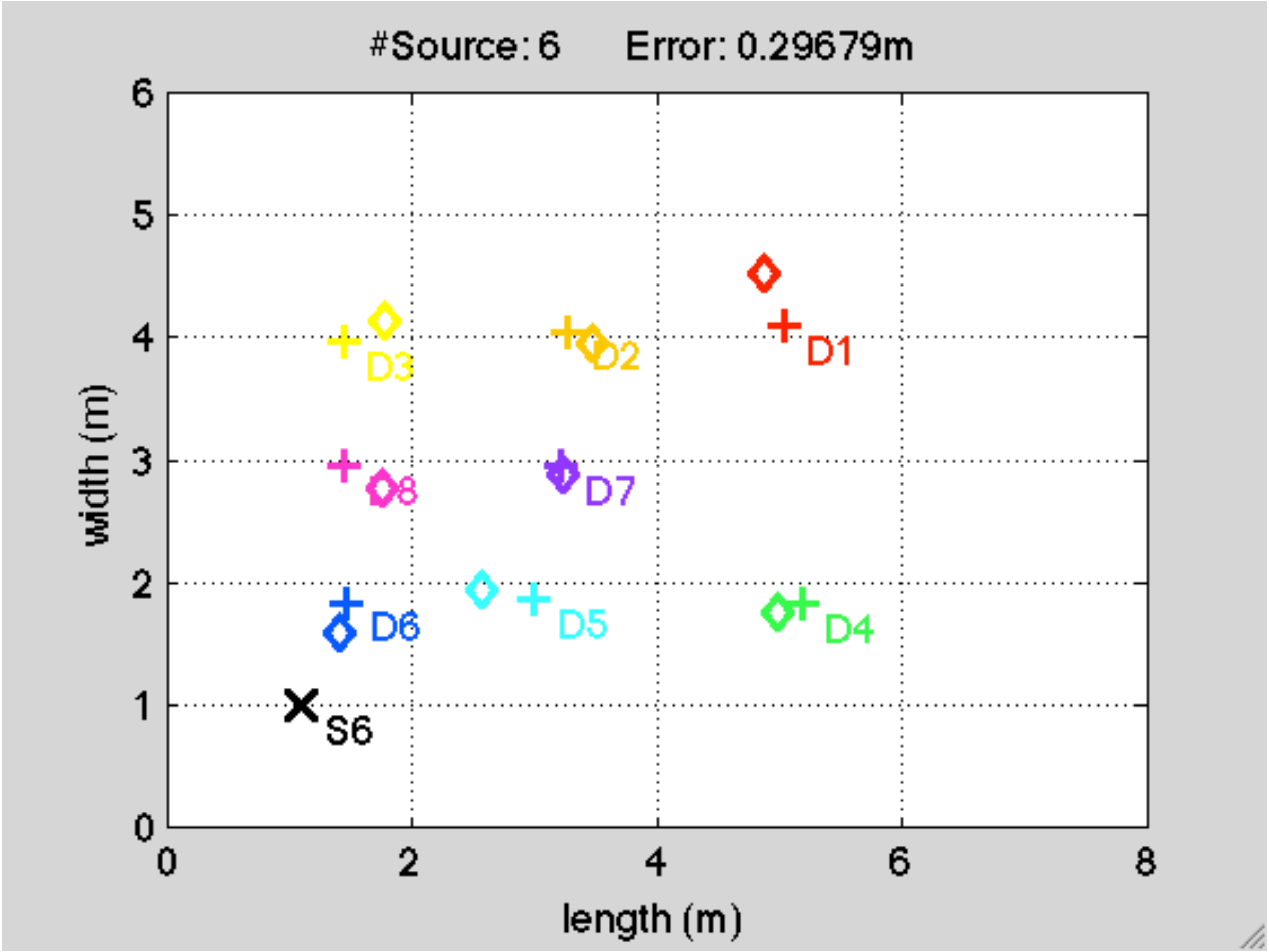

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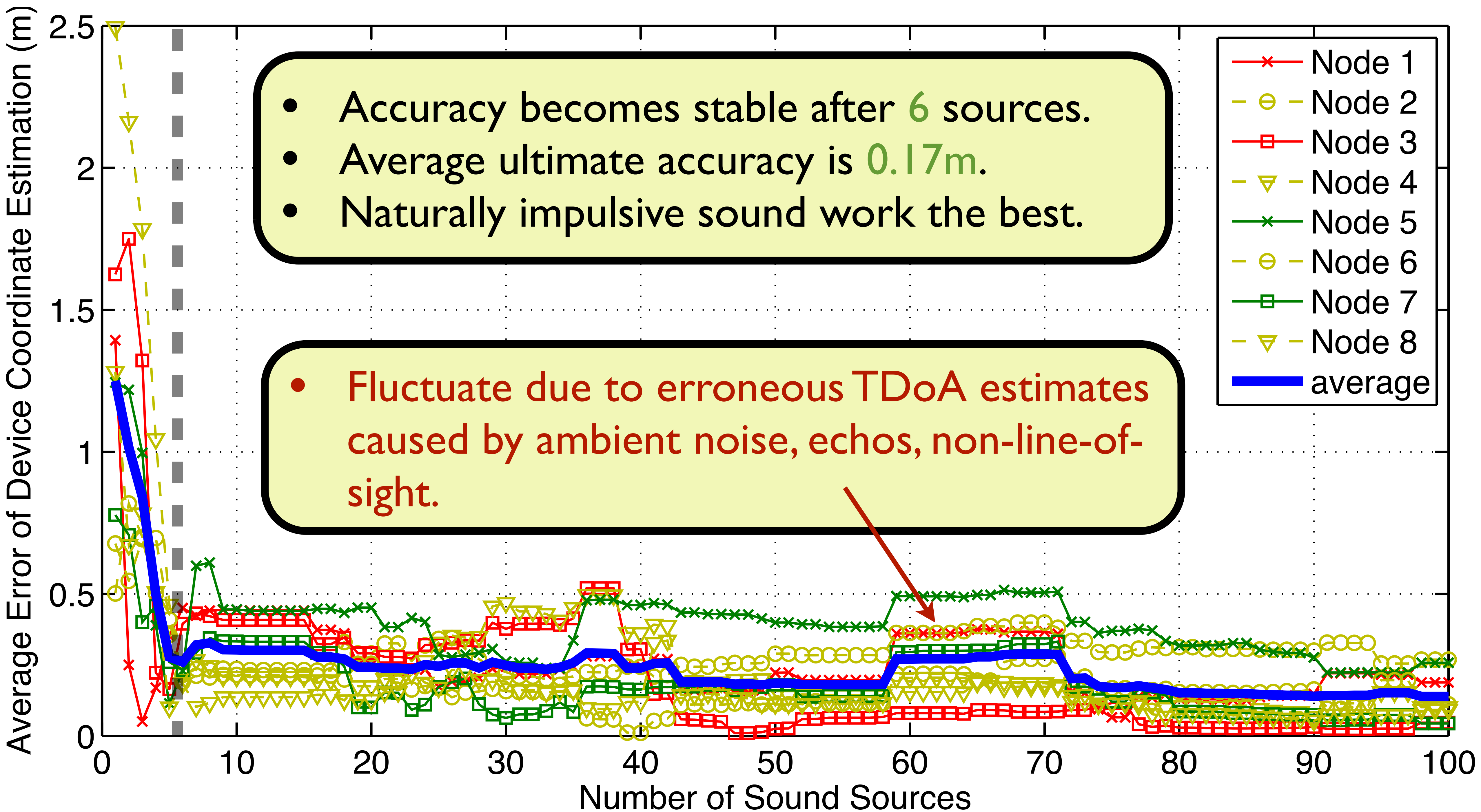
Location Errors vs. #Sound Sources



Conclusions

- Novel approach - prove that using *ambient sound* in physical arrangement detection is possible.
- PANDAA achieves 0.17m accuracy in the meeting-room experiments given uniformly distributed sound sources.