Communication Technologies 2 (CT2)

Machine Learning:

Applications and Algorithms

Wi-Fi Fingerprinting

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Lecture in WS 2018 / 2019
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Outline

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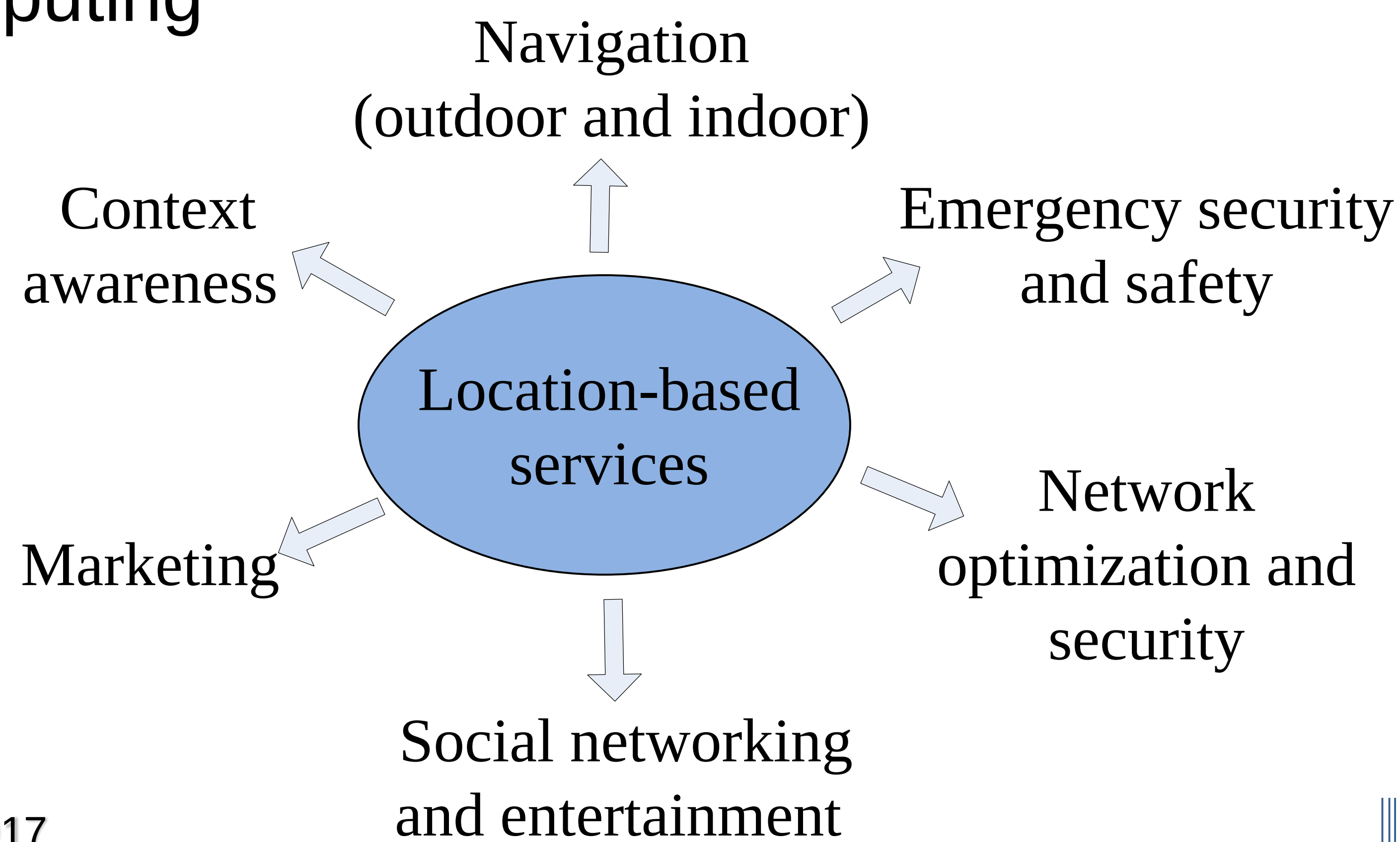
- Location-based services
- Indoor positioning
- Wi-Fi based positioning
- Wi-Fi fingerprinting system
- DCCLA algorithm
- Challenges

Location-based Services

- The location information provided is now one of the most important contexts for context-aware computing



The Global Positioning System (GPS)

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- Widely used for providing positioning services.
- Require line-of-sight (LoS) transmission with the GPS satellites.
- Poor coverage for indoor environments

Source: http://www.mio.com/

Free-space Path Loss

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- Assume there are no obstructions between the transmitter and receiver. The signal propagates along a straight line
- Free-space path loss is defined as the path loss of the free-space model:

$$P_L\,(\mathrm{dB}) = 10\log_{10}\frac{P_t}{P_r} = -10\log_{10}\frac{G_l\lambda^2}{(4\pi d)^2}.$$

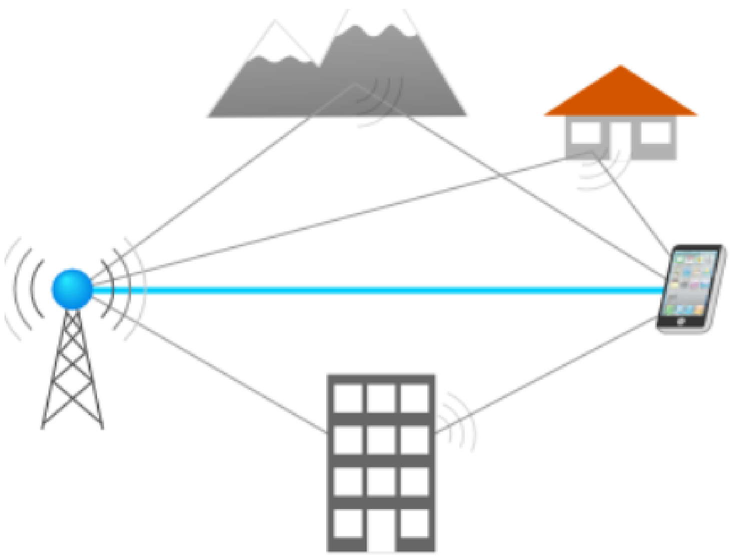
d: distance between the transmit and receive antennas

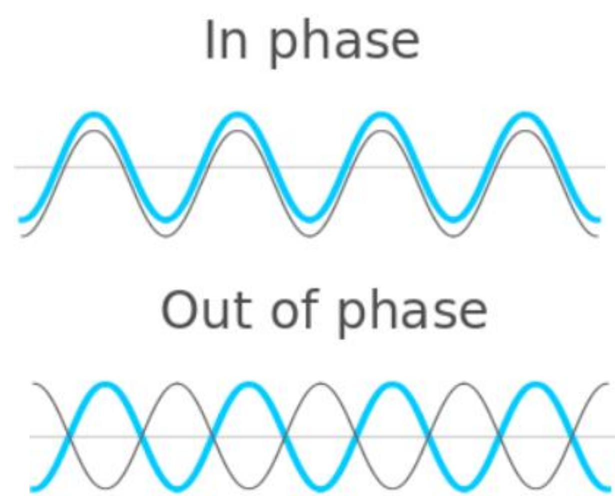
ʎ: the wavelength of the transmitted signal

G_l: the product of the transmit and receive antenna gains

Free-space Path Loss

- Difficult to model the radio propagation in the indoor environment:
  - Multipath, fading
  - non light-of-sight transmission because of obstacles





Source:
http://wiki.yatebts.com/index.php/Radio_Propagation_Concepts

Indoor Positioning

- Different locations can be distinguished by particular features surrounded those locations
  - light, noise, temperature
  - radio signals: Bluetooth, GSM or Wi-Fi
- Good characteristic help to recognize different locations.
- The selected characteristic should be stable over time.

Wi-Fi Positioning System

- Uses the received signal strengths (RSS) from surrounded access points (AP) to locate a mobile node.
- Two methods of using the Wi-Fi RSS to determine a receiver's position
  - lateration methods
  - fingerprinting methods

Methods & positioning principle

- Time of Arrival (TOA)
- Time Difference of Arrival (TDOA)
- RSS-Based (Signal Attenuation-Based)
- Roundtrip time of flight of the signal (RTOF)
- Angulation estimation (AOA Estimation)
- Receive Signal Strength (RSS)

Trilateration methods

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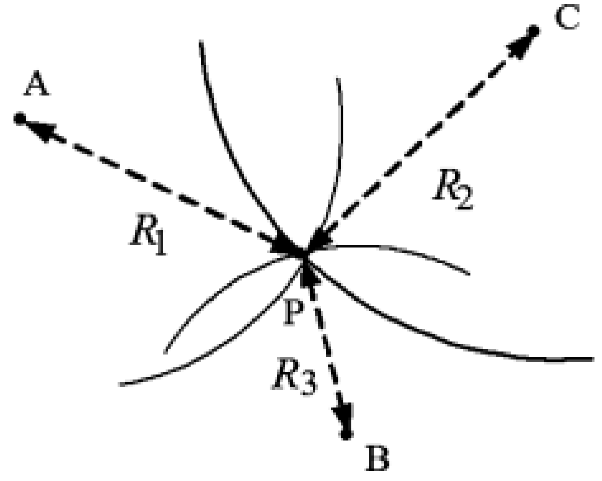
- Time of Arrival (TOA)
  - Measure the propagation time
  - Calculate the distance between the receiver and the transmitter.
  - The clock of transmitters and receivers must be precisely synchronized

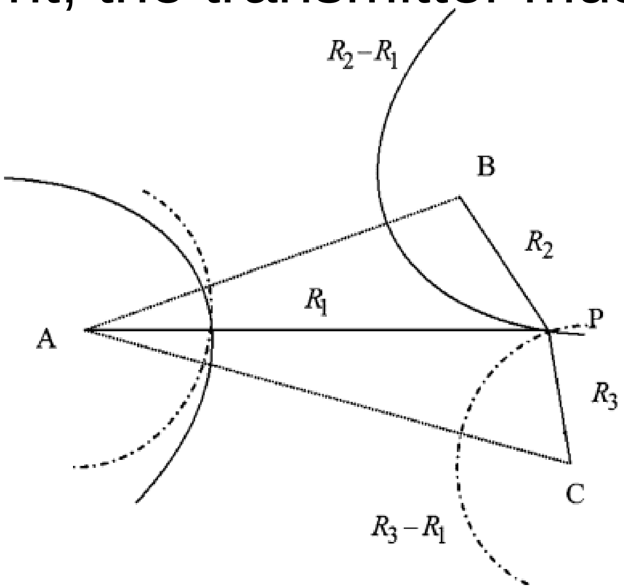


Positioning based on TOA/RTOF measurements.

Source: [2]

Trilateration methods

- Time Difference of Arrival (TDOA)
  - the time difference to send signal to multiple receivers
  - The hyperbolic has a constant range difference between the two measuring units.
  - For each TDOA measurement, the transmitter must lie on a hyperbolic.



Source: [2]

Trilateration methods

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- RSS-Based (Signal Attenuation-Based)
    - Calculate the attenuation of emitted signal strength
    - Base on the signal path loss model, estimate the travel distance
- Roundtrip time of flight of the signal (RTOF)
    - Measure the propagation time from the transmitter to the receiver and back

Fingerprinting method

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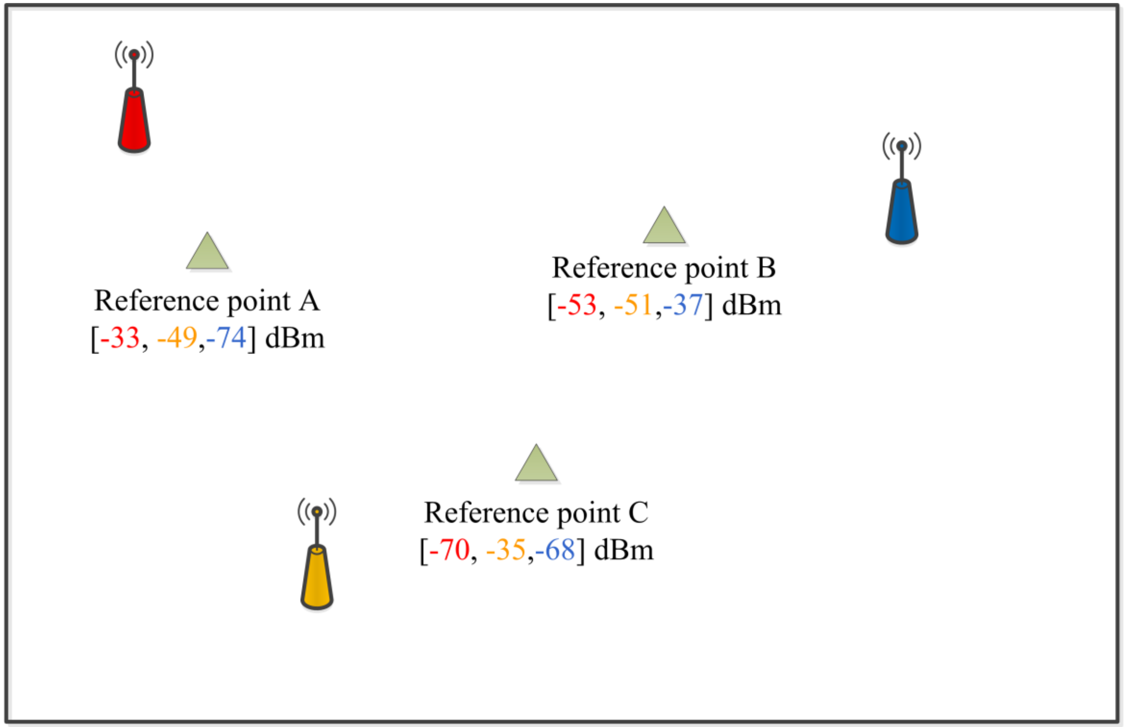
- Human fingerprint is unique
  - Collect human fingerprint and store in a database
  - To identify any person, compare his/her fingerprint with the fingerprinting database.

Source: [1]

Wi-Fi signal

ComTec

- MAC address
- Receive signal strength (RSS)
- Service set identifier (SSID)
- Channel (frequency)



Wi-Fi signal

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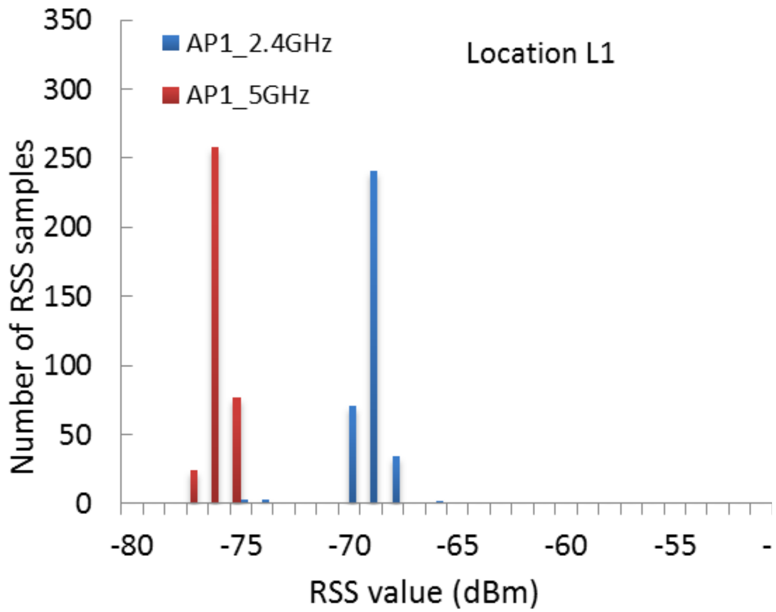
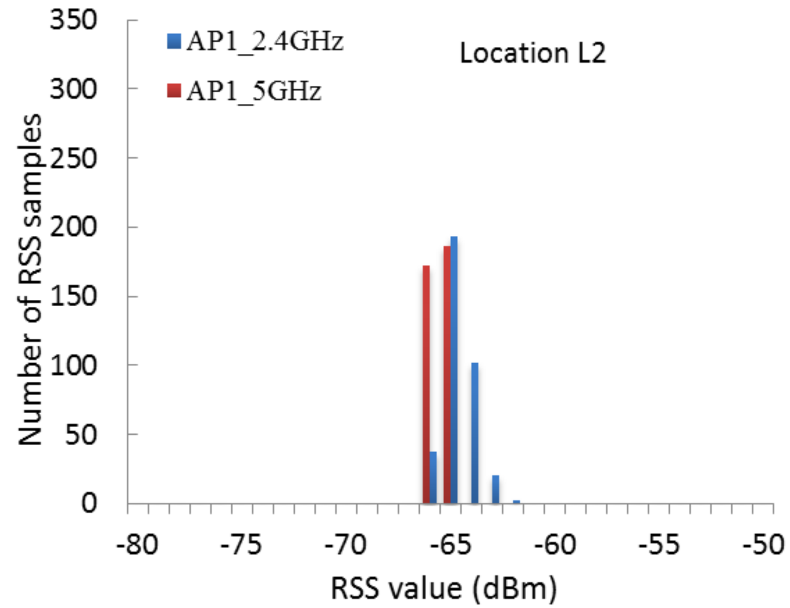
Source: [1]

Wi-Fi signal

ComTec





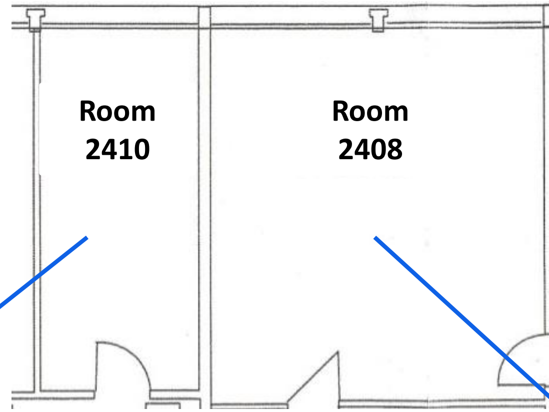
Wi-Fi RSS histogram in 2 adjacent rooms

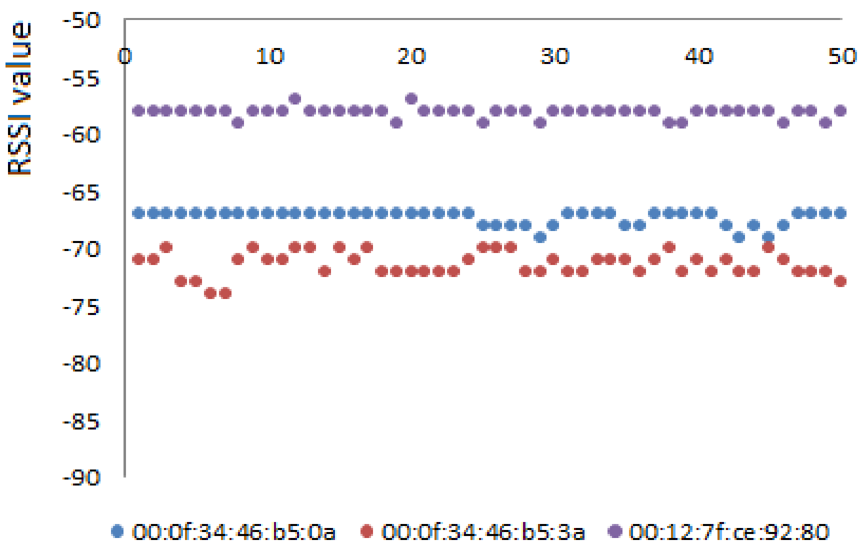
Wi-Fi fingerprinting

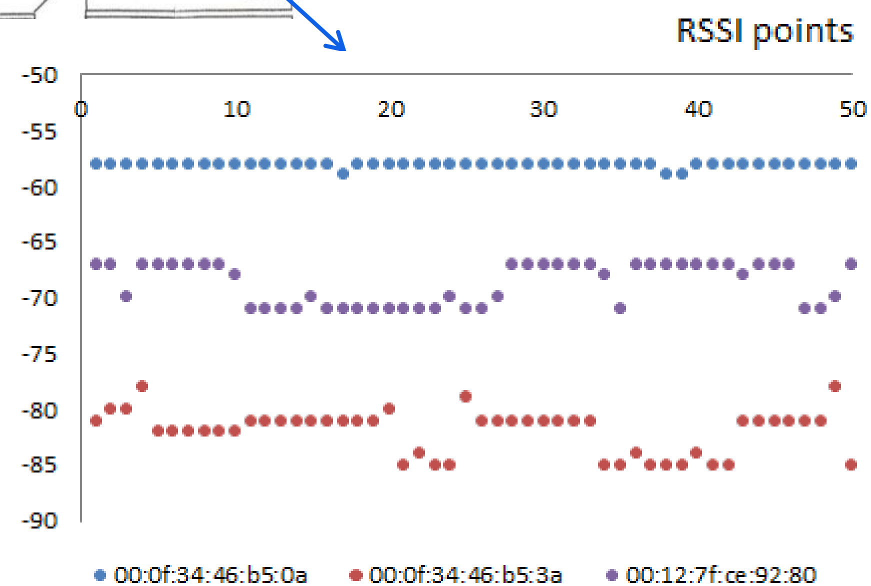
- The fingerprinting technique uses location specific RSSI pattern of neighboring WLAN APs to distinguish different locations
- Not require the dedicated infrastructure installation.
  – Easy to implement
  – Reduce cost

Wi-Fi fingerprinting

What is
Wi-Fi Fingerprint





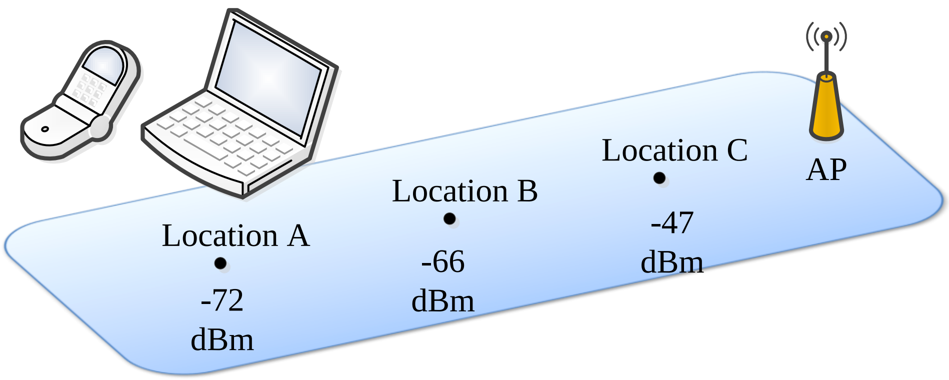


Wi-Fi fingerprint

RSSI: Received Signal Strength Indicator

Concepts

- Wi-Fi fingerprint
  - Wi-Fi information sensed at a location



Concepts

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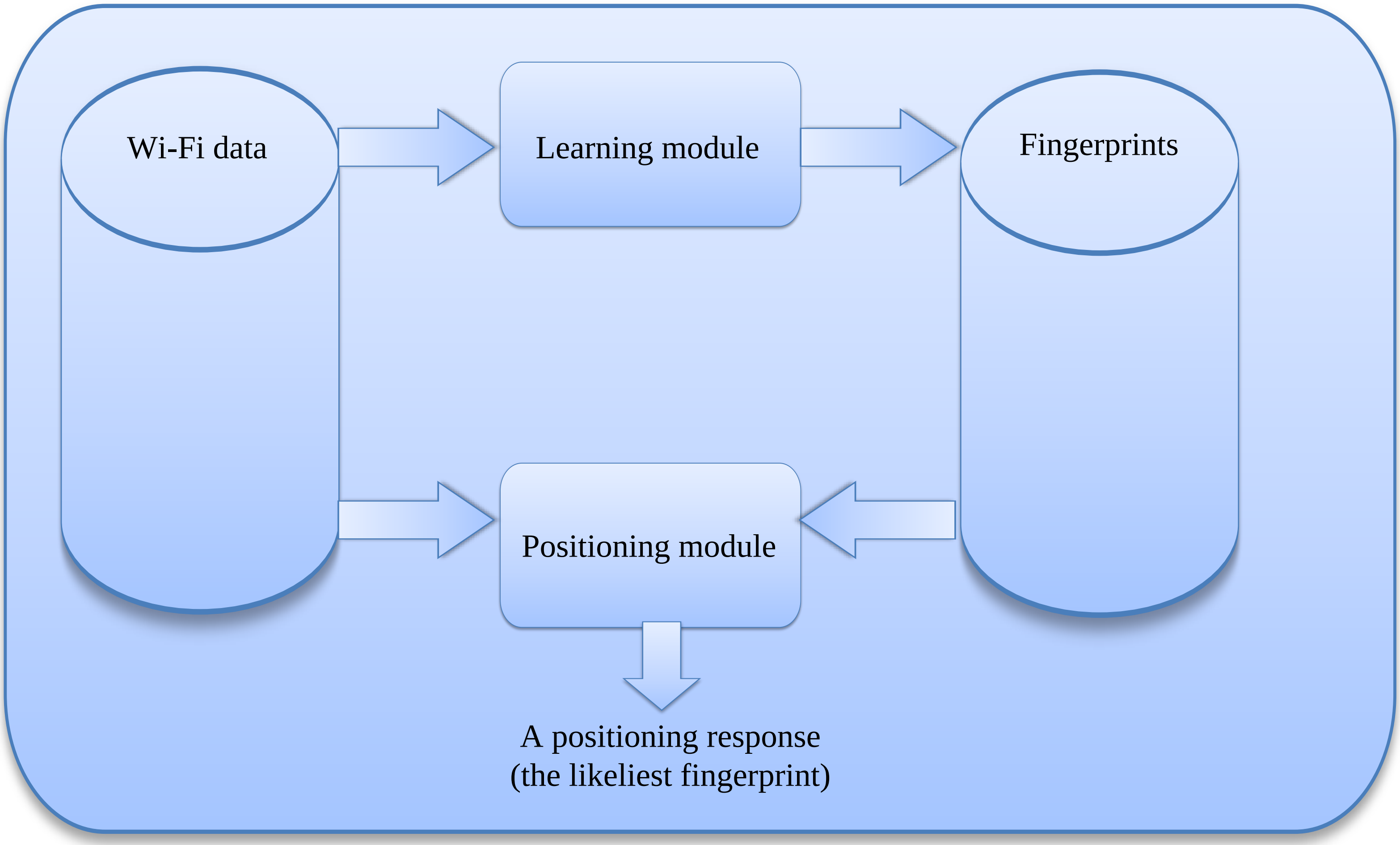
- Wi-Fi fingerprint
  - Wi-Fi information sensed at a location
- Wi-Fi fingerprinting
  - practice of recording the fingerprint of Wi-Fi signal
  - the method of finding the particular pattern of Wi-Fi signal in a particular location
- Wi-Fi fingerprint database
  - a database which contains the generated fingerprints
  - radio map

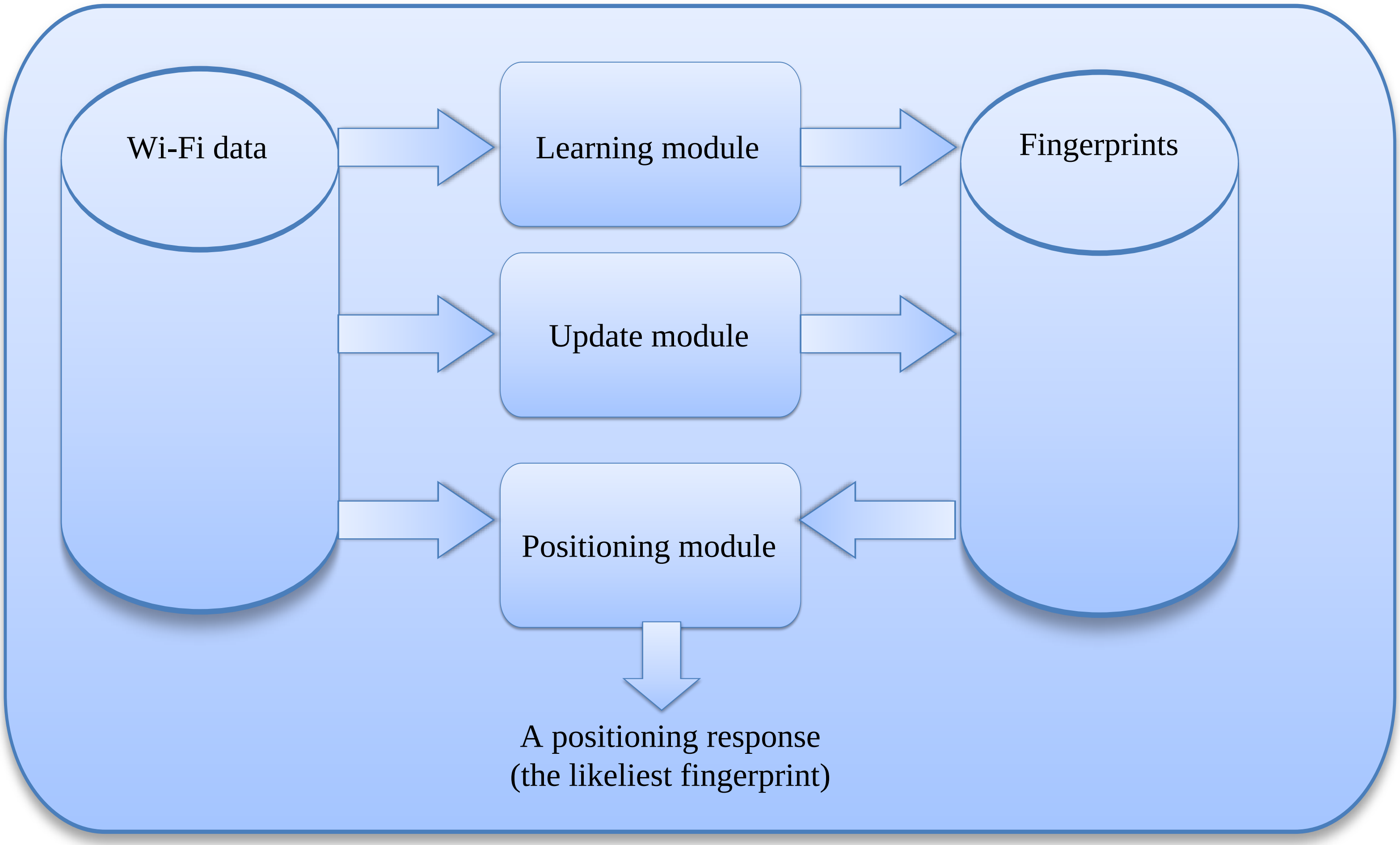
Overview of Wi-Fi fingerprinting System



Source: [1]

Overview of Wi-Fi fingerprinting System

ComTec



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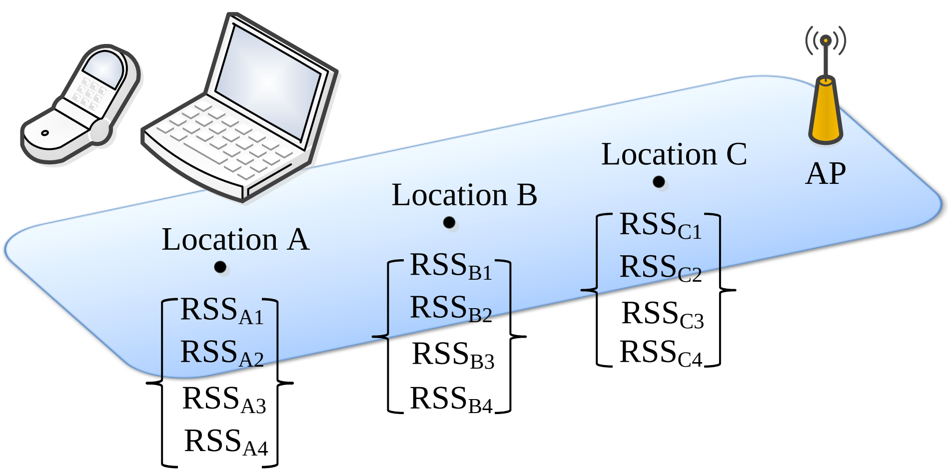
Overview of Wi-Fi fingerprinting System

- Learning phase (training, offline phase)
  - Collecting Wi-Fi data
  - Generating Wi-Fi fingerprint: building a database containing Wi-Fi fingerprints



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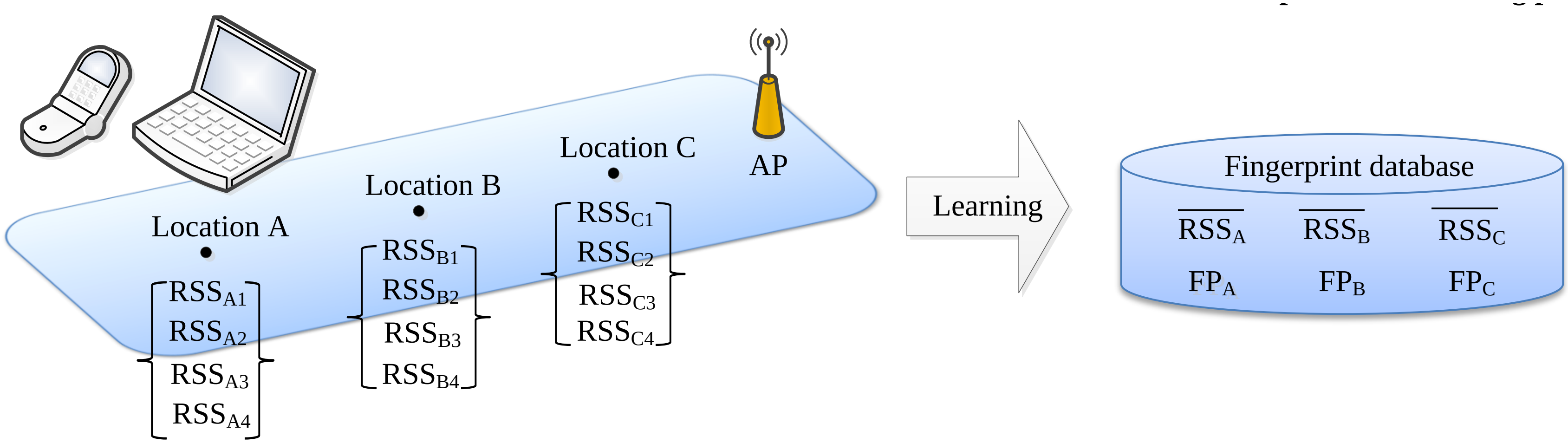
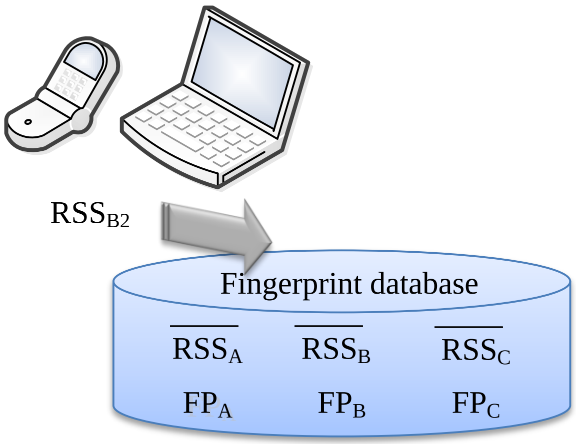


Source: [1]

Overview of Wi-Fi fingerprinting System

- Positioning phase (testing, online phase)
  - Comparing the current Wi-Fi scans with the FP database to infer the location



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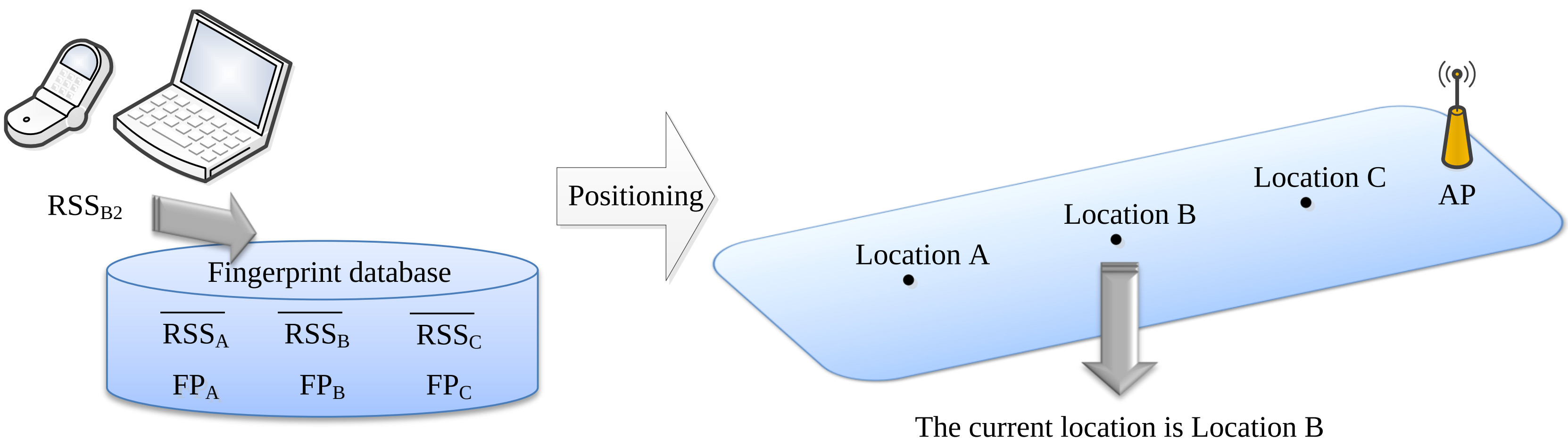

Source: [1]

Components of Wi-Fi fingerprinting System

- Wi-Fi APs
  - broadcast Wi-Fi signal
- Mobile devices
  - collect the Wi-Fi RSS from APs
  - manage fingerprint database
  - execute the learning and positioning algorithms
  - user interface (UI)
- Users
  - carry the mobile device in their daily lives
  - interact with the mobile device through the UI.

Components of Wi-Fi fingerprinting System

- Wi-Fi APs
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  - carry the mobile device in their daily lives
  - interact with the mobile device through the UI.

May be done on a computer

Scanning methods

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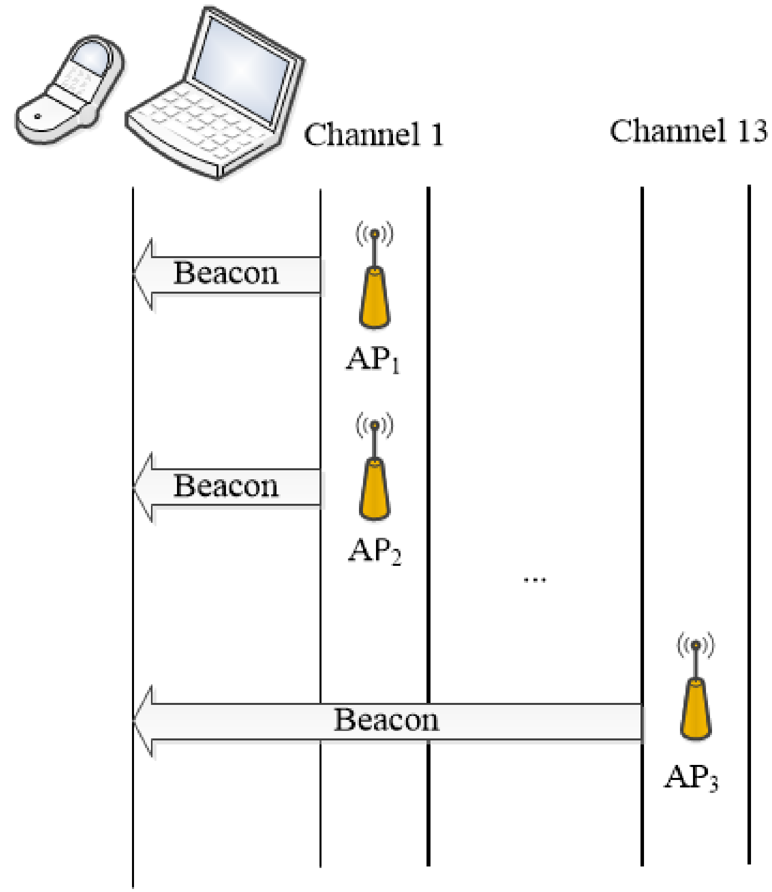
- Passive scanning
  - Moves to each channel in the channel list
  - Listen to the beacon frames from nearby APs



Passive scanning

Source: [1]

Scanning methods

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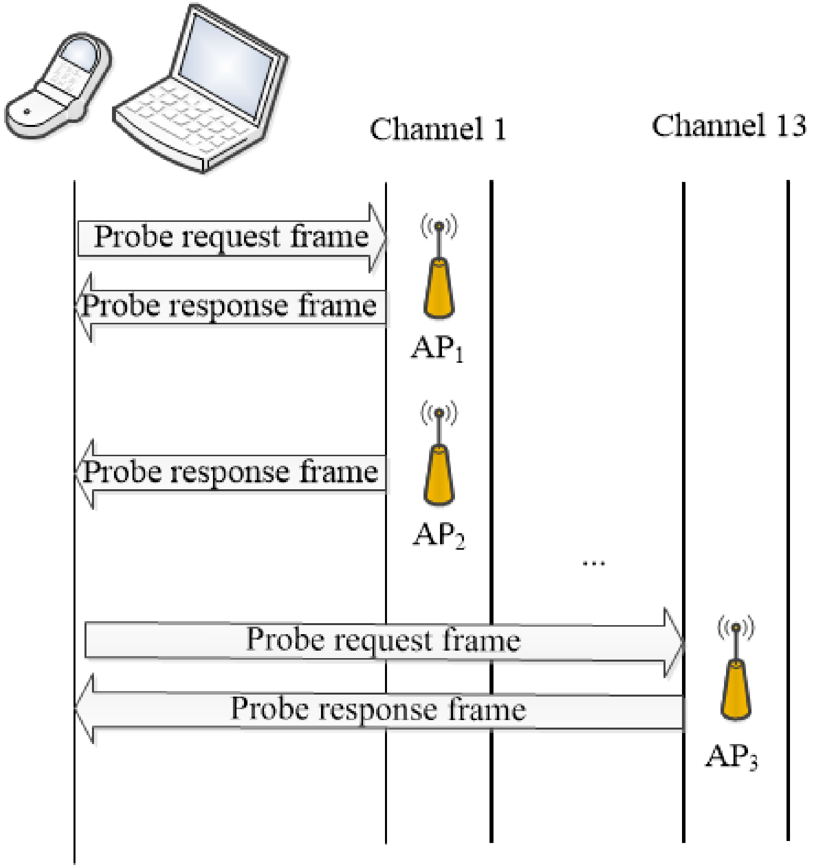
- Active scanning:
  - Mobile device transmits a Probe Request frame on each of the channel
  - Wait to receive response from any APs
  - Move on to the next channel
  - This process is iterated until all channels have been scanned



Active scanning

Source: [1]

Wi-Fi collection approaches

- Grid-based
  - split a selected area into many small grids
  - measure Wi-Fi signal in those grids
- Interpolation-based
  - measure Wi-Fi data in observed locations
  - based on the fingerprints of the observed locations, interpolate fingerprints for other locations
- Path survey (War-driving)
  - collect Wi-Fi data when moving
  - record the walking distances at the same time

Wi-Fi collection approaches

- Dead Reckoning
  - infer location based on previously determined locations
  - combine with the traveled distance and the direction of movement
- Place learning
  - discover the significant locations where people spend much time by analyzing various sensor data
- Crowdsourcing
  - Using raw Wi-Fi data, fingerprints contributed by different users, devices

Learning approaches

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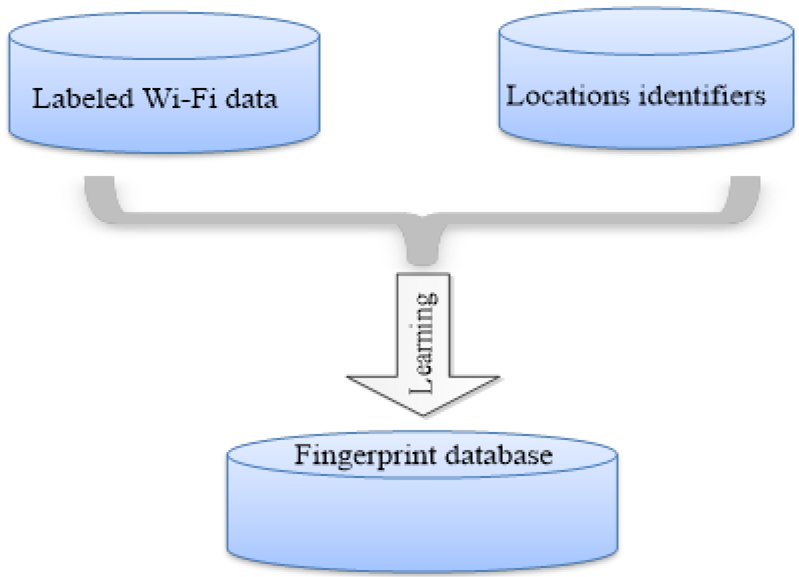
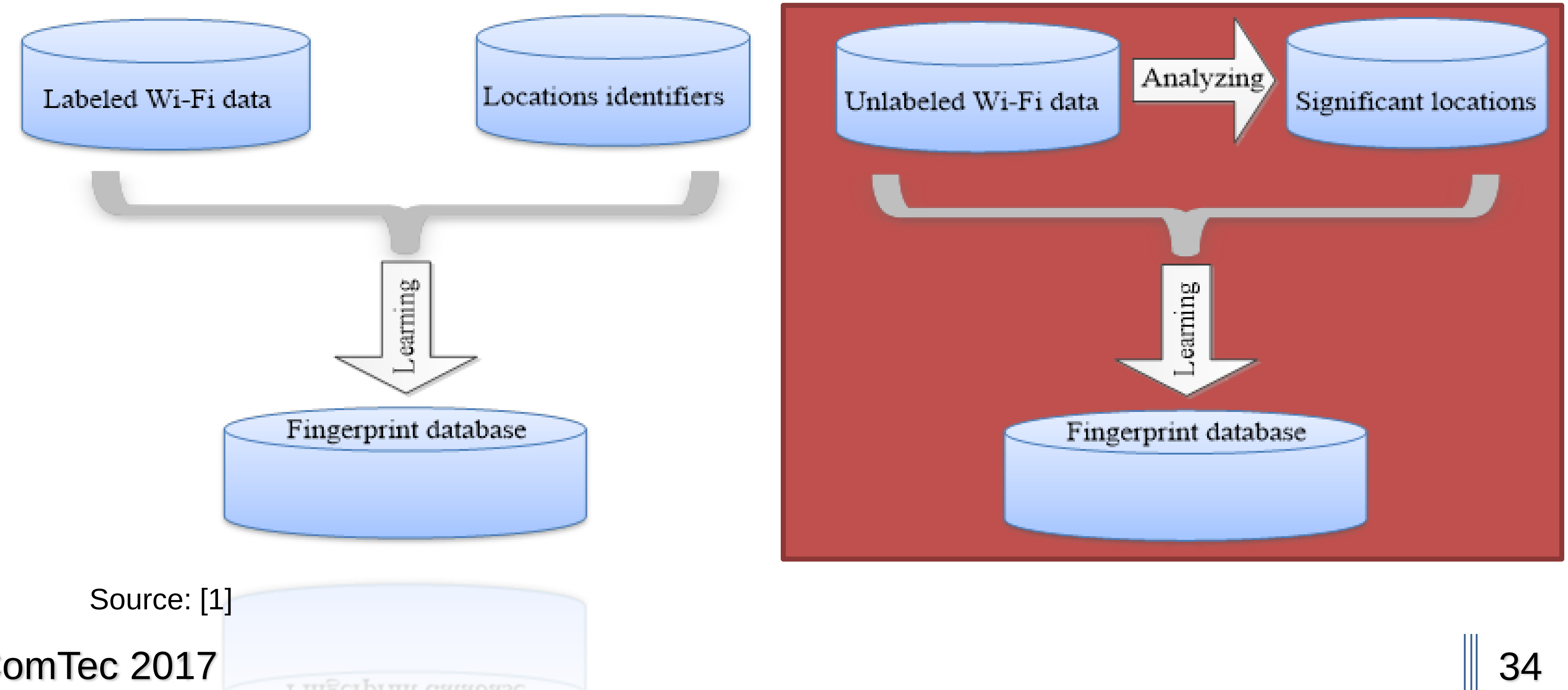
- Supervised
- Semi supervised



Source: [1]

Learning approaches

- Supervised
- Semi supervised
- Unsupervised



Source: [1]

Fingerprint feature

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MAC$_i$: MAC address of AP$_i$
$\overline{RSS_i}$: averaged received signal strength of AP$_i$

- Deterministic technique
  - Mean RSS value

$$FP_l = \{MAC_1:\overline{RSS_1}, \dots\ MAC_p:\overline{RSS_p}\} \mid (p \in \mathbb{N}_+)$$

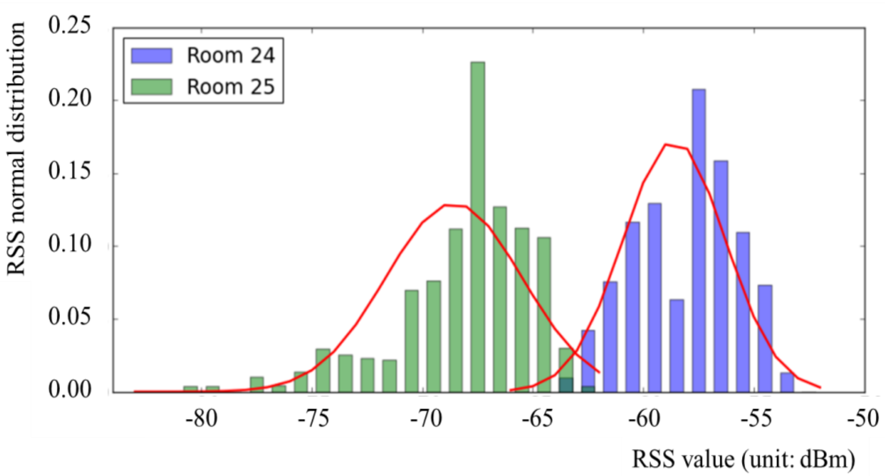
  - Wi-Fi scan

$$S_l^i = \{MAC_1: RSS_1^i, \dots, MAC_p: RSS_p^i\} \mid (i, p \in \mathbb{N}_+)$$

  - RSS range

```
00:24:fe:04:b2:d3 : [-58,-66]
00:24:fe:ac:72:02 : [-71,-79]
```

  - RSS histogram



Source: [1]

Fingerprint feature

ComTec

- Deterministic technique
  - Wi-Fi ratio: the RSS ratio between pairs of APs

$$r(AP_i, AP_j) = \frac{RSS_i}{RSS_j} \mid (i, j \in \mathbb{N}_+;\ i < j)$$

  - RSS difference: the differences between pairs of APs

$$d(AP_i, AP_j) = RSS_i - RSS_j \mid 1 \leq i < j \leq n$$

  - AP rank: rank values are assigned to APs based on their RSS

$$FP_l = \{1: MAC_i, \ldots, p: MAC_j\} \mid (RSS_i \geq RSS_j;\ i, j, p \in \mathbb{N}_+)$$

-The response rate: the times of sensing the AP divided by the times of scans.

MAC_i: MAC address of AP_i
RSS_i: received signal strength of AP_i

Fingerprint feature

- Probabilistic technique
  - Gaussian distribution
    - In case the RSS values of an AP are distributed as a Gaussian model.
    - A statistical signature, as a fingerprint, is generated for each location by using the Gaussian model.
  - Non-Gaussian distribution
    - In case the RSS distribution is non-Gaussian, an improved double-peak Gaussian distribution has been proposed to approximate the RSS distribution.
  - Log-normal distribution
    - The RSS distribution may be asymmetric

Accuracy

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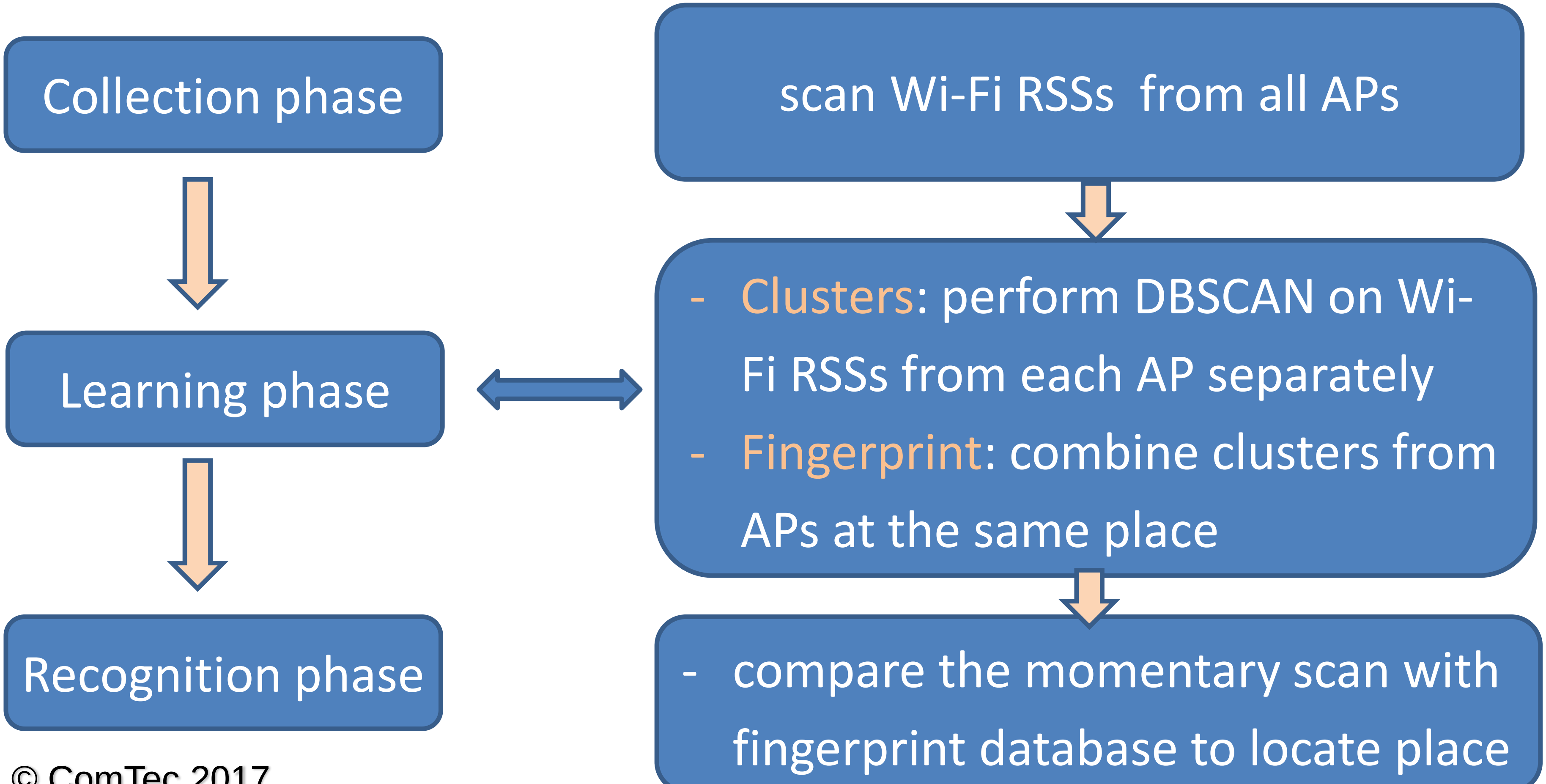
- In meter
  - how close is the estimated location to the true location indicated as *error distance (m)*
- Room level
  - locating a user within a room

DCCLA algorithm

- Wi-Fi Fingerprinting-based localization
- Unsupervised Density-based Clustering method



Density-based clustering

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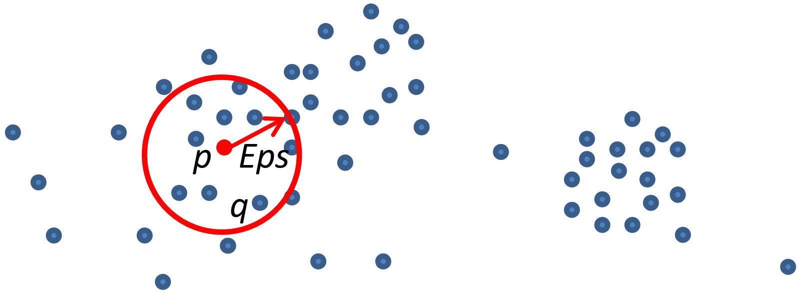
- the *density-based spatial clustering of applications with noise* (DBSCAN) algorithm utilizes concepts of *neighborhood* and *neighborhood-density to extract clusters*.
- 2 parameters
  - *Eps*: radius of the neighborhood
  - *MinPts*: minimum number of points in a cluster



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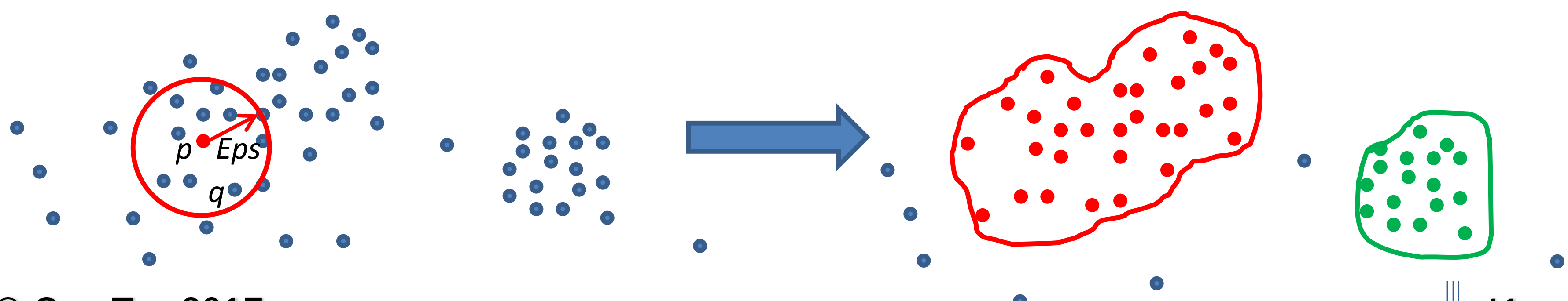
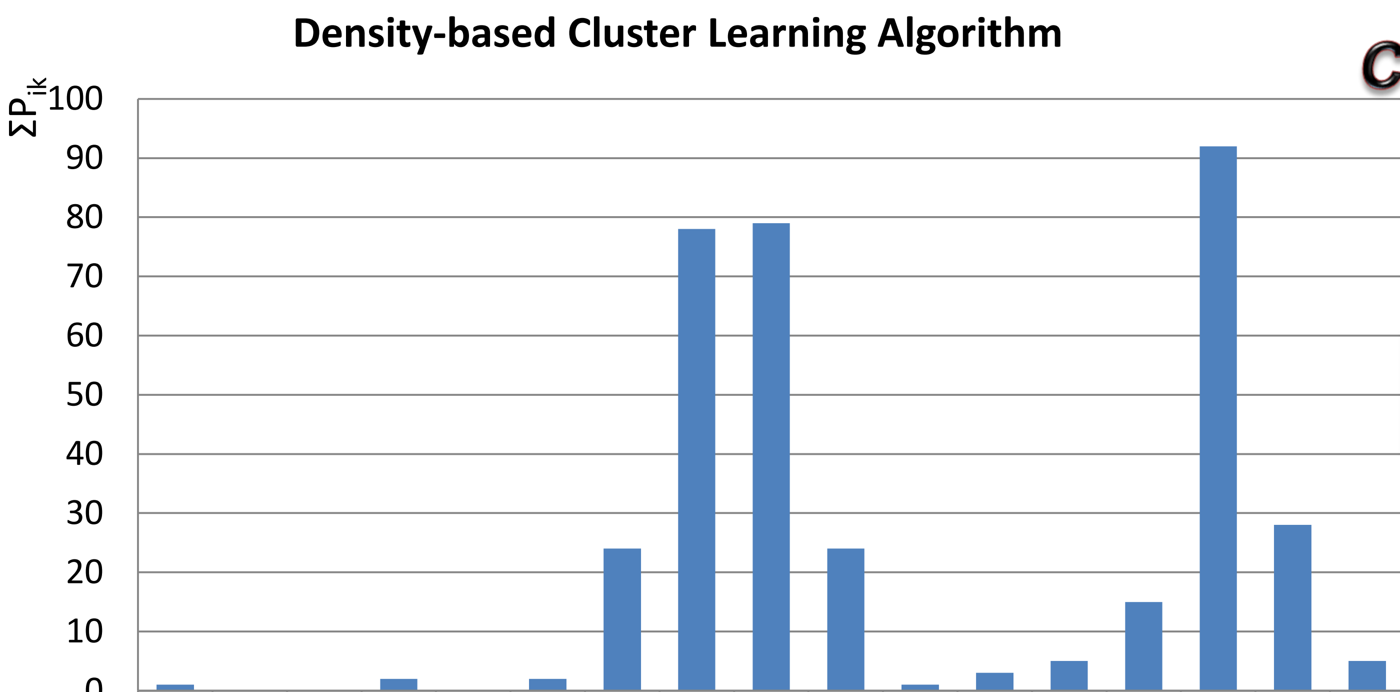


Wi-Fi clustering using DBSCAN

- Discover clusters
  - perform DBSCAN on each AP to discover high-density clusters.
  - cluster: consecutive RSS range with high RSS density
- Fingerprint
  - Clusters appear at the same time from different APs

Wi-Fi clustering using DBSCAN

ComTec



Clusters ?

NR = 2
MinPts = 120

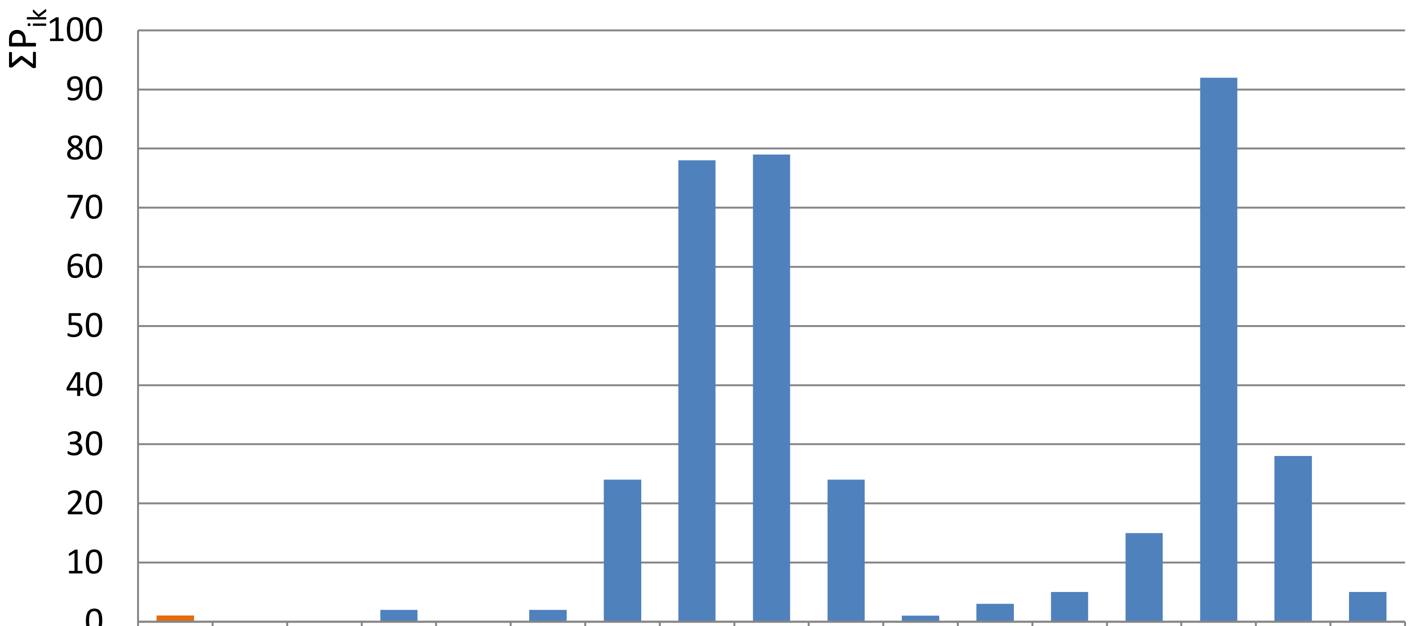
	-78	-77	-76	-75	-74	-73	-72	-71	-70	-69	-68	-67	-66	-65	-64	-63	-62	RSSI$_{ik}$ (dBm)
$\sum_{k=m}^{m} P_{ik}$ →	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5	

Data in a Wi-Fi database: collected in room 2408 between 09:00 - 09:30 on 15.08.2012. *MAC$_i$ = 00:0f:34:46:b5:0a*
$\sum_{k=-78}^{-62} P_{ik}$ = 359

Wi-Fi clustering using DBSCAN

ComTec

Density-based Cluster Learning Algorithm



NR = 2
MinPts = 120

RSSI$_{ik}$ (dBm)	-78	-77	-76	-75	-74	-73	-72	-71	-70	-69	-68	-67	-66	-65	-64	-63	-62
$\sum_{k=m}^{m} P_{ik}$	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5

$$\rho\ (P_{ik}) = \sum_{k=-78}^{-76} P_{ik} = 1 < 120$$

Wi-Fi clustering using DBSCAN

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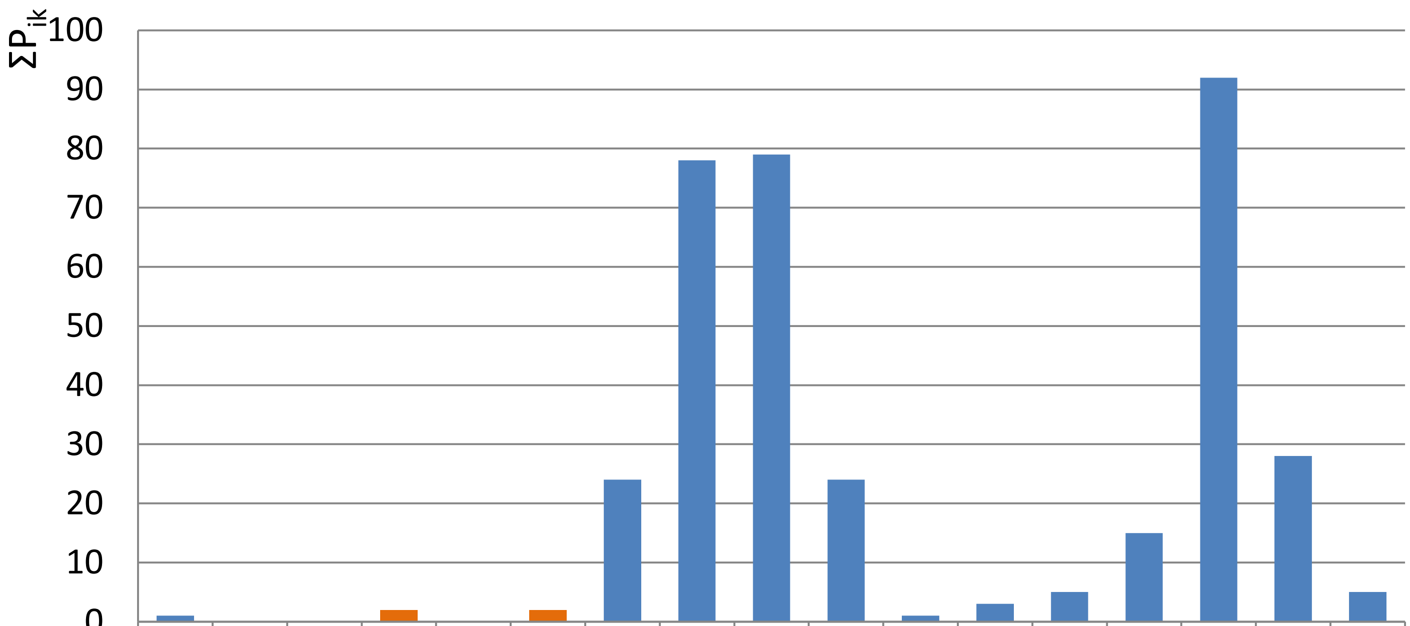
Density-based Cluster Learning Algorithm



$RSSI_{ik}$ (dBm)	-78	-77	-76	-75	-74	-73	-72	-71	-70	-69	-68	-67	-66	-65	-64	-63	-62
$\sum_{k=m}^{m} P_{ik}$	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5

NR = 2
MinPts = 120

$$\rho\,(P_{ik}) = \sum_{k=-75}^{-73} P_{ik} = 4 < 120$$

Wi-Fi clustering using DBSCAN

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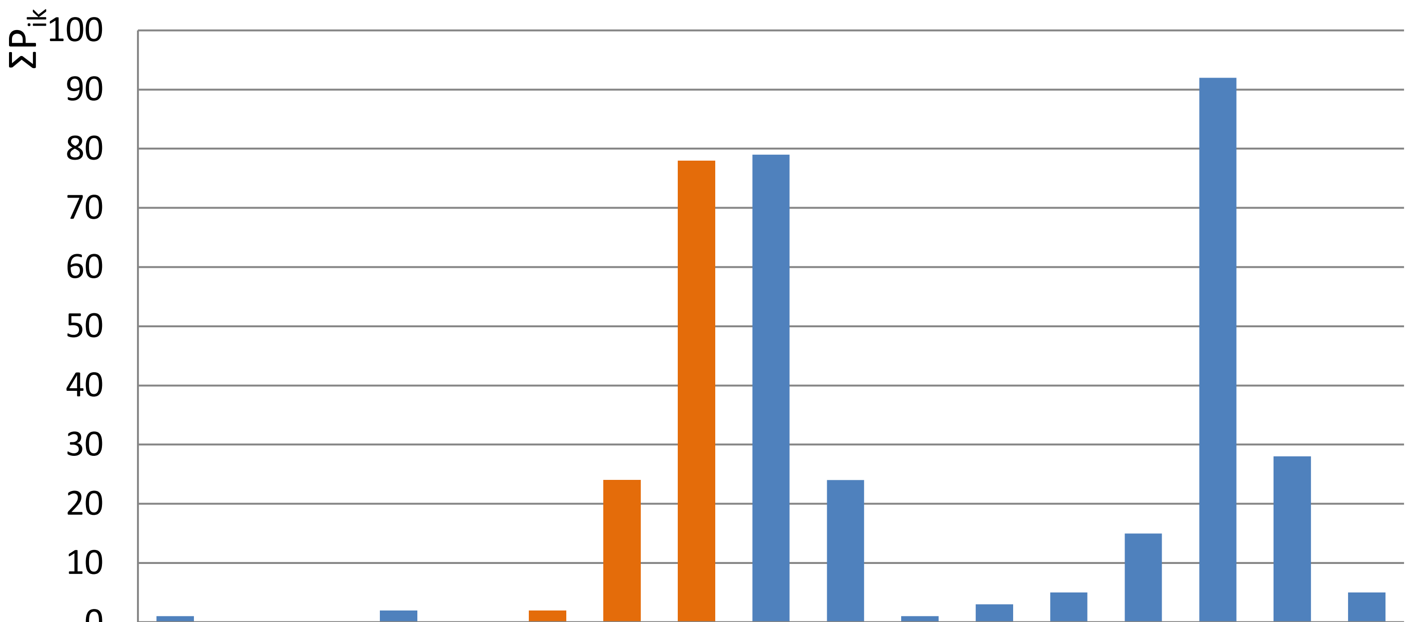
Density-based Cluster Learning Algorithm



	-78	-77	-76	-75	-74	-73	-72	-71	-70	-69	-68	-67	-66	-65	-64	-63	-62	← $RSSI_{ik}$ (dBm)
$\sum_{k=m}^{m} P_{ik}$ →	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5	

NR = 2
MinPts = *120*

$$\rho\ (P_{ik}) = \sum_{k=-73}^{-71} P_{ik} = 104 < 120$$

Wi-Fi clustering using DBSCAN

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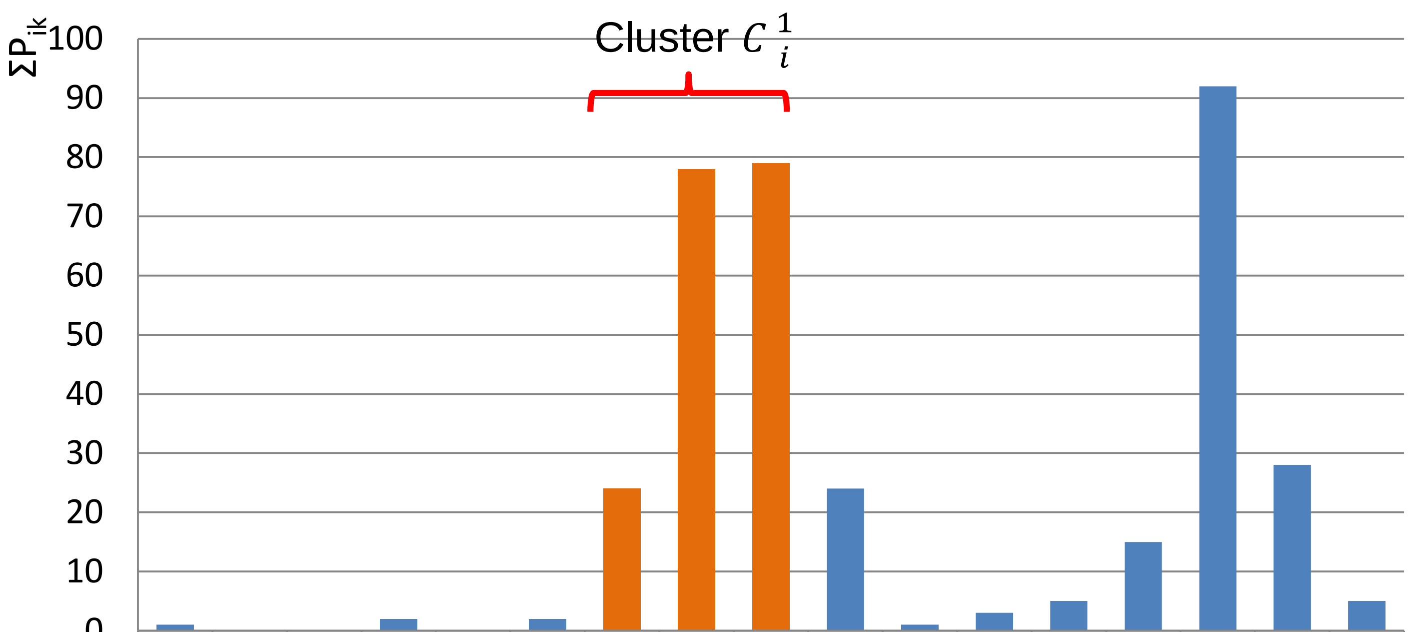
Density-based Cluster Learning Algorithm



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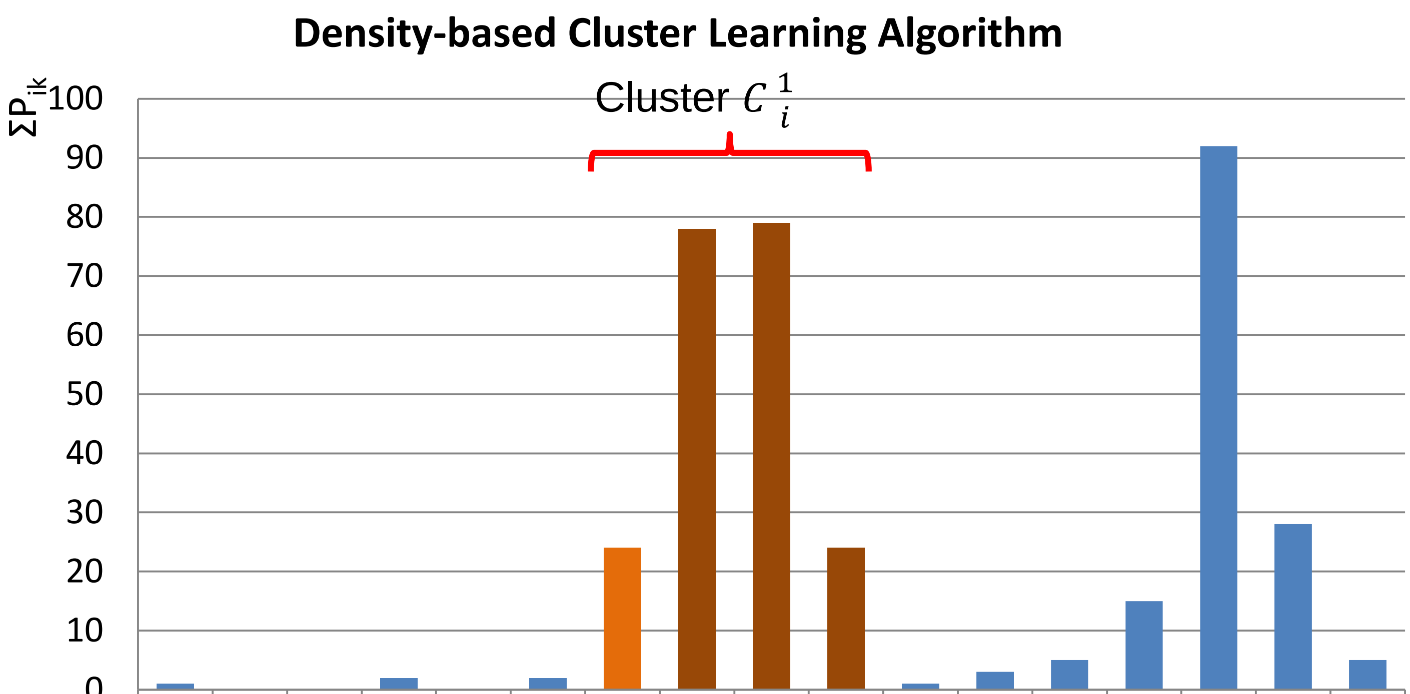
$\sum_{k=m}^{m} P_{ik}$	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5

NR = 2
MinPts = 120

$$\rho\ (P_{ik}) = \sum_{k=-72}^{-70} P_{ik} = 181 \geq 120$$

Wi-Fi clustering using DBSCAN

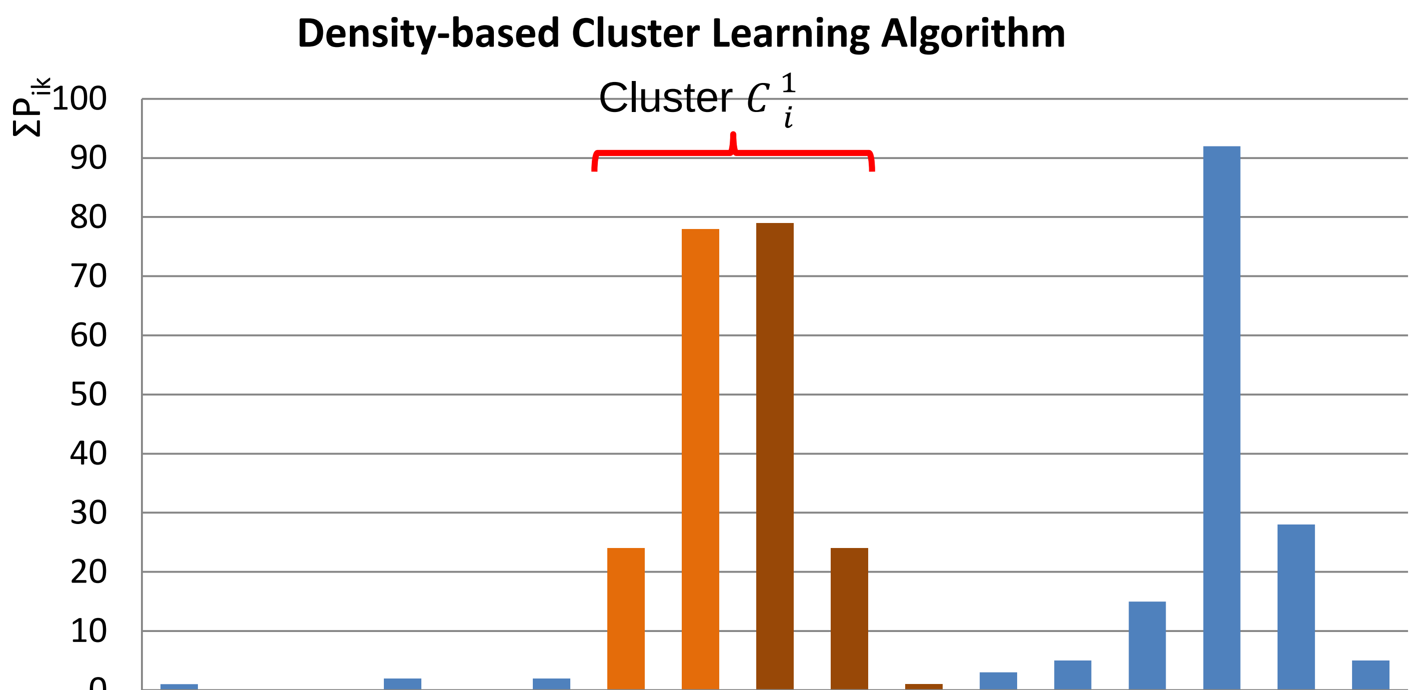


	-78	-77	-76	-75	-74	-73	-72	-71	-70	-69	-68	-67	-66	-65	-64	-63	-62	← $RSSI_{ik}$ (dB)
$\sum_{k=m}^{m} P_{ik}$ →	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5	

NR = 2
MinPts = 120

$$\rho\ (P_{ik}) = \sum_{k=-71}^{-69} P_{ik} = 181 \geq 120$$

Wi-Fi clustering using DBSCAN



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$\sum_{k=m}^{m} P_{ik}$	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5

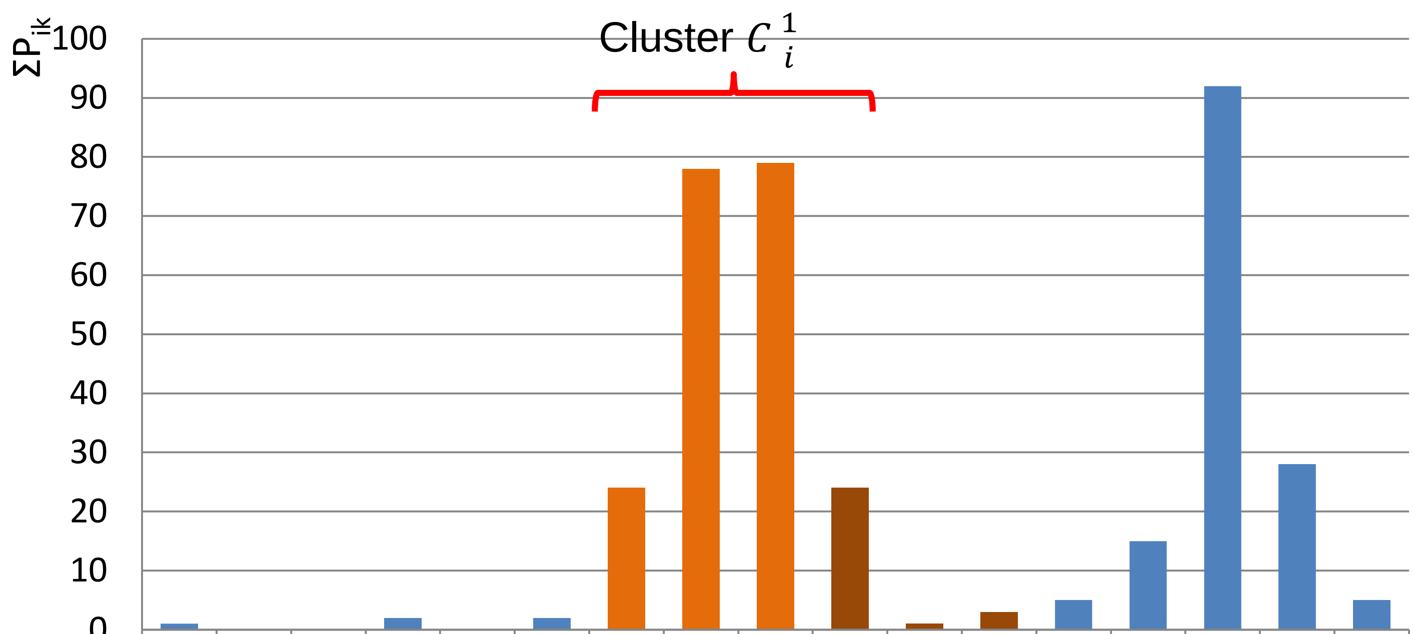
NR = 2
MinPts = 120

$$\rho\ (P_{ik}) = \sum_{k=-70}^{-68} P_{ik} = 104 < 120$$

Note: if $\rho\ (P_{ik}) < 120$, the density check will continue, since P_{ik} with RSSI$_{ik}$=-69 dB still belongs to the cluster C_i^1

Wi-Fi clustering using DBSCAN

Density-based Cluster Learning Algorithm



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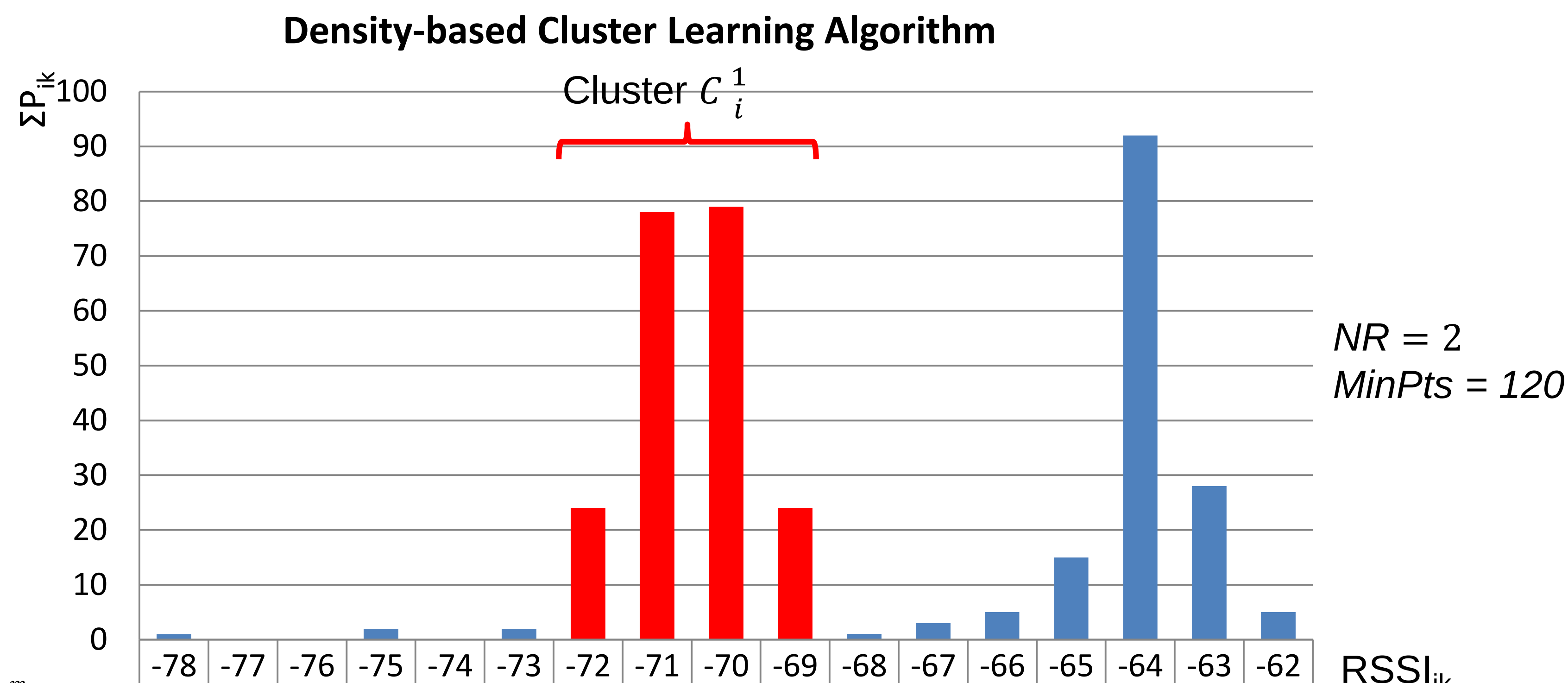
$\sum_{k=m}^{m} P_{ik}$	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5

NR = 2
MinPts = 120

$$\rho\ (P_{ik}) = \sum_{k=-69}^{-67} P_{ik} = 28 < 120$$

Wi-Fi clustering using DBSCAN

ComTec



$RSSI_{ik}$ (dBm)	-78	-77	-76	-75	-74	-73	-72	-71	-70	-69	-68	-67	-66	-65	-64	-63	-62
$\sum_{k=m}^{m} P_{ik}$	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5

$$C_i^1 = \{MACi,\ -72dB, -69dB\}$$

Wi-Fi clustering using DBSCAN

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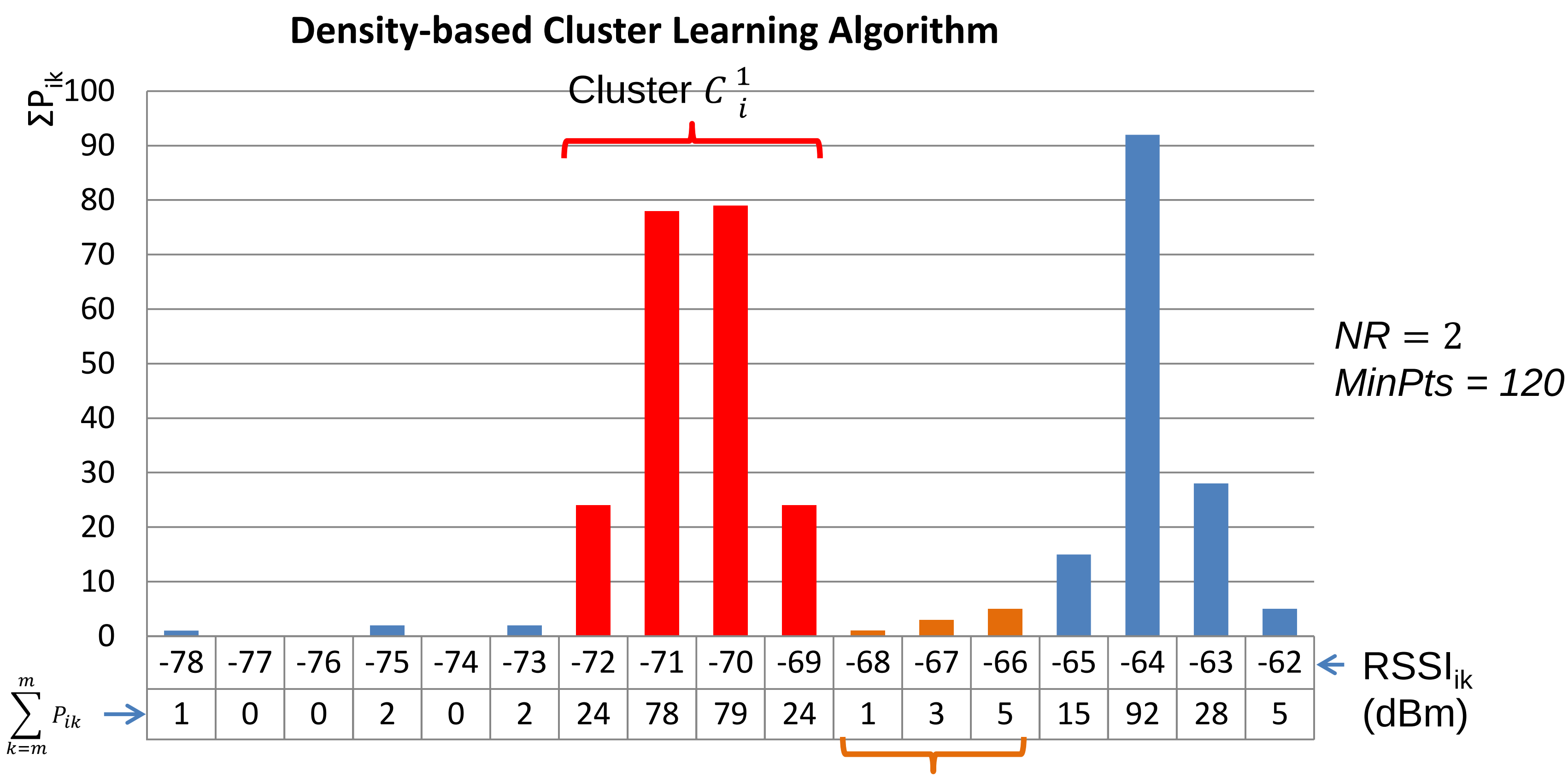

$$\rho\,(P_{ik}) = \sum_{k=-68}^{-66} P_{ik} = 9 < 120$$

Wi-Fi clustering using DBSCAN

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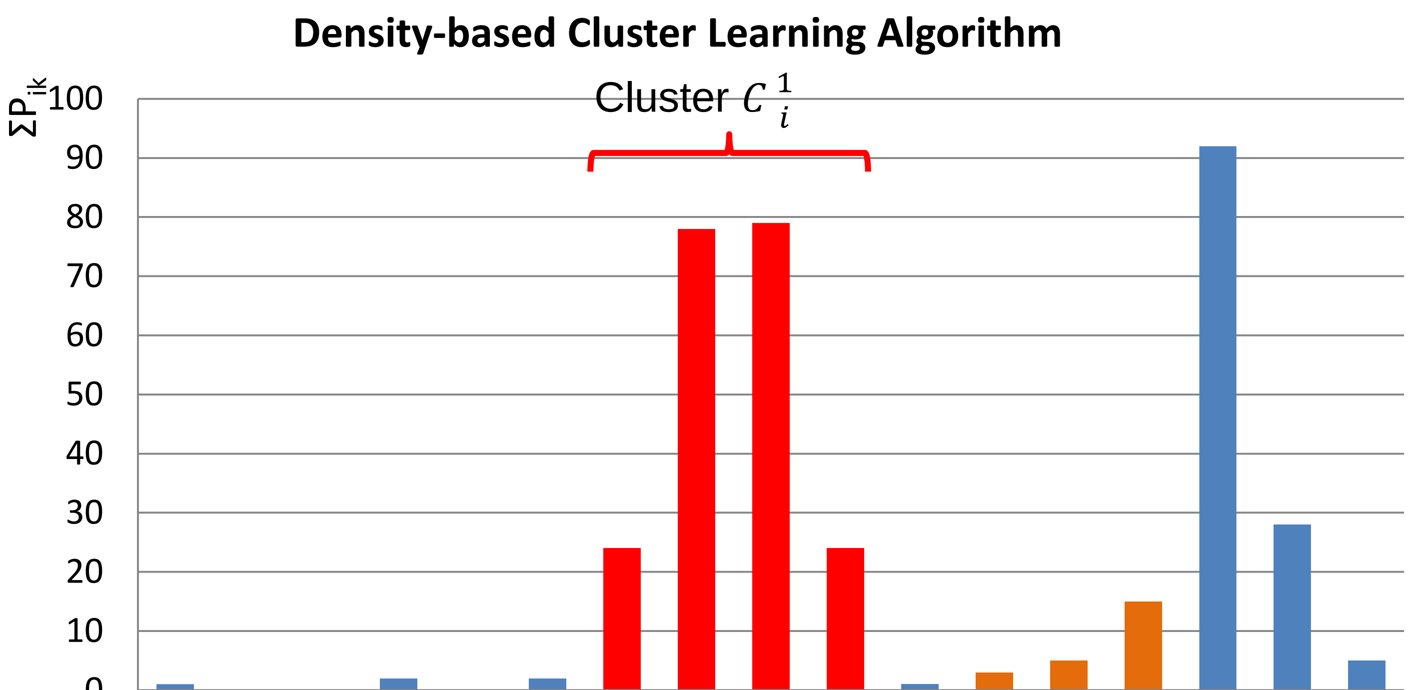


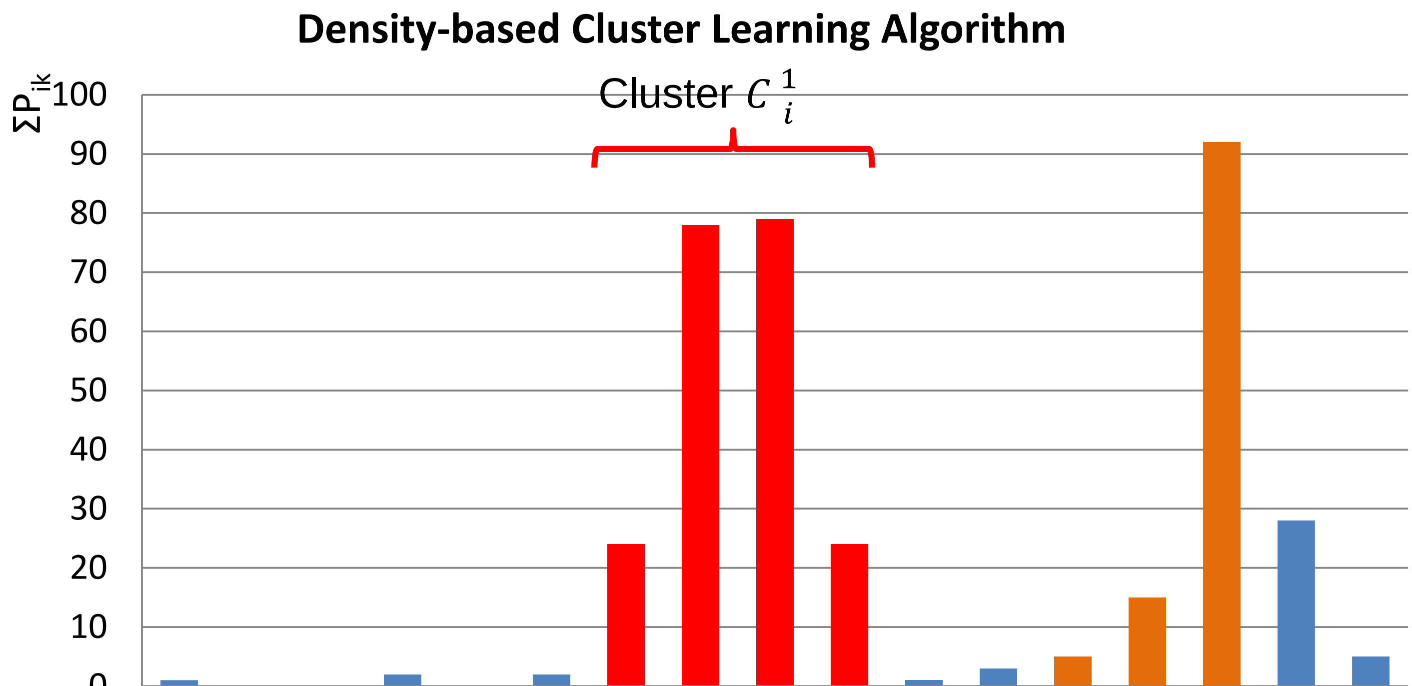
	-78	-77	-76	-75	-74	-73	-72	-71	-70	-69	-68	-67	-66	-65	-64	-63	-62	← $RSSI_{ik}$ (dBm)
$\sum_{k=m}^{m} P_{ik}$ →	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5	

NR = 2
MinPts = 120

$$\rho(P_{ik}) = \sum_{k=-67}^{-65} P_{ik} = 23 < 120$$

Wi-Fi clustering using DBSCAN

ComTec



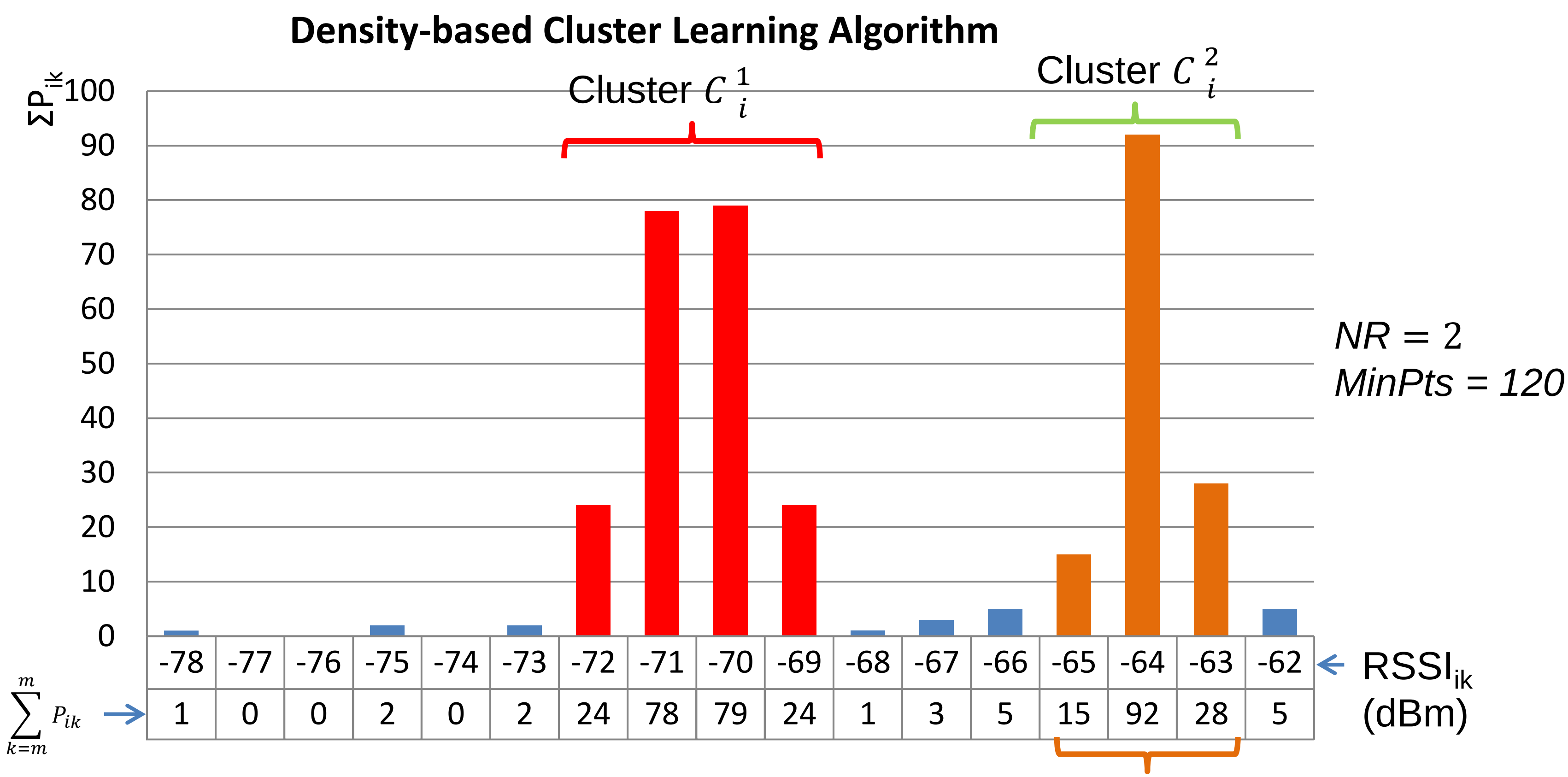
	-78	-77	-76	-75	-74	-73	-72	-71	-70	-69	-68	-67	-66	-65	-64	-63	-62
$\sum_{k=m}^{m} P_{ik}$	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5

$RSSI_{ik}$ (dBm)

NR = 2
MinPts = 120

$$\rho\ (P_{ik}) = \sum_{k=-66}^{-64} P_{ik} = 112 < 120$$

Wi-Fi clustering using DBSCAN



$$\rho\ (P_{ik}) = \sum_{k=-65}^{-63} P_{ik} = 135 \geq 120$$

Wi-Fi clustering using DBSCAN

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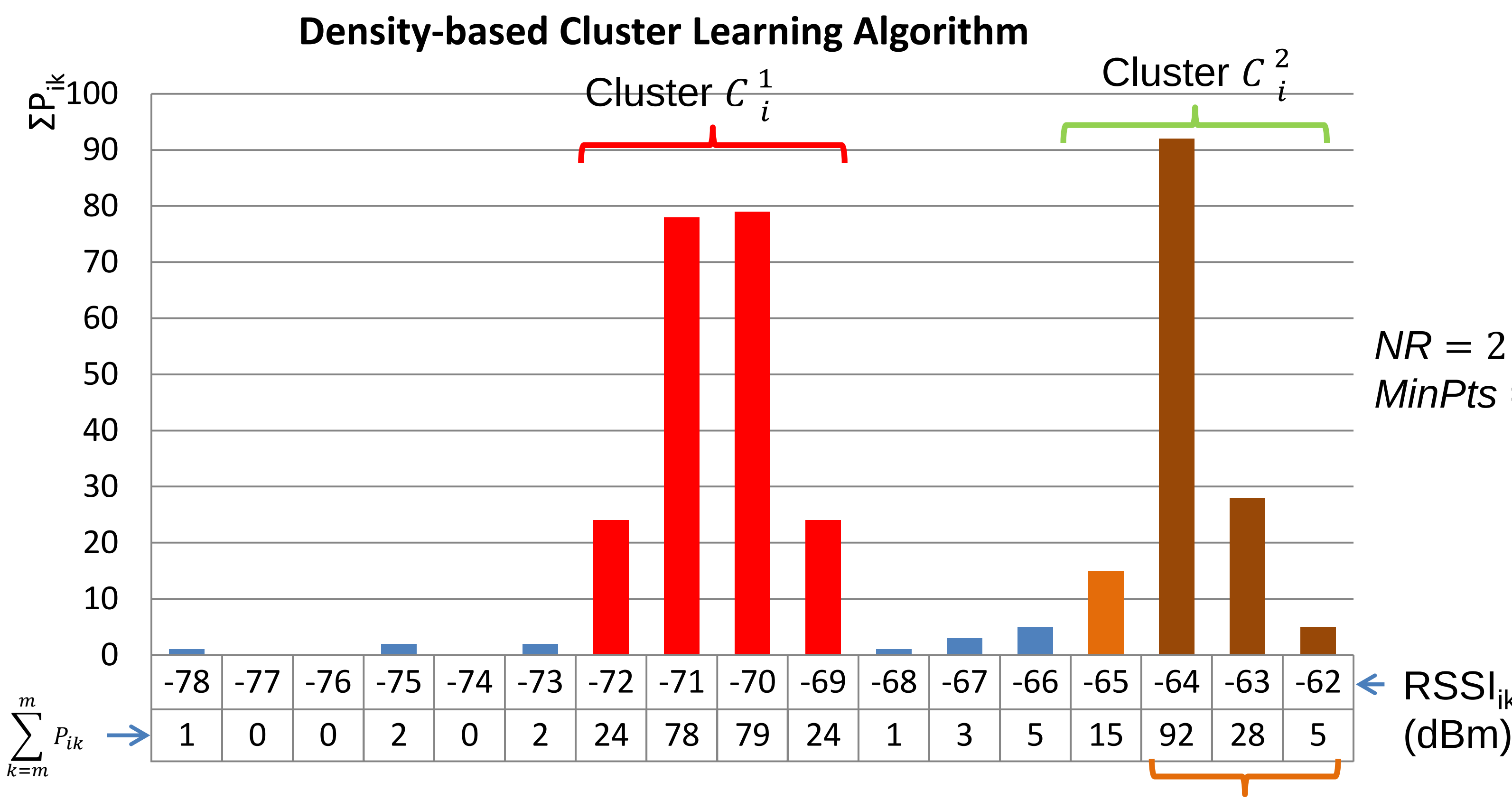
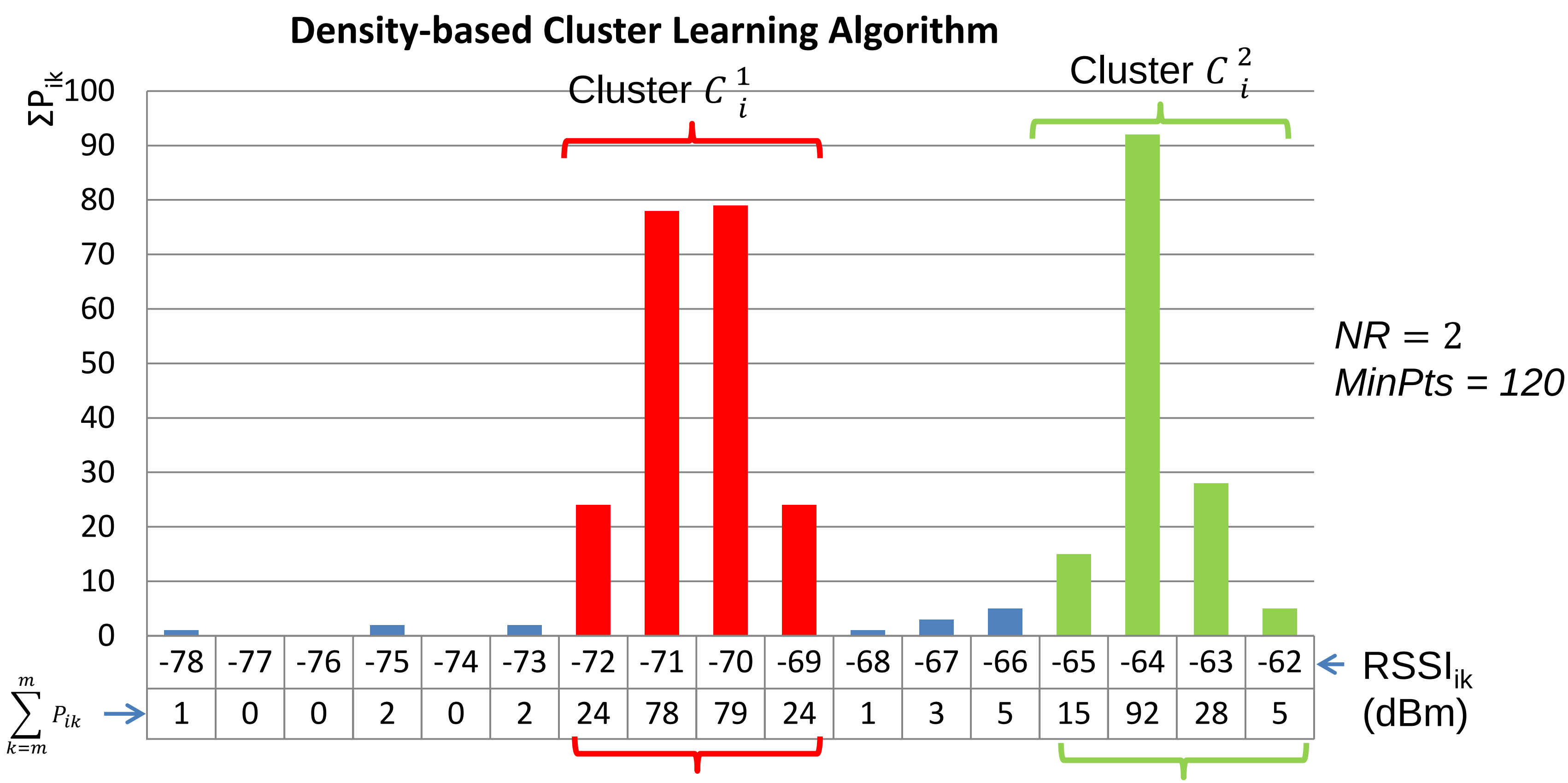


$RSSI_{ik}$ (dBm)	-78	-77	-76	-75	-74	-73	-72	-71	-70	-69	-68	-67	-66	-65	-64	-63	-62
$\sum_{k=m}^{m} P_{ik}$	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5

NR = 2
MinPts = 120

$$\rho(P_{ik}) = \sum_{k=-64}^{-62} P_{ik} = 125 \geq 120$$

Wi-Fi clustering using DBSCAN

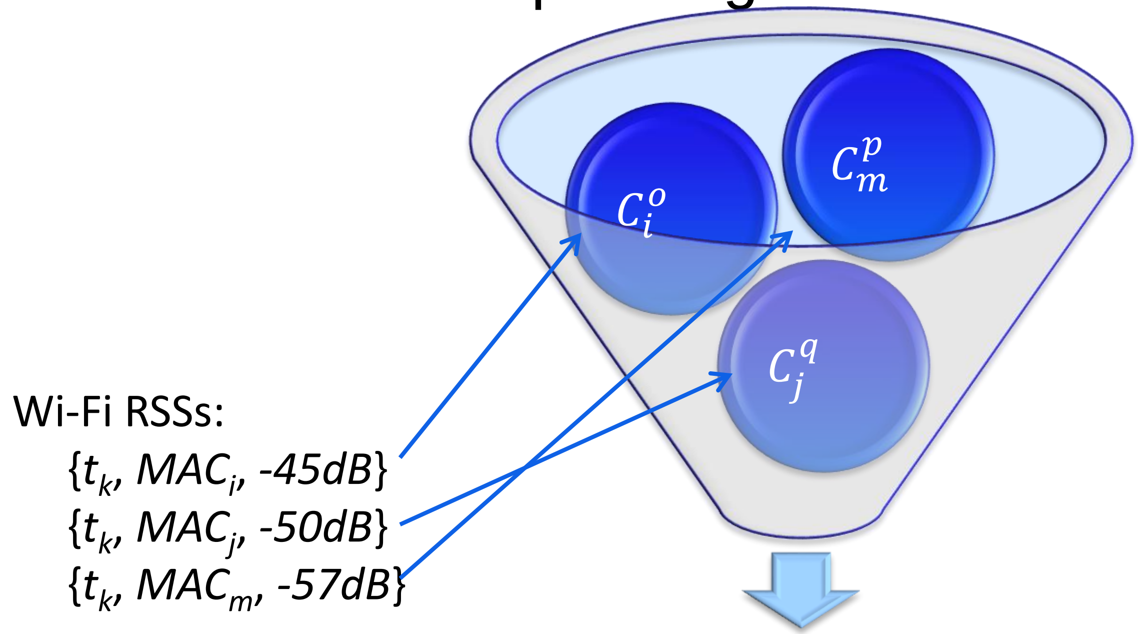


$RSSI_{ik}$ (dBm)	-78	-77	-76	-75	-74	-73	-72	-71	-70	-69	-68	-67	-66	-65	-64	-63	-62
$\sum_{k=m}^{m} P_{ik}$	1	0	0	2	0	2	24	78	79	24	1	3	5	15	92	28	5

$C_i^1 = \{MACi,\ -72dB, -69dB\}$ $\quad$ $C_i^2 = \{MACi,\ -65dB, -62dB\}$

Positioning phase

– Compare the current Wi-Fi RSSs with learned Wi-Fi fingerprints
– The user returns to a location corresponding to this fingerprint



$$FP_k = \left\{C_i^o, \dots, C_j^q\right\}$$

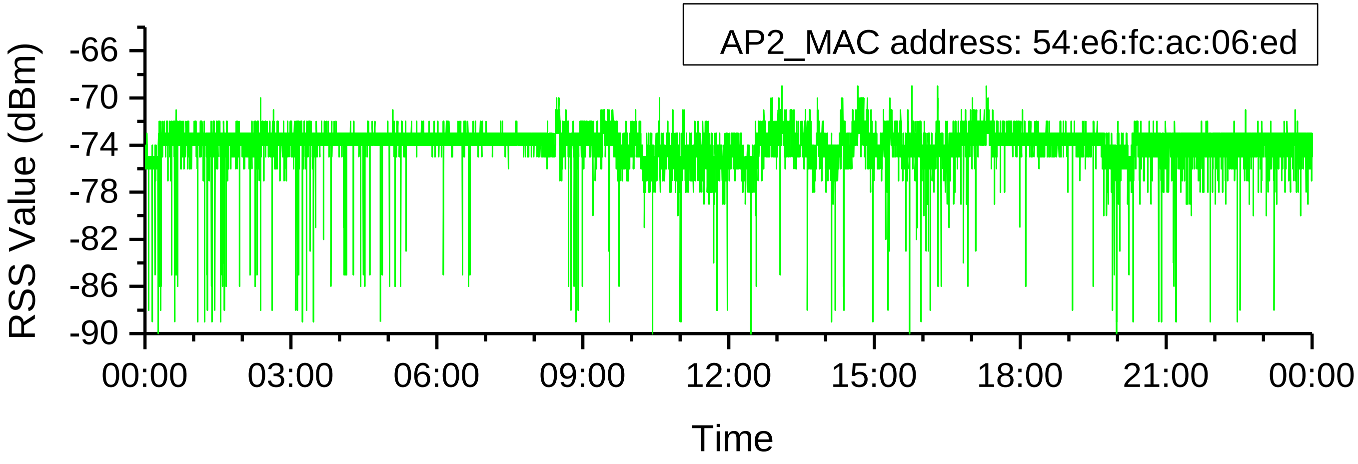
Source: [1]

Common Positioning approaches

- Nearest neighbor
  - Euclidean distance, Manhattan distance
- Probabilistic framework
  - Estimating the likelihood function, e.g., histogram, kernel, Gaussian
- Neural network
- Support vector machine
- Filtering approaches

RSS fluctuation

- Human presence
- Obstacles
- Change of environment



Source: [1]

Device heterogeneity

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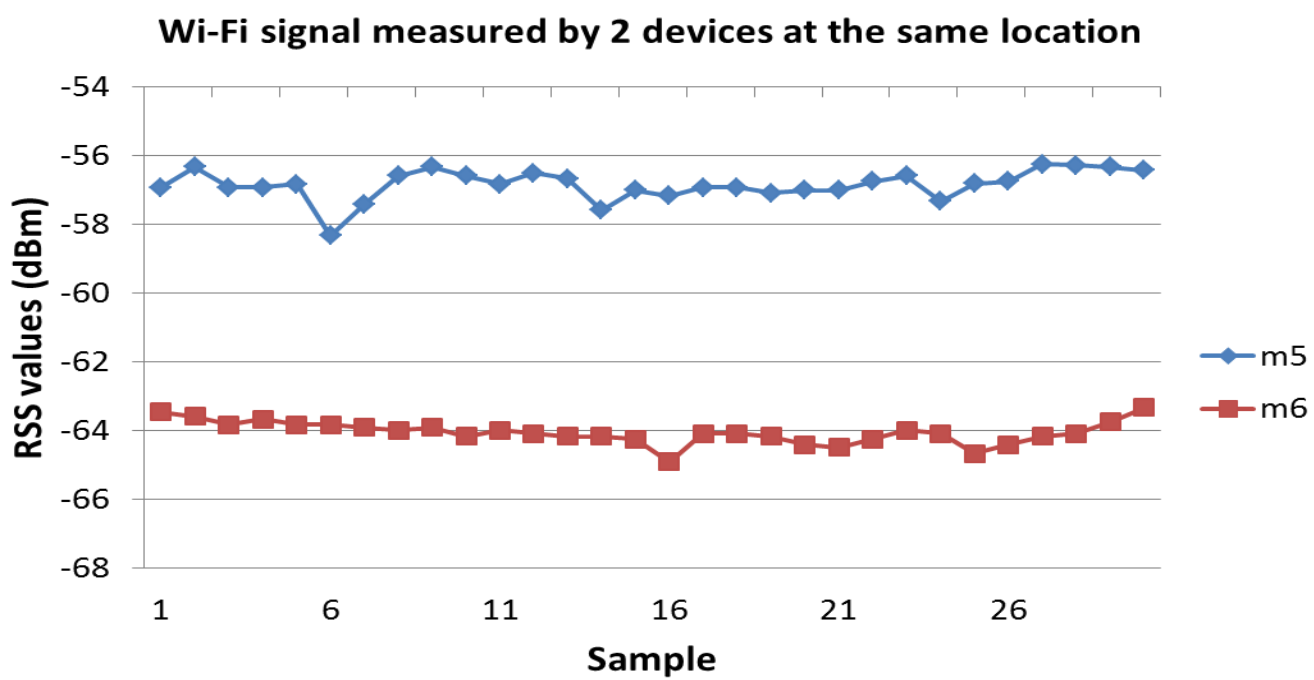
- Different devices are used in the training phase and positioning phase
- Those devices may have different Wi-Fi chipset, different antenna gain



Solving Device heterogeneity

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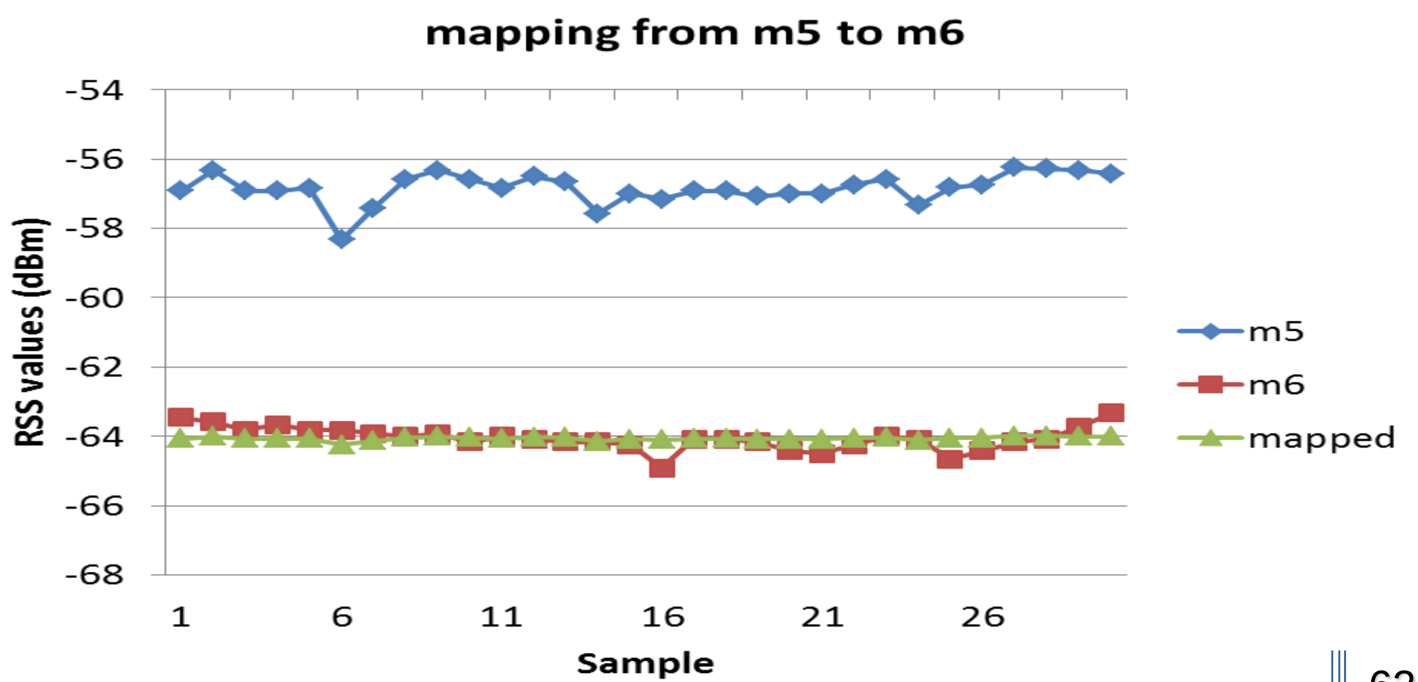
- Mapping device
  - Manual calibration
  - Linear transformation method
  - Ranking method



Solving Device heterogeneity

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- Extract features that do not depend on hardware
- Spatial mean normalization (SMN)

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad \hat{x}_i = F(x_i|1,...,N)) = x_i - \bar{x}$$

- Signal strengths difference (SSD)

$$d(AP_i, AP_j) = RSS_i - RSS_j$$

- Hyperbolic Location Fingerprinting (HLF)

$$r(AP_i, AP_j) = \frac{RSS_i}{RSS_j} \qquad nlr(AP_i, AP_j) = \log r(AP_i, AP_j) - \log(\frac{1}{RSS_{max}})$$

2.4 GHz vs 5 GHz

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- The free space path loss index depends on the frequency of the signal

$$P_L\,(\mathrm{dB}) = 10\log_{10}\frac{P_t}{P_r} = -10\log_{10}\frac{G_l\lambda^2}{(4\pi d)^2}.$$

- The output power limit is different
- Different characteristic:
  - Scattering inside the building
  - Damping through water
  - Wall penetration
  - Fast fading

Other factors

- Energy consumption
- Response rate
- Fingerprint database
- Different frequency
- Number of scan per location estimate
- Influence of the number of Wi-Fi APs
- Combination with other sensors

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