Locating in Fingerprint Space:
Wireless Indoor Localization with Little Human Intervention

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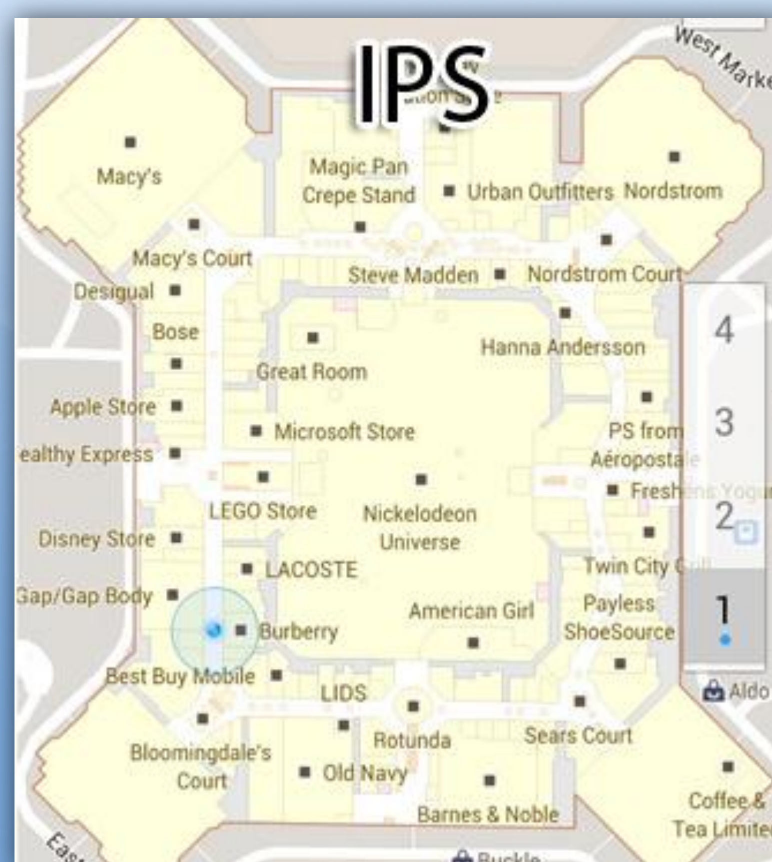
Outline

- Motivations
- Solutions
- Evaluations
- Discussions
- Conclusions

Global vs. Indoor Positioning System

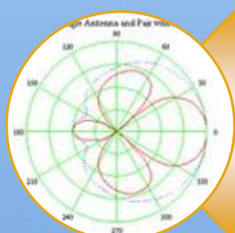
GPS dominates outdoor positioning.



IPS is of great importance and huge demand.

Various Indoor Localization Solutions

Fingerprinting



Modeling

- LPDL, ToA, TDoA, AoA, etc

Cost

Accuracy

Ubiquity

Fingerprinting-based method becomes the promising solution for ubiquitous IPS.

Fingerprinting-based techniques

- Two stages: Training and Operating

Training

- Site survey (a.k.a calibration)
- Associate fingerprints with locations.
- Constructing fingerprint database

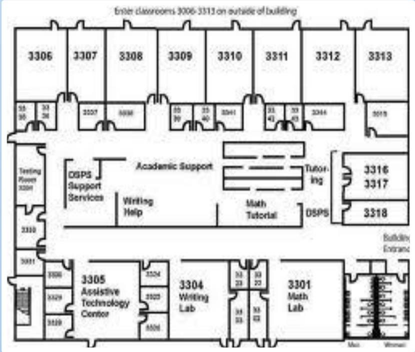
Fingerprint Database

Operating

- Query location with a sample
- Retrieve the fingerprint database the matched fingerprint

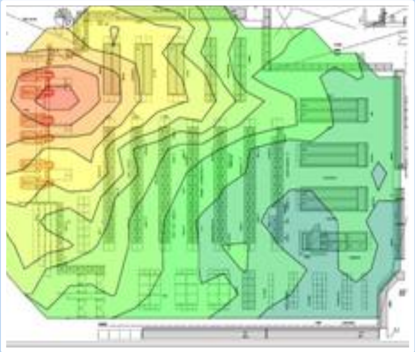
Site survey

- Engineers record the RSS fingerprints (e.g., WiFi signal strengths from multiple APs) at every location and accordingly build a fingerprint database (a.k.a. radio map).



Floor plan

Surveying



Radio map

Site survey

- Drawbacks:
  - Time-consuming and labor-intensive
  - Vulnerable to environmental dynamics
  - Limiting the availability of indoor localization and navigation services like Google Maps 6.0

In the end of 2011, Google released Google Map 6.0 that provides indoor localization and navigation available only at some selected airports and shopping malls in the US and Japan. The enlargement of applicable areas is strangled by pretty limited fingerprint data of building interiors.

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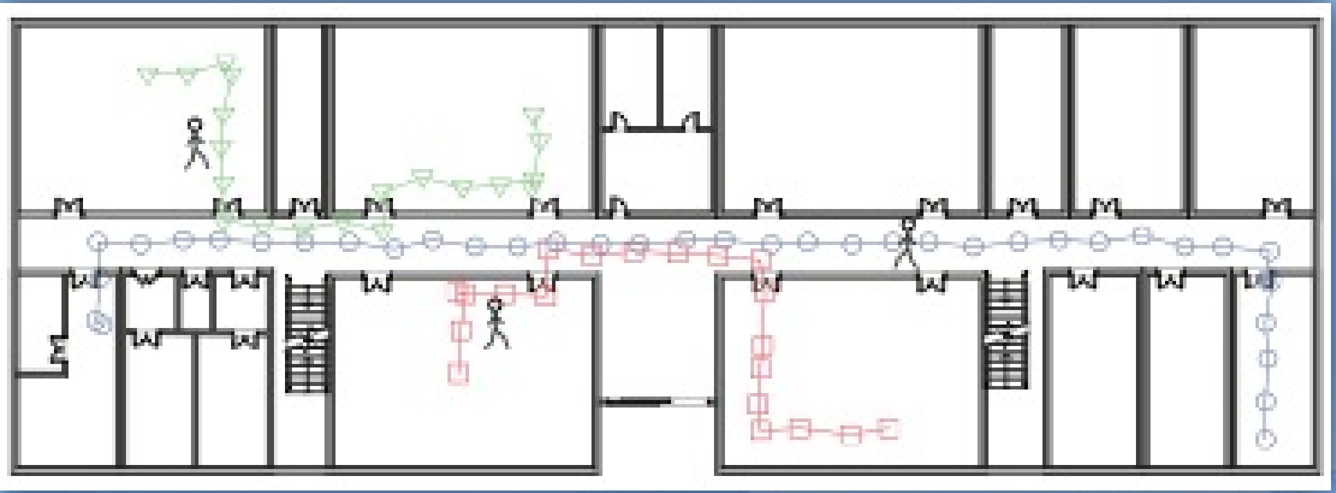
Our Basic Ideas

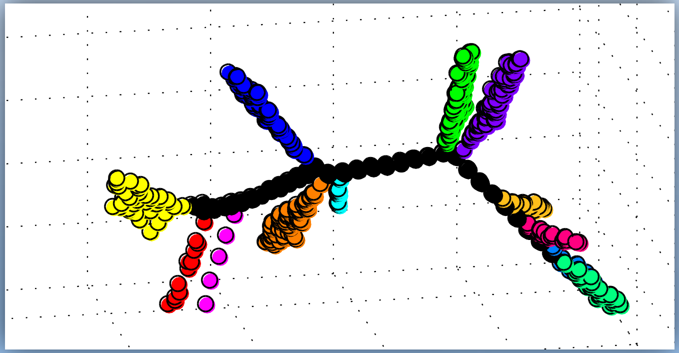
Crowdsourcing the site-survey by mobile users.

- User movements, i.e., moving paths, indicate the geographically connections between separated RSS fingerprints.

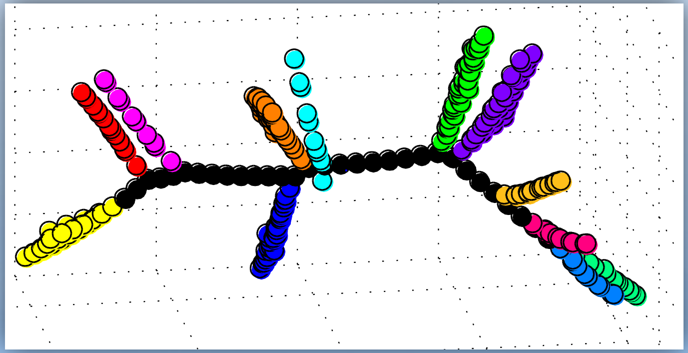


User moving paths in a building

Our Basic Ideas



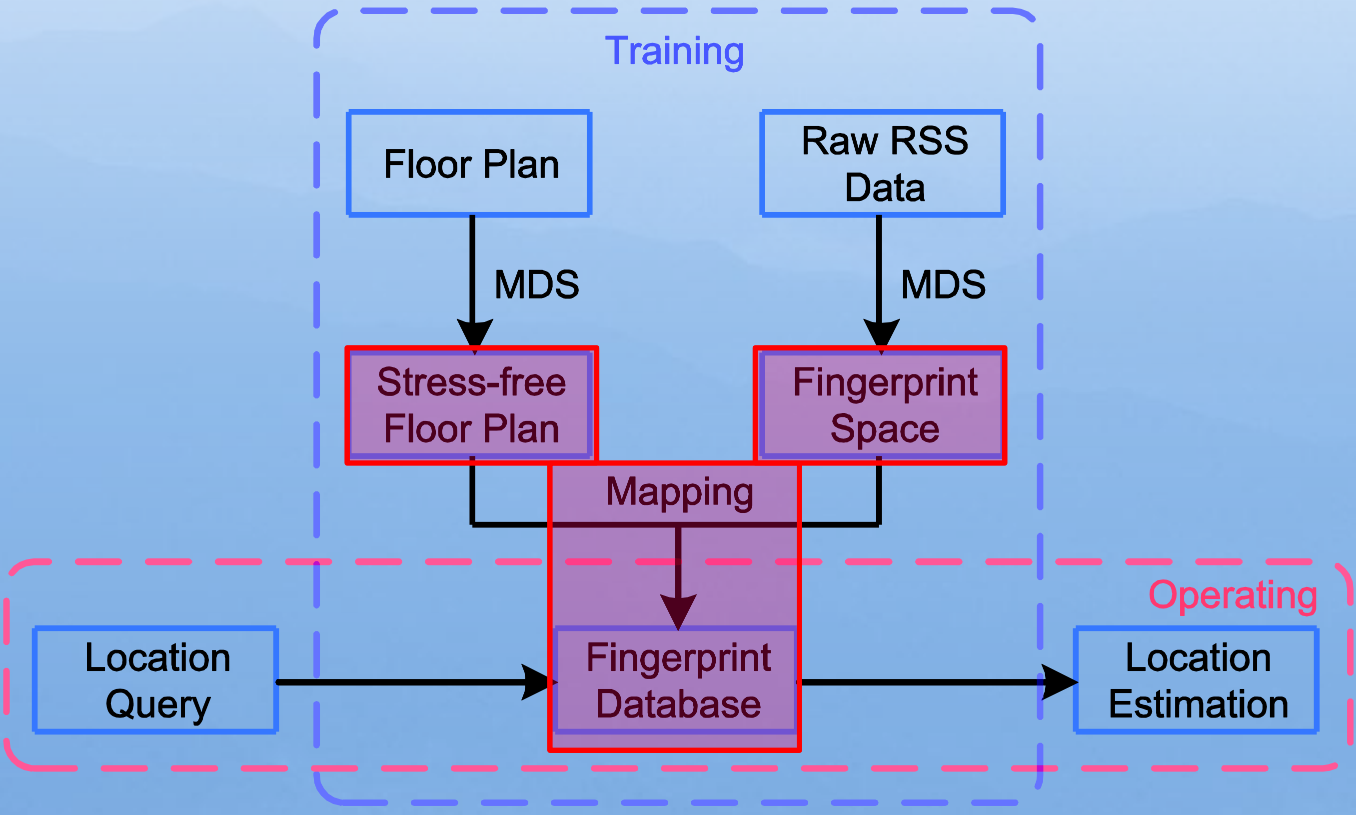
Connected fingerprints form a high dimension ***fingerprint space***, in which the distances among fingerprints, measured by user mobility, are preserved.



Reform the floor plan to the ***stress-free floor plan***, a high dimension space in which the distance between two locations reflects their walking distances.

Spatial similarity of stress-free floor plan and fingerprint space enables fingerprints labeled with real locations, which would be done only by site survey previously.

LiFS Design



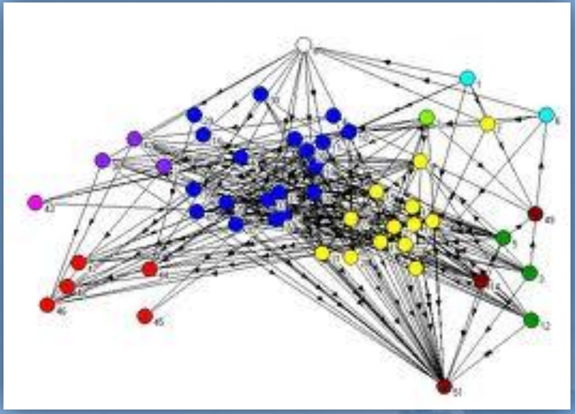
System Architecture

Multi-dimensional Scaling

- Multidimensional scaling (MDS) is a set of statistical techniques used in information visualization for exploring similarities or dissimilarities in data.
- An MDS algorithm starts with a matrix of item-item dissimilarities, then assigns a location to each item in *d*-dimensional space, where *d* is specified a priori.

$$\Delta := \begin{pmatrix} \delta_{1,1} & \delta_{1,2} & \cdots & \delta_{1,I} \\ \delta_{2,1} & \delta_{2,2} & \cdots & \delta_{2,I} \\ \vdots & \vdots & & \vdots \\ \delta_{I,1} & \delta_{I,2} & \cdots & \delta_{I,I} \end{pmatrix}$$

Distance matrix



d-dimensional space

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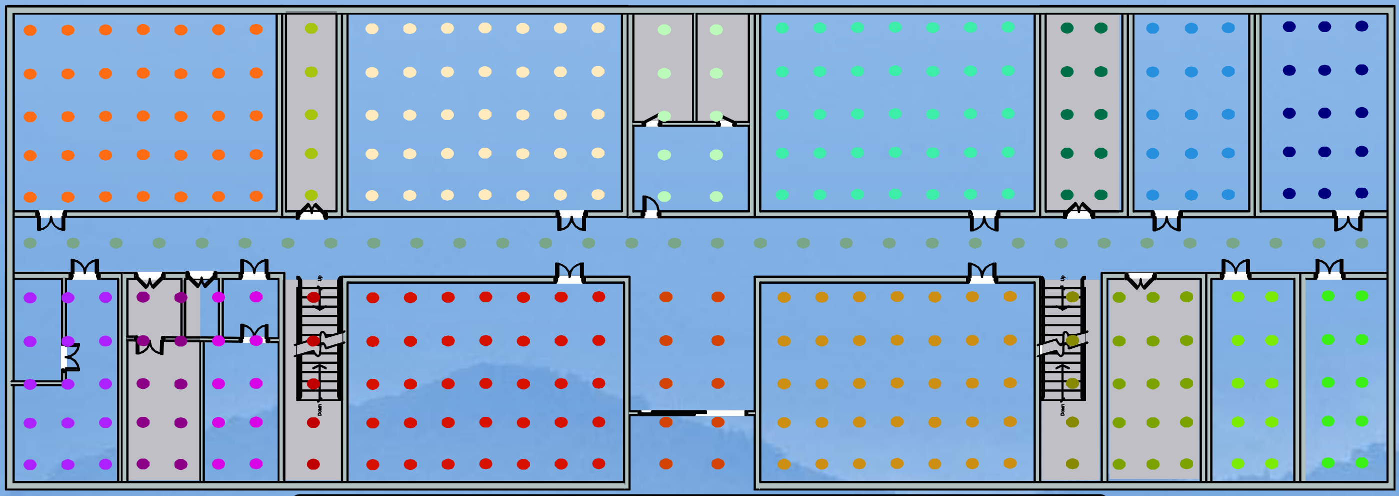
Stress-free Floor Plan

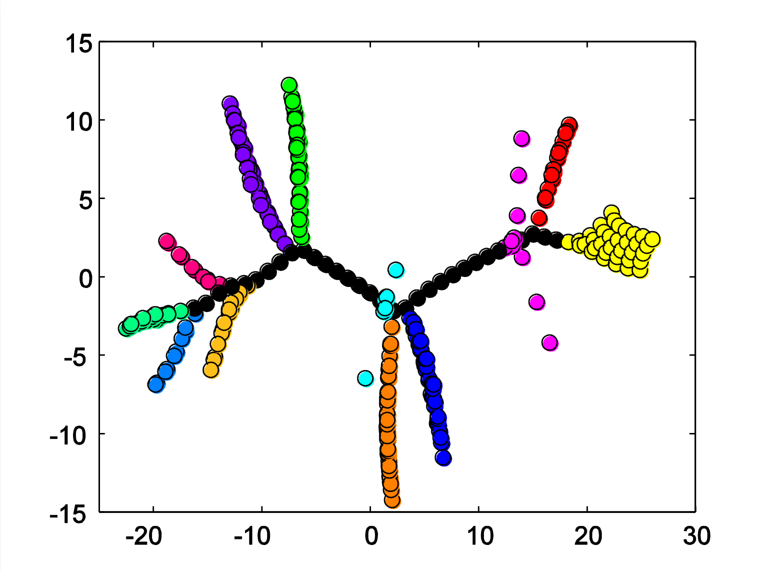
- Sampling the floor plan with a unit length (=2m).
- Geographical distance between two locations does not necessarily equal to their walking distance.
- Due to the constraints (walls, doors, and other obstacles) imposed by floor plan itself.



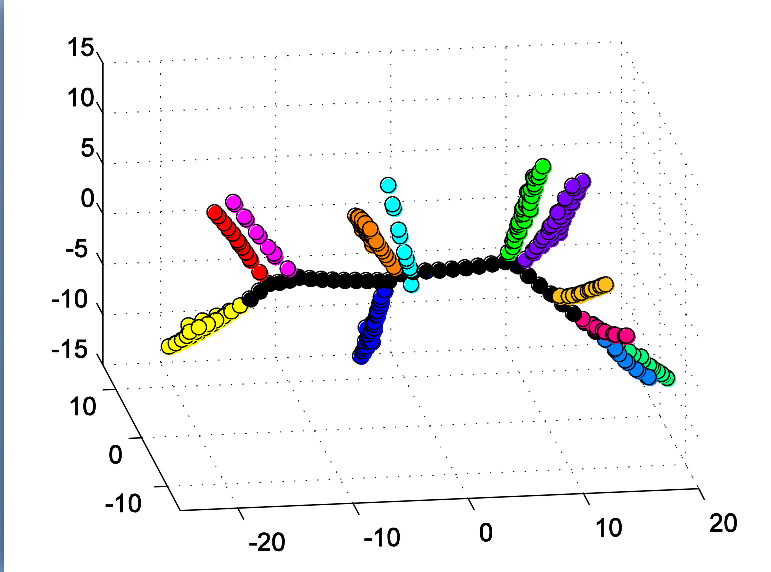
Floor plan with sample locations.

Stress-free Floor Plan

- Construct stress-free floor plan in high dimension Euclidean space using MDS.



2D stress-free floor plan.



3D stress-free floor plan.

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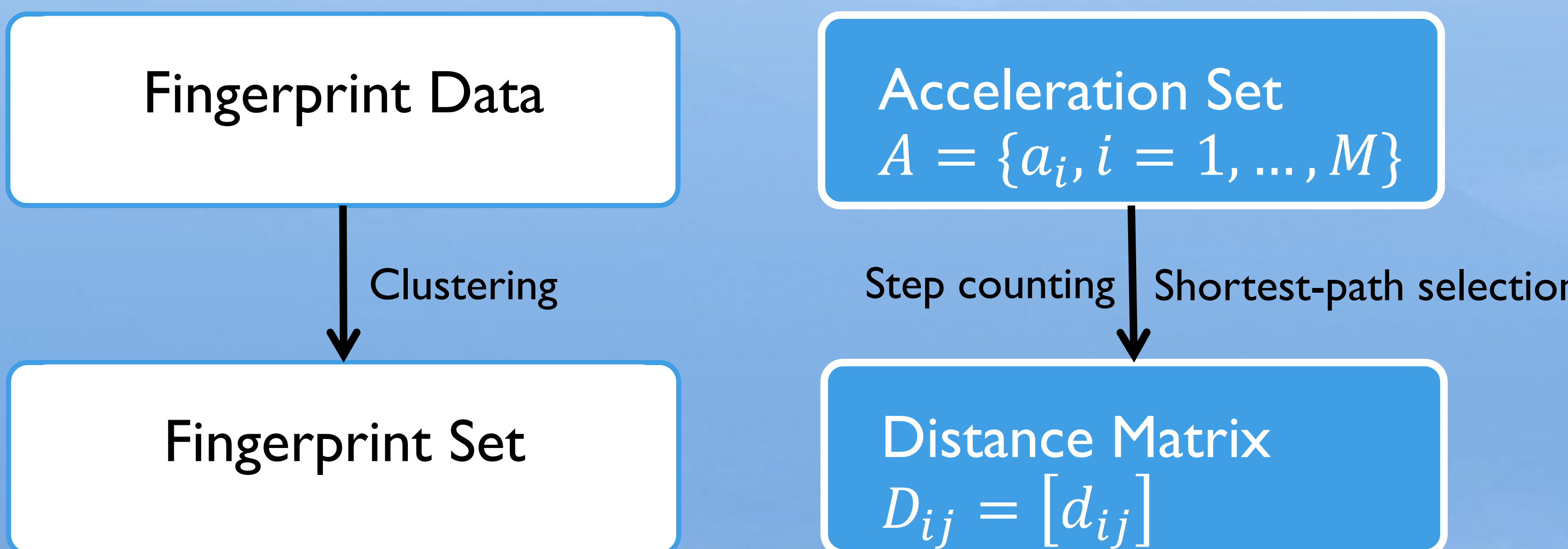
Data Collection

- Collect fingerprints and users' mobility data (only acceleration in LiFS) during their routine indoor movements.



Clustering Fingerprints

- Clustering
  - Cluster fingerprints from the same or close locations
  - Parameter is determined by fingerprint samples collected at a given location (when phones are not moving).

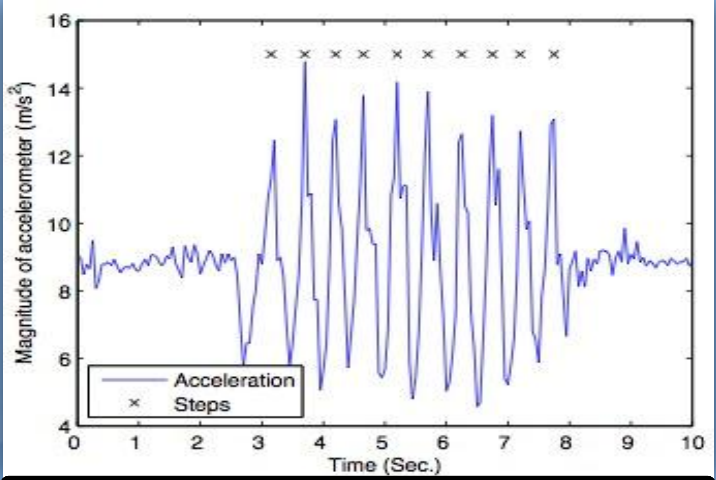
$$f_i = [s_1, s_2, \dots, s_m], f_j = [t_1, t_2, \dots, t_m]$$

$$\delta_{ij} = \left\| f_i - f_j \right\|_1 = \sum_{k=1}^{m} |s_k - t_k|$$

If $\delta_{ij} > \epsilon$, treat f_i and f_j as different fingerprint points.

Distance Matrix

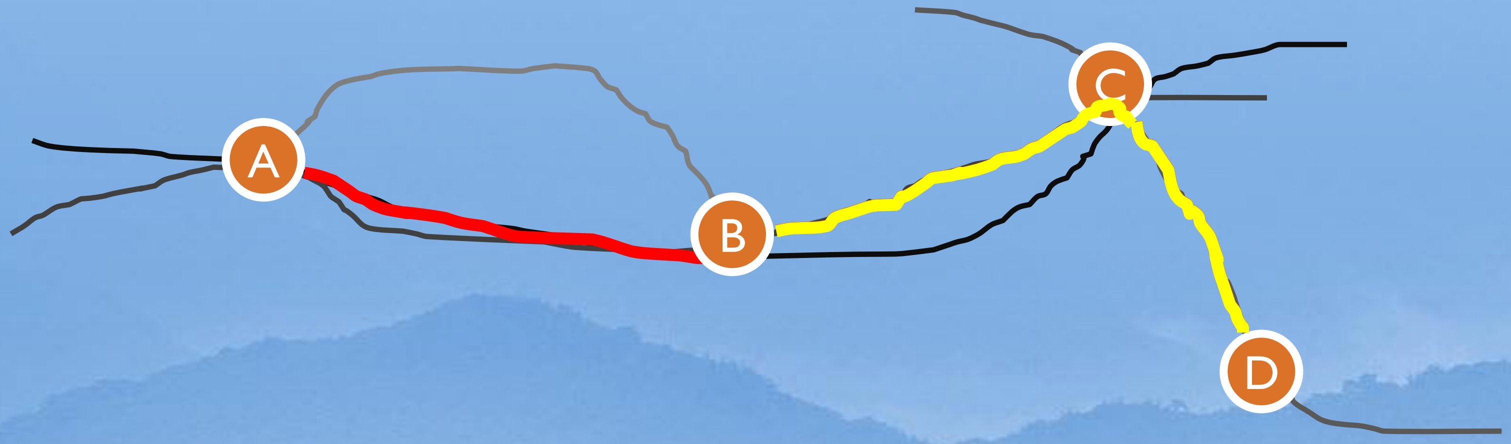
- From acceleration to distance
  - Theoretically, by dead-reckoning (integrating acceleration twice w.r.t. time). Accumulation Error
  - We count footsteps, using a local variance threshold method. Accurate



Acceleration of 10 steps

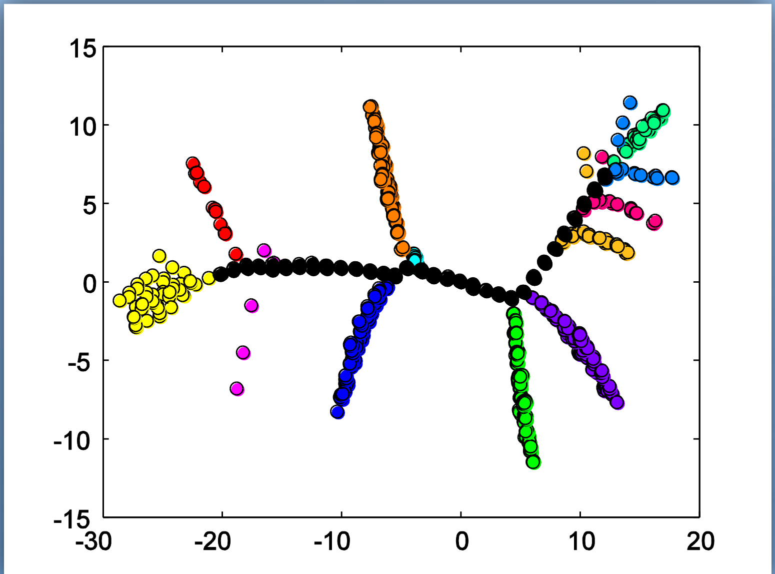
Distance Matrix

- Shortest-path selection
  - More than one path passing through two fingerprints
  - Simply select the shortest one as the distance between them.
  - Floyd-Warshall algorithm to compute all-pair shortest paths of fingerprints.

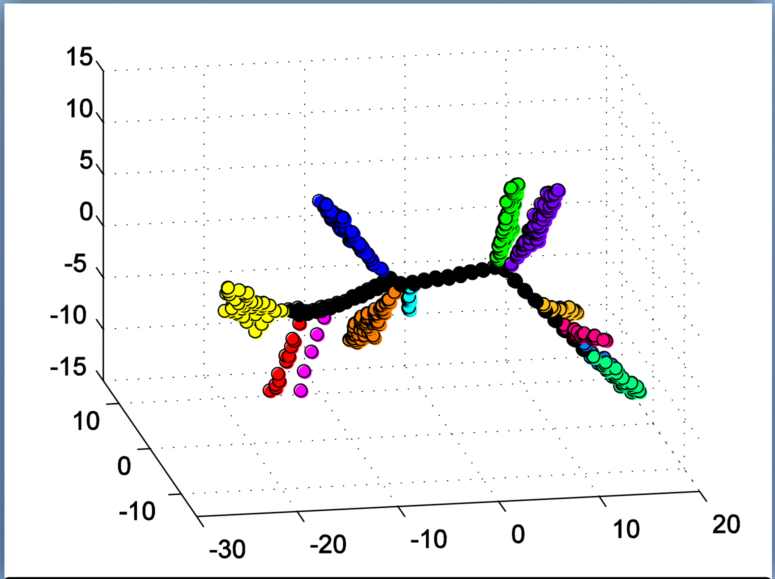


Fingerprint Space Construction

- According to distance matrix, transform all points in to a d-dimension Euclidean space, i.e., the fingerprint space, using MDS.



2D fingerprint space.



3D fingerprint space.

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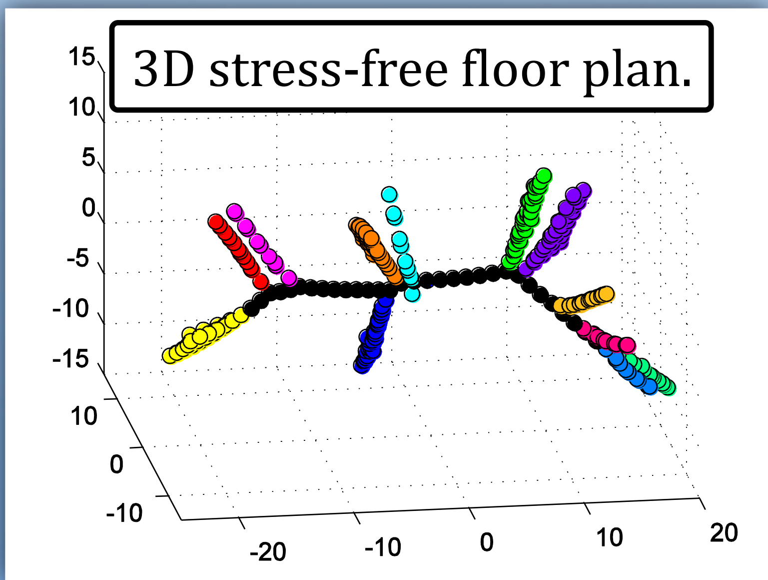
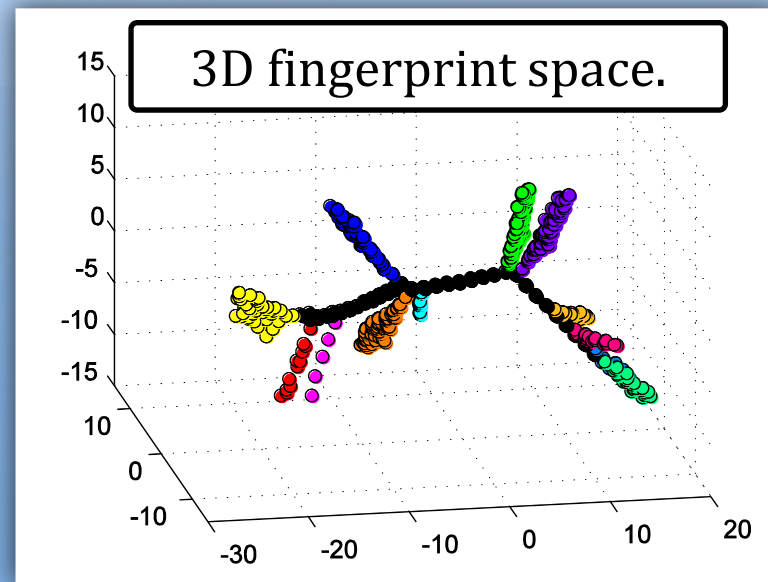
Mapping

- Mapping the fingerprint space to the stress-free floor plan to obtain fingerprint-location database.





The mapping seems easy for humans, for computers, however, it is non-trivial.

Mapping

- Our Solution: Mapping corridors first, then rooms.

- Mapping
  - Feature Extraction
    - Corridor Recognition
    - Room Recognition
  - Space Transformation
    - Reference Point Mapping
    - Floor-level Transformation
    - Room-level Transformation

Corridor Recognition

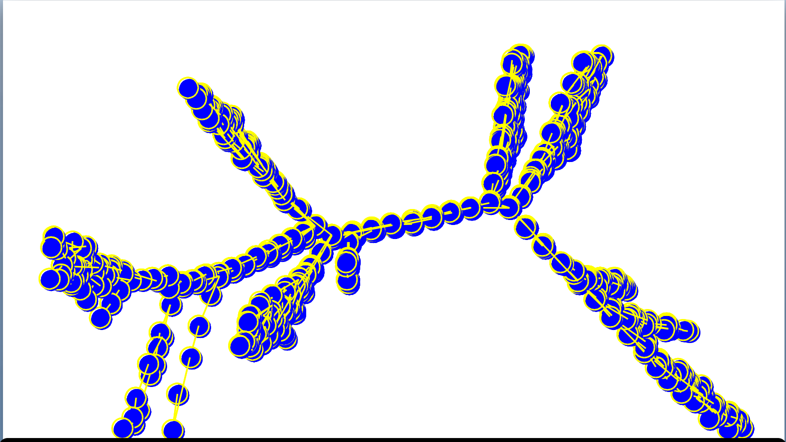
- Build the Minimum Spanning Tree(MST) that connects all fingerprints in F.
- Corridors F_c: Fingerprints collected at corridors reside in core positions in fingerprint space, which have relatively large centrality values.

Betweenness centrality

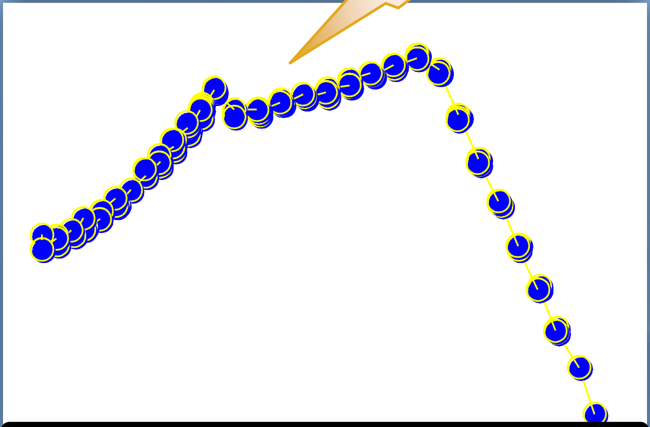
$$B(v) = \sum_{s \neq t \neq v \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

- Rooms F_{R_i}: Remove corridor points from the fingerprint space and cluster the remaining points into k clusters

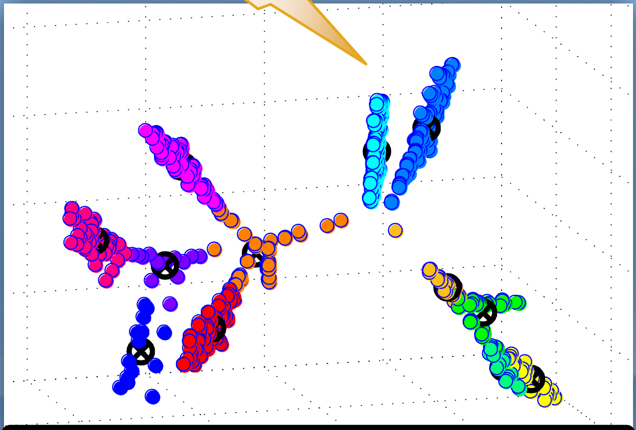
Corridor Recognition



MST of 3D fingerprint space.



MST of corridor points.



Clustering rooms

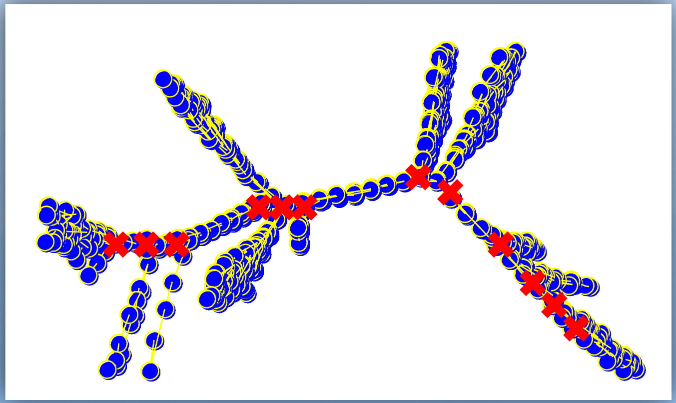
Reference Point Extraction

- Reference Point Mapping: Find keys from the doors!

Finding the key reference points

$$(\hat{f}_i, \hat{f}_i') = \underset{f \in F_{R_i}, f' \in F_c}{\arg\min} \|f - f'\|,$$

$$F_D = \{\hat{f}_i', i = 1,2, \dots, k\}$$



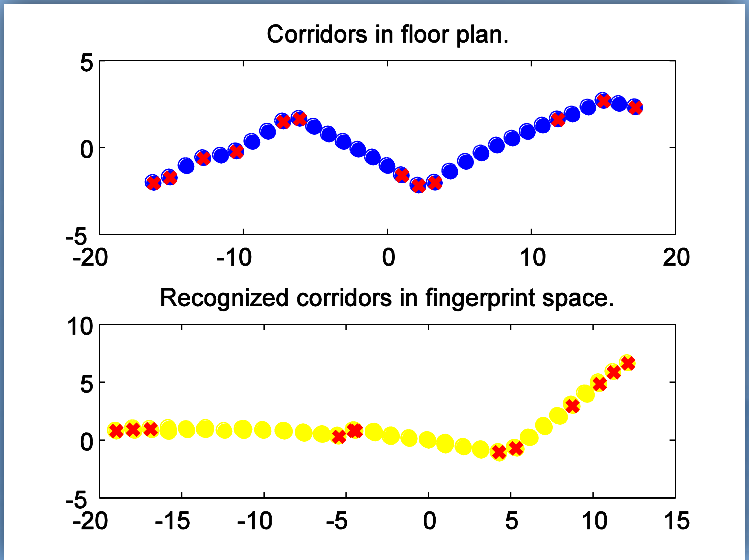
- Find the set of corresponding points $P_D = \{p_1, p_2, \dots, p_k\}$ in the floor plan, which denote the set of sample locations in the corridor that are the closest to every door.

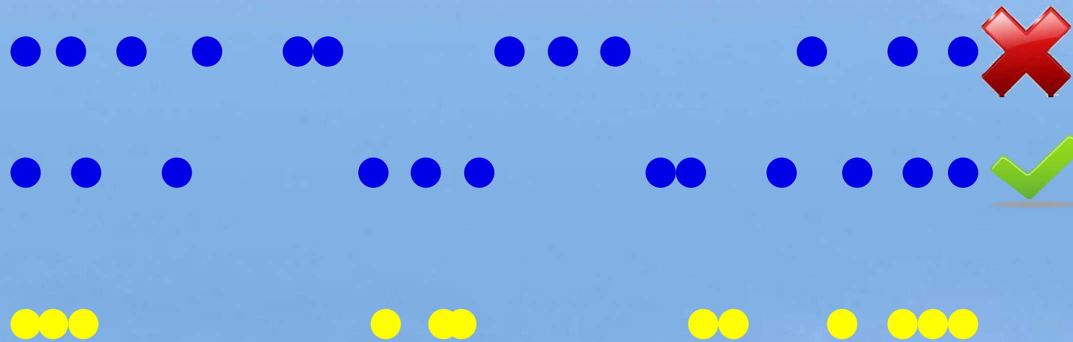
Reference Point Mapping

- Mapping F_D to P_D

Reference point mapping

$$\sigma_1 : f_i \mapsto p_i;$$
$$\sigma_2 : f_i \mapsto p_{k-i+1};$$



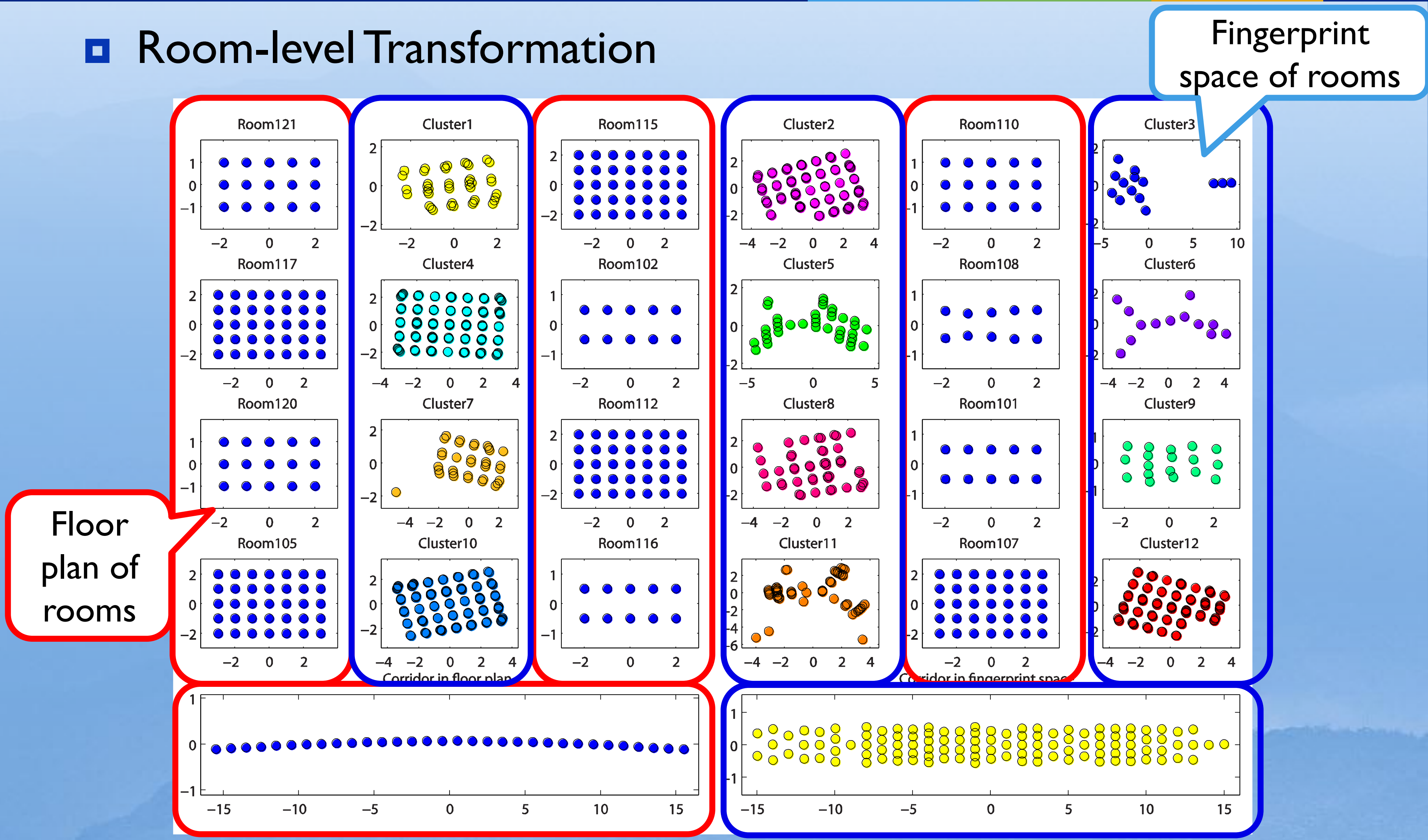


Space Transformation

- Room-level Transformation
  - Using MDS, the fingerprints from one room are transformed to d-dimension space.
  - In the same way, the sample locations from each room are mapped to d-dimension stress-free floor plan.
  - Using doors and room corners as reference points, the fingerprints and sample locations are linked determinately by the transformation matrix above discussed.

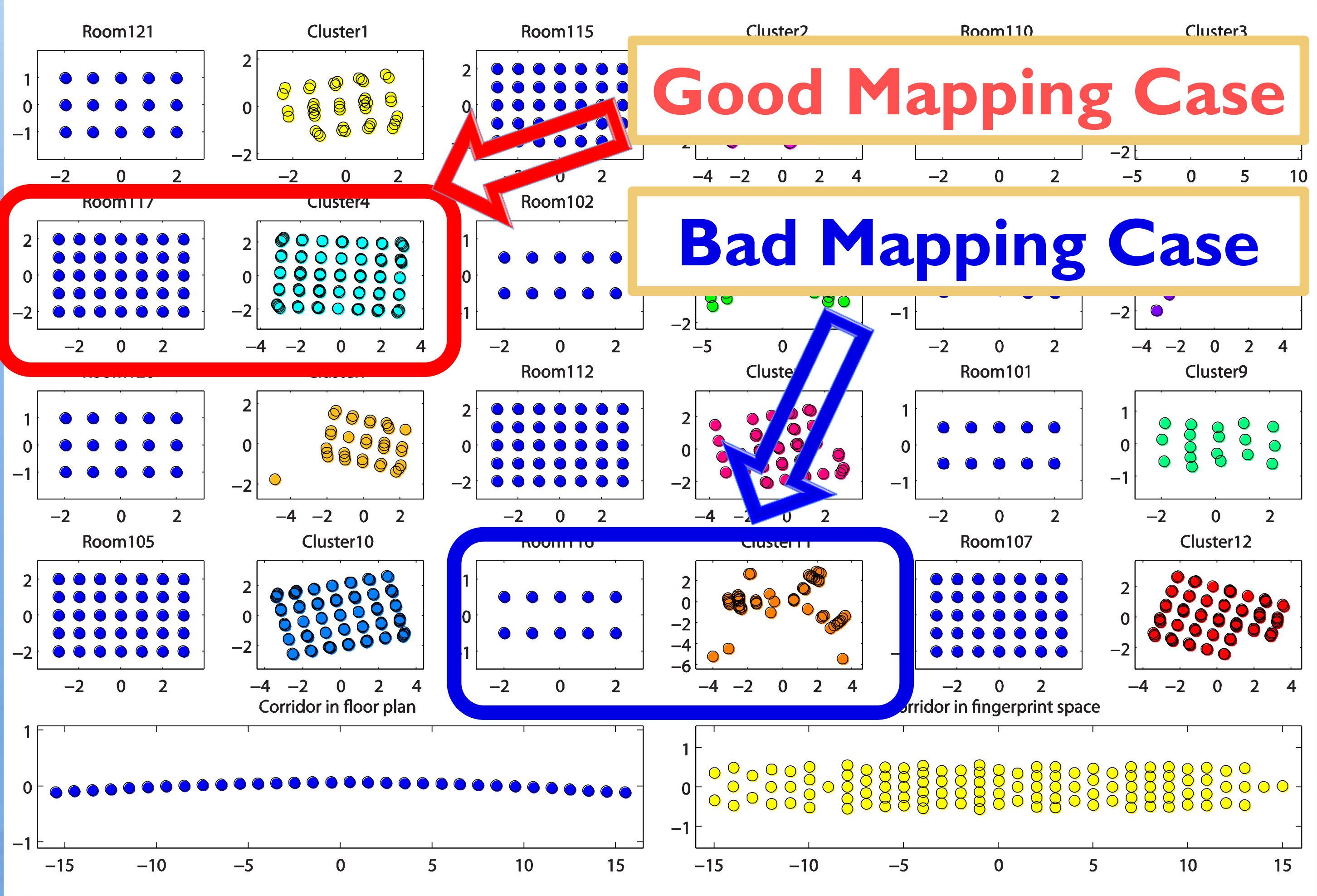
Space Transformation

- Room-level Transformation



Space Transformation

- Room-level Transformation



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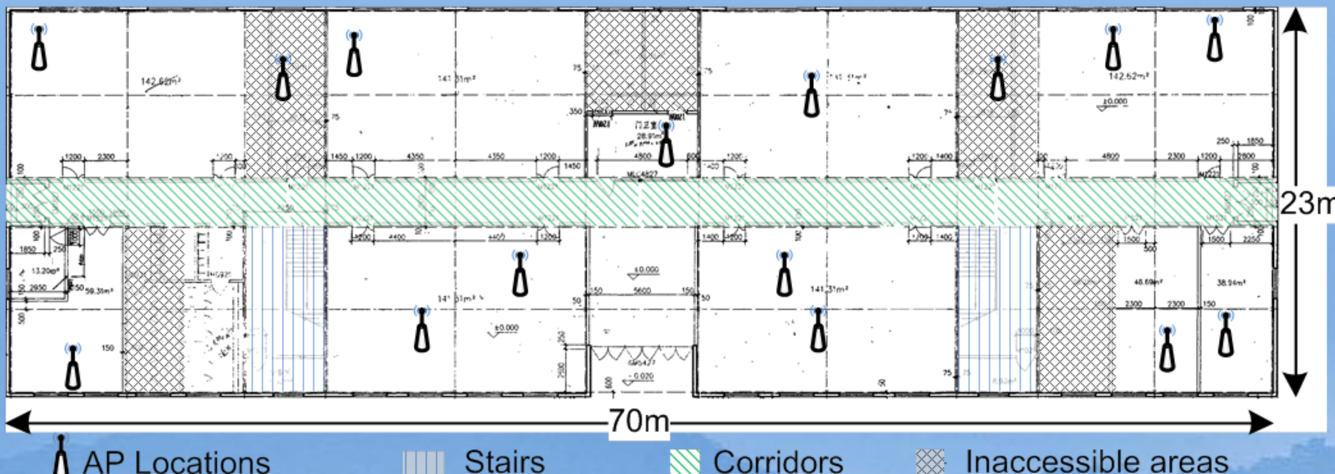
Evaluations

- We implemented LiFS on Android phones (Google Nexus S).
- We conducted experiments in a typical office building in Tsinghua University.
- Size of 1600m^2, with 5 large rooms of 142m^2, 7 small ones with different sizes and the other 4 inaccessible rooms.
- Totally m= 26 APs are installed (some with known locations).



Floor plan of the experiment field.

Evaluations

- We sample the floor plan every $4m^2$ and obtain 292 location points over all accessible areas.
- We collect 600 traces by asking 4 volunteers to walk through areas of interests for 5 hours.
- For each trace, record WiFi with period of about 4 seconds and accelerations with frequency of about 50Hz.

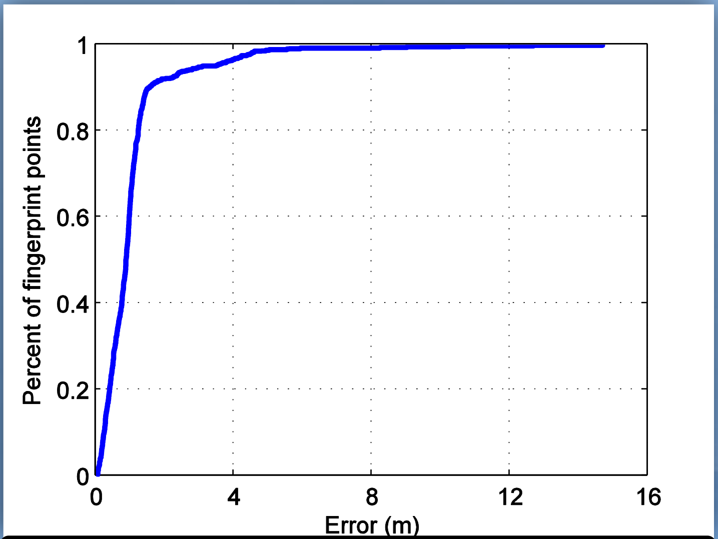
- Metrics

$$Location\_Error = \|L(f) - L'(f)\|$$

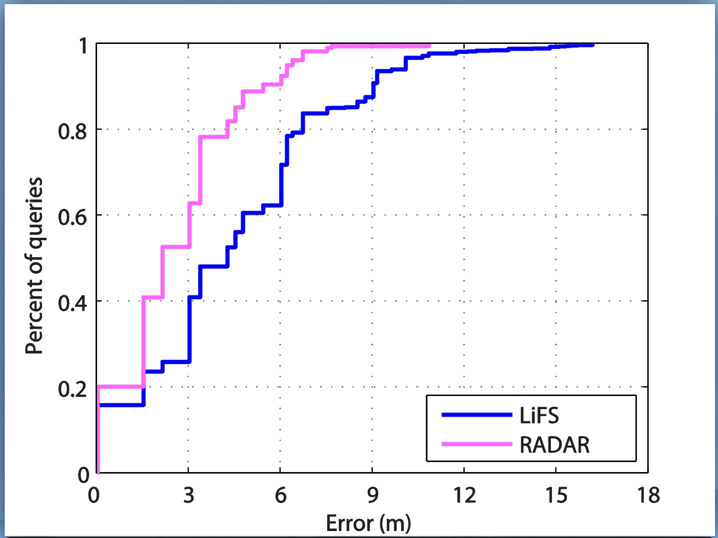
$$Room\_Error = \frac{1}{N}\sum_{f \in F} I(R(f) \neq R'(f))$$

Performance

- The location error of up to 96% points is lower than 4m. In addition, the average mapping error of is only 1.33m.
- The average localization error of LiFS is 5.88m, larger than RADAR (3.42m) which needs site survey.
- The room error rate is only 10.91%.



CDF of mapping error.



CDF of localization error.

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Discussion

- Applicability
  - LiFS fits a majority of office buildings but may fail in large open environments, such as hall, atrium, gymnasium, or museum.
  - Reference points (e.g., last reported GPS, elevator, stairs, or other recognizable landmarks) are beneficial to improve the applicability of LiFS in large open environments.

Discussion

- Comparison with SLAM
  - Simultaneous Localization and Mapping (SLAM)
  - Standard SLAM relies on
    - 1) the ability to sense and match discrete entities such as landmarks or obstacles detected by sonar or laser range-finders;
    - 2) precisely controlled movement of robots to depict discovered environments.
- LiFS is free of dead-reckoning and only uses accelerometers to count walking steps.

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Conclusion

- Summarizing the advantages of LiFS
  - No need to site survey.
  - No extra infrastructure or hardware.
  - Independence from AP or GPS information.
  - Free of erroneous dead-reckoning.
  - No explicit participations on users.

Conclusions

- We design LiFS, an indoor localization system based on off-the-shelf WiFi infrastructure and mobile phones.
- By exploiting user motions from mobile phones, we successfully remove the site survey process of traditional approaches.
- Real experiment results show that LiFS achieves comparable location accuracy to previous approaches even without site survey.

Any Questions?

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