Zero-configuration, Robust Indoor Localization: Theory and Experimentation

Hyuk Lim, Lu-Chuan Kung, Jennifer Hou, Haiyun Luo

University of Illinois
at Urbana Champaign

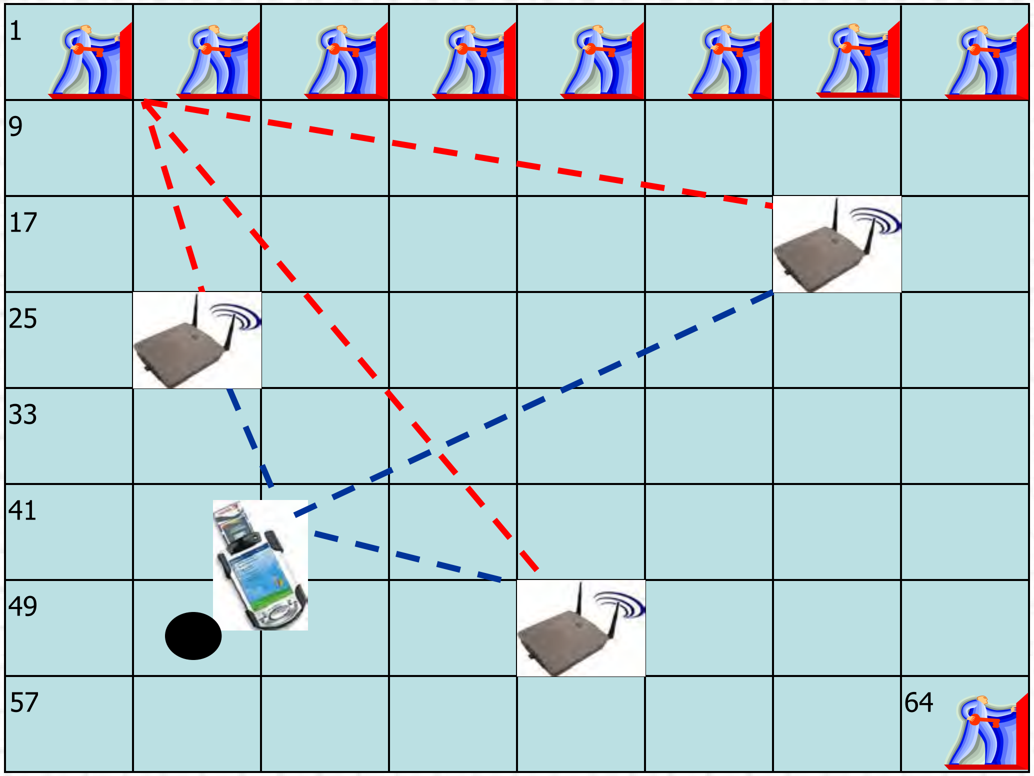
Indoor Localization

- Fine-grained indoor localization and tracking of 802.11-enabled devices with existing 802.11 WLAN deployments.

- Location-aware applications: Ubiquitous office/home, visitor guidance, network management/resource planning, and wireless network attacker localizer.

Existing Methods

- Received signal strengths (RSSs) pattern-matching approach



For each cell,

$$S^i = < s_1^i, s_2^i, s_3^i >$$

For a client to be localized,

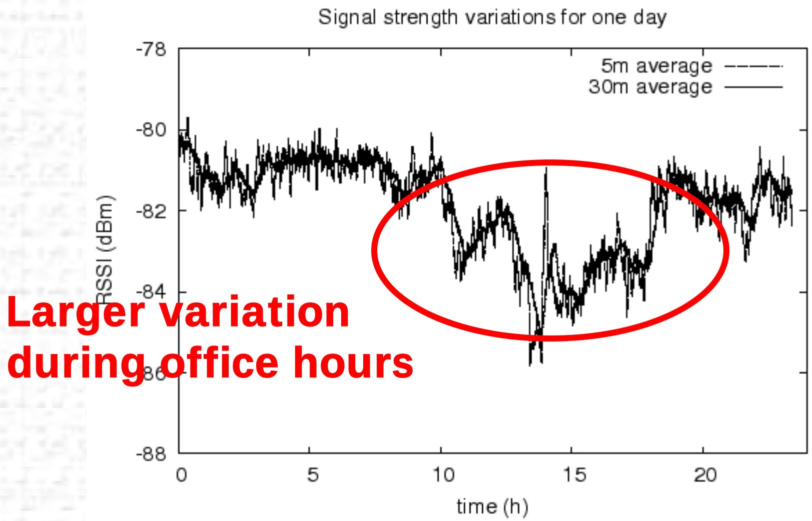
$$S^c = < s_1^c, s_2^c, s_3^c >$$

Pick a cell that gives the mi nimum distance between S^i and S^c as the location of the client.

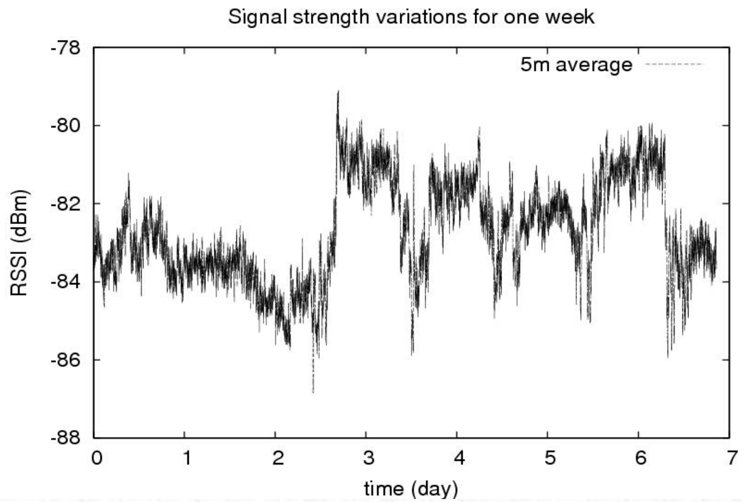
- Requires offline calibration process.
- Good if the RSSs do not change dramatically.

- **Time-varying signal strength**: Received signal strengths (RSSs) fluctuate due to RF fading, human mobility, and other dynamic changes of the indoor environment.

One day



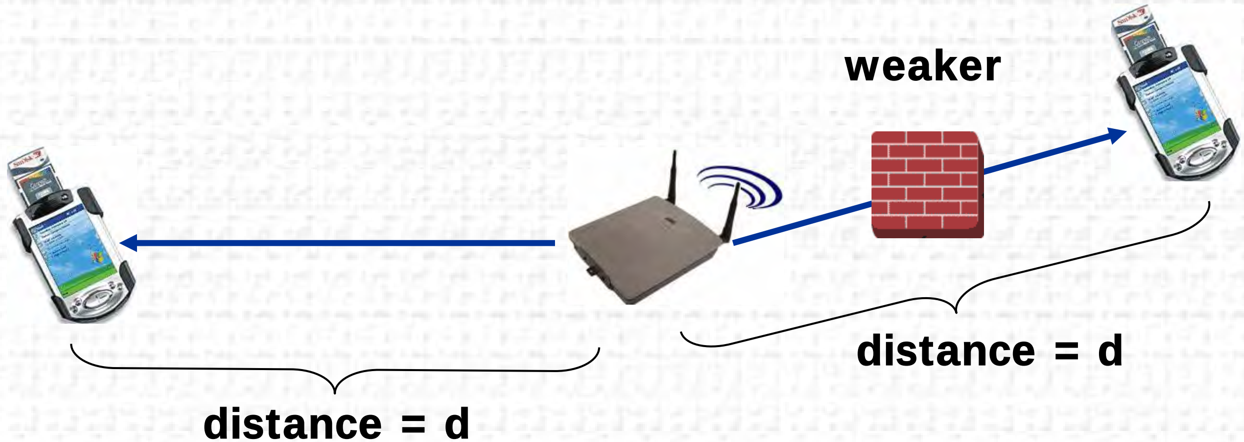
One week



- **Configuration overhead**: Frequent full-scale, on-site survey and training are expensive.
  - ex) 5 minutes x 64 cells = 5.3 hours

Existing Methods (cont'd)

- **Path loss model based approach**
  - **Inaccurate due to anisotropy of signal attenuation**: RF signals are attenuated differently along different directions.



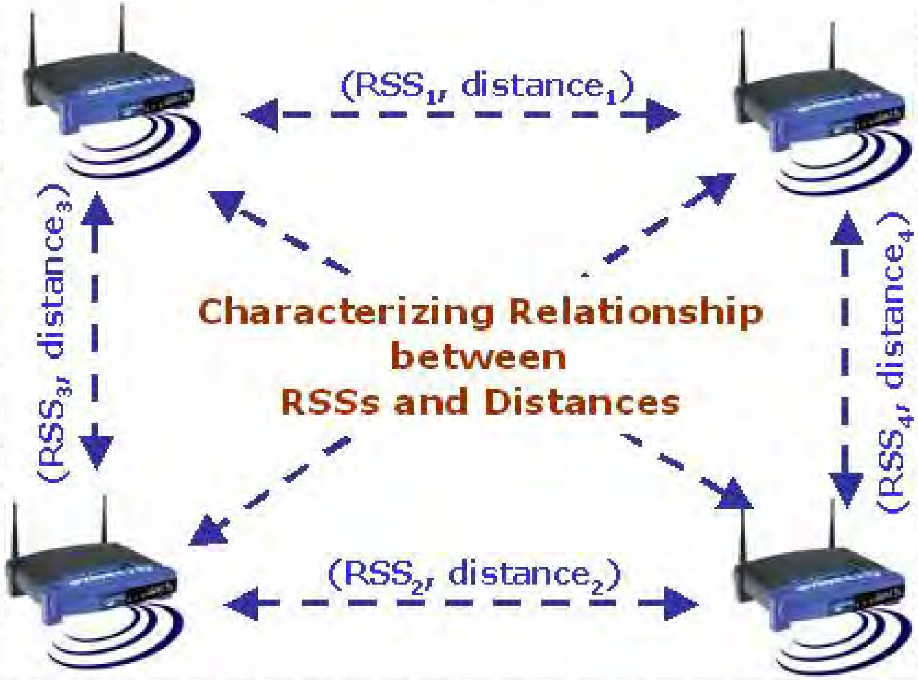
- **Dedicated hardware based approach**:
  - Localization system usually employs expensive and specialized hardware.
  - ex) Ubisense with UWB technology

Our Approach

- **Zero configuration**
  - Our localization system auto-configures itself on-line and adapts to the time-varying environmental dynamics.
- **Robustness**
  - We compensate for noisy and time-varying 802.11 signal strength measurements with the truncated singular value decomposition.
- **Accuracy**
  - We achieve an accuracy of 2.5m (median error) for indoor localization.
- **Cost**
  - Our system is grounded on the innovation that turns the off-the-shelf 802.11-enabled devices (Linksys WRT54G) into wireless monitors. These routers are inexpensive ($50 per router).

Algorithm

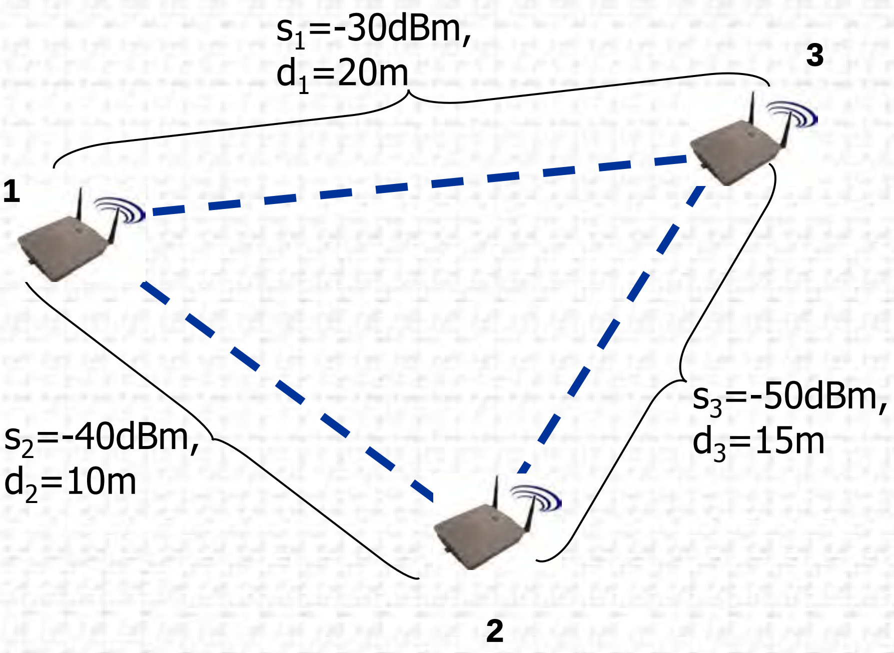
- **Basic idea**
  - Given: locations of APs & distances between APs,
  - Continuously monitor RSSs between APs and detect dynamic environmental changes in the area.



Our APs measure RSSs from other APs as well as clients to be localized!

Signal-Distance Map (SDM)

- Construct signal-distance map (SDM) from RSS measurements between APs.
  - Obtain a linear mapping in logarithm scale of both RSS and distance: ex) RSS [in dB unit] = $P_0 + \alpha \log$ (distance)
  - Least square solution: $T = DS^T(SS^T)^{-1}$, where S and D are RSS and distance matrices.



$$\log\left[\begin{bmatrix} d_0 \\ 10 \\ 20 \end{bmatrix} \begin{bmatrix} 10 \\ d_0 \\ 15 \end{bmatrix} \begin{bmatrix} 20 \\ 15 \\ d_0 \end{bmatrix}\right] = T \bullet \left[\begin{bmatrix} s_0 \\ 40 \\ 30 \end{bmatrix} \begin{bmatrix} 40 \\ s_0 \\ 50 \end{bmatrix} \begin{bmatrix} 30 \\ 50 \\ s_0 \end{bmatrix}\right]$$

where d_0 and s_0 are self-distance and self-RSS.

T is 3x3 matrix, and T_{ij} represents the effect of RSS to j^{th} AP on distance to i^{th} AP.

Robust Computation of SDM

- Matrix inversion incurred by $T = DS^T(SS^T)^{-1}$
  - Singular value decomposition (SVD)

$$S = U \bullet \begin{bmatrix} \Sigma & 0 \\ 0 & 0 \end{bmatrix} \bullet V^T \qquad U = [u_1, \cdots, u_M] \qquad \Sigma = \mathrm{diag}(\sigma_1, \cdots, \sigma_W)$$

$$V = [v_1, \cdots, v_M]$$

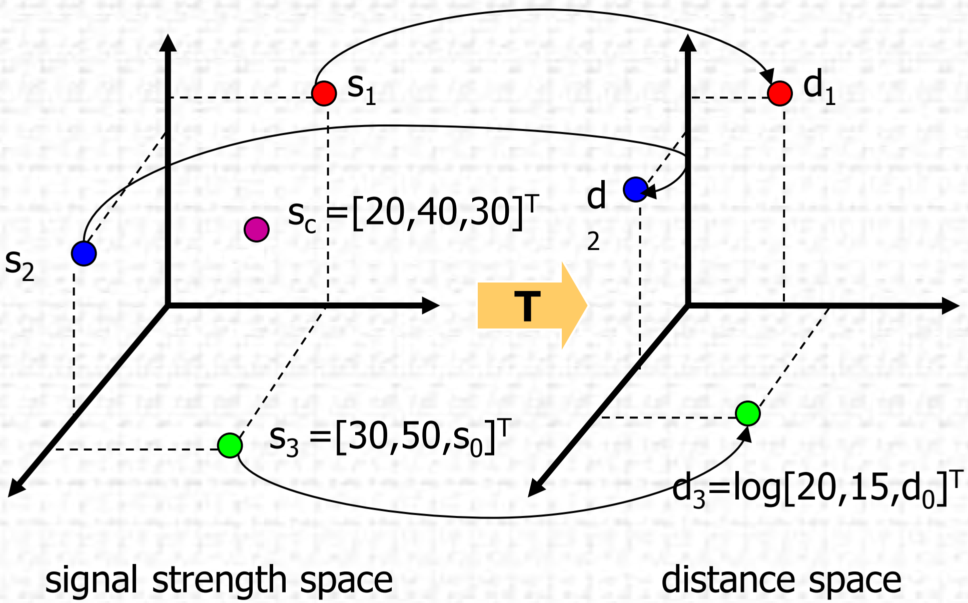
$$S^T(SS^T)^{-1} = V \bullet \begin{bmatrix} \Sigma^{-1} & 0 \\ 0 & 0 \end{bmatrix} \bullet U^T = \sum_{i=1}^{W} \frac{1}{\sigma_i} v_i u_i^T$$

- Truncated pseudo-inversion technique
  - Discarding components corresponding to small (near-zero) singular values by truncating terms at an earlier index $\gamma < w$.
  - $T = D \bullet \sum_{i=1}^{\gamma} \frac{1}{\sigma_i} v_i u_i^T$
  - Cumulative percentage method for selecting γ ($\tau^*=0.98$).

$$\tau(\gamma) = \frac{\sum_{i=1}^{\gamma} \sigma_i}{\sum_{i=1}^{W} \sigma_i} \geq \tau^*$$

Location Estimation for Clients

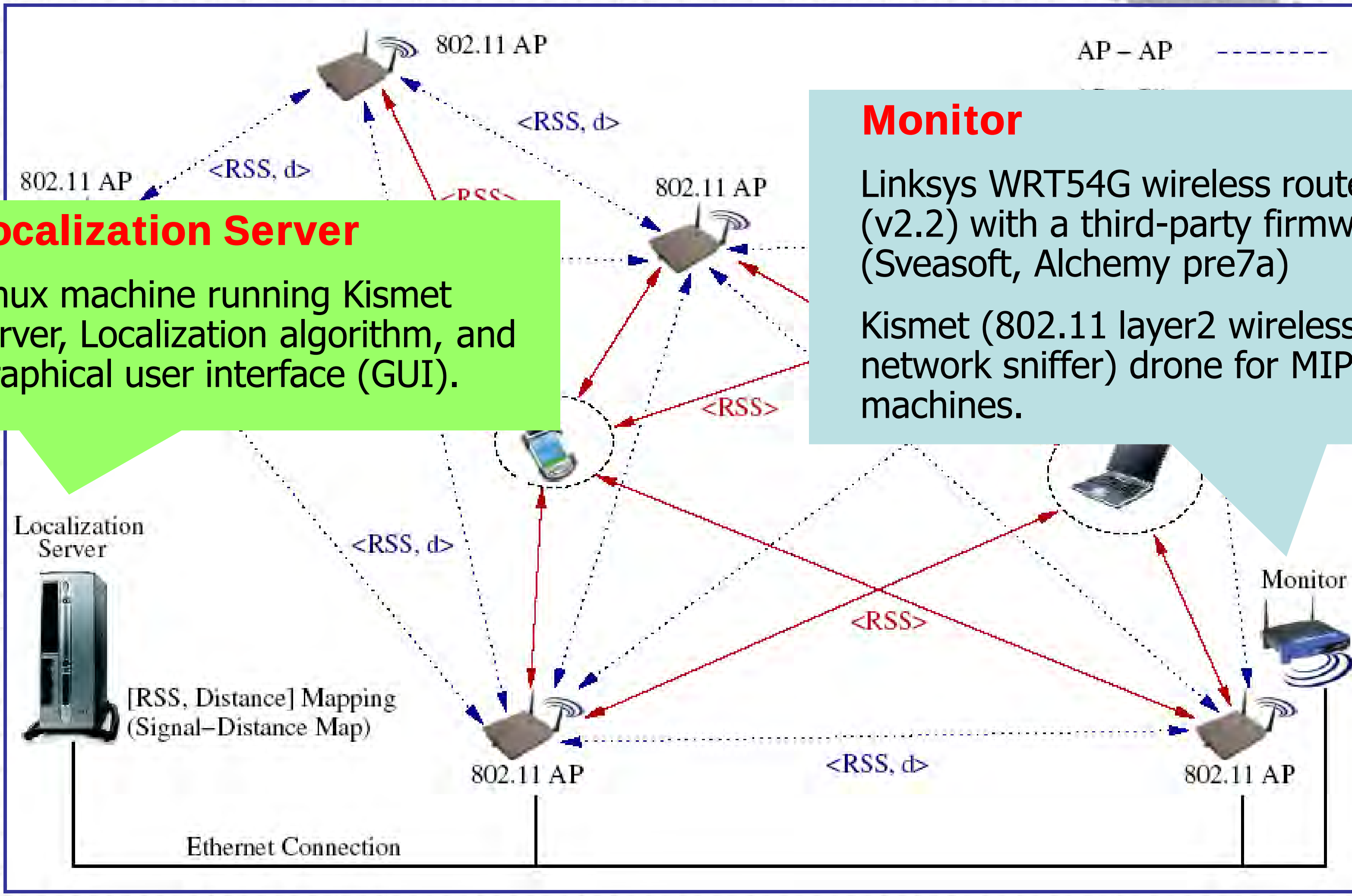
- Signal to distance transformation



$$d_c = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} = \exp(T \bullet \begin{bmatrix} 20 \\ 40 \\ 30 \end{bmatrix})$$

- Distance to location transformation
  - Use triangular methods: calculate the location with the locations of and the estimated distances to APs.

Implementation



Localization Server

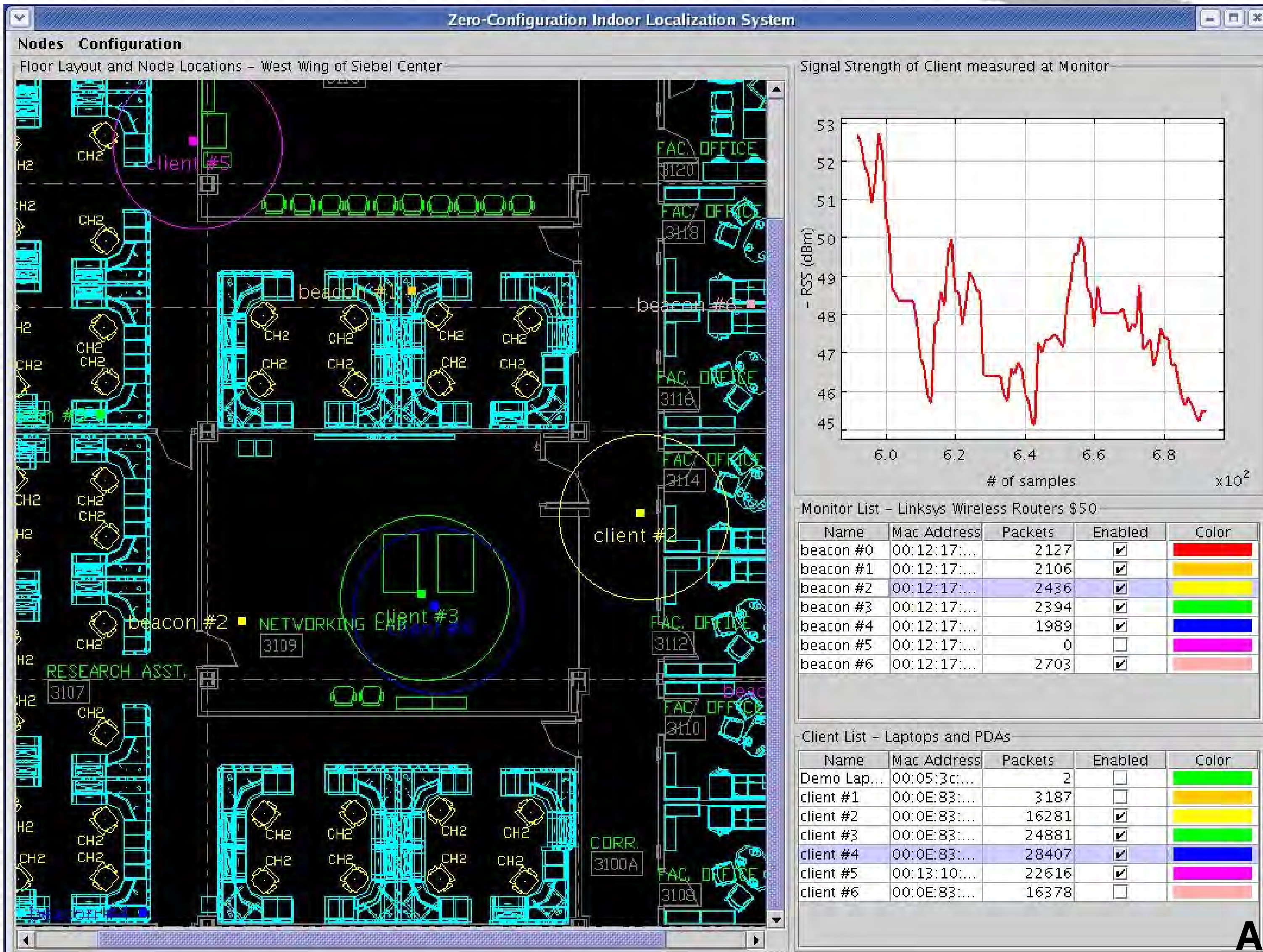
Linux machine running Kismet server, Localization algorithm, and Graphical user interface (GUI).

Monitor

Linksys WRT54G wireless routers (v2.2) with a third-party firmware (Sveasoft, Alchemy pre7a)

Kismet (802.11 layer2 wireless network sniffer) drone for MIPS machines.

Implementation (cont'd)



Area = 600 m^2
4-6 Monitors

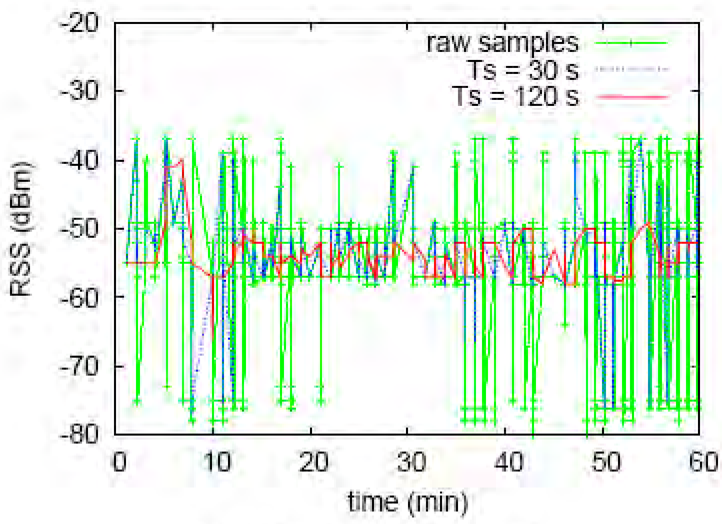
Experiments

- Wireless network setups
  - Monitor: Linksys WRT54 with IEEE 802.11 b/g, channel 2/7, and power (28/56 mW).
  - Client: Sharp Zaurus PDA (OS: Linux) with Linksys WCF-12 CF wireless card.
- Localization algorithms for comparison
  - Proposed signal-distance map (SDM) based algorithm.
  - Proximity in Signal Space (PSS) proposed by Gwon and Jain [MobiWac:04].
- Measurement direction
  - Client-assisted: Client measures RSSs from APs and localizes itself.
  - Monitor-assisted : Monitors measure RSSs from a client while it is transmitting wireless packets.

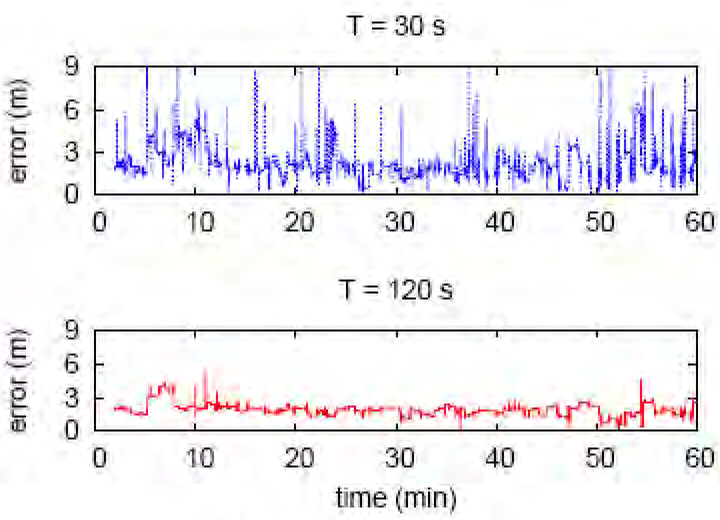
Performance wrt RSS Sampling

- Preprocessing RSS measurements
  - Sample RSS measurements at an instance with the median filter with an interval T_s, which determines the maximum estimation delay.

$$\bar{s}(t) = \text{median}(s(\tau) \mid t - T_s < \tau \le t)$$



(a) RSSs of *n4* measured at *n2*

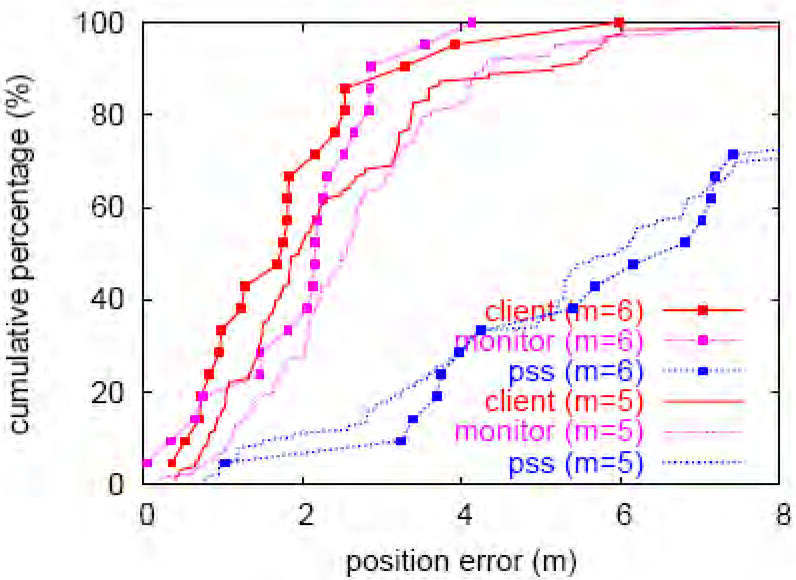


(b) localization errors of *n2*

We set T_s = 60 s for our experiments

Localization Performance

- IEEE 802.11b / Channel 2 / Power = 28 mW / # of Monitors = 5, 6

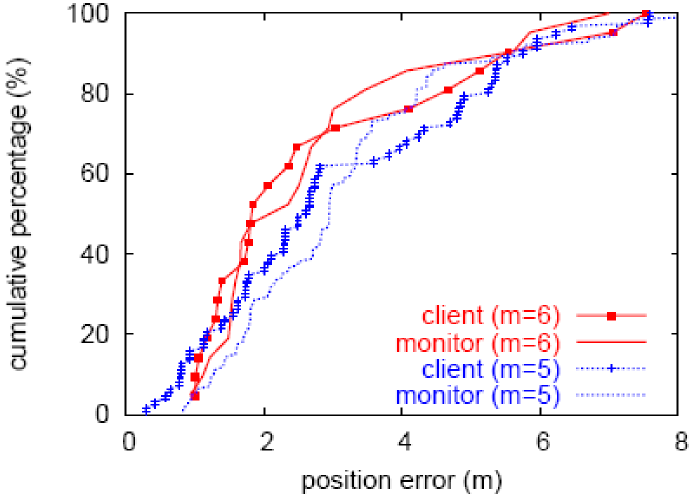


M	algorithm	25 %	median	75 %	mean
6	SDM (client)	0.83	1.76	2.16	1.87
6	SDM (monitor)	1.47	2.16	2.52	2.05
6	PSS	3.74	6.80	7.41	7.09
5	SDM (client)	1.36	1.95	3.21	2.43
5	SDM (monitor)	1.76	2.56	3.37	2.71
5	PSS	3.68	5.97	8.14	6.40

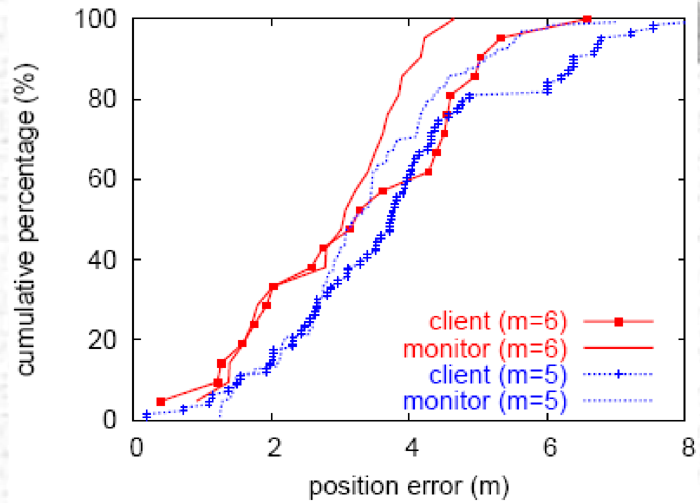
- SDM method outperforms PSS.
- Client-assisted approach gives the better accuracy.
- The more monitors give the better accuracy.

Performance wrt Parameters

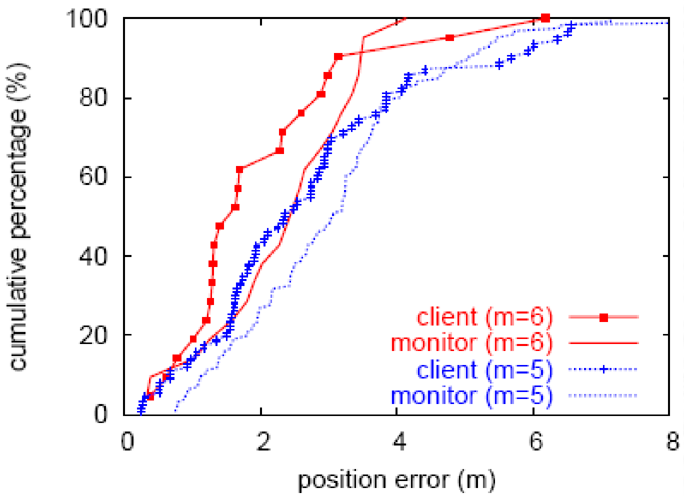
Channel = 7



Power = 56 mW

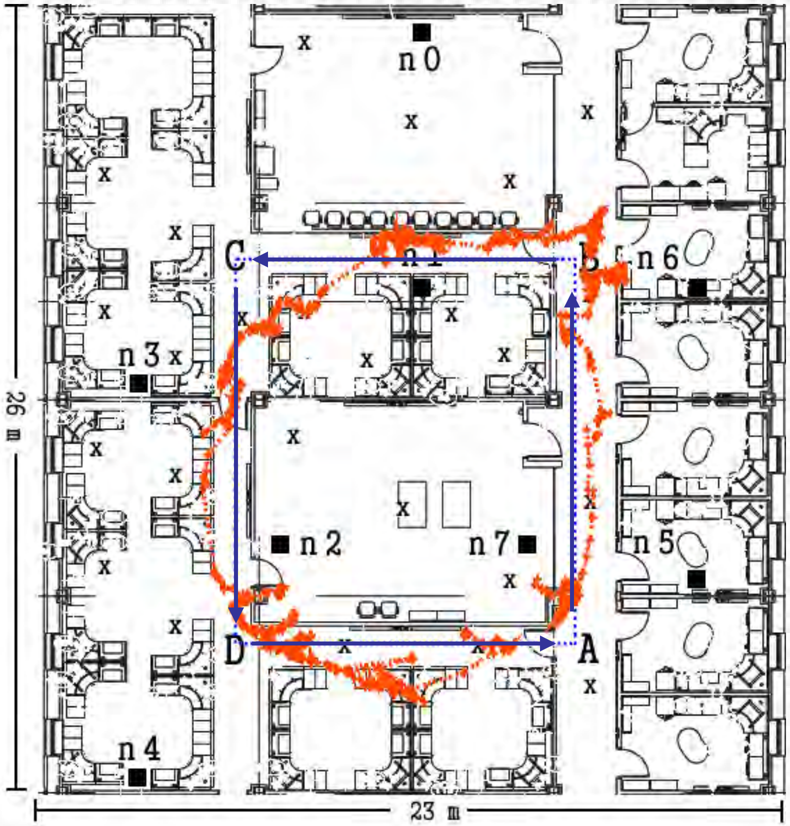


IEEE 802.11 g

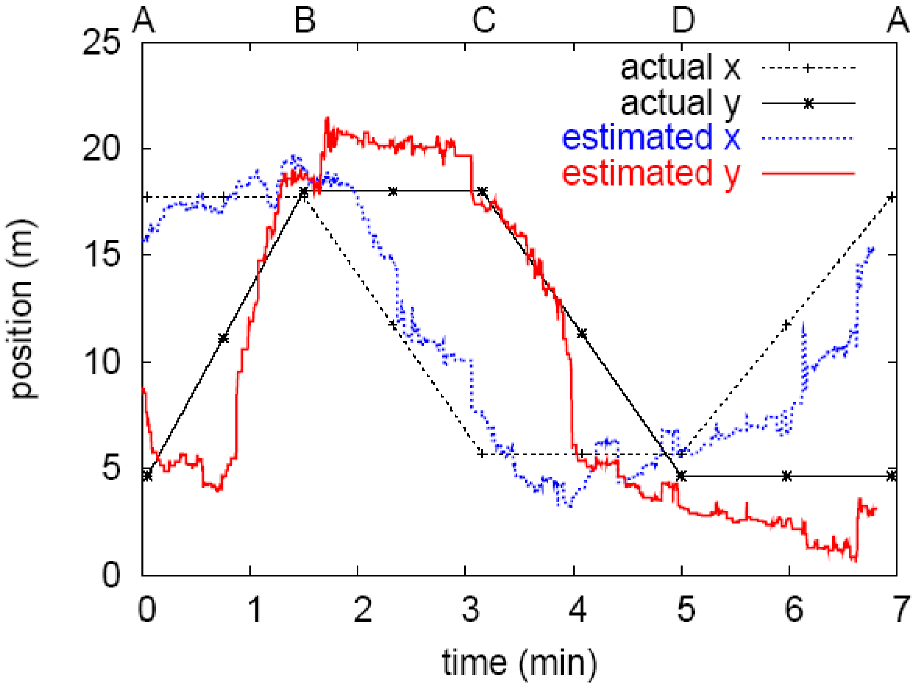


- SDM method achieves robust performance to wireless network parameter settings.
- The increase of tx power does not help for accuracy.

Tracking Performance



Walking trajectory



The achieved accuracy for mobile user is ±3m.

Accuracy depends on the speed & the packet transmitting rate of mobile users.

Summary

- Robust and accurate localization performance without manual configurations.
- Value-added service in Wi-Fi network infrastructure for free.

- As future work, we will investigate
  - (i) where to place or select wireless monitors for better performance,
  - (ii) how to design the filter for signal strength measurements wrt packet transmission rate and movement speed for better tracking performance.