SCPL: Indoor Device-Free Multi-Subject Counting and Localization Using Radio Signal Strength

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Joint work with

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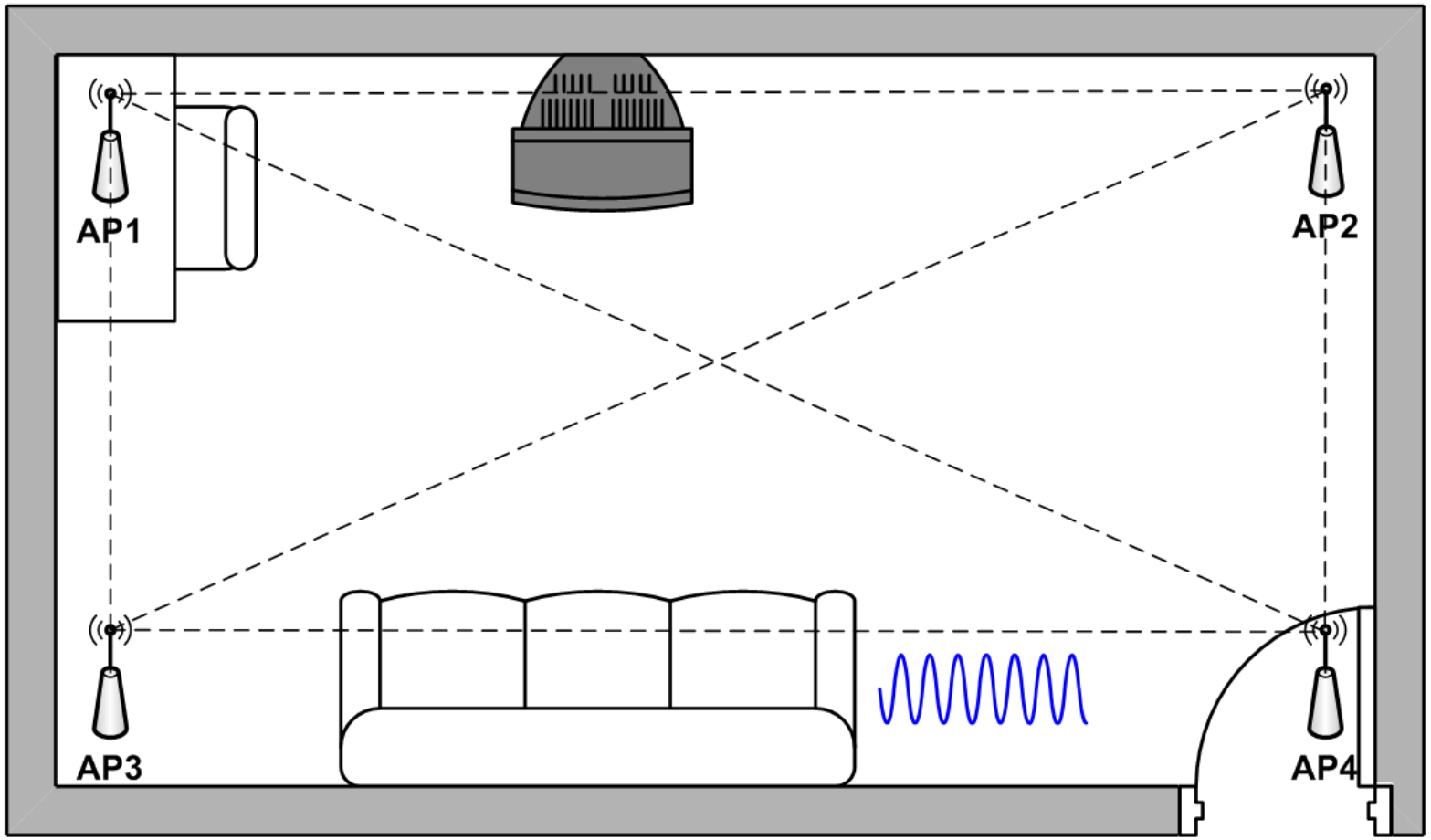
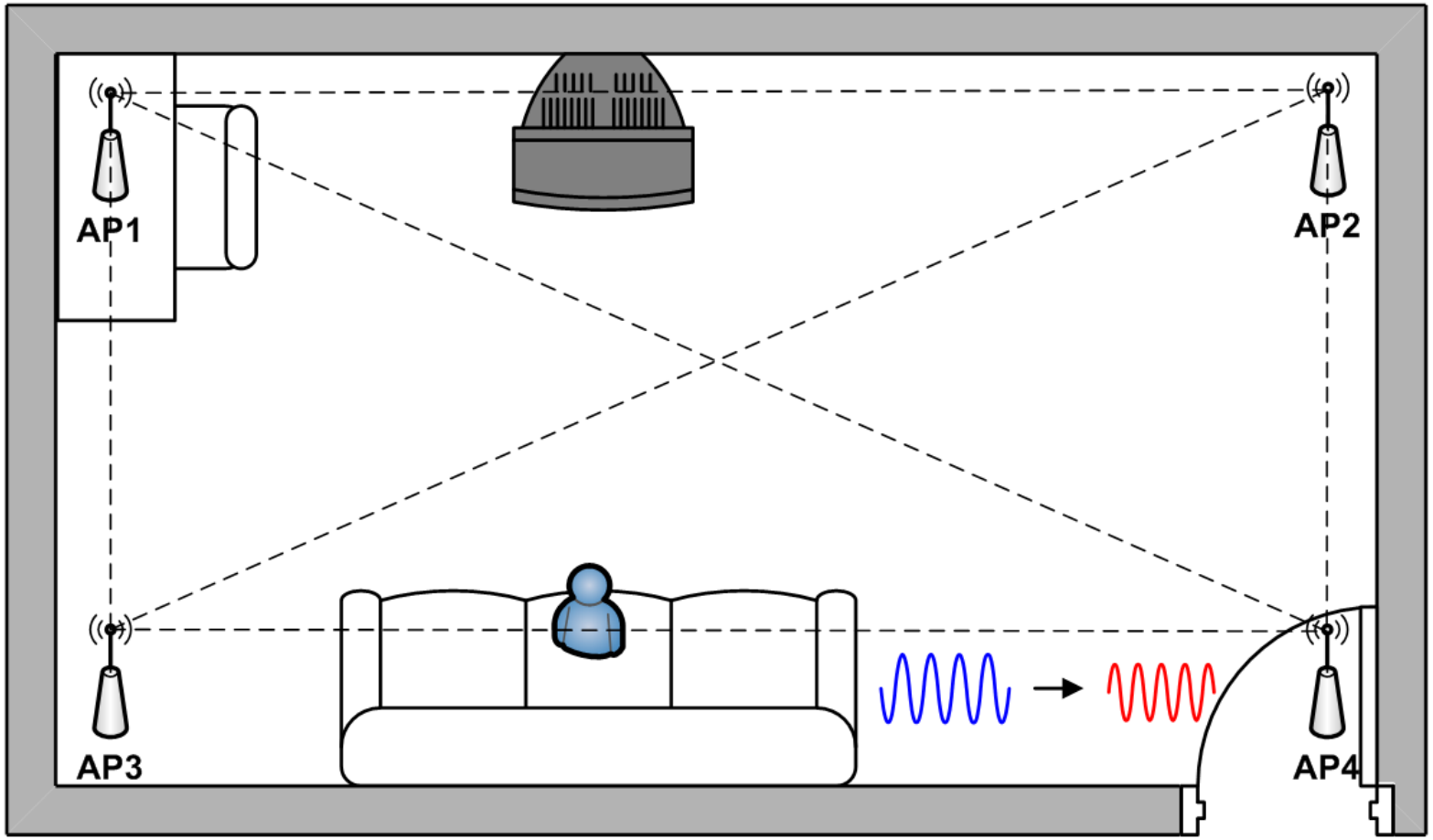
Device-free Localization



Device-free Localization



Why Device-free Localization?

- Monitor indoor human mobility

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Elder/health care

Why Device-free Localization?

- Monitor indoor human mobility

Traffic flow statistics

Why Device-free Localization?

- Monitor indoor human mobility

Traffic flow statistics

Why Device-free Localization?

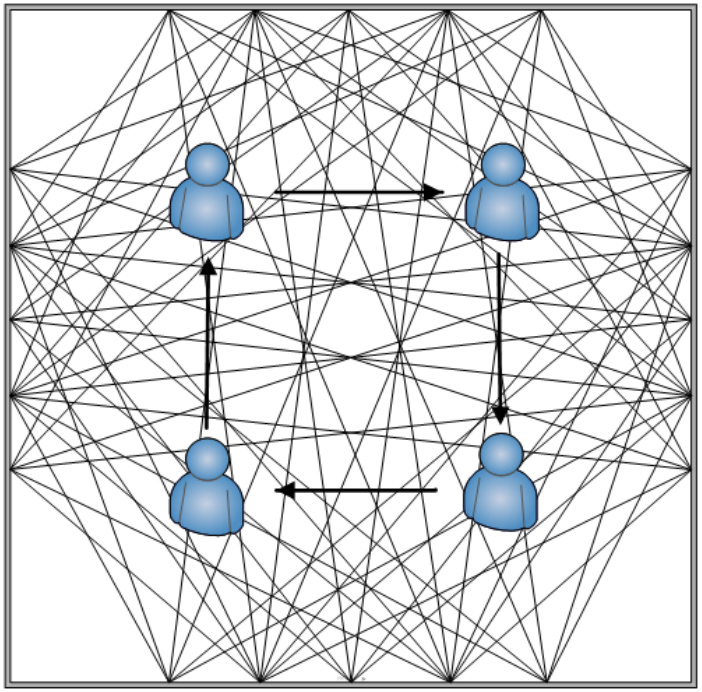
- Monitor indoor human mobility
  - Health/elder care, safety
  - Detect traffic flow
- Provides privacy protection
  - No identification

Why Device-free Localization?

- Monitor indoor human mobility
  - Health/elder care, safety
  - Detect traffic flow
- Provides privacy protection
  - No identification
- Use existing wireless infrastructure

Previous Work

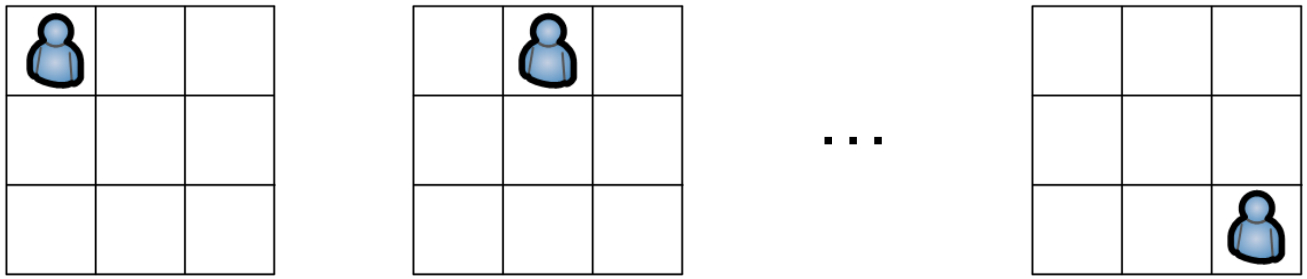
- Single subject localization
  - Fingerprinting-based approach



Fingerprinting N Subjects

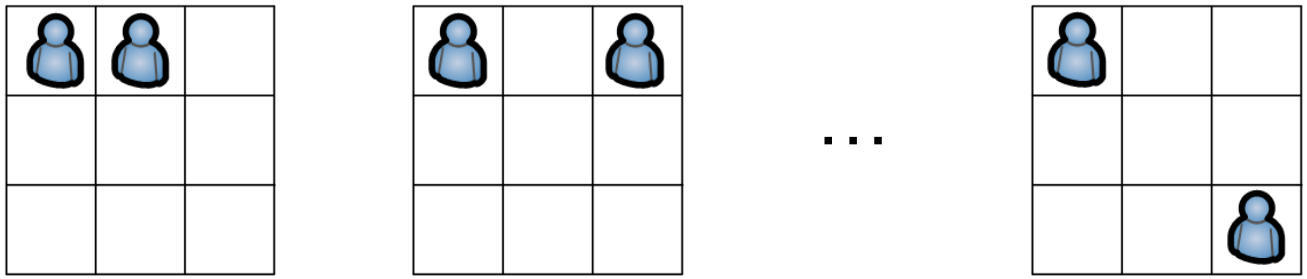
- Multiple subjects localization
  - Needs to take calibration data from N people for localizing N people

Fingerprinting N Subjects

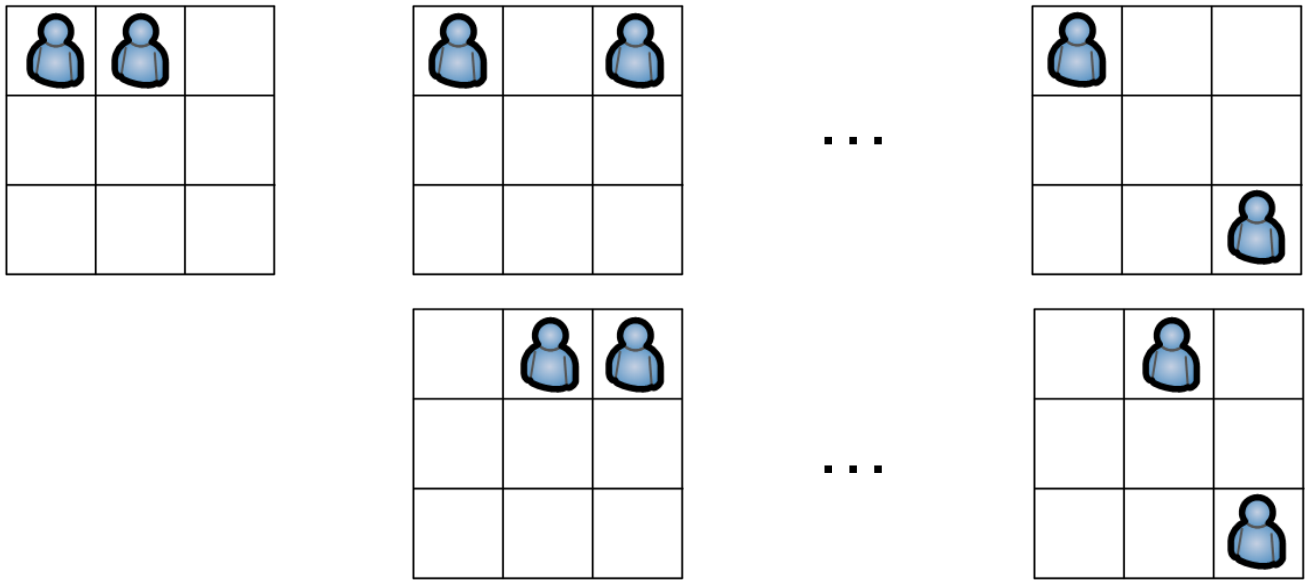


9 trials in total for 1 person

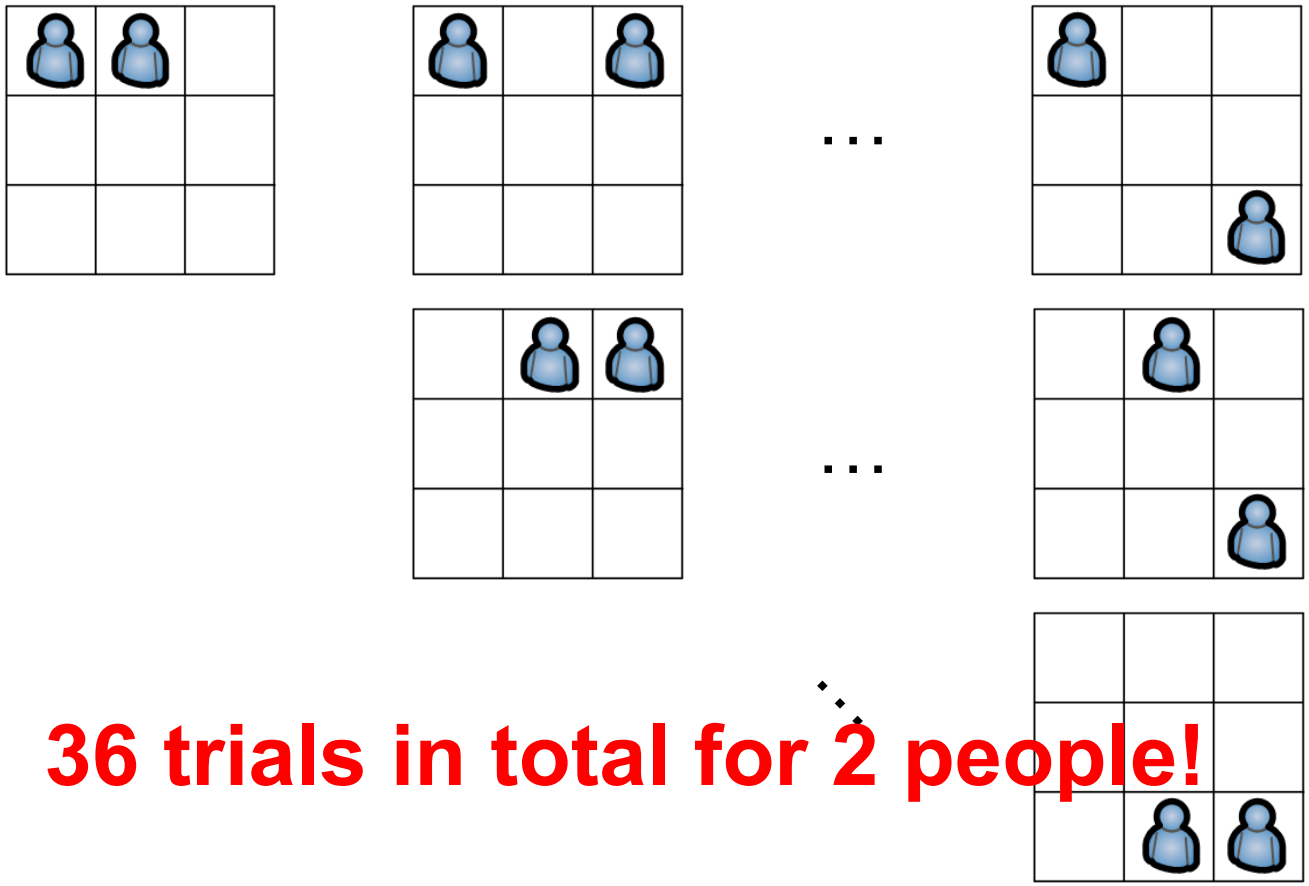
Fingerprinting N Subjects



Fingerprinting N Subjects



Fingerprinting N Subjects



36 trials in total for 2 people!

Fingerprinting N Subjects

	1 person
9 cells	9

9 × 1 min = 9 min

Fingerprinting N Subjects

	1 person	2 people
9 cells	9	36
36 cells	36	630

630 × 1 min = 10.5 hr

Fingerprinting N Subjects

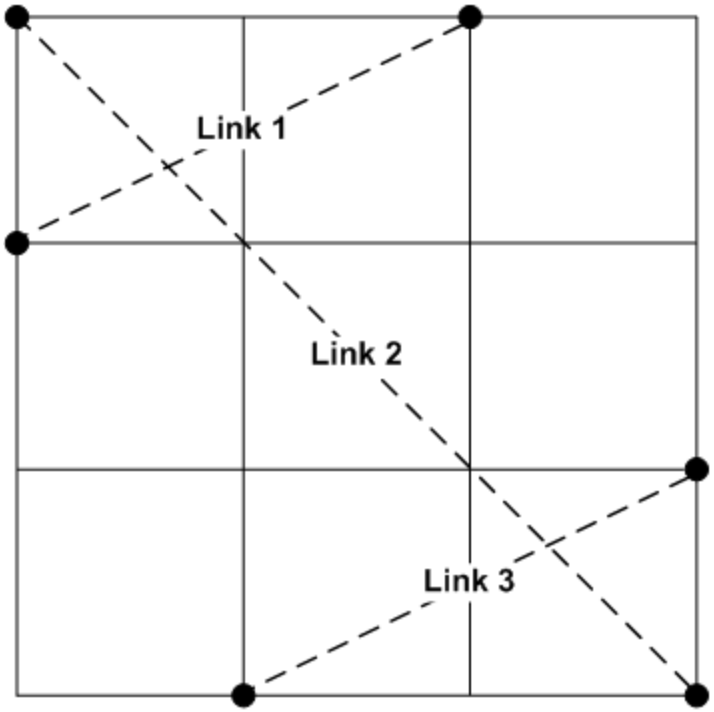
	1 person	2 people	3 people
9 cells	9	36	84
36 cells	36	630	7140
100 cells	100	4950	161700

161700 × 1 min = 112 days
The calibration effort is prohibitive !

SCPL

- Input
  - Collecting calibration data only from 1 subject (D1)
  - Observed RSSI change caused by n subjects
- Output
  - *count* and *localize* N subjects.
- Main Insight:
  - If the number n is known, localizing n subjects is strightforward

No Subjects

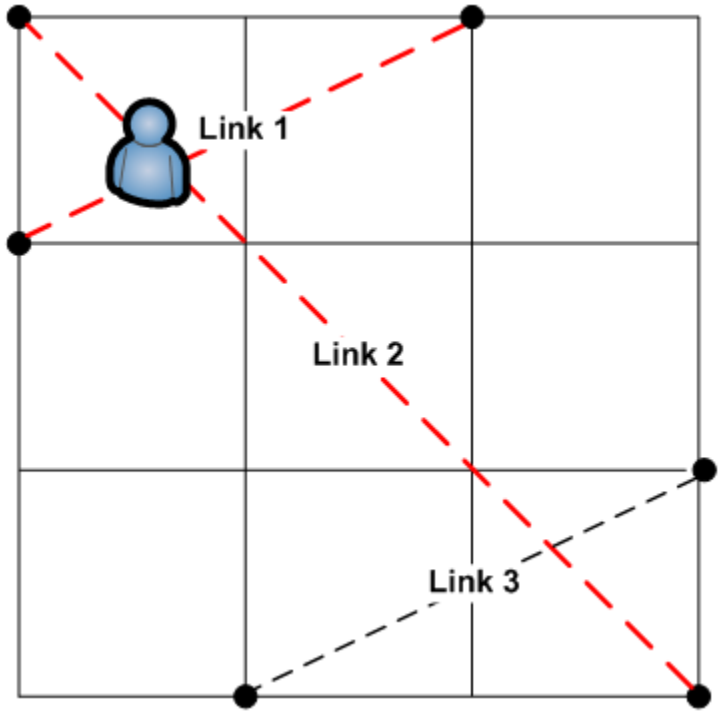


Link 1 change ~~~ 0 dB

Link 2 change ~~~ 0 dB

Link 3 change ~~~ 0 dB

One Subject

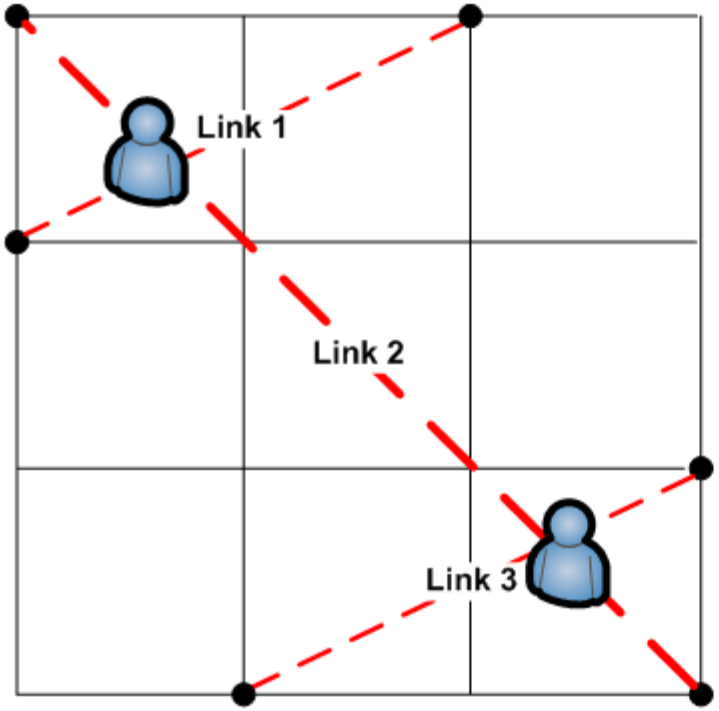


Link 1 change 4 dB

Link 2 change 5 dB

Link 3 change 0 dB

Two Subjects



Link 1 change 4 dB

Link 2 change 7 dB

Link 3 change 5 dB

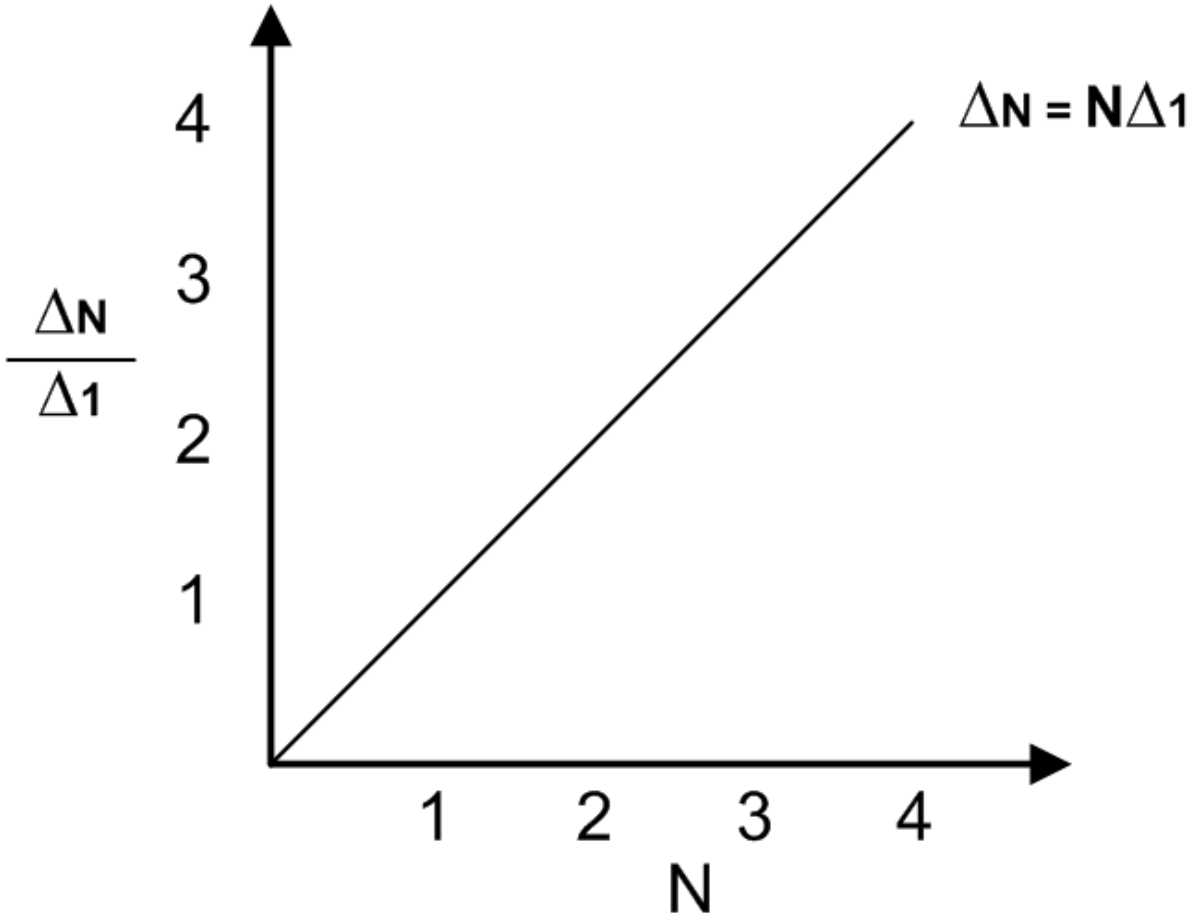
Measurement

	N = 0	N = 1	N = 2
Link 1	0	4	4
Link 2	0	5	7
Link 3	0	0	5
Total (Δ_N)	0	9	16

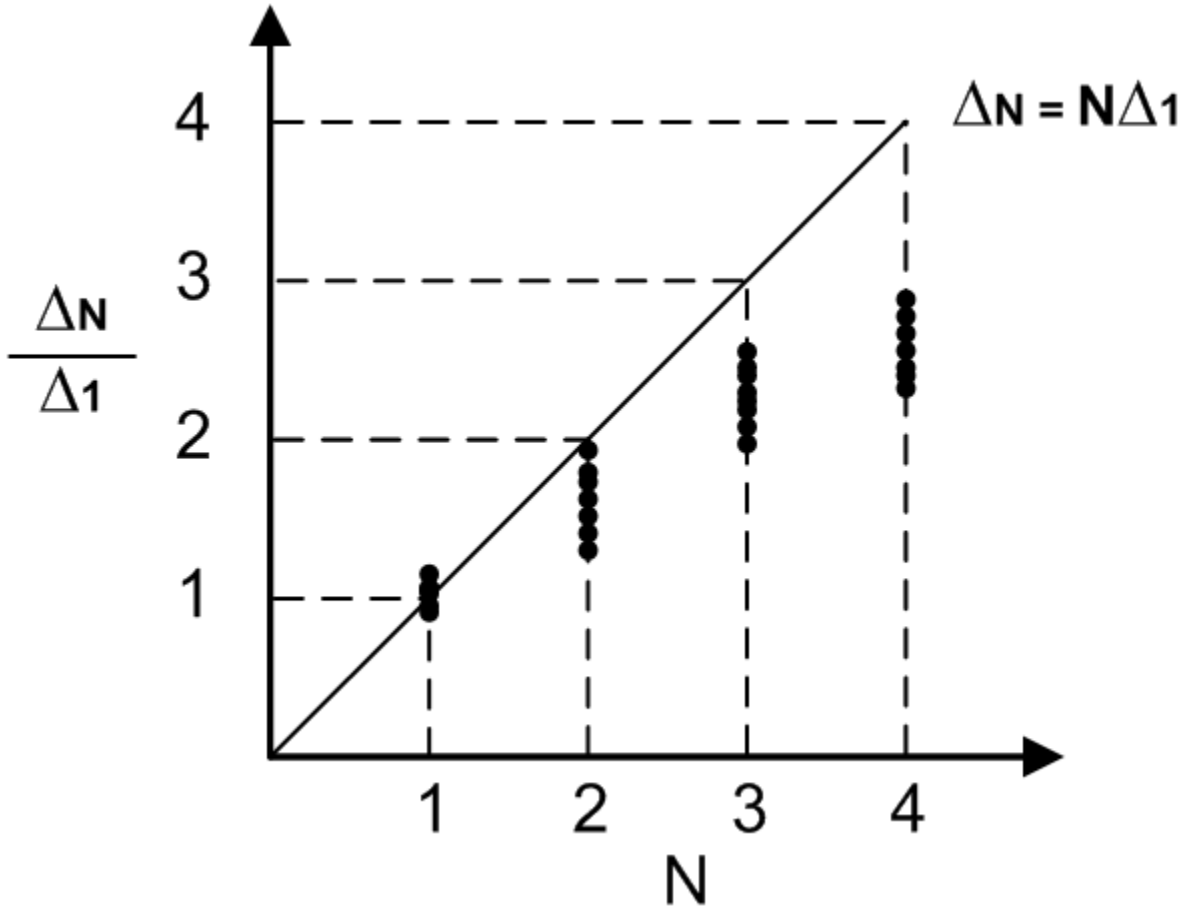
$\Delta_N \propto N$?

$\Delta_N / \Delta_1 = N$?

Measurement

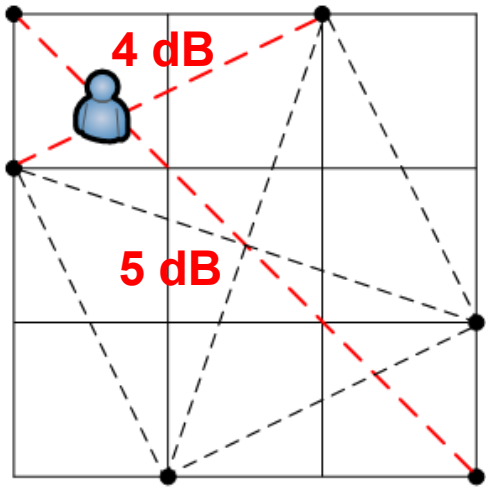


Measurement

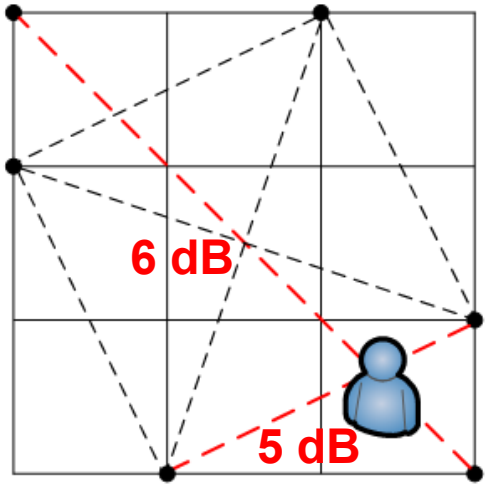


$\Delta_N / \Delta_1 \neq N$

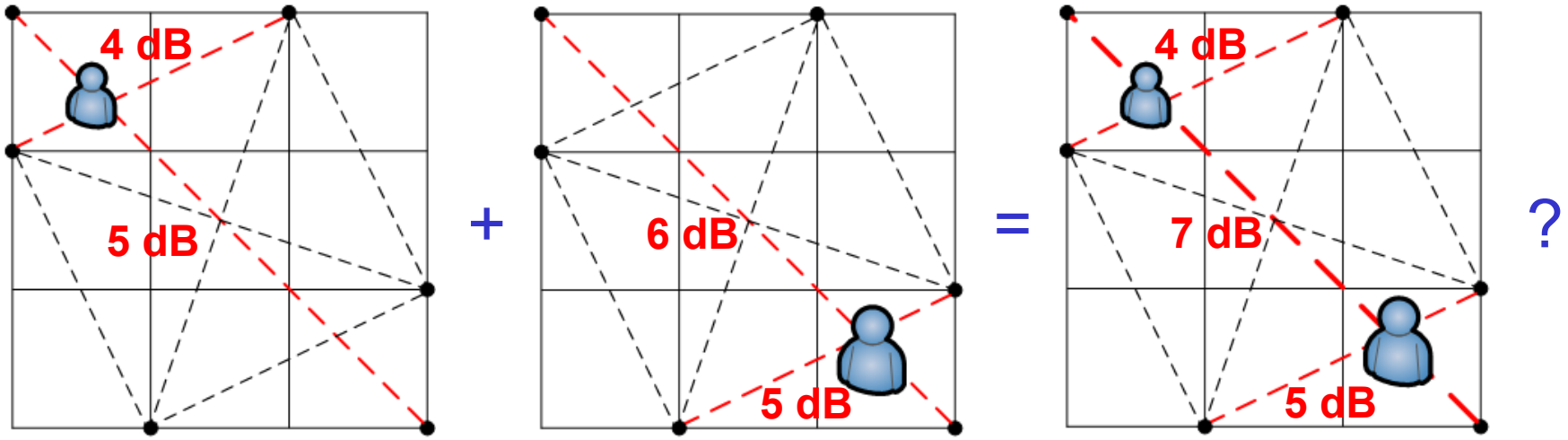
Measurement



Measurement



Measurement

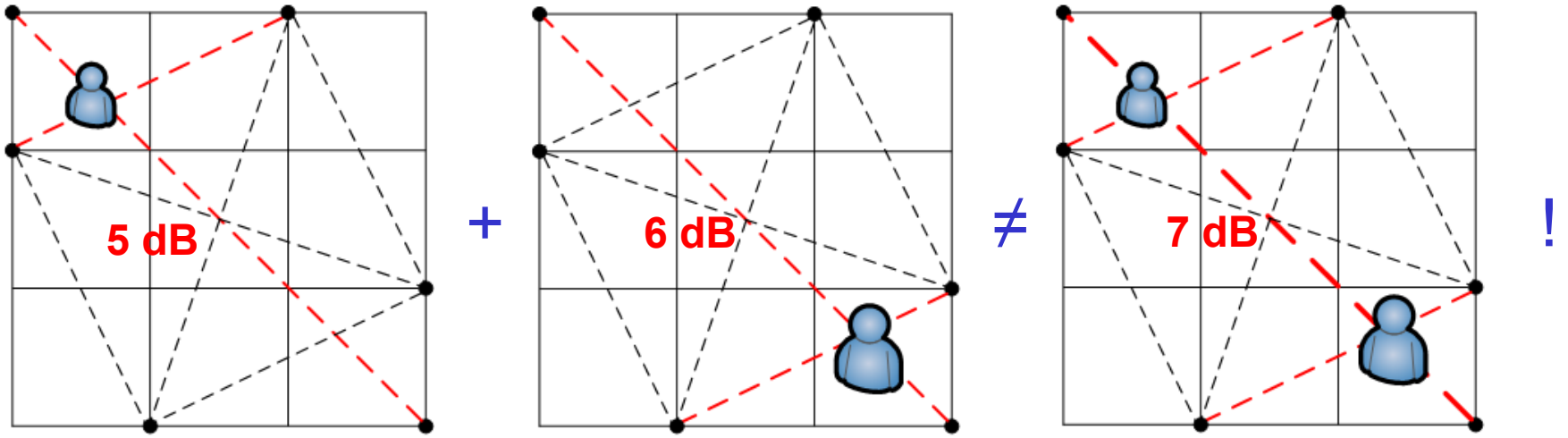


4 dB + 0 dB = 4 dB √

5 dB + 6 dB = 11 dB ≠ 7 dB X

0 dB + 5 dB = 5 dB √

Measurement



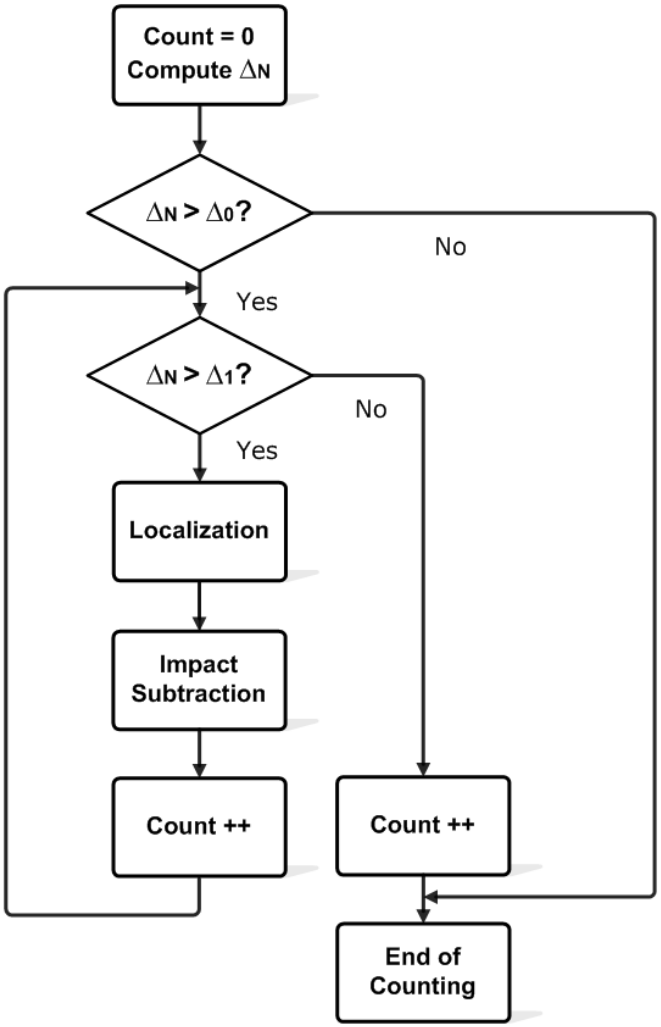
5 dB + 6 dB ≠ 7 dB X

Shared links observe nonlinear fading effect from multiple people

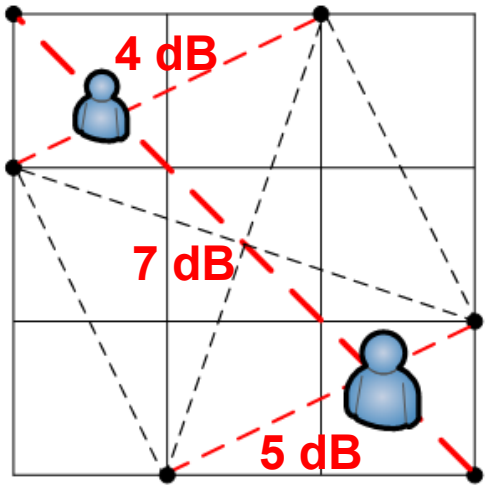
SCPL Part I
Sequential Counting (SC)

Counting algorithm

Sequential Counting Algorithm



Phase 1: Detection



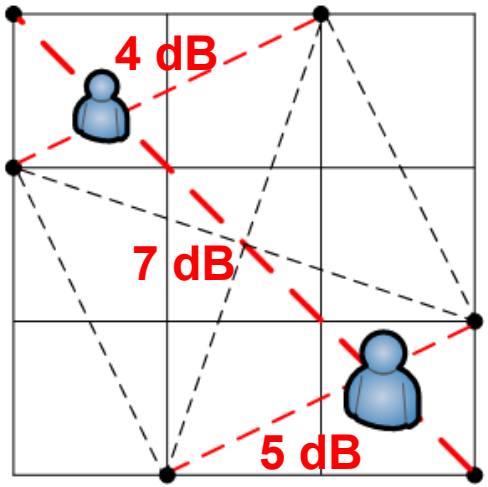
Measurement in 1st round

$\Delta_N = 4 + 7 + 5 = 16$ dB

$\Delta_N > \Delta_1$

Subject Count ++

Phase 2: Localization



Measurement in 1st round

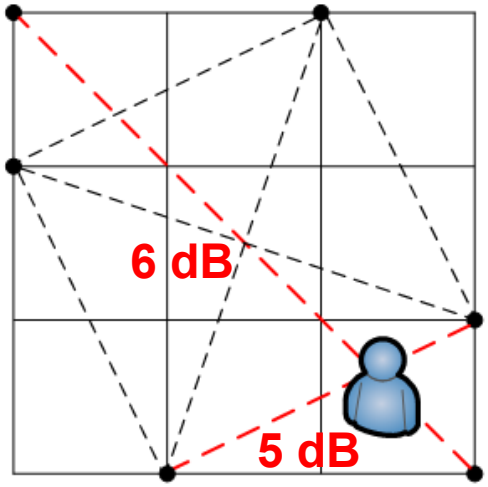
PC-DfP:

$$q = \underset{i \in \mathcal{S}}{\operatorname{argmax}} P(O|S_i)$$

← **Find this guy**

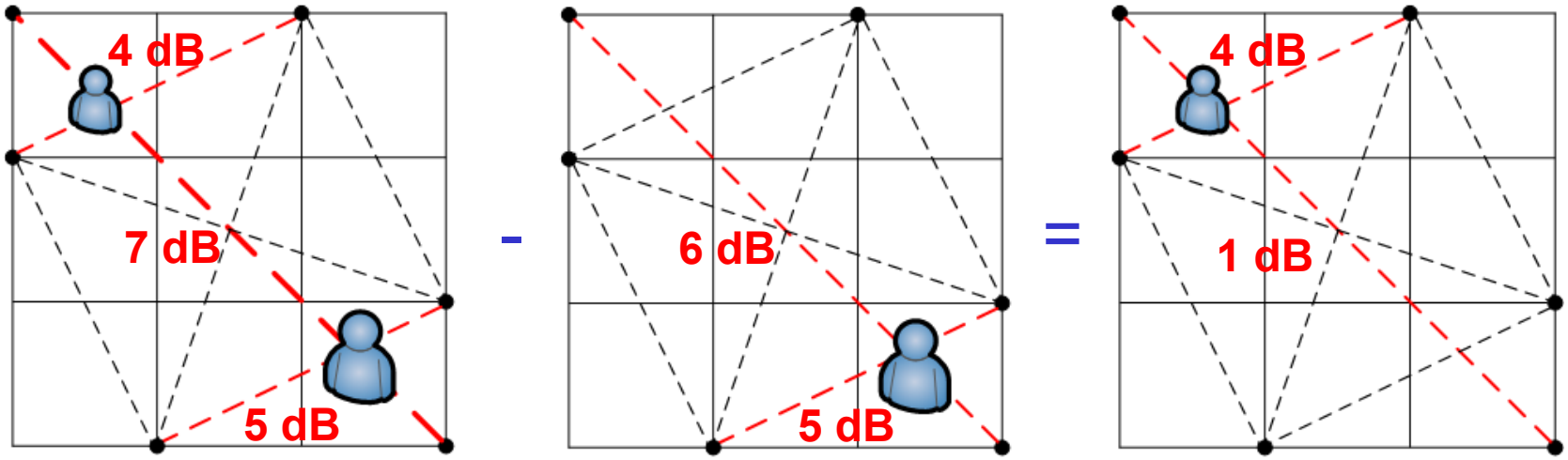
C. Xu, B. Firner, Y. Zhang, R. Howard, J. Li, and X. Lin. Improving rf-based device-free passive localization in cluttered indoor environments through probabilistic classification methods. In *Proceedings of the 11th international conference on Information Processing in Sensor Networks*, IPSN '12

Phase 3: Subtraction



Calibration data

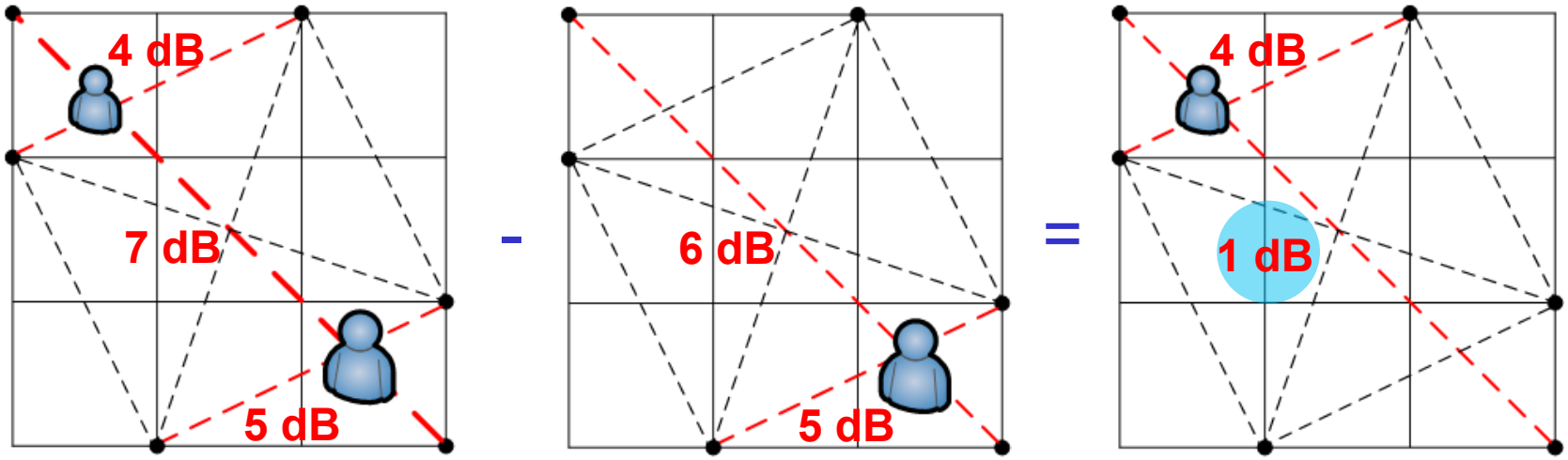
Phase 3: Subtraction



Measurement in 1st round | **Calibration data** | **Measurement In 2nd round**

Subject count ++
Go to the next iteration…

Phase 3: Subtraction



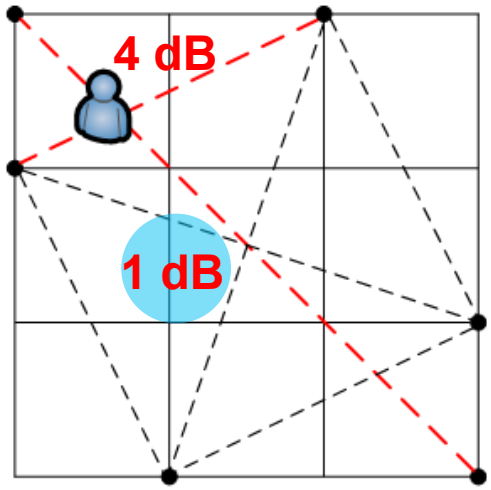
Measurement in 1st round | **Calibration data** | **Measurement In 2nd round**

Subject count ++

Go to the next iteration…

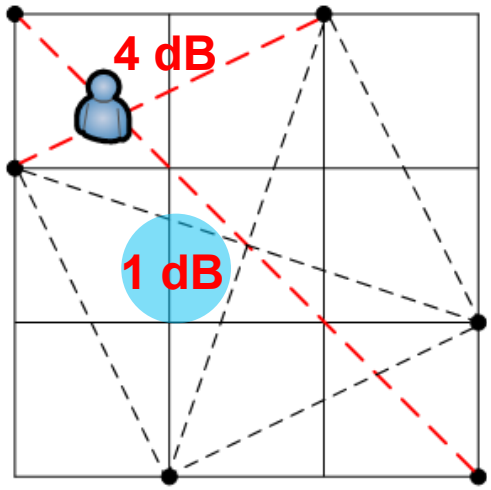
Hold on …

Phase 3: Subtraction

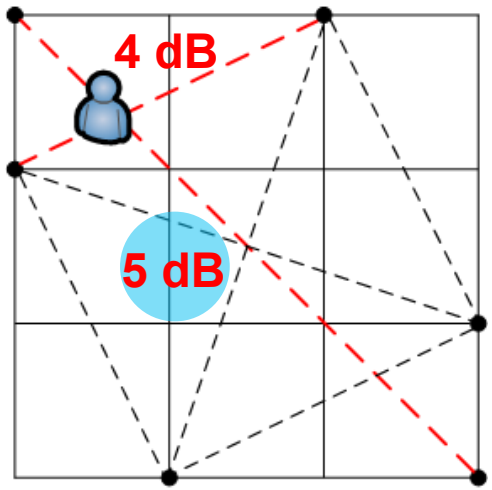


Measurement In 2nd round

Phase 3: Subtraction

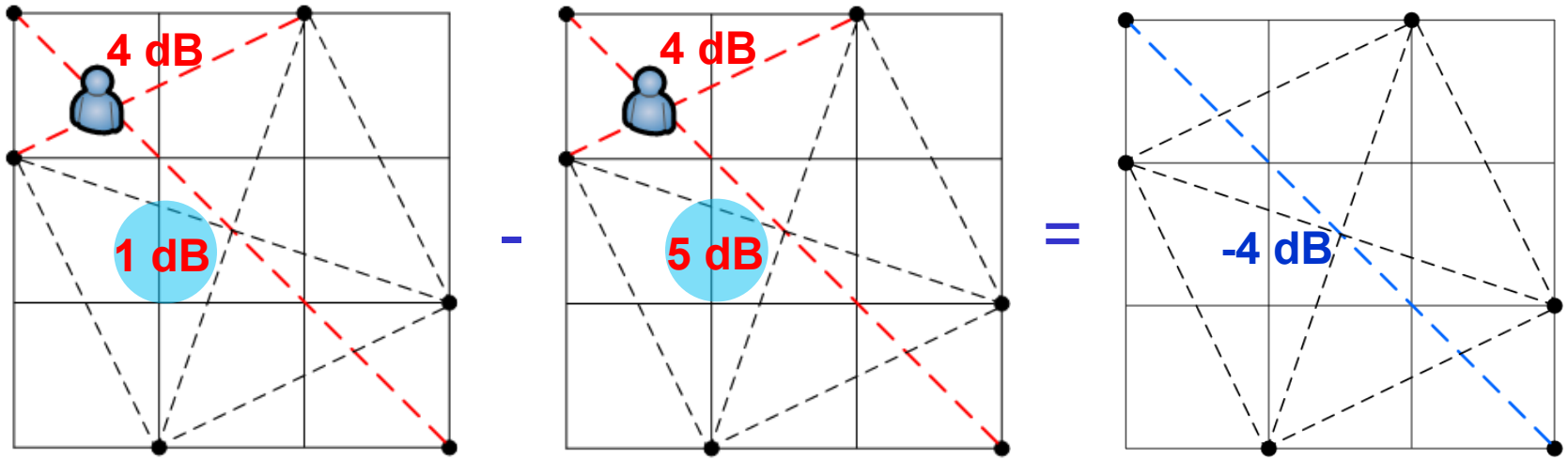


Measurement
In 2nd round



Calibration
data

Phase 3: Subtraction

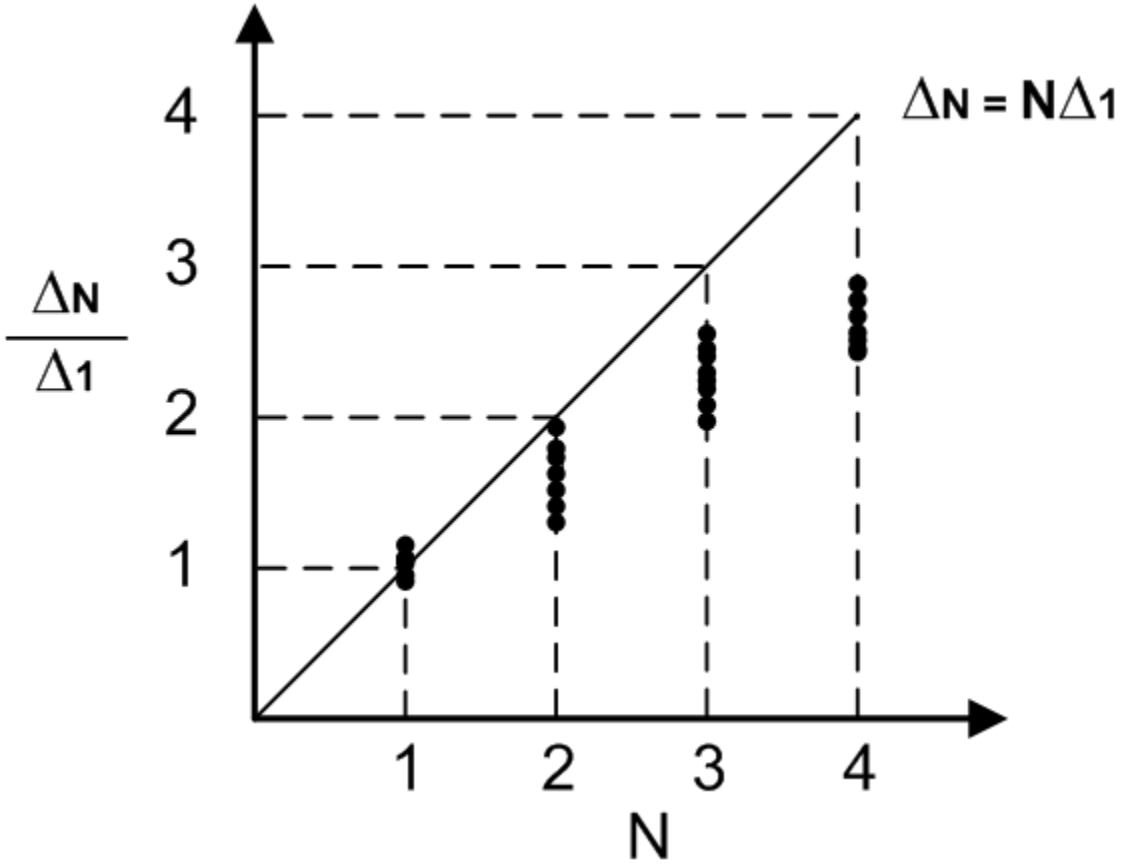


Measurement In 2nd round

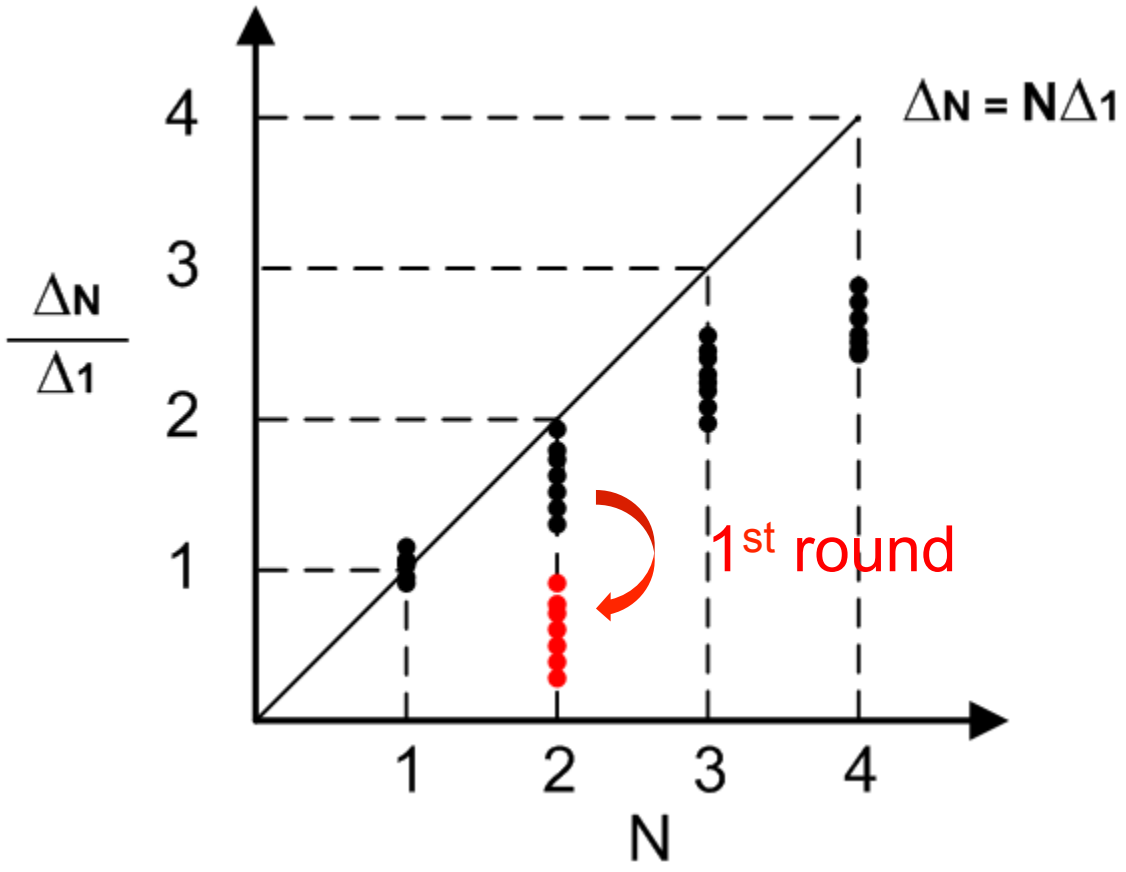
Calibration data

We over-subtracted its impact on shared link!

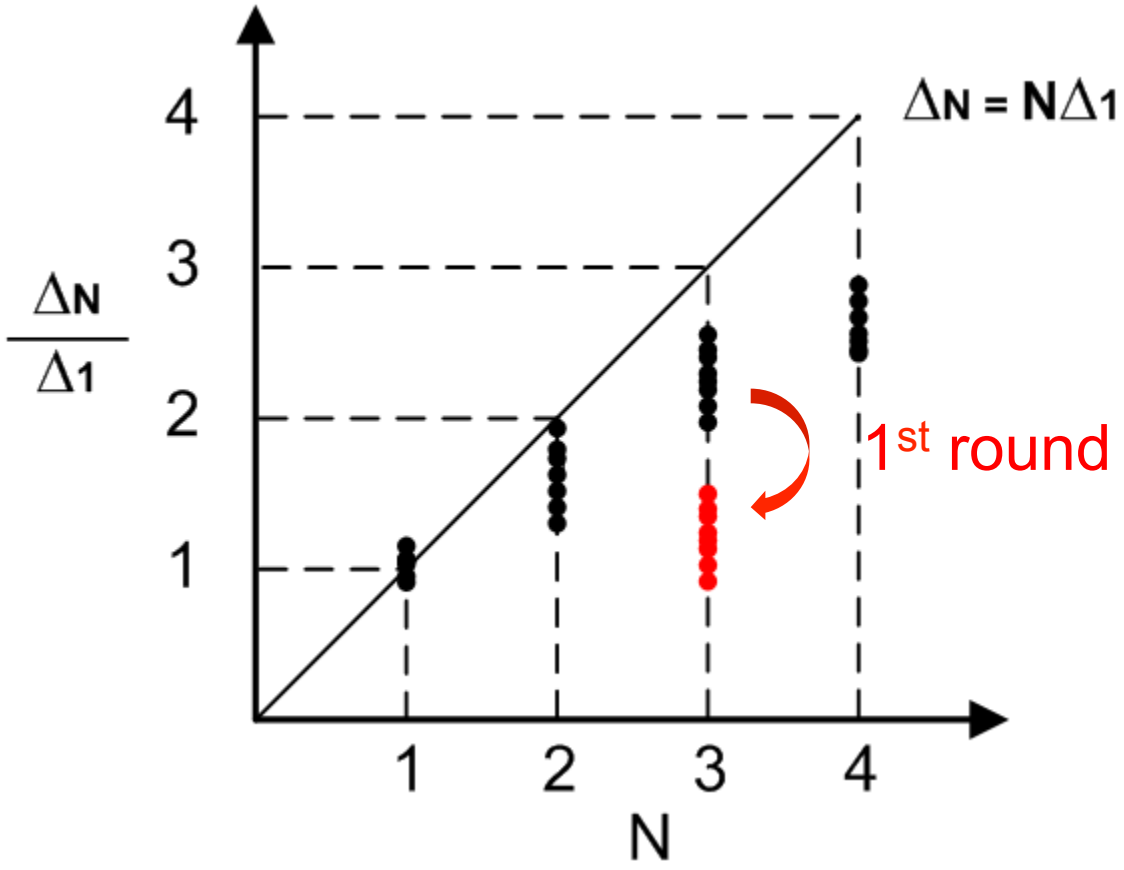
Measurement



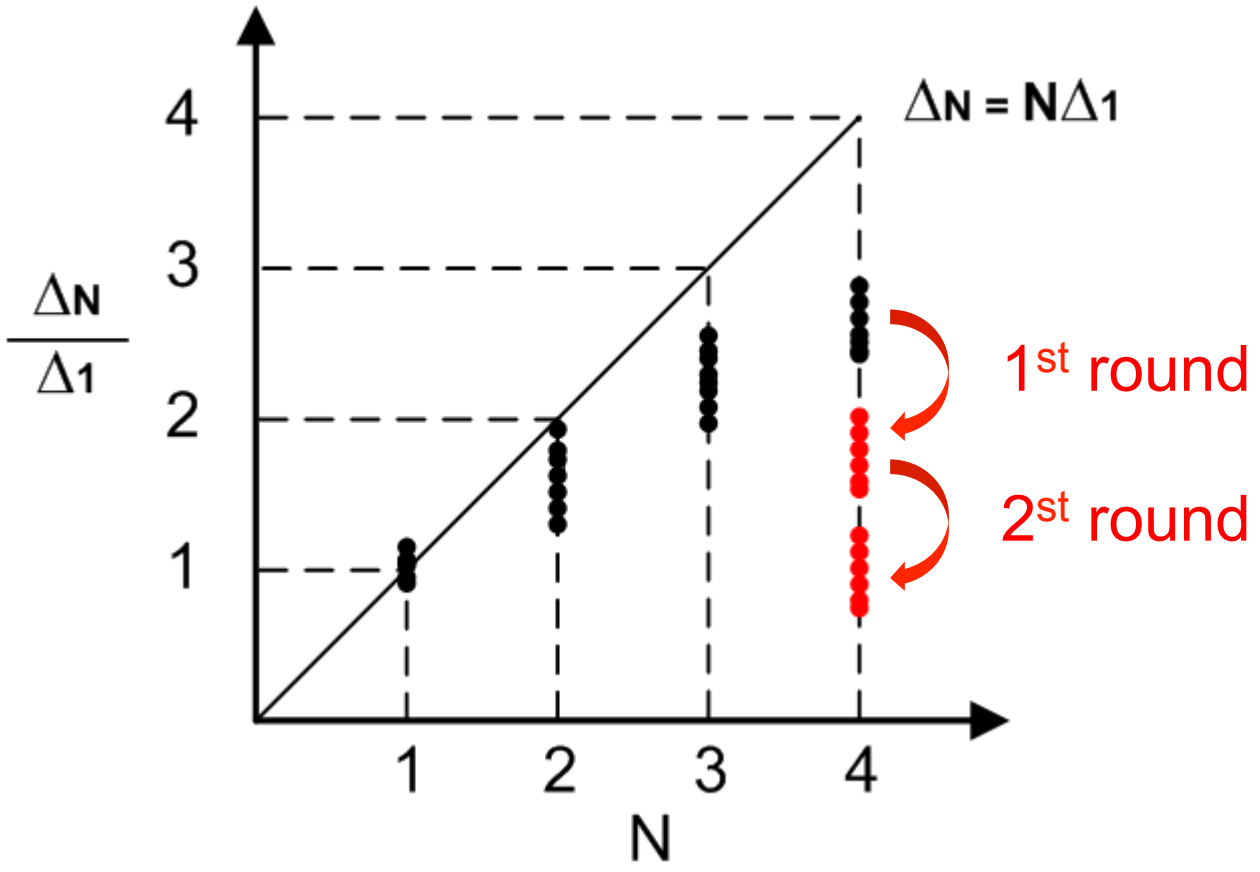
Measurement



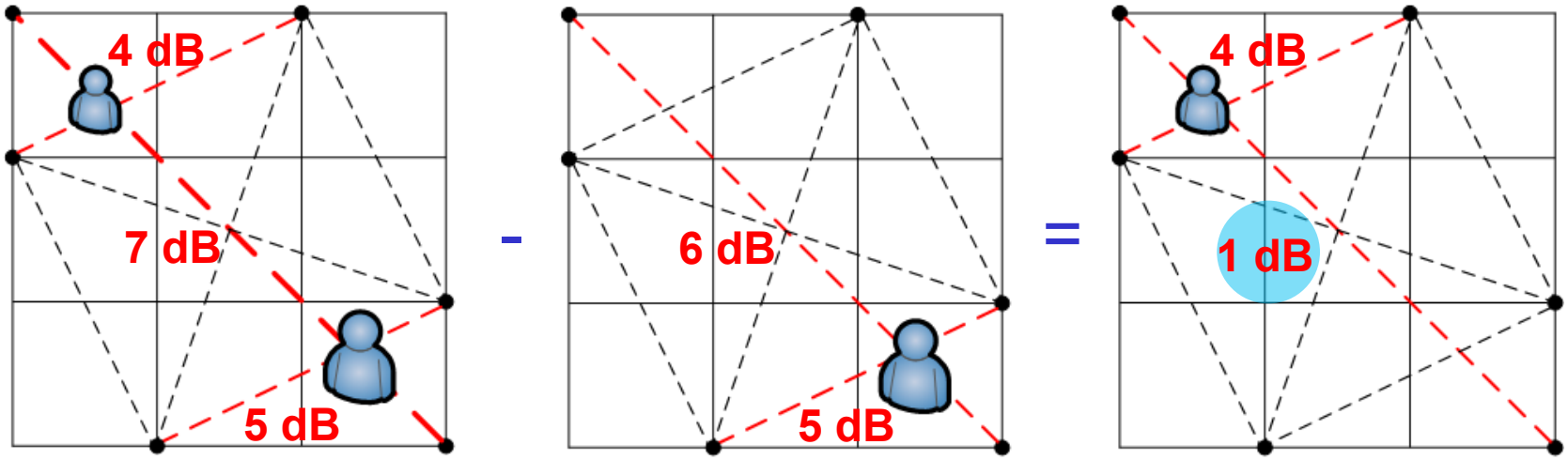
Measurement



Measurement



Phase 3: Subtraction



Measurement in 1st round | **Calibration data** | **Measurement In 2nd round**

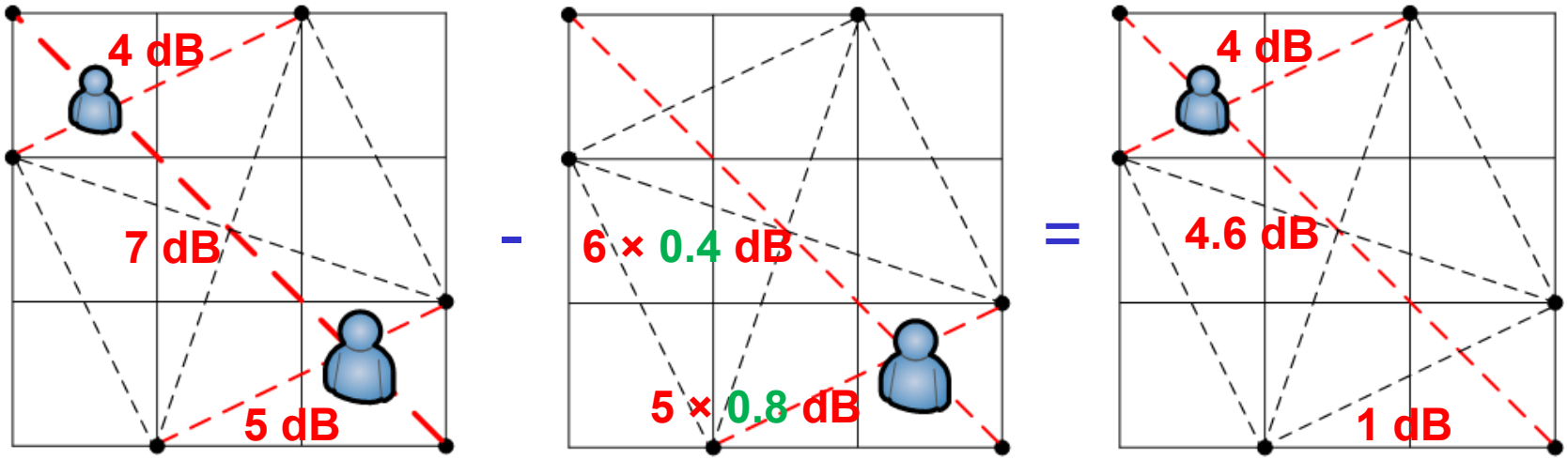
We need to multiply a coefficient $\beta \in [0, 1]$ when subtracting each link

Location-Link Correlation

- To mitigate the error caused by this over-subtraction problem, we propose to multiply a location-link correlation coefficient before successive subtracting:

$$\beta_{il} = \frac{h_{ii}^{l}}{\sqrt{\sum_{j=1}^{K} {h_{ij}^{l}}^{2}}} \qquad h_{ij} \leftarrow E\left[\mathcal{D}_{Il}\mathcal{D}_{Jl}\right]$$

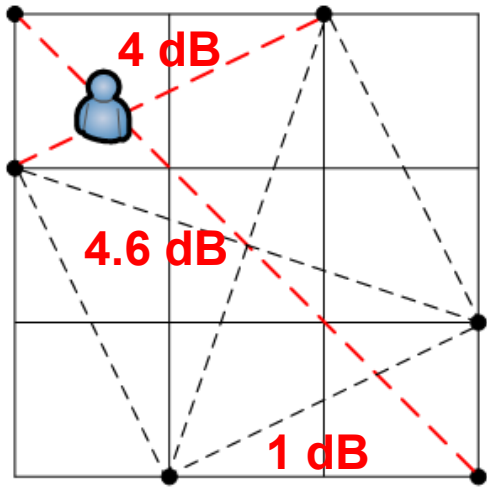
Phase 3: Subtraction



Measurement in 1st round | **Calibration Data** | **Measurement in 2nd round**

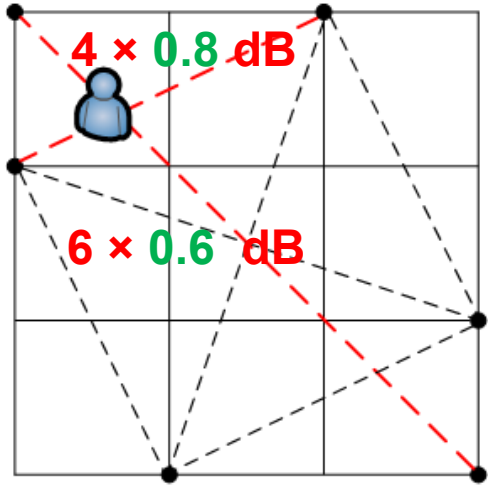
Subject count ++
Go to the next iteration…

Phase 3: Subtraction



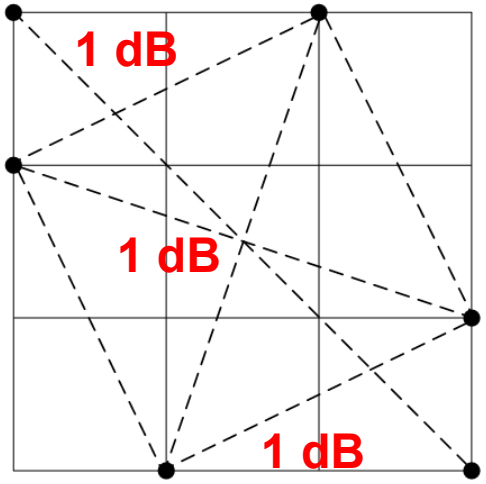
Measurement in 2nd round

-



Calibration data

=



Measurement in 3rd round

We are done !

SCPL Part II
Parallel Localization (PL)

Localization

- Cell-based localization
  - Allows use of context information
  - Reduce calibration overhead
  - Classification problem formulation

C. Xu, B. Firner, Y. Zhang, R. Howard, J. Li, and X. Lin. Improving rf-based device-free passive localization in cluttered indoor environments through probabilistic classification methods. In *Proceedings of the 11th international conference on Information Processing in Sensor Networks*, IPSN '12

Linear Discriminant Analysis

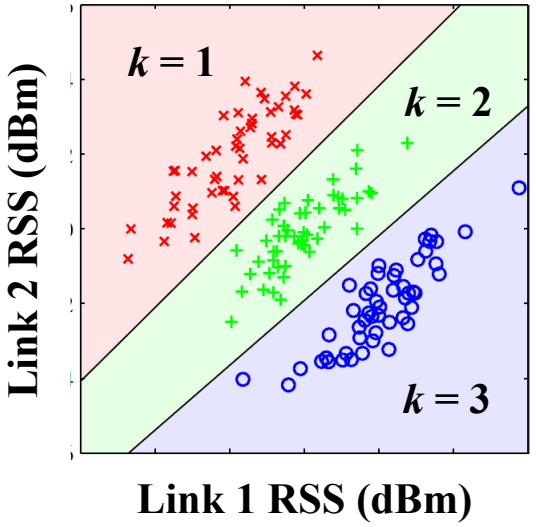
- RSS measurements with person's presence in each cell is treated as a class/state *k*
- Each class k is Multivariate Gaussian with common covariance

$$f_k(x) = \frac{1}{(2\pi)^{\frac{L}{2}} |\Sigma|^{\frac{1}{2}}} exp\left[-\frac{1}{2}(x-\mu_k)^T \Sigma^{-1} (x-\mu_k)\right]$$

- Linear discriminant function:

$$\delta_k(x) = x^T \Sigma^{-1} \mu_k - \frac{1}{2} \mu_k{}^T \Sigma^{-1} \mu_k + \log \pi_k$$

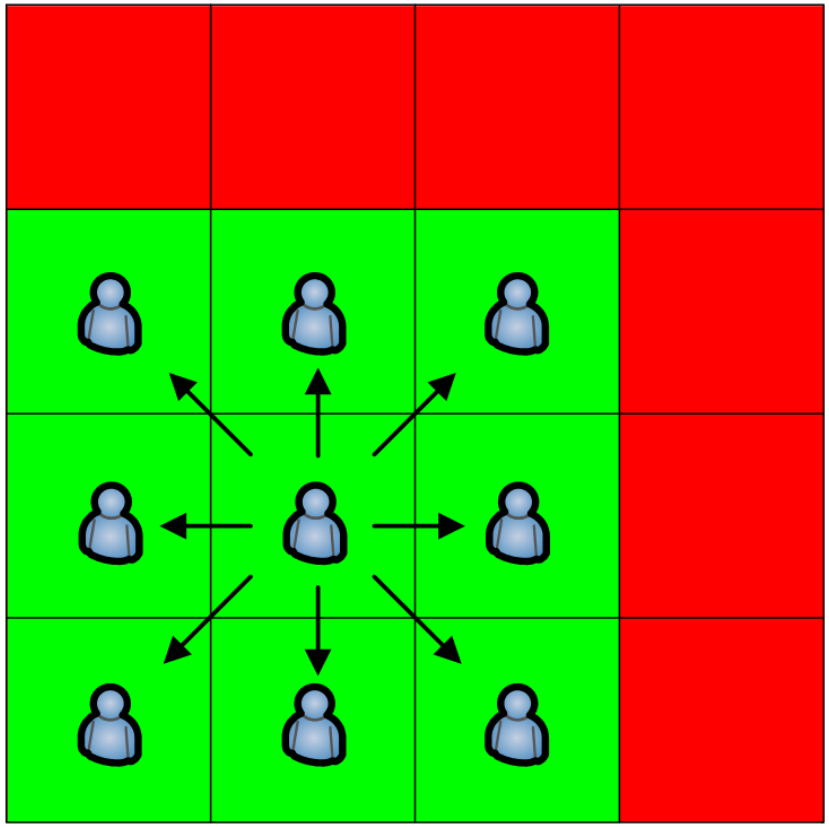
$$\hat{y} = argmax_k \delta_k(x)$$



Localization

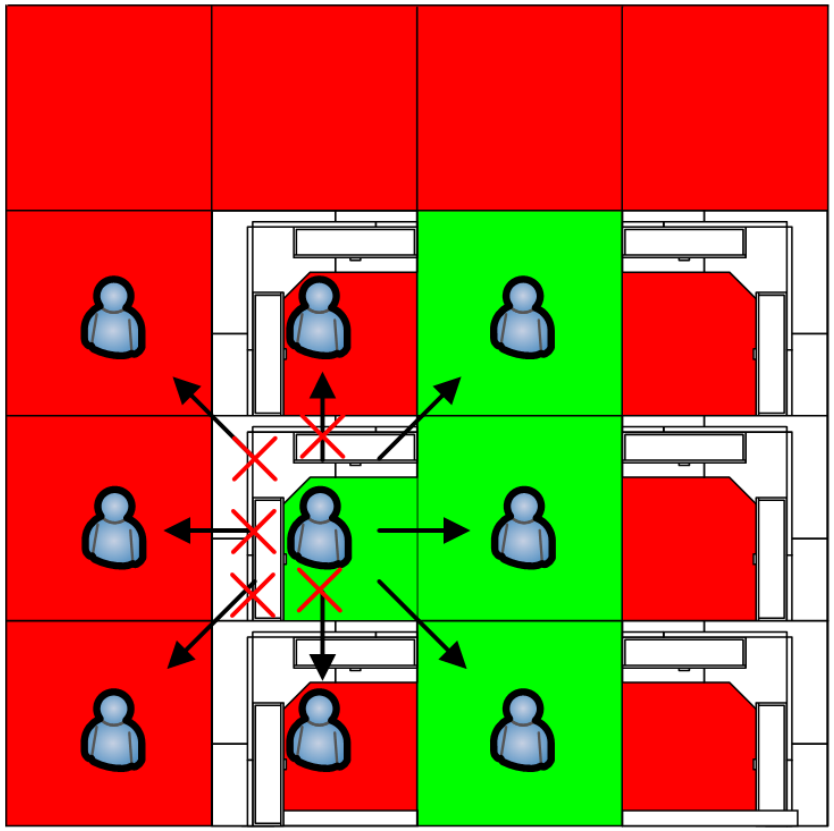
- Cell-based localization
- Trajectory-assisted localization
  - Improve accuracy by using human mobility constraints

Human Mobility Constraints



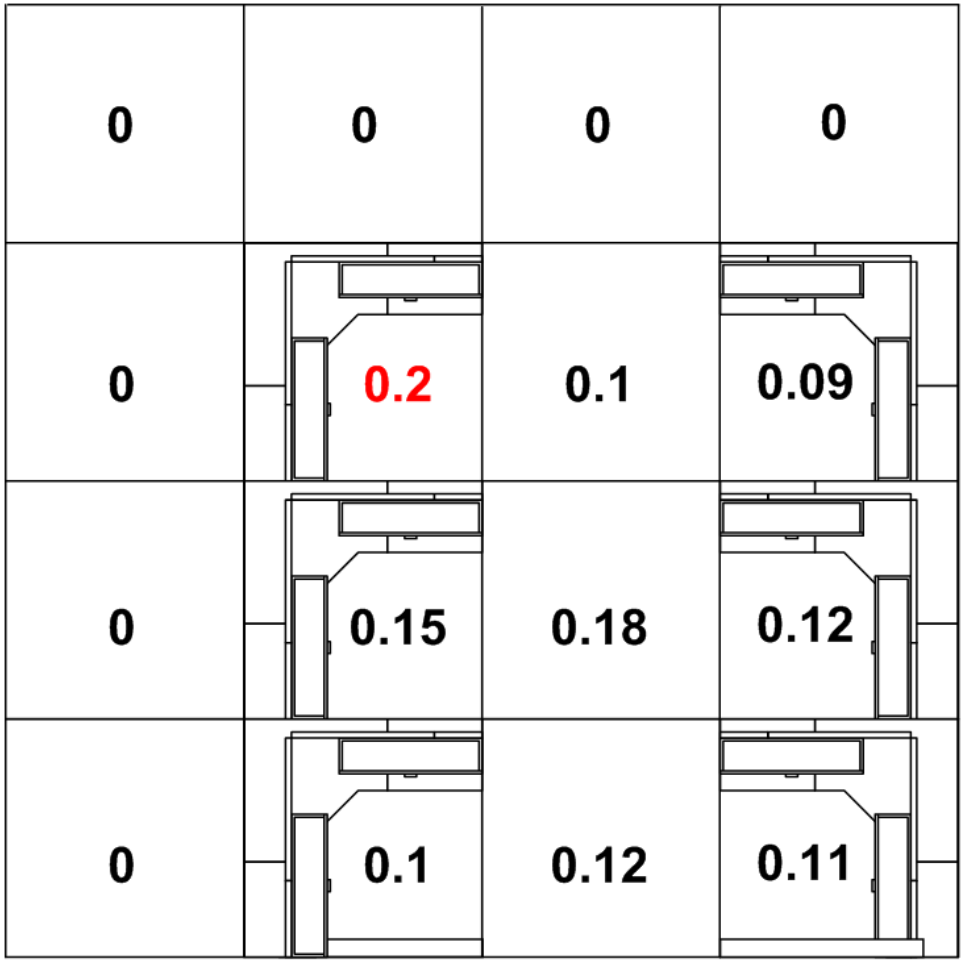
You are free to go anywhere with limited step size inside a ring in free space

Human Mobility Constraints

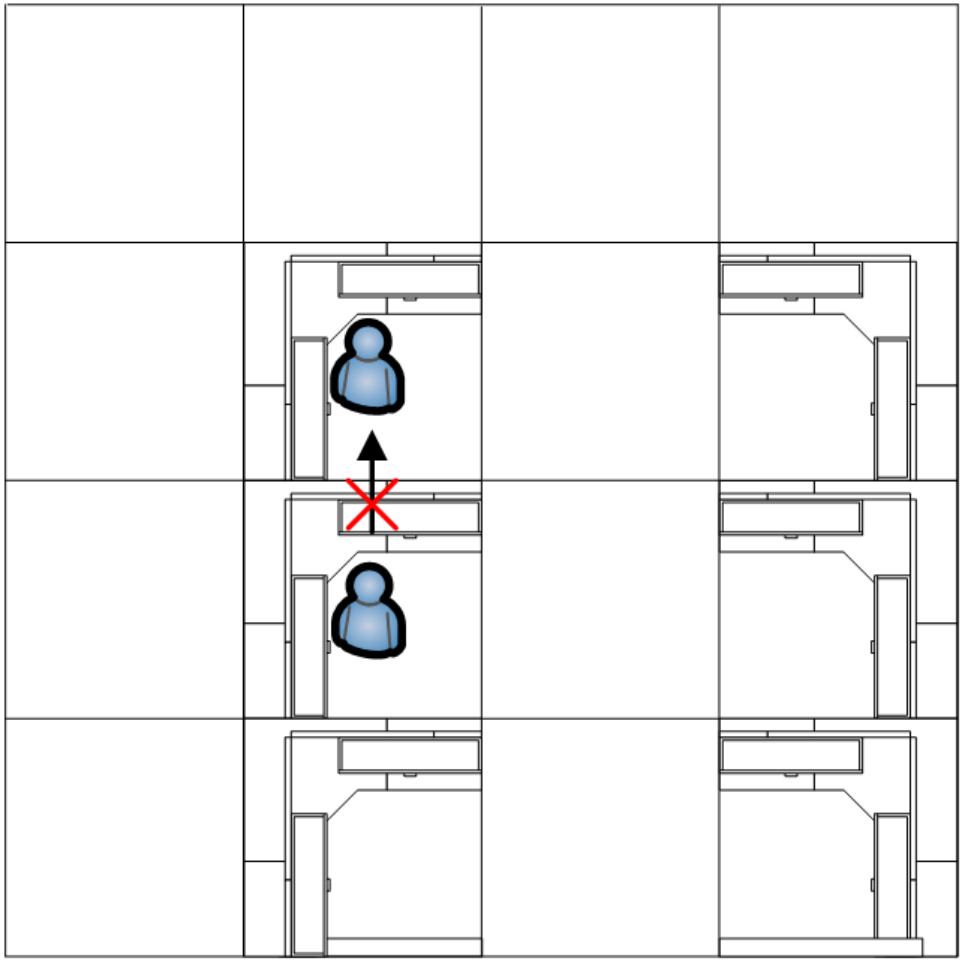


In a building, your next step is constrained by cubicles, walls, etc.

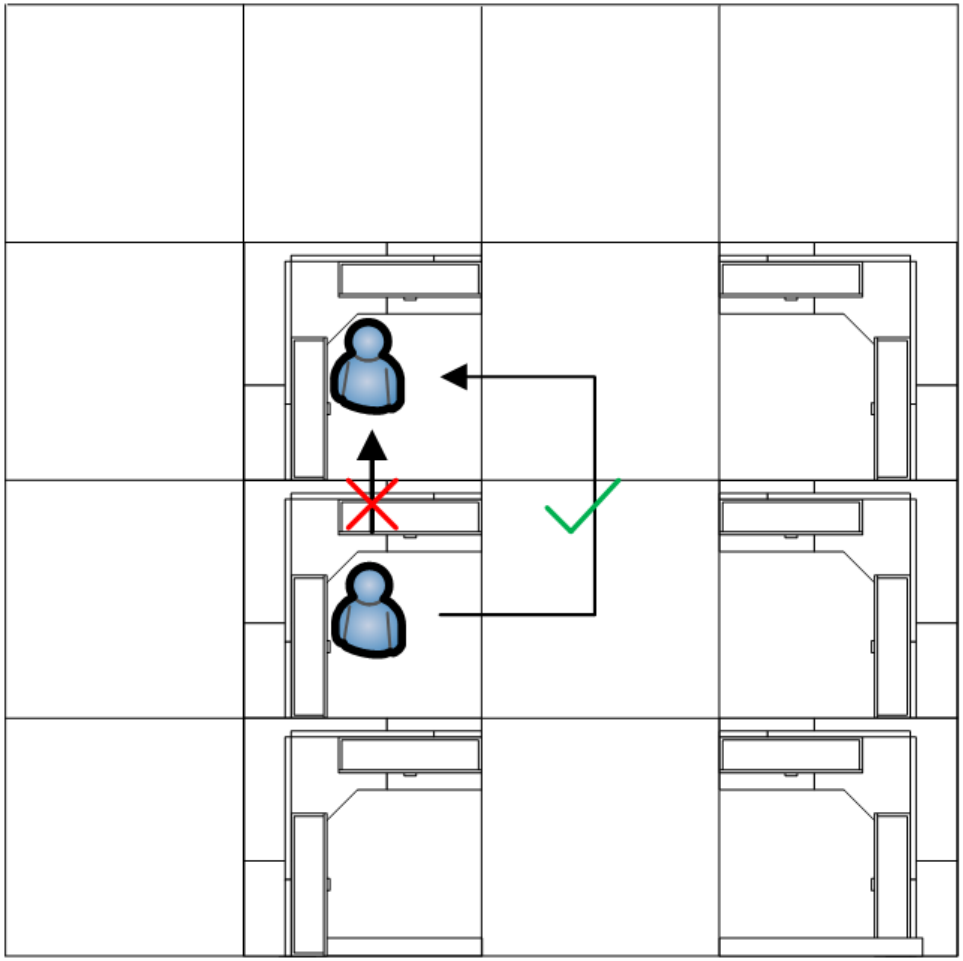
Phase 1: Data Likelihood Map



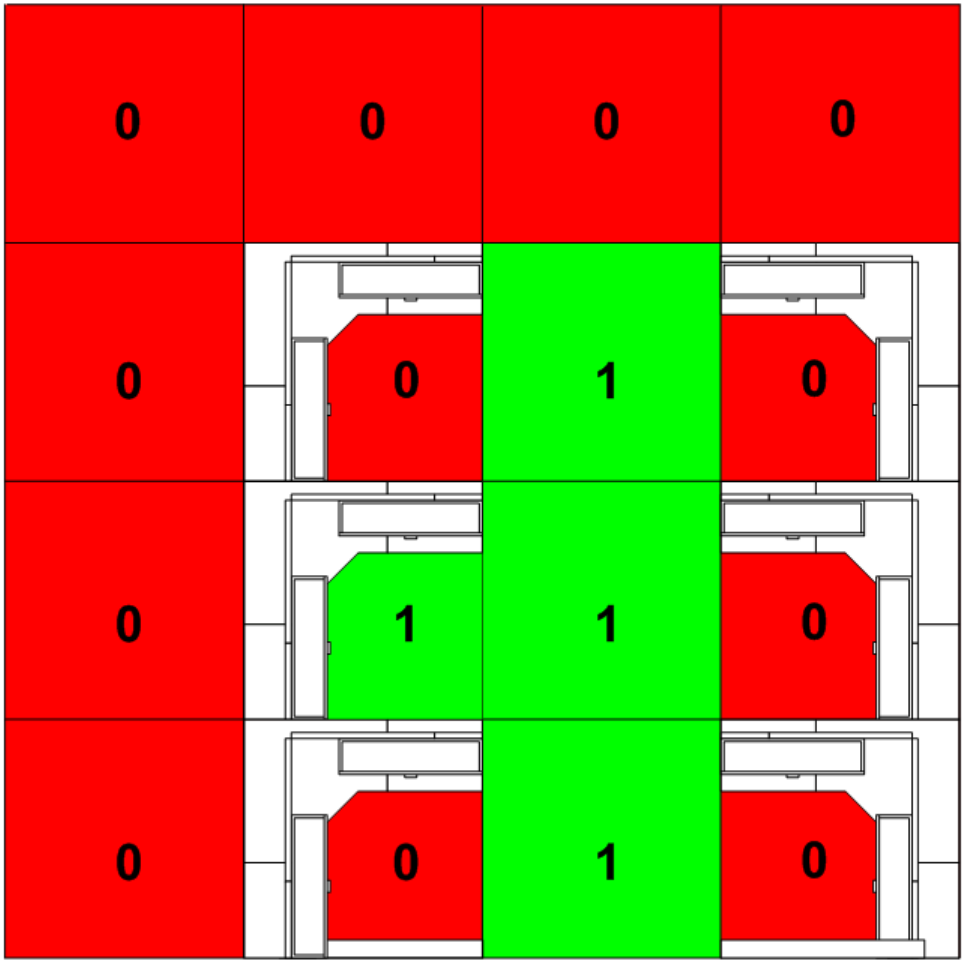
Impossible movements



Impossible movements

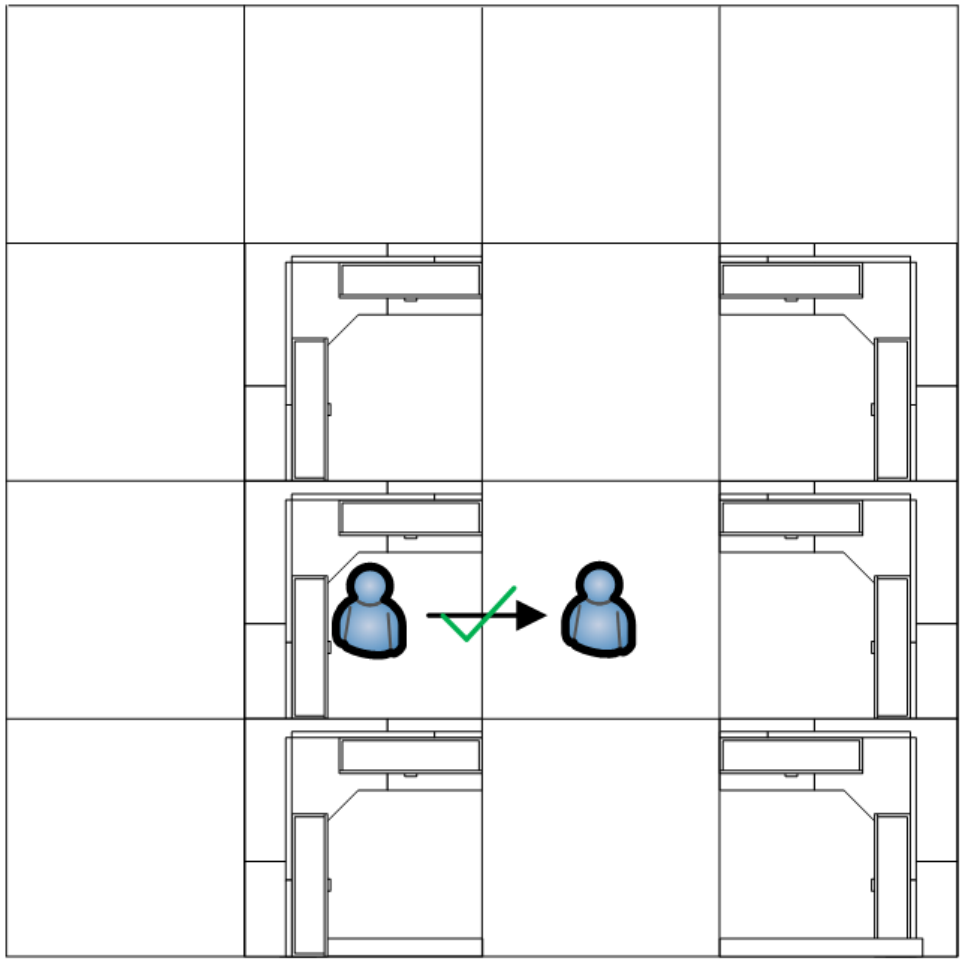


Phase 2: Trajectory Ring Filter



Phase 3: Refinement

Here you are!



Viterbi optimal trajectory

- **Single subject localization**

$$V_j(t) = \underset{q_1, q_2, \ldots, q_{t-1}}{\operatorname{argmax}} \; P(q_1 q_2 \ldots q_t = j, O_1 O_2 \ldots O_t | T, \delta)$$

- **Multiple subjects localization**

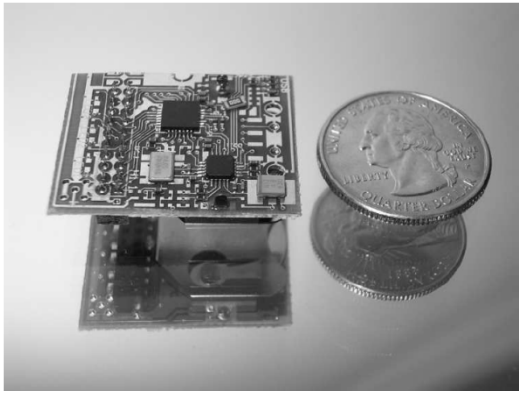
$$\texttt{ViterbiScore} = F_j = \sum_{i=1}^{C} \delta_{q_t^i}(O_t) T_{q_{t-1}^i q_t^i}$$

$\Pi \leftarrow$ is the set of all the possible permutations of $\binom{K}{C}$

$Q_i \leftarrow \operatorname{argmax}_{j \in \Pi} \texttt{ViterbiScore}(Q_{i-1}, Q_j, \delta_{1:K}(O_i), T)$

System Description

- Hardware: PIP tag
  - Microprocessor: C8051F321
  - Radio chip: CC1100
  - Power: Lithium coin cell battery

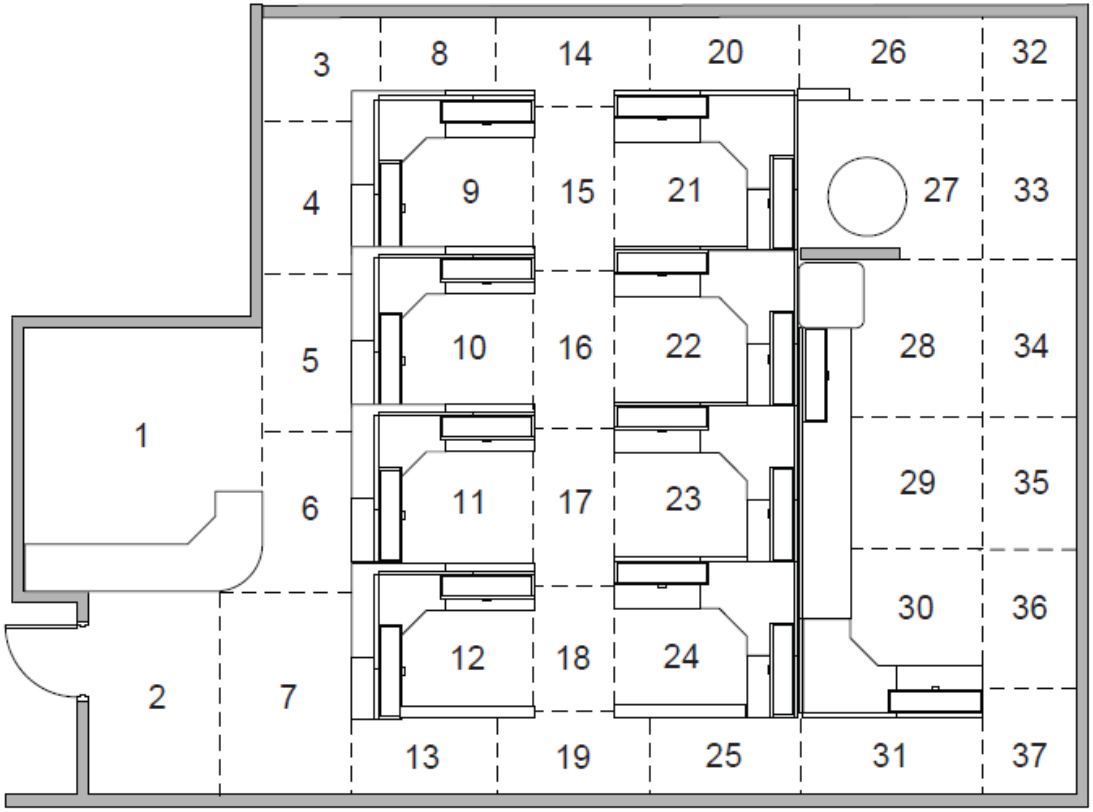


- Protocol: Unidirectional heartbeat (Uni-HB)
  - Packet size: 10 bytes
  - Beacon interval: 100 msec

Office deployment

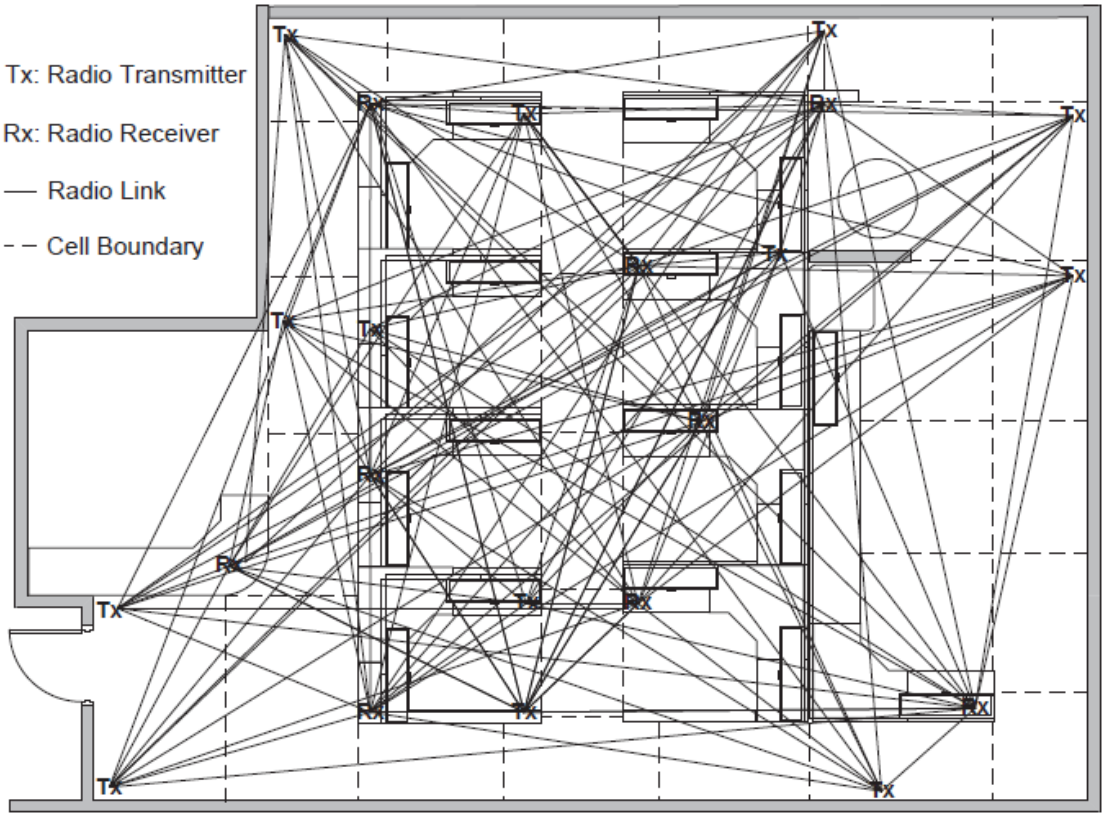
Total Size: 10 × 15 m

Office deployment



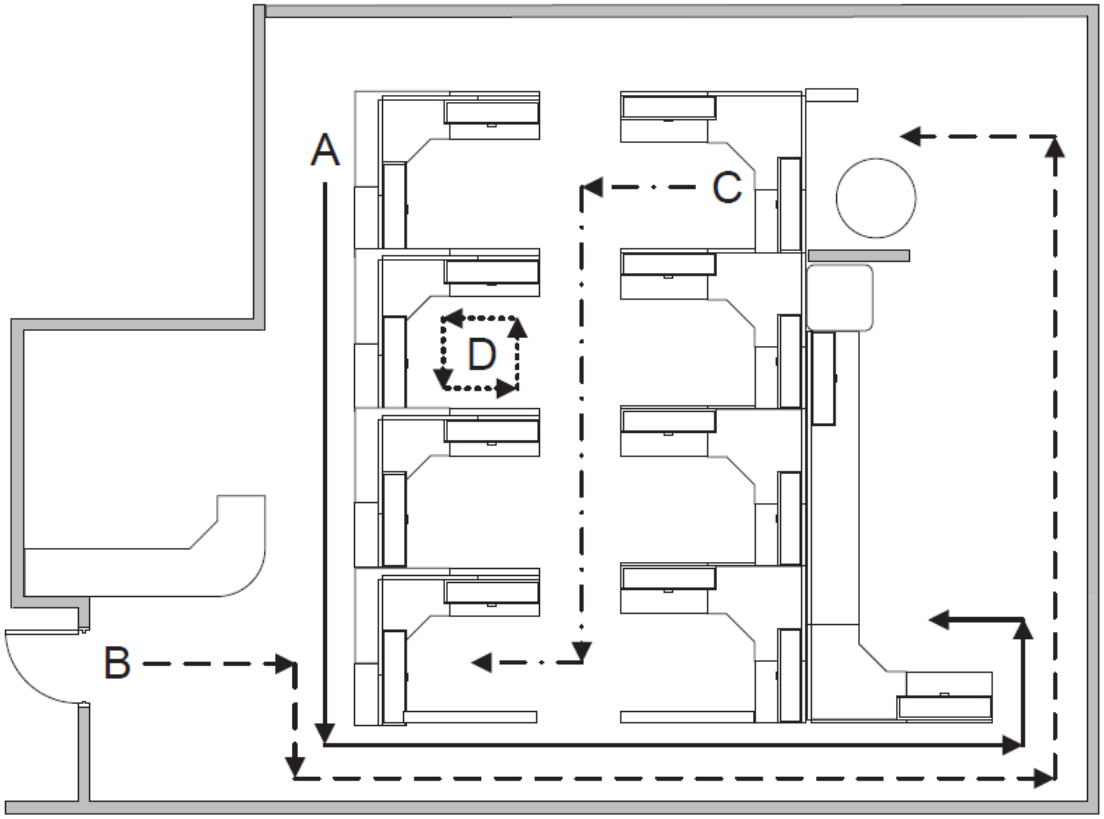
37 cells of cubicles, aisle segments

Office deployment



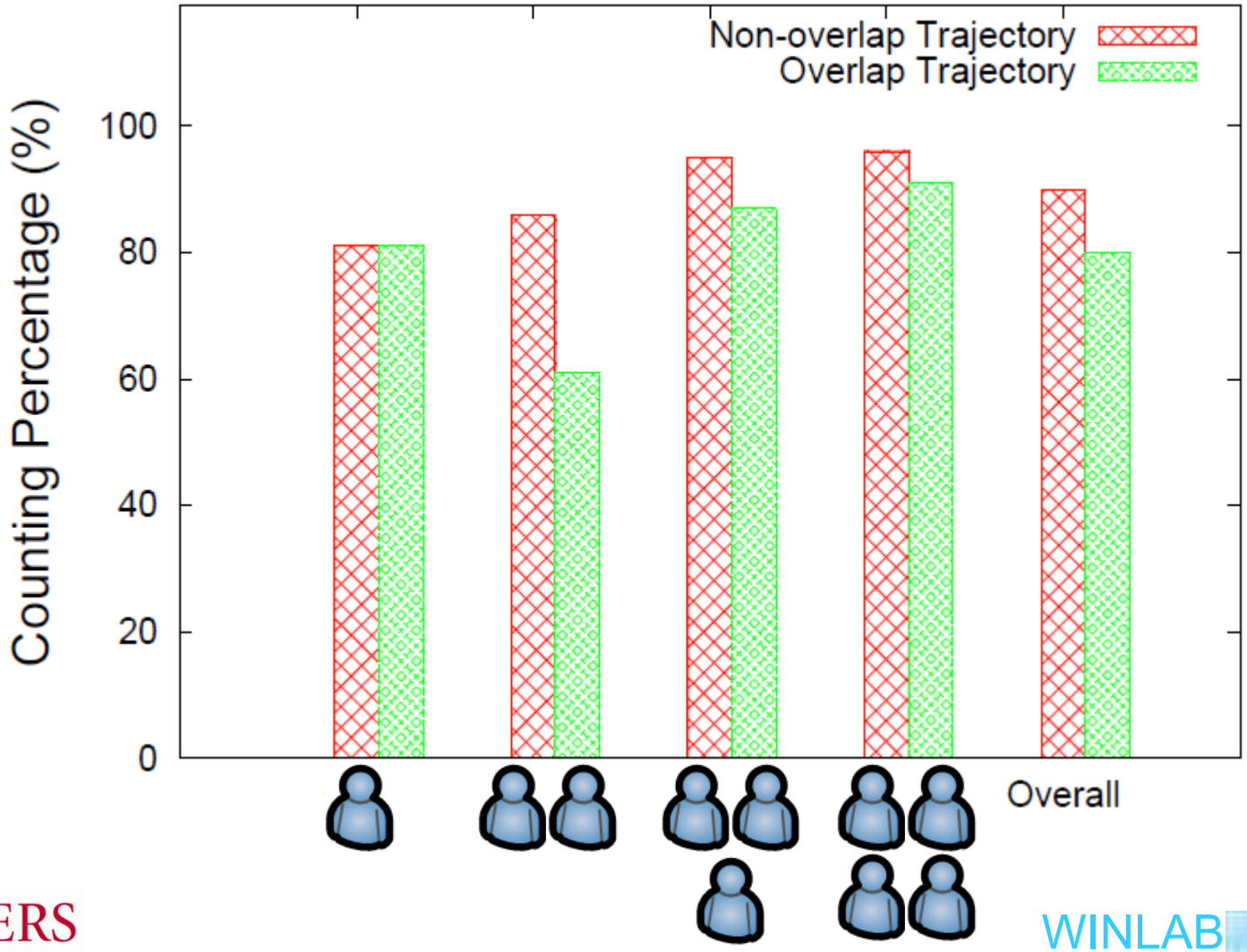
13 transmitters and 9 receivers

Office deployment

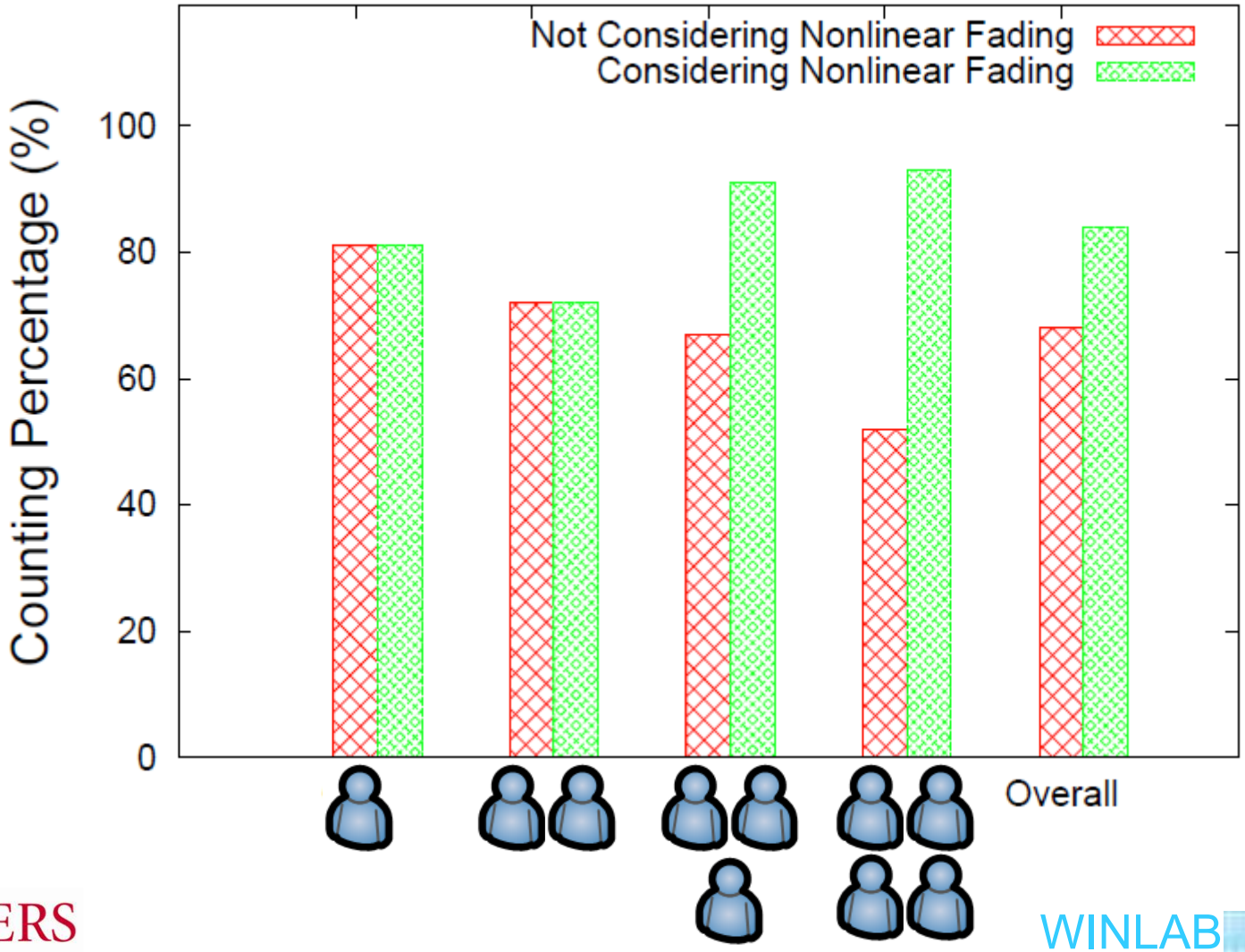


Four subjects' testing paths

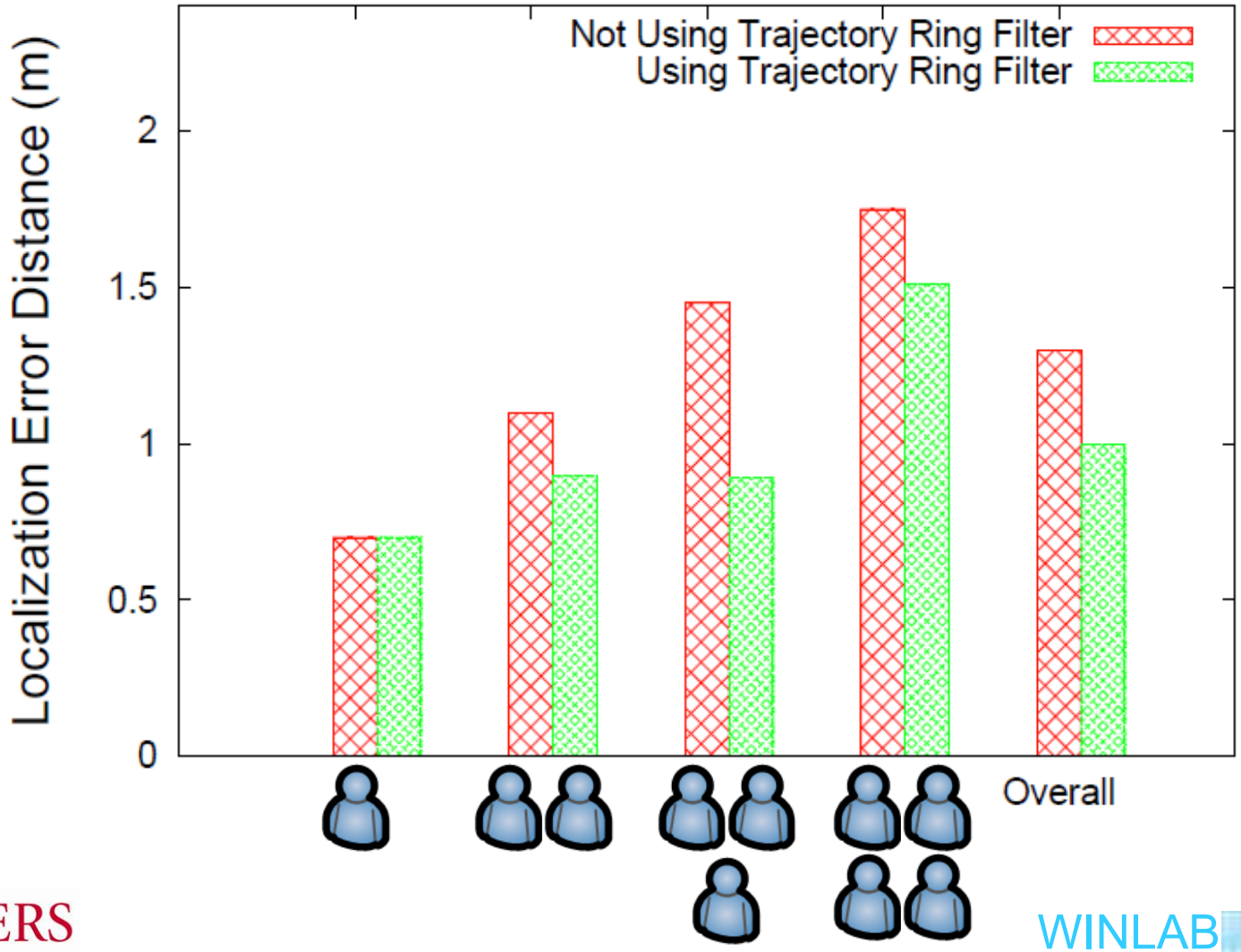
Counting results



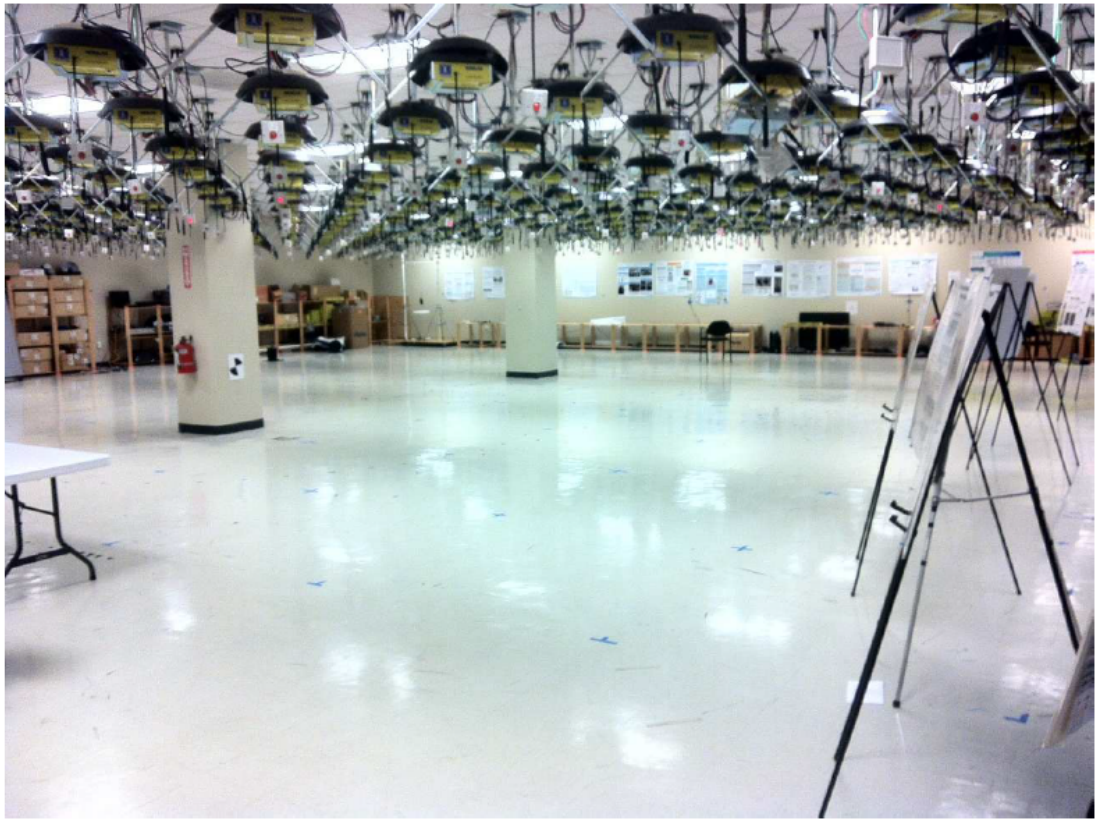
Counting results



Localization results

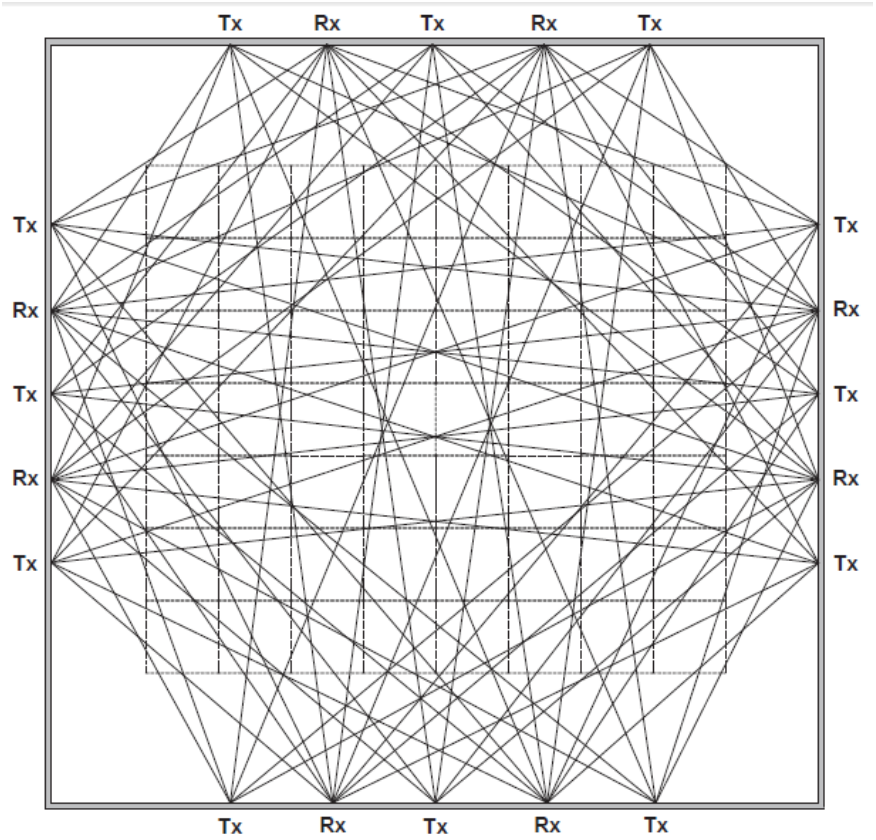


Open floor deployment



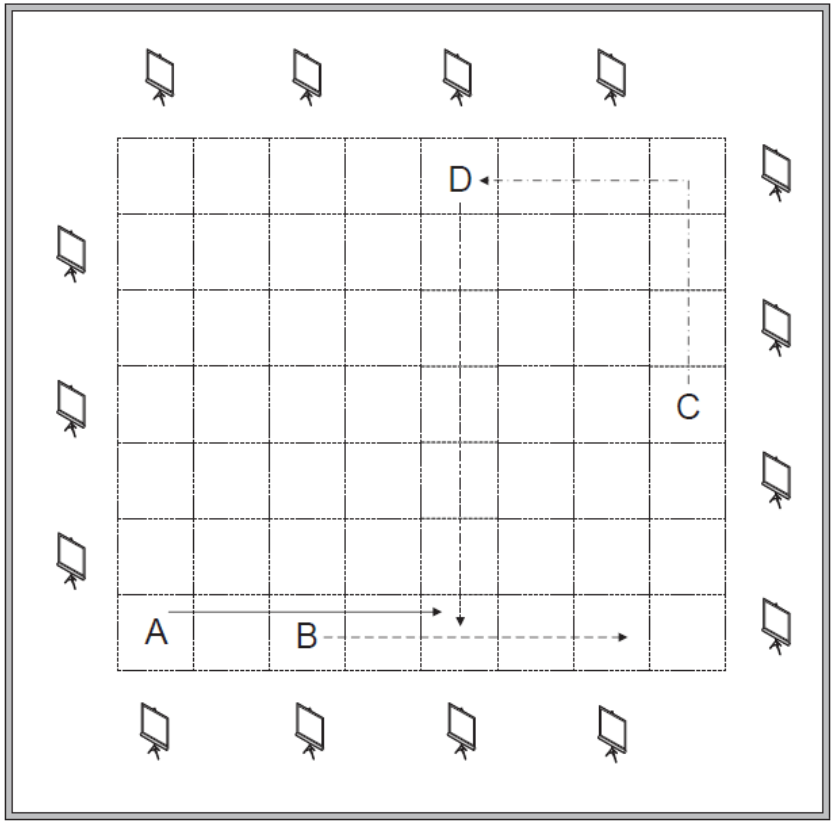
Total Size: 20 × 20 m

Open floor deployment



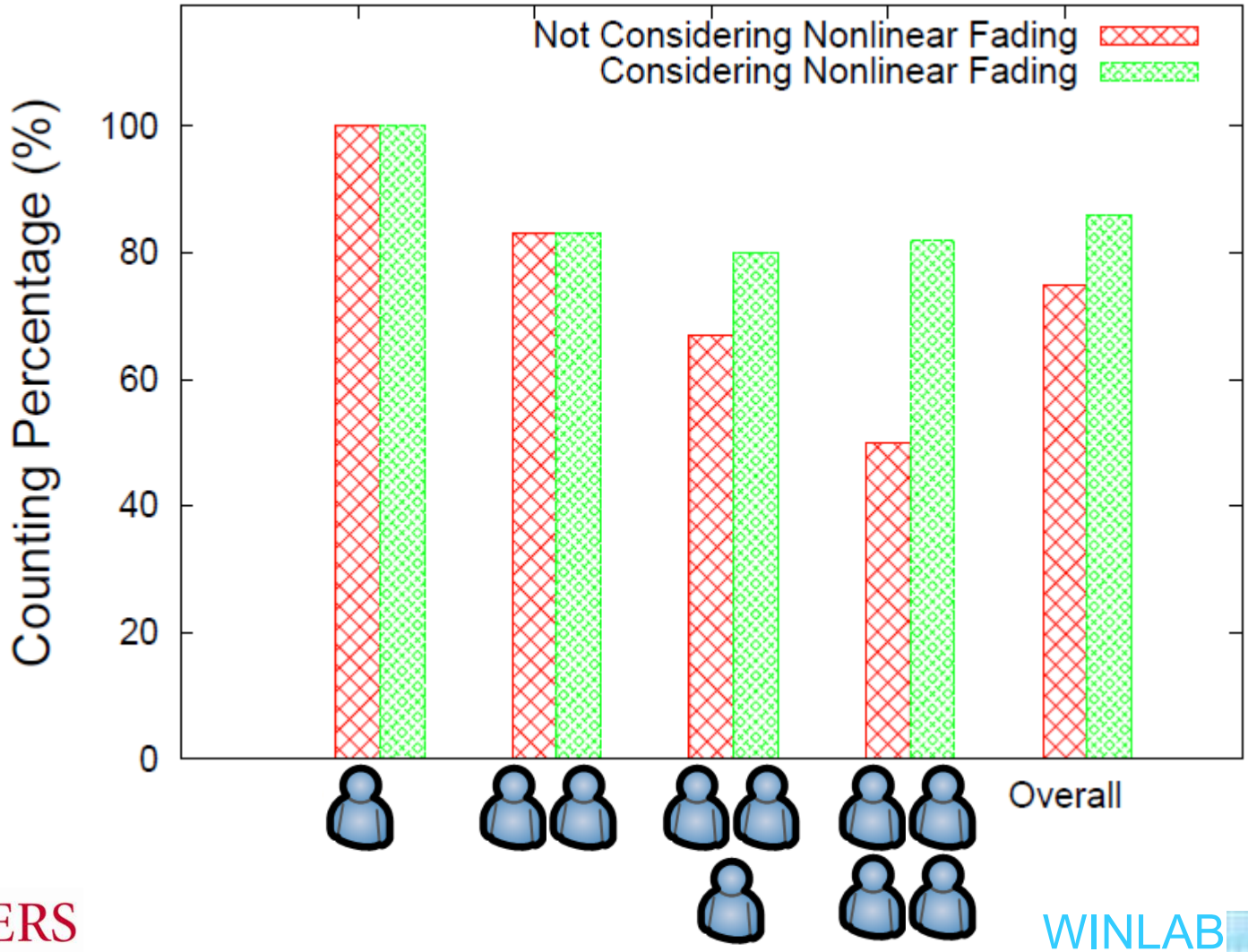
56 cells, 12 transmitters and 8 receivers

Open floor deployment

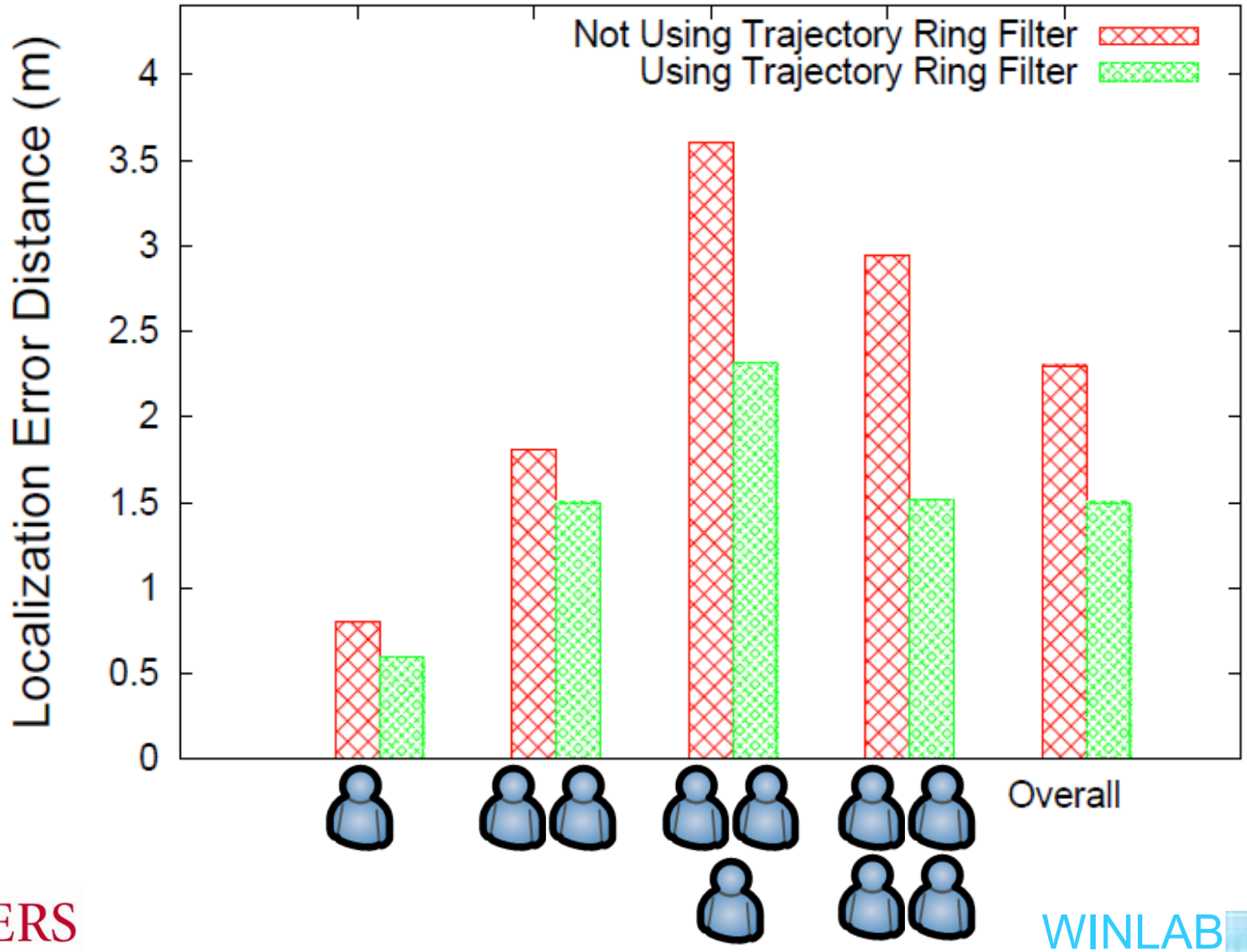


Four subjects' testing paths

Counting results



Localization results



Conclusion and Future Work

- **Conclusion**
  - **Calibration data collected from one subject can be used to count and localize multiple subjects.**
  - **Though indoor spaces have complex radio propagation characteristics, the increased mobility constraints can be leveraged to improve accuracy.**
- **Future work**
  - **Count and localize more than 4 subjects**

Q & A

Thank you