Localization, Beacon Placement and Mapping for Range-Based Indoor Localization Systems

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Applications

Mobile interaction

Safety in disasters

Augmented reality/Virtual reality

Factory automation

Smart buildings

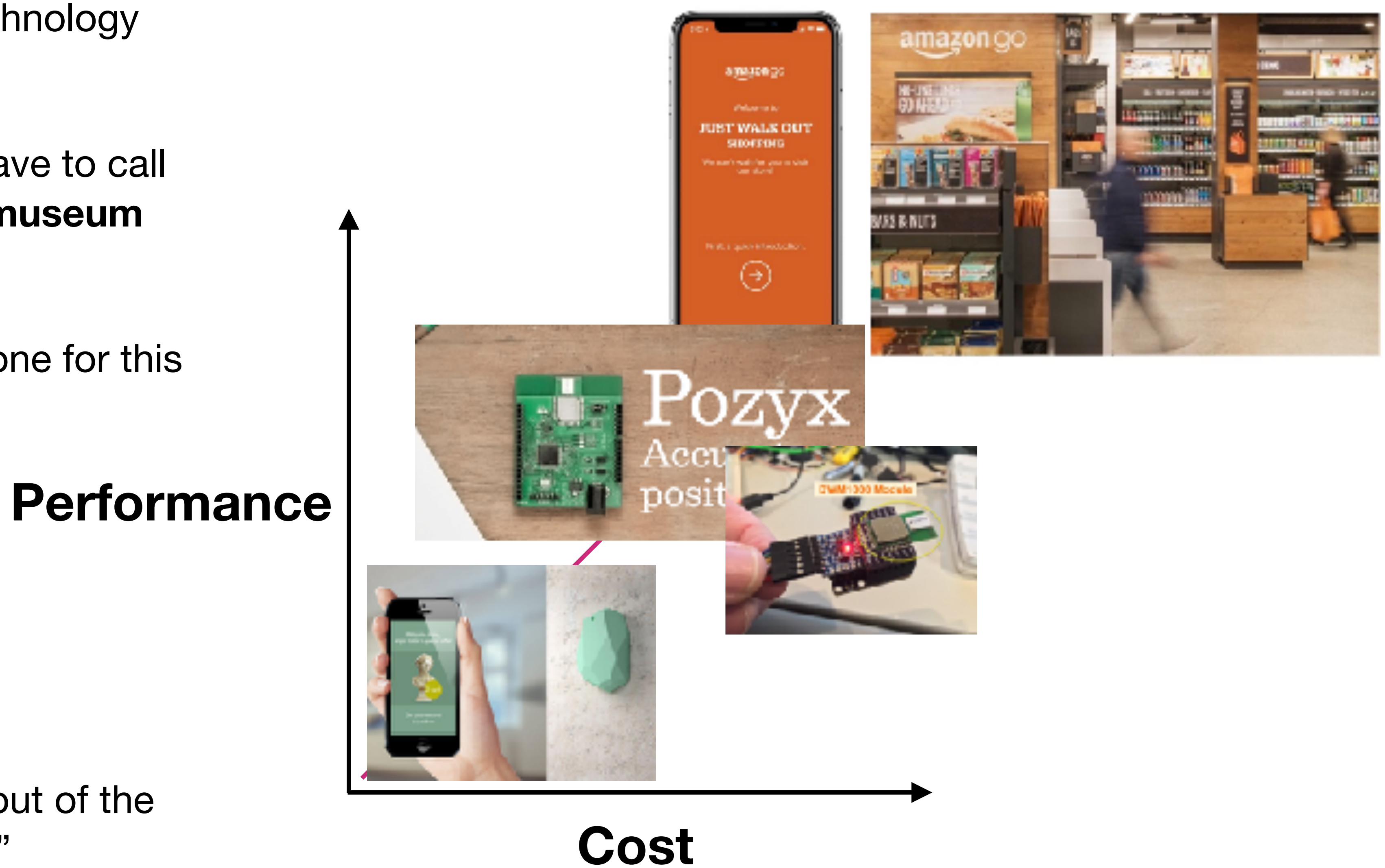
Key requirement: Localization

Localization today

From museums..
“technical **costs** of **purchasing** the technology and **installing** the technology..”

“When we move around exhibits, we have to call the companies again to **calibrate the museum again**..”

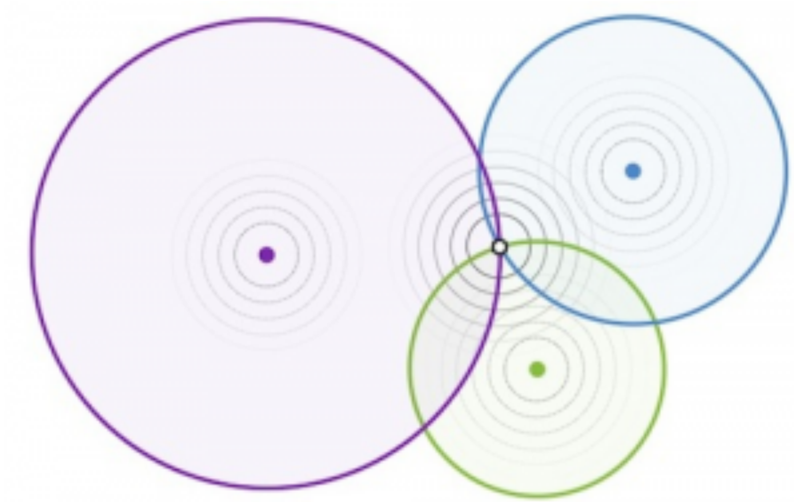
“The users require a certain type of phone for this to work..”



From firefighters..
“the most reliable way to find our way out of the building is to **trace back the fire hose**”

“**Go in pairs** to lower the chance of getting lost..”

Localization system components

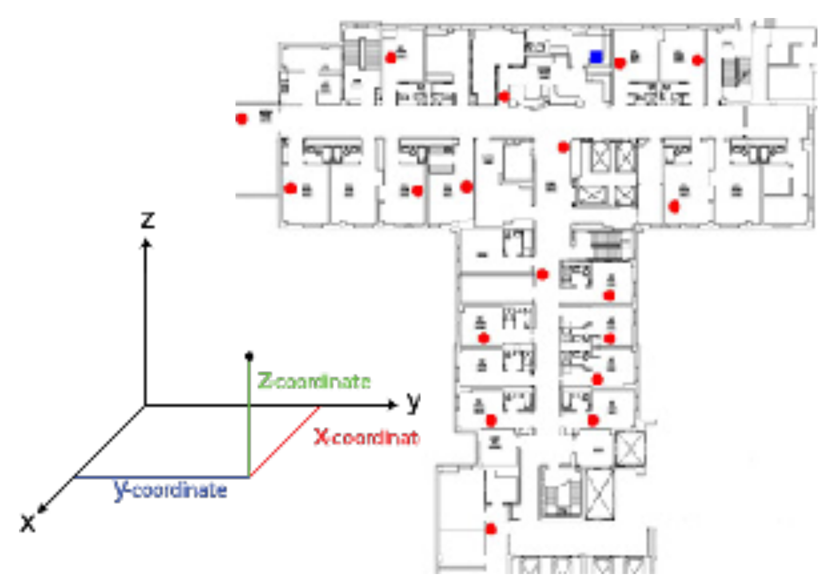


Estimation

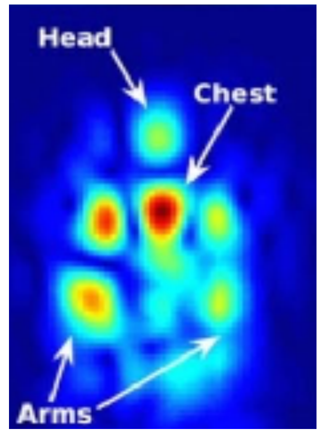
Sensors

Deployment

Ultra-Wideband



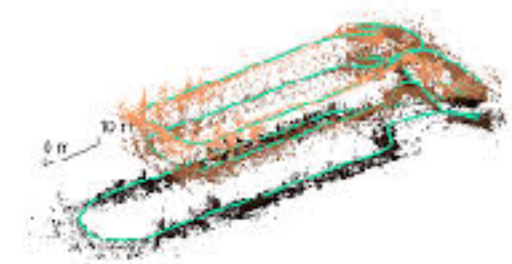
A lot of cool work in different areas of localization



Deep learning-based methods

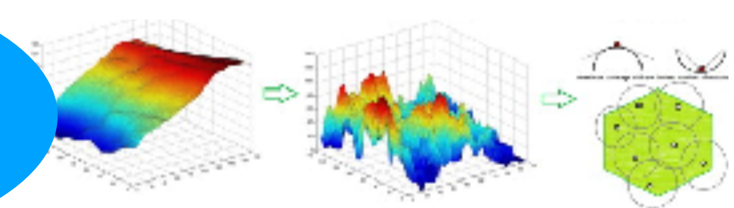
Map matching

Estimation



Visual inertial tracking

Optimal sensor placement



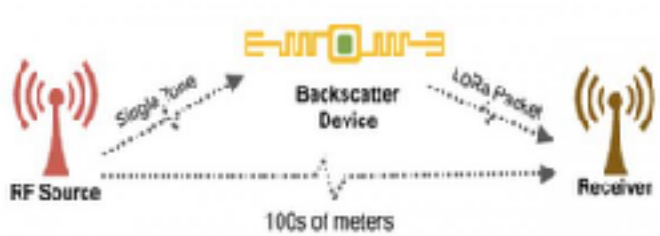
Lidar

Sensors

Deployment

Wireless

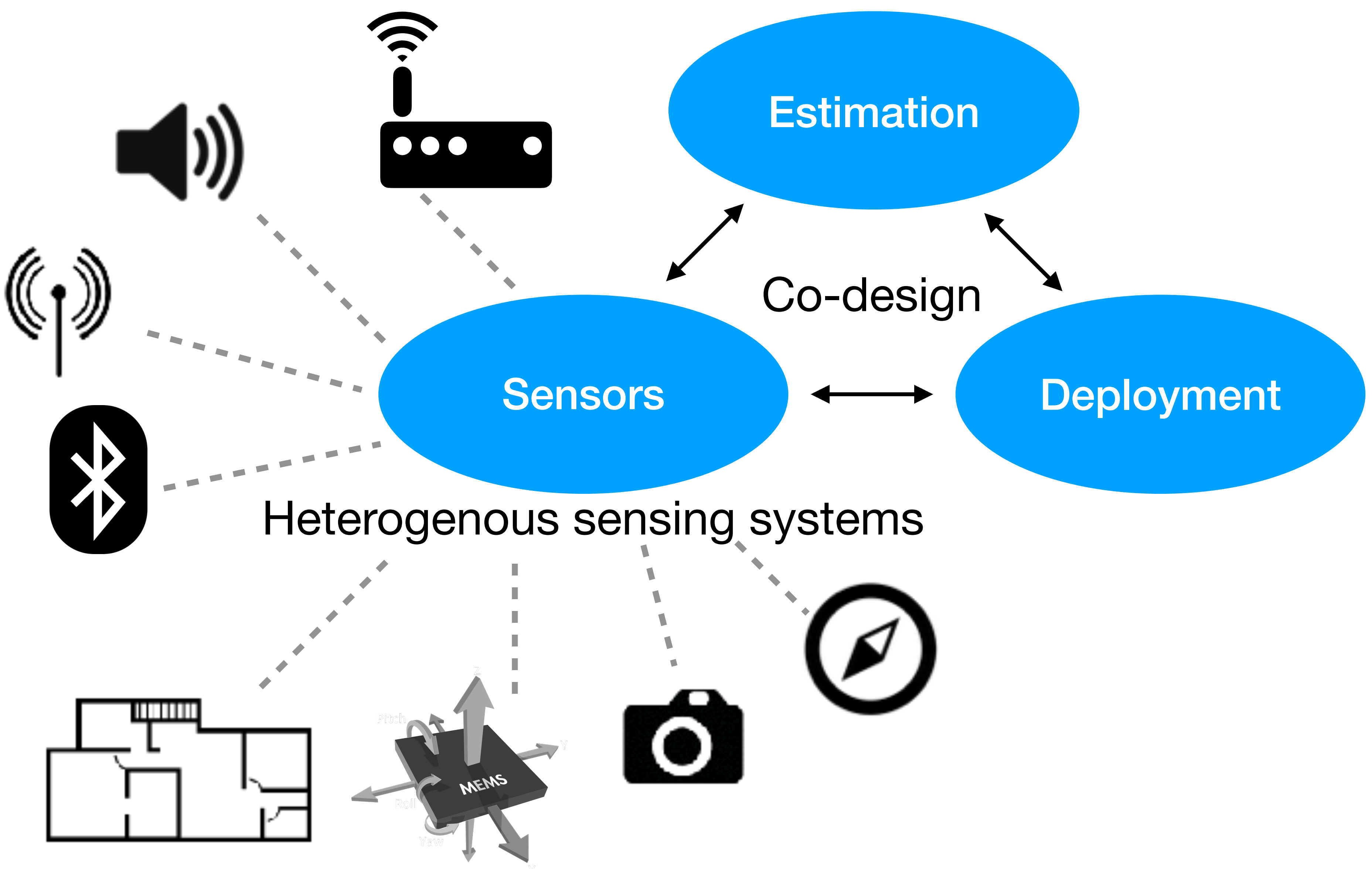
Simultaneous localization and mapping



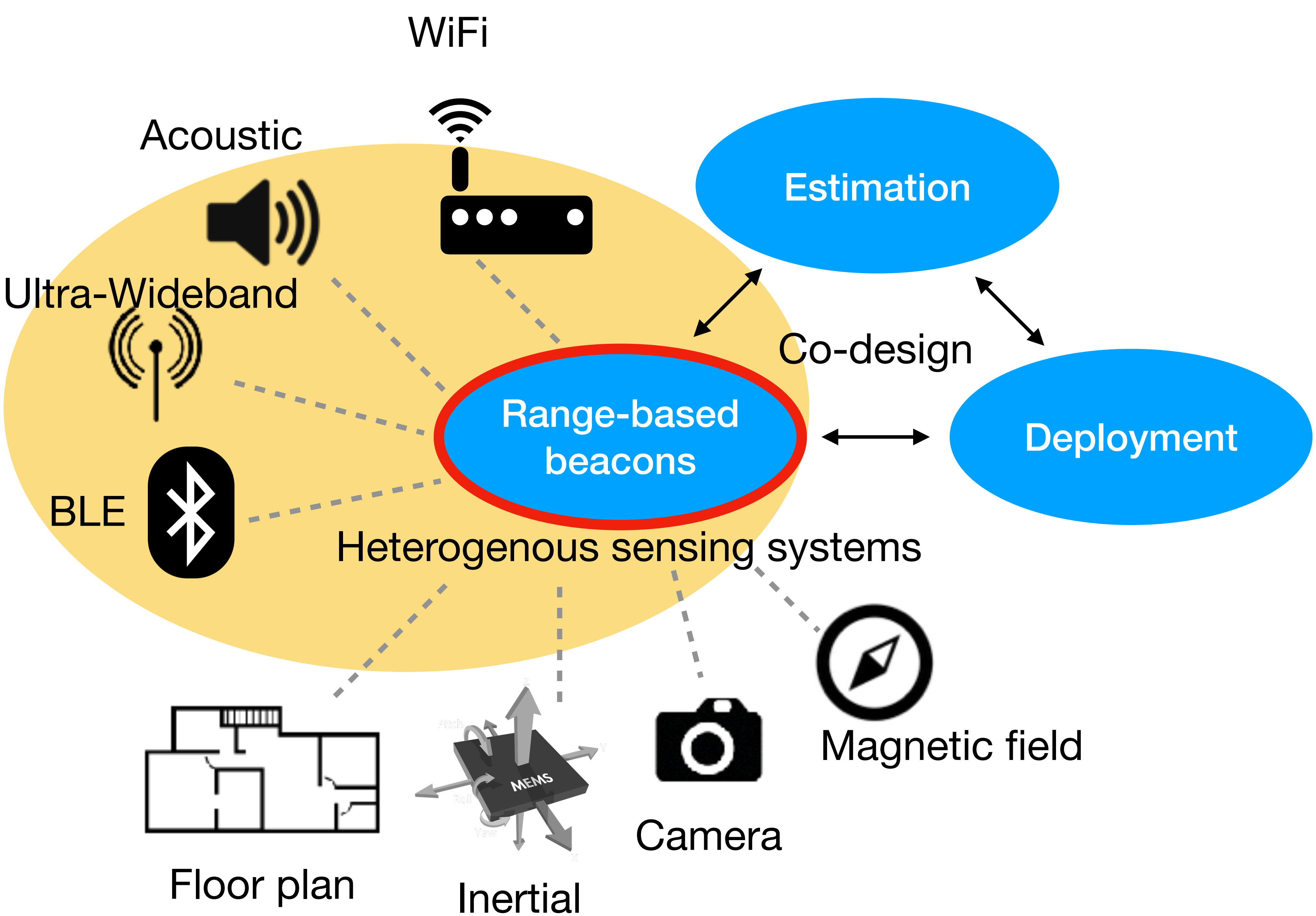
Backscatter

Depth sensors

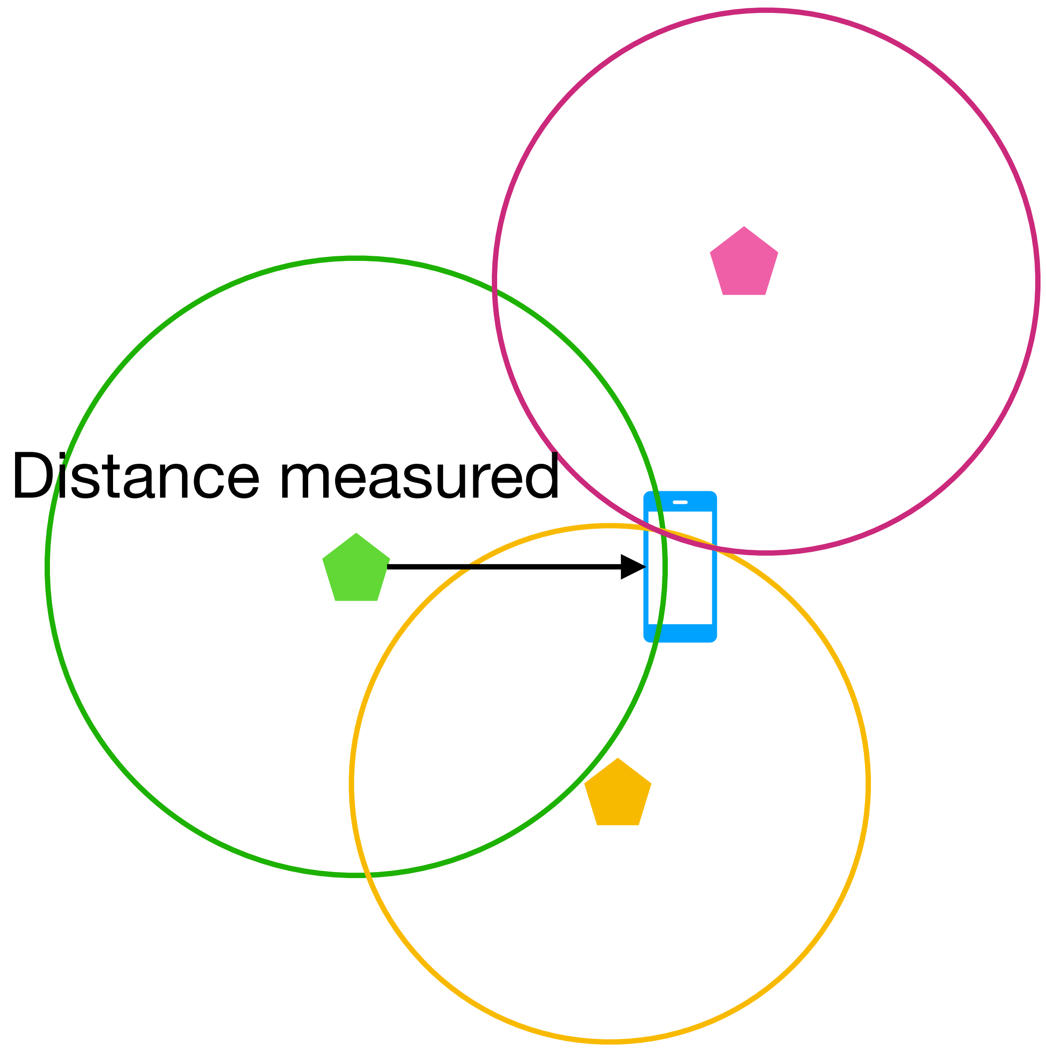
Our approach



This dissertation



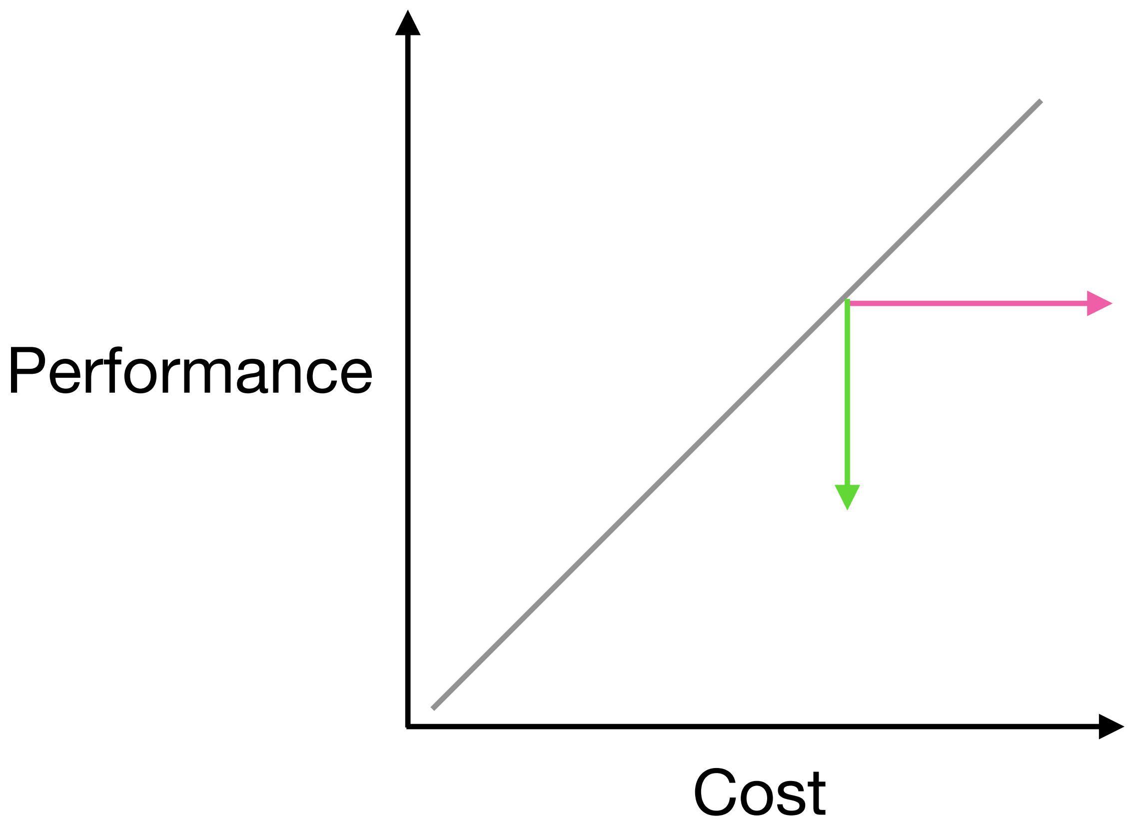
Range-based localization systems



Promise:

- Capable of accurate positioning (10-30cm)
- Instant time-to-first fix (don't need to walk around before getting a location)
- Emerging standards in commodity devices: WiFi 802.11mc, Bluetooth Low Energy 5, Ultra-Wideband

Range-based localization challenges in the real-world



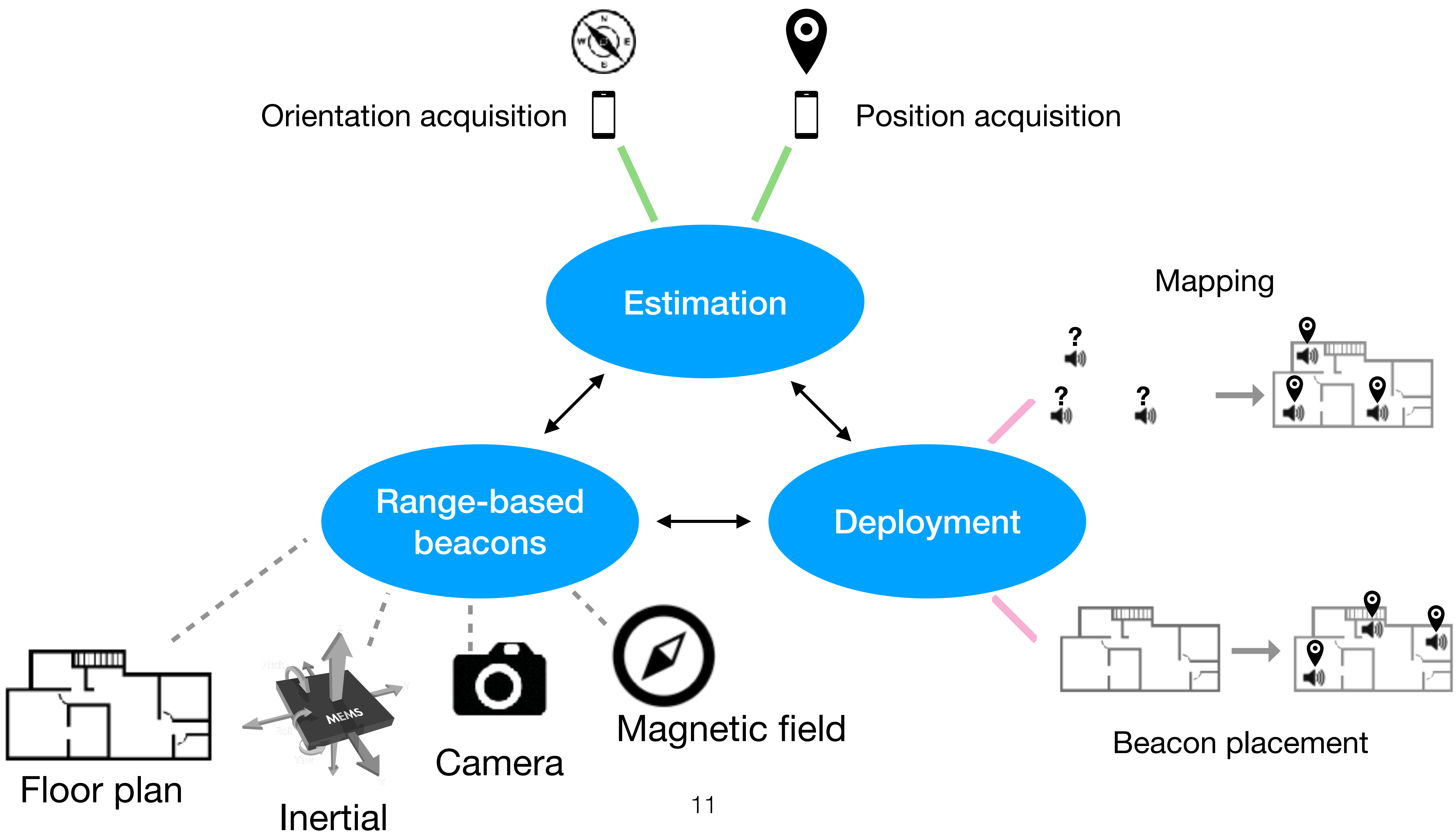
Deployment

- Beacon placement
  - Expertise required to place beacons
  - Typically too many beacons are placed
- Mapping
  - Requires expensive instrumentation
  - Re-mapping and re-calibrating increases cost

Estimation

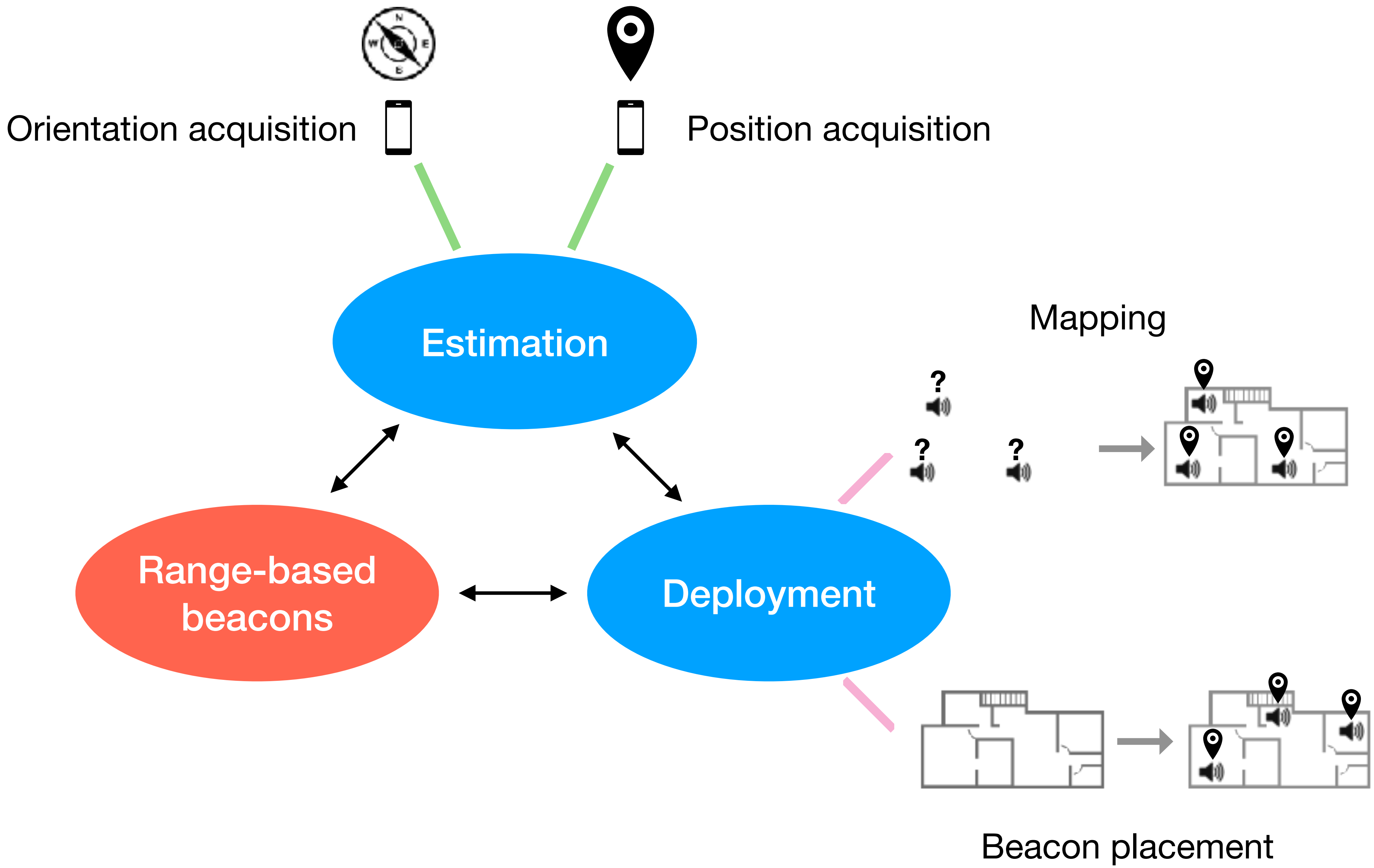
- Location acquisition
  - Inaccurate when there are too few LOS measurements
  - Inaccurate when there are NLOS measurements
- Orientation acquisition
  - Takes time to estimate and requires users to walk around

Overview of this dissertation



This dissertation proposes a methodology for fusing additional sources of information to improve range-based indoor localization systems by reducing the infrastructure required while maintaining high performance in terms of accuracy and time-to-acquire the location and orientation.

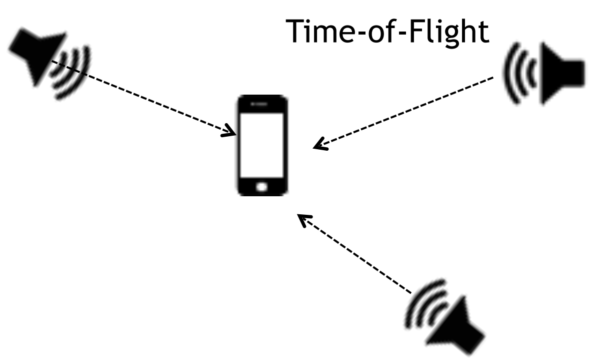
Overview



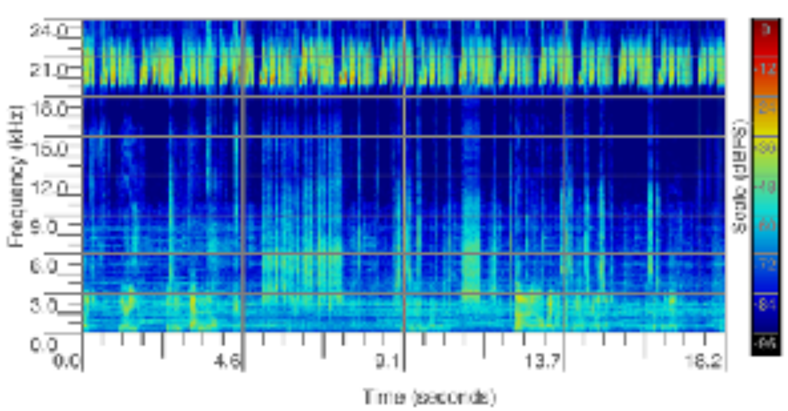
Orientation acquisition
Position acquisition
Estimation
Mapping
Range-based beacons
Deployment
Beacon placement

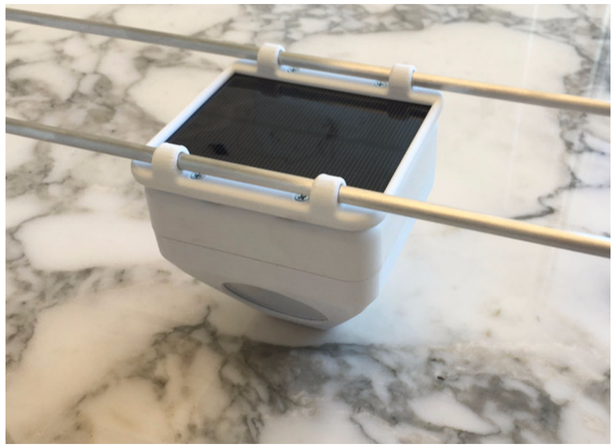
Acoustic ranging

Acoustic Location Processing System (ALPS)



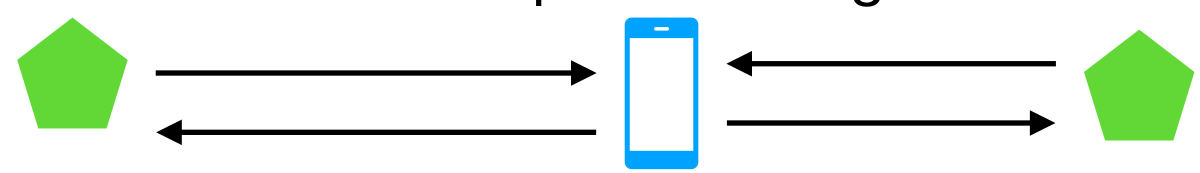
- Near-ultrasound (18-20kHz) communication
- Decodable using existing mobile hardware
- Highly-scalable / Privacy Preserving
- 15cm ranging accuracy





Ultra-Wideband (UWB) ranging

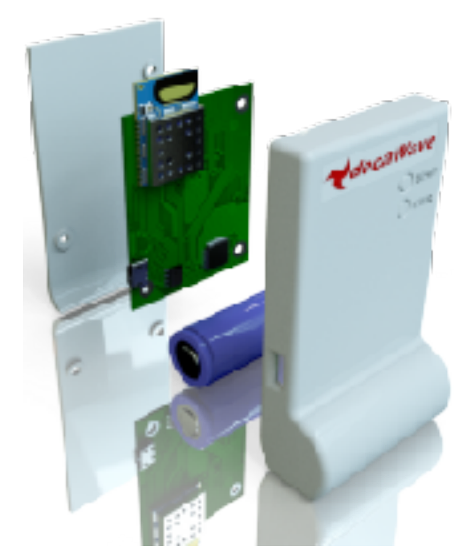
Round-trip time-of-flight



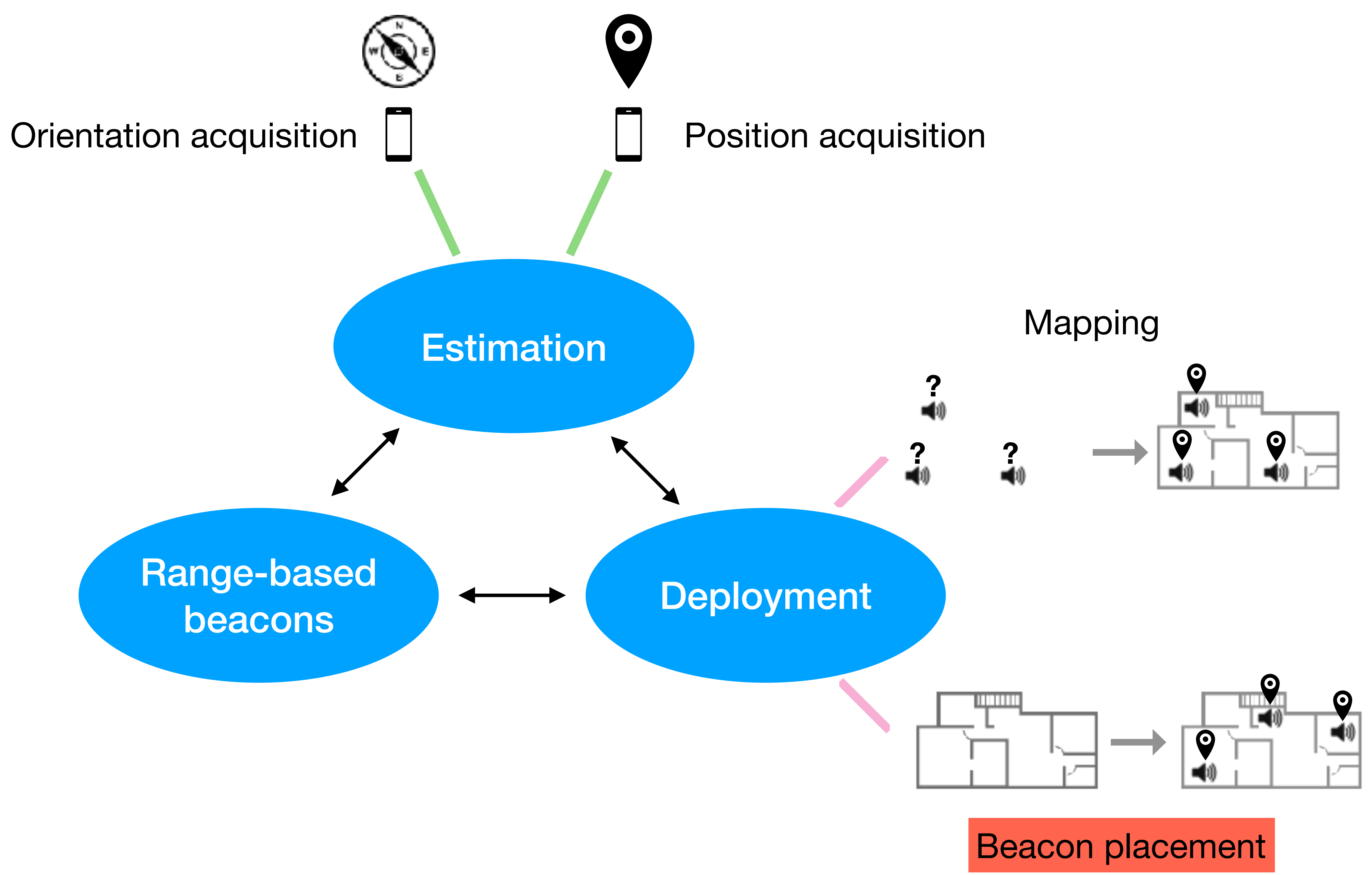
- 500Mz-1GHz bandwidth
- 30cm ranging accuracy
- Chipsets readily available
- Does not need time-synchronization across nodes

Tag

Beacon



Overview



Orientation acquisition
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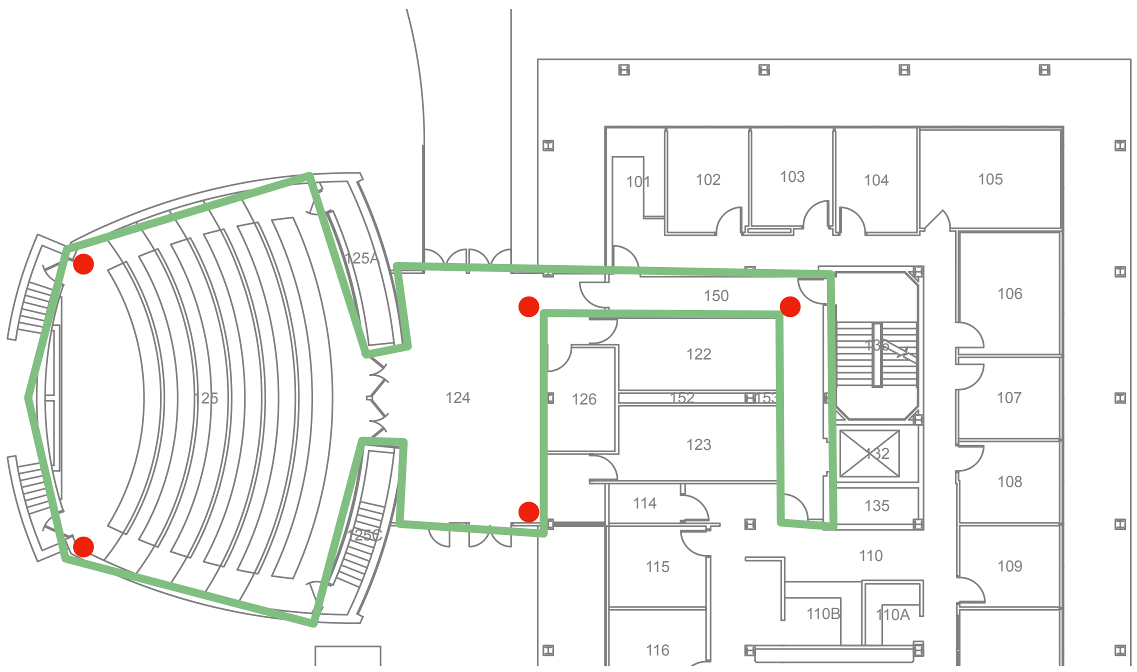
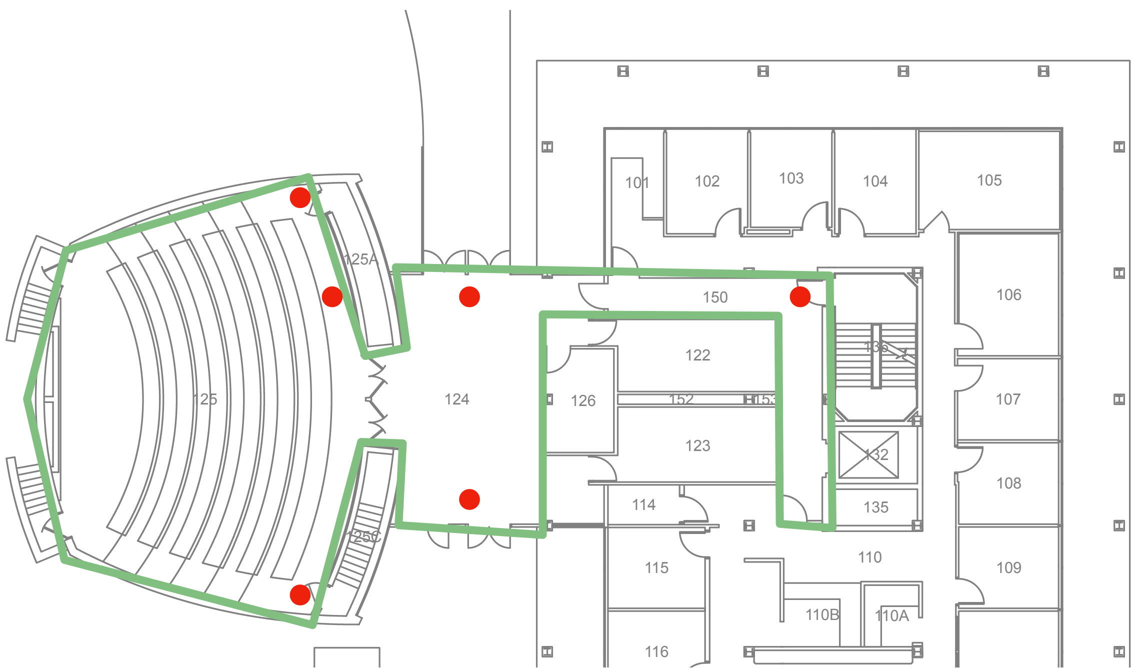
Beacon placement

Which placement is better?

Placement 1



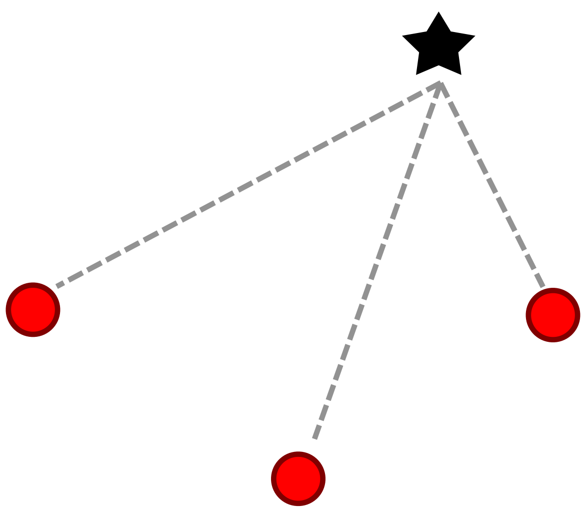
Placement 2



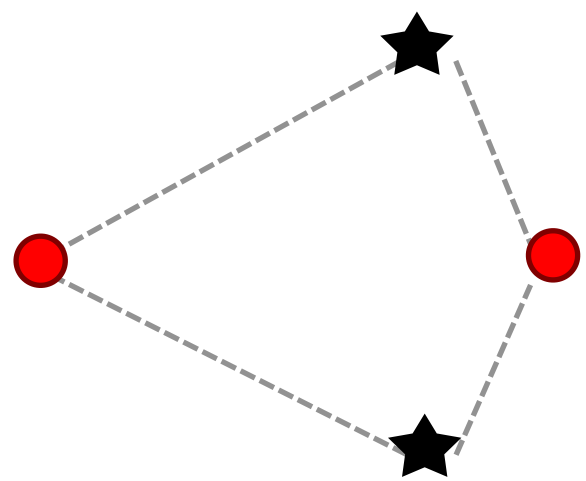
- How to minimize the number of beacons?
- How to systematically compare two placements?

Localizing with two beacons

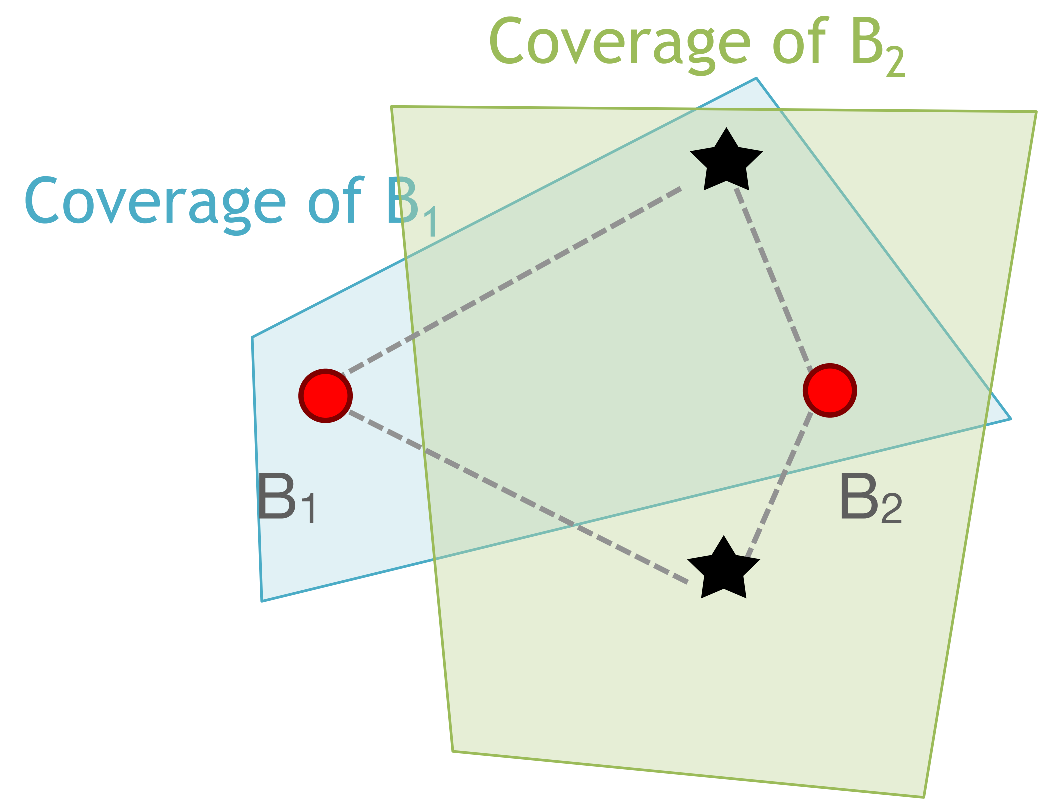
Uniquely localizable



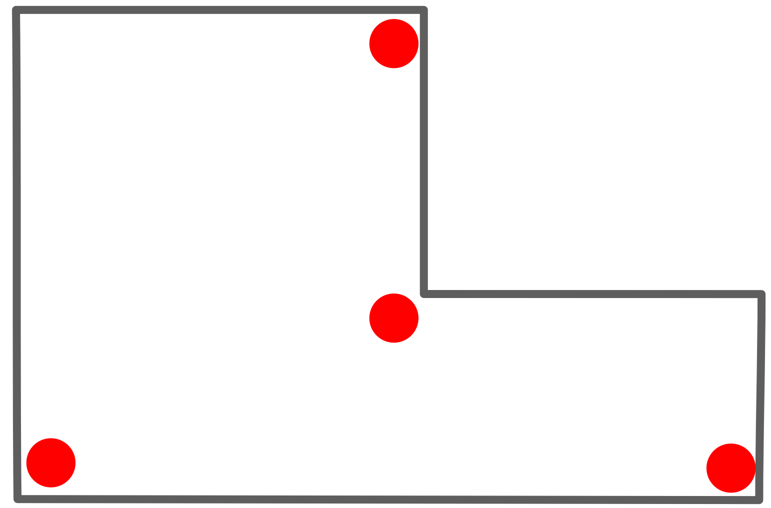
Not uniquely localizable



Uniquely localizable

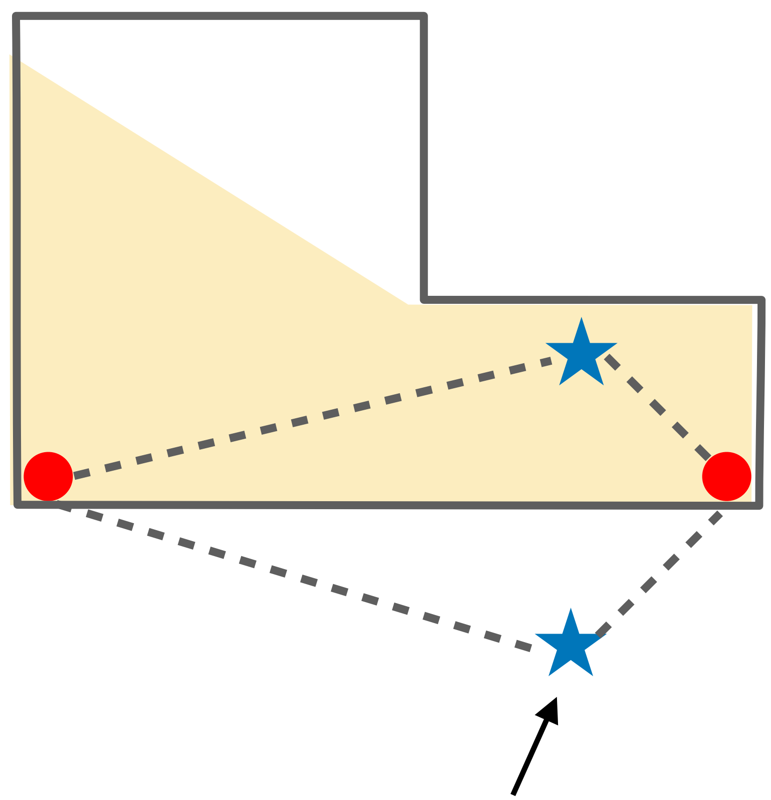


Typical placement



Require at least 4 beacons for all regions to be visible to at least 3 beacons

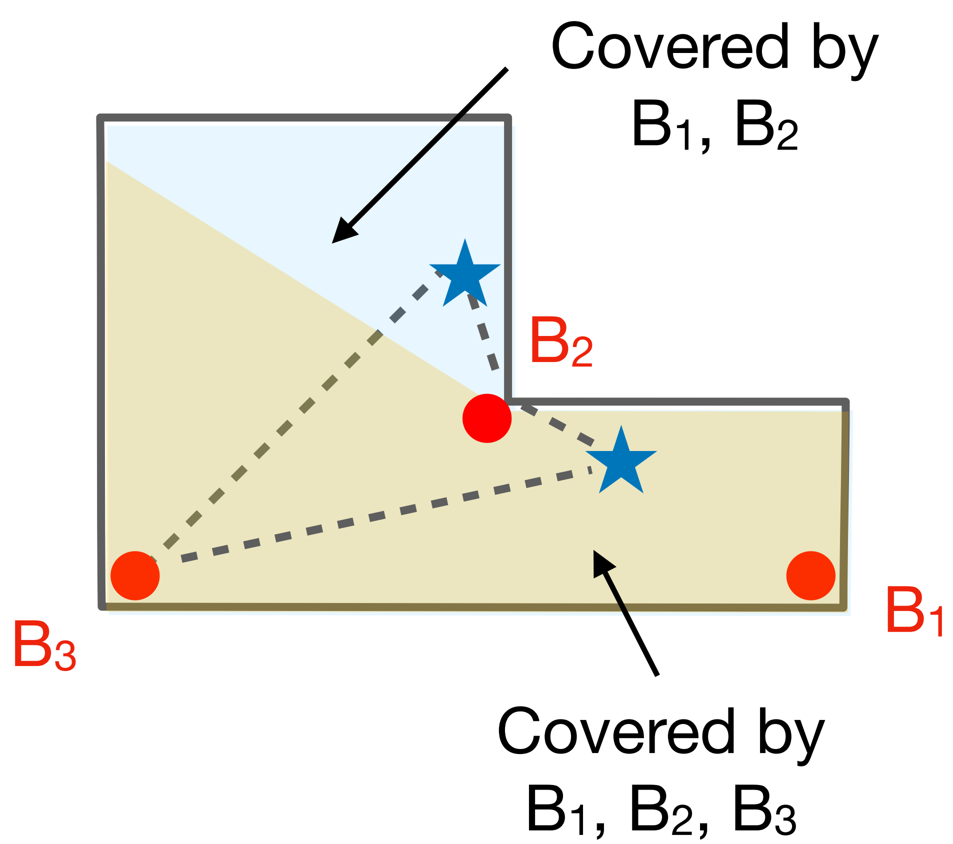
Localizing with two beacons



Can eliminate this as it is out of coverage of both beacons

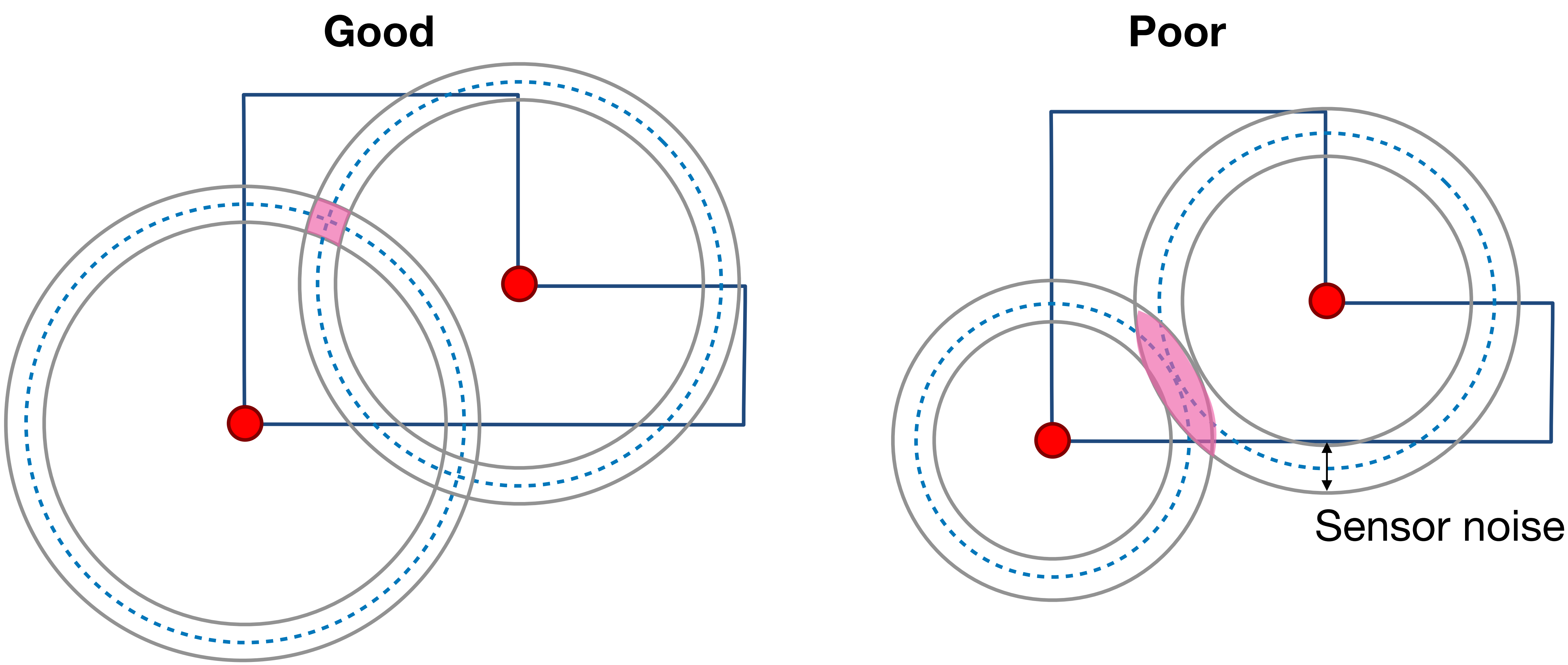
Localizing with two beacons

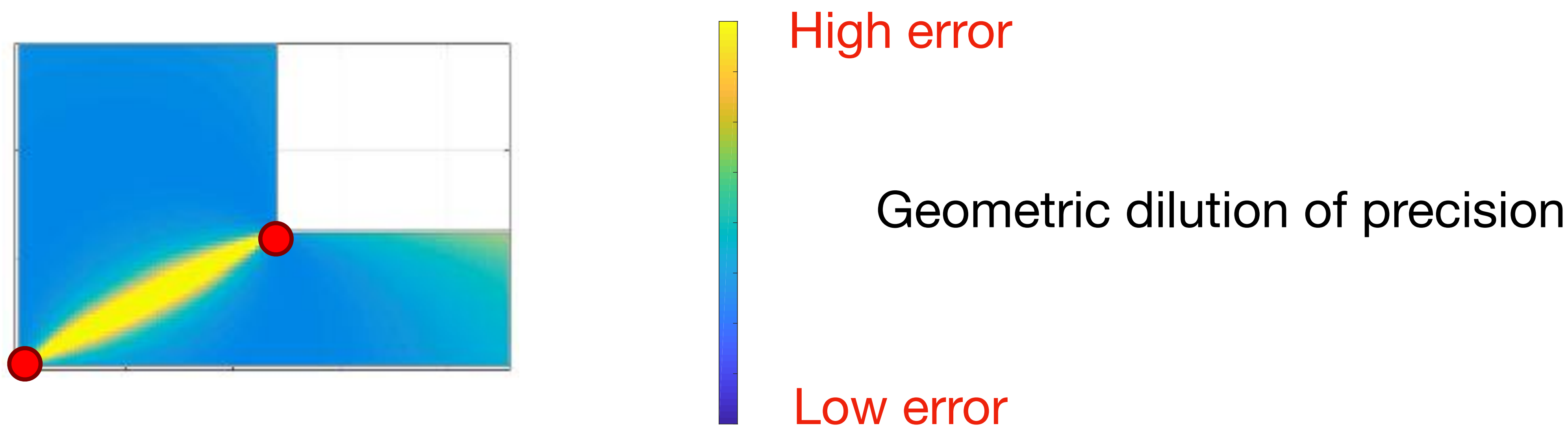
We can resolve this ambiguity based on whether measurement from B_1 was received



Idea: By leveraging floor plan geometry, we can <u>uniquely localize</u> using reduced number of beacons

Geometry of beacons impacts accuracy





Impact of geometry is quantified by Geometric Dilution of Precision (GDOP)

GDOP

$$GDOP(X_i, C_B(X_i)) = \sqrt{\frac{N_b}{\sum_{k=1}^{N_b-1}\sum_{j=k+1}^{Nb} A_{kj}}}$$

$$A_{kj} = |\sin(\theta_k - \theta_j)|$$

Angle subtended between beacon j and X_k

CRLB

Variance in range measurement of beacon i

$$\sigma^2(X_i, C_B(X_i)) = \frac{\sum_{k=1}^{N_b} \sigma_{r,i}^{-2}}{\sum_{k=1}^{N_b-1}\sum_{j=k+1}^{Nb} \sigma_{r,k}^{-2}\sigma_{r,j}^{-2} A_{kj}^2}$$

Cramer-Rao Lower Bound on variance in position estimate

CRLB-GDOP relation

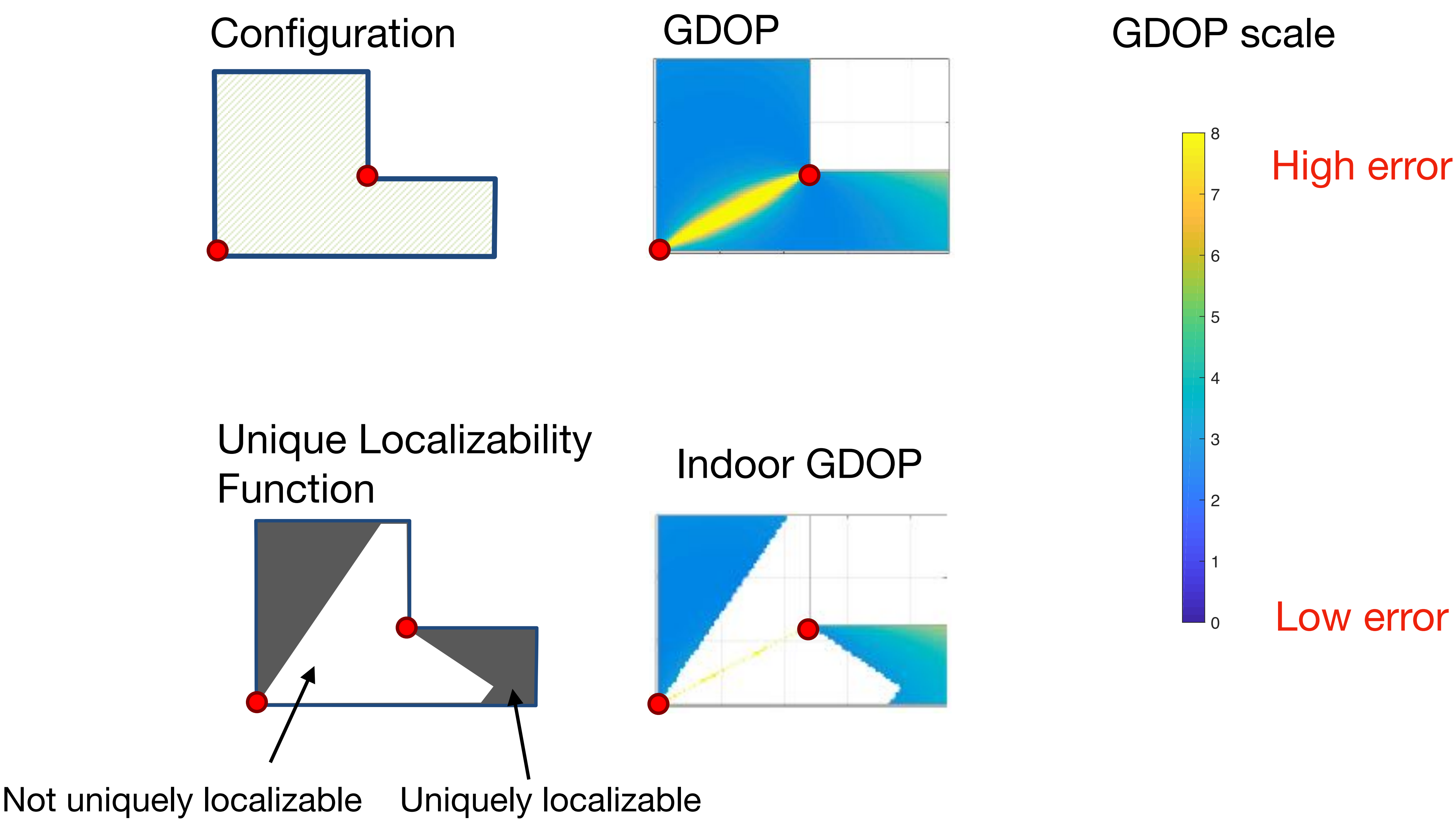
Assuming ranging noise constant (with beacon, with distance):

$$\sigma(X_i, C_B(X_i)) = \sigma_r \times \sqrt{\frac{N_b}{\sum_{k=1}^{N_b-1}\sum_{j=k+1}^{Nb} A_{kj}}}$$

$$\sigma(X_i, C_B(X_i)) = \sigma_r \times GDOP(X_i, C_B(X_i))$$

Variance in location estimate (with the best possible estimator) is proportional to GDOP

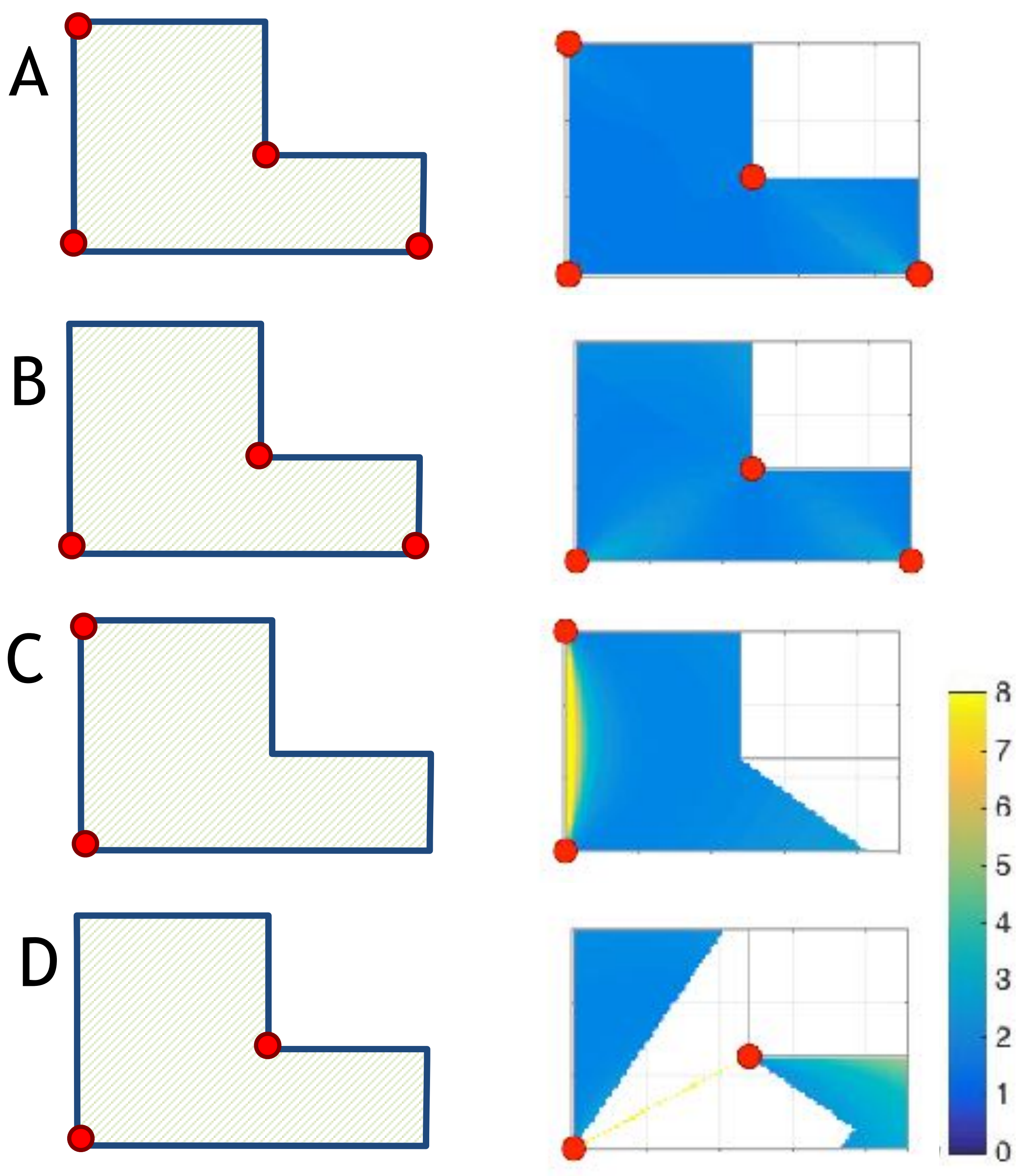
Defined a new metric that combines the ideas of unique localizability and GDOP

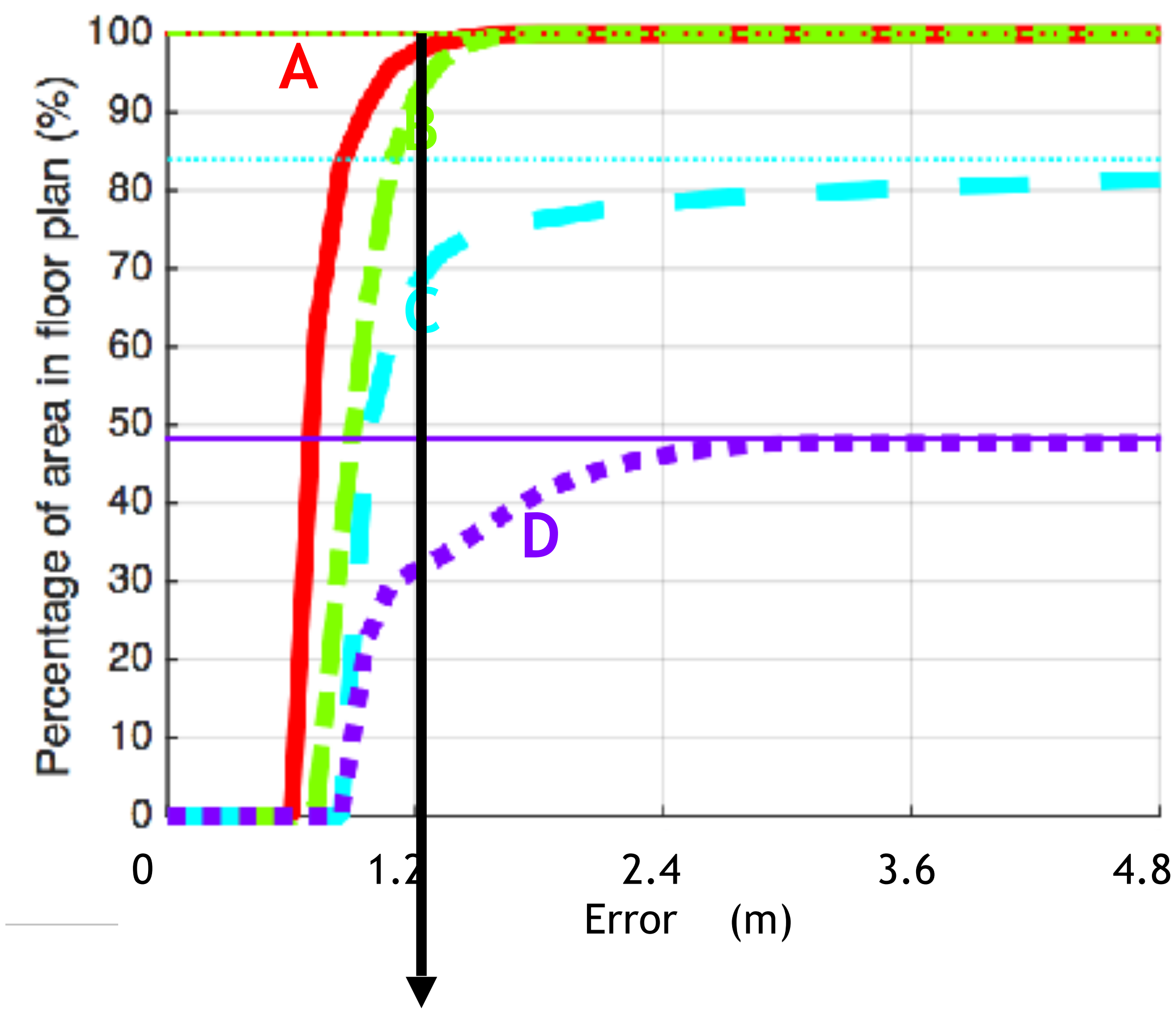


Quantified the quality of a beacon placement

Configuration

Indoor GDOP

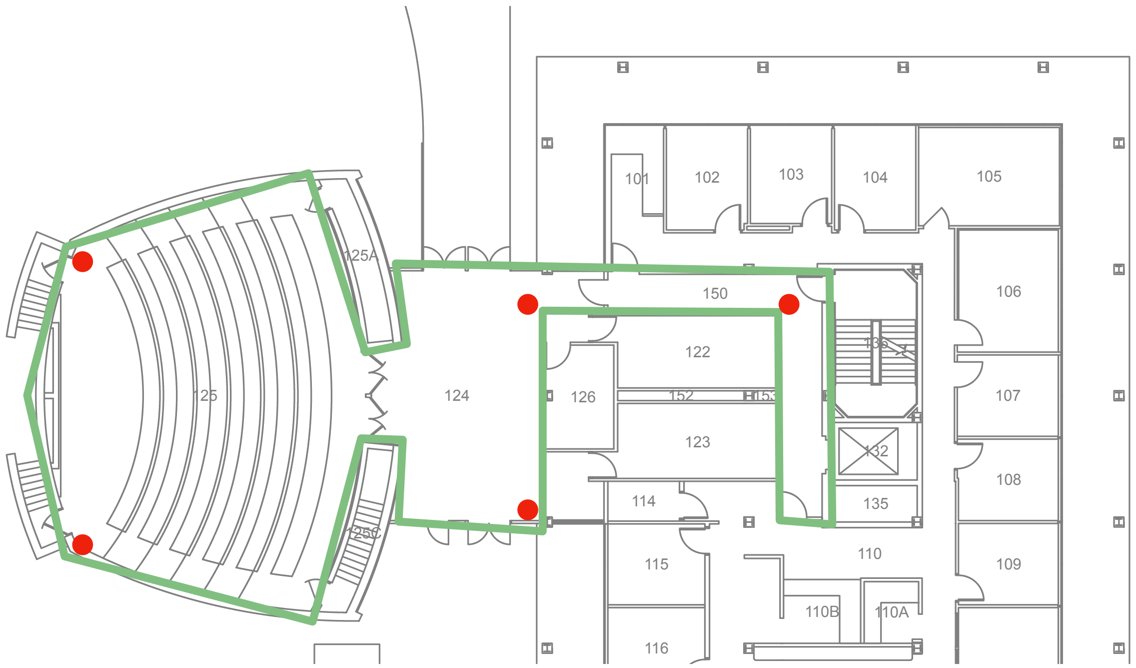




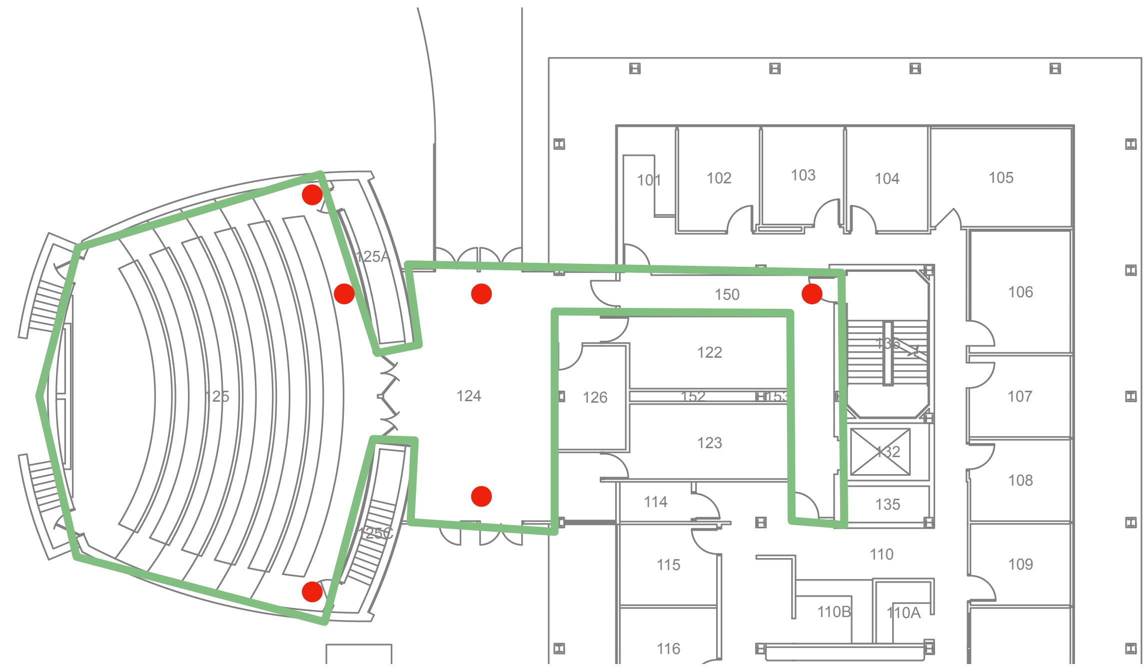
For error < 1.2m,
typical approach 4 beacons;
2 may be enough

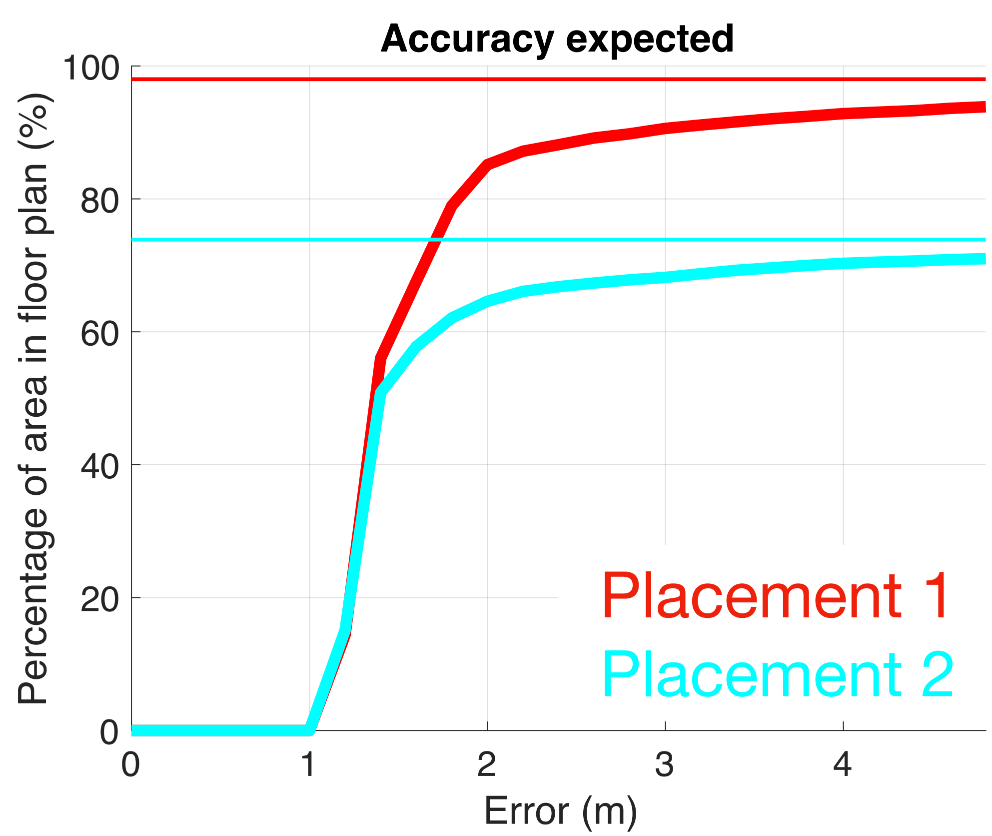
We can now compare placements

Placement 1



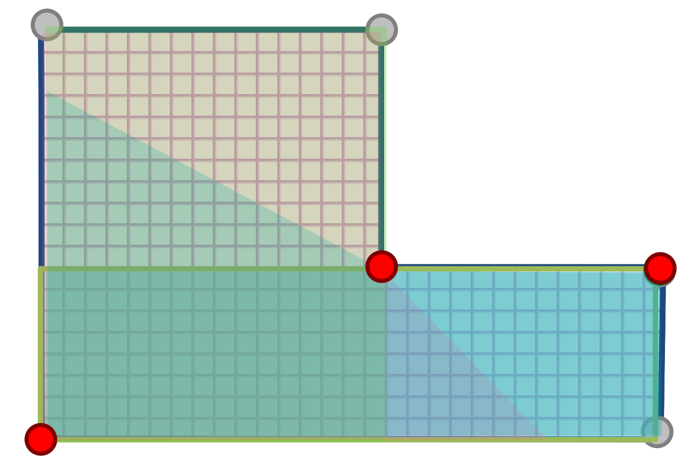
Placement 2



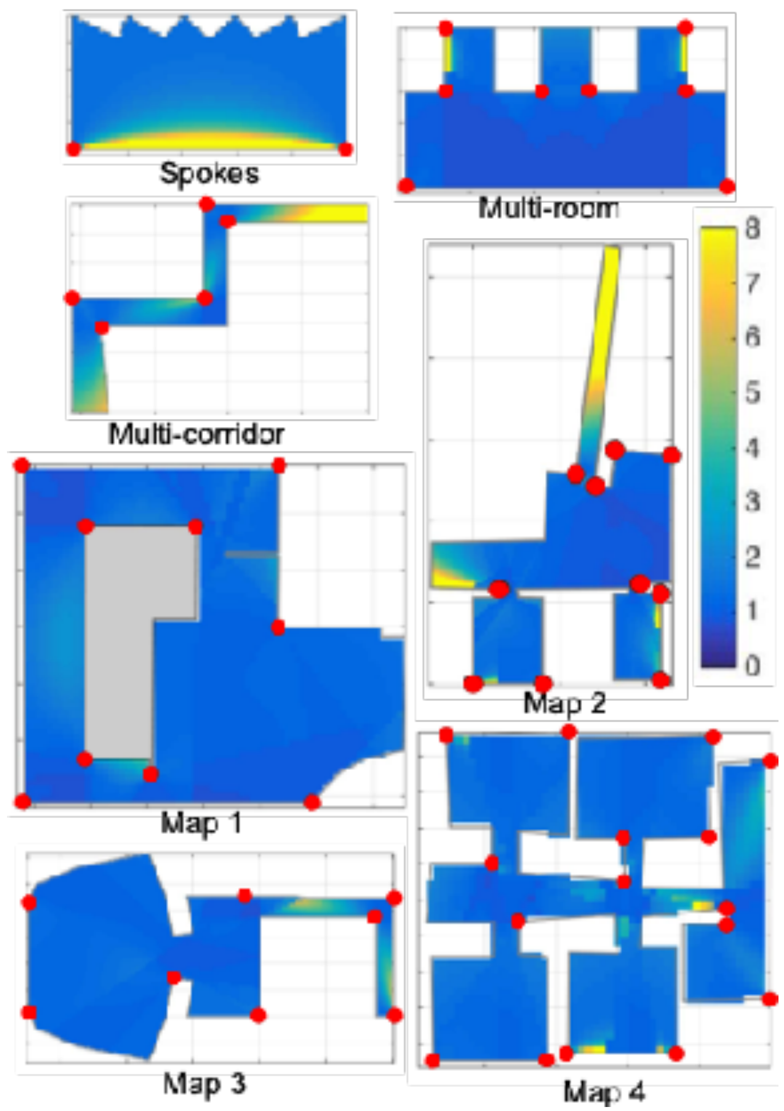


Beacon placement algorithm

- **Given**
  - Floor plan
    $$X = \{x_i | 1 \leq i \leq N_X\}$$
  - Candidate beacon locations
    $$B = \{b_i | 1 \leq i \leq N_B, b_i \in X, N_B \leq N_X\}$$
    $$B \subseteq X$$
  - Beacon coverage models
    $$C_B(b) \subseteq X$$
  - Design constraints
    - Number of beacons
    - Minimum number of beacons that satisfy accuracy requirement
- **Find**
  - Beacon configurations of smallest size that satisfies the constraint
    $$P = \{p_{i,} | 1 \leq i \leq N_P, N_P \leq N_B\}$$
    $$P \subseteq B$$
- **Algorithm**
  - Compute the coverage map of beacons
    $$C_X(x) \subseteq B$$
  - Partition the floor plans into disjoint regions (*zones*) each covered by unique beacon set
    $$Z = Z_1 \cup Z_2 \cup \cdots \cup Z_{N_Z}$$
    $$\forall Z_i, Z_j, i \neq j, Z_i \cap Z_j = \emptyset$$
    $$Z_i = \{x_i \in X | C_X(x_i) = C_X(x_j), x_j \in X\}$$
    $$C_Z(Z_i) = C_X(x_i), x_i \in Z_i$$
  - Repeat until design constraint met
    - For largest unlocalized *zone*
      - Select the candidate beacon that maximizes the improvement in quality of beacon configuration (defined by coverage or accuracy)



Results of automated beacon placement



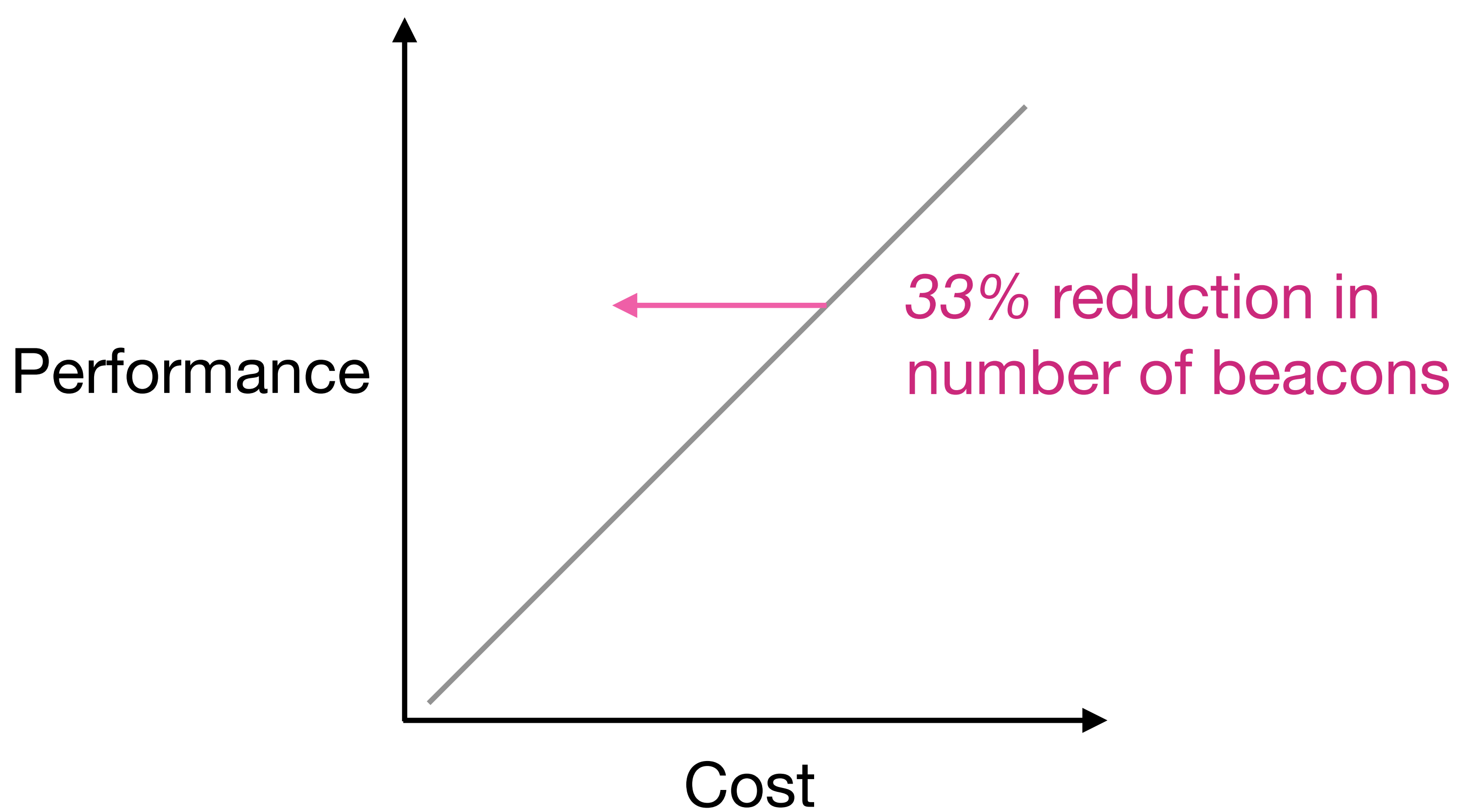
On average 33% reduction in number of beacons as compared to typical placements, while maintaining the same localization coverage.

Niranjini Rajagopal, Sindhura Chayapathy, Bruno Sinopoli, and Anthony Rowe. Beacon placement for range-based indoor localization. In *Indoor Positioning and Indoor Navigation (IPIN), 2016 International Conference on*, pages 1–8. IEEE, 2016.

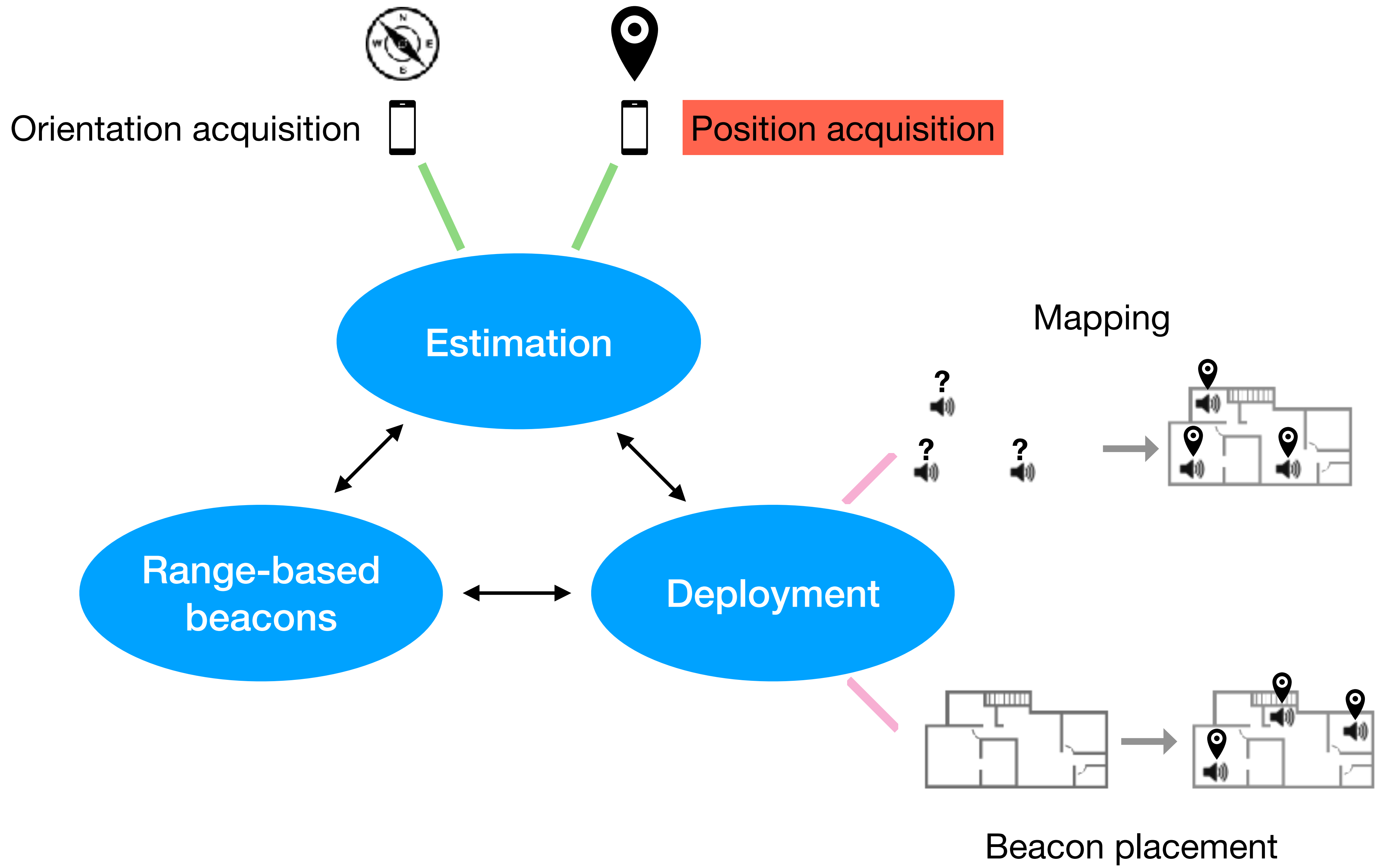
Haotian Wang, Niranjini Rajagopal, Anthony Rowe, Bruno Sinopoli, and Gao Jie. Efficient beacon placement algorithms for time-of-flight indoor localization. Under Review.

Beacon placement contributions

1. Systematic methodology for integrating the floor plan geometry
2. Defined *Unique Localization* with range-based beacons
3. Defined metrics to quantify *quality of a beacon configuration*
4. Designed placement algorithms, available in open-source toolchain



Overview



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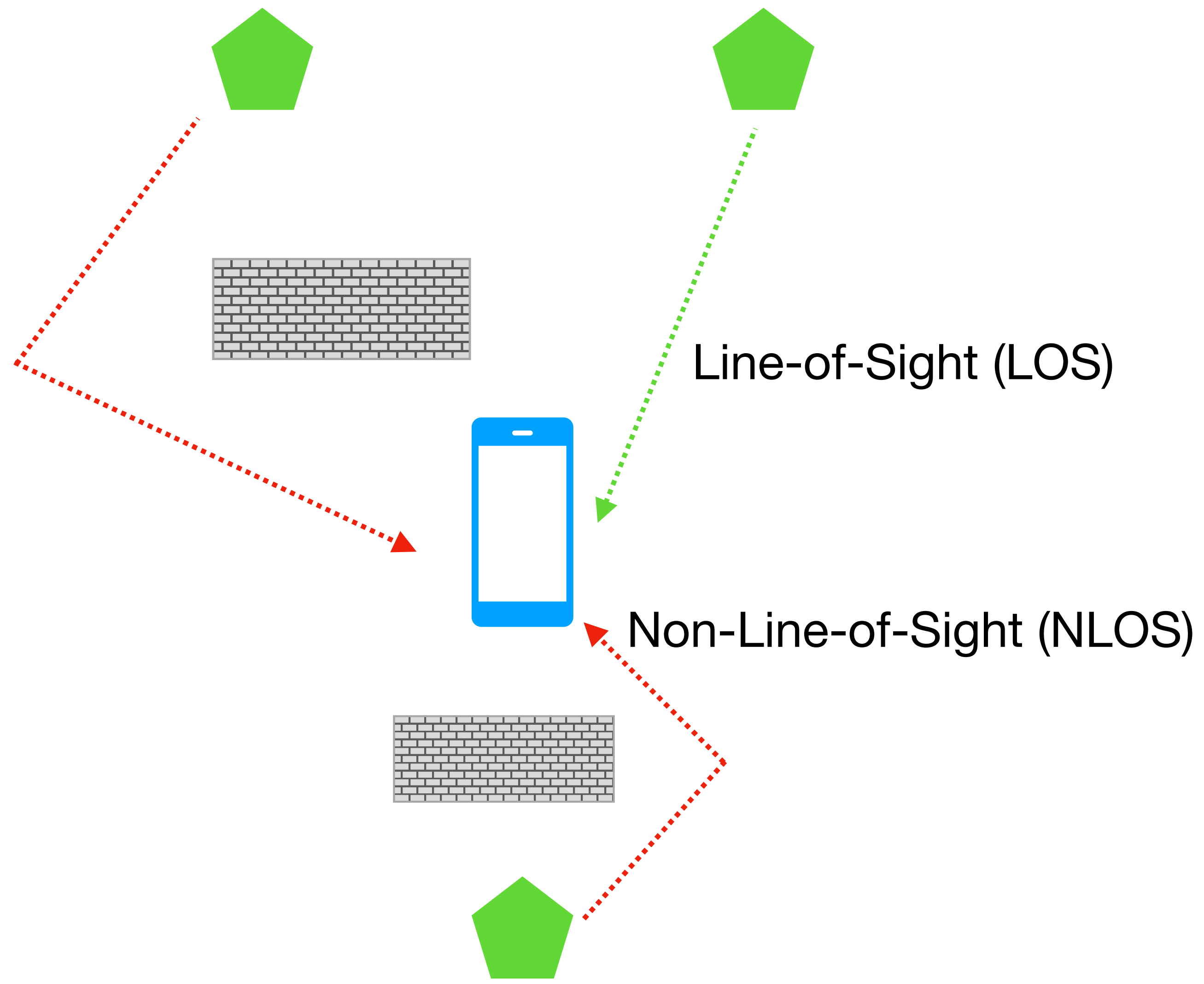
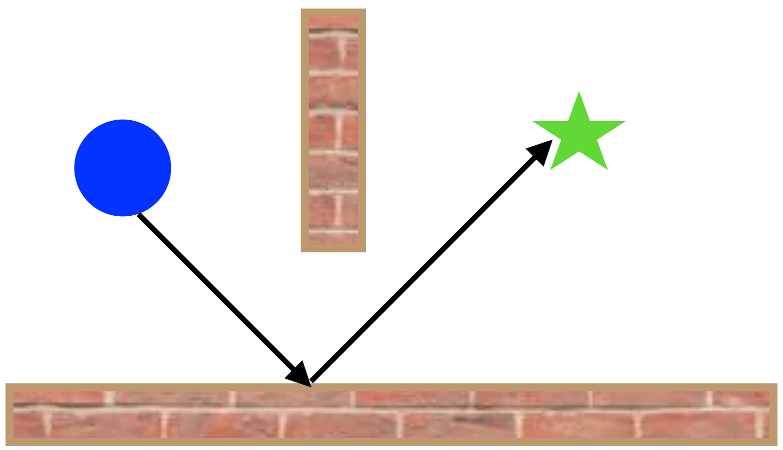
Location acquisition challenge

Non line-of-sight signals



Beacon coverage model

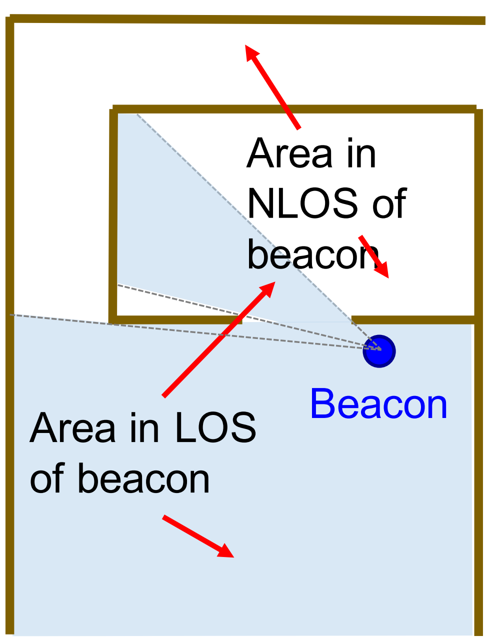


NLOS caused by reflections

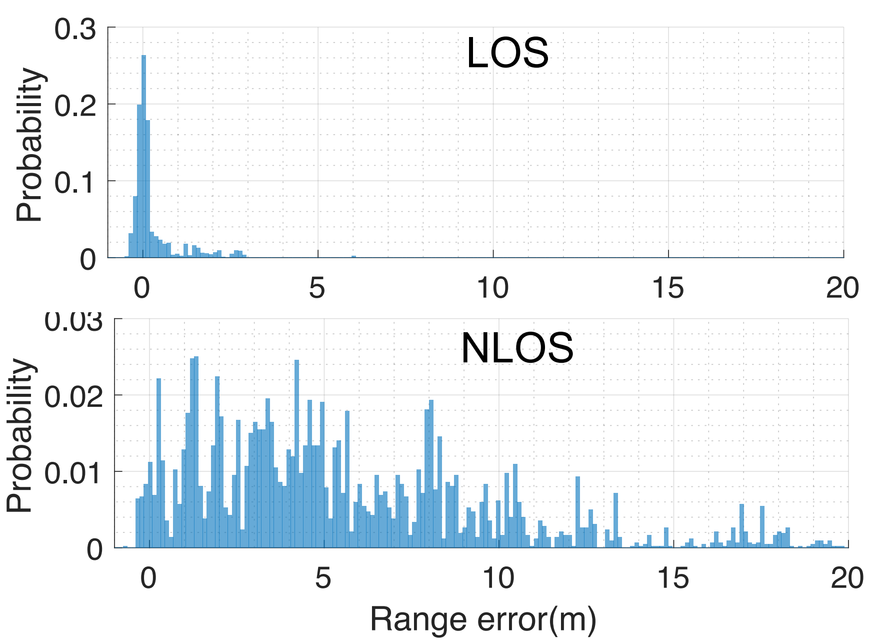
Model:

Ray-tracing coverage model

- LOS range error ~ 0
- NLOS range error > 0



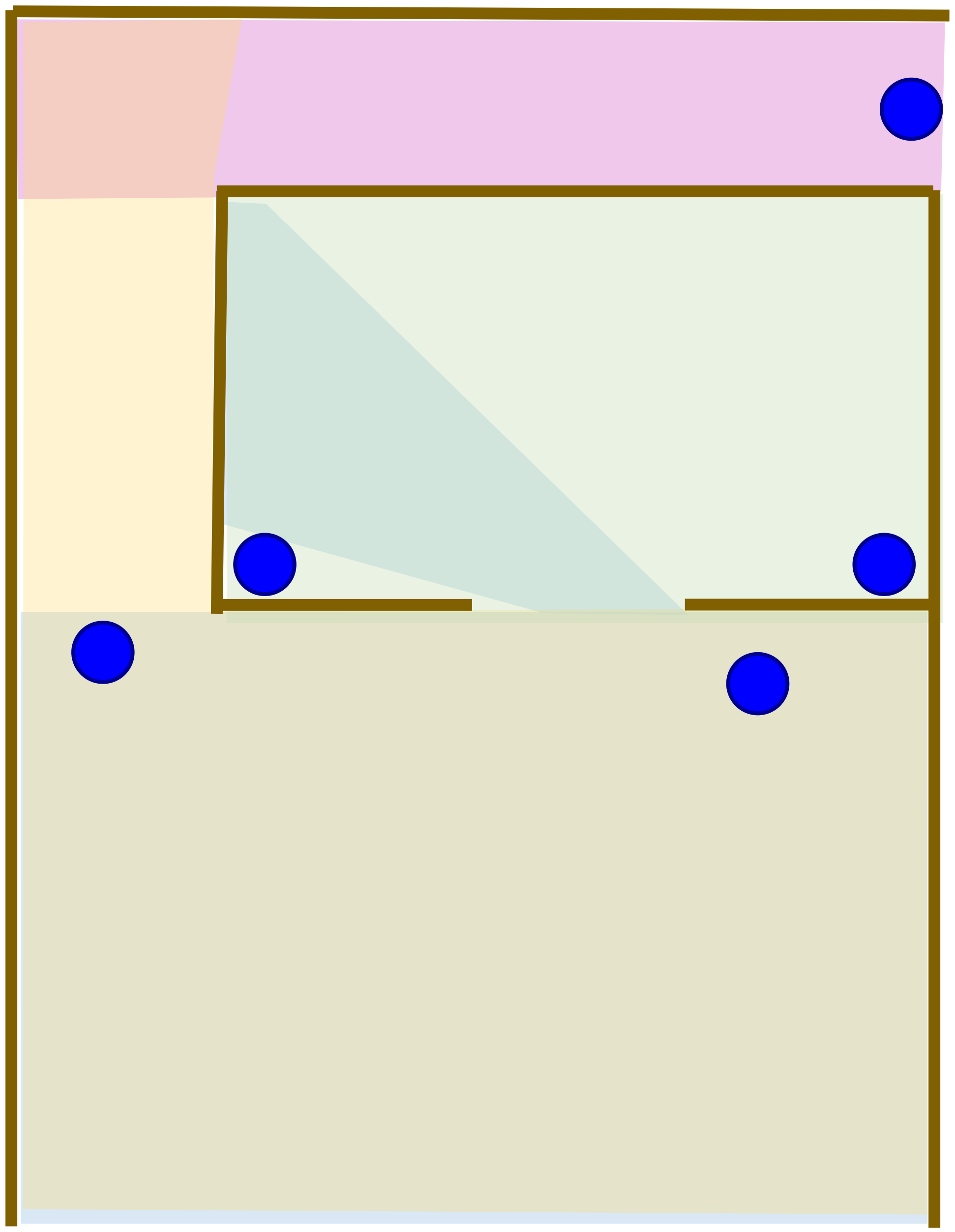
Beacon coverage model



Experimental verification of model

Extending to multiple beacons

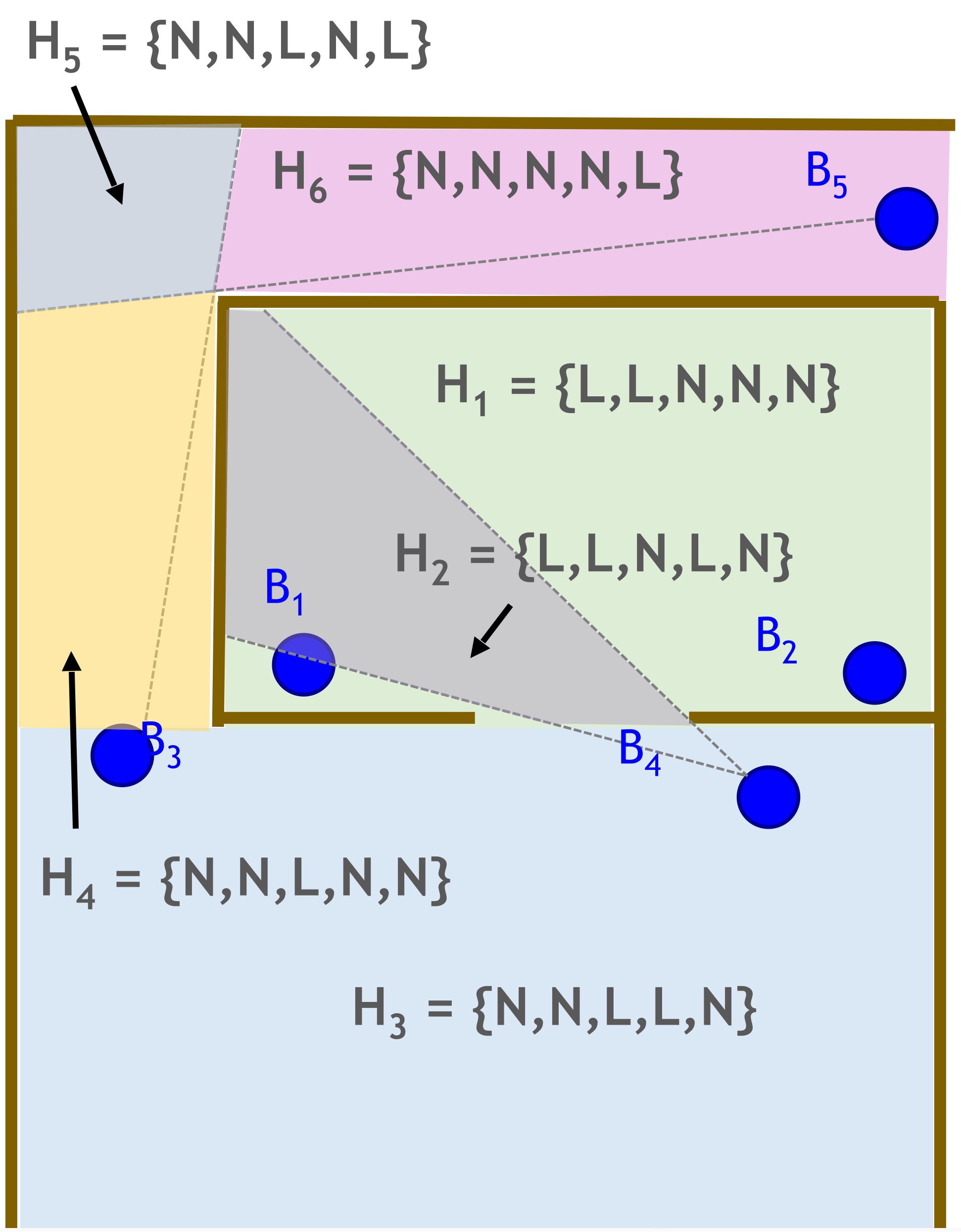
The floor plan is partitioned into disjoint regions, each of which is consistent with a single hypothesis of LOS and NLOS beacons



Key Idea: Leverage geometry

- Absence of signals and incorrect NLOS signals is useful information, when considered jointly across beacons

Floor-plan aware location-solver



Niranjini Rajagopal, Patrick Lazik, Nuno Pereira, Sindhura Chayapathy, Bruno Sinopoli, and Anthony Rowe. Enhancing indoor smartphone location acquisition using floor plans. In *Proceedings of the 17th ACM/IEEE International Conference on Information Processing in Sensor Networks*, pages 278–289. IEEE Press, 2018.

A hypothesis H_i assumes the set of LOS beacons $H_i(B^L)$ and NLOS beacons $H_i(B^N)$.

We evaluate consistency of each hypothesis with the NLOS model and beacon coverage model

Checking for consistency of hypothesis:

- C_1: Consistency with beacon coverage
  $H_i(B^L) \cap B_r \subseteq B^L(X_i)$
  $H_i(B^N) \cap B_r \subseteq B^N(X_i)$
- C_2: Consistency with NLOS error model
  $\forall k$: $B_k \in H_i(B^N) \cap B_r$, $[R_k - \| B_k - X_i \| > 0]$

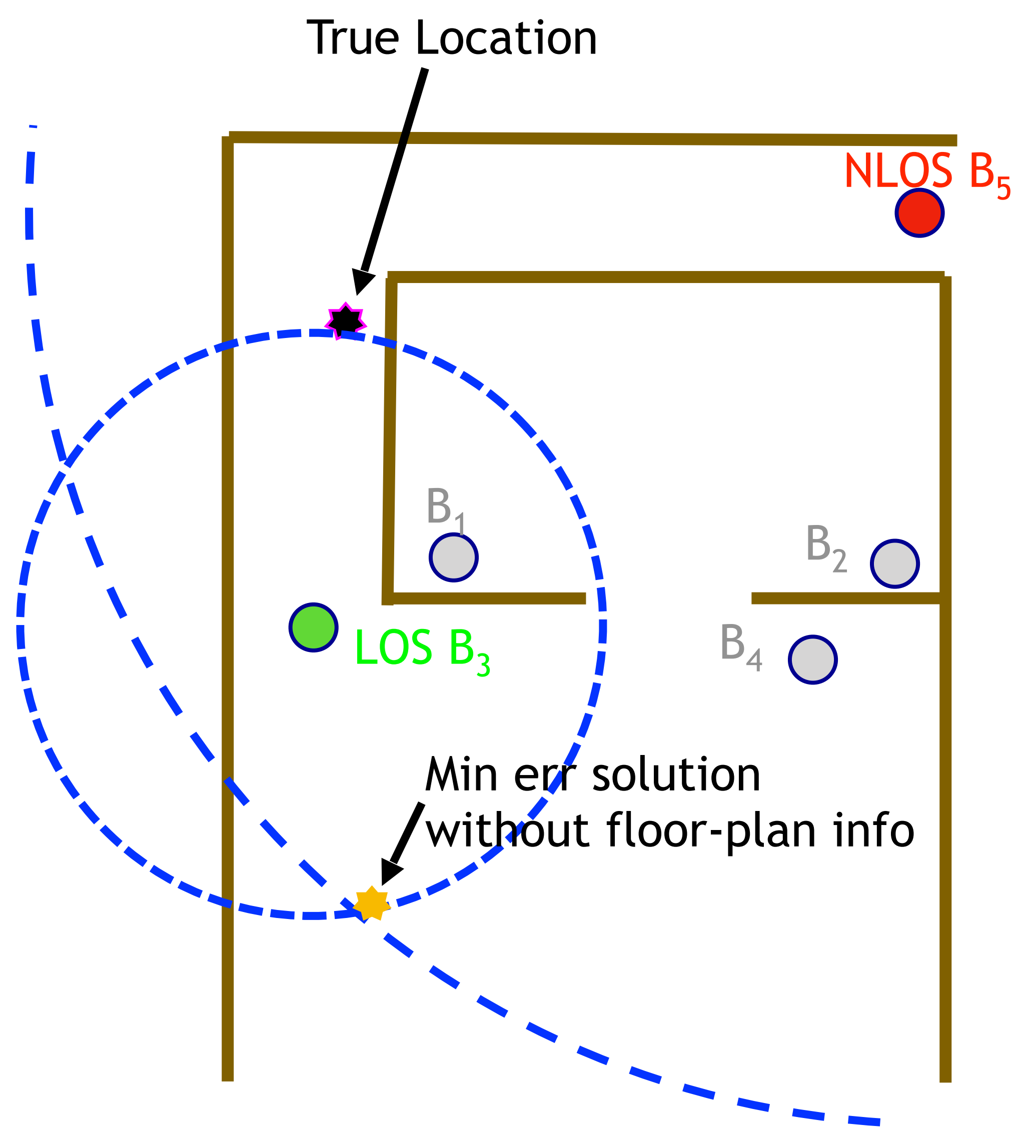
Comparing consistent hypothesis:

$$residue_{LOS}(X_i) = \frac{1}{N} \sum_k (R_k - \| B_k - X_i \|)$$

$$\forall k : B_k \in H_i(B^L) \cap B_r$$

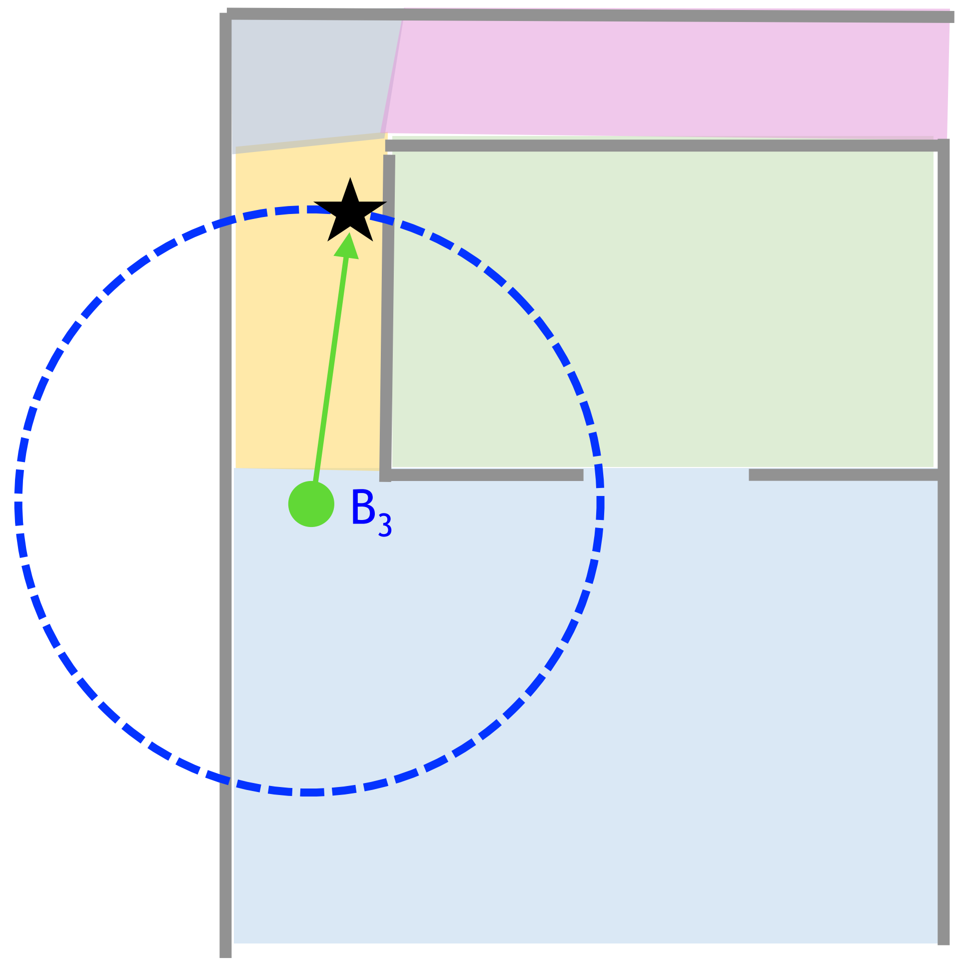
$$L(X) = \exp^{-residue_{LOS}{}^2(X)} \times \#missing_{LOS}(X)^{p(missing_{LOS})}$$

Floor-plan aware location solver



Floor-plan aware location solver

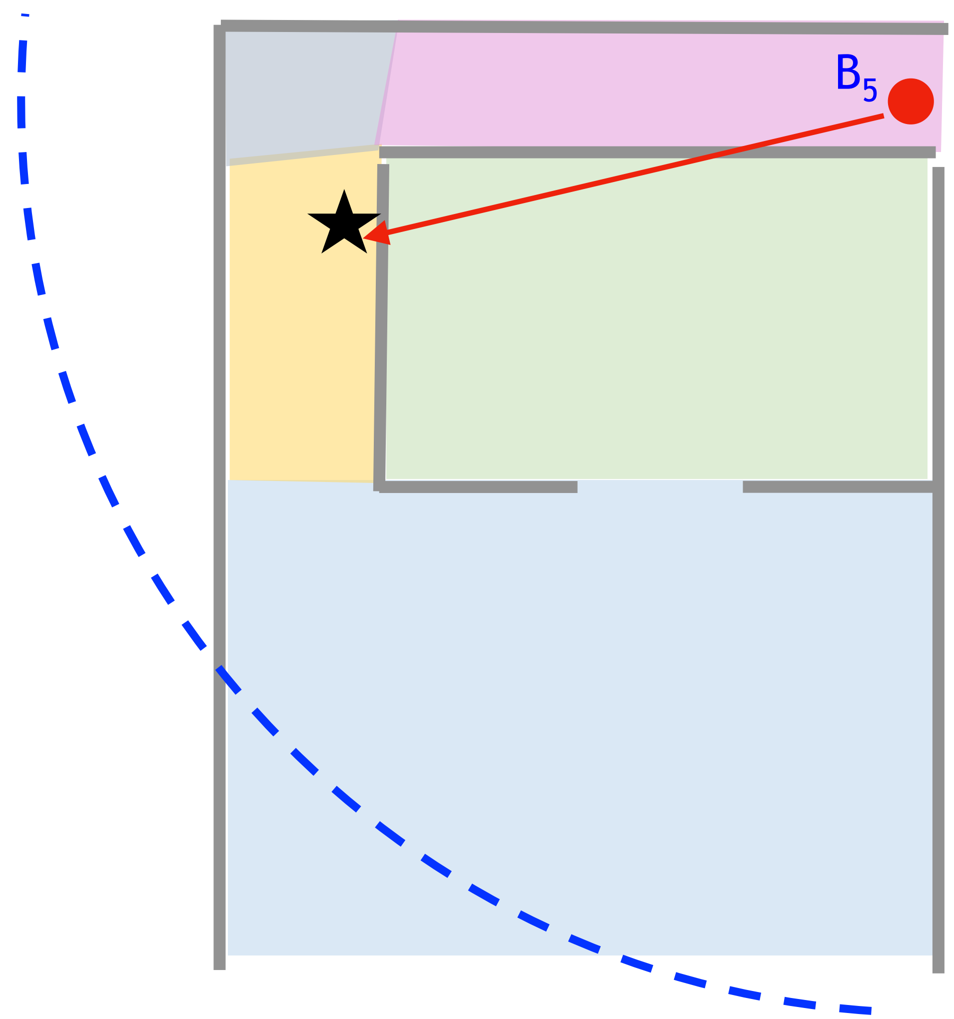
★ and ● B_3 are in LOS and range error ~ 0, consistent with LOS model



- C_1: Consistency with beacon coverage
  $H_i(B^L) \cap B_r \subseteq B^L(X_i)$
  $H_i(B^N) \cap B_r \subseteq B^N(X_i)$
- C_2: Consistency with NLOS error model
  $\forall k$: $B_k \in H_i(B^N) \cap B_r$, $[R_k - \| B_k - X_i \| > 0]$

Floor-plan aware location solver

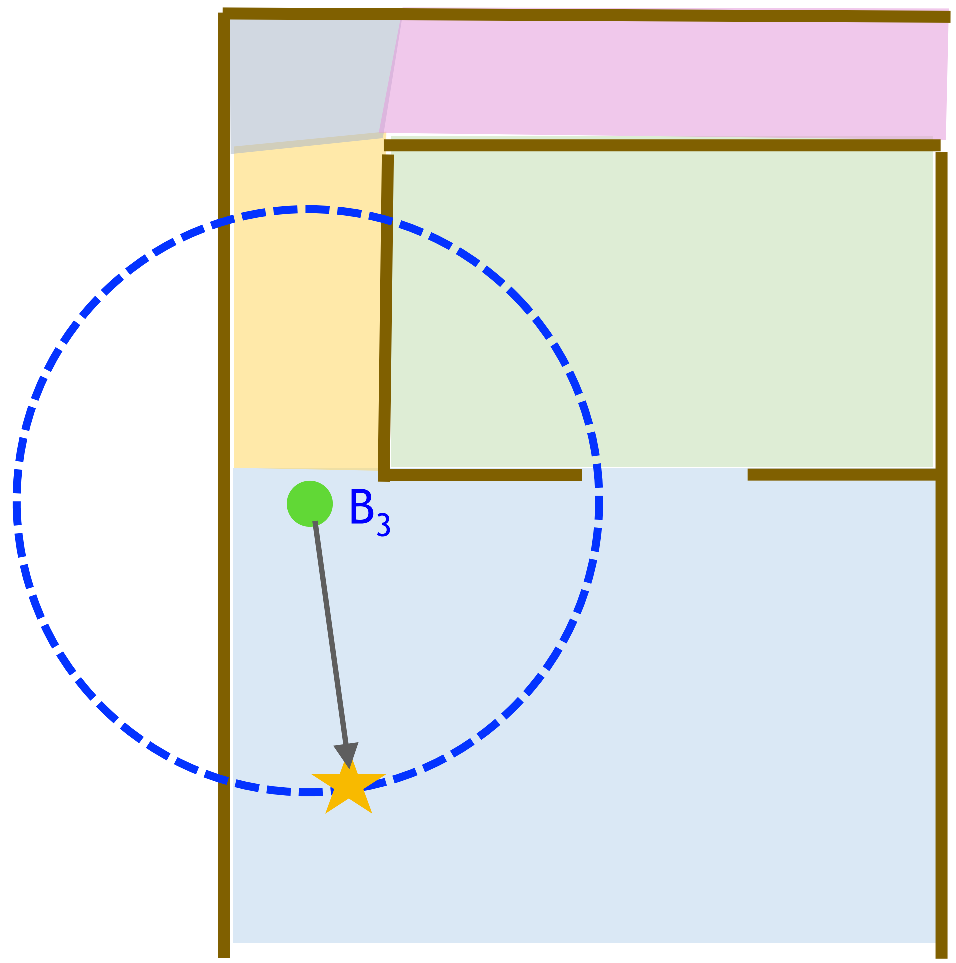
★ and ● B_5 are in NLOS and range error > 0, <u>consistent</u> with NLOS model



- C_1: Consistency with beacon coverage
  $H_i(B^L) \cap B_r \subseteq B^L(X_i)$
  $H_i(B^N) \cap B_r \subseteq B^N(X_i)$
- C_2: Consistency with NLOS error model
  $\forall k$: $B_k \in H_i(B^N) \cap B_r$, $[R_k - \| B_k - X_i \| > 0]$

Floor-plan aware location solver

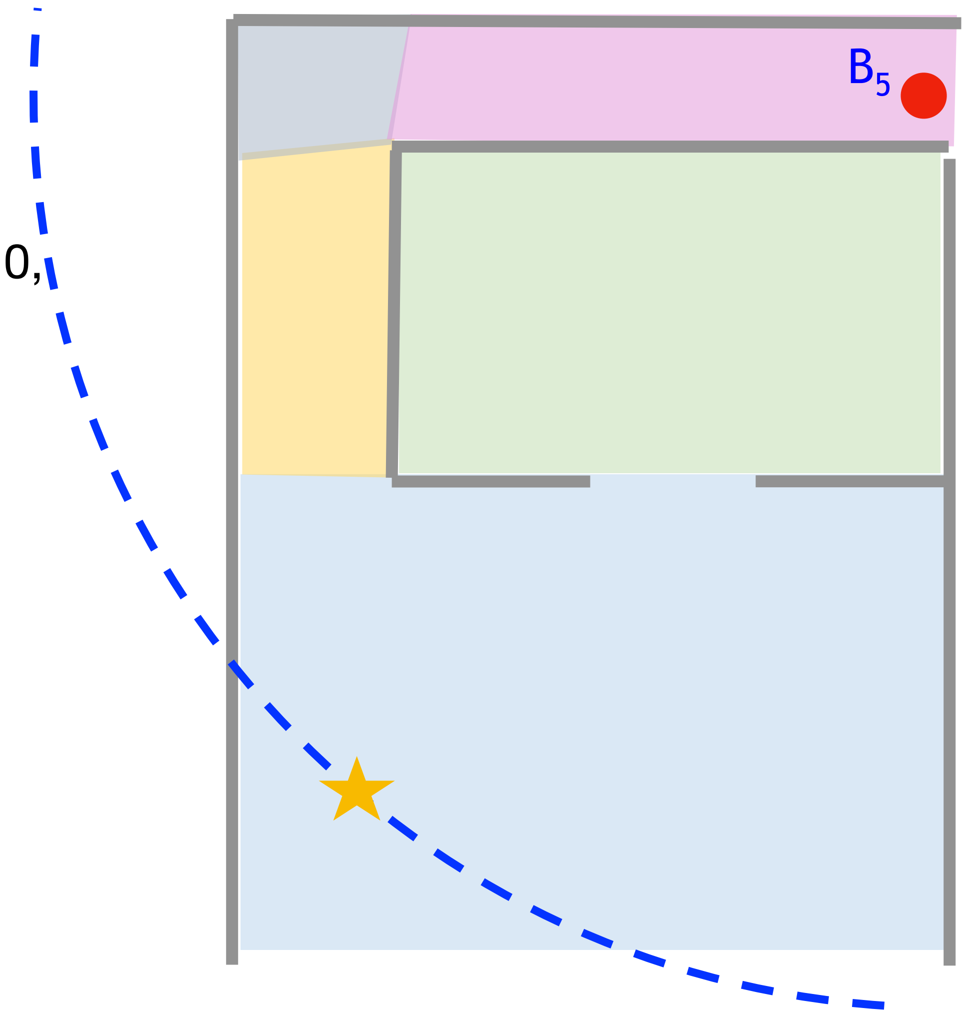
★ and ● B_3 are in LOS and range error ~ 0, consistent with LOS model



- C_1: Consistency with beacon coverage
  $H_i(B^L) \cap B_r \subseteq B^L(X_i)$
  $H_i(B^N) \cap B_r \subseteq B^N(X_i)$
- C_2: Consistency with NLOS error model
  $\forall k$: $B_k \in H_i(B^N) \cap B_r$, $[R_k - \| B_k - X_i \| > 0]$

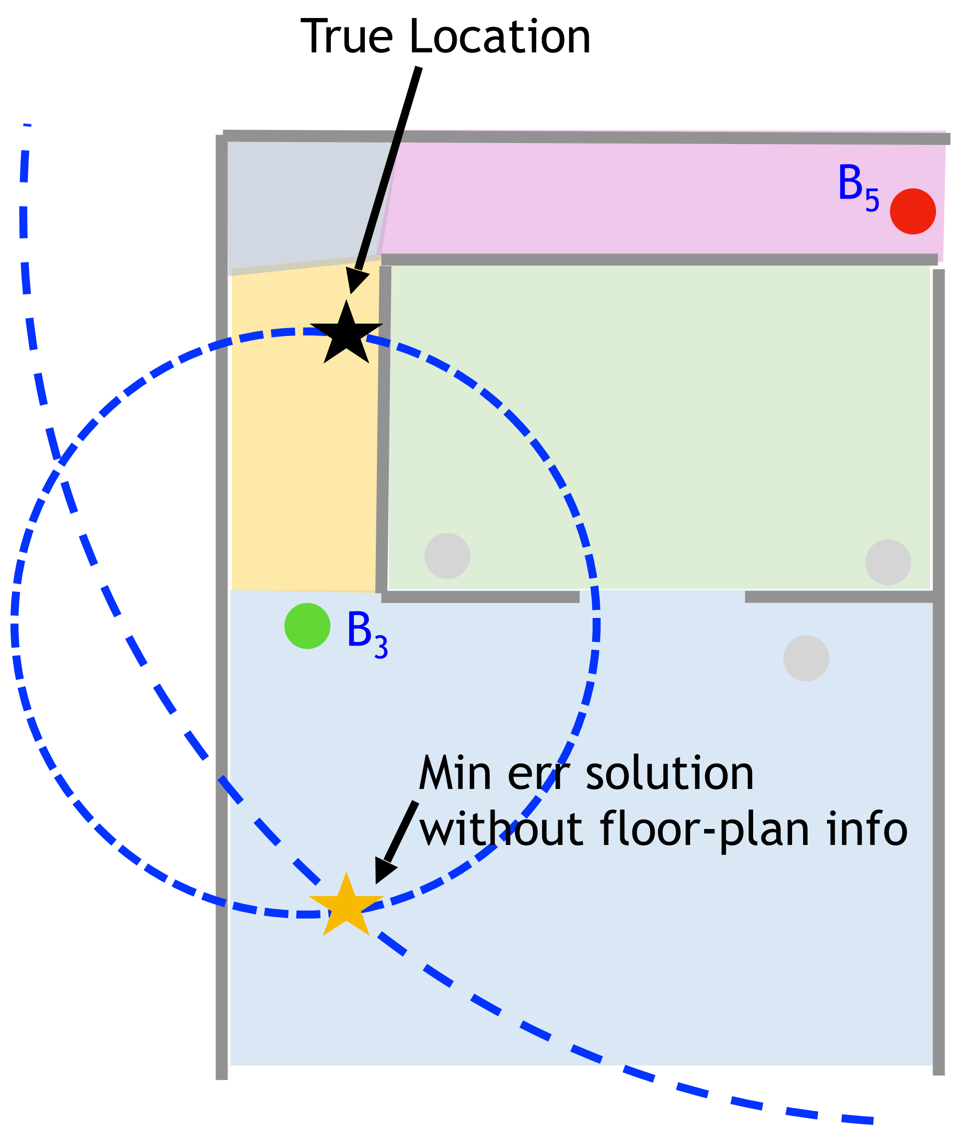
Floor-plan aware location solver

★ and ● B_5 are in NLOS and range error ~ 0,
<u>inconsistent</u> with NLOS model



- C_1: Consistency with beacon coverage
  $H_i(B^L) \cap B_r \subseteq B^L(X_i)$
  $H_i(B^N) \cap B_r \subseteq B^N(X_i)$
- C_2: Consistency with NLOS error model
  $\forall k\colon B_k \in H_i(B^N) \cap B_r, [R_k - \| B_k - X_i \| > 0]$

Floor-plan aware location solver



Location ★ is more likely than ★ since

★ and ● B_3 are in LOS and range error ~ 0,
<u>consistent</u> with LOS model

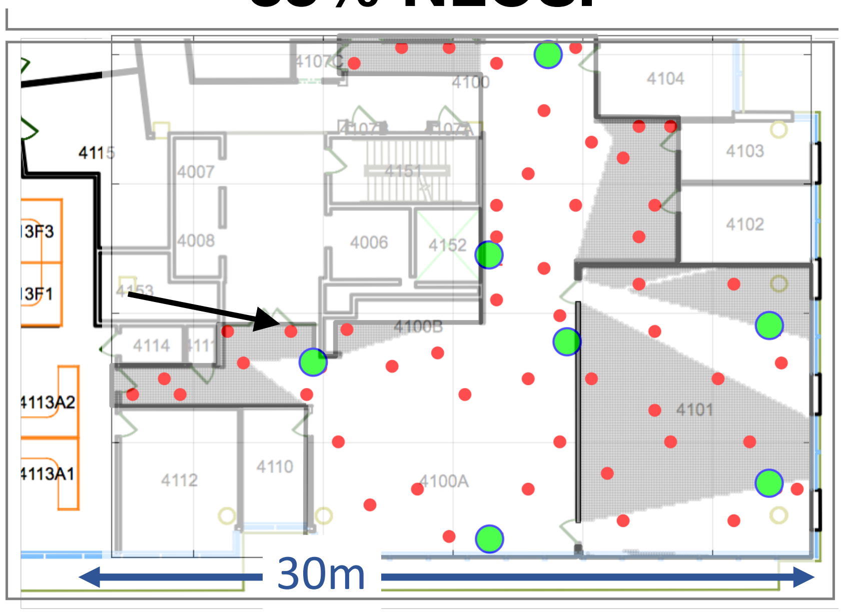
★ and ● B_5 are in NLOS and range error > 0,
<u>consistent</u> with NLOS model

★ and ● B_3 are in LOS and range error ~ 0,
<u>consistent</u> with LOS model

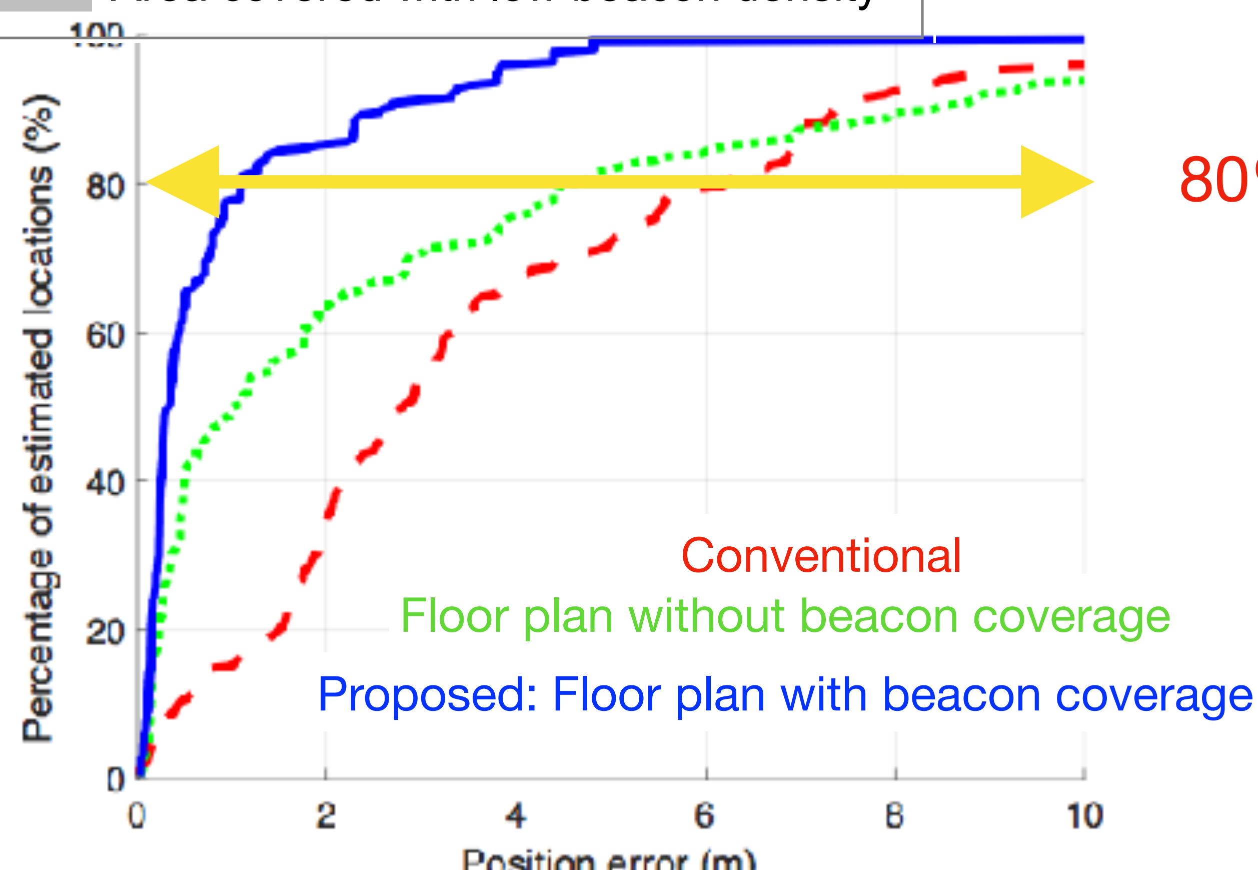
★ and ● B_5 are in NLOS and range error ~ 0,
<u>inconsistent</u> with NLOS model

Localization performance

33% NLOS!



Beacon   Test point   Area covered with low beacon density



80% error improved from 6m to 1m

Analysis of solver robustness

The true location X_T and hypothesis H_T are consistent by definition. Hence

$$\forall k : B_k \in H_T(B^L) \cap B_r, [R_k - \| B_k - X_T \| = 0]$$
$$\forall k : B_k \in H_T(B^N) \cap B_r, [R_k - \| B_k - X_T \| > 0]$$

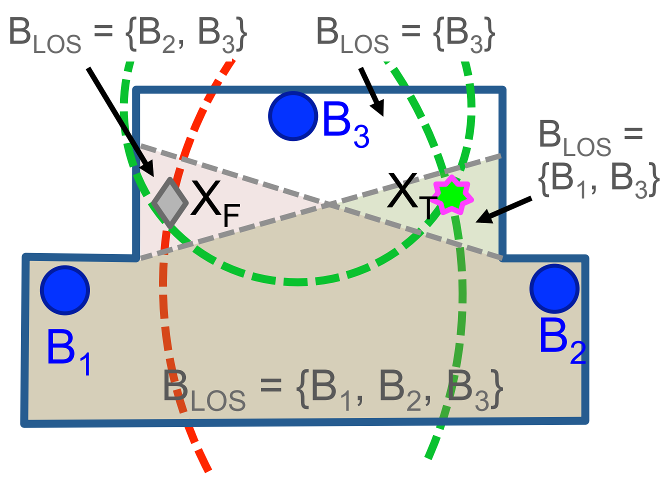
In order for an incorrect location X_F and hypothesis H_F to be consistent:

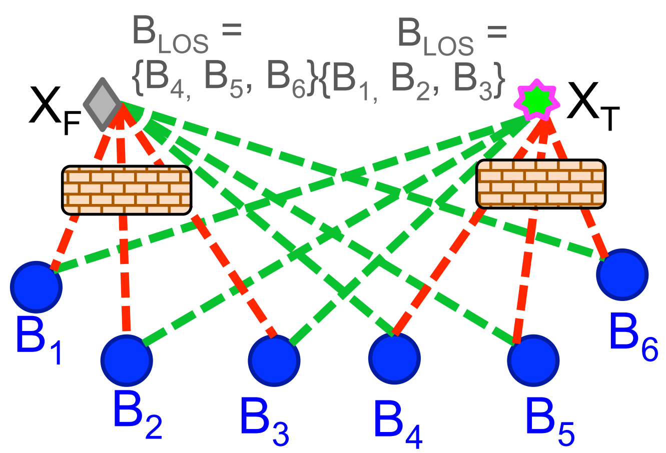
$$\forall k : B_k \in H_F(B^L) \cap B_r, [R_k - \| B_k - X_F \| = 0]$$
$$\forall k : B_k \in H_F(B^N) \cap B_r, [R_k - \| B_k - X_F \| > 0]$$

Every beacon in range imposes one of the four constraints:

According to H_T, $B_k \in$	**According to H_F, $B_k \in$**	**Constraint**
$H_T(B^L)$	$H_F(B^L)$	$\| B_k - X_T \| = \| B_k - X_F \|$
$H_T(B^L)$	$H_F(B^N)$	$\| B_k - X_T \| > \| B_k - X_F \|$
$H_T(B^N)$	$H_F(B^L)$	$\| B_k - X_T \| < \| B_k - X_F \|$
$H_T(B^N)$	$H_F(B^N)$	$\| B_k - X_F \| > R_k, \| B_k - X_T \| > R_k$
$H_T(B^N)$	$H_F(B^N)$	$\| B_k - X_F \| > R_k, \| B_k - X_T \| > R_k$

Analysis of solver robustness



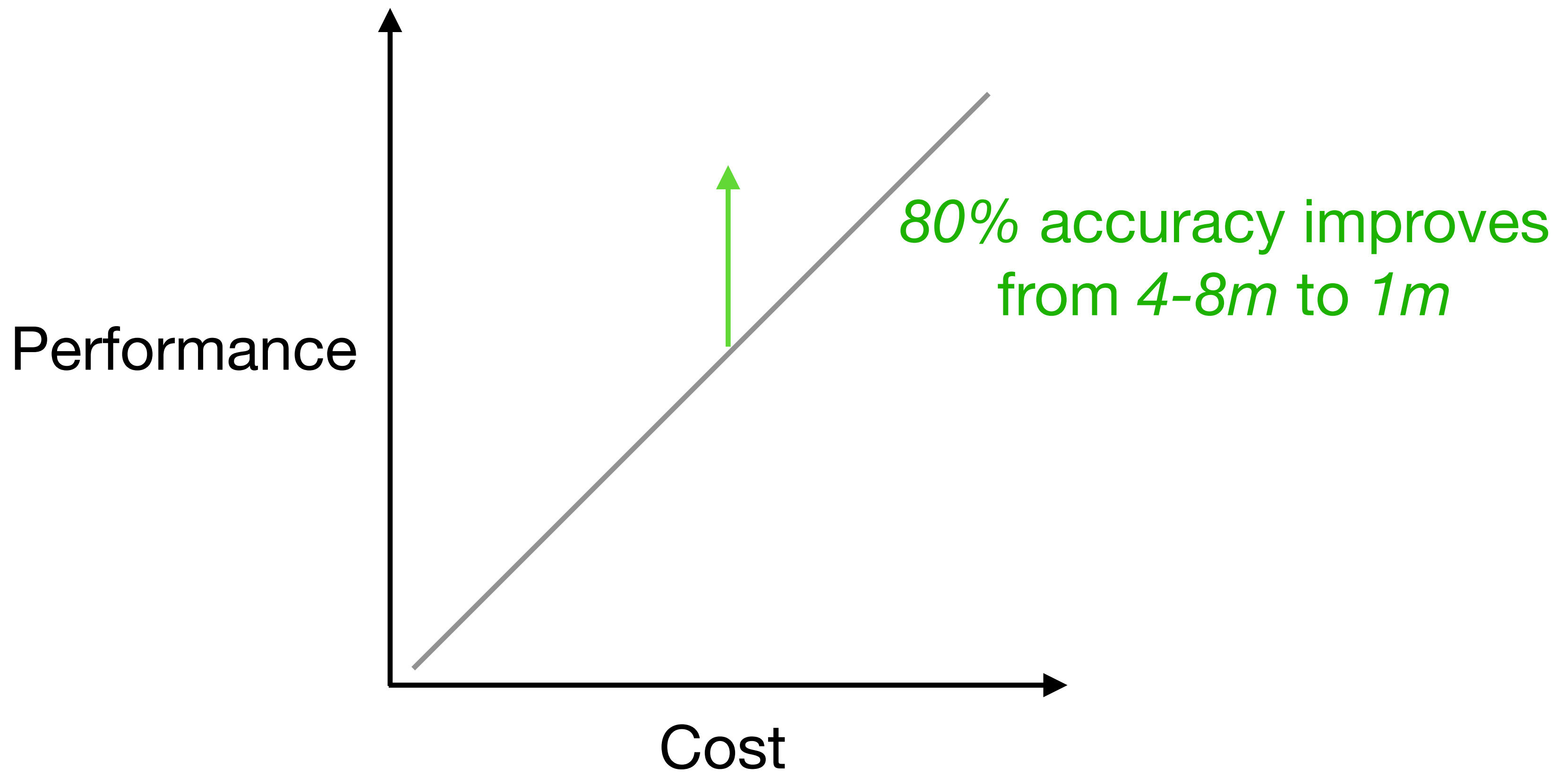


If all the expected LOS ranges are received,
then the solver is robust to any amount of NLOS,
except for certain geometries that rarely occur in practice.

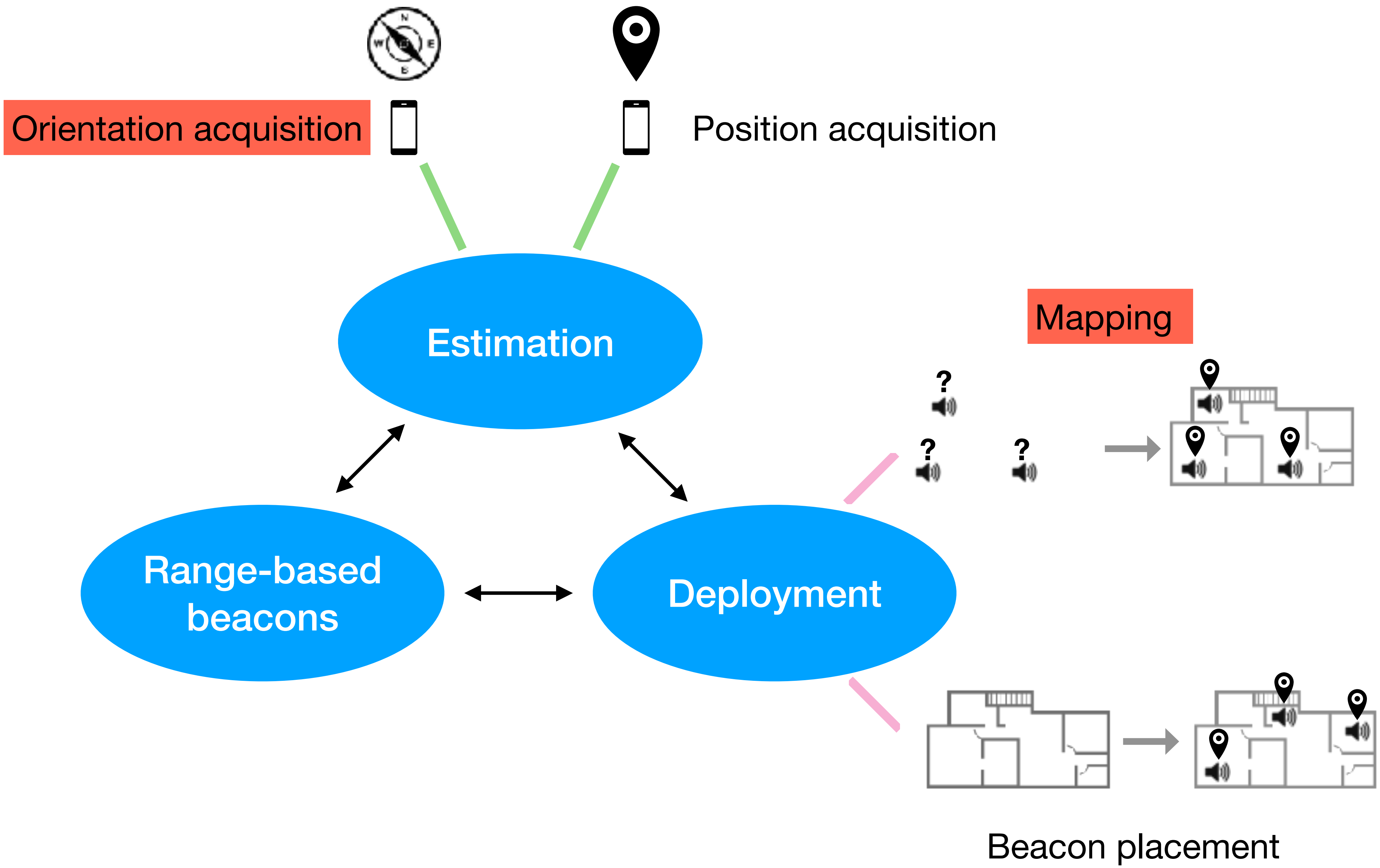
Location acquisition contribution

- Systematic methodology to integrate floor plan geometry and beacon coverage models —> robust location solver.

- Solver detects NLOS signals with 92% accuracy.



Overview

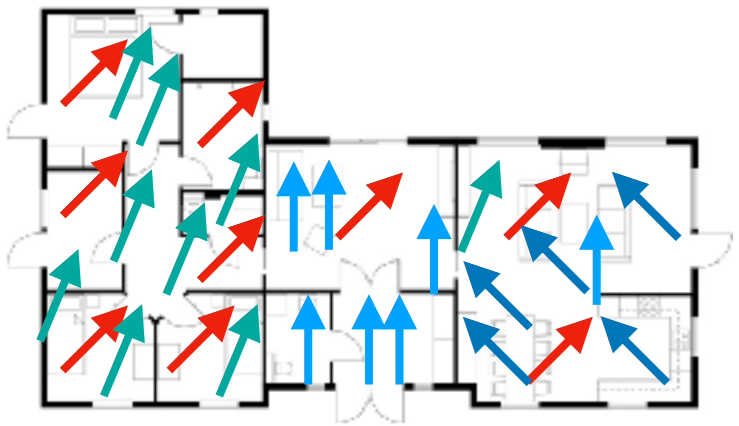


Orientation acquisition
Position acquisition
Estimation
Mapping
Range-based beacons
Deployment
Beacon placement

Maps for range-based localization systems

Beacon locations

Floor plans

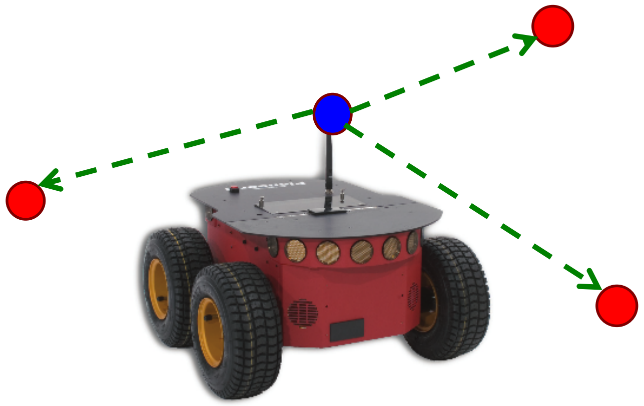


Spatially varying vectored signals

Mapping approaches

Typical

LIDAR



Robots

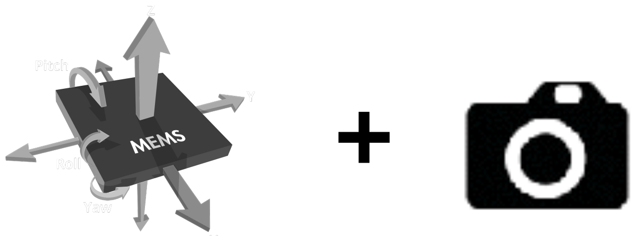
Experts + instruments

Proposed

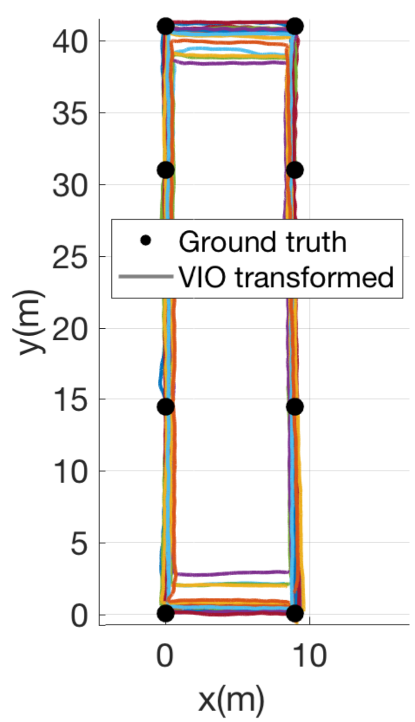
Pedestrians walking with phones

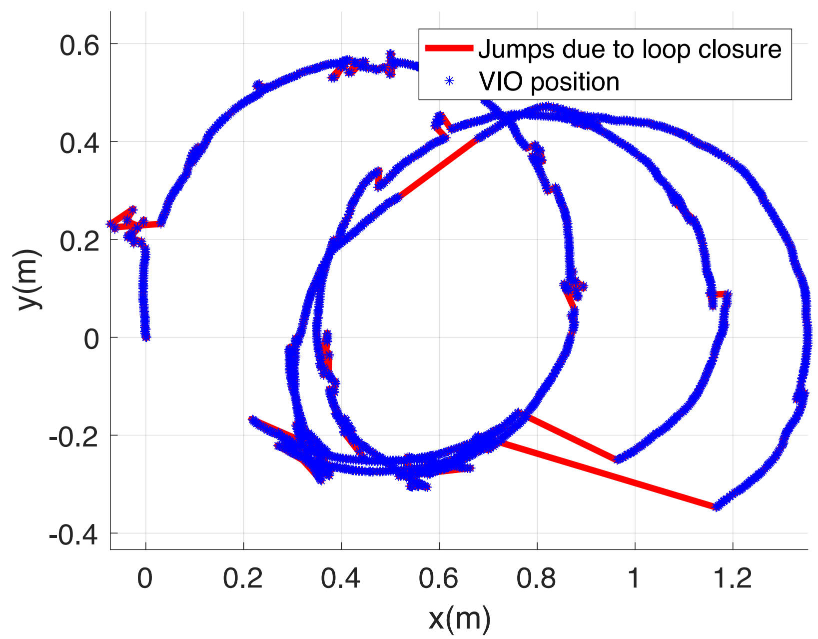
- Low-cost
- Low-effort
- Adapts over time
- Accurate

Accurate tracking with Visual Inertial Odometry (VIO)



Inertial Camera





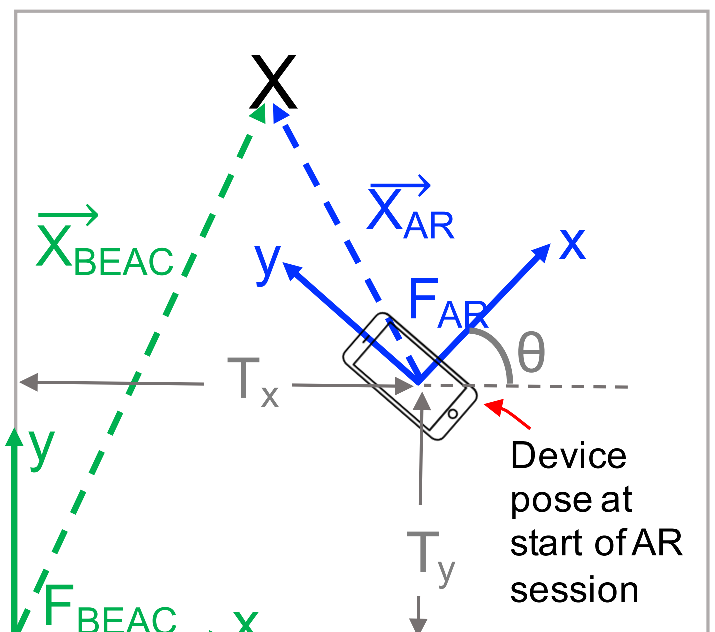
Accurate tracking

Suffers when visual features are poor

Fuse beacon ranges and VIO for accurate tracking

Inertial Camera Beacons

Problem formulation



$$X_{BEAC} = R(\theta_{AR \to BEAC}).X_{AR} + T_{AR \to BEAC}$$

$$R(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$T_{AR \to BEAC} = [T_x, T_y, T_z]^T$$

State estimation using a Particle Filter

- Estimate 5 states: Four transformation variables and scale of VIO
- VIO updates states
- Range measurements update the weight

Fusion of VIO and acoustic ranges

With accurate real-time tracking, we can now support mapping.

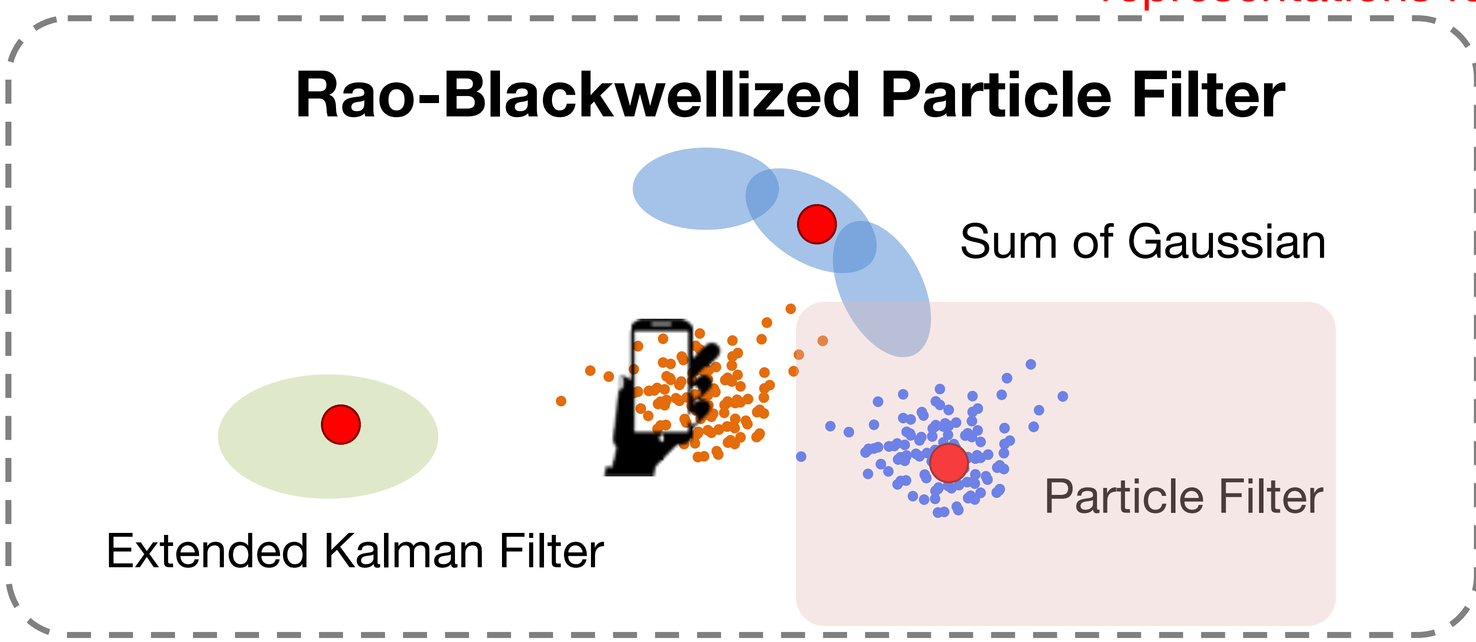
Beacon mapping

Rao-Blackwellization

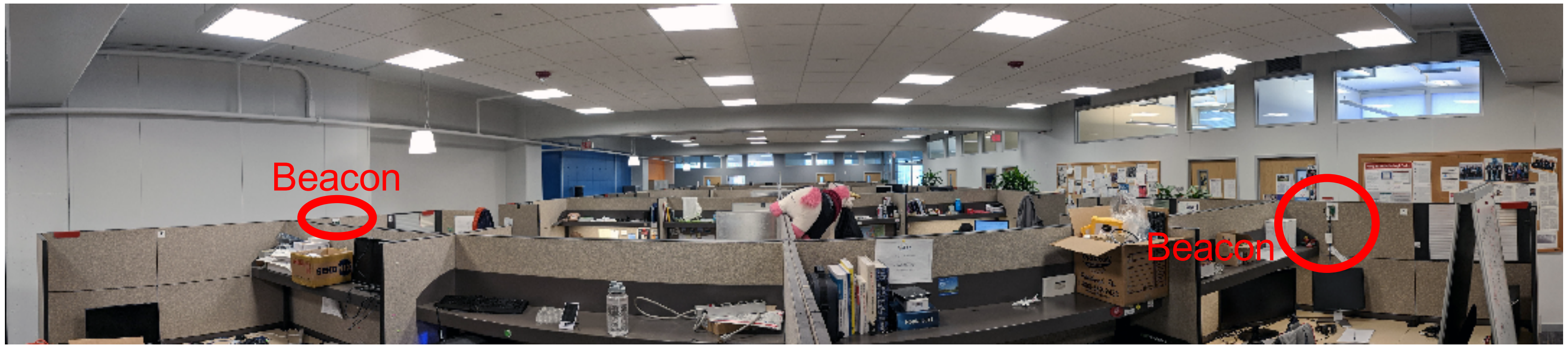
Mobile device Beacons VIO Beacon ranges

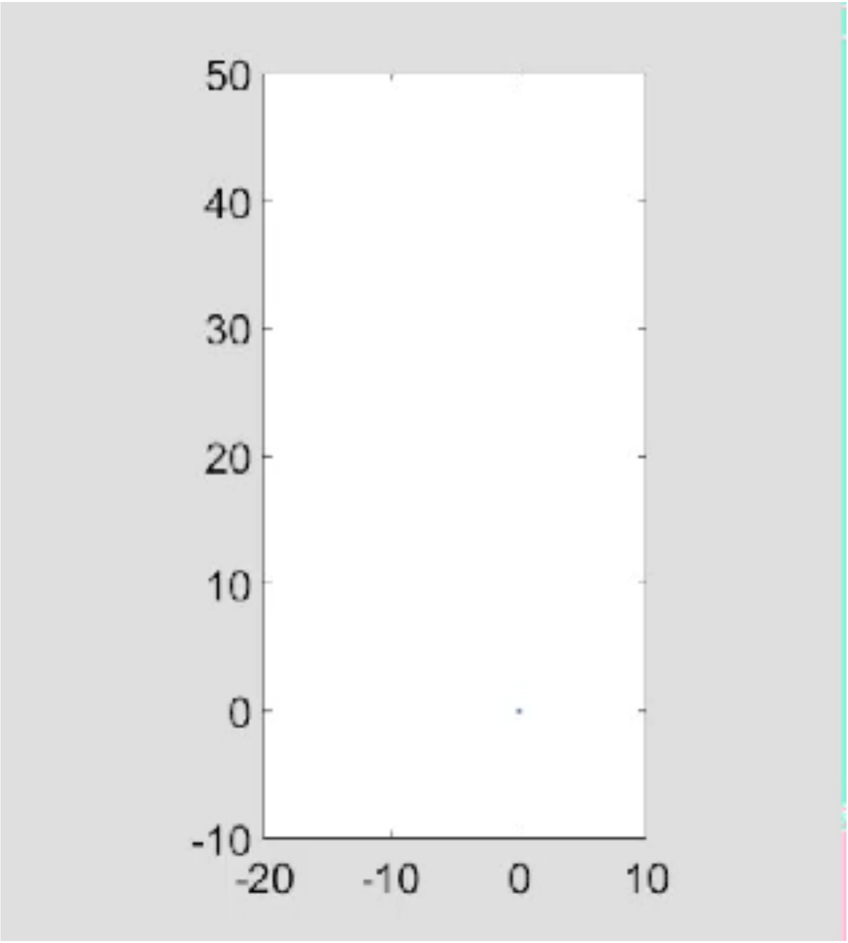
$$P(X, B_1, ...B_N / U, Z)$$

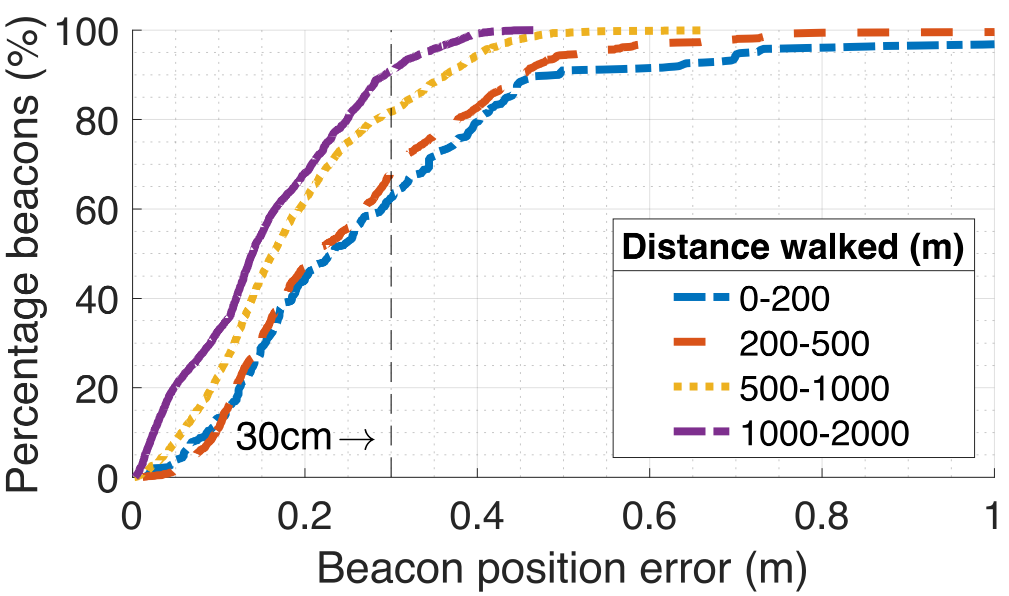
Can use different probabilistic representations for beacons



Beacon mapping evaluation

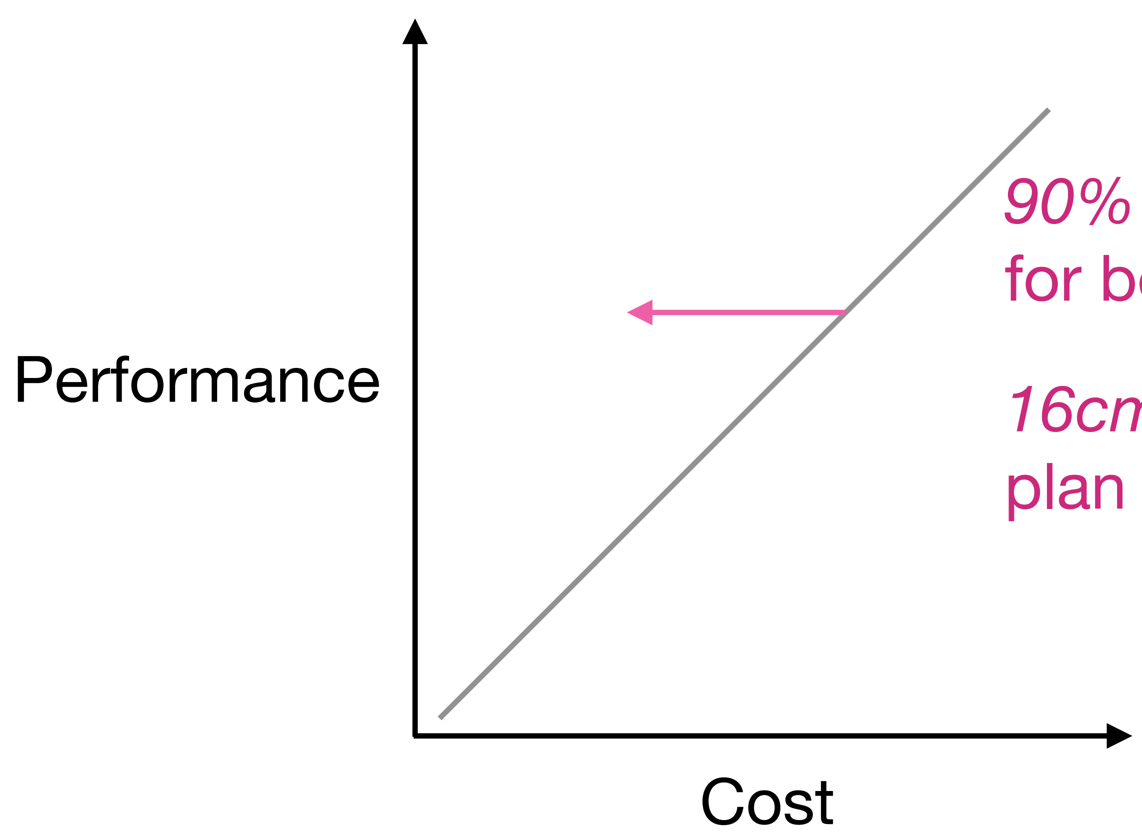






Contributions to mapping

- Crowdsourced pedestrian-aided mapping process that simply requires users to walk around with phones that can be held in any orientation.



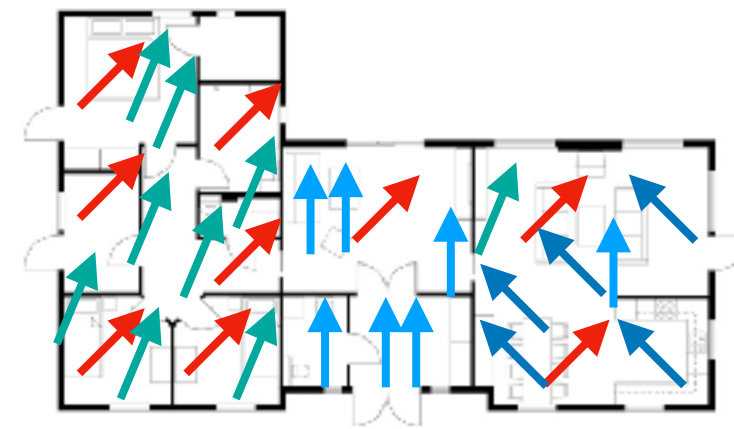
90% accuracy of *30cm* for beacon mapping.

16cm accuracy for floor plan mapping

Maps for range-based localization systems

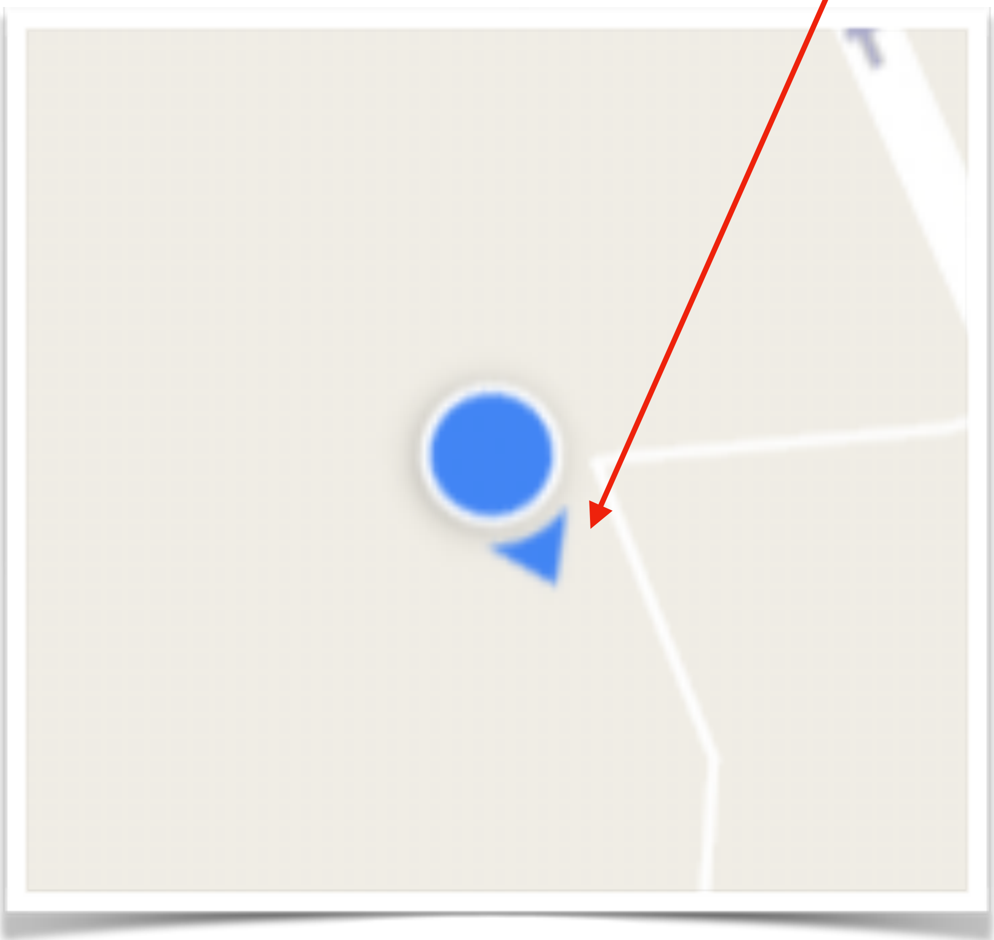
Beacon locations

Floor plans



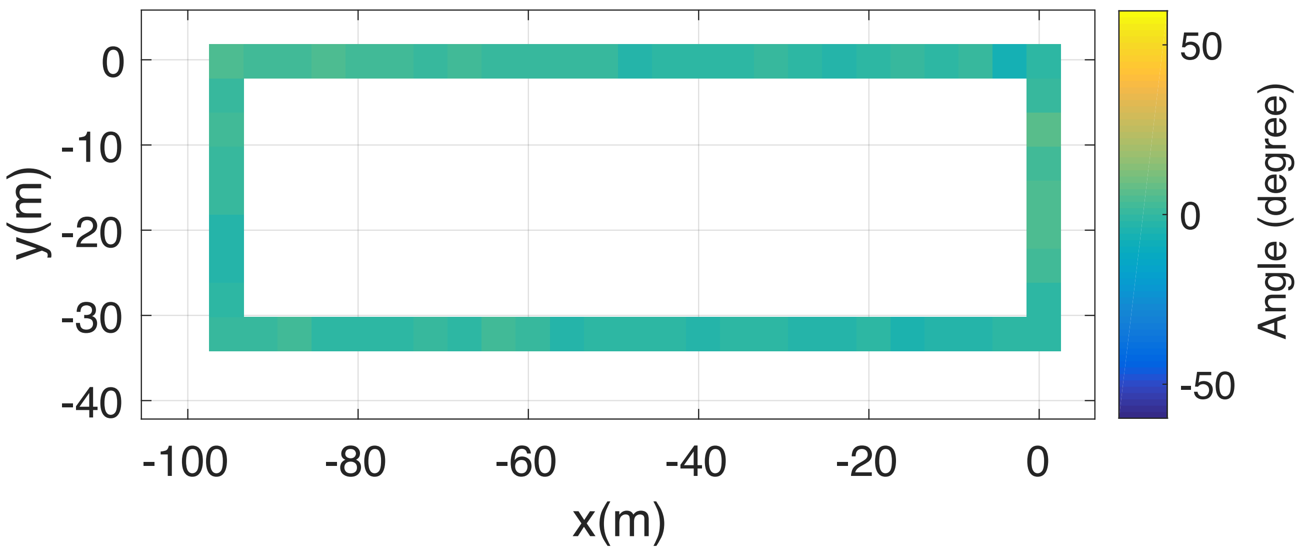
Spatially varying vectored signals

Rapid orientation acquisition

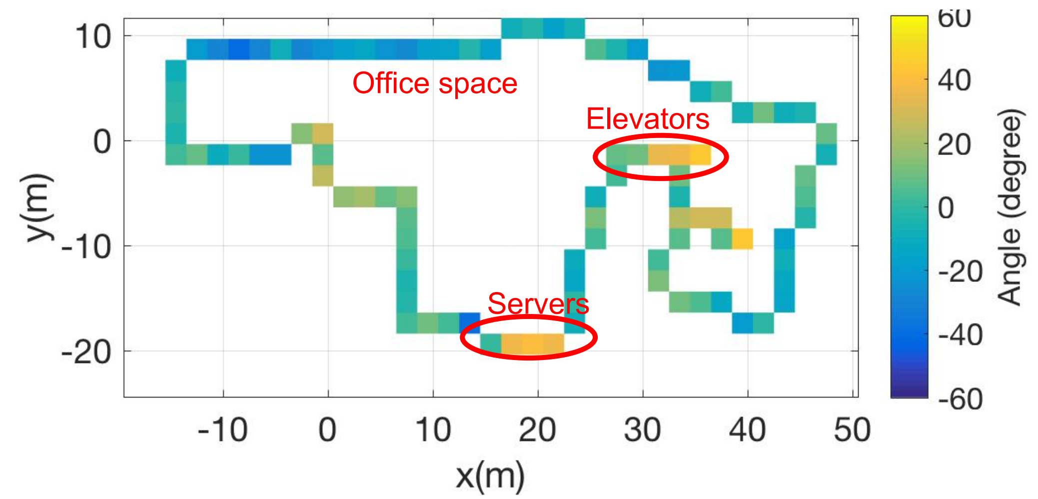


Compass is unreliable indoors

Outdoors



Indoors

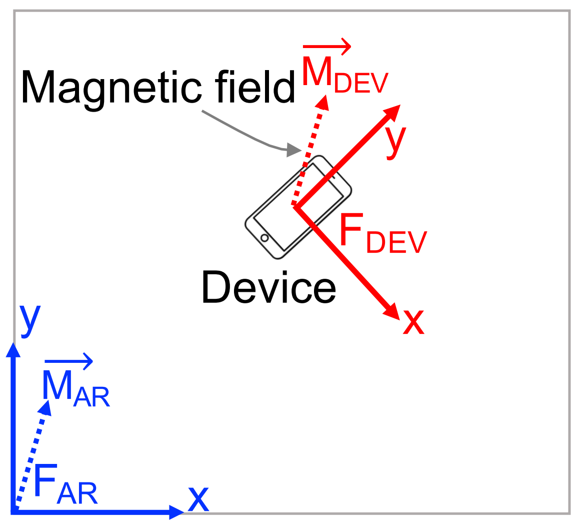


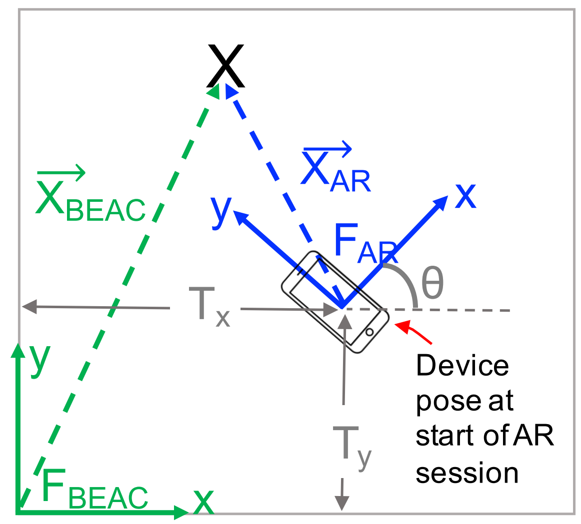
If we can map the magnetic field, then we can use it for acquiring orientation.

Niranjini Rajagopal, John Miller, Krishna Kumar Reghu Kumar, Anh Luong, and Anthony Rowe, **Improving Augmented Reality Relocalization Using Beacons and Magnetic Field Maps**, (To appear in) The 10th International Conference on Indoor Positioning and Indoor Navigation, IPIN 2019

Magnetic field mapping process

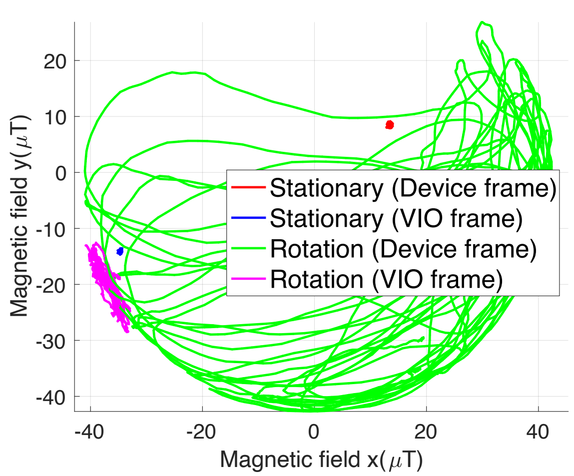
Accurate 6DoF tracking with VIO makes it possible to map vectored signals

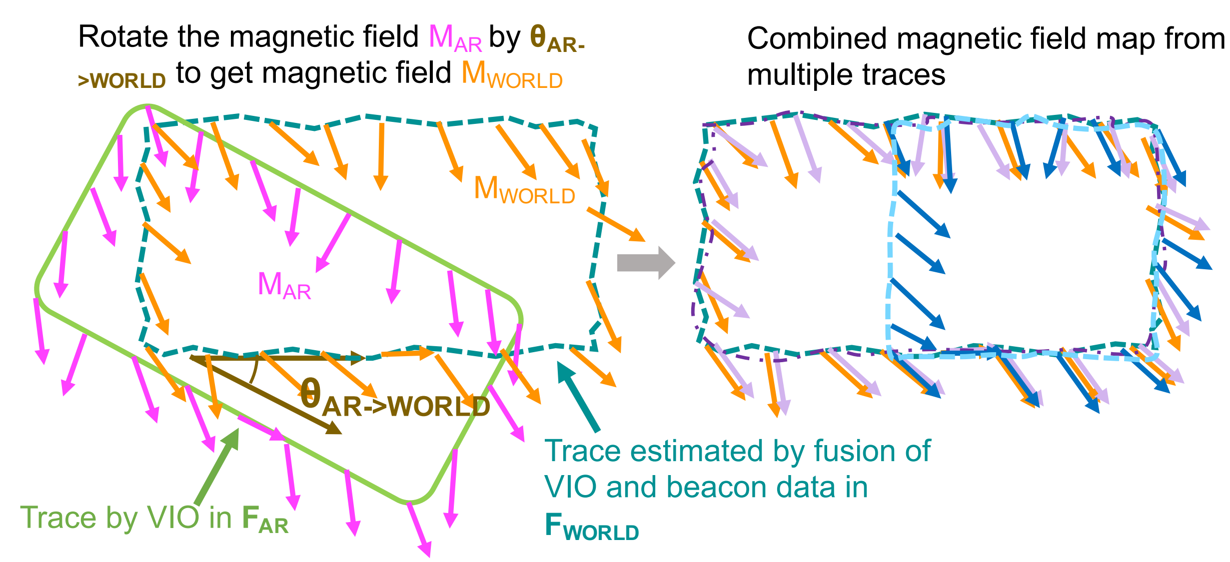




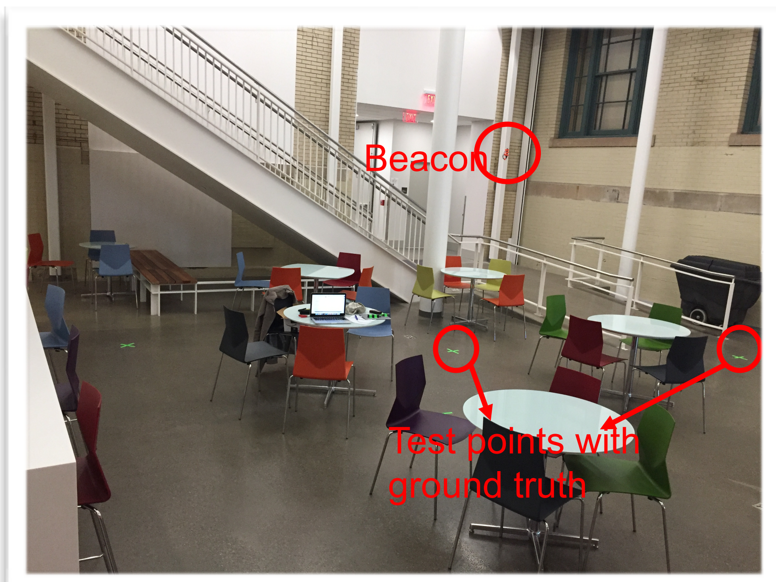
First, we convert the magnetic vector from device frame to VIO frame

Next, we convert the magnetic vector from VIO frame to beacon frame





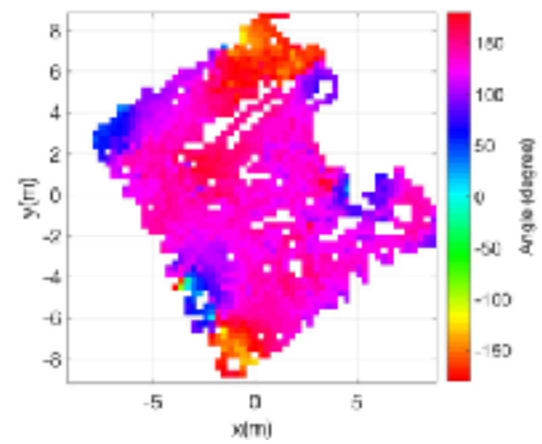
Indoor magnetic field maps



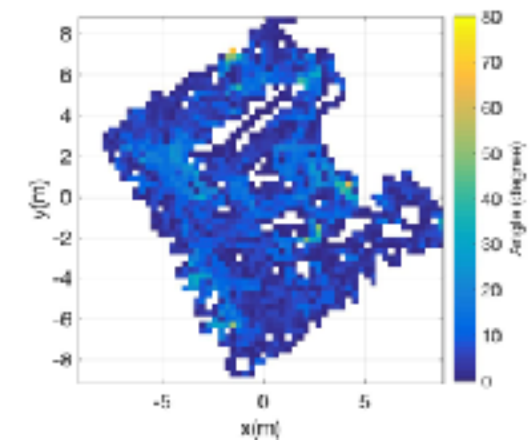
Cafe in Scott Hall, CMU

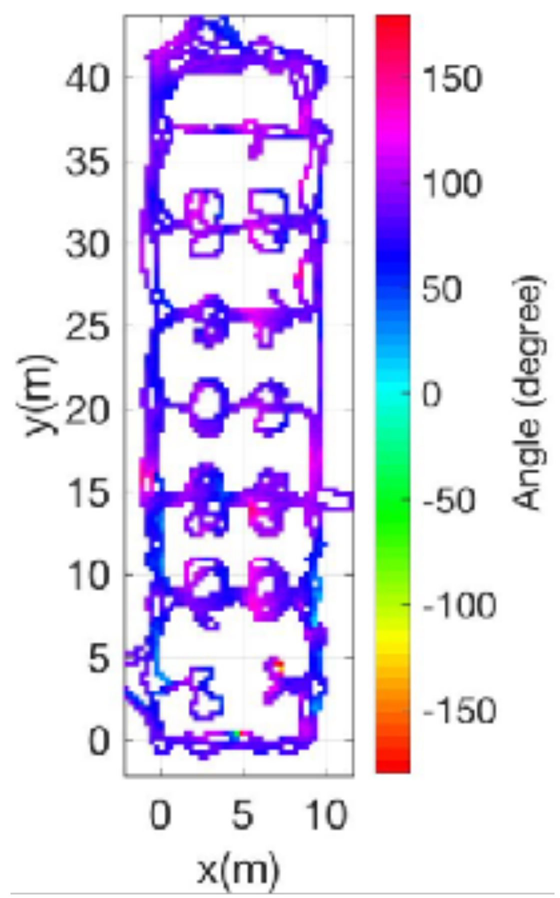
Office space in CIC, CMU

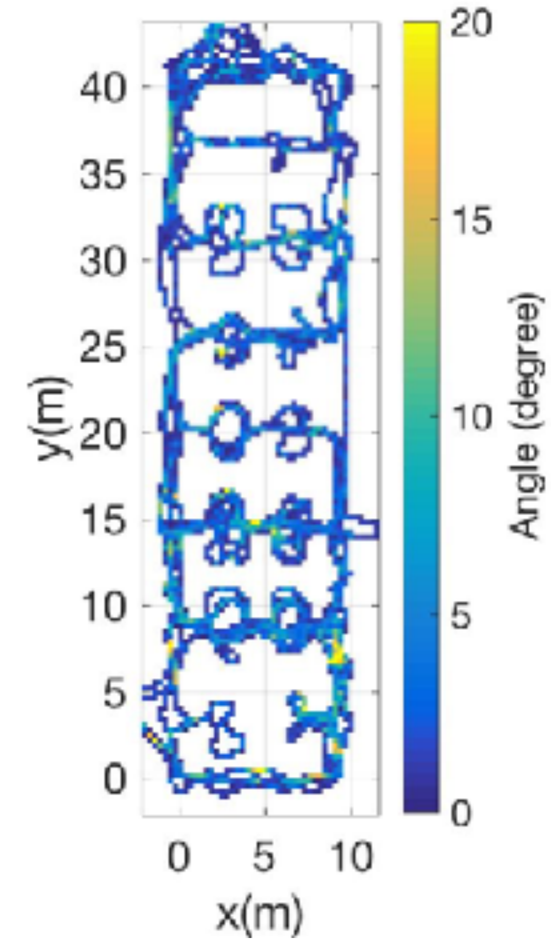
Mean



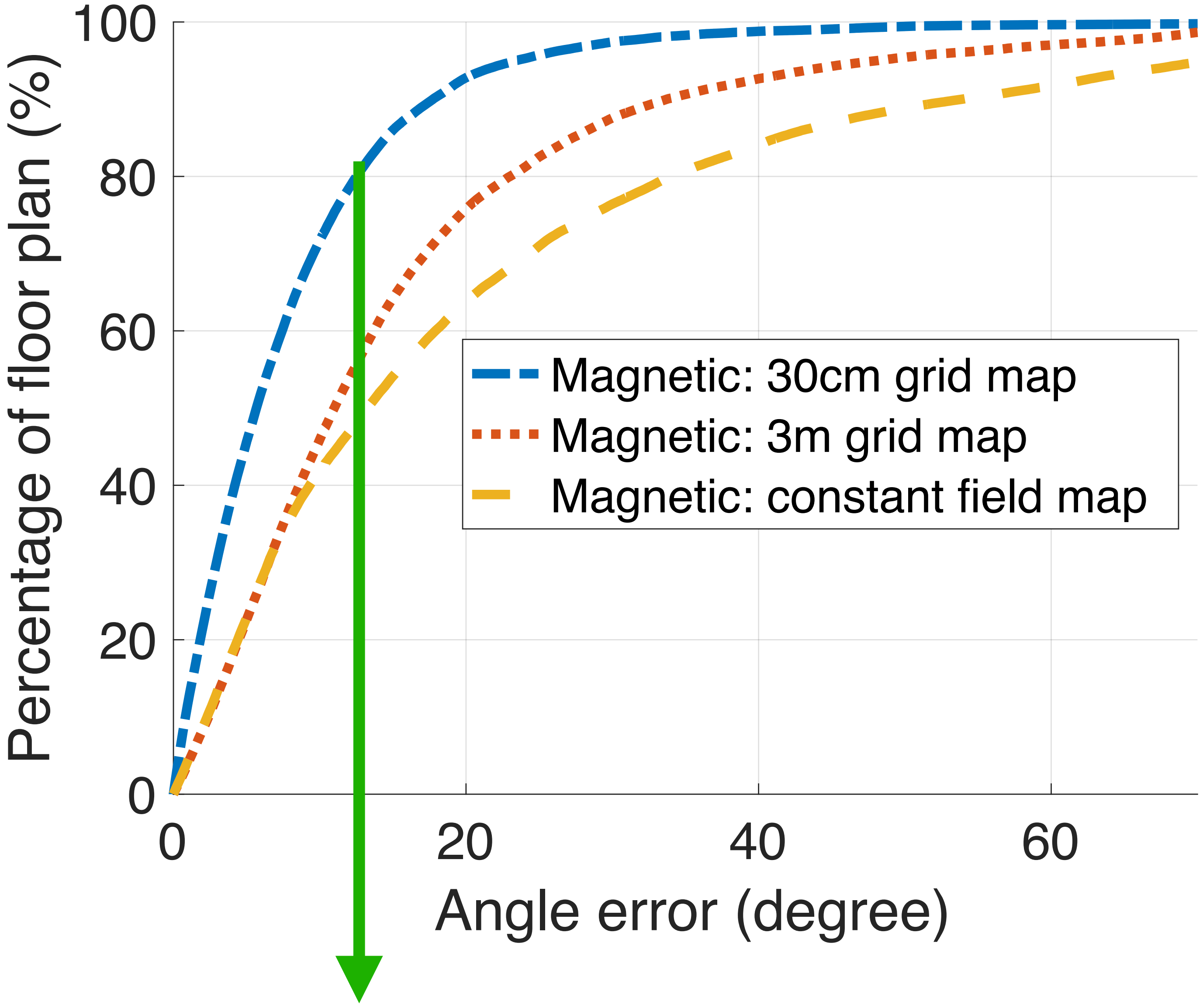
Standard deviation







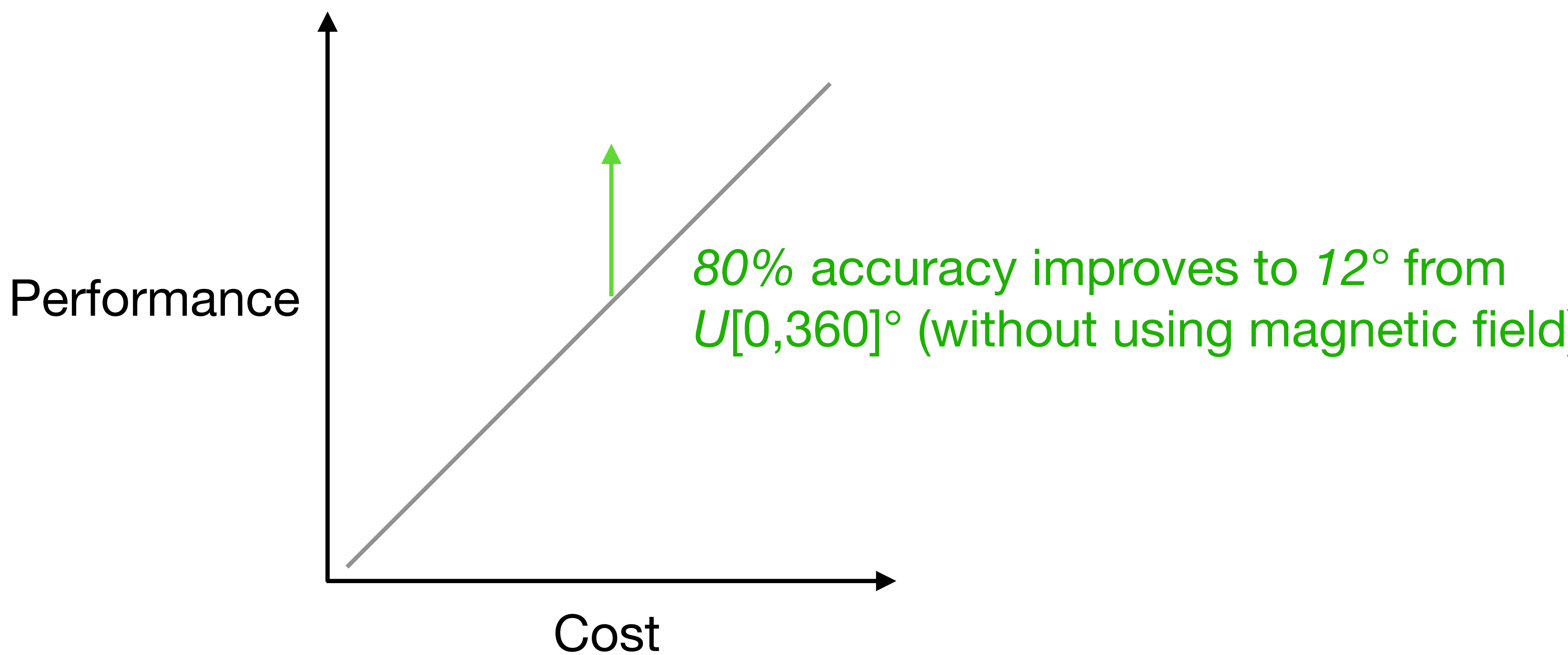
Rapid orientation acquisition performance



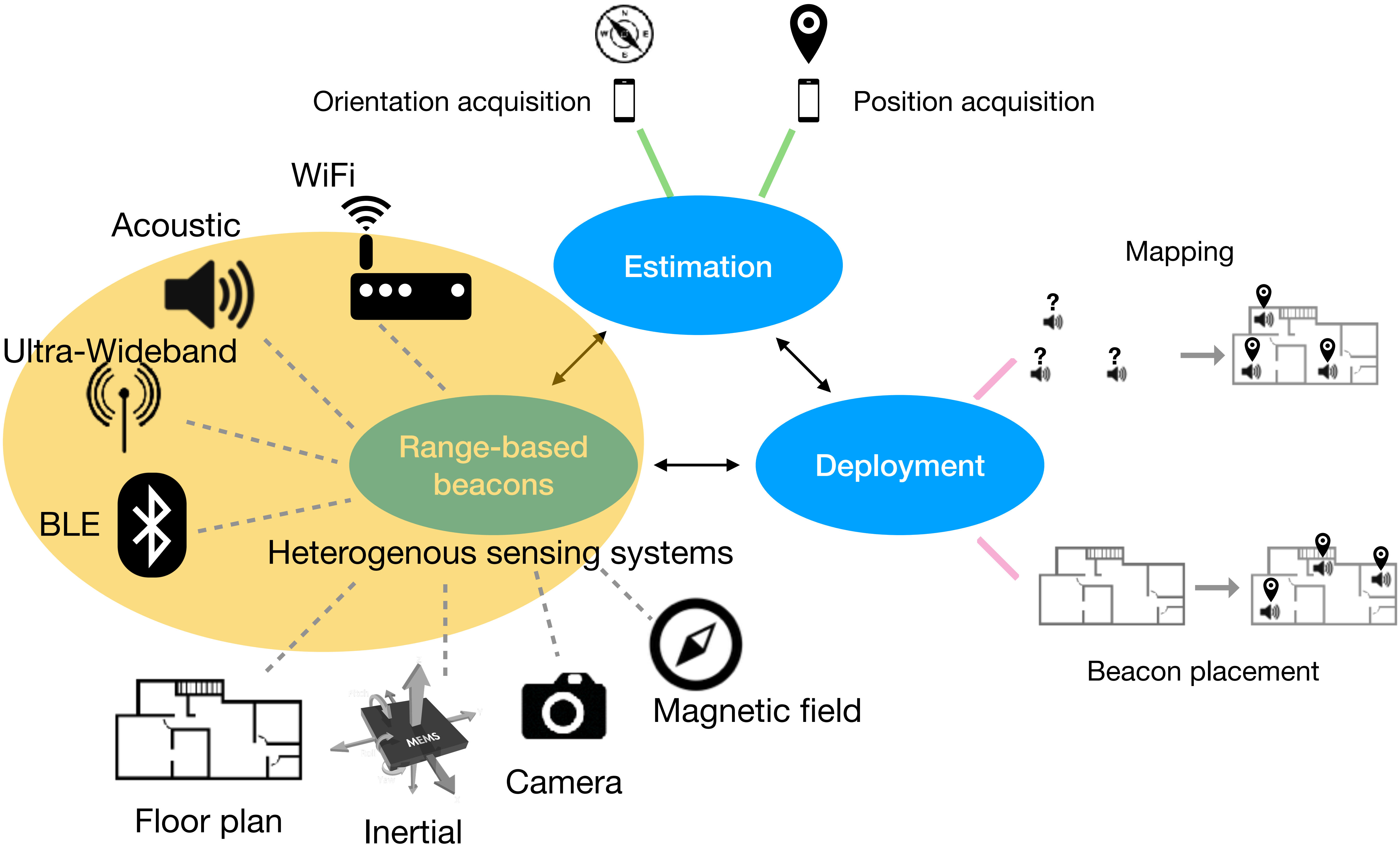
80% accuracy of 12 degree

Orientation acquisition contributions

- A method to for rapid orientation acquisition by fusing beacon ranges, VIO and the magnetic field sensor data.
- A method to created vectored maps of magnetic field indoors, using pedestrian-held devices.

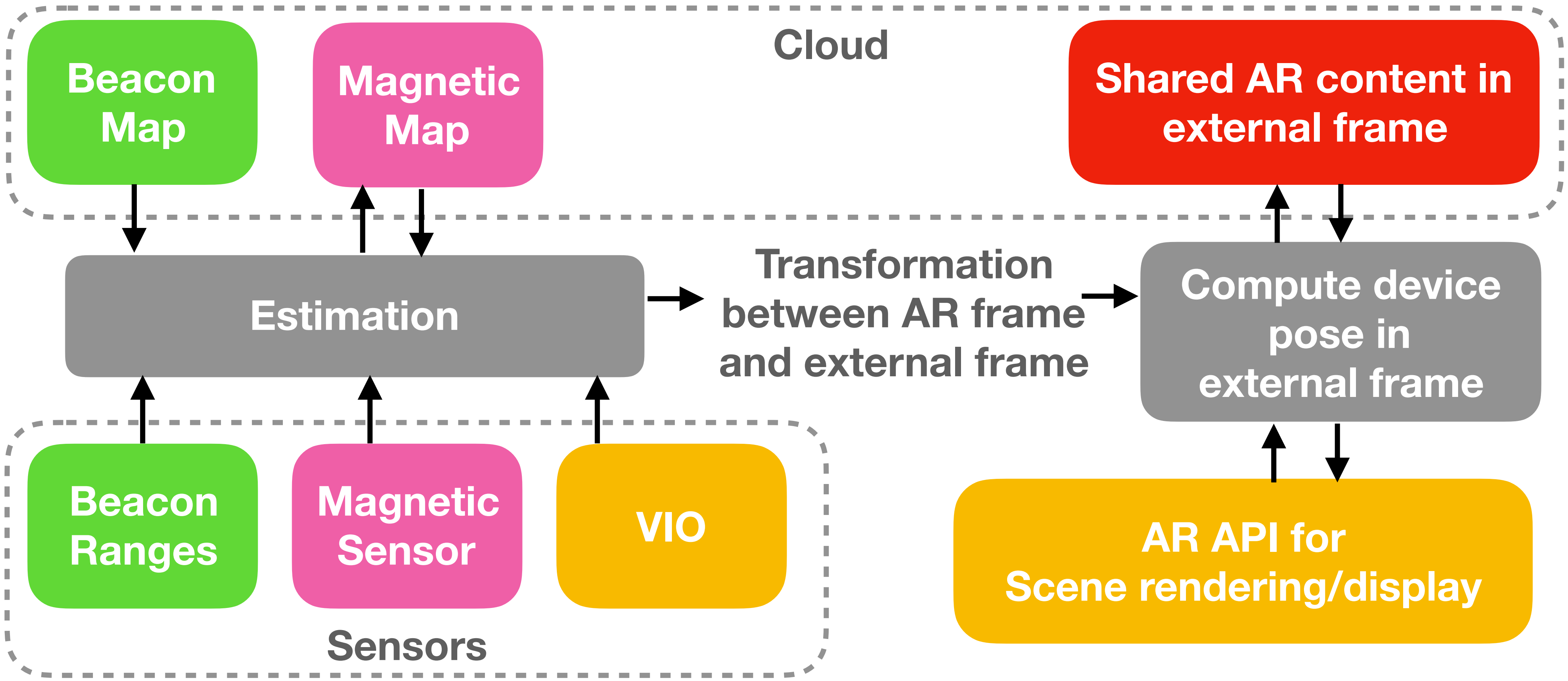


Overview



Orientation acquisition
Position acquisition
WiFi
Acoustic
Ultra-Wideband
BLE
Estimation
Mapping
Range-based
beacons
Deployment
Heterogenous sensing systems
Magnetic field
Camera
Floor plan
Inertial
MEMS
Beacon placement

Rapid and accurate
orientation and location acquisition



We can now support
persistent multi-user Augmented Reality applications

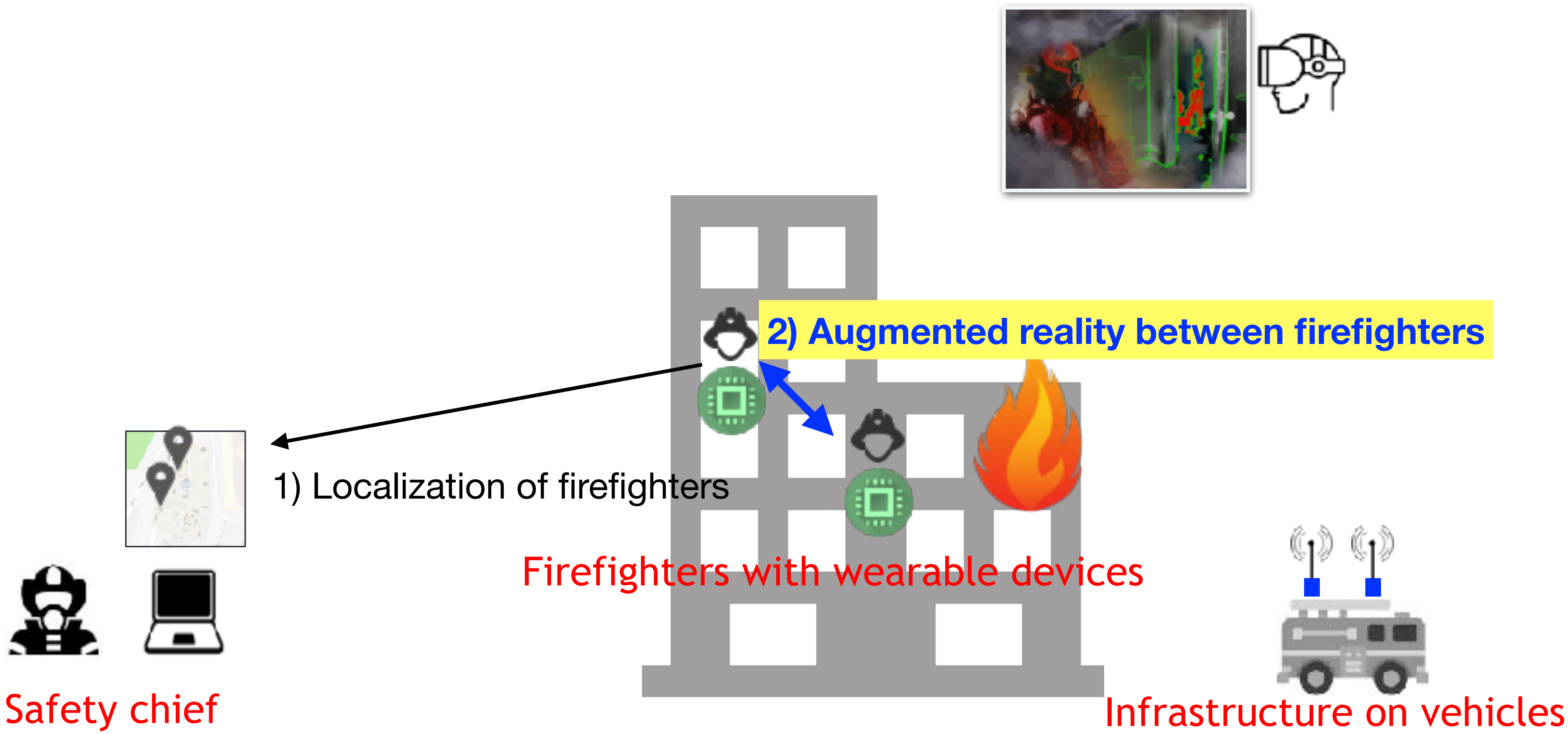
Application: Firefighter safety

Mobile Phone Localization with UWB and Visual Inertial Odometry

February 1st, 2019

https://youtu.be/8TOGCbijKSI

Application: Firefighter safety

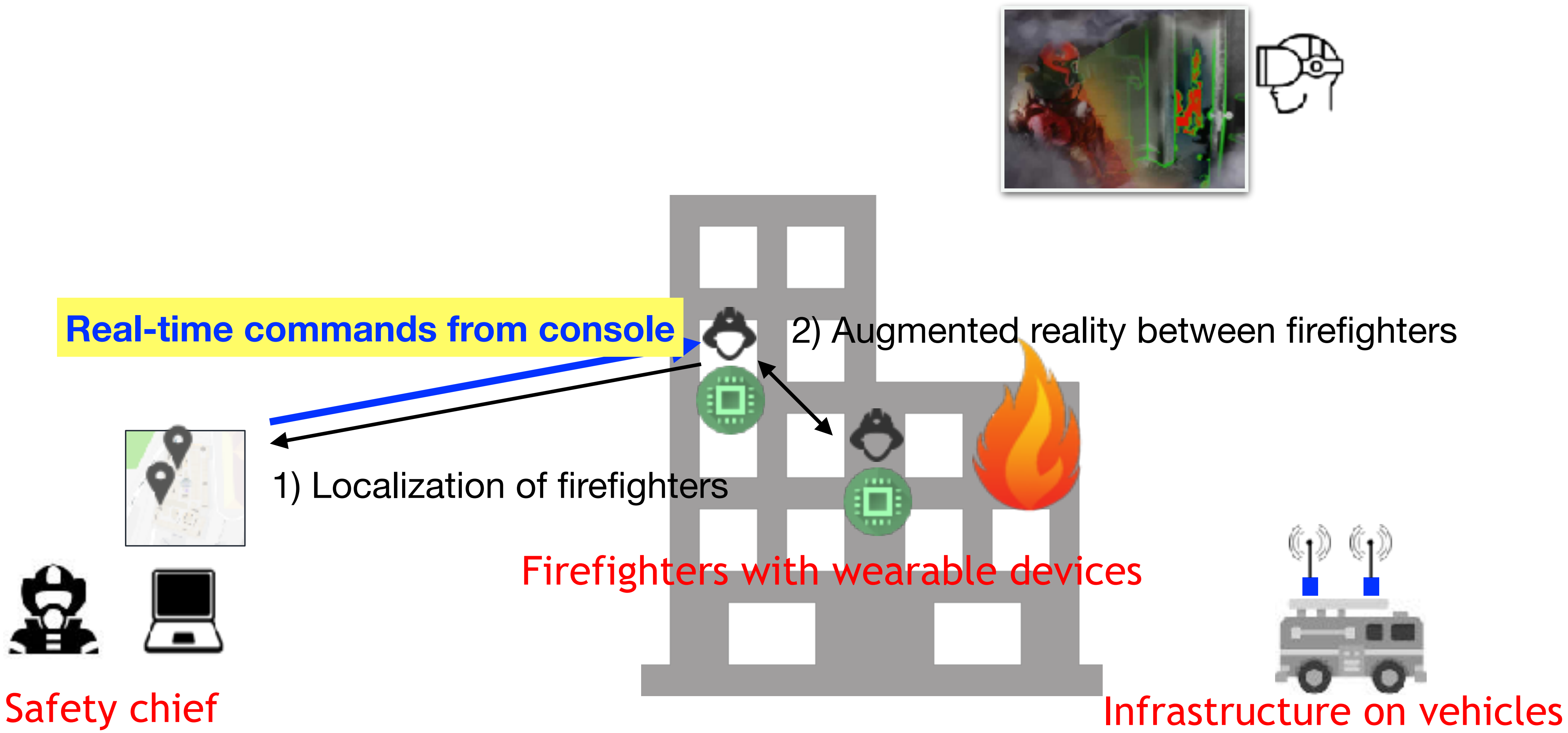


AR Tracking of UWB Tag

February 1st, 2019

https://youtu.be/1-28gaorJxA

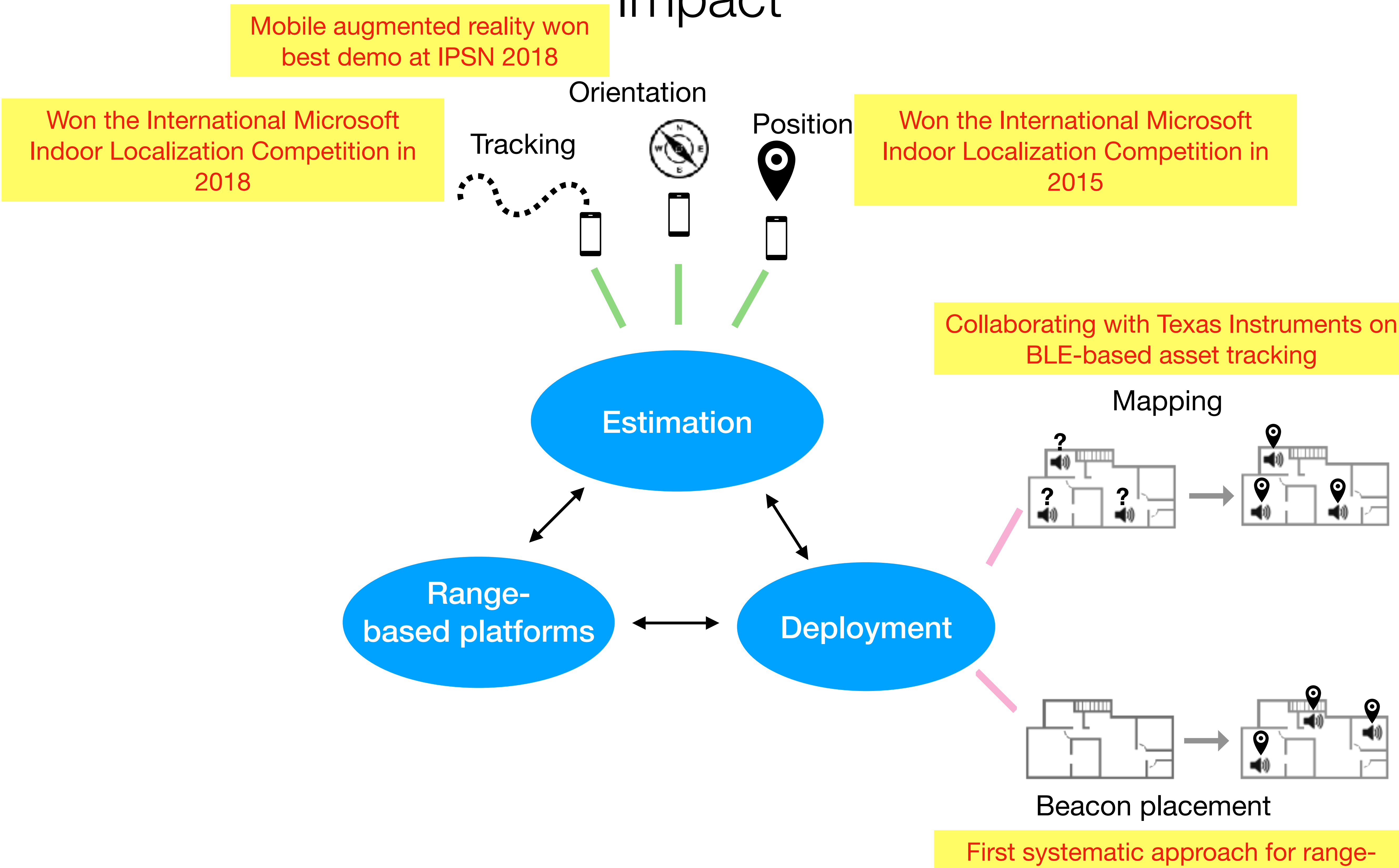
Application: Firefighter safety



Dropping AR Markers
from a Command Console
February 1st, 2019

https://youtu.be/iO3Vg641jKk

Impact



Mobile augmented reality won best demo at IPSN 2018
Won the International Microsoft Indoor Localization Competition in 2018
Orientation
Tracking
Position
Won the International Microsoft Indoor Localization Competition in 2015
Collaborating with Texas Instruments on BLE-based asset tracking
Mapping
Estimation
Range-based platforms
Deployment
Beacon placement
First systematic approach for range-based beacon placement

Publications

- Niranjini Rajagopal, John Miller, Krishna Kumar Reghu Kumar, Anh Luong, and Anthony Rowe, **Improving Augmented Reality Relocalization Using Beacons and Magnetic Field Maps**, (To appear in) The 10th International Conference on Indoor Positioning and Indoor Navigation, IPIN 2019

- Niranjini Rajagopal, Patrick Lazik, Nuno Pereira, Sindhura Chayapathy, Bruno Sinopoli and Anthony Rowe, **Enhancing Indoor Smartphone Location Acquisition using Floor Plans** , The 17th International Conference on Information Processing in Sensor Networks, IPSN 2018

- Niranjini Rajagopal, Sindhura Chayapathy, Bruno Sinopoli, Anthony Rowe, **Beacon Placement for Range-Based Indoor Localization**, The 7th International Conference on Indoor Positioning and Indoor Navigation, IPIN 2016

- Patrick Lazik, Niranjini Rajagopal, Oliver Shih, Bruno Sinopoli, Anthony Rowe, **ALPS: A Bluetooth and Ultrasound Platform for Mapping and Localization**, The 13th ACM Conference on Embedded Networked Sensing Systems, November, SenSys 2015

- Patrick Lazik, Niranjini Rajagopal, Bruno Sinopoli, Anthony Rowe, **Ultrasonic Time Synchronization and Ranging on Smartphones**, 21st IEEE Real-Time and Embedded Technology and Applications Symposium, Seattle, Washington, April 13th, RTAS 2015

Future directions

- Device discovery, time-synchronization and multiple access in an ecosystem with heterogeneous devices with unknown identities.
- Secure range-based localization systems that are robust to distance reduction and enlargement attacks at all layers of the localization stack.
- Tools for human-in-the-loop mapping with real-time feedback on the system performance.
- Low-level integration of sensors that is application-driven and accounts for power and computational resources.

Collaborators

Prof. Anthony Rowe

Anh Luong

John Miller

Krishna Kumar

Nuno Pereira

Patrick Lazik

Sindhura Chayapathy

Prof. Bruno Sinopoli

NIST National Institute of Standards and Technology U.S. Department of Commerce

NSF

TerraSwarm

CONIX RESEARCH CENTER

Texas Instruments

BOSCH

Thank you