Crowdsourced Indoor Localization for Diverse Devices through Radiomap Fusion

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Motivation of our work

- Traditional RSS radiomap construction
  - **Laborious:** Collectors need to visit several locations
  - **Time consuming:** A large volume of data is required
  - **Short-lived:** Radiomap becomes obsolete with time
  - **Expensive:** Cost can be prohibitive when the task is undertaken by trained professionals

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- Crowdsourcing comes to the rescue
  - Volunteers are collecting location dependent RSS samples, which they later contribute to the system
  - Crowdsourced systems (e.g., *Active Campus*, *Place Lab*, *Redpin*, *WiFiSLAM*, *Molé*, *Elekspot*, *FreeLoc*)

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  - Crowdsourced systems (e.g., *Active Campus*, *Place Lab*, *Redpin*, *WiFiSLAM*, *Molé*, *Elekspot*, *FreeLoc*)
- Or maybe not?
  - Filtering incorrect contributions (aka polluted data)
  - Handling non-uniform fingerprint distribution
  - Managing the increasing radiomap size
  - Copying with heterogeneous mobile devices

Crowdsourcing with RSS Fingerprints

Offline (training) phase

- Reference locations $\{L : \ell_i = (x_i, y_i),\ i = 1, \ldots, l\}$, n APs
- Device $D^{(m)}$ visits $\{L^{(m)} : \ell_i = (x_i, y_i),\ i = 1, \ldots, l^{(m)}\}$, where $m = 1, \ldots, M$, $L^{(m)} \subseteq L$ and $L = \bigcup_{m=1}^{M} L^{(m)}$
- Reference fingerprint $\mathbf{r}_i^{(m)} = [r_{i1}^{(m)}, \ldots, r_{in}^{(m)}]^T$ collected at ℓ_i is used to create the device-specific radiomap $\mathbf{R}^{(m)} \in \mathbb{Z}^-_{l^{(m)} \times n}$
- Crowdsourced radiomap $\mathbf{R} \in \mathbb{Z}^-_{l \times n}$

$$r_{ij} = \frac{1}{M_i} \sum_{m=1}^{M_i} r_{ij}^{(m)}, \quad 1 \leq M_i \leq M \qquad (1)$$

Online (localization) phase

- Use $\mathbf{R}$ and the new fingerprint $\mathbf{s} = [s_1, \ldots, s_n]^T$ measured at the unknown location ℓ by the user carried device $D^{(m')}$
- $\widehat{\ell}(\mathbf{s}) = \arg\min_{\ell_i} d_i^2, \quad d_i^2 = \sum_{j=1}^{n} \left(r_{ij} - s_j\right)^2$

Localization with DIFF Fingerprints

Radio propagation model

$$RSS[dBm] = A - 10\gamma \log_{10} d + X, \quad X \sim \mathcal{N}(0, \sigma^2) \qquad (2)$$

DIFF approach[1]

- Takes the difference between all pairwise AP combinations
- The new fingerprints contain $\binom{n}{2} = \frac{n(n-1)}{2}$ RSS differences
- Crowdsourced radiomap $\tilde{\mathbf{R}}$ contains $\tilde{\mathbf{r}}_i = [\tilde{r}_{i12}, \ldots, \tilde{r}_{i(n-1)n}]^T$ where $\tilde{r}_{ijk} = r_{ij} - r_{ik}$, $1 \le j < k \le n$
- $\tilde{\mathbf{s}} = [\tilde{s}_{12}, \ldots, \tilde{s}_{(n-1)n}]^T$ where $\tilde{s}_{jk} = s_j - s_k$, $1 \le j < k \le n$
- $\widehat{\ell}(\tilde{\mathbf{s}}) = \arg\min_{\ell_i} \tilde{d}_i^2$, $\tilde{d}_i^2 = \sum_{k=2}^{n} \sum_{j=1}^{k-1} \left(\tilde{r}_{ijk} - \tilde{s}_{jk}\right)^2$
- Higher dimensionality leads to increased computations

[1] F. Dong, et al., A calibration-free localization solution for handling signal strength variance, in MELT, 2009.

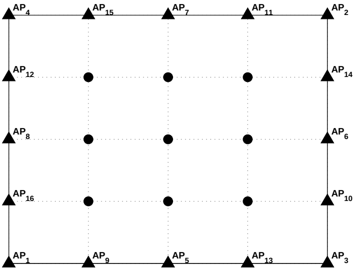
Localization with SSD Fingerprints

SSD approach[2]

- Subtracts the RSS value of an anchor AP from the other RSS values in the original fingerprint
- The new fingerprints contain $n-1$ independent RSS differences
- Crowdsourced radiomap $\check{\mathbf{R}}$ contains $\check{\mathbf{r}}_i = [\check{r}_{i1}, \ldots, \check{r}_{i(n-1)}]^T$ where $\check{r}_{ij} = r_{ij} - r_{ik},\ j = 1, \ldots, n,\ j \neq k$
- $\check{\mathbf{s}} = [\check{s}_1, \ldots, \check{s}_{n-1}]^T$ where $\check{s}_j = s_j - s_k,\ j = 1, \ldots, n,\ j \neq k$
- $\widehat{\ell}(\check{\mathbf{s}}) = \arg\min_{\ell_i} \check{d}_i^2,\quad \check{d}_i^2 = \sum_{\substack{j=1 \\ j\neq k}}^{n} \left(\check{r}_{ij} - \check{s}_j\right)^2$
- Lower dimensionality leads to higher localization errors

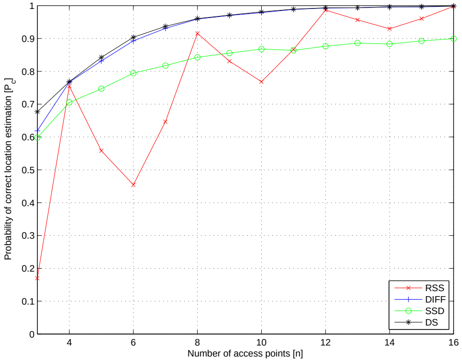
[2] A. Mahtab Hossain, et al., SSD: a robust RF location fingerprint addressing mobile devices' heterogeneity, in IEEE Transactions on Mobile Computing, 2013.

Simulation Setup



- Radiomap $\mathbf{R}^{(1)}$ contains RSS values $r_{ij}^{(1)}$ generated by the propagation model of (2) with $A = -22.7\,\mathrm{dBm}$, $\gamma = 3.3$
- Radiomap $\mathbf{R}^{(m)}$ contains RSS values such that $r_{ij}^{(m)} = \alpha_{1m} r_{ij}^{(1)} + \beta_{1m}, \; m = 2, \ldots, M,$
- All M devices contribute their radiomaps $\mathbf{R}^{(m)}$ to get the crowdsourced RSS radiomap $\mathbf{R}$ according to (1), $\tilde{\mathbf{R}}$ and $\check{\mathbf{R}}$
- User carries $D^{(1)}$ and may reside at any location
- Probability of correct location estimation $P_c = \frac{N_c}{N_s}$

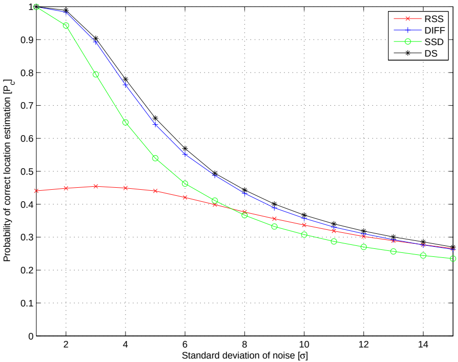
Varying number of APs



P_c for localizing device $D^{(1)}$ with $M = 2$ devices and $\sigma = 3\,\text{dBm}$

- DIFF is better than SSD and performs equally well with DS
- RSS usually performs poorly, e.g., $P_c = 0.45$ for $n = 6$ APs
- For a large number of APs, e.g., $n > 11$, RSS looks fine
- For RSS, there are peaks in the P_c curve at $n \in \{4, 8, 12, 16\}$ because the APs are evenly distributed around the area

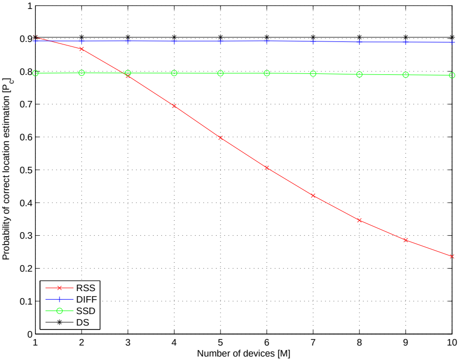
Varying noise standard deviation



P_c for localizing device $D^{(1)}$ with $M = 2$ devices and $n = 6$ APs

- Under low noise conditions ($\sigma = 1, 2\,\mathrm{dBm}$), the performance of SSD is similar with DIFF
- When $\sigma \geq 3\,\mathrm{dBm}$, P_c is decreased by 5%–10% for SSD
- DIFF attains the same level of performance with DS
- For RSS, $P_c < 0.5$ even under low noise conditions

Varying number of crowdsourcing devices



P_c for localizing device $D^{(1)}$ with $\sigma = 3\,\text{dBm}$ and $n = 6$ APs

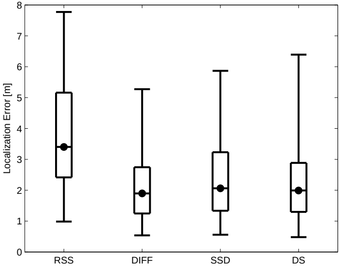
- P_c decays linearly for the RSS approach
- DIFF and SSD approaches are extremely robust and their performance is not affected as more devices contribute data
- DIFF performs better than SSD and is very close to DS

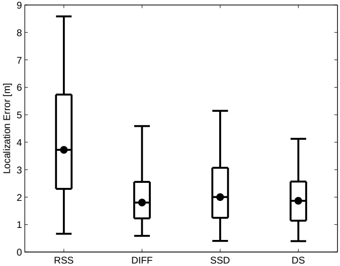
Measurement Setup

- Experimental data collected at the KIOS Research Center[3]
  - RSS samples collected with 5 devices (HP iPAQ PDA, Asus eeePC laptop, HTC Flyer Android tablet, HTC Desire and Samsung Nexus S Android smartphones)
  - 2100 location-tagged fingerprints for each device collected at 105 reference locations
  - 960 location-tagged fingerprints for each device collected at 96 test locations
- Performance evaluation
  - Used the reference data to build device-specific radiomaps and crowdsourced radiomaps with different device combinations
  - Used the test data to evaluate various crowdsourcing approaches in terms of the localization error
  - RSS, DIFF and SSD approaches for crowdsourcing compared with DS (device-specific) RSS radiomap

[3] The KIOS dataset is available to download at `http://goo.gl/u7IoG`

Two-device crowdsourced radiomaps





Localization of the iPAQ (left) and Desire (right) devices

- Two contributing devices (iPAQ, Nexus) that fully cover the localization area for crowdsourcing the radiomap
- Differential approaches reduce error that is comparable to DS
- For iPAQ, the median error is 3.4 m for RSS against 2 m for DIFF and SSD (75th percentile drops from 5.2 m to 3 m)
- DIFF approach filters out high errors more effectively

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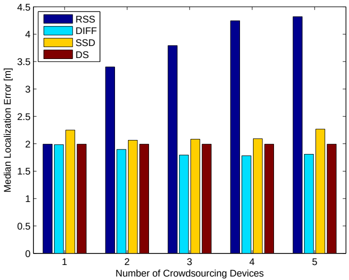
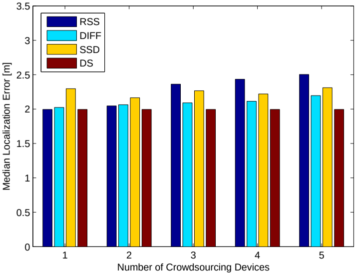
Crowdsourcing with multiple devices





Localization of the iPAQ with fully overlapping radiomaps (left) and the eeePC with non-overlapping radiomaps (right)

- RSS performs poorly, e.g., for 5 devices the median error is 4.3 m compared to 1.8 m for DIFF and 2.3 m for SSD
- For DIFF and SSD the localization error does not vary significantly as suggested by the simulations
- DIFF outperforms SSD for any number of devices

Concluding Remarks

- **Notes**
  - Crowdsourcing stands as the only viable solution for building the radiomap considering effort, time and cost
  - Our community has not appreciated its potential (0 papers in IPIN'10-11, 1 in IPIN'12 and 2 in IPIN'13)
- **Our Contributions**
  - Evaluated DIFF and SSD methods for creating the RSS differences from the original RSS fingerprints
  - Simulation and experimental findings indicate that differential fingerprinting is a promising solution
  - DIFF performs better than SSD at the expense of higher computational complexity
- **Future Work**
  - Investigate other issues related to crowdsourcing, e.g. polluted data, non-uniform fingerprint distribution and the fast growing radiomap size

Thank you for your attention

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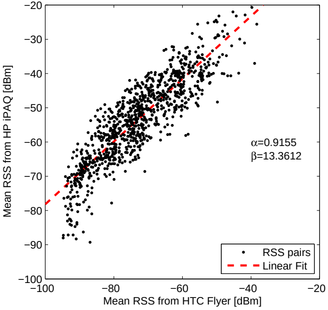
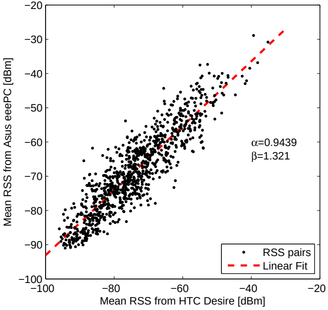
Extra Slides

Linear relation between RSS values





- Several studies report a linear relation between the RSS values measured by heterogeneous devices
- $r_{ij}^{(m_2)} = \alpha_{m_1 m_2} r_{ij}^{(m_1)} + \beta_{m_1 m_2},\ m_1, m_2 \in \{1, \ldots, M\}$, where $(\alpha_{m_1 m_2}, \beta_{m_1 m_2})$ are the coefficients between $D^{(m_1)}$ and $D^{(m_2)}$
- Direct fusion of the different RSS radiomaps using (1) may degrade the quality of the crowdsourced radiomap