Indoor Localization Using Wireless Networks

Itaru Abe, Shizuki Goto, Ryoichiro Hayasaka, Hannah Horner, Eric Lybrand

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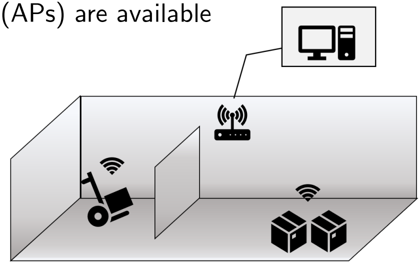
Outline

Introduction

Background Information

- NEC corporation: providing Internet and Communication Technology (ICT) services/products
- NEC is focusing on wireless networks

- Indoor localization for automation
  - At factory/construction site
  - Wireless Local Area Network (WLAN)
  - Existing access points (APs) are available
  - Cost effective



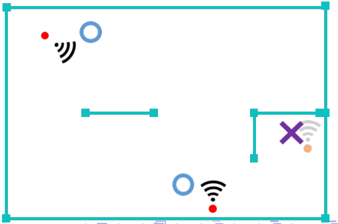
Indoor localization: previous studies

Localization

- Use multiple APs and following data
  - Time difference of received signal
  - Angle of signal arrival
- Prepare reference data by pre collected Received Signal Strength (RSS) : Fingerprinting
- Calculate location based on RSS : Path loss model

AP placement

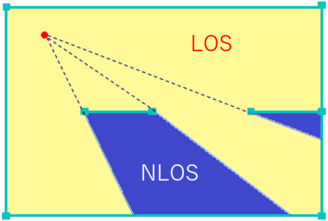
- Some mathematical optimization theories applied
  - Genetic algorithm etc.

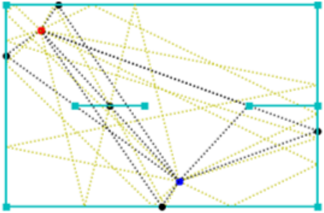


Challenges

Signal strength varies easily because of several different causes.

- Line of Sight(LOS) and Non Line of Sight(NLOS)
- Multipath reflection
  - Reflection off of wall
  - Attenuation of wall pass-through
  - Signal absorption of wall
  - Decay ratio depends on the angle of incidence
- Obstacle and its material (e.g. wall, furniture, people)
- Device orientation





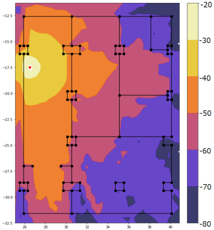
Problem Statement

NEC's expectations from this project;

- New algorithm to estimate quality of wireless communication at any points by capture data at some points.
- Simulation models with accurate and light-weight to estimate quality of wireless communication at any points.
- Indoor localization algorithm with high accurately by using wireless communication data.

Our Approaches/Purposes

- Simulation
  - Simplification of the algorithm while maintaining its quality
- Localization
  - Mathematical approach to RSS value
  - Estimation of the distance between AP and user by using path-loss model
- AP placement
  - Optimization of AP placement by *k*-means algorithm



Simulating Signal Strength Indoors

Simulation Design

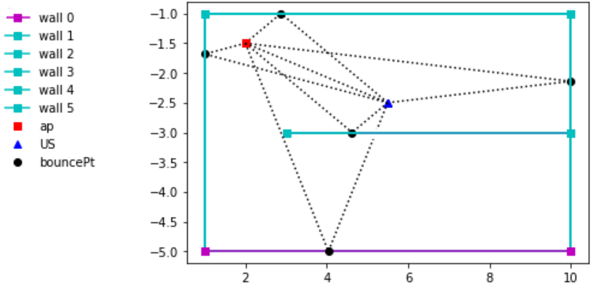
To simplify the simulation,

- Only need location of walls, AP location(s) in 2D
- Walls are all the same material, same thickness
- Consider only 1 reflection

Process Overview

For each grid point,

1. Find direct path and one-reflection paths from AP
2. Calculate power decay by reflection and pass through along each path
3. Aggregate power decay → RSS



Power decay and RSS

- Friis equation (power decay by squared distance d)[1]

$$P_r = FSPL(d) = P_t \left(\frac{c}{4\pi df} \right)^2 G_{ra} G_{ta}$$

- Reflection loss coefficient (depending on angle θ_i)[2]

$$R_{ref(\theta_i)} = \left(\frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} \right)^2, \frac{\sin \theta_i}{\sin \theta_t} = \frac{n_{wall}}{n_{air}}$$

- Pass through loss coefficient (depending on angle θ_i)

$$R_{pas(\theta_i)} = a(1 - R_{ref(\theta_i)}), \; a = 0.316$$

- Total signal power and RSS

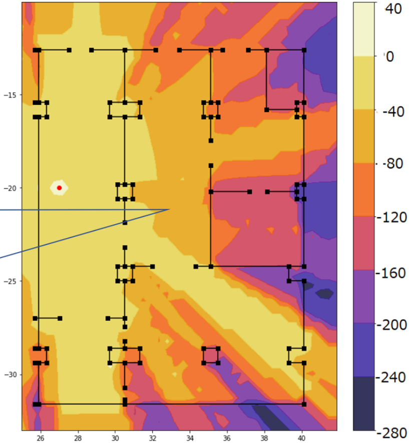
$$P_{all} = P_r \prod^{N_{ref}} R_{ref} \prod^{N_{pas}} R_{pas}, \quad RSS = 10 \log_{10} \left(\frac{P_{all}}{1 \; mW} \right) [dBm]$$

Simulated Heatmap (Midterm presentation)

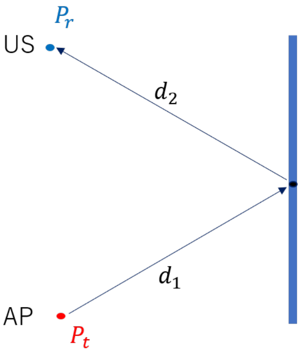
Drawback

- Simulated RSS is too small (RSS > -80 dBm)

→ modify distance decay



Modification in calculation of distance decay



$$FSPL(d) = \left(\frac{c}{4\pi f} \cdot \frac{1}{d}\right)^2$$

Mid-term

$$P_r = P_t \times FSPL(d_1) \times FSPL(d_2) \times R_{ref}$$

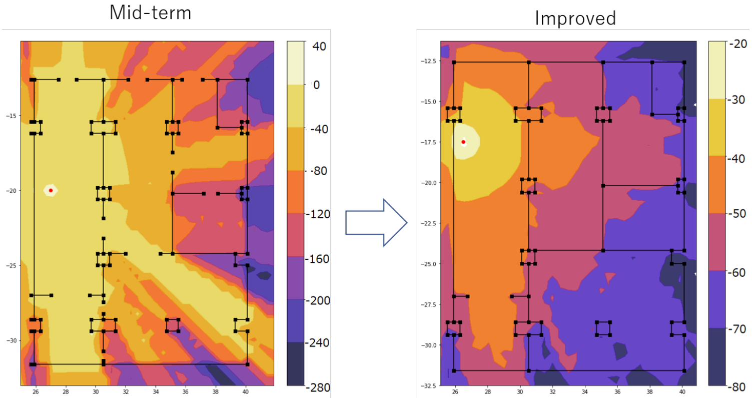
Improved

$$P_r = P_t \times FSPL(d_1 + d_2) \times R_{ref}$$

FSPL: Free Space Path Loss

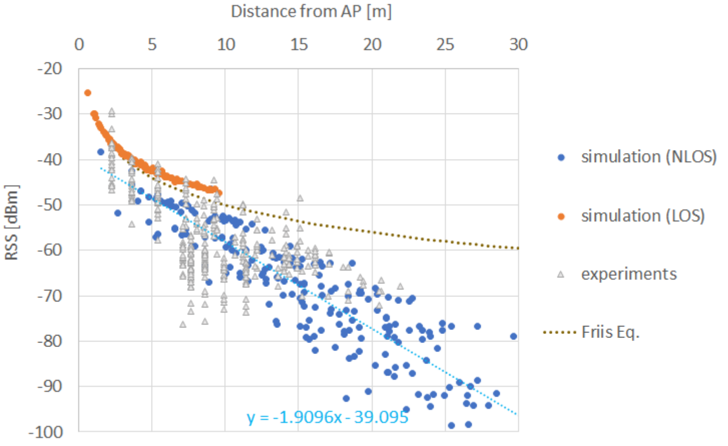
Simulation Improvement

Midterm : RSS= -280 $\sim$ 40 dBm (unrealistic)
Improved: RSS= -80 $\sim$ -20 dBm (realistic)



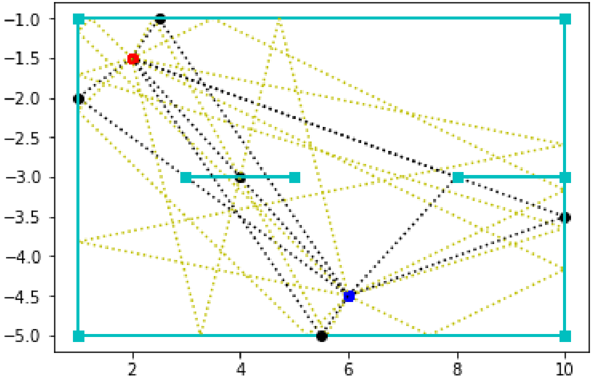
RSS vs. Distance

NLOS simulation agrees well with experiments.

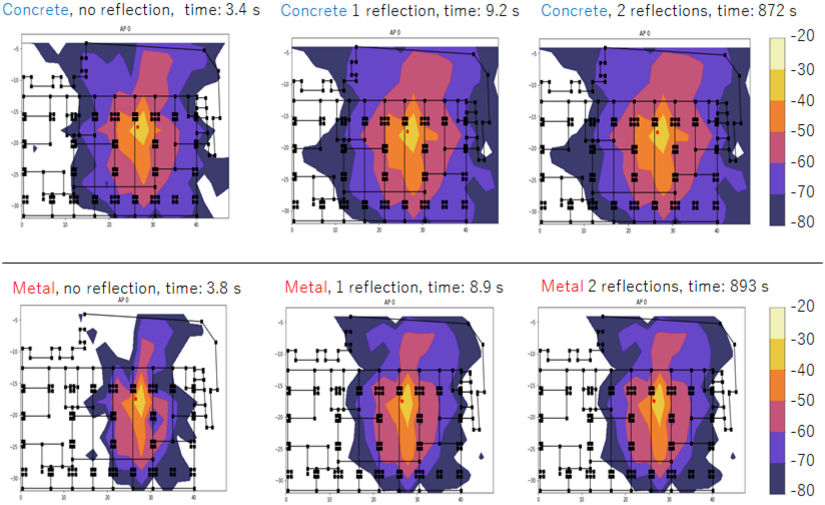


Two reflection

The effect of two reflections can be neglected?



Comparison between no, one, and two reflection



Quick summary: Simulation

1. Realistic RSS can be obtained by simulation.
2. One reflection is enough (two reflections can be neglected).

$\rightarrow$ Apply this simulation to optimization of AP placement.

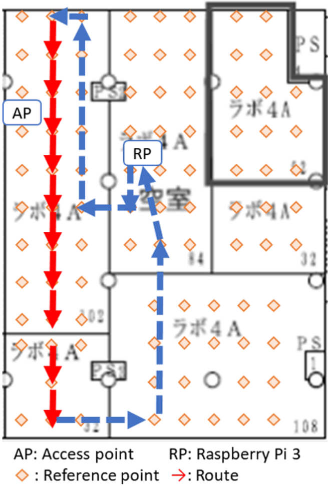
$\rightarrow$ Use regression line for Lozalization.

The Actual Behavior of Signal Strength

Experiment Design

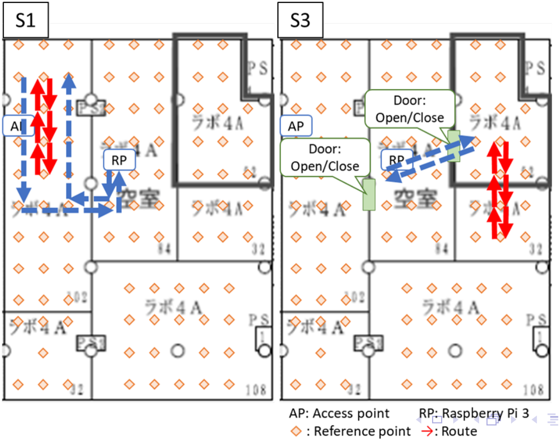
1. Create grid of reference points for our rooms
2. RSS values in 2.4 GHz captured and filtered by Wireshark following several routes of connected reference points
3. Analyze the measured RSS value
   - Compare to simulations
   - Mathematical analysis

→ Distance estimation



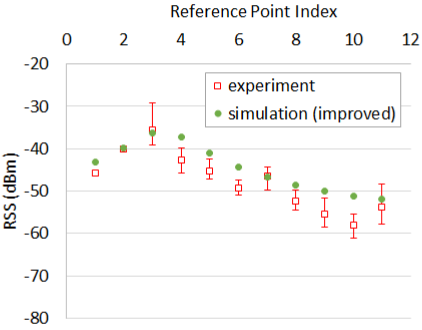
Change modification from midterm presentation

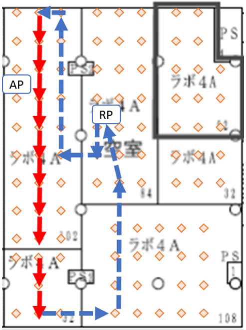
- Sampling ratio: 0.1-1.0 sec
- Set new routes with the exact experimental conditions:
  - Securing LOS or not
  - Doors close/open



Comparing Experiments to Simulations

LOS route



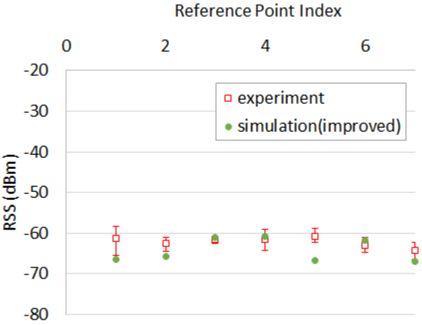


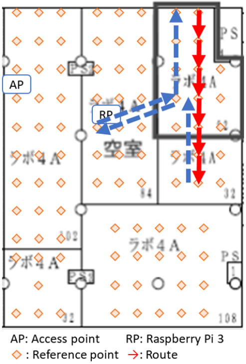
AP: Access point RP: Raspberry Pi 3
◇ : Reference point →: Route

- RSS value showed peak in the nearest point of AP
- Simulation data completely corresponded in some points

Comparing Experiments to Simulations (cont)

NLOS route

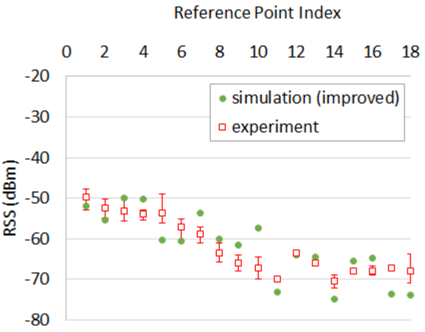


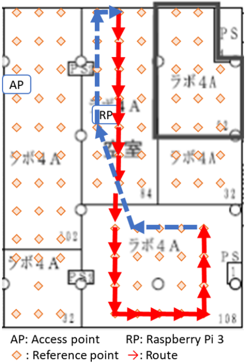


- RSS value was almost constant
- Simulation data completely matched almost all of the points

Comparing Experiments to Simulations (cont)

LOS+NLOS route





- RSS value showed decreasing tendency
- Simulation data showed same tendency and close value

Tracking the Continuous Behavior of Signal Strength

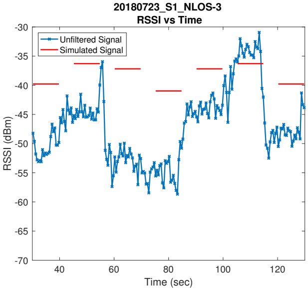


Figure: Experiment with rate equal to 2Hz. Standard deviation of RSS is 6.39.

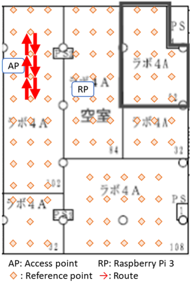


Figure: Path taken for experiment in figure to the left.

- Simulations tell us RSS at reference points in ideal conditions
- In non-ideal settings the mismatch is more pronounced: line of sight obstruction, device orientation

Tracking the Continuous Behavior of RSS

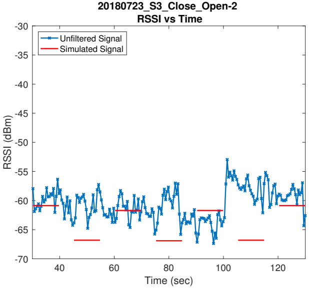


Figure: Experiment with rate equal to 2Hz. Standard deviation of RSS is 2.68.

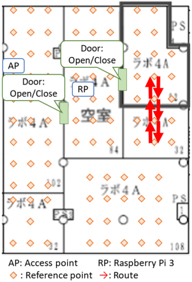


Figure: Path taken for experiment in figure to the left.

- Variance of RSS appears to decay as a function of line of sight.
- Experiments and simulations are more aligned in strong non-line-of-sight settings

Consequences for Localization

The Old Model

- Standard log-distance path loss model

$$RSS = T_x - 10n\log_{10}(d)$$

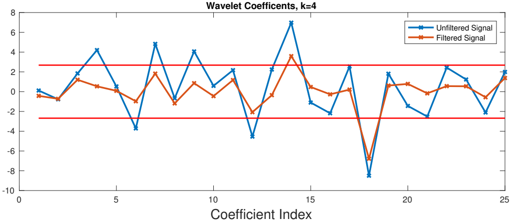
  where n is a fixed path loss exponent, T_x the log of transmission power for WiFi access point.

- Static path loss models (incorrectly) assume RSS varies continuously with distance.

Our New Model

- We propose dynamically changing n as a function of time and RSS.
- Use sharp changes, or jumps, in RSS to detect line of sight change.

Jump Detection



- Use wavelet coefficients to detect jumps.
- Denoise received signal strength using *RiskShrink*.
- Difference between filtered and unfiltered RSS curves is "noise".
- Reject wavelet coefficients that fall below the $1 - \alpha$ percentile of noise's wavelet coefficients.

Jump Detection Results

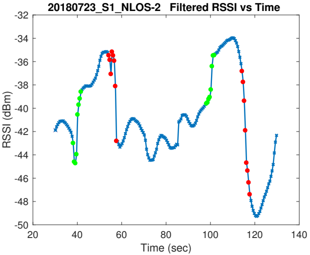


Figure: Experiment with rate equal to 2Hz. Standard deviation in consecutive time differences is 0.21 seconds.

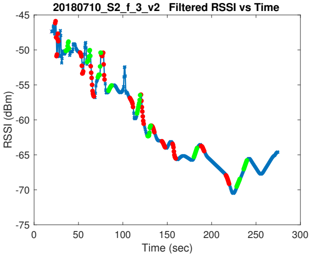


Figure: Experiment with rate equal to 2Hz. Standard deviation in consecutive time differences is 2.44 seconds.

- Choose rejection rate $0 < \alpha < 1$ and a scale k to denoise.
- Works well if RSS is sampled at a rate greater than 1Hz with small deviations in rate.
- Large deviations in the sampling rate cause poor performance.

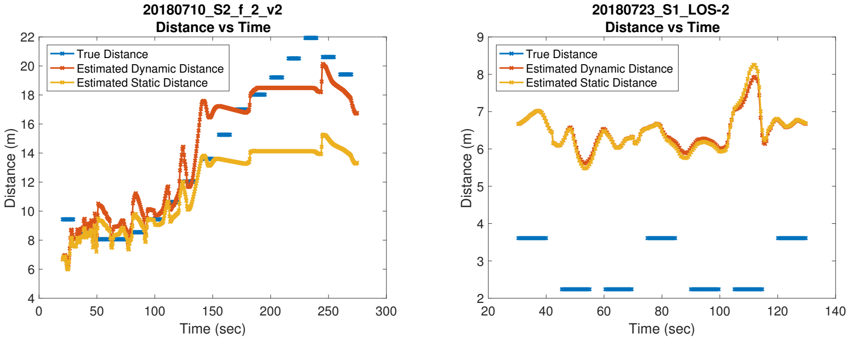
Dynamic Path Loss Models

- Adjust path loss exponent according to the magnitude of jump in RSS.
- For a jump over $[t_0, t_1]$ set

$$n(t_1) = n(t_0) - \beta(\Delta RSS)$$

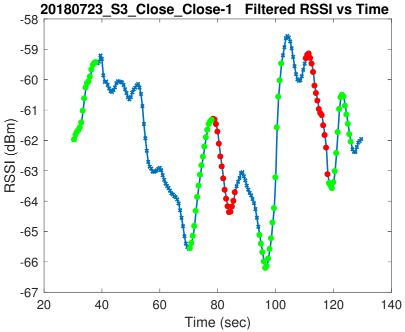
  where β is a predetermined constant, e.g. $\beta = 1/10$ means a jump of 10dBm results in a change of 1 in exponent.
- Must choose an initial path loss exponent to start with.

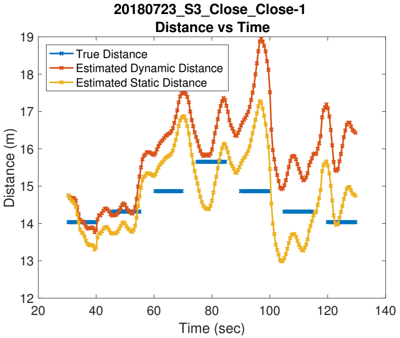
Dynamic Path Loss Performance



- When all jumps are detected with few false positives, jump detection is superior to static path loss models.
- When jumps are mild, the dynamic model behaves as the static path loss model.

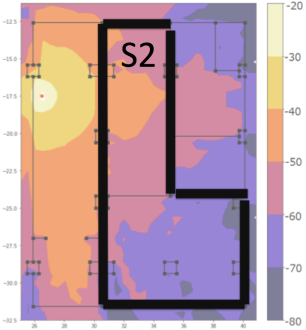
Dynamic Path Loss Performance, Continued





- Dynamic path loss model is only as good as jump detection.
- Missing a jump could propagate distance estimation error forward in time.

Modest Improvements



$$\sigma_s^2 = \text{average (static error)}^2$$
$$\sigma_d^2 = \text{average (dynamic error)}^2$$

Region	σ_s	σ_d
S1	1.44m	1.40m
S2	3.71m	2.19m
S3	1.13m	0.95m

- Dynamic path loss models are better when transitioning between regions of good coverage and regions of bad coverage.
- Only one of our experiment regions had this feature: S2.

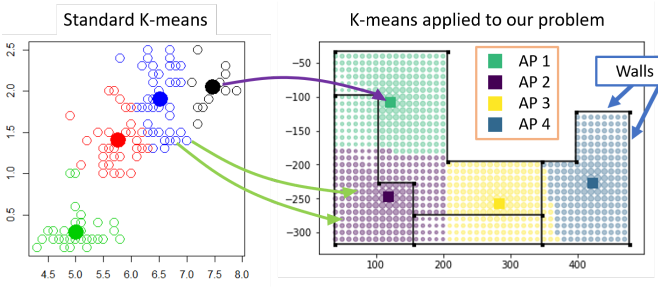
Localization Suggestions

- Factor in other features, e.g. type of device, device orientation.
- Higher order RSS statistics may classify severity of non-line-of-sight.
- Use more access points: collaborated jump detection.

If we use more access points, our simulations tell us how to optimally place them.

Optimizing WiFi Access Point Locations

K-means Algorithm



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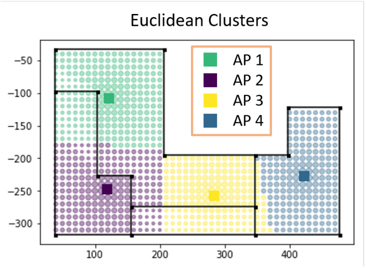
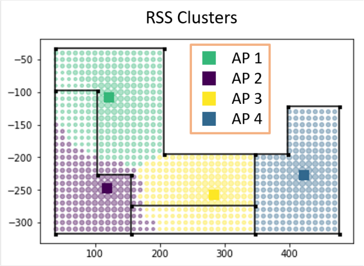
- Cluster centers = Access Points
- Data = points in building
- K-means creates evenly distributed clusters, minimizing "distance" to nearest AP
- RSS negatively correlates to distance from AP $\longrightarrow$ minimizing this might lead to good AP placement choices
- Method should scale well to larger problems with many APs

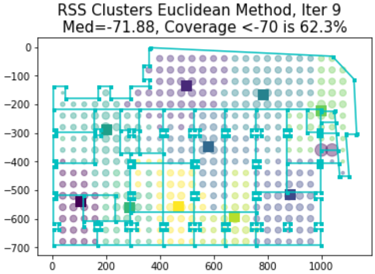
Distance Metrics





- Euclidean Method: only Euclidean distance used
- RSS Method: only simulated RSS
- Hybrid Method: Euclidean distance used, after convergence use simulated RSS

Experiment Overview

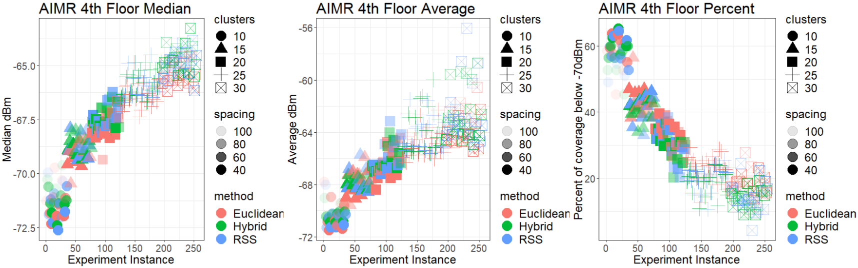


1. Decide density of data points (example uses 40)
2. Decide number of clusters/APs (example has 10)
3. Generate random initial centers
4. If necessary move centers so they are inside building
5. Perform Euclidean k-means algorithm, store performance data
6. Repeat with same initial centers, using Hybrid method and RSS method

Preliminary Observations

- General
  - There can be bad initial centers, so many trials needed
  - Best coverage percent isn't always the final iteration (overall trends still hold)
- Comparisons
  - Hybrid method and RSS method perform better than Euclidean
  - Hybrid requires (slightly) fewer RSS iterations
  - RSS method sometimes found the lowest percent placements, so Hybrid is not strictly better

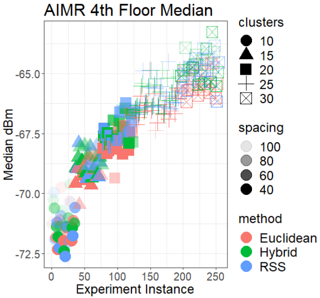
Performance



- Hybrid and RSS overall outperform Euclidean
- Observed similar trends for demo building

How to decide AP placement

1. Use Euclidean method to gather approximate performance information for several cluster numbers
2. Decide number of APs (based on user's priorities, for ex. good coverage, average RSS, balance, etc)
3. Use Hybrid and RSS method to gather placement candidates
4. Choose optimal placement (based on user's priorities)



Example: if a median signal strength of at least -68 dBm is desired for the AIMR 4th Floor, we recommend ≈ 15 AP units.

Next Steps

- To improve computation runtime:
  - Parallelize code
  - Filter RSS calculation
  - Use more equally spaced initial centers
  - Find optimal cutoff for RSS iterations
- To further analyze performance:
  - Test more floor plans
  - Test the validity of using different levels of data spacing (this could help runtime as well)
  - Compare performance with other placement models (or human-generated placements)

Conclusion

Conclusions

- Simulated fingerprints seem to work just as well as fingerprints. Could decrease cost of fingerprinting.
- Incorporating global features of RSS data appears to greatly improve path loss models in some cases.
- Simulations allow us to estimate optimal placement of APs according to various metrics, e.g. maximizing average RSS, minimizing low-coverage area.