State Estimation and Motion Tracking for Spatially Diverse VLC Networks

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Outline

- Motivation
- Visible Light Communication
- Kalman Filtering
- System Model
- Results and Conclusions

Consider This…

We live in a society where access to information is ubiquitous.

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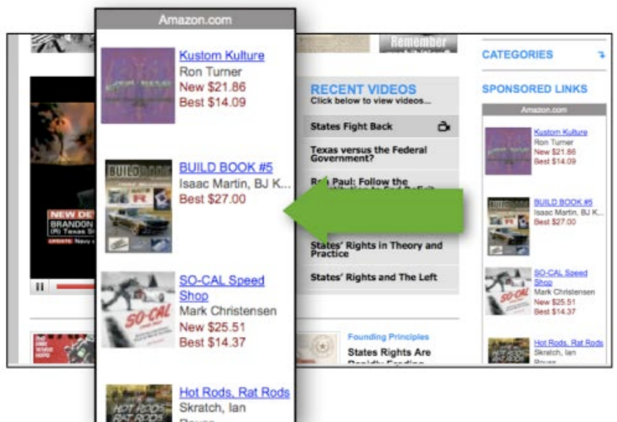

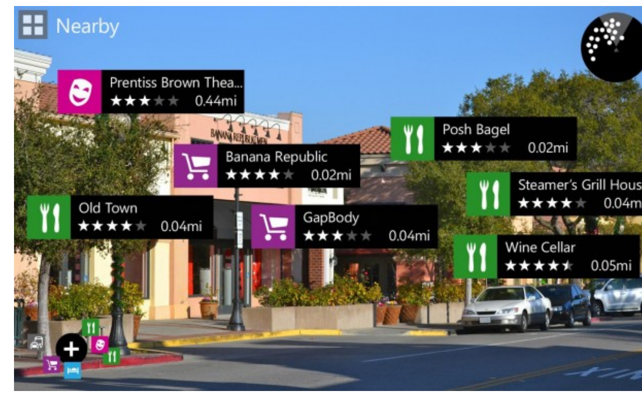

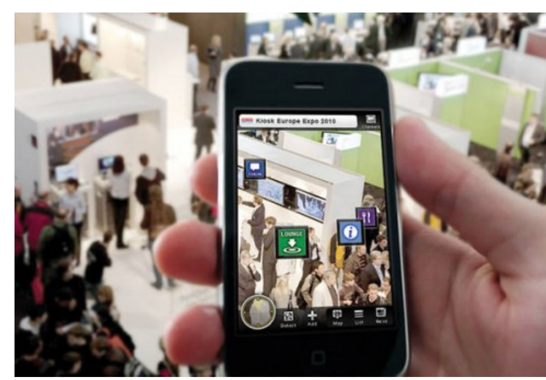

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SMART LIGHTING

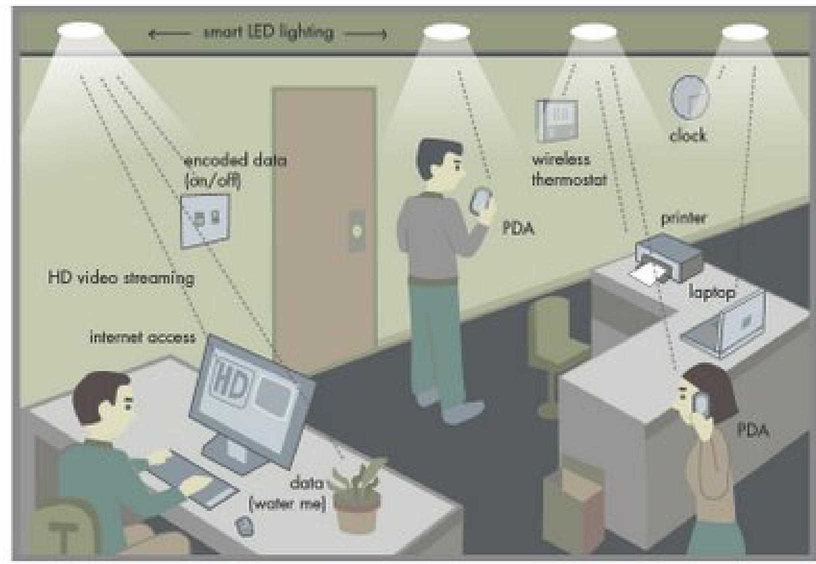
Motivation: *Indoor Localization*

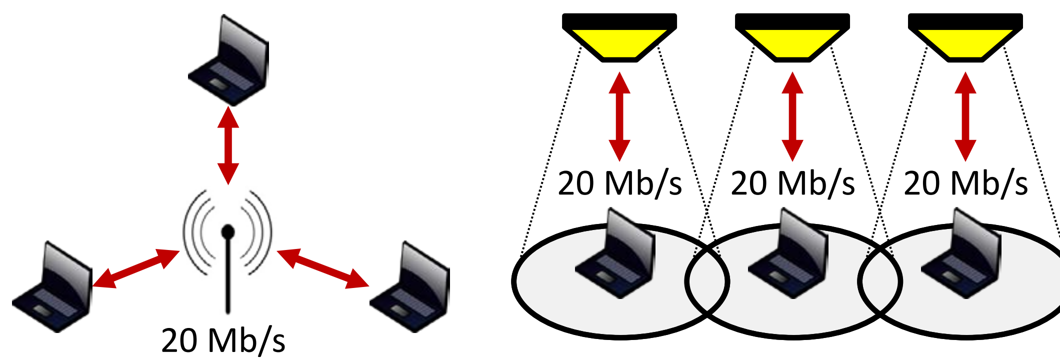
- Personalized local information
  - Augmented knowledge of surroundings
  - Targeted advertisement
  - Indoor navigation
- Communication Systems
  - Handover in VLC or heterogeneous networks
  - Traffic routing based on dynamic traffic patterns
- We propose a novel state estimation model
  - Approximates user location and motion path
  - Predicts future state through use of recursive estimation

High aggregate throughput…
Data is everywhere!

Visible Light Communication (VLC)

- Intensity Modulation / Direct Detection (IM/DD)
- Dual Purpose System
  - Fully functional lighting system
  - Wireless data communication
- Benefits
  - Dual use
  - Secure connections
  - Unregulated spectrum
  - *Signal Directionality*
  - High bandwidth density

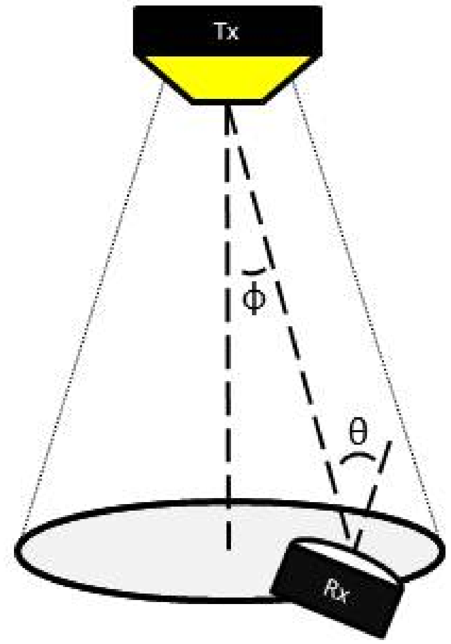




VLC Channel Model

- Transmitted power, P_t, distance, D, receiver area, A_r, and angle at the transmitter and receiver account for LOS received power.

$$P_r = \frac{P_t T(\phi) A_r g(\theta)}{D^2}$$

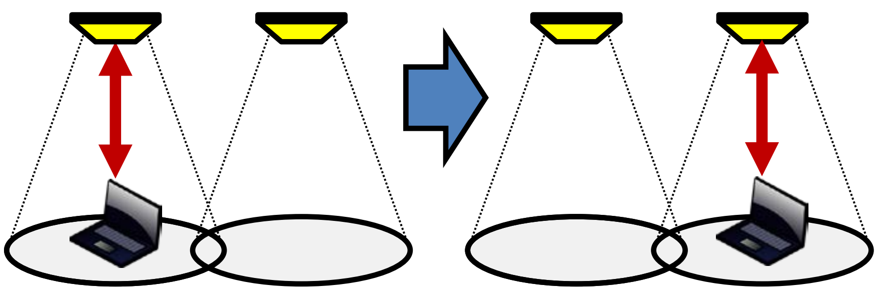


- LEDs and photodiodes have an angle dependent gain typically modeled as

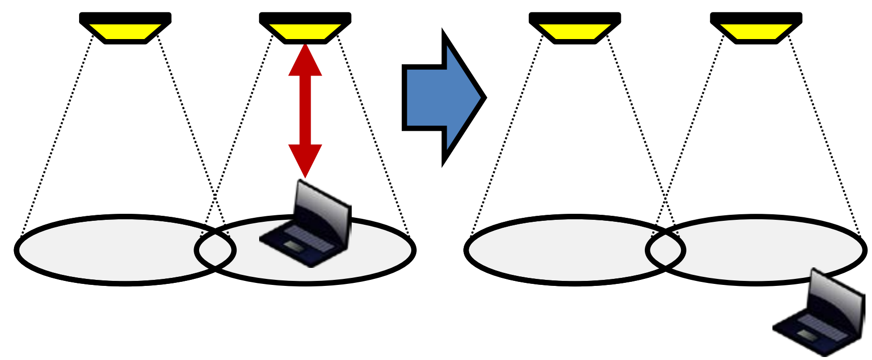
$$T(\phi) = \frac{n+1}{2\pi} cos^n(\phi) \qquad g(\theta) = cos(\theta)$$

VLC Network Considerations

- Fast and accurate handover protocols are necessary to maintain connectivity throughout the environment.
  - HHO: Transfer between VLC channels
  - VHO: Transfer between media (e.g. VLC to RF)
- RSI allows for basic handover methods, but motion tracking provides an opportunity for predictive methods.



Horizontal Handover (HHO)



Vertical Handover (VHO)

Kalman Filtering

- Discrete time linear state models can be employed to describe the behavior of dynamic systems.

$$\boldsymbol{x}[t+1] = \boldsymbol{A}x[t] + \boldsymbol{G}w[t] \qquad y[t] = \boldsymbol{C}x[t] + \boldsymbol{H}v[t]$$

- Kalman Filters observe a series of noisy measurements, then recursively estimate the system state and predict the next state.
  1. Initialization
  2. Prediction
  3. Measurement
  4. Update

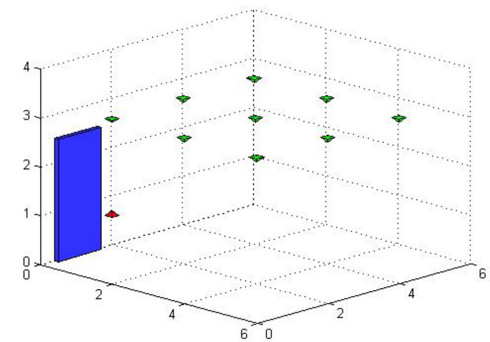
- Since measurement in our system is non-linear, we observe extensions of the basic KF.
  - Extended Kalman Filter (EKF)
  - Unscented Transform (UT)

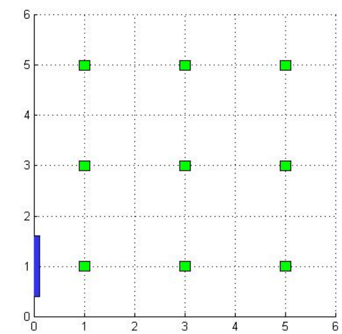
System Model

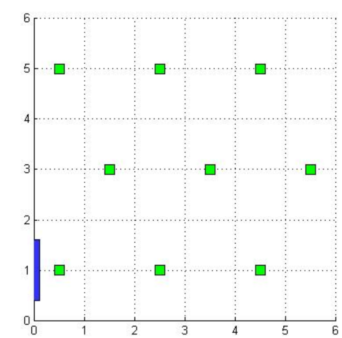
- Empty 6m X 6m X 4m room with grid or cell layout.
- New user location is normally distributed with expected value below a hotspot.
- Users move with zero mean acceleration in the x and y direction.
- Observe a linear state model, $\boldsymbol{x}[t]$, with transition matrix, $\boldsymbol{A}$, and nonlinear measurement, $\boldsymbol{y}$.

$$\boldsymbol{x}[t+1] = \boldsymbol{A}\boldsymbol{x}[t] + \boldsymbol{w}[t] \qquad \boldsymbol{y}[t] = h[\boldsymbol{x}[t], t] + \boldsymbol{v}[t]$$

- Process noise, $\boldsymbol{w}$, and measurement noise, $\boldsymbol{v}$, are independent, zero-mean, Gaussian white noise with covariance matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$, respectively.







System Model – Scenario I

- Receiver is directed perpendicular to floor, such that $\phi = \theta$.
- State represents position and velocity in x and y.
- Measurement observes signal power from the set of transmitters.

$$\boldsymbol{x} = \left[x, V_x, y, V_y\right]' \qquad \boldsymbol{y} = \left[P_{r,1j}, P_{r,2j}, \dots, P_{r,9j}\right]' + \boldsymbol{v}[t]$$

$$\boldsymbol{A}_I = \begin{bmatrix} 1 & dt & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & dt \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- $P_{r,1j}$ is dependent on ϕ_{ij}, θ_{ij}, and D_{ij}.

$$D_{ij}^2 = (X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2$$

$$\phi_{ij} = \theta_{ij} = \arctan\left(\frac{\sqrt{(X_i - x)^2 + (Y_i - y)^2}}{Z_i - z}\right)$$

$$\boldsymbol{Q}_I = q \cdot \begin{bmatrix} \frac{dt^3}{3} & \frac{dt^2}{2} & 0 & 0 \\ \frac{dt^2}{2} & dt & 0 & 0 \\ 0 & 0 & \frac{dt^3}{3} & \frac{dt^2}{2} \\ 0 & 0 & \frac{dt^2}{2} & dt \end{bmatrix}$$

$$\boldsymbol{R}_I = r_{sig} \cdot I_{9x9}$$

System Model – Scenario II

- Incorporate device rotation in the state model.

$$\boldsymbol{x} = \left[x, V_x, y, V_y, \theta_{el}, \theta_{az}\right]'$$

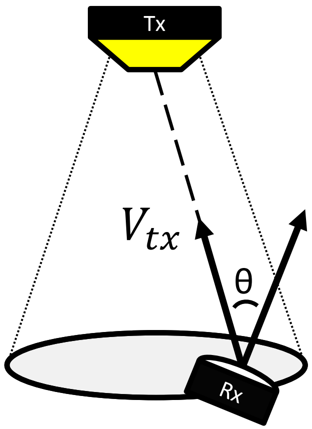
$$\boldsymbol{A}_{II} = \begin{bmatrix} A_I & \bar{0} \\ \bar{0} & \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \end{bmatrix} \qquad \boldsymbol{Q}_{II} = \begin{bmatrix} Q_I & \bar{0} \\ \bar{0} & \begin{bmatrix} (q_\theta)dt & 0 \\ 0 & (q_\theta)dt \end{bmatrix} \end{bmatrix}$$

- The acceptance angle, θ_{ij}, is now dependent on θ_{el} and θ_{az}.

$$V_{rx} = \{\cos(\theta_{el}) \cdot \sin(\theta_{az}), \sin(\theta_{el}) \cdot \sin(\theta_{az}), \cos(\theta_{az})\}$$

$$V_{tx,i} = \{(X_i - x), (Y_i - y), (Z_i - z)\}$$

$$\cos(\theta_{ij}) = \frac{V_{rx} \cdot V_{tx,i}}{|V_{rx}||V_{tx,i}|}$$



System Model – Scenario III

- Additional measurements for θ_{el} and θ_{az} are included.

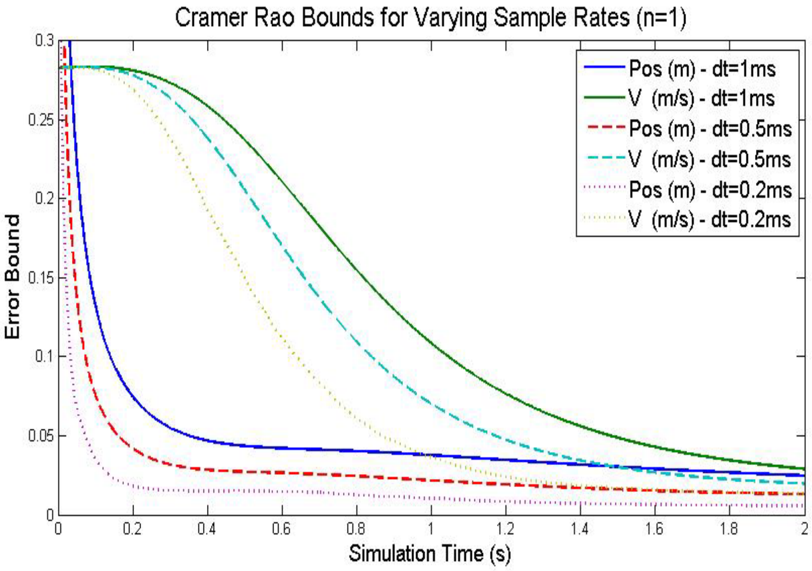
$$\boldsymbol{y} = \left[P_{r,1j}, P_{r,2j}, \dots, P_{r,9j}, \theta_{el}, \theta_{az}\right]' + \boldsymbol{v}[t]$$

$$\boldsymbol{R}_{III} = \begin{bmatrix} \boldsymbol{R}_I & \bar{0} \\ \bar{0} & r_\theta \cdot I_{2x2} \end{bmatrix}$$

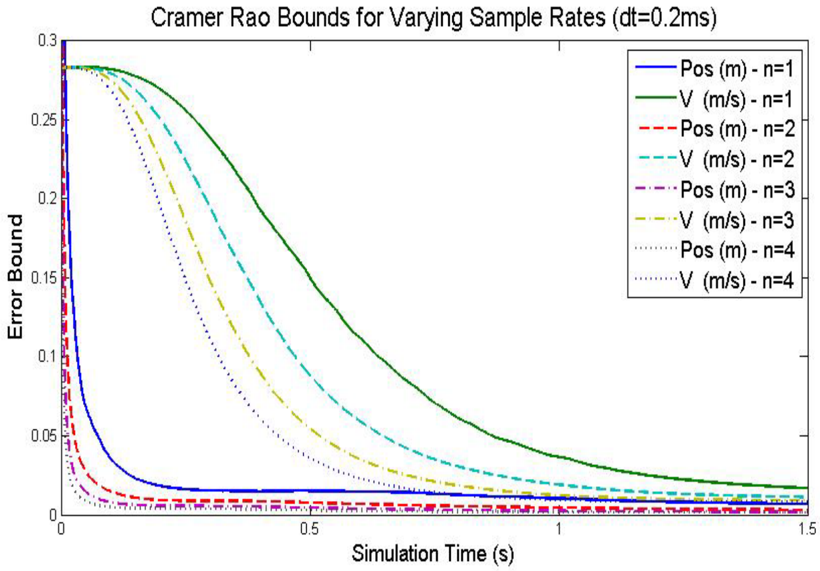
- We aim to show that additional sensors (e.g. accelerometers or gyroscopes) can improve performance in a realistic scenario.

Results

- We first observe Cramer Rao Bounds (CRB) for the simulated data.



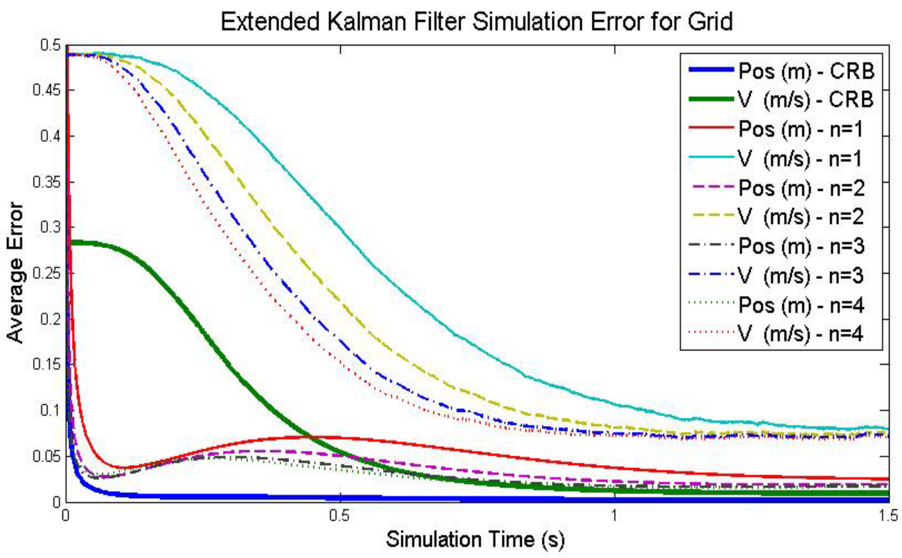
Cramer Rao Bounds for multiple sampling rates



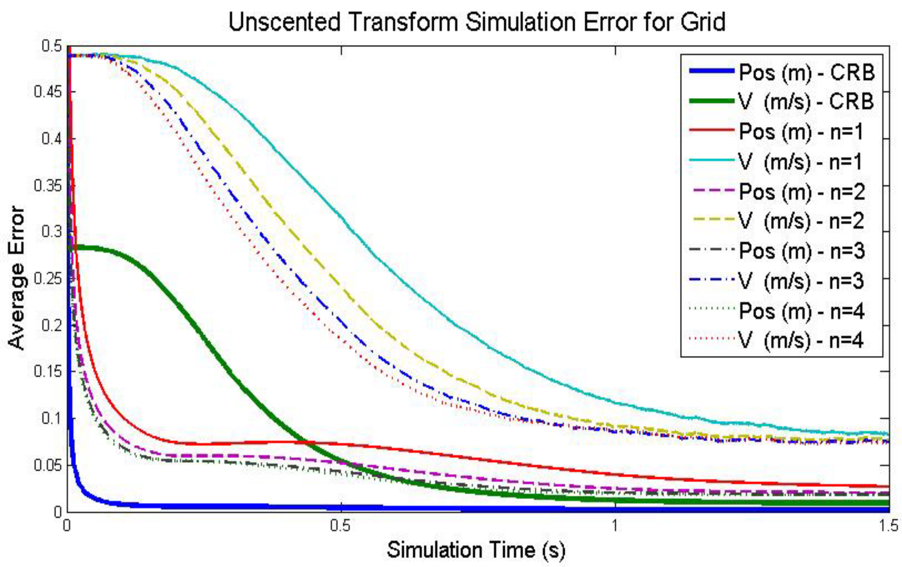
Cramer Rao Bounds for multiple transmitter orders

Results

- We next compare estimations to the actual position and velocity.



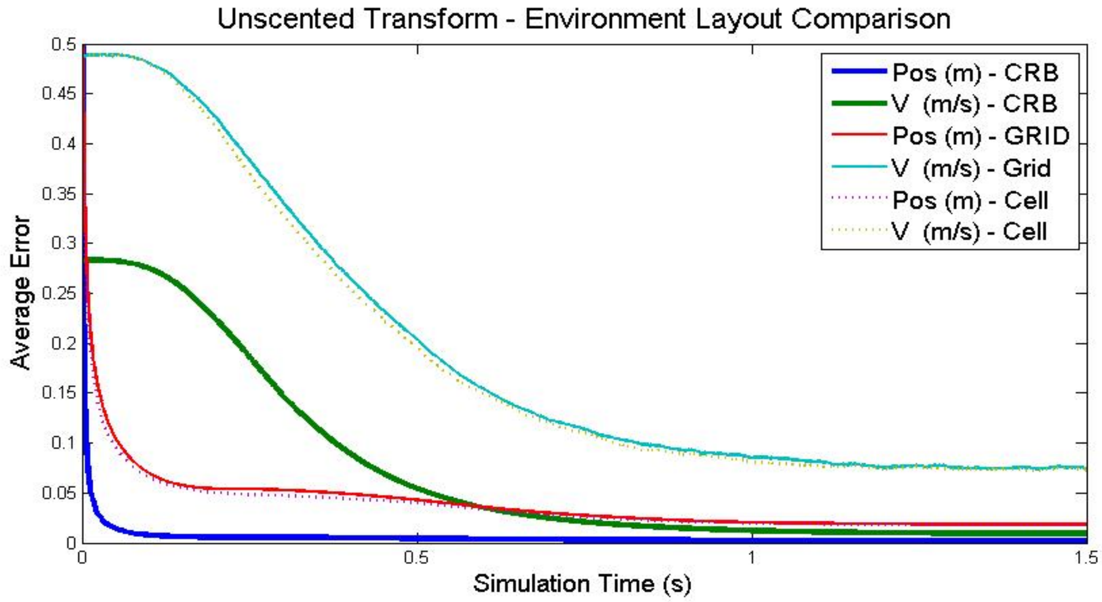
Simulation results for the Extended Kalman Filter



Simulation results for the Unscented Filter

Results

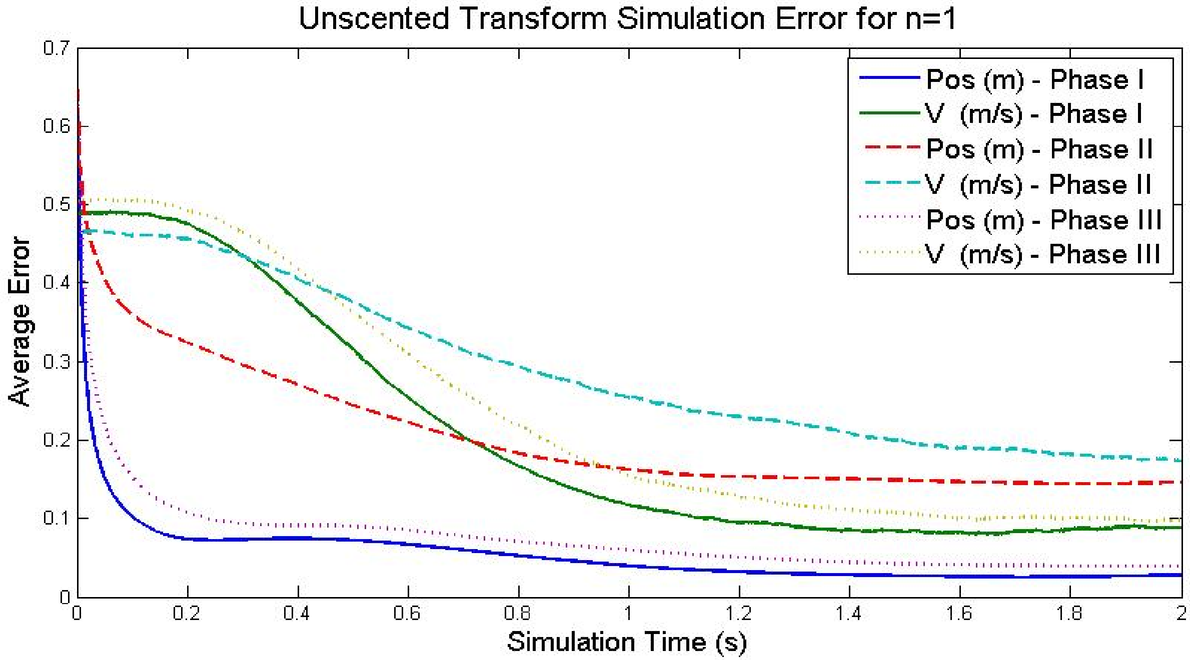
- Cellular and grid layouts show similar performance; however the initial distribution in the cellular scenario was not located directly below a transmitter.



Simulation results comparing grid and cellular layouts

Results

- Scenario II shows a significant performance loss over Scenario I; however the additional sensors in Scenario III provide similar performance to that of Scenario I.



Simulation results comparing scenarios I, II, and III

Conclusions

- We have provided a novel state estimation model leveraging the lighting infrastructure to approximate user location and motion under realistic conditions.
- Simulation results on an empty room show position and velocity results with average error of 5cm and 10cm/s, respectively.
- We recognize that additional complexities occur due to dynamic signal conditions from obstructions and signal reflections.
    - Non-ideal luminaire output
    - Receiver Optics
    - Multipath Signals
    - User obstruction
- Results are applicable for positioning systems and asset tracking as well as assisted handover or beam steering for indoor VLC networks

Questions

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Table of Parameters

Parameter	Phase I	Phase II / III
System Parameters		
P_t (W)	5	5
A_r (mm^2)	300	300
dt (ms)	0.2, 0.5, 1	0.2
n	1,2,3,4	1
Initial Expectations		
E[x,y] (m)	[0.99, 0.99]	[0.99, 0.99]
E[V_x,V_y] (m/s)	[0.8, 0.8]	[0.8, 0.8]
E[θ_{el},θ_{az}] (°)	-	[0,0]
Σ[x,y] (m)	[0.5,0.5]	[0.5,0.5]
Σ[V_x,V_y] (m/s)	[0.2,0.2]	[0.2,0.2]
Σ[θ_{el},θ_{az}] (°)	-	$[\frac{\pi}{180}, \frac{\pi}{4}]$
Noise Parameters		
r_{sig}	$3.5 \cdot 10^{-8}$	$3.5 \cdot 10^{-8}$
r_θ	-	$\frac{\pi}{360}$
q	10^{-2}	10^{-2}
q_θ	-	$\frac{\pi}{360}$

Kalman Filter Details

- **Prediction**

$$\boldsymbol{x}_{t+1|t} = \boldsymbol{A}\boldsymbol{x}_{t|t} + \boldsymbol{B}u[t] + \boldsymbol{G}E\{w[t]\}$$
$$\boldsymbol{\Sigma}_{t+1|t} = \boldsymbol{A}\boldsymbol{\Sigma}_{t|t}\boldsymbol{A}^T + \boldsymbol{G}\boldsymbol{Q}\boldsymbol{G}^T$$
$$\boldsymbol{y}_{t+1|t} = \boldsymbol{C}\boldsymbol{x}_{t|t} + \boldsymbol{D}u[t] + \boldsymbol{H}E\{v[t]\}$$

- **Estimation**

$$\boldsymbol{x}_{t+1|t+1} = \boldsymbol{x}_{t+1|t} + \boldsymbol{K}_{t+1}\boldsymbol{v}_{t+1}$$
$$\boldsymbol{\Sigma}_{t+1|t+1} = [\boldsymbol{I} - \boldsymbol{C}\boldsymbol{K}_{t+1}]\boldsymbol{\Sigma}_{t+1|t}$$

- Innovations

$$\boldsymbol{v}_{t+1} = \boldsymbol{y}_{t+1} - \boldsymbol{y}_{t+1|t}$$

- Kalman Gain

$$\boldsymbol{K}_{t+1} = \boldsymbol{\Sigma}_{t+1|t}\boldsymbol{C}^T\left[\boldsymbol{C}\boldsymbol{\Sigma}_{t+1|t}\boldsymbol{C}^T + R\right]^{-1}$$