Contact Tracing for Healthcare Workers in an Intensive Care Unit

Jingwen Zhang

09/21/2023

CPSL
Cyber-Physical Systems Laboratory

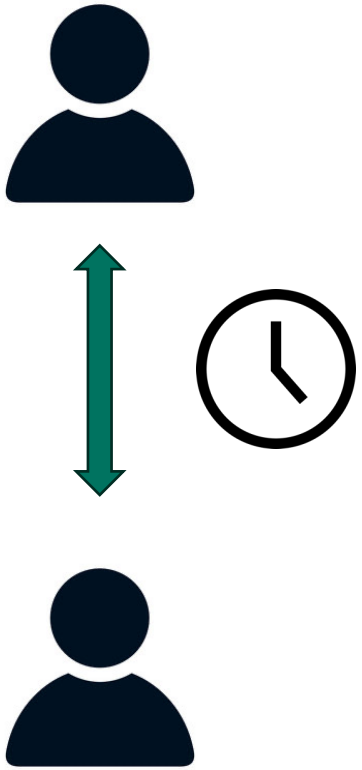
Washington University in St. Louis

Contact Tracing for Covid-19

CPSL
Cyber-Physical Systems Laboratory

Contact tracing (CT) is an effective method to prevent the spread of COVID-19

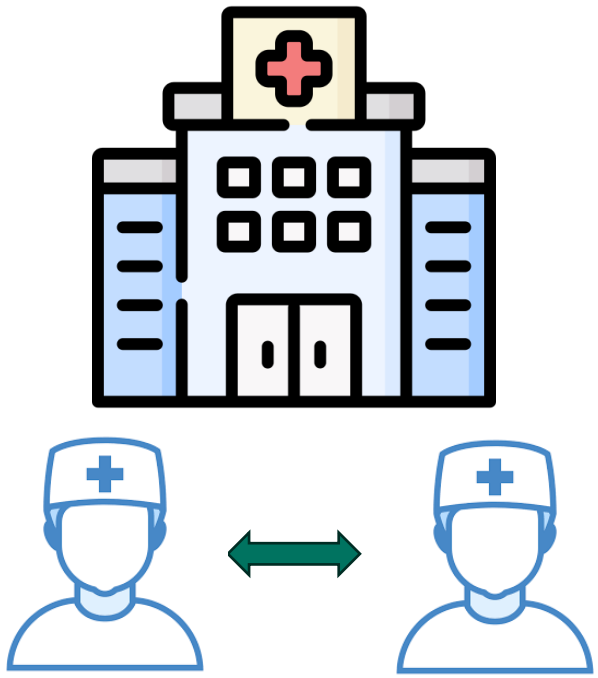
- What is **contact tracing:** identifying, assessing, and managing the people who had close contact with the infected person
- What is **close contact:** “being within 6 feet of an infected person for a total of 15 minutes or more over a 24-hour period”



Why Contact Tracing System

CPSL
Cyber-Physical Systems Laboratory

- Typically, contact tracing is done manually
  - Time consuming and laborious (up to 3 days [1])
  - Inaccurate/Incomplete memory
- **Goal:** an automated contact tracing systems for healthcare workers
  - Hospital environment
  - Clinician-to-clinician close contact (excluding patient-to-clinician contact)

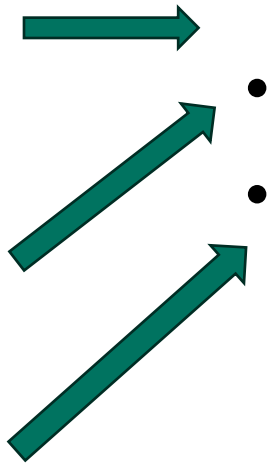


[1] Luca Ferretti, Chris Wymant, Michelle Kendall, Lele Zhao, Anel Nurtay, Lucie Abeler-Dörner, Michael Parker, David Bonsall, and Christophe Fraser. 2020. Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. Science 368, 6491 (2020), eabb6936.

Devices for CT in the ICU

CPSL
Cyber-Physical Systems Laboratory

- Smartphones
  - Bluetooth Low Energy (BLE)
  - Proximity detection based on signal strength [2]
- Camera
  - Computer vision
- UWB beacons
  - Time difference of arrival, angle of arrival…
  - Better accuracy
- BLE beacons 



- Infectious concerns
- Privacy concerns
- Expensive

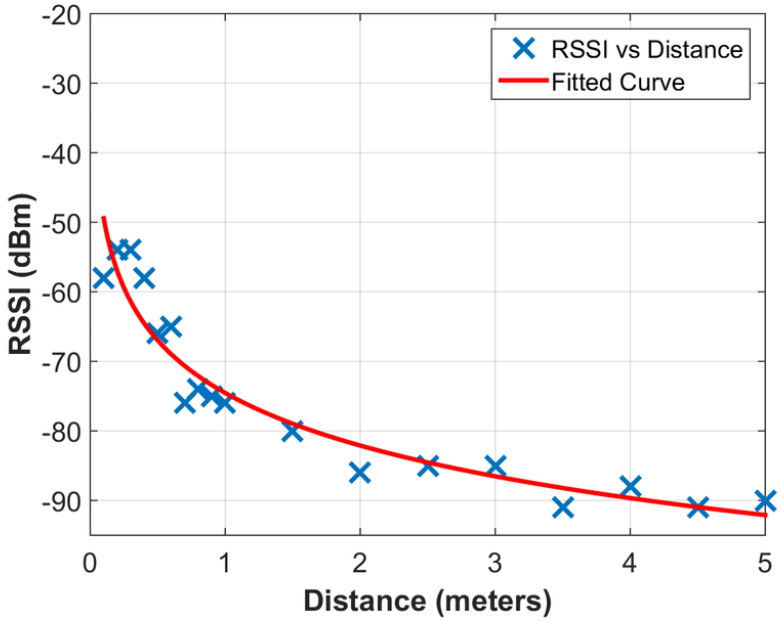
[2] 2020. Privacy-Preserving Contact Tracing-Apple and Google. Retrieved July23, 2020 from https://covid19.apple.com/contacttracing

BLE Signal

CPSL
Cyber-Physical Systems Laboratory

- BLE Received Signal Strength Indicator (RSSI)
- Free-space path loss (ideal conditions with free space, no obstacles or reflections:

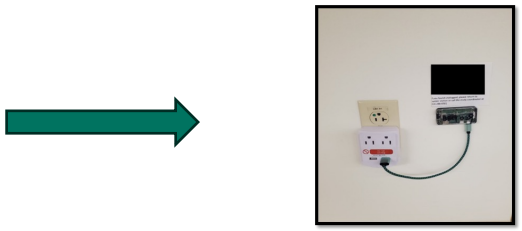
$$Distance = 10^{((RSSI_0 - RSSI) / (10 * n))}$$



$RSSI_0$: RSSI at reference location (1m)
n: depends on environment (~2)



Beacon (Transmitter)



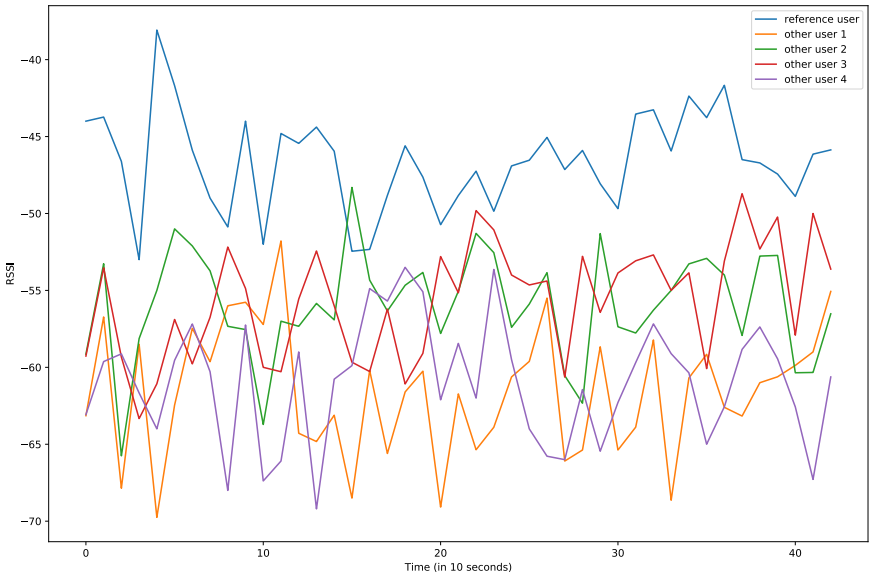
Anchor (Receiver)

Noisy BLE Signal

CPSL
Cyber-Physical Systems Laboratory

beaconConfigStats

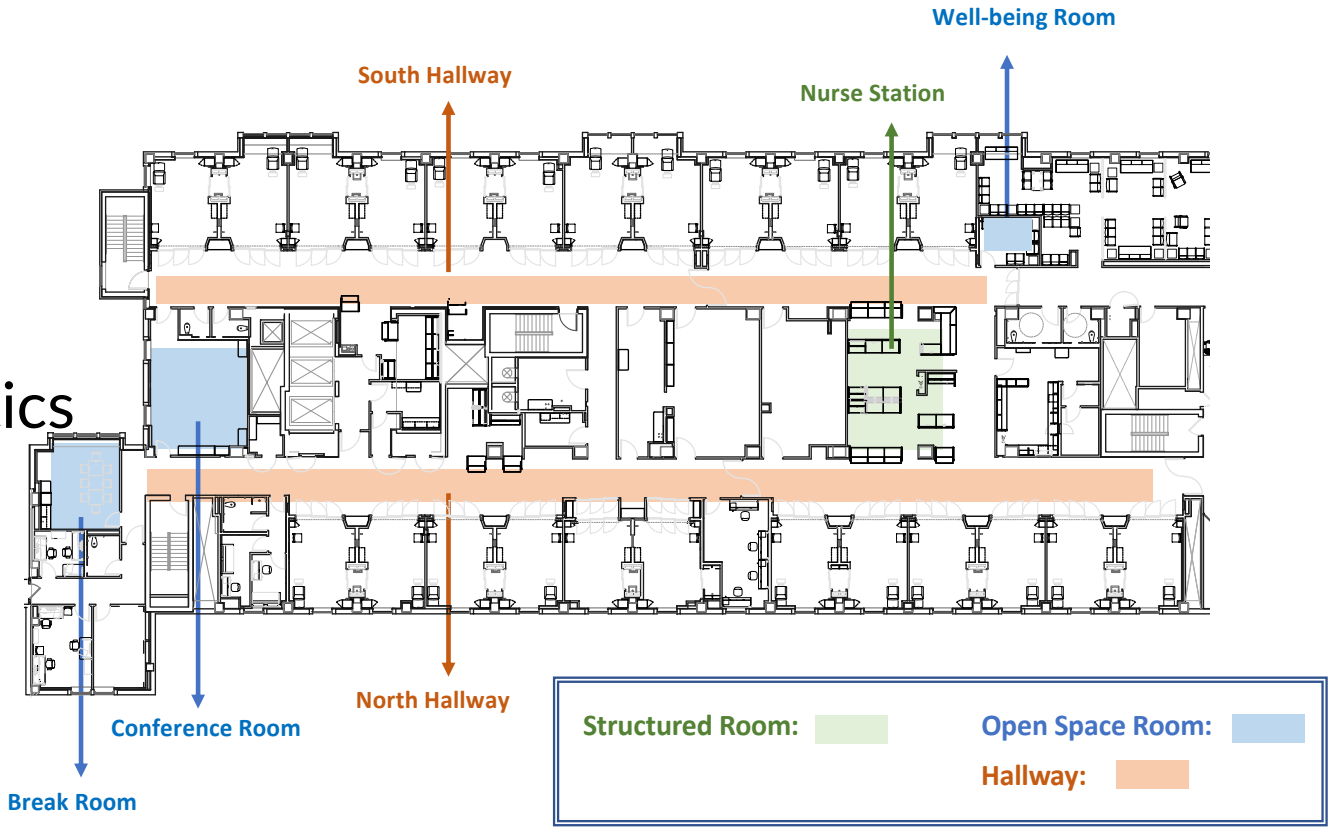
_id	obstacle	distance	power	orientation	mean	min	max	median	std
601c6b9ea4847d9ad4cd9ddc	NONE	0m	0dBm	North	-46.45	-50	-31	-48	4.70637865
601c6bdf33e4f0c6da0a885a	NONE	0m	-4dBm	North	-49.15	-53	-34	-51	4.946579027
601c6c1366870d8cf8fd6968	NONE	0m	-8dBm	North	-51.45	-57	-36	-52	5.173023245
601c6c7b2e3be93d64f5342e	NONE	1m	-8dBm	North	-55.51666667	-62	-40	-59	7.188719192
601c6c8b2e3be93d64f5346b	NONE	1m	-8dBm	East	-75.01666667	-90	-54	-74	7.799373436
601c6c9c2e3be93d64f534a8	NONE	1m	-8dBm	South	-76.7	-96	-57	-74	7.966667849
601c6cae2e3be93d64f534e5	NONE	1m	-8dBm	West	-63.06666667	-69	-47	-63	5.721996412
601c6ce630a5b9238901e5ea	NONE	1m	-4dBm	North	-59.4	-65	-46	-61	4.854492939
601c6cf630a5b9238901e627	NONE	1m	-4dBm	East	-72.45	-87	-48	-74	7.040861369
601c6d0530a5b9238901e664	NONE	1m	-4dBm	South	-75.73333333	-84	-58	-73	7.467140824
601c6d1630a5b9238901e6a1	NONE	1m	-4dBm	West	-62.16666667	-72	-44	-64	6.752693541
601c6d4c4d7ef434cd33cfd0	NONE	1m	0dBm	North	-53.68333333	-61	-34	-54	5.419649331
601c6d5b4d7ef434cd33d00d	NONE	1m	0dBm	East	-65.68333333	-81	-44	-67	7.525080475
601c6d6a4d7ef434cd33d04a	NONE	1m	0dBm	South	-77.26666667	-87	-67	-80	6.490845357
601c6d7c4d7ef434cd33d087	NONE	1m	0dBm	West	-57.38333333	-63	-41	-58	5.596886746
601c6dbdfda2a7d594dce543	NONE	2m	0dBm	North	-53.21666667	-57	-39	-55	4.755341926
601c6dd8fda2a7d594dce580	NONE	2m	0dBm	East	-64.76666667	-73	-48	-65	6.992409121
601c6de9fda2a7d594dce5bd	NONE	2m	0dBm	South	-67.6	-73	-49	-69	5.263239964
601c6df9fda2a7d594dce5fa	NONE	2m	0dBm	West	-64.91666667	-77	-44	-63.5	8.334717399
601c6e480b89ba8be7d0025b	NONE	2m	-4dBm	North	-60	-67	-47	-63	6.871705682
601c6e560b89ba8be7d00298	NONE	2m	-4dBm	East	-74.03333333	-84	-57	-74	5.599535897
601c6e670b89ba8be7d002d5	NONE	2m	-4dBm	South	-77.13333333	-84	-58	-79	5.362982558
601c6e770b89ba8be7d00312	NONE	2m	-4dBm	West	-70.25	-79	-49	-72.5	6.429869387



Challenges of CT

CPSL
Cyber-Physical Systems Laboratory

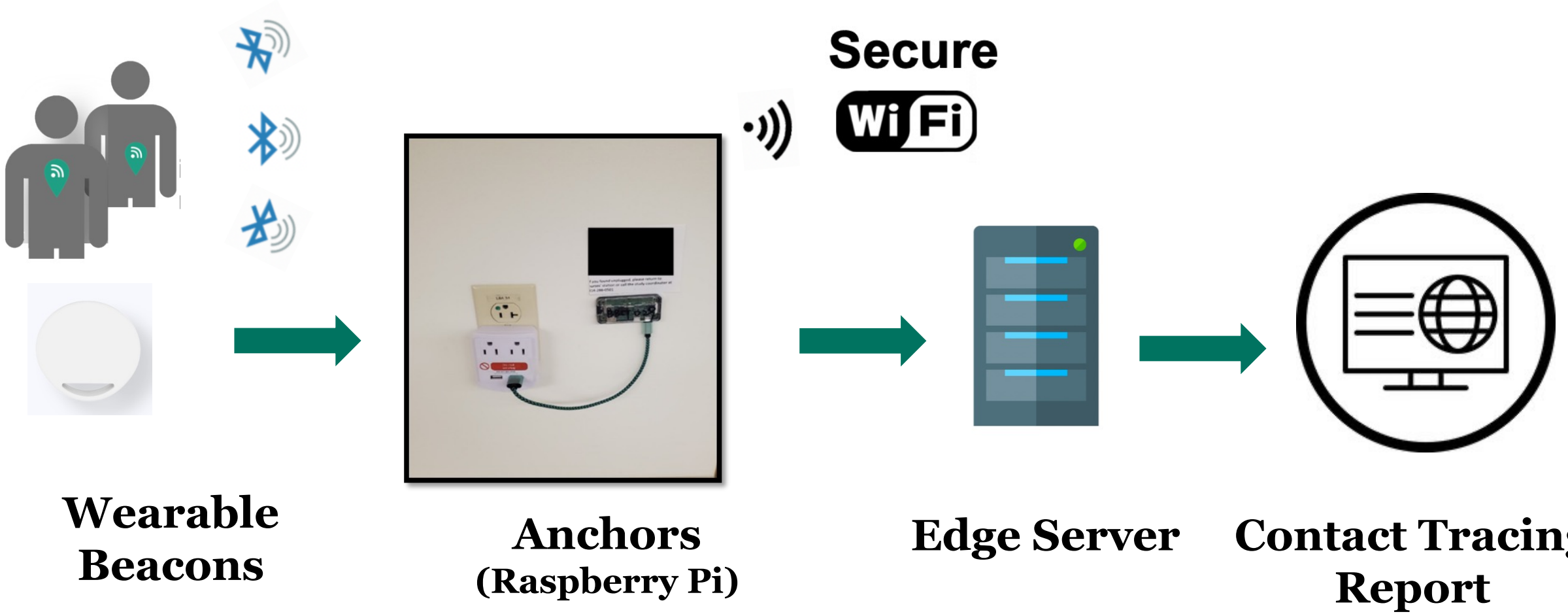
- **Noisy** signal data
  - Body shadowing
  - Furniture
  - Wall
  - ……
- Diverse **environment** characteristics
- Different **working patterns**



No contact tracing methods outperform others in all rooms

CATCH System

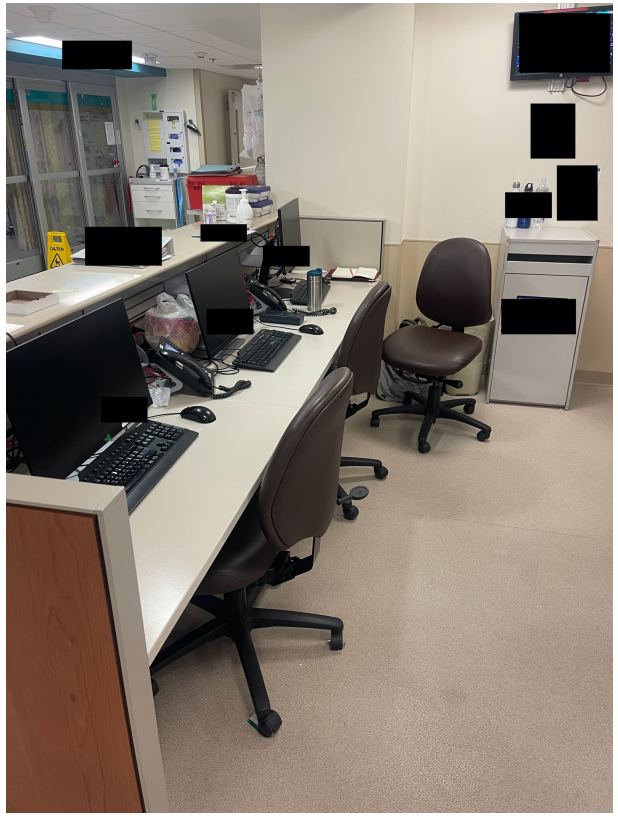
CPSL
Cyber-Physical Systems Laboratory

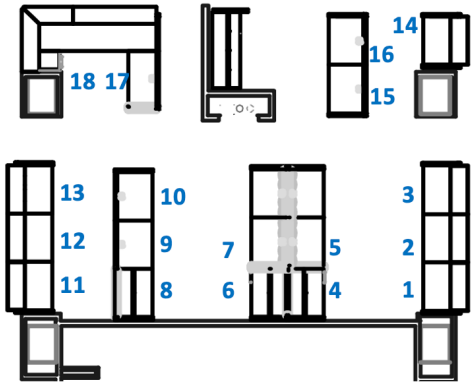


Diverse Environment

CPSL
Cyber-Physical Systems Laboratory

- Open space room
  - Random locations
- Structured room
  - Signal blockage: computers
- Hallway
  - Multipath effect: long and narrow





Floor plan of nurse station,
Blue number: computer index

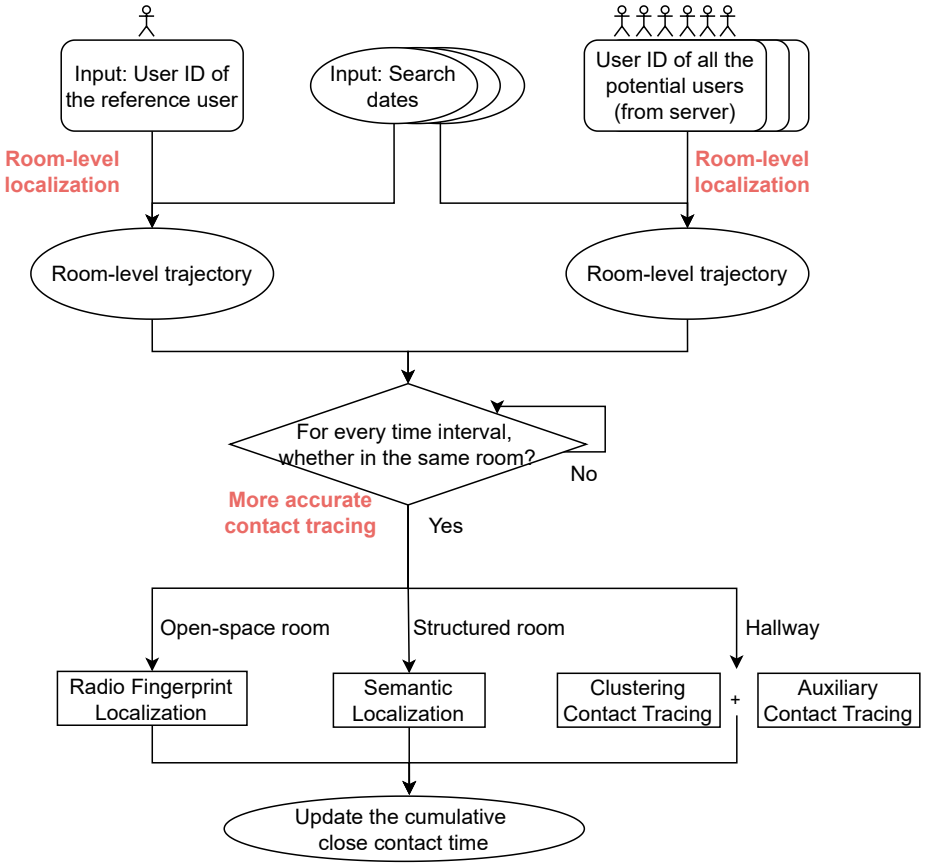
Diverse Environment

CPSL
Cyber-Physical Systems Laboratory

- Open space room
  - Random locations
- Structured room
  - Signal blockage: computers
- Hallway
  - Multipath effect: long and narrow
  - Body shadowing: patient round

- Structured room
  - Locations are relatively fixed
  - Semantic localization
- Hallway
  - Anchors aligned in two lines
  - Cluster detection

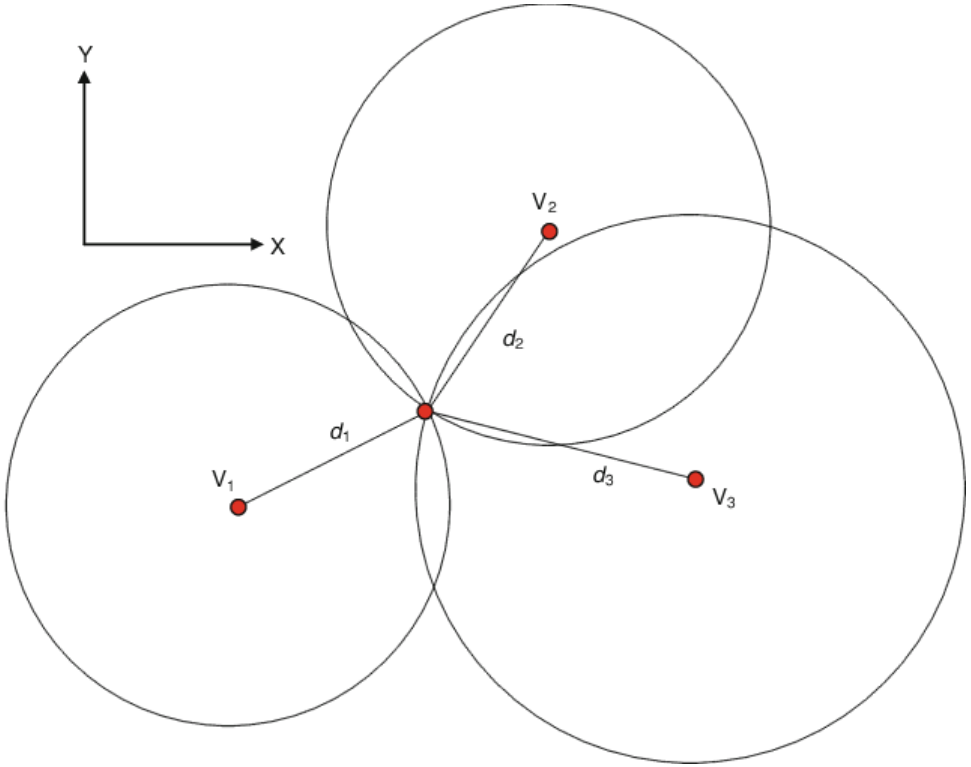
CATCH Pipeline



- First level: room-level tracing
  - Major vote from the strongest 3 anchors (Accuracy > 97%)
  - Add temporal smoothness
- Second level: contact tracing methods with better accuracy based on room type
  - Open space (existing Fingerprint methods)
  - Structed room (Our proposed Graph-based Fingerprint method)
  - Hallway (Our proposed Clustering Contact Tracing method)

No contact tracing methods outperform others in all rooms

Trilateration



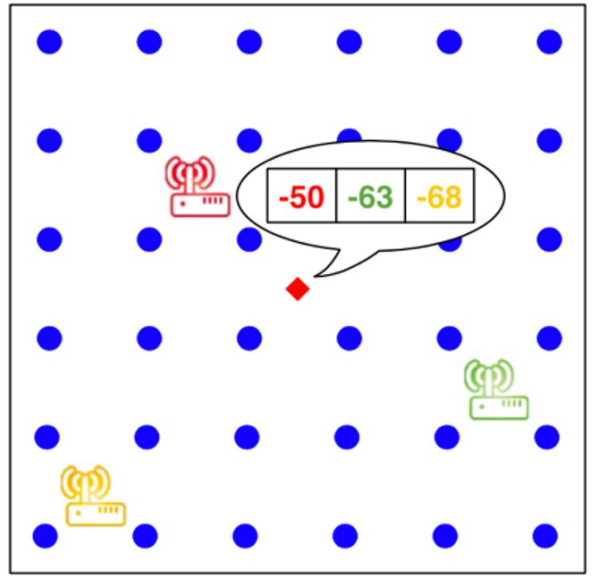
RSSI → Distance between beacon and anchor → Trilateration

Less stable than Fingerprint

Radio Fingerprint

CPSL
Cyber-Physical Systems Laboratory

- The RSSI vectors are recorded as the fingerprint for one location
  - Training data are collected at each reference point (blue dots)
  - Predict the user location by comparing the RSSI to the training dataset
  - K-nearest neighbors algorithm is usually used
- In open space room, distance between two users is computed between estimated locations by Radio Fingerprint



More Stable but time consuming

Graph Signal

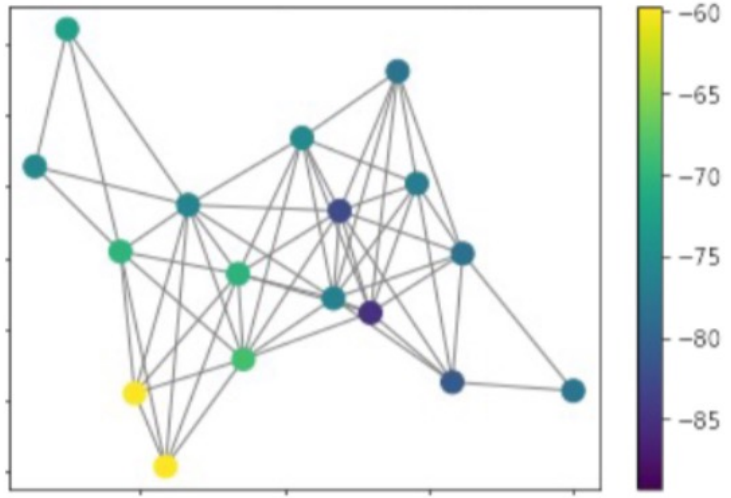
CPSL
Cyber-Physical Systems Laboratory

Challenge: Similar fingerprint for adjacent semantic locations

Idea: Add more information into input vectors

How:

- Transform RSSI vector into a graph signal to incorporate the location of the anchors
- Integrate local variation of graph signal



Node: anchor
Edge: determined by the physical distance between two anchors
Signal: RSSI values from all the anchors

Graph-based Fingerprint

CPSL
Cyber-Physical Systems Laboratory

- Local variation describes local smoothness of the graph signal
- Generate Adjacency matrix A
  - A[i][j] has larger value if the physical distance between $anchor_i$ and $anchor_j$ is shorter
- Degree matrix D: diagonal matrix, $D[i][i] = sum_j A[i][j]$
- Laplacian matrix L = A – D
- Local variation: L*RSSI vector
  - Weighted sum of difference with its neighbors
- Input vector: [Local variation vector, Original RSSI vector]

Clustering CT for Hallways

CPSL
Cyber-Physical Systems Laboratory

- Noisy signal
  - Only use the order of RSSI values instead of the actual RSSI values
- Patient round
  - Utilize this information to develop clustering contact tracing method

Rank-biased Overlap +
DBSCAN clustering

RBO

CPSL
Cyber-Physical Systems Laboratory

- Is a similarity measure for ranked lists
- Can handle non-conjointness (two ranked lists have different items)
- RBO gives more weights to top items (controlled by a hyperparameter p)

User 1: [Anchor 4, Anchor 0, Anchor 8, Anchor 9]
User 2: [Anchor 4, Anchor 0, Anchor 9, Anchor 8] → RBO similarity is higher

User 3: [Anchor 4, Anchor 0, Anchor 8, Anchor 9]
User 4: [Anchor 0, Anchor 4, Anchor 8, Anchor 9]

RBO

CPSL
Cyber-Physical Systems Laboratory

To obtain a single score for measuring the similarity between two ranked lists, we utilize the extrapolation version of RBO [53]. Let R and L be two ranked lists, R_i and L_i is the ith item in list R and L respectively. $R_{i:j}$ is the set of items from R_i to R_j. At each depth d, the overlap of R and L is the size of the intersection of $R_{1:d}$ and $L_{1:d}$:

$$x_{R,L,d} = |R_{1:d} \cap L_{1:d}| \tag{2}$$

The extrapolation version of RBO evaluated at depth d is:

$$RBO_{R,L,d} = \frac{x_{R,L,d}}{d} \cdot p^d + \frac{1-p}{p} \sum_{i=1}^{d} \frac{x_{R,L,i}}{i} \cdot p^i \tag{3}$$

The hyperparameter p in RBO controls the degree of top weightedness, where larger p values will make the weights of all the items more equal. The original version of RBO is designed for indefinite ranked lists, however, for our contact tracing task, we only focus on the strongest d anchors, namely the length of our ranked list is d. Hence, we control the value of p to assign most of the weights (over 99%) to the top d items. The overall weight of the top d items in RBO is:

$$w_d = 1 - p^d - \frac{d(1-p)}{p}\left(\sum_{i=1}^{d} \frac{p^i}{i} + ln(1-p)\right) \tag{4}$$

- Sort the anchors based on RSSI values (top d anchors)
- Use RBO to compute similarity score ($\in [0, 1]$)

DBSCAN

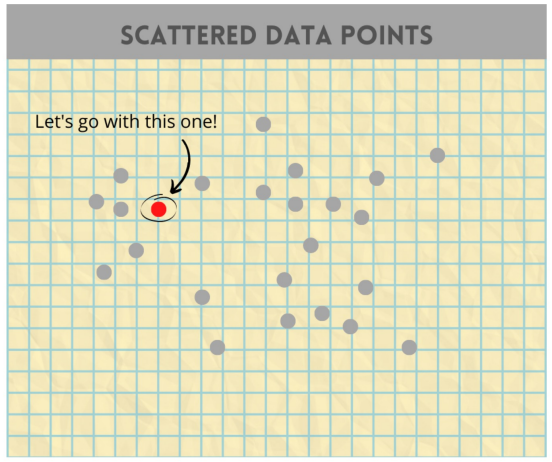
CPSL
Cyber-Physical Systems Laboratory

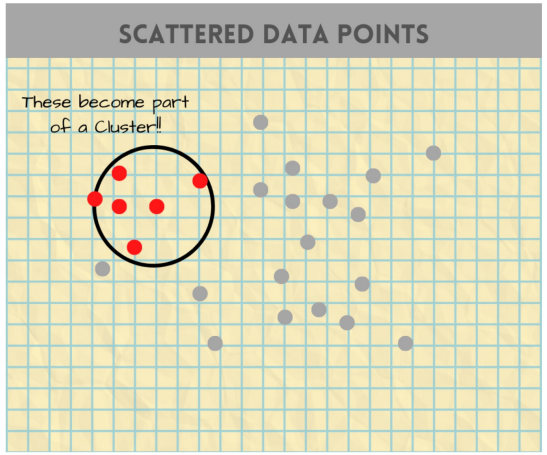
"Given a set of points in some space, it groups together points that are closely packed together (points with many nearby neighbors), marking as outliers points that lie alone in low-density regions (whose nearest neighbors are too far away)"

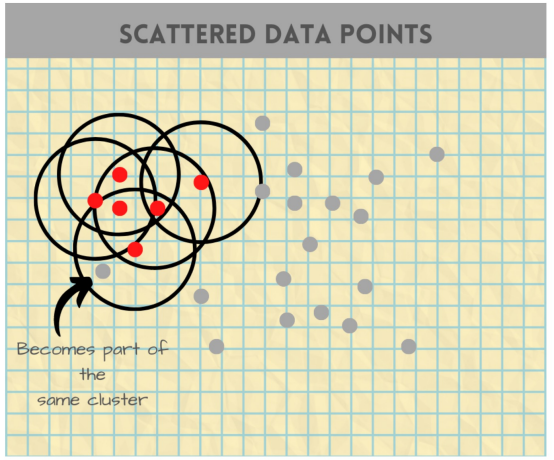
- Density-based
  - A group of healthcare workers working together
- Accommodate "noise"
  - Other healthcare workers working in hallways

DBSCAN

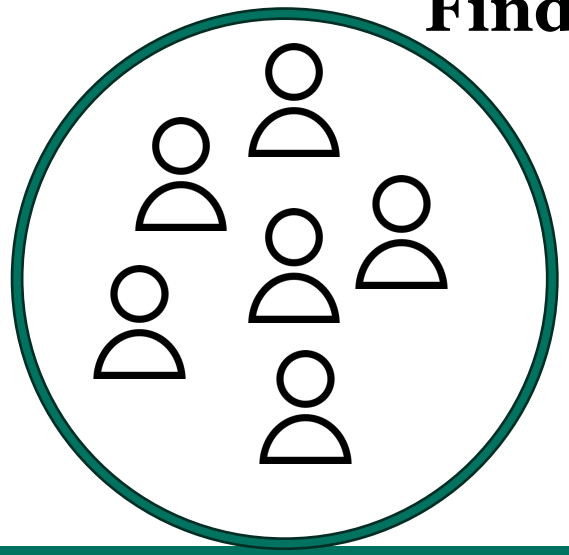
CPSL
Cyber-Physical Systems Laboratory







Find a Cluster!





"noise"

- A point *p* is a *core point* if at least minPts points are within distance ε of it (including *p*).
- Merge the overlapping clusters into one
- Noise: one node does not belong to any cluster
- **ε = 1 – RBO Score**

Evaluation

CPSL
Cyber-Physical Systems Laboratory

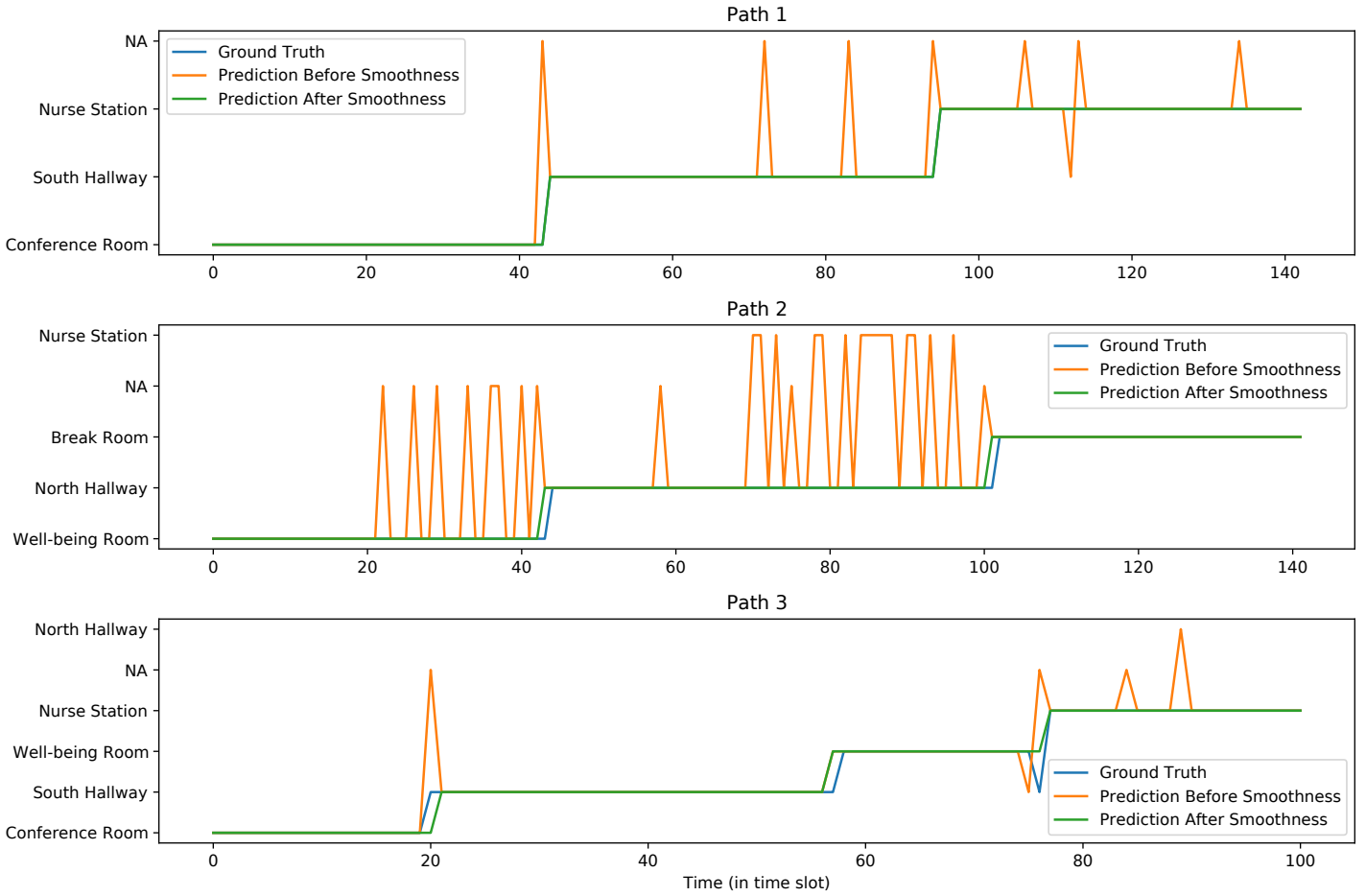
- High-level evaluation: CDC's standard
  - Subjectively evaluation with a case study
- Low-level evaluation as a surrogate
  - 10-second granularity
  - Binary prediction
    - positive: Within 6 feet or in the same patient round
    - negative: Otherwise

Evaluation: Room-level Tracing

CPSL
Cyber-Physical Systems Laboratory

Table 1. Room-level Accuracy Results

	Duration (Minutes)	Accuracy before smoothing	Accuracy after smoothing
Trajectory 1	23.8	0.942	1.000
Trajectory 2	23.7	0.803	0.986
Trajectory 3	16.8	0.941	0.970



Evaluation: Open Space Room

CPSL
Cyber-Physical Systems Laboratory

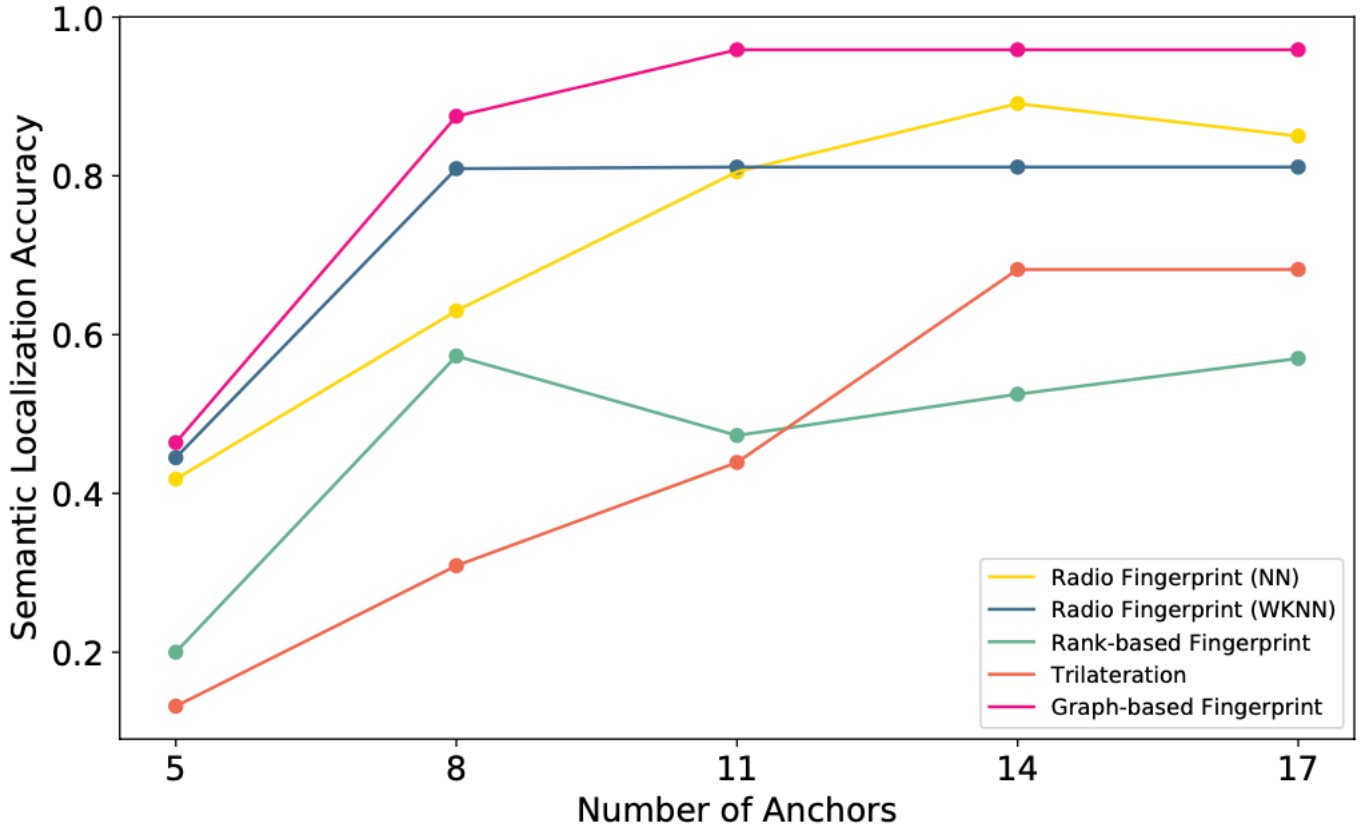
Method	AUROC	AUPRC	Sensitivity	Specificity	Accuracy	F1 Score
Radio Fingerprint (NN)	0.823	0.900	0.684	0.854	0.741	0.779
Radio Fingerprint (WKNN)	**0.933**	**0.967**	**0.895**	0.851	**0.880**	**0.909**
Rank-based Fingerprint	0.646	0.785	0.261	0.851	0.457	0.390
Graph-based Fingerprint	**0.939**	**0.969**	**0.891**	0.847	**0.876**	**0.906**
Trilateration	0.623	0.788	0.291	0.851	0.478	0.426
RBO Similarity	0.848	0.932	0.697	0.839	0.745	0.784

Testing data: 44.5 minutes

- +: Within 6 feet
- -: Otherwise

- AUROC: Area Under the Receiver Operating Characteristic Curve
- AUPRC: Area Under the Precision-Recall Curve

Evaluation: Structed Room



Testing data: 33 minutes

- +: Within 6 feet
- -: Otherwise

Evaluation: Hallways

CPSL
Cyber-Physical Systems Laboratory

	Method	Sensitivity	Specificity	Accuracy	F1 Score
Need Fingerprint	Radio Fingerprint (NN)	0.364	0.845	0.476	0.516
	Radio Fingerprint (WKNN)	0.424	0.851	0.523	0.577
	Rank-based Fingerprint	0.403	0.855	0.508	0.557
	Graph-based Fingerprint	0.647	0.850	0.694	0.764
Do not Need Fingerprint	Trilateration	0.498	0.844	0.579	0.644
	RBO Similarity (Ours without DBSCAN)	0.829	0.850	0.834	0.884
	Clustering (Ours)	**0.865**	0.857	**0.864**	**0.907**

Testing data: 238 minutes

- +: In the same patient round
- -: Otherwise

Evaluation in Hallways

CPSL
Cyber-Physical Systems Laboratory

	Method	Sensitivity	Specificity	Accuracy	F1 Score
Need Fingerprint	Radio Fingerprint (NN)	0.364	0.845	0.476	0.516
	Radio Fingerprint (WKNN)	0.424	0.851	0.523	0.577
	Rank-based Fingerprint	0.403	0.855	0.508	0.557
	Graph-based Fingerprint	0.647	0.850	0.694	0.764
Do not Need Fingerprint	Trilateration	0.498	0.844	0.579	0.644
	RBO Similarity (Ours without DBSCAN)	0.829	0.850	0.834	0.884
	Clustering (Ours)	**0.865**	0.857	**0.864**	**0.907**

Testing data: 238 minutes
- +: In the same patient round
- -: Otherwise

- RBO similarity improved the performance significantly
- Utilizing DBSCAN improved the performance further
- **Fingerprint data is not needed**

An Example in Hallways

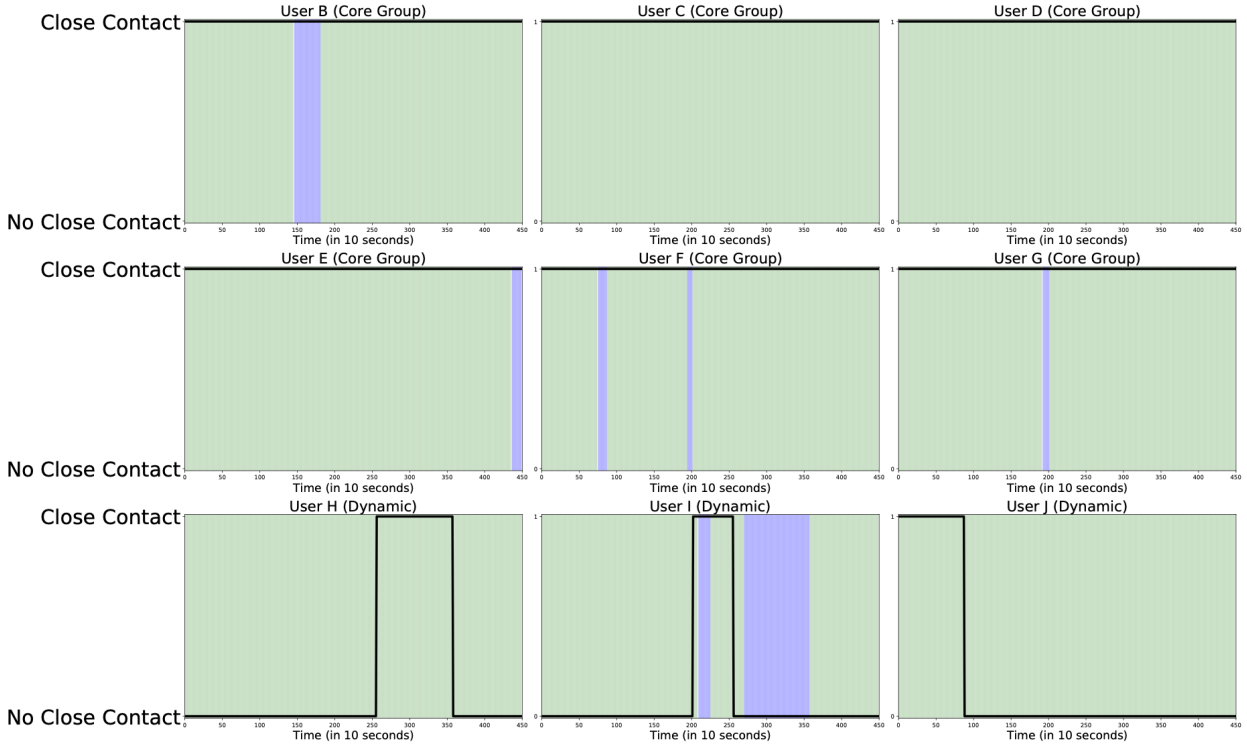


Fig. 6. Clustering results during a patient round in the South hallway. Black lines represent the ground truth. The blue region represents the time intervals when the estimation results differ from the ground truth (including false positives and false negatives). The green region represent the time intervals when the estimation results are consistent with ground truth. The top two rows represent the core group members, and the last row shows the dynamic members.

Patient round = core members + dynamic members

Case Study

CPSL
Cyber-Physical Systems Laboratory

- "conducted a user study with an attending physician simulating the standard contact tracing practice over one week"
- "In this case study, CATCH estimated that **31** users were in close contact with the attending physician. Among these 31 users, CATCH was able to detect all **27** users listed by the attending physician. "

Reference User	Date Range	Number of Close Contacts	Computation Time (Minutes)
Nurse	10/30/21 - 11/05/21	12	24.32
Resident	09/14/21 - 09/20/21	28	43.07
Pharmacist	09/11/21 - 09/17/21	17	20.76
Therapist	10/30/21 - 11/05/21	13	27.76
Dietitian	11/20/21 - 11/26/21	12	18.57
Attending Physician	11/20/21 - 11/26/21	31	34.98

Privacy and Maintenance

CPSL
Cyber-Physical Systems Laboratory

Privacy

- All user information is anonymous for security and privacy reasons.

Maintenance

- Beacon
  - If no data for over 14 days, the system will notify the study coordinator
- Anchor
  - If heartbeat signal is missing for over 1 hour, the system will notify the study coordinator

Summary

CPSL
Cyber-Physical Systems Laboratory

- Identified various representative contact tracing scenarios in the ICU
- Designed a suite of contact tracing methods tailored for different scenarios in the hospital unit
- Deployed CATCH system using commercial BLE beacons and Raspberry Pi devices in a real-world ICU.
- Presented empirical results in the ICU that demonstrate the improved accuracy of our contact tracing system compared to existing methods.