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Range Domain IMM Filtering with Additional Signal Attenuation Error Mitigation of Individual Channels for WLAN RSSI-based Position-Tracking

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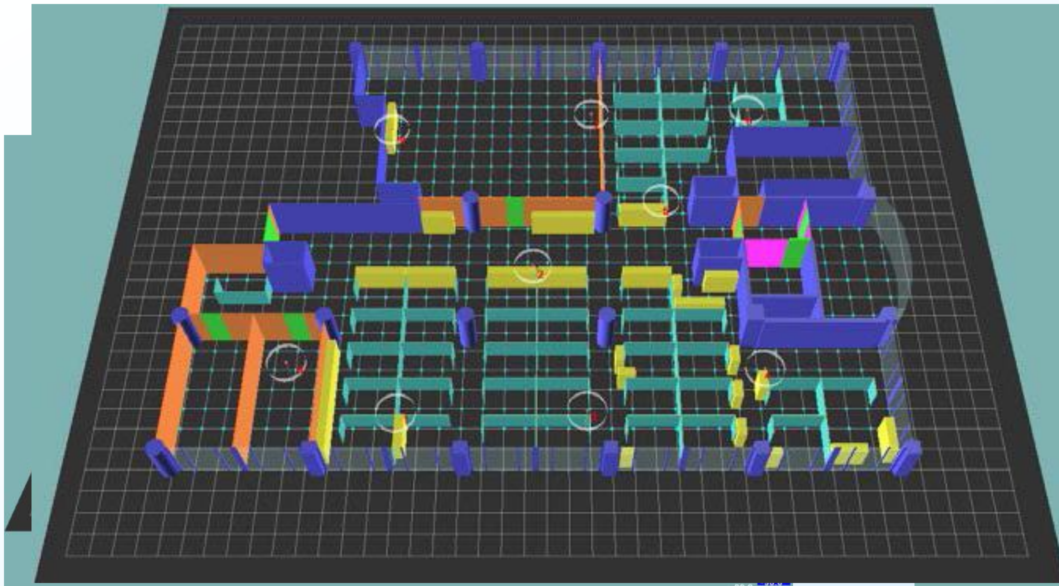
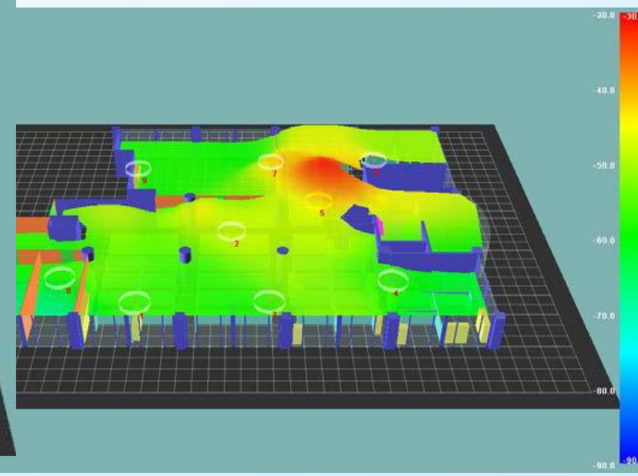
I. Introduction (2/2)

- **Indoor Localization**



sured RSSI in Real Environment



※ In indoor environments, there exist ASAE (Additional Signal Attenuation Error) caused by wall penetration, NLOS (Non-Line-of-Sight) signals, multipath signals, etc.

→ This may cause large localization errors

II. RSSI-based Range Measurement (1/2)

- **RSSI (Received Signal Strength Indicator)-based Range Measurement**
  - **Friis's Formula :**

$$L = 20 \log_{10}\left(\frac{4\pi f d}{c}\right)$$

where L : signal attenuation size

d : range of a propagation path

c : velocity of light (2.99792458×10^8 m/s)

f : frequency of radio waves (WiFi, 2.4×10^9 Hz)

  - **Another Signal Propagation Model :**

$$\tilde{S}_k^j = \bar{S} - 10\,\alpha \log_{10}\left(\frac{r_k^j}{\bar{r}}\right) - \delta S_k^j + w_k^j \equiv S_k^j - \delta S_k^j + w_k^j$$

where $\tilde{S}_k^j$: RSSI measurement [dBm] from AP j in time k

r_k^j : range between a mobile node and AP j

$\bar{S}$: RSSI mean value at a reference known distance $\bar{r}$ such as 1 m

α : attenuation factor in the free space

w_k^j : additive white Gaussian noise (AWGN)

δS_k^j : signal strength level additional signal attenuation error (ASAE) caused by wall penetration, NLOS error signal, and multipath signals

II. RSSI-based Range Measurement (2/2)

- **RSSI (Received Signal Strength Indicator)-based Range Measurement**
  - $\bar{S}$ and α can be calculated using the obtained RSSI measurements

$$\begin{bmatrix} \hat{\bar{S}} \\ \hat{\alpha} \end{bmatrix} = (M^T M)^{-1} M^T \begin{bmatrix} \tilde{S}_1 \\ \tilde{S}_2 \\ \vdots \\ \tilde{S}_m \end{bmatrix} \quad \text{where} \quad M = \begin{bmatrix} 1 & -10\log_{10}(r_1/\bar{r}) \\ 1 & -10\log_{10}(r_2/\bar{r}) \\ \vdots & \vdots \\ 1 & -10\log_{10}(r_m/\bar{r}) \end{bmatrix}$$

  - The RSSI measurement can be converted into range measurement :

$$\tilde{r}_k^j = \bar{r} \cdot 10^{\tilde{\beta}_k^j} \quad \text{where} \quad \tilde{\beta}_k^j = \frac{\hat{\bar{S}} - \tilde{S}_k^j - \delta S_k^j + w_k^j}{10\hat{\alpha}} \cong \frac{\hat{\bar{S}} - \tilde{S}_k^j}{10\hat{\alpha}} \qquad (Eq.(1))$$

  - It is assumed that the signal strength level ASAE has the following properties :

$\delta S_k^j \geq 0,$: always positive real number

$E[\delta S_k^j \delta S_l^j] = 0, \quad k \neq l, \quad and$: temporally uncorrelated property

$E[\delta S_k^j \delta S_k^i] = 0, \quad j \neq i$: ASAE in the measurements obtained from different APs are not correlated

III-1. Model-free Localization (1/2)

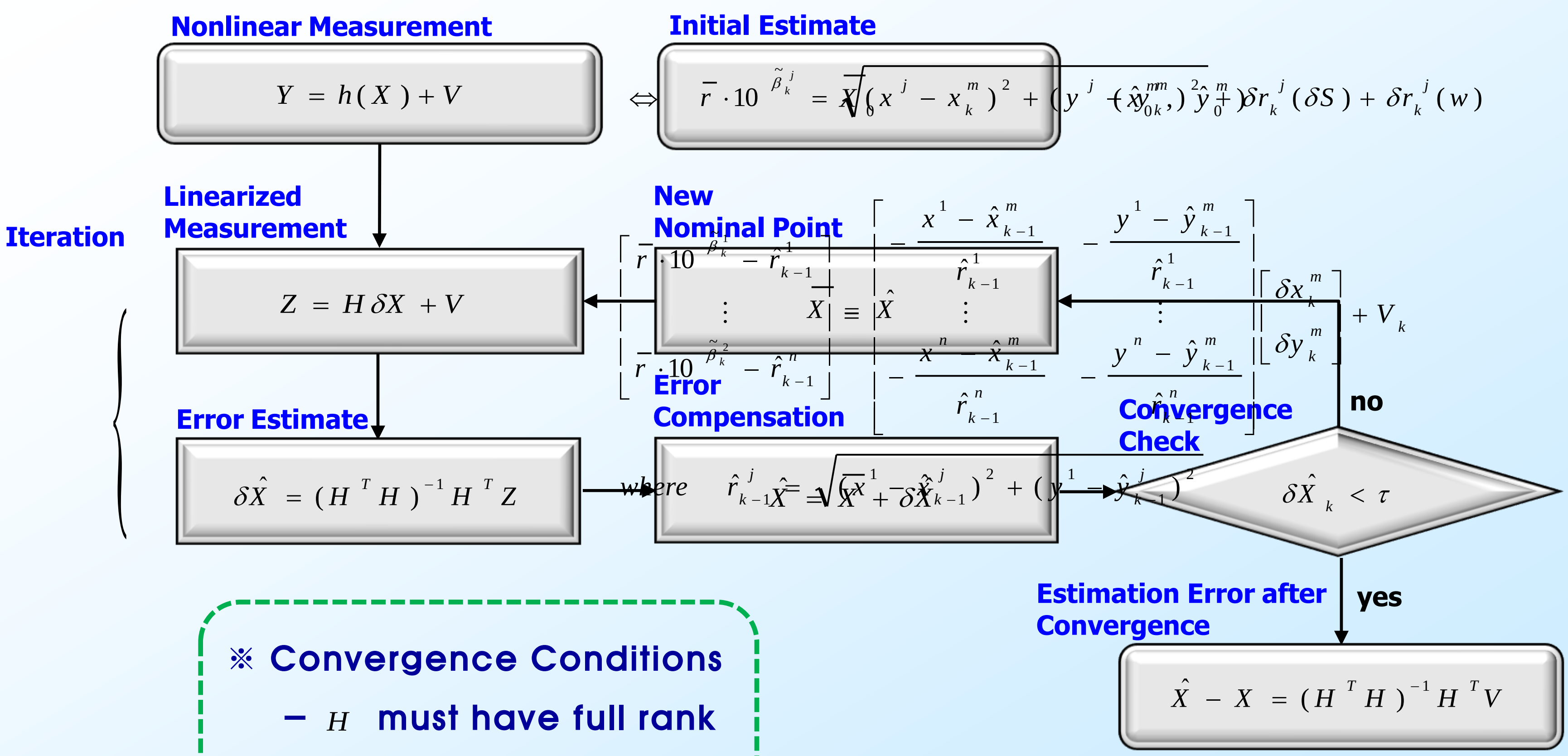
- **Range Equation (2-Dimension)**

$$\tilde{r}_k^{\,j} = \bar{r} \cdot 10^{\tilde{\beta}_k^{\,j}}$$

$$= \sqrt{(x^j - x_k^m)^2 + (y^j - y_k^m)^2} + \delta r_k^j(\delta S) + \delta r_k^j(w)$$

  - For estimating $(x_k^m, \; y_k^m)$
    - Iterative Methods
      - ✓ J. M. Mendel, *Lessons in Estimation Theory for Signal Processing, Communications,* and Control, Prentice-Hall International, Inc., 1995.
    - Linear Closed-form Solutions
      - ✓ I. Biton, M. Koifman, and I. Y. Bar-Itzhack, "Improved direct solution of the Global Positioning System equation," *Journal of Guidance, Control, and Dynamics*, vol. 21, no. 1, 1998, pp. 45-49.
      - ✓ S. Y. Cho, and B. D. Kim, "Linear closed-form solution for wireless localisation with ultra-wideband/chirp spread spectrum signals based on difference of squared range measurements," IET Wireless Sensor Systems, vol. 3, iss. 4, Dec. 2013, pp. 255-265.

- **One of the Iterative Methods : ILS (Iterative Least Squares) Method**



※ **Convergence Conditions**

- H **must have full rank**
- δX_0 **must be small**

III-2. Model-based Localization Filter (1/2)

- **CV (Constant Velocity) Model**
  - **Process Model :**

$$X_{k+1}^{CV} = F^{CV} X_k^{CV} + w_k$$

$$\Leftrightarrow \begin{bmatrix} x_{k+1}^m \\ \dot{x}_{k+1}^m \\ y_{k+1}^m \\ \dot{y}_{k+1}^m \end{bmatrix}^{CV} = \begin{bmatrix} 1 & T & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T \\ 0 & 0 & 0 & 1 \end{bmatrix}^{CV} \begin{bmatrix} x_k^m \\ \dot{x}_k^m \\ y_k^m \\ \dot{y}_k^m \end{bmatrix}^{CV} + w_k, \quad w_k \sim N(0, Q^{CV})$$

  - **Measurement Model :**

$$z_k = H_k^{CV} \delta X_k^{CV} + v_k$$

$$\Leftrightarrow z_k = \begin{bmatrix} -\dfrac{x^1 - \hat{x}_k^m}{\hat{r}_k^1} & 0 & -\dfrac{y^1 - \hat{y}_k^m}{\hat{r}_k^1} & 0 \\ \vdots & \vdots & \vdots & \vdots \\ -\dfrac{x^n - \hat{x}_k^m}{\hat{r}_k^n} & 0 & -\dfrac{y^n - \hat{y}_k^m}{\hat{r}_k^n} & 0 \end{bmatrix}^{CV} \delta X_k^{CV} + v_k, \quad v_k \sim N(0, R^{CV})$$

III-2. Model-based Localization Filter (2/2)

- **EKF (Extended Kalman Filter)**
  - Enter prior estimate $\hat{x}_0^-$ and its error covariance P_0^-
  - Compute Kalman gain : $K_k = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)^{-1}$
  - Update estimate with measurement :

$$\begin{aligned} \Delta\hat{x}_k &= \Delta\hat{x}_k^- + K_k \left[z_k - h(x_k^*) - H_k \Delta\hat{x}_k^- \right] \\ &= \Delta\hat{x}_k^- + K_k \left[z_k - \left(h(x_k^*) + H_k \Delta\hat{x}_k^- \right) \right] \\ &= K_k \left(z_k - h(x_k^*) \right) \end{aligned}$$

  - State variable update : $x_k^* + \Delta\hat{x}_k = x_k^* + K_k \left[z_k - h(x_k^*) \right]$

$$\Leftrightarrow \hat{x}_k = \hat{x}_k^- + K_k \left(z_k - \hat{z}_k^- \right) \quad \textit{where} \quad \hat{x}_k^- = x_k^* = f(\hat{x}_{k-1})$$

  - Compute error covariance for updated estimate : $P_k = (I - K_k H_k) P_k^-$
  - Time propagation : $x_{k+1}^* = f\left(x_k^*\right)$

$$P_{k+1}^- = \Phi_k P_k \Phi_k^T + Q_k$$

IV. ASAE Mitigation (1/4)

- **When ASAE is considered, Eq. (1) can be rewritten as**

$$\tilde{r}_k^j = \bar{r} \cdot 10^{\frac{\hat{S} - \tilde{S}_k^j}{10\hat{\alpha}}}$$

$$= \bar{r} \cdot 10^{\frac{\hat{S} - (S_k^j - \delta S_k^j + w_k^j)}{10\hat{\alpha}}}$$

$$= \bar{r} \cdot 10^{\frac{\hat{S} - \tilde{S}_k^j}{10\hat{\alpha}}} \cdot 10^{\frac{\delta S_k^j}{10\hat{\alpha}}} \cdot 10^{\frac{-w_k^j}{10\hat{\alpha}}}$$

first order Maclaurin series

$$\cong r_k^j \left(1 + \ln(10^{1/10\hat{\alpha}}) \cdot \delta S_k^j\right)\left(1 + \ln(10^{-1/10\hat{\alpha}}) \cdot w_k^j\right)$$

$$\cong r_k^j + \frac{2.3026\, r_k^j}{10\hat{\alpha}} \delta S_k^j - \frac{2.3026\, r_k^j}{10\hat{\alpha}} w_k^j$$

$$\equiv r_k^j + \delta r_k^j(\delta S_k^j) + \delta r_k^j(w_k^j)$$

❖ **range errors caused by the ASAE :**

$$\delta r_k^j(\delta S_k^j) \geq 0,$$
$$E[\delta r_k^j \delta r_l^j] = 0,\ k \neq l,\ \text{and}$$
$$E[\delta r_k^j \delta r_k^i] = 0,\ j \neq i$$

IV. ASAE Mitigation (2/4)

- **Measurement vs. Estimated Range**
  - **Measurement :** $\tilde{r}_k^j = r_k^j + \delta r_k^j(\delta S_k^j) + \delta r_k^j(w_k^j)$
  - **Estimated Range :**

$$\begin{aligned}\hat{r}_k^j &= \sqrt{(x^j - \hat{x}_k^m)^2 + (y^j - \hat{y}_k^m)^2} \\ &= \sqrt{(x^j - (x_k^m + \delta x_k^m))^2 + (y^j - (y_k^m + \delta y_k^m))^2} \\ &\cong r_k^j - \frac{x^j - x_k^m}{r_k^j}\delta x_k^m - \frac{y^j - y_k^m}{r_k^j}\delta y_k^m \\ &\equiv r_k^j + \delta r_k^j(\delta P_k^j)\end{aligned}$$

- **Residual of the Range Measurement**

$$\zeta_k = \begin{bmatrix} \tilde{r}_k^1 - \hat{r}_k^1 \\ \vdots \\ \tilde{r}_k^n - \hat{r}_k^n \end{bmatrix} = \begin{bmatrix} r_k^1 + \delta r_k^1(\delta S_k^1) + \delta r_k^1(w_k^1) \\ \vdots \\ r_k^n + \delta r_k^n(\delta S_k^n) + \delta r_k^n(w_k^n) \end{bmatrix} - \begin{bmatrix} r_k^1 + \delta r_k^1(\delta P_k^1) \\ \vdots \\ r_k^n + \delta r_k^n(\delta P_k^n) \end{bmatrix}$$

$$= \begin{bmatrix} \delta r_k^1(\delta S_k^1) + \delta r_k^1(w_k^1) - \delta r_k^1(\delta P_k^1) \\ \vdots \\ \delta r_k^n(\delta S_k^n) + \delta r_k^n(w_k^n) - \delta r_k^n(\delta P_k^n) \end{bmatrix}$$

IV. ASAE Mitigation (3/4)

- **ASAE Estimation of Individual Channels**
  - j th element ζ_k^j of the residual ζ_k can be extracted and can be rewritten as

$$\delta r_k^j(\delta S_k^j) = \zeta_k^j + \delta r_k^j(\delta P_k^j) - \delta r_k^j(\delta w_k^j) \qquad (Eq.(2))$$

  - Taking the expectation on both sides Eq. (2), the following channel-wise ASAE estimate can be obtained :

$$\begin{aligned}\delta \hat{r}_k^j(\delta S_k^j) &= E[\delta r_k^j(\delta S_k^j)] \\ &= E[\zeta_k^j] + E[\delta r_k^j(\delta P_k^j)] - E[\delta r_k^j(\delta w_k^j)]\end{aligned}$$

where

$$E[\delta r_k^j(\delta w_k^j)] = 0$$

$E[\delta r_k^j(\delta P_k^j)]$ can converge into near zero if localization filter is completely observable

  - Since one of the ASAE properties is always positive, the ASAE can be estimated as follows:

$$\delta \hat{r}_k^j(\delta S_k^j) = E[\zeta_k^j] = \left|\zeta_k^j\right|, \quad j \in \{1, 2, and \;, n\}$$

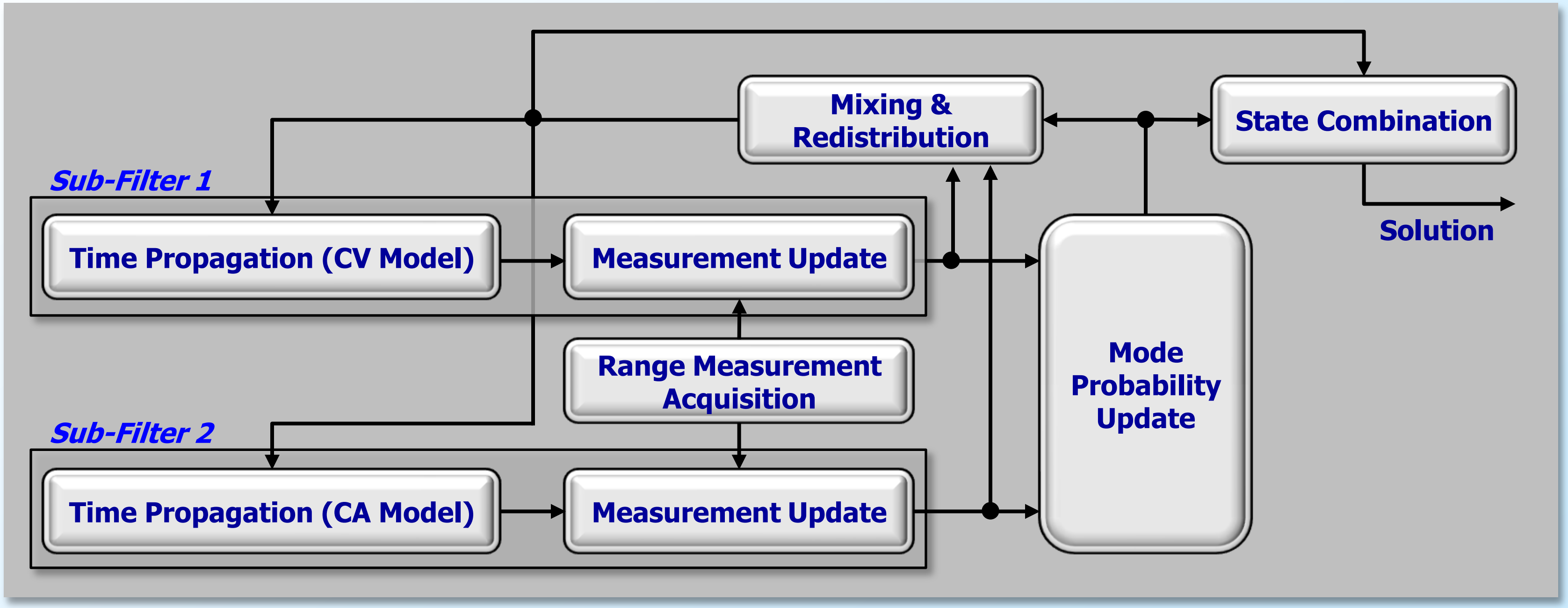
IV. ASAE Mitigation (4/4)

- **Using the estimate of the ASAE of Individual Channels, the residual is refined before processing the measurement-update in the localization filter**

$$\bar{\zeta}_k = \begin{bmatrix} \tilde{r}_k^1 - \hat{\delta}_k^1 - \hat{r}_k^1 \\ \vdots \\ \tilde{r}_k^n - \hat{\delta}_k^n - \hat{r}_k^n \end{bmatrix}$$

V. IMM Filtering (1/4)

- **Model–based Filtering**
  - It is clear that the dynamic model is very important in the filter
  - A stand–alone CV model–based filter cannot localize the MN (Mobile Node) accurately due to the flexible walking dynamics of a pedestrian with the MN
  - So, in this paper, an IMM (Interacting Multiple Model) filter with two different dynamic models – CV and CA (Constant Acceleration) models – is adopted.



V. IMM Filtering (2/4)

- **CA (Constant Acceleration) Model**
  - **Process Model :**

$$X_{k+1}^{CA} = F^{CA} X_k^{CA} + w_k$$

$$\Leftrightarrow \begin{bmatrix} x_{k+1}^m \\ \dot{x}_{k+1}^m \\ \ddot{x}_{k+1}^m \\ y_{k+1}^m \\ \dot{y}_{k+1}^m \\ \ddot{y}_{k+1}^m \end{bmatrix}^{CA} = \begin{bmatrix} 1 & T & \frac{T^2}{2} & 0 & 0 & 0 \\ 0 & 1 & T & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & T & \frac{T^2}{2} \\ 0 & 0 & 0 & 0 & 1 & T \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{CA} \begin{bmatrix} x_k^m \\ \dot{x}_k^m \\ \ddot{x}_k^m \\ y_k^m \\ \dot{y}_k^m \\ \ddot{y}_k^m \end{bmatrix}^{CA} + w_k, \quad w_k \sim N(0, Q^{CA})$$

  - **Measurement Model :**

$$z_k = H_k^{CA} \delta X_k^{CA} + v_k$$

$$\Leftrightarrow z_k = \begin{bmatrix} -\frac{x^1 - \hat{x}_k^m}{\hat{r}_k^1} & 0 & 0 & -\frac{y^1 - \hat{y}_k^m}{\hat{r}_k^1} & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ -\frac{x^n - \hat{x}_k^m}{\hat{r}_k^n} & 0 & 0 & -\frac{y^n - \hat{y}_k^m}{\hat{r}_k^n} & 0 & 0 \end{bmatrix}^{CA} \delta X_k^{CA} + v_k, \quad v_k \sim N(0, R^{CA})$$

V. IMM Filtering (3/4)

(0) Initialization

(0.1) Markov Transition Matrix : $M := \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}$, where $m_{11} + m_{21} = m_{12} + m_{22} = 1$

(0.2) Initial Mode Probability : $\mu_0 := \begin{bmatrix} n_0^1 \\ n_0^2 \end{bmatrix}$, where $n^1 + n^2 = 1$

(0.3) Normalization Factor : $\bar{c}_0 = M^T \mu_0 := \begin{bmatrix} c_{1,0} \\ c_{2,0} \end{bmatrix}$

(1) After Measurement Update

(1.1) Likelihood Ratio Calculation : $\Lambda_k := \begin{bmatrix} \lambda_k^1 \\ \lambda_k^2 \end{bmatrix}$, $\lambda_k^j = \frac{1}{\sqrt{2\pi \left\| C_k^j \right\|}} \exp\left\{ -\frac{1}{2k} (\bar{\zeta}_k^j)^T (C_k^j)^{-1} \bar{\zeta}_k^j \right\}$

where $C_k^j = H_k^j P_k^j (H_k^j)^T + R^j$

※ It is assumed that the sequences of the purified residuals are white Gaussian with zero-mean

(1.2) Mode Probability Update : $n_k^j = \frac{\lambda_k^j c_{k-1}^j}{\lambda_k^1 c_{k-1}^1 + \lambda_k^2 c_{k-1}^2}$

V. IMM Filtering (4/4)

(2) Mixing / Redistribution

(2.1) Mixing Probability : $\eta_k := \begin{bmatrix} g_{11,k} & g_{12,k} \\ g_{21,k} & g_{22,k} \end{bmatrix}$, *where* $g_{ij,k} = \dfrac{m_{ij} n_k^i}{m_{1j} n_k^1 + m_{2j} n_k^2}$

(2.2) States : $\begin{bmatrix} \bar{X}_k^{CV} \\ \bar{X}_k^{CA\_PV} \end{bmatrix} = \eta_k^T \begin{bmatrix} \hat{X}_k^{CV} \\ \hat{X}_k^{CA\_PV} \end{bmatrix}$

(2.3) Covariance Matrices : $\begin{bmatrix} \bar{P}_k^{CV} \\ \bar{P}_k^{CA\_PV} \end{bmatrix} = \eta_k^T \begin{bmatrix} P_k^{CV} + [\hat{X}_k^{CV} - \bar{X}_k^{CV}][\hat{X}_k^{CV} - \bar{X}_k^{CV}]^T \\ P_k^{CA\_PV} + [\hat{X}_k^{CV\_PV} - \bar{X}_k^{CV\_PV}][\hat{X}_k^{CV\_PV} - \bar{X}_k^{CV\_PV}]^T \end{bmatrix}$

※ $X_k^{CA\_PV}$ and $P_k^{CA\_PV}$ denote the position and velocity parts in X_k^{CA} and P_k^{CA} , respectively

(3) Data Combination

$$\hat{X}_k = \bar{X}_k^{CV} n_k^1 + \bar{X}_k^{CA\_PV} n_k^2$$

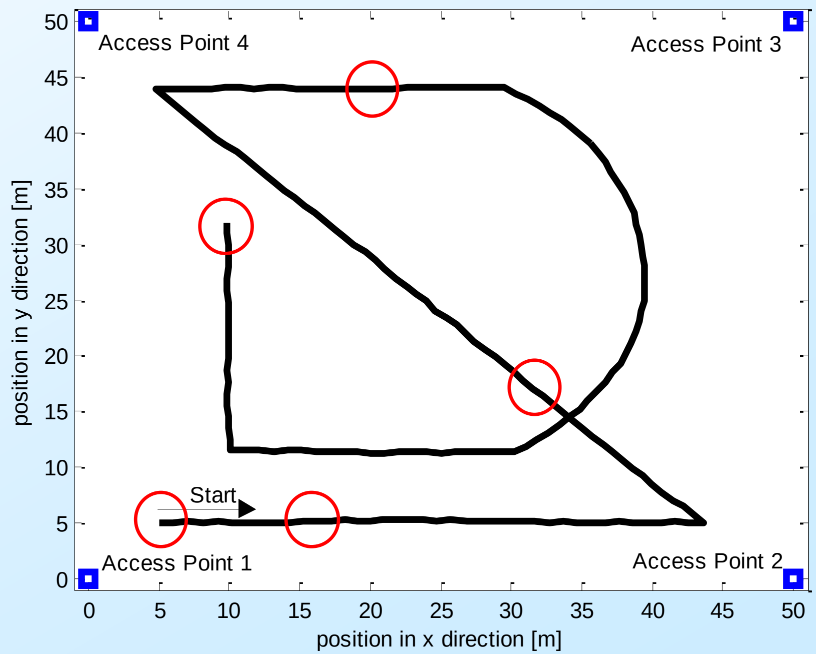
VI. Simulation Results (1/3)

- **Model**
  - **Signal Propagation Model :** $\tilde{S}_k^j = \bar{S} - 10\alpha \log_{10}(\frac{r_k^j}{\bar{r}}) - \delta S_k^j + w_k^j$

    where $\bar{r} = 1.0[m]$, $\bar{S} = -30.0[dBm]$, $\alpha = 3.0$

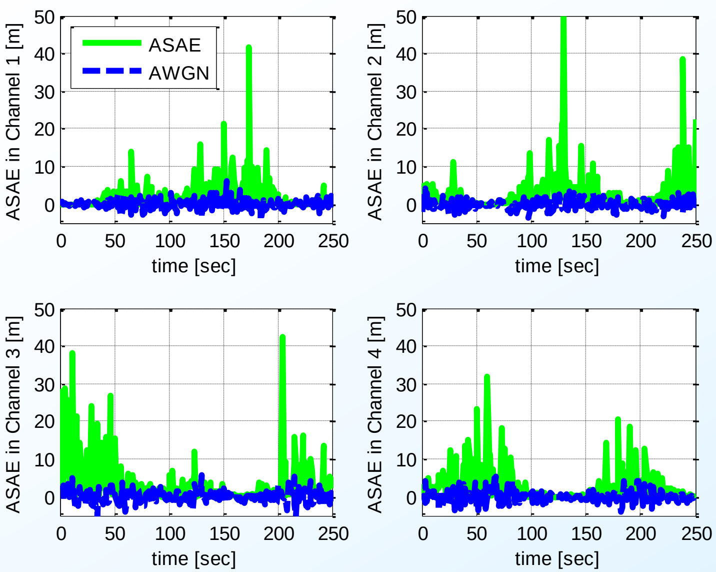
    - **ASAE :** $\delta S_k^j = \sum_{i=1}^{2} (0.015 * r_k^j * v_k)^2$, $where \quad v_k \sim N(0.0,\ 1.0)$
    - **AWGN :** $w_k^j = v_k / 2.0$

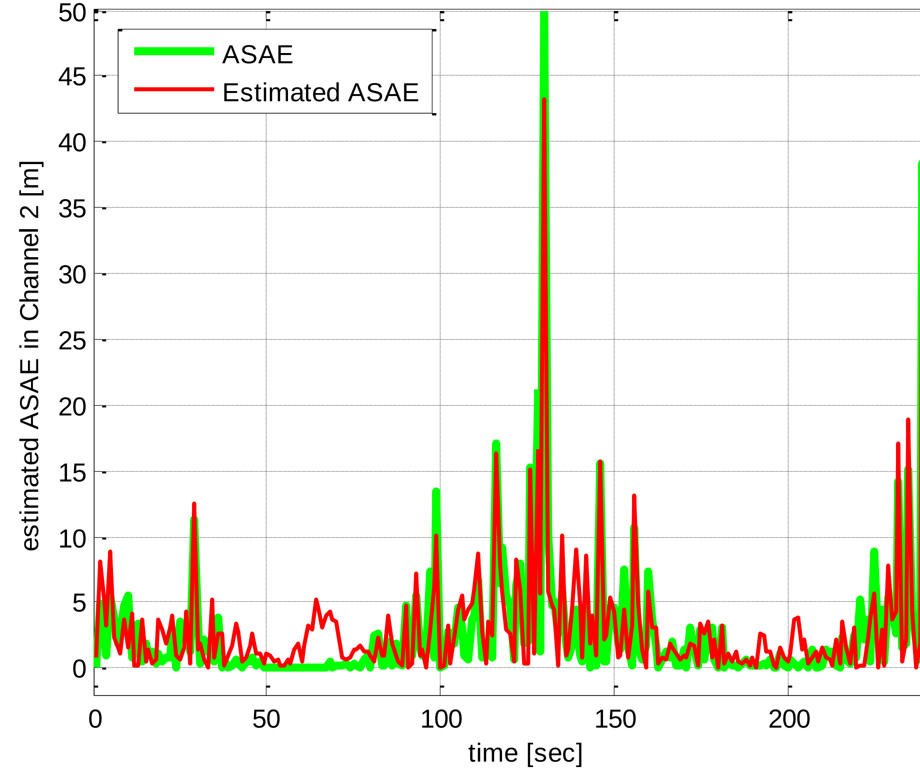
- **Trajectory**
  - **Walking Speed :** $1.0 + 0.05 * v_k \ [m/s]$
  - **# of APs : 4**
  - ◯ **: Stop**



VI. Simulation Results (

- **ASAE and AWGN of Individual Channel**



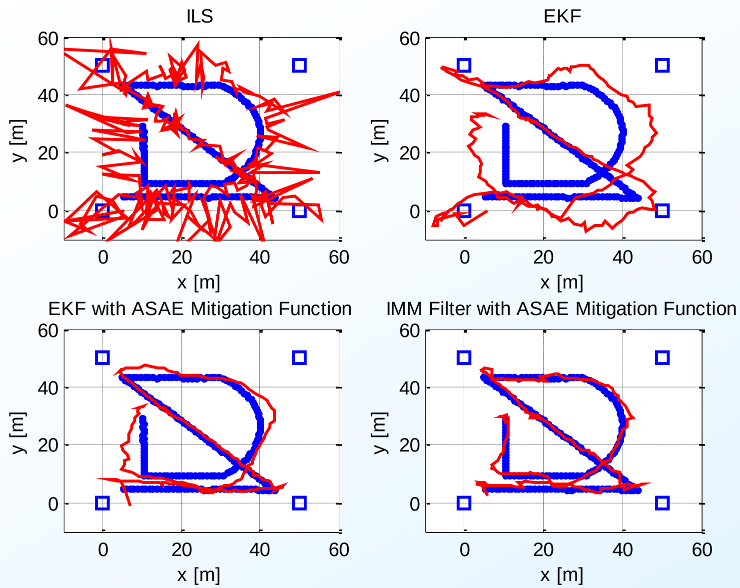


- **ASAE Estimation Error**

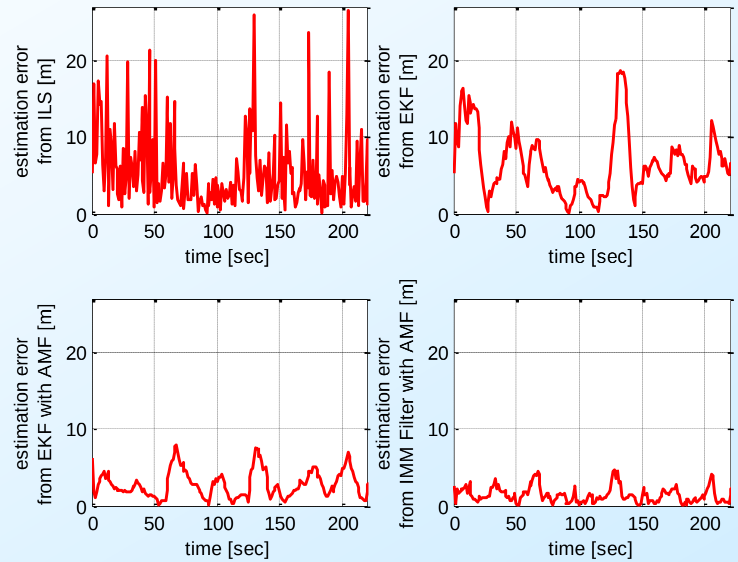
	Channel 1	Channel 2	Channel 3	Channel 4
Mean [m]	0.5763	0.5712	0.6427	0.7323
S. D. [m]	1.6877	1.9421	2.0090	2.0401

VI. Simulation Results (3/3)

- **Results of Position-Tracking**



- **Position-Tracking Errors**



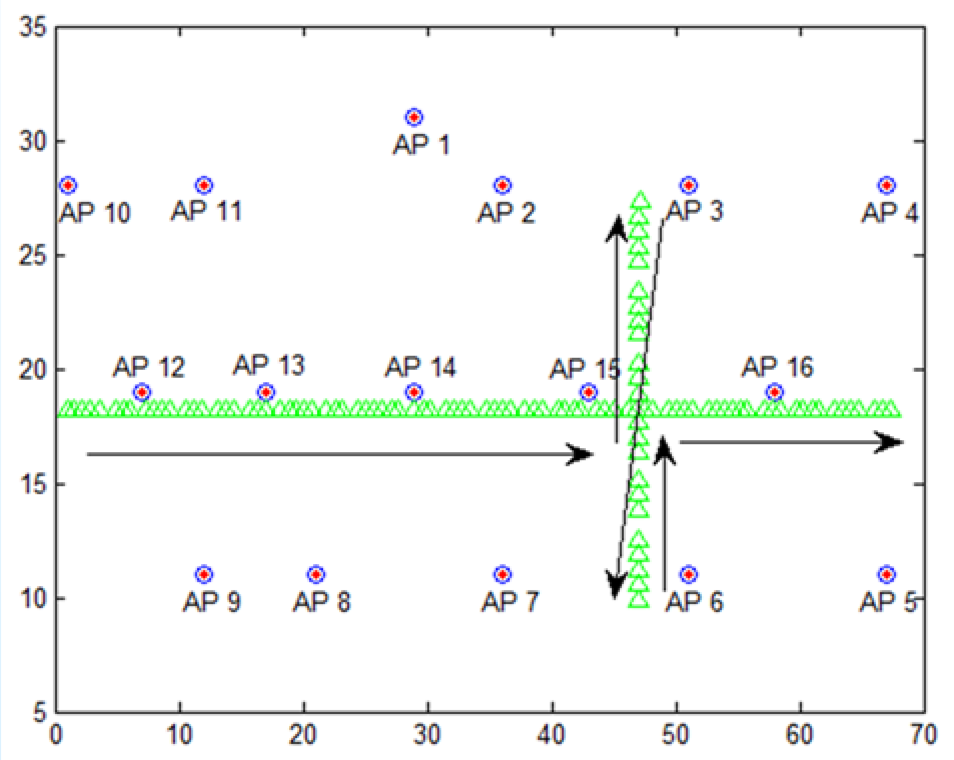
- **Root Mean Square Errors of the Position-Trackingt Estimates**

	ILS	EKF	EKF with AMF	IMM Filter with AMF
Mean [m]	5.4789	6.6710	2.9636	1.4214
S. D. [m]	5.0056	3.9373	1.7764	1.0258

VII. Experimental Results (1/6)

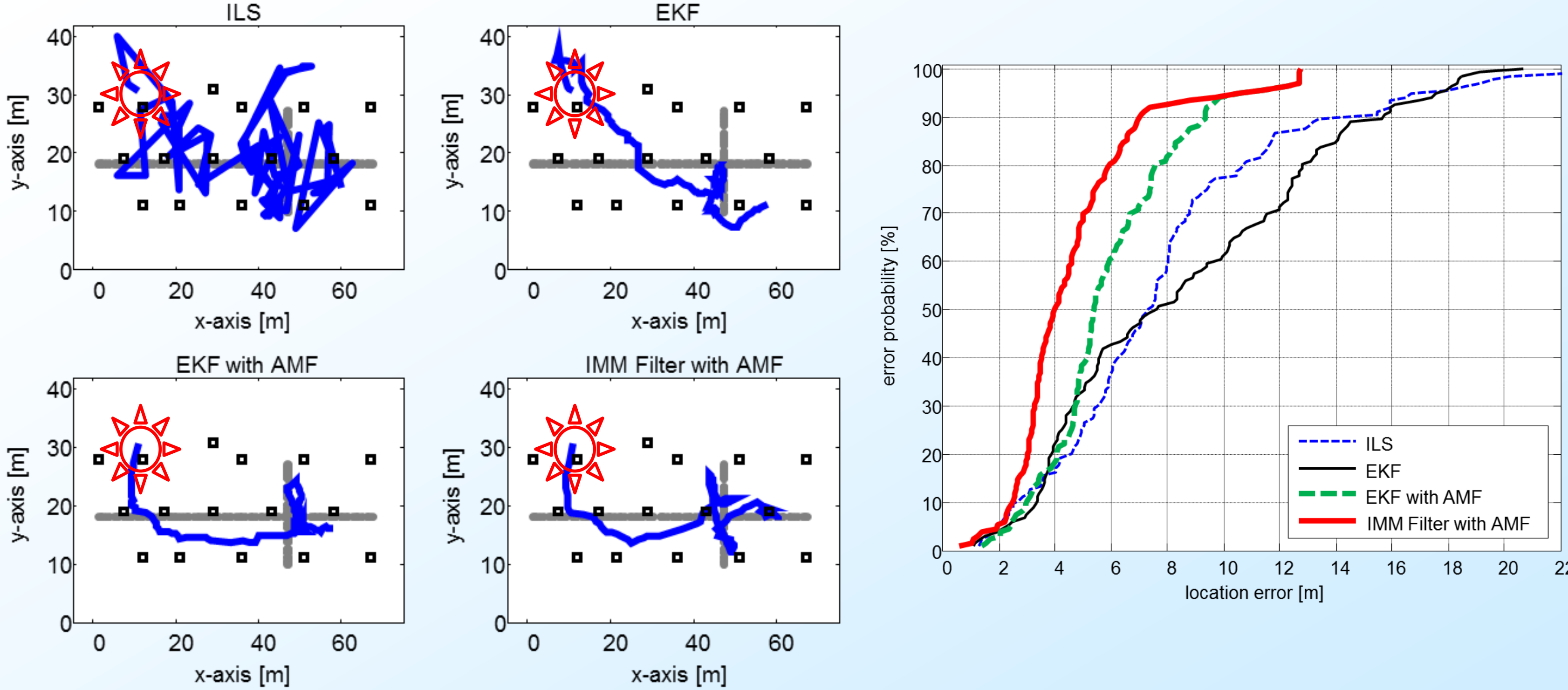
- **Experimental Environments**
  - Using the Smart Phone–based RSSI Acquisition S/W
  - # of APs : 16
  - Used Signal > −65 [*dBm*]
  - Average AP Number used for Localization : 4.17
  - In the Signal Propagation Model

$$\bar{r} = 1.0[m],\quad \hat{S} = -17.0[dBm],\quad \hat{\alpha} = 3.5$$



VII. Experimental Results (2/6)

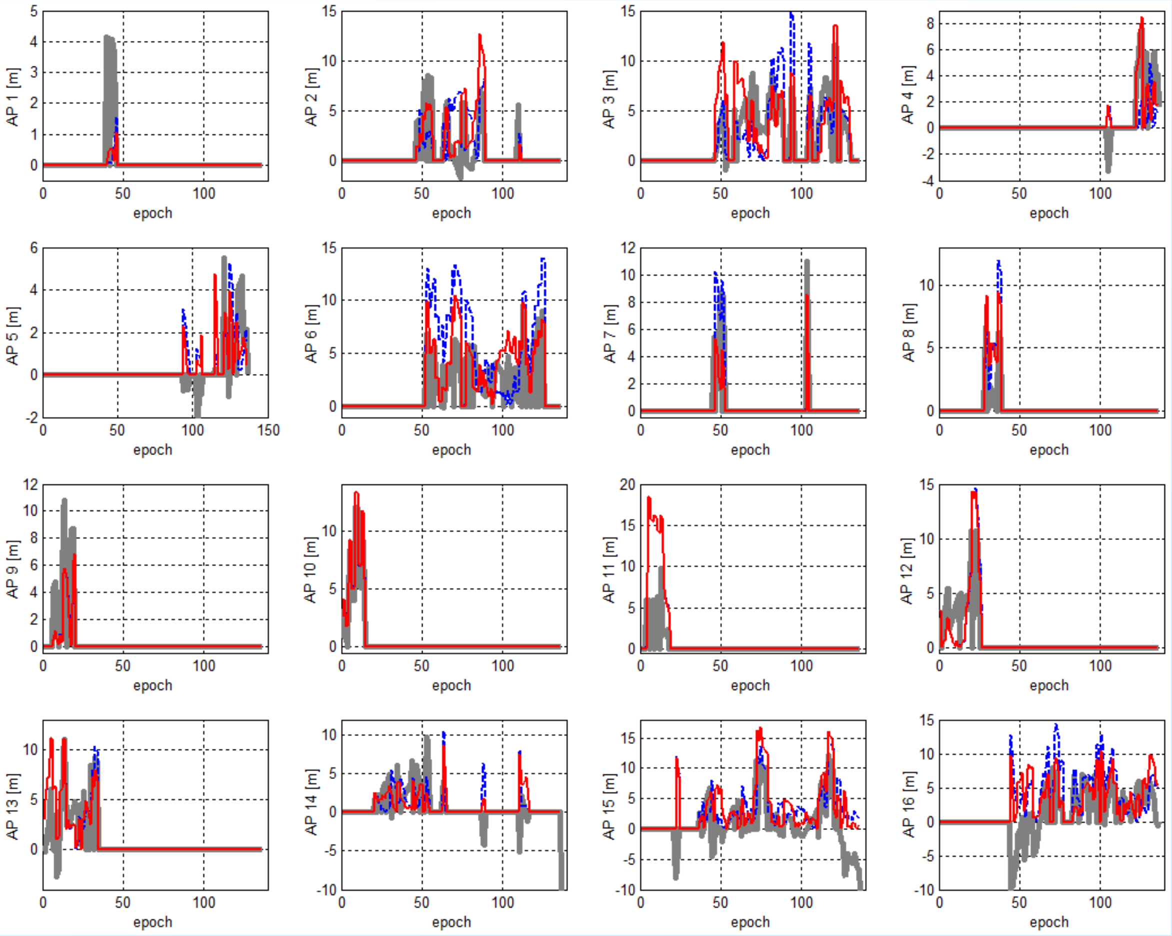
- **Case I : Initial location of each filter is set by the solution of the ILS method**



	ILS	EKF	EKF with AMF	Presented Filter
Mean [*m*]	7.9361	8.5505	5.9669	4.6666
S. D. [*m*]	4.4621	4.8414	2.4759	2.4684

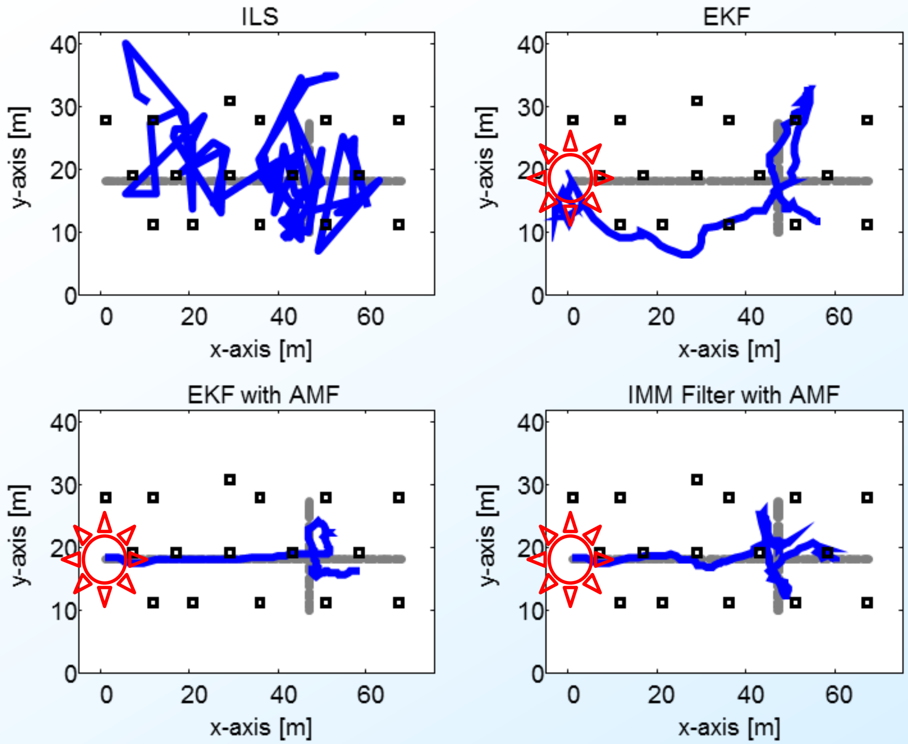
VII. Experimental Results (3/6)

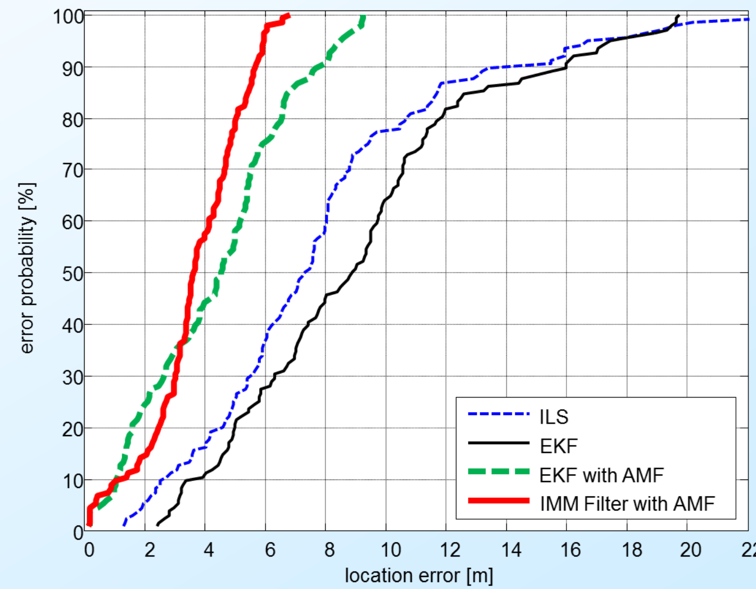
- **Case I : ASAE Estimates of Individual Channels**
  - Gray Solid Lines
    : Calculated ASAE using the raw RSSI, locations of the APs, and true locations of the mobile node
  - Blue Dashed Lines
    : Estimates from the EKF with AMF
  - Red Solid Lines
    : Estimates from the IMM filter with AMF



VII. Experimental Results (4/6)

- **Case II : Initial location of each filter is set by the true location**

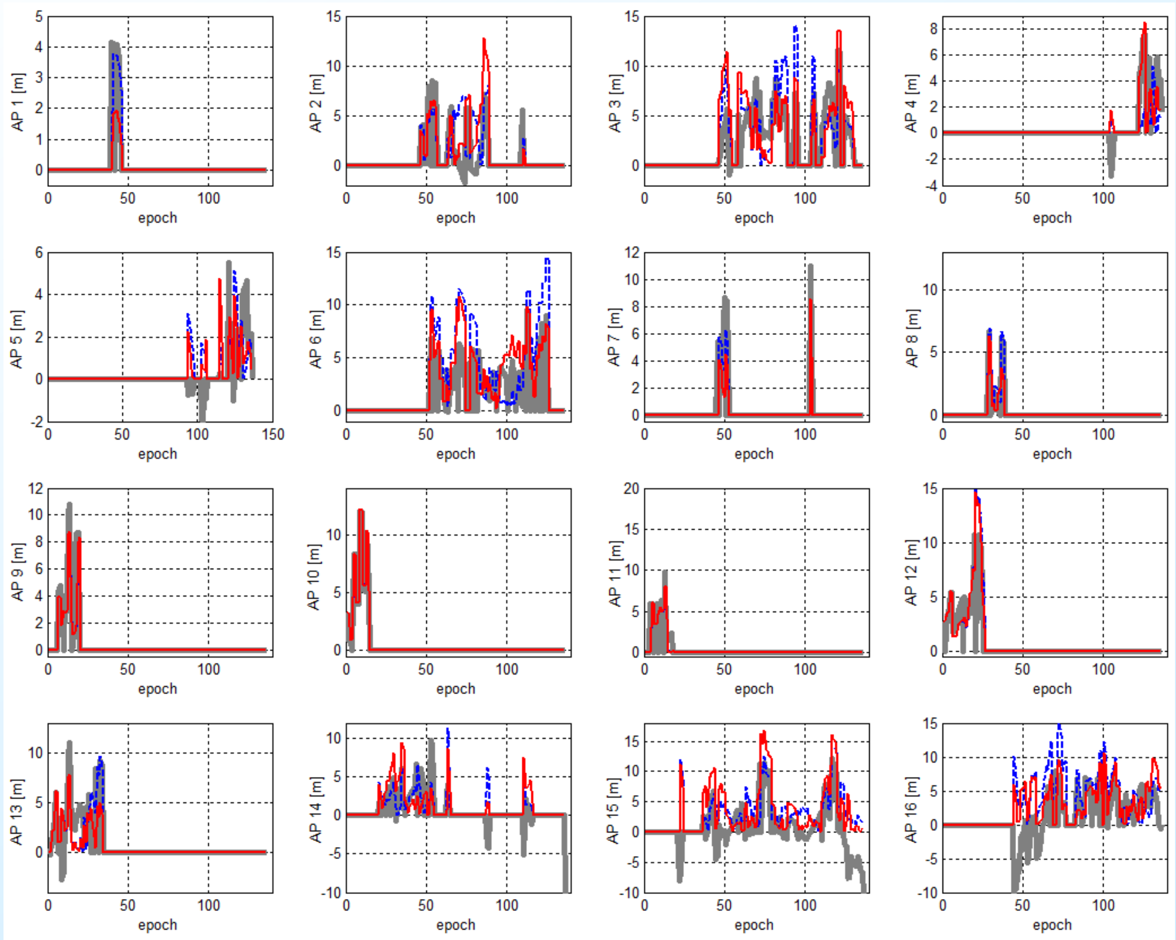




	ILS	EKF	EKF with AMF	Presented Filter
Mean [*m*]	7.9361	9.0957	4.3401	3.6679
S. D. [*m*]	4.4621	4.3059	2.4579	1.5937

VII. Experimental Results (5/6)

- **Case II : ASAE Estimates of Individual Channels**
  - **Gray Solid Lines**
    : Calculated ASAE using the raw RSSI, locations of the APs, and true locations of the mobile node
  - **Blue Dashed Lines**
    : Estimates from the EKF with AMF
  - **Red Solid Lines**
    : Estimates from the IMM filter with AMF



VII. Experimental Results (6/6)

- **Summary of the Localization Errors and ASAE Estimation Error**

			Localization Methods			
			ILS	EKF	EKF with AMF	IMM Filter with AMF
Case I	Localization Error	CEP [*m*]	7.3440	7.6125	5.3764	3.9721
		3σ [*m*]	22.3152	20.0453	12.7283	12.7282
	ASAE Estimation Error	Mean [m]	-	-	0.9699	0.8506
		S. D. [m]	-	-	2.3029	2.0564
Case II	Localization Error	CEP [*m*]	7.3440	8.8978	4.5498	3.6259
		3σ [*m*]	22.3152	19.7222	9.2400	6.7274
	ASAE Estimation Error	Mean [m]	-	-	0.8443	0.7738
		S. D. [m]	-	-	2.0499	1.8502

Conclusions

- **Range domain IMM filtering with additional signal attenuation error mitigation of individual channels for WLAN RSSI–based position–tracking**

  - RSSI–based range measurement calculation and error analysis
  - Model–based localization filter : CV model and EKF
  - ASAE mitigation technology
  - IMM filtering to adapt the walking conditions
  - Simulation results–based performance analysis
  - Experimental results–based performance confirmation

- It can be expected that WLAN RSSI–based indoor position–tracking technology can be advanced by the filter proposed in this paper.

Thank You for Your Attention !

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