Location Verification of Crowd-Sourced Sensors

Christopher Kitras[*], Carter Pollan[*], Kyle Myers[*], Camille Wirthlin Tischner[†], Philip Lundrigan[*]

[*]Brigham Young University
[†]Utah State University

Outline

- Background Motivation
- Current State of the Device Registration
- New Device Registration Process
- Proximity Validation Tests
- Change of Location Detection (CoLD)
- Change of Location Tests
- Conclusion

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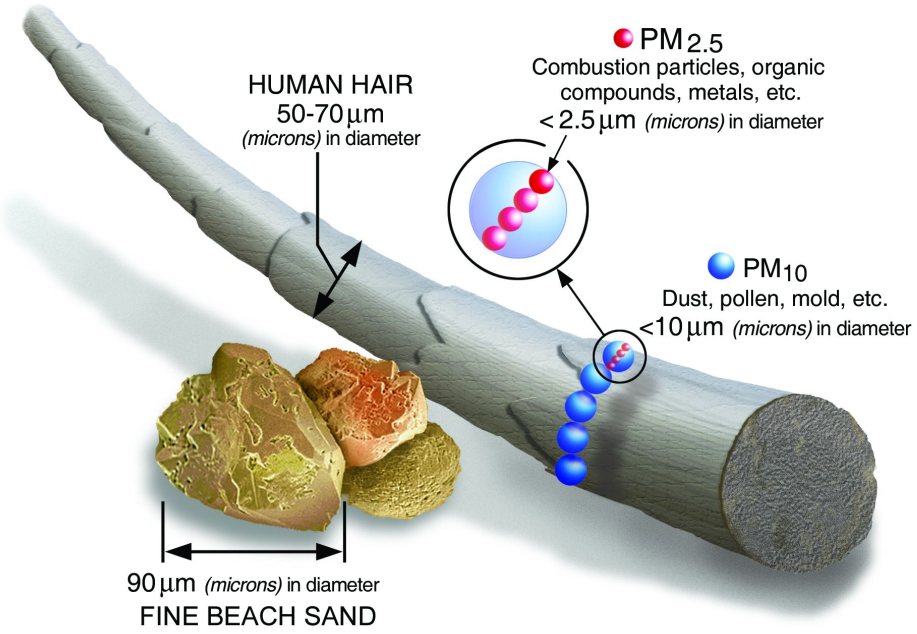
Why Air Quality?

- Climate change has exacerbated air quality crises
- PM2.5 is sediment of a diameter of ≤2.5μm
- PM2.5 enters directly into the bloodstream due to its small size.
- Growing focus on monitoring PM2.5 to track impact



Source: U.S. EPA

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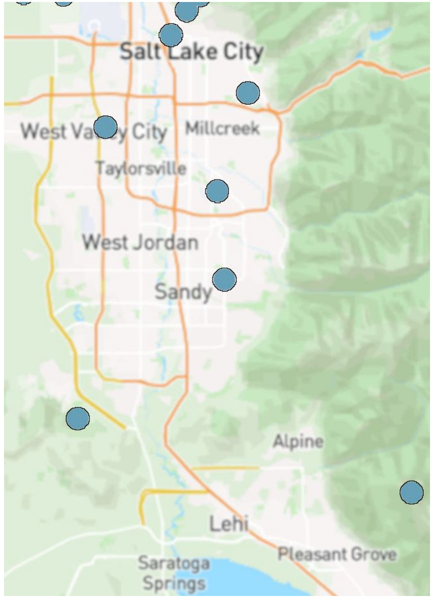
Government Sensor Density

- Air quality monitoring is regulated in the United States[3]
- Mandated air quality stations deployed and monitored by government
- Must be calibrated on a frequent basis by trained personnel
- Very expensive to deploy and maintain (i.e. $10,000+)[1]



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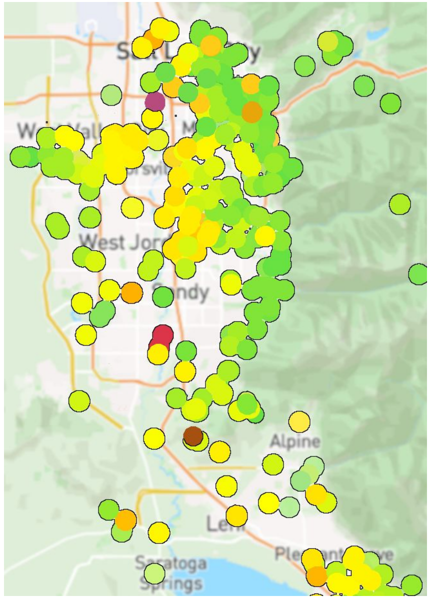
Citizen Science Sensor Density

- Citizen Science (i.e. Crowd Sourced sensors) are sold by companies and deployed by enthusiasts/users
- Sensors are calibrated in firmware by the company (i.e. baked in correction factor)
- Low cost: ~$230/unit[2]
- This leads to greater sensor density



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Support
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Mountlake Terrace
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Shoreline
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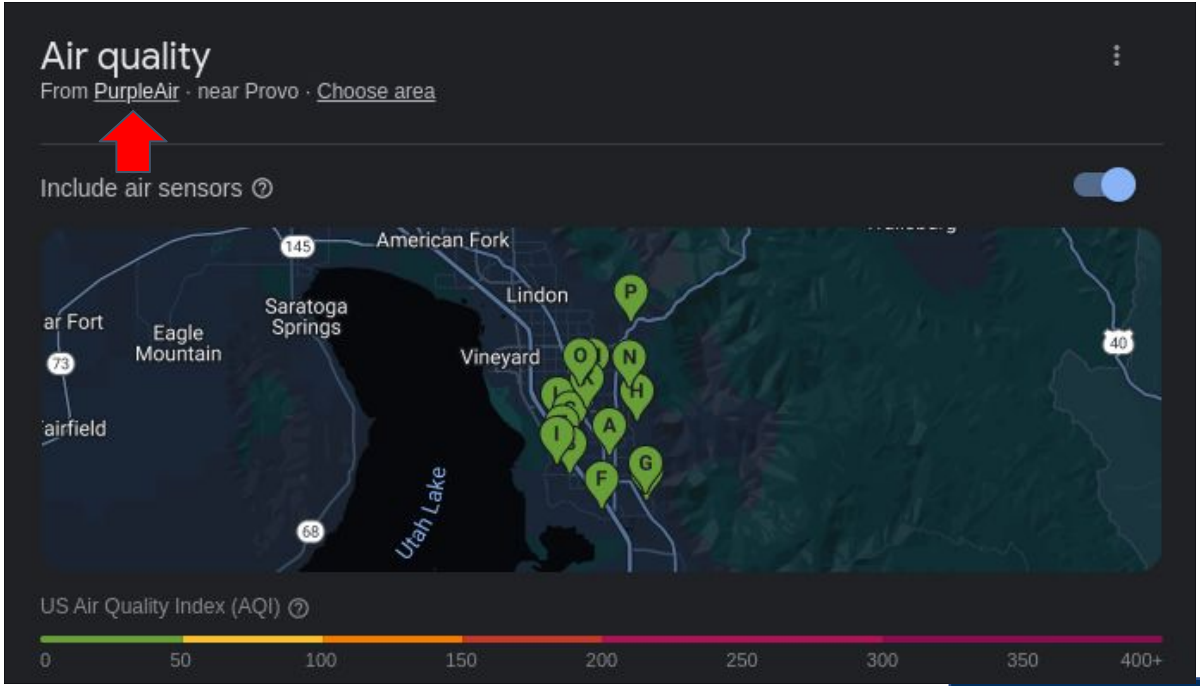
Sensor Data in the Wild

- Citizen science data is becoming more trusted
- A simple Google search shows air quality from local sources



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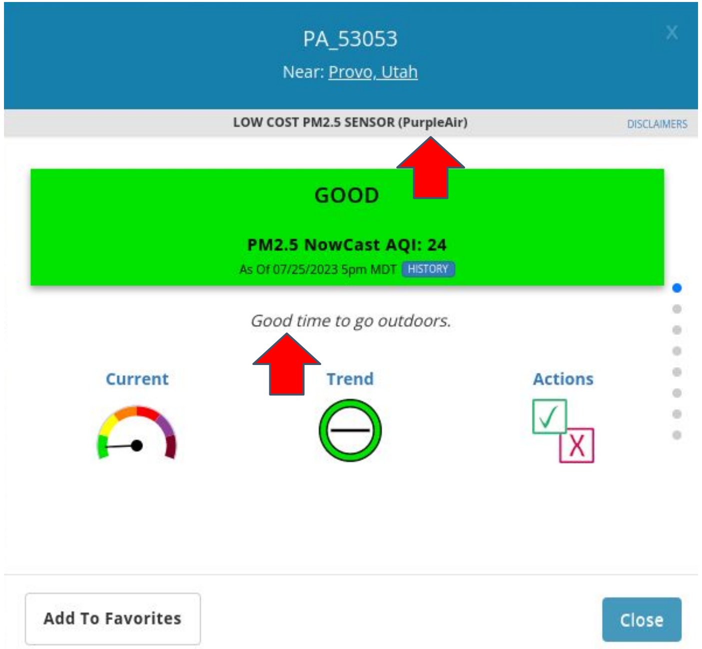
Sensor Data in the Wild

- AirNow also shows citizen science-based PM2.5 readings
- Citizen science data is everywhere!



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Problem

Device-Id (MAC)*

Printed on the device label just above the bar code. Please include the colons (:)

xx:xx:xx:xx:xx:xx

Associated Email *

This email address would have been used in the device purchase or other communication with PurpleAir. *(A copy of this sensor registration will be e-mailed to this address.)*

Associated email address

Installed*

Outside | Inside

Location Name*

The name that appears on the map

Visibility*

Public (everyone) | Private (only me)

☑ Set a location on the map

Map Location*
(drag the marker to adjust)

Latitude 21.2758001

Longitude -157.8251292

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Problem

- With this lack of location verification, anyone from **absent-minded, well-meaning users to malicious actors** intent on ruining the integrity of the system's data could falsely **place a sensing device anywhere on the map**.

- People are making **important health decisions** on data that cannot be trusted

- How can we prove that a sensing **device is installed in its registered location without extra hardware?**

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Related Work

Some previous efforts to pinpoint location of a device:

1. GPS: requires extra hardware, finicky outside of certain situations, i.e building cover, etc.
2. WiGle: WiFi fingerprinting database. Not as useful in rural locations. Not great for real-time verification
3. IP Geolocation databases Geolocate and GeoIP2: not very granular, dependant on ISP conformity and population density

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Our Solution

- We aimed to create a solution that:
    - verifies a device's location **without extra hardware**
    - **detects any changes** in the device's location
    - scales to be deployed on any system **without requiring a platform-specific application**
- These design goals **prevent** the need for **recalling and retrofitting devices** with localization hardware, prevent device relocation after verification, and ensure accessibility to users with unsupported smartphone models.

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Solution

We assume that a viable solution will ensure:

1. **Proximity of a registering device** with trusted geolocation services to a WiFi device
2. **Detect any change of location** of the WiFi device after a verified registration

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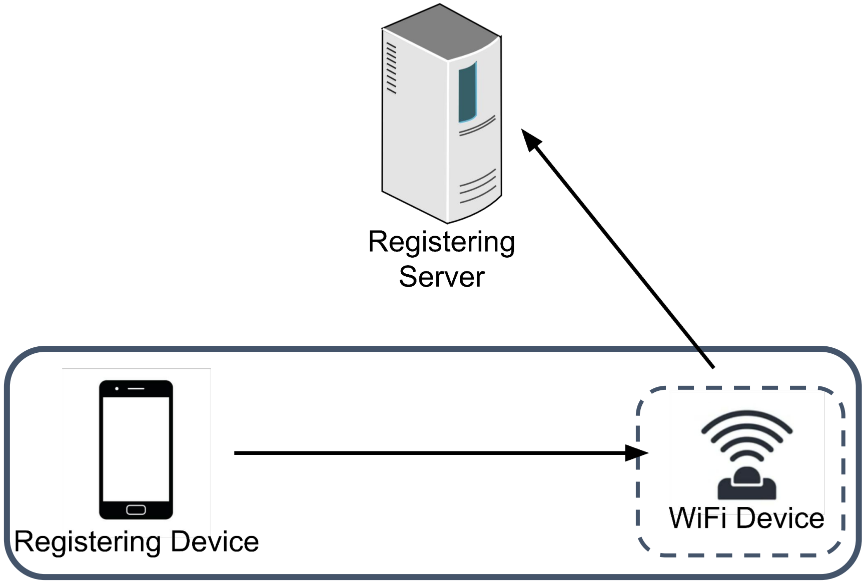
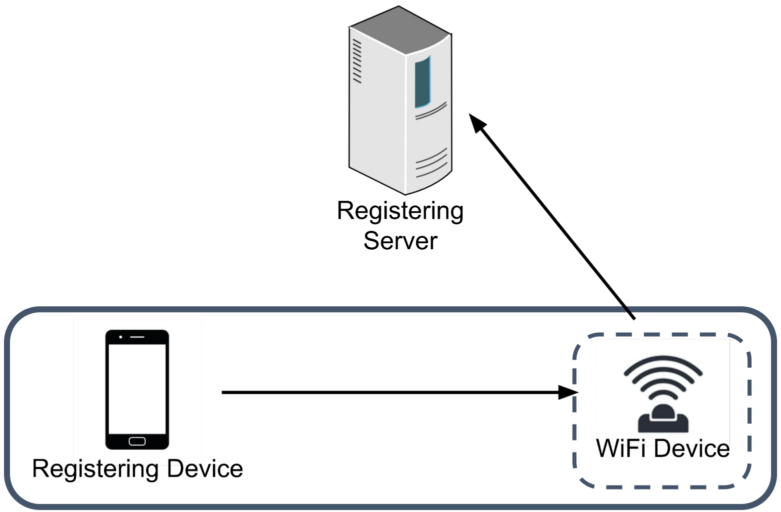
Registration Model



Registration Model

- WiFi Device (sensor) establishes access point
- Registering Device (phone) connects to WiFi Device and provides network credentials
- Location registration is done via user input or device installer
- There usually little to no verification of this process



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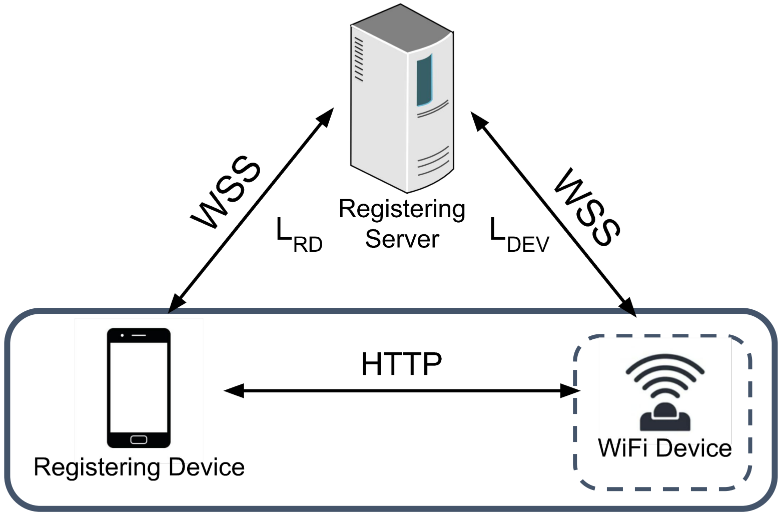
New Registration Model

- Use WebSockets to measure the latencies between phone and registering server (L_{RD}) and the sensor and registering server (L_{DEV}).
- Registration token (T_{REG}) is shared between all nodes to ensure integrity
- Define a tolerance between latencies (L_{TOL}) and ensure $|L_{RD} - L_{DEV}| \leq L_{TOL}$



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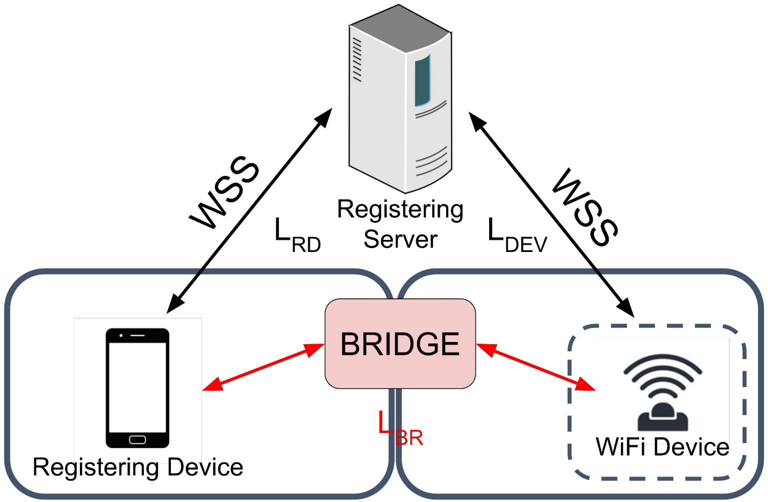
Adversarial Model

A supposed attacker:

- Has complete control over their network, local packets, firmware on sensor, and software on phone
- Can perform man-in-the-middle attacks on packets in their network
- Can relay packets through different devices (i.e. a bridge) to give appearance of different location of origin



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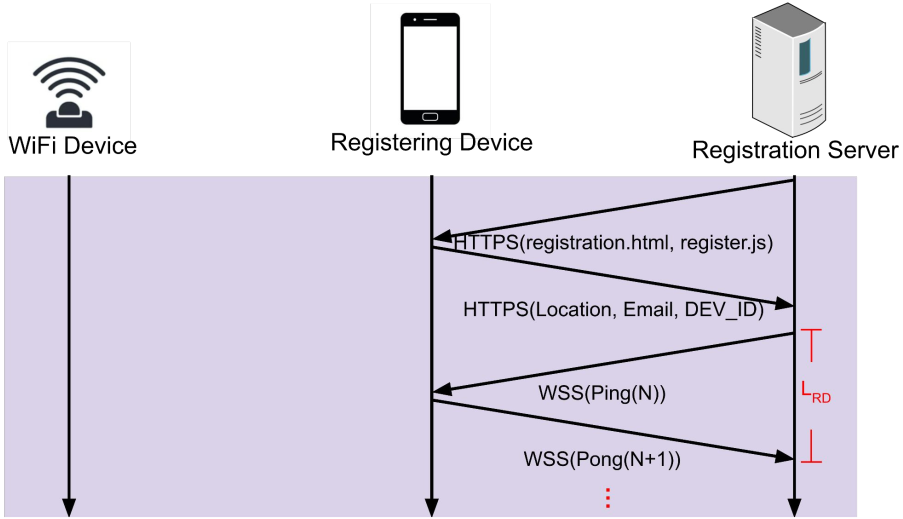
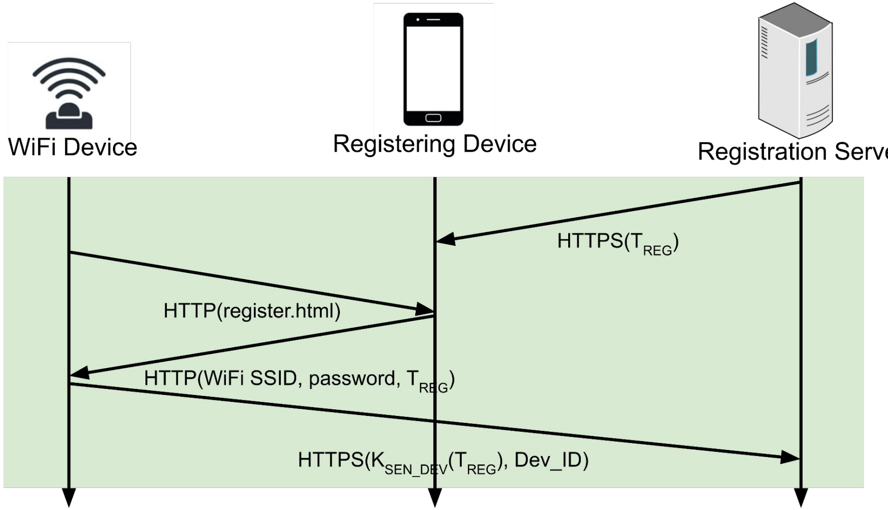
Registration Flow

Pre-existing credentials are shared from phone to Registration Server and L_{RD} is derived



Registration Flow

Registration server assigns T_{REG} to phone who passes this to the WiFi Device



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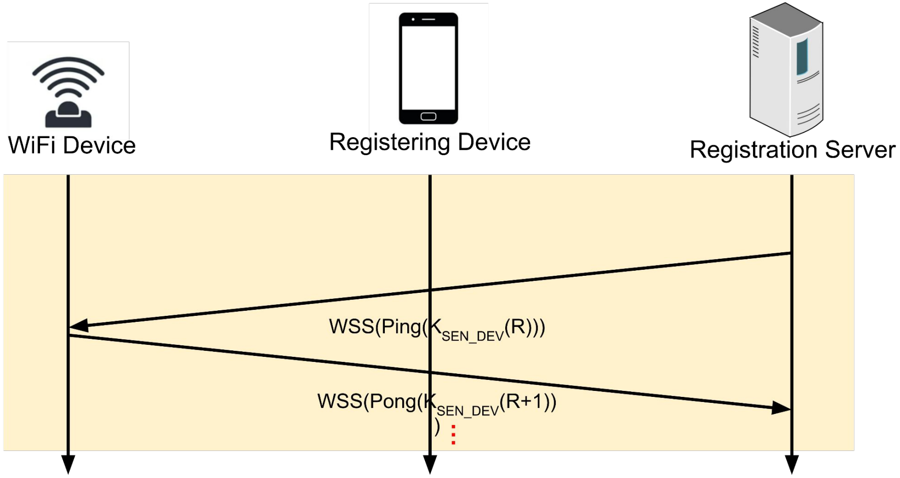
Registration Flow

After receiving network credentials, sensor and Registration server derive L_{DEV}



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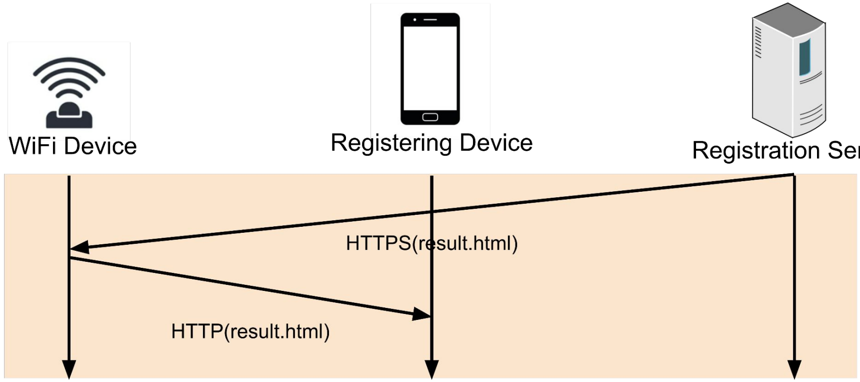
Registration Flow

Registration server checks $|L_{RD} - L_{DEV}| \leq L_{TOL}$ and accepts or rejects registration session



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Some Development Challenges

- Solution must run in a browser!
- Changing a window from the registration page to the WiFi Device AP
    - RFC 1918
    - No redirecting from broader to smaller network type
- Minimize ping times with WebSockets to avoid overhead of repeated HTTPS requests

Although these requirements may seem strict and obstructive of creative solutions, compliance to them ensures that **anyone from any web browser can carry out the new registration process**.

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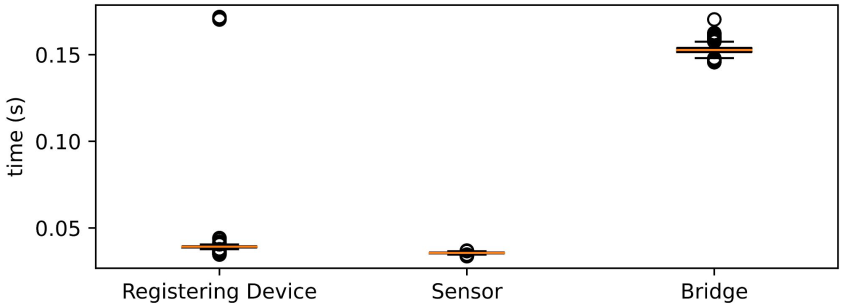
Comparing Latencies

- Measured L_{RD} and L_{DEV} over the span of a day
- $L_{RD} - L_{DEV} \approxeq 5ms$
- Measured latency of a bridged setup (L_{BR})
- $L_{BR} - L_{RD} \approxeq 125ms$
- Set L_{TOL} such that $|L_{RD} - L_{DEV}| \leq L_{TOL} \leq L_{BR}$



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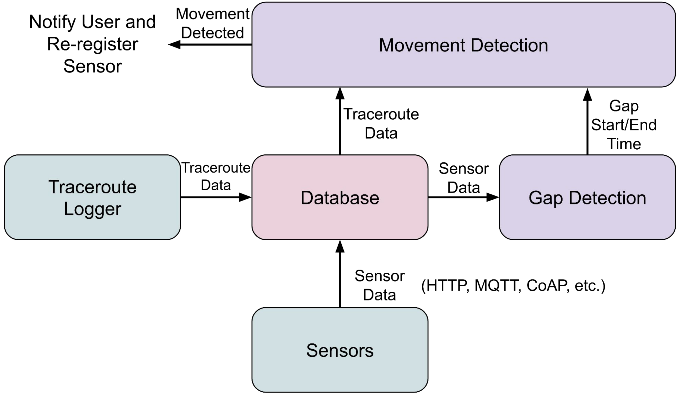
CoLD Algorithm

- Gather sensor data and poll sensors for traceroute data
- Detect unexpected gaps caused by loss of internet connection/power greater than defined threshold T_{GAP}
- Upon a gap $\geq T_{GAP}$ we take a sample of trusted traceroute data (1 week) and a sample of new traceroute data
- If samples are 90%+ alike, the gap is ignored, else the data is flagged and the sensor is marked for re-registration



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Experiment Procedure

G
A
P

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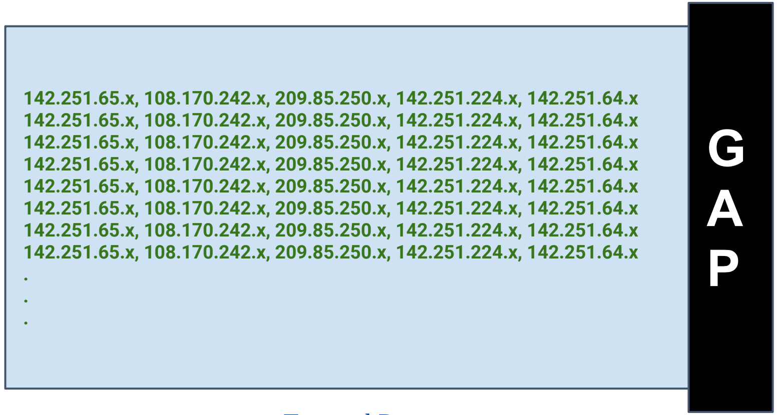
Experiment Procedure



Trusted Data

Experiment Procedure

142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 142.251.64.x
142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 142.251.64.x
142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 142.251.64.x
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Trusted Data

GAP

142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 209.251.64.x
142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 209.251.64.x
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142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 209.251.64.x
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Questionable Data

Experiment Procedure

142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 142.251.64.x, x.x.x.x, y.y.y.y, z.z.z.z

Trusted Data

142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 209.251.64.x, a.a.a.a, b.b.b.b, c.c.c.c

Questionable Data

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Experiment Procedure

142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 142.251.64.x, x.x.x.x, y.y.y.y, z.z.z.z

Trusted Data

142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 209.251.64.x, a.a.a.a, b.b.b.b, c.c.c.c

Questionable Data

50%

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Experiment Procedure

Acceptance threshold in our system is 90%+

Trusted Data	Questionable Data
142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 142.251.64.x, x.x.x.x, y.y.y.y, z.z.z.z	142.251.65.x, 108.170.242.x, 209.85.250.x, 142.251.224.x, 209.251.64.x, a.a.a.a, b.b.b.b, c.c.c.c

50%

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Experiment Procedure

In three different geographical regions we did the following:

1. Run framework normally for at least 1 week
2. Simulate a gap event
3. Fetch trusted data and a sample of questionable data
4. Compare data samples and assign a score
5. Create a confusion matrix to compare accuracy of scoring future data to past data

	L	M	N	O
L	99.1	0	0	0
M	0	99.9	0	0
N	0	0	99.9	23.9
O	0	0	1.8	98.0

(a) Rural Area

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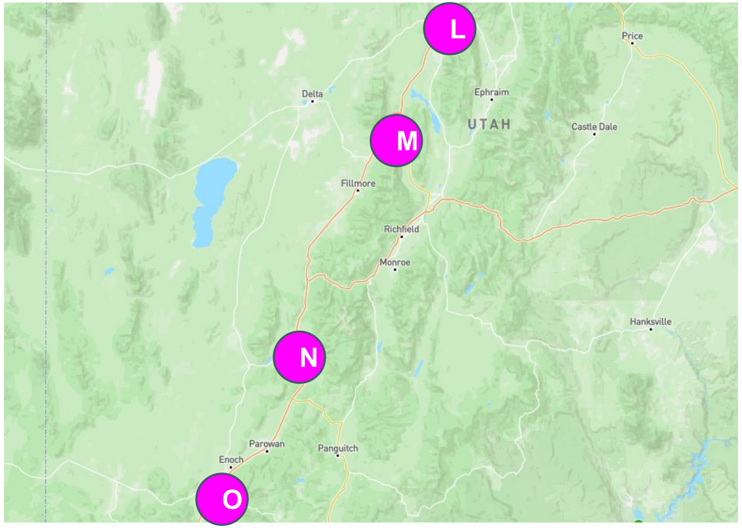
Rural Area Test

- Nodes are ~40 miles (64 km) apart
- Compare current node with other node's traceroute data
- Average of ~99.23% same node recognition
- Highest recognition in N to O with 23.9%



	L	M	N	O
L	99.1	0	0	0
M	0	99.9	0	0
N	0	0	99.9	23.9
O	0	0	1.8	98.0

(a) Rural Area

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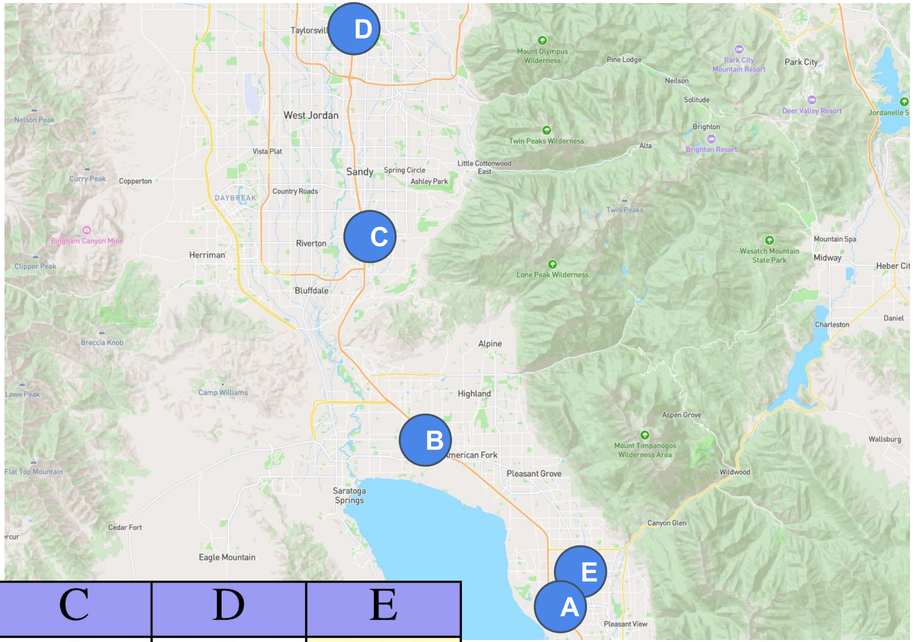
Inter-City Test

- Nodes are ~8 miles (13 km) apart
- Average of ~98.76% same node recognition
- Highest recognition in A to E with 14.6%



	A	B	C	D	E
A	99.9	0	0	0	14.6
B	0	96.39	0	0	0
C	0	0	99.7	0	0
D	0	0	0	98.0	0
E	11.3	0	0	0	99.8

(b) Inter-City

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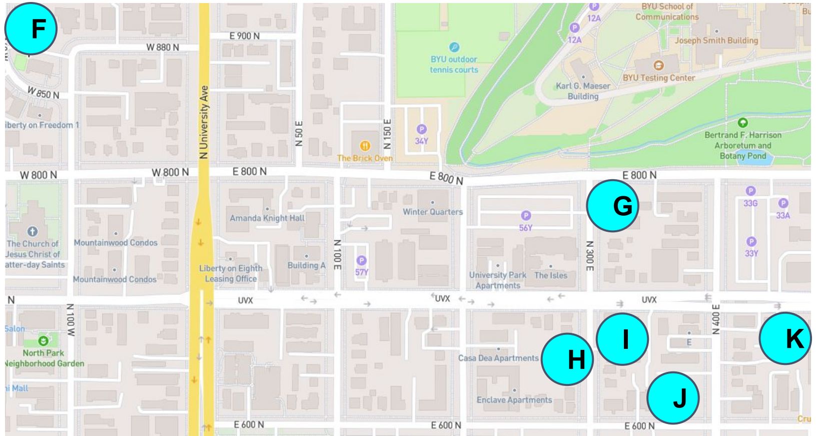
Intra-City Test

- Nodes are a few city blocks apart
- Average of ~98.47% same node recognition
- Highest recognition across several pairings with a 66.6%



	F	G	H	I	J	K
F	99.9	0	66.6	0	0	66.6
G	0	96.3	0	0	0	0
H	66.6	0	99.9	0	0	66.6
I	0	0	0	94.9	0	0
J	0	0	0	0	99.9	0
K	66.6	0	66.6	0	0	99.9

(c) Intra-City

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Conclusion

- Created a solution that **detects location and change of location**
- **No need of retrofitting** sensors with more hardware
- Experiments indicate a high rate of success with self identifying across:
  - Distant cities
  - Neighboring cities
  - Same city
- Solution can run on **any registering device** with a browser and localization engine
- Framework provides the necessary key for **automatic, low-cost location verification** for citizen science devices

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Questions?

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References

1. Gryech I, Ben-Aboud Y, Guermah B, Sbihi N, Ghogho M, Kobbane A. MoreAir: A Low-Cost Urban Air Pollution Monitoring System. Sensors (Basel). 2020 Feb 13;20(4):998. doi: 10.3390/s20040998. PMID: 32069821; PMCID: PMC7071408.
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3. https://www.epa.gov/laws-regulations/summary-clean-air-act (Clean Air Act, 1970)

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