
UNIVERSITÀ
DI TRENTO

# Estimating the number of people based on Wi-Fi probe request frames

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# About this Project

Internship at U-Hopper:

Big Data Analytics

Business Intelligence

Chatbot

IoT solutions

Artificial Intelligence solutions

# Problem Statement

Badly handled demand can lead to overcrowding

and inefficiency of the services

→ Inefficient and bad organized service leads to higher costs

→ Badly managed overcrowding during this global pandemic period

due to COVID-19 leads to long queues and new infections


# Research Statement

Is it possible to continuously estimate the number of people

in a place of interest based on the Wi-Fi probe request frames?

# Thesis Objectives

→ Capture and analysis of Wi-Fi probe request frames

→ Data extraction, transmission and storage

→ Analysis of Wi-Fi probe request frames patterns

→ Provide an estimate of the number of customers

# State of the Art

→ Analysis of different methods to count/estimate people

Infrared sensors, LSE, treadle switch-based systems, Video methods,

Audio methods, Wi-Fi, Bluetooth, BLE, LTE, Radar, RFID approaches

→ Many fields of applicability and different implementations

# Why Wi-Fi solution?

High diffusion of Wi-Fi devices

High accuracy using machine learning

Low-cost implementation

Real-time data transmission

User privacy ensured

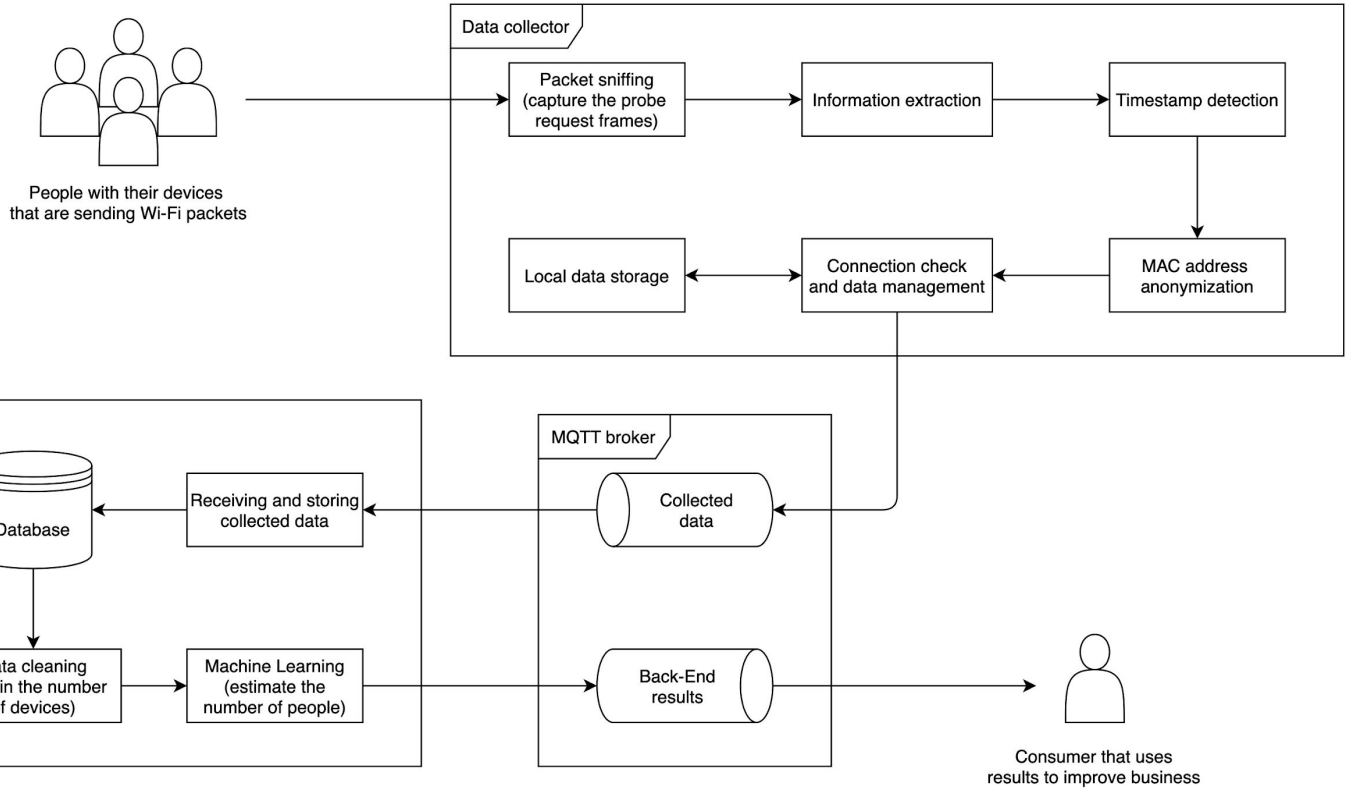

Standard 802.11 → Management frames → Probe request frames

# Results

Designed and developed a system for this problem that could work in several context

Tested the system in a Cafe and collected 4 weeks of data and manually-annotated ground truth

# System Architecture



# Data Collector Logic

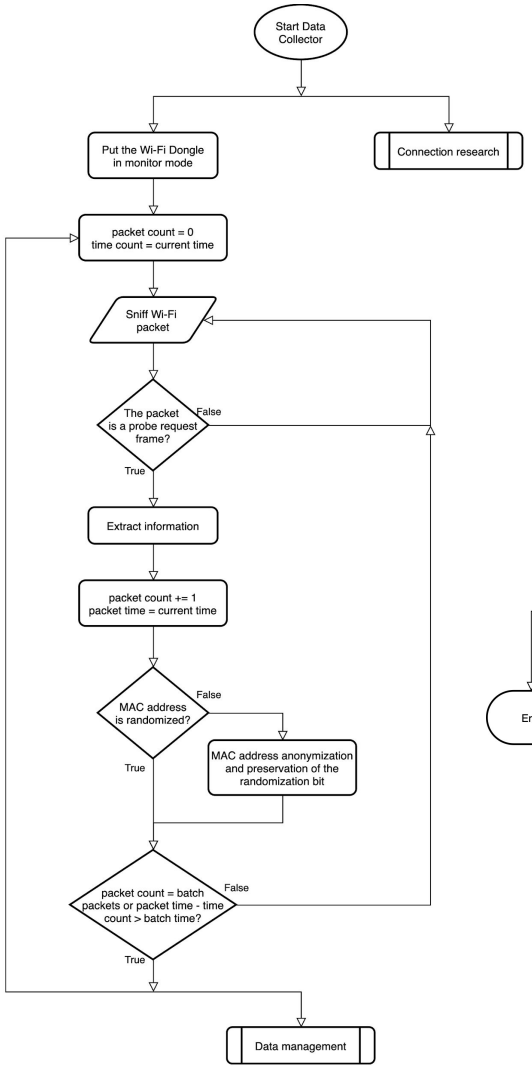
Packet sniffing using Scapy → Information extraction

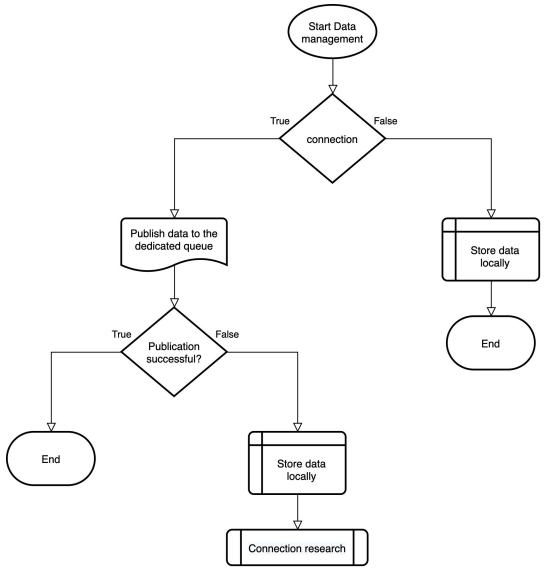
MAC address anonymization using BLAKE2s

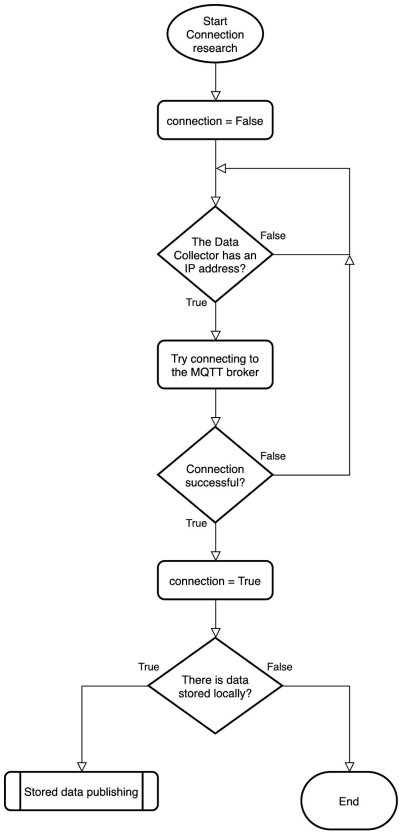
Check connection → Local storage / MQTT transmission

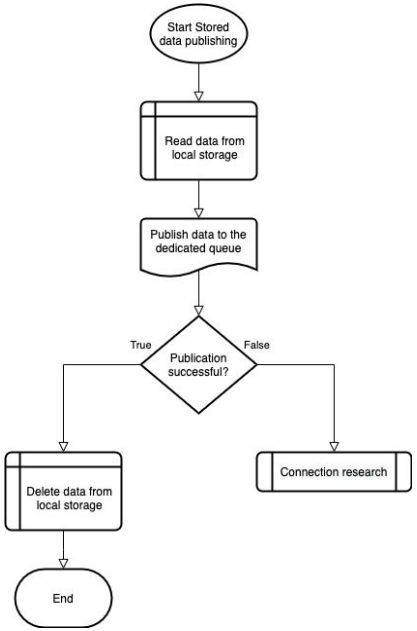
Connect and login to the MQTT broker (username and password)

→ Publish batches to the dedicated queue


Start Data Collector
Put the Wi-Fi Dongle in monitor mode
Connection research
packet count = 0
time count = current time
Sniff Wi-Fi packet
The packet is a probe request frame?
False
True
Extract information
packet count += 1
packet time = current time
MAC address is randomized?
False
True
MAC address anonymization and preservation of the randomization bit
packet count = batch packets or packet time - time count > batch time?
False
True
Data management


Start Data management
connection
True
False
Publish data to the dedicated queue
Store data locally
End
Publication successful?
True
False
End
Store data locally
Connection research


Start Connection research
connection = False
The Data Collector has an IP address?
False
True
Try connecting to the MQTT broker
Connection successful?
False
True
connection = True
There is data stored locally?
True
False
Stored data publishing
End


Start Stored data publishing
Read data from local storage
Publish data to the dedicated queue
Publication successful?
True
False
Delete data from local storage
Connection research
End

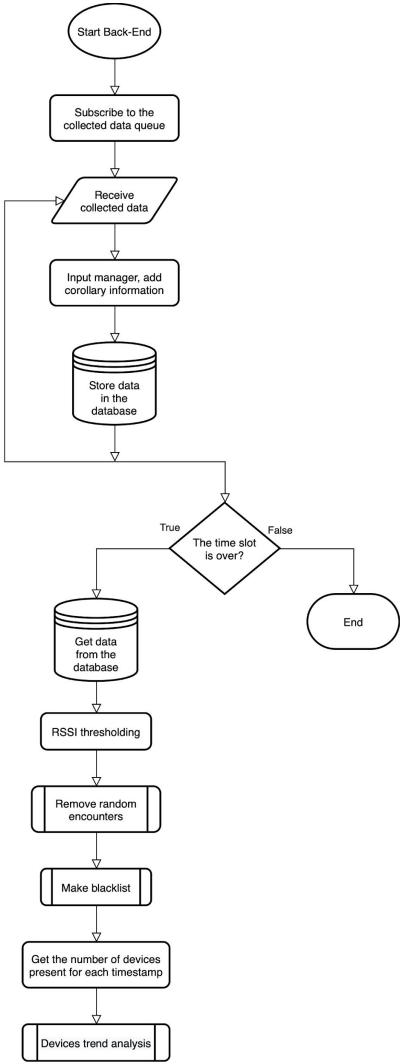
# Back-End Logic

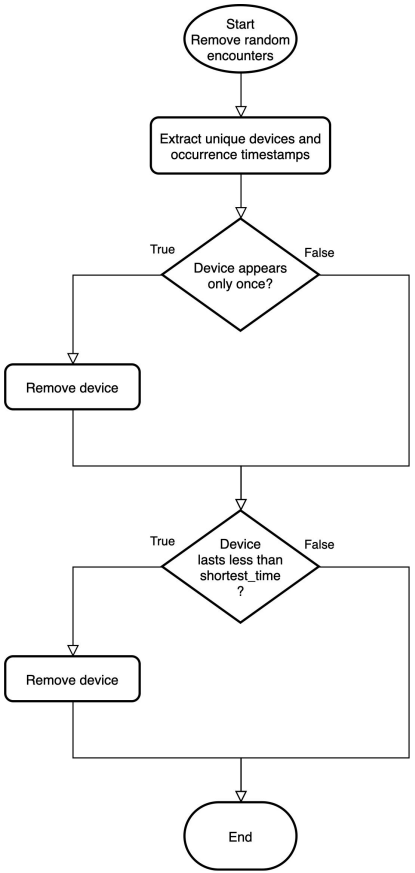
Publish to a topic → MQTT broker forwards the data to the subscribers

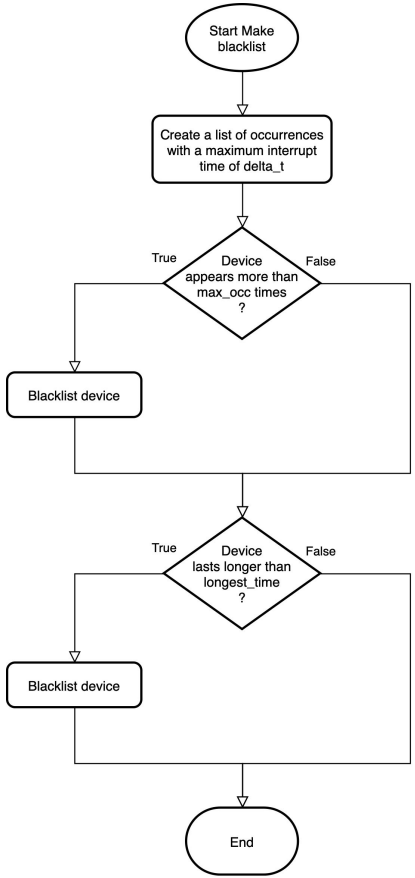
MQTT receiver in the Back-End → Subscription and storage in a database

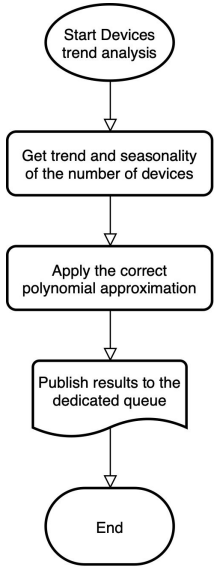
Data cleaning → RSSI threshold, random encounters, blacklist → # devices

Machine Learning algorithm → Fit degree and coefficients of polynomial approximations using trend and seasonality of the # devices → # people

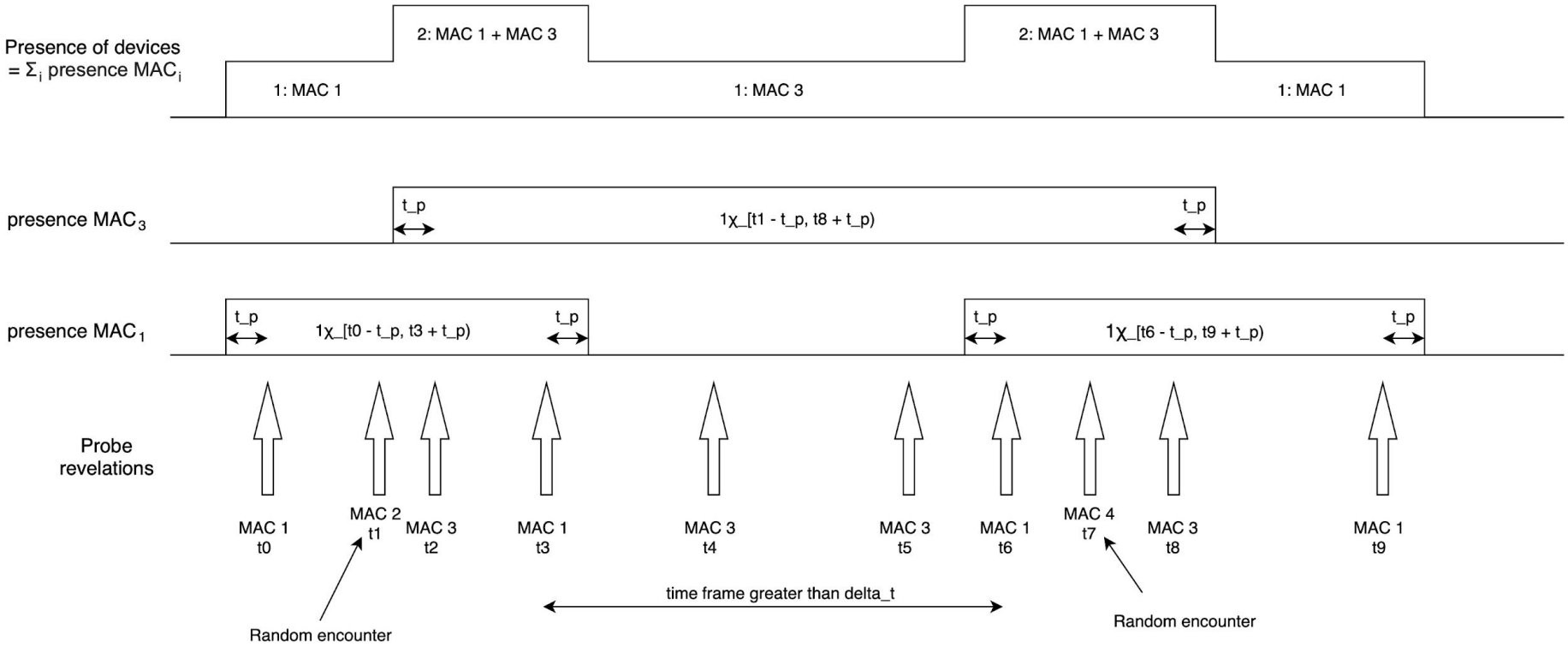

Start Back-End
Subscribe to the collected data queue
Receive collected data
Input manager, add corollary information
Store data in the database
True
The time slot is over?
False
End
Get data from the database
RSSI thresholding
Remove random encounters
Make blacklist
Get the number of devices present for each timestamp
Devices trend analysis


Start Remove random encounters
Extract unique devices and occurrence timestamps
True
Device appears only once?
False
Remove device
True
Device lasts less than shortest_time ?
False
Remove device
End

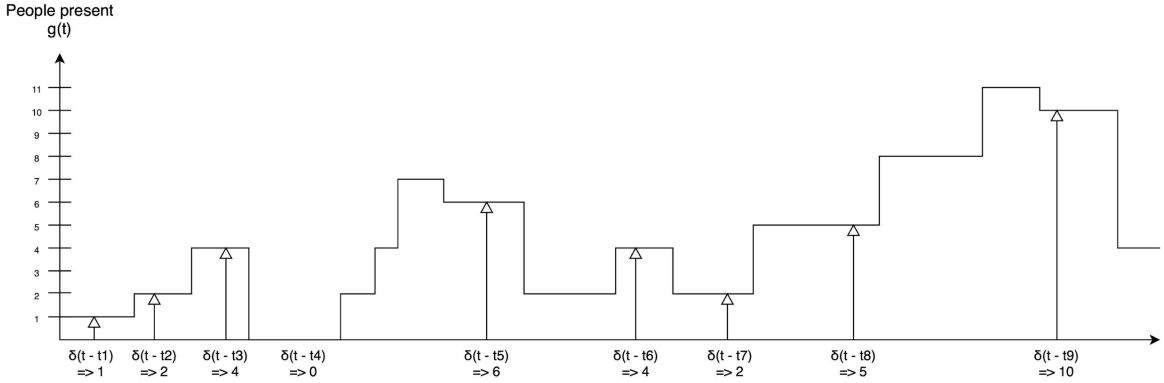

Start Make blacklist
Create a list of occurrences with a maximum interrupt time of delta_t
True
Device appears more than max_occ times ?
False
Blacklist device
True
Device lasts longer than longest_time ?
False
Blacklist device
End

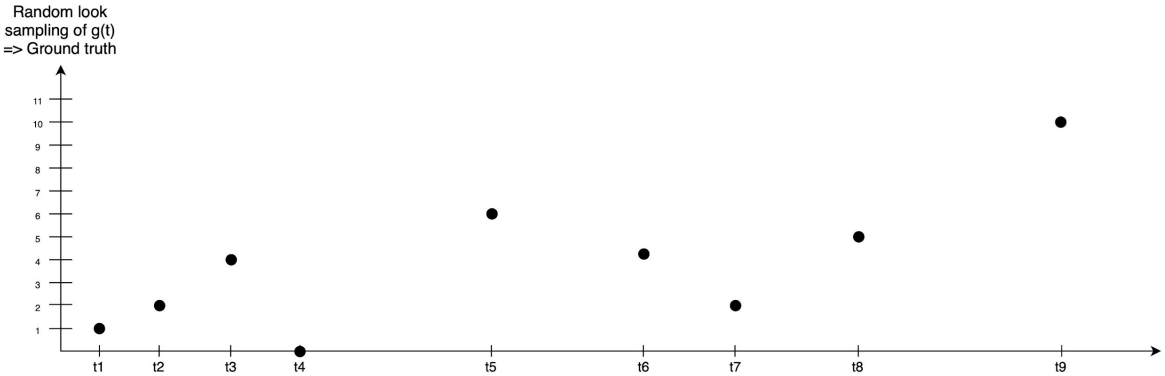

Start Devices trend analysis
Get trend and seasonality of the number of devices
Apply the correct polynomial approximation
Publish results to the dedicated queue
End

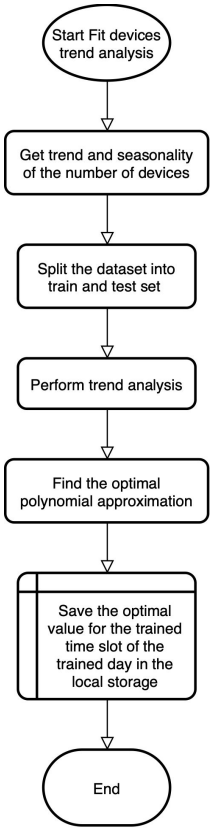
# Presence of devices



# Ground Truth Collection



# Feasibility Test at Home

| Devices | | Day 1 | | | Day 2 | | | Day 3 | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | # probes | RSSI range 1 | RSSI range 2 | # probes | RSSI range 1 | RSSI range 2 | # probes | RSSI range 1 | RSSI range 2 | |
| Wi-Fi gate | 6410 | -75 ÷ -81 | | 4959 | -65 ÷ -77 | | 4819 | -65 ÷ -75 | | omnipresent, send 2/4 probe every ~ 30 sec, static, ~ 6/7 m away |
| Smart TV | 6 | -83 ÷ -89 | | / | | | / | | | static in the living room, ~ 6/7 m away |
| PlayStation 4 | 13660 | -71 ÷ -83 | | 5 | -71 ÷ -75 | | 5 | -75 ÷ -81 | | static in the living room, ~ 6/7 m away |
| iMac | 294 | -83 ÷ -91 | | 197 | -79 ÷ -87 | | 59 | -75 ÷ -85 | | static in my bedroom, ~ 10 m away |
| MacBook | 32 | -87 ÷ -91 | -61 ÷ -67 | / | | | / | | | range 1 → far, not in the kitchen; range 2 → nearby, in the kitchen |
| Mom's Samsung | 38 | -75 ÷ -91 | | 3 | -73 ÷ -79 | | / | | | far, not in the kitchen (Wi-Fi usually turned off) |
| Grandma's Samsung | / | | | / | | | 39 | -71 ÷ -81 | -57 ÷ -65 | range 1 → far, not in the kitchen; range 2 → nearby, in the kitchen |
| Thomas's Samsung | 103 | -75 ÷ -89 | -57 ÷ -69 | 49 | -71 ÷ -79 | -51 ÷ -69 | 166 | -73 ÷ -81 | -47 ÷ -69 | range 1 → far, not in the kitchen; range 2 → nearby, in the kitchen |
| Dad's iPhone | 94 | -75 ÷ -91 | -55 ÷ -65 | 1547 | -77 ÷ -83 | -49 ÷ -67 | 1170 | -69 ÷ -83 | -35 ÷ -67 | range 1 → far, not in the kitchen; range 2 → nearby, in the kitchen |
| Mattia's iPhone | 1377 | -77 ÷ -91 | -59 ÷ -75 | 978 | -75 ÷ -85 | -49 ÷ -65 | 2051 | -73 ÷ -85 | -49 ÷ -67 | range 1 → far, not in the kitchen; range 2 → nearby, in the kitchen |
| My iPhone | 40 | -79 ÷ -91 | -65 ÷ -67 | 54 | -73 ÷ -85 | 59 | 98 | -73÷ -83 | -53 ÷ -67 | range 1 → far, not in the kitchen; range 2 → nearby, in the kitchen |
| Printer | / | | | 1 | -81 | | / | | | static in my bedroom, ~ 10 m away |
| Other Wi-Fi dongle | / | | | 13084 | -19 ÷ -23 | -37 ÷ -63 | 12188 | -19 ÷ -23 | -37 ÷ -61 | another Wi-Fi dongle, 1/2 probe every 6/7 sec → value swings sometimes |
| Samsung Galaxy J3 | 17 | -85 ÷ -91 | | / | | | / | | | non-home device |
| Samsung Galazy A20e | / | | | 1 | -83 | | / | | | non-home device |
| Randomized MACs | 626 | | | 568 | | | 1190 | | | probes with randomized MAC address, vague values of the RSSI |
| | | | | | | | | | | |
| Total | 22698 | | | 21445 | | | 21785 | | | average of 22000 Wi-Fi probe request frames for ~ 18 hours |

3 days of data collection, ~66.000 Wi-Fi PRF → detecting devices in the area

# Validation

→ Raspberry Pi in a Cafe where I annotate manually the ground truth

→ Eclipse Mosquitto Broker MQTT of U-Hopper on their server

→ MQTT receiver and MongoDB on U-Hopper server using Docker containers and using a volume for persisting data

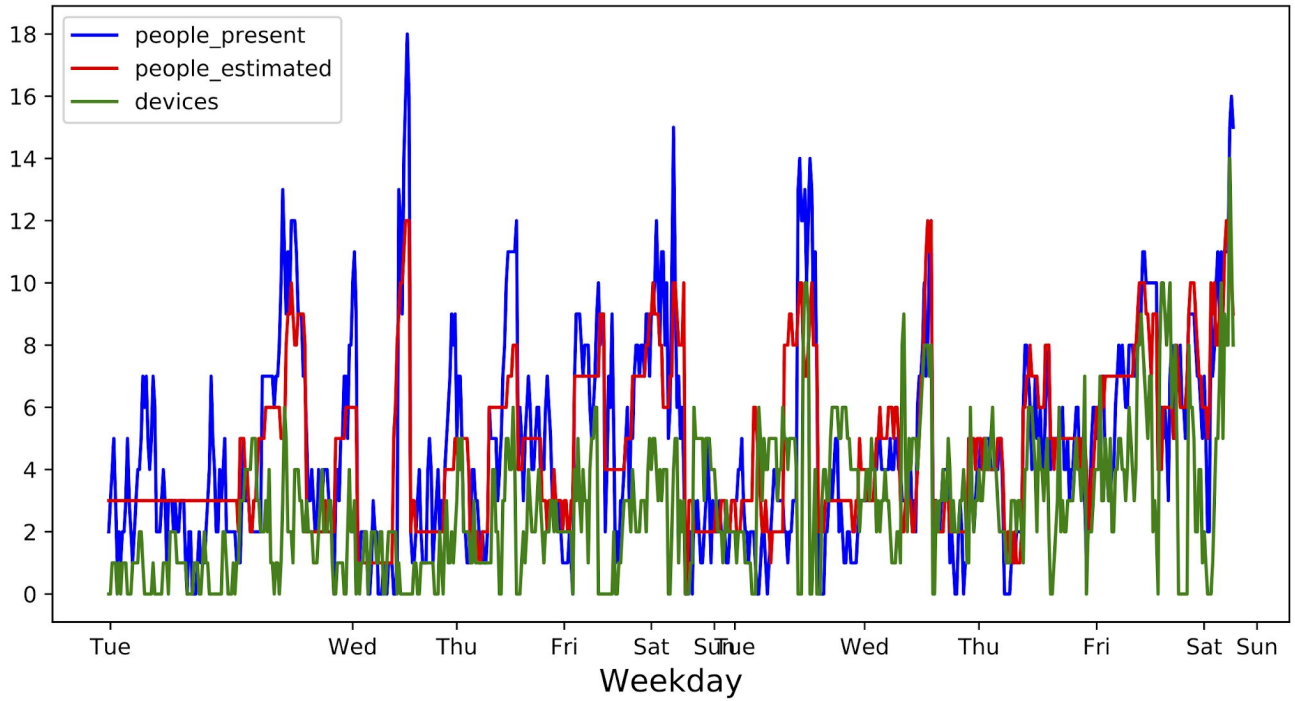
→ Analyzer/Estimator on my pc to use on the volume + collected ground truth to test accuracy and reliability of the proposed system

# Results

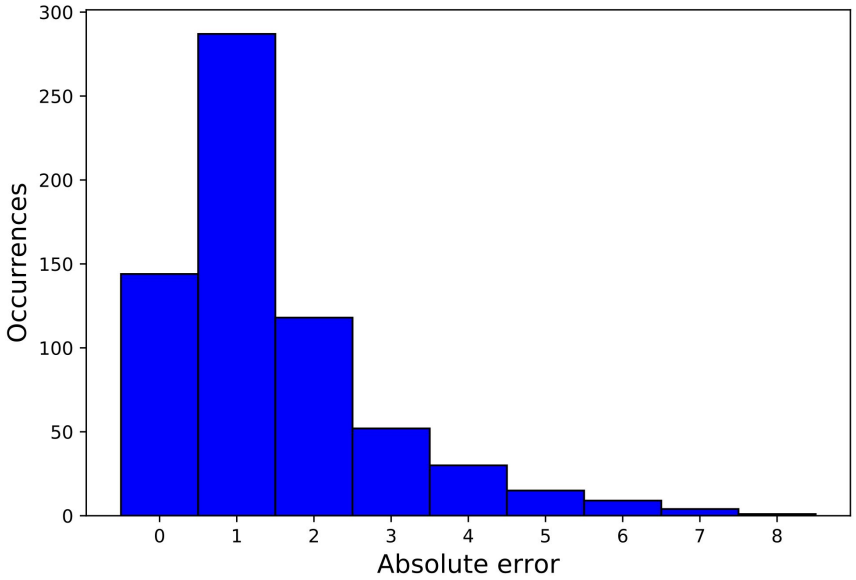
| | 2020-06-16 | 2020-06-17 | 2020-06-18 | 2020-06-19 | 2020-06-20 | 2020-06-21 | | Total1 |
|---|---|---|---|---|---|---|---|---|
| Probe captured | 24011 | 19329 | 22533 | 23041 | 19062 | 11238 | | 119214 |
| Ttotal MACs | 1489 | 873 | 1281 | 1307 | 1447 | 1187 | | 7584 |
| MACs only registered once | 909 | 504 | 753 | 852 | 1002 | 634 | | 4654 |
| MACs lasted shorter than 20 seconds | 443 | 280 | 395 | 344 | 342 | 447 | | 2251 |
| MACs occurred more than 10 times throughout the day | 2 | 3 | 3 | 3 | 2 | 0 | | 13 |
| MACs lasted longer than 7200 seconds in any of it's occurrences | 4 | 2 | 5 | 5 | 4 | 3 | | 23 |
| MACs remained | 131 | 84 | 125 | 103 | 97 | 103 | | 643 |
| Manual annotations | 116 | 61 | 63 | 51 | 37 | 12 | | 340 |
| | | | | | | | Mean Absolute Error | 1.461 |
| | | | | | | | Mean Squared Error | 4.039 |
| | | | | | | | Scaled_MAE_trend/count | 0.448 |
| | | | | | | | Scaled_MSE_trend/count | 0.700 |

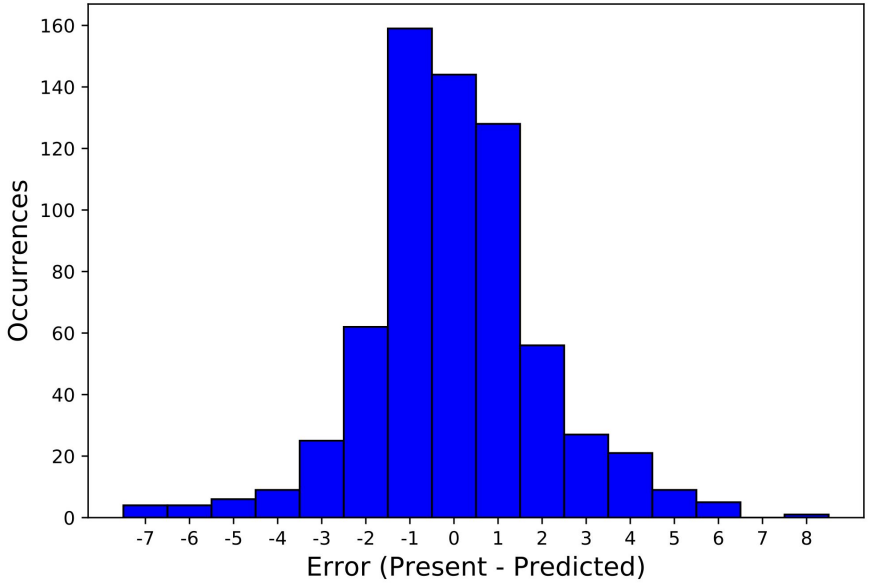
| 2020-06-23 | 2020-06-24 | 2020-06-25 | 2020-06-26 | 2020-06-27 | 2020-06-28 | | Total2 | Total |
|---|---|---|---|---|---|---|---|---|
| 45730 | 56835 | 58203 | 61900 | 28941 | 19768 | | 271377 | 390591 |
| 1579 | 2260 | 2293 | 2282 | 1182 | 715 | | 10311 | 17895 |
| 333 | 490 | 509 | 462 | 242 | 106 | | 2142 | 6796 |
| 1060 | 1568 | 1543 | 1577 | 805 | 517 | | 7070 | 9321 |
| 0 | 2 | 1 | 2 | 0 | 0 | | 5 | 18 |
| 6 | 5 | 6 | 8 | 3 | 3 | | 31 | 54 |
| 180 | 195 | 234 | 233 | 132 | 89 | | 1063 | 1706 |
| 76 | 67 | 69 | 63 | 31 | 14 | | 320 | 660 |
| | | | | | | Mean Absolute Error | 1.461 | 1.461 |
| | | | | | | Mean Squared Error | 4.039 | 4.039 |
| | | | | | | Scaled_MAE_trend/count | 0.448 | 0.448 |
| | | | | | | Scaled_MSE_trend/count | 0.700 | 0.700 |

# Results

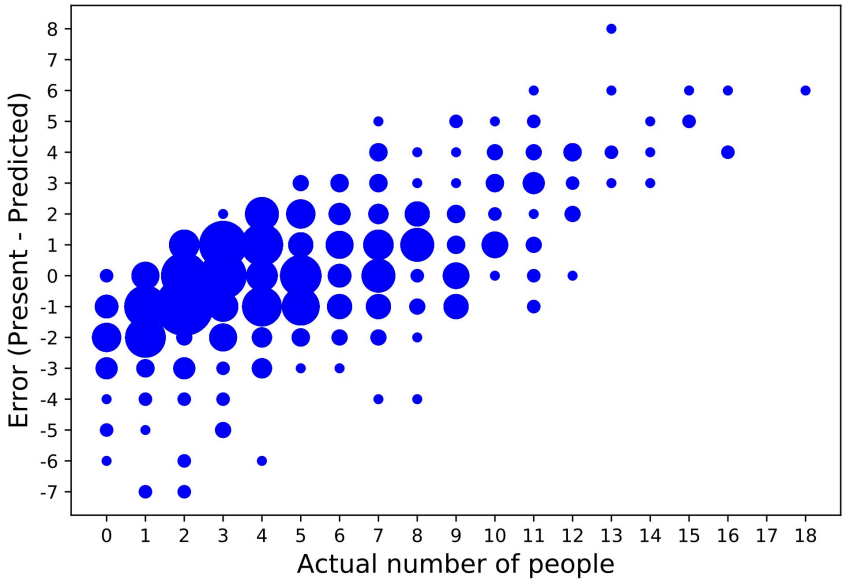

people_present
people_estimated
devices
18
16
14
12
10
8
6
4
2
0
Tue
Wed
Thu
Fri
Sat
Sun
Tue
Wed
Thu
Fri
Sat
Sun
Weekday

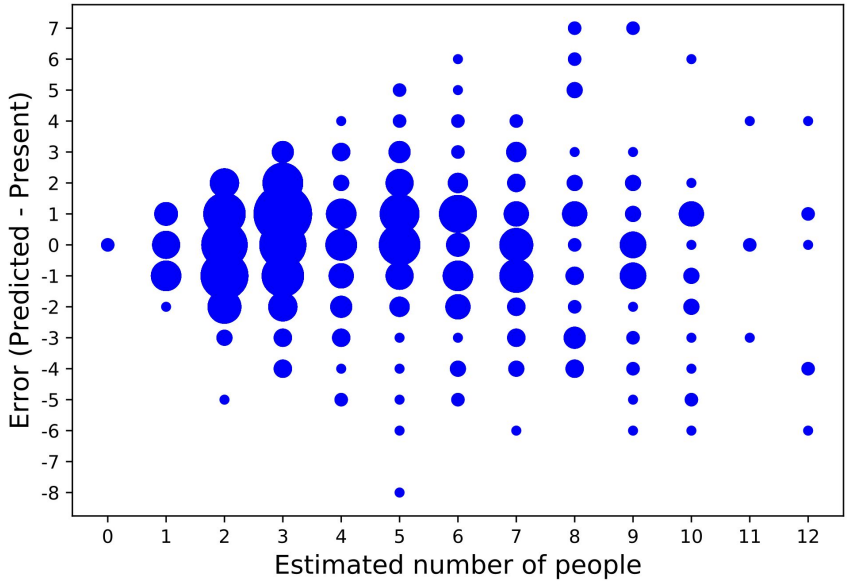
# Results


Occurrences
Absolute error
0
50
100
150
200
250
300
0
1
2
3
4
5
6
7
8


Occurrences
Error (Present - Predicted)
0
20
40
60
80
100
120
140
160
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8

# Results


Error (Present - Predicted)
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Actual number of people


Error (Predicted - Present)
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
0 1 2 3 4 5 6 7 8 9 10 11 12
Estimated number of people


# Summary

→ It is possible to continuously estimate the number of people based on the Wi-Fi probe request frames

→ Designed and developed a system to do that

→ Tested the system in a Cafe and collected 4 weeks of data and manually-annotated ground truth


# Future Works

→ Real-Time integration

→ Test the system in different context

→ Improve the Machine Learning model