Target tracking with distributed sensing:

information-theoretic bounds, and the integration with imaging and scheduling for urban terrains

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Outline

- Overview and contributions
- Previous work (Chap. 2, joint work with Hua Li)
  - Zero-error target tracking through limited querying of binary sensors
- Ongoing work (Chap. 3 & 4)
  - Multitarget-Multisensor Tracking in an Urban Environment
- Future work (Chap. 5)
  - Adaptive Sensing in an Urban Environment: Closing the Loop
- Timeline

Overview

- Start: Fall 2002
  - Restart: Fall 2003 (under Prof. Chong)
- Graduation: Spring 2008 (tentative)
- Publications
  - 2 published in conference proceedings
  - 1 submitted to journal
  - 1 in preparation

Contributions

- Theoretic bounds on tracking
  - Proved necessary and sufficient conditions on the number of queries required to follow/track/*d*-track a target that moves according to a Markov chain
  - Relevance of results
    - Application to the restrictive sensor network setting
    - Explores the duality between Rényi-Ulam games and target tracking

Contributions

- Theoretic bounds on tracking
  - Publications
    - P. R. Barbosa, H. Li, E. K. P. Chong, J. Hannig, and S. R. Kulkarni, “Zero-error target tracking through limited querying of binary sensors,” *Proc. 44th Annual Allerton Conference on Communications, Control, and Computing,* pp. 1424-1431, Sept. 2006
    - H.Li, P. R. Barbosa, E. K. P. Chong, J. Hannig, and S. R. Kulkarni, “Zero-error target tracking with limited communication,” submitted to *IEEE JSAC* (under review)

Contributions

- Closed-loop active sensing system
  - Compared to a traditional baseline system
  - Demonstrated through Monte Carlo simulations
    - 9% increase on the number of confirmed tracks
    - 10x reduction on uncertainty ellipse volume
    - 2 times reduction on position MSE

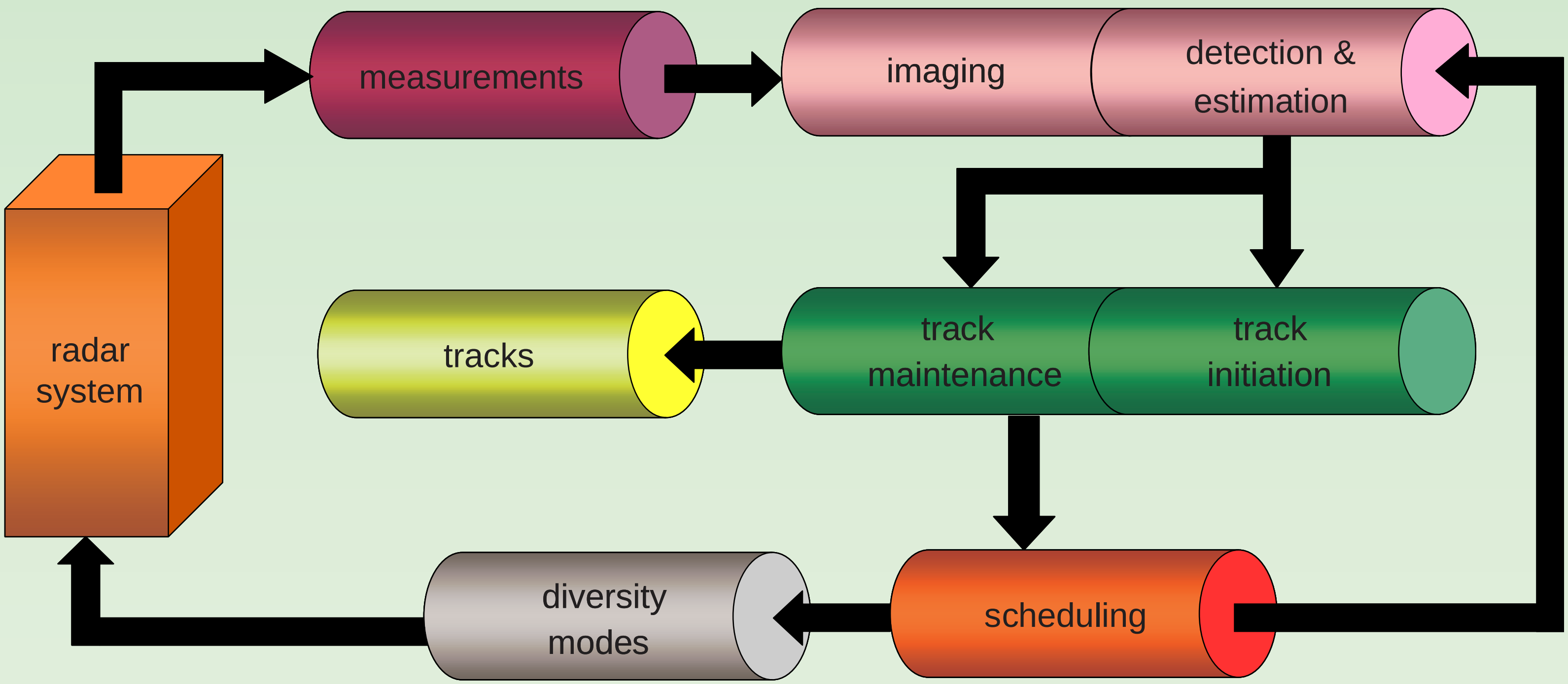
Contributions

- Closed-loop active sensing system
  - Relevance of results
    - First tracker that simultaneously addresses signal processing, tracking, and scheduling issues
    - Understanding of how distinct levels of diversity interact with the elements of the urban environment for increased performance
  - Publications
    - Paper to be submitted to SPIE 2008 Signal and Data Processing of Small Targets

Contributions

- Adaptive sensing
  - Introduce novel two-level scheduler
    - Waveform scheduler
    - Transmitter scheduler
  - POMDP formulation
    - Got tracking community's attention
  - Relevance of results
    - Closed-loop adaptive tracking system
    - High-performance without computational burden of an "all non-myopic" scheduler

The Overall System



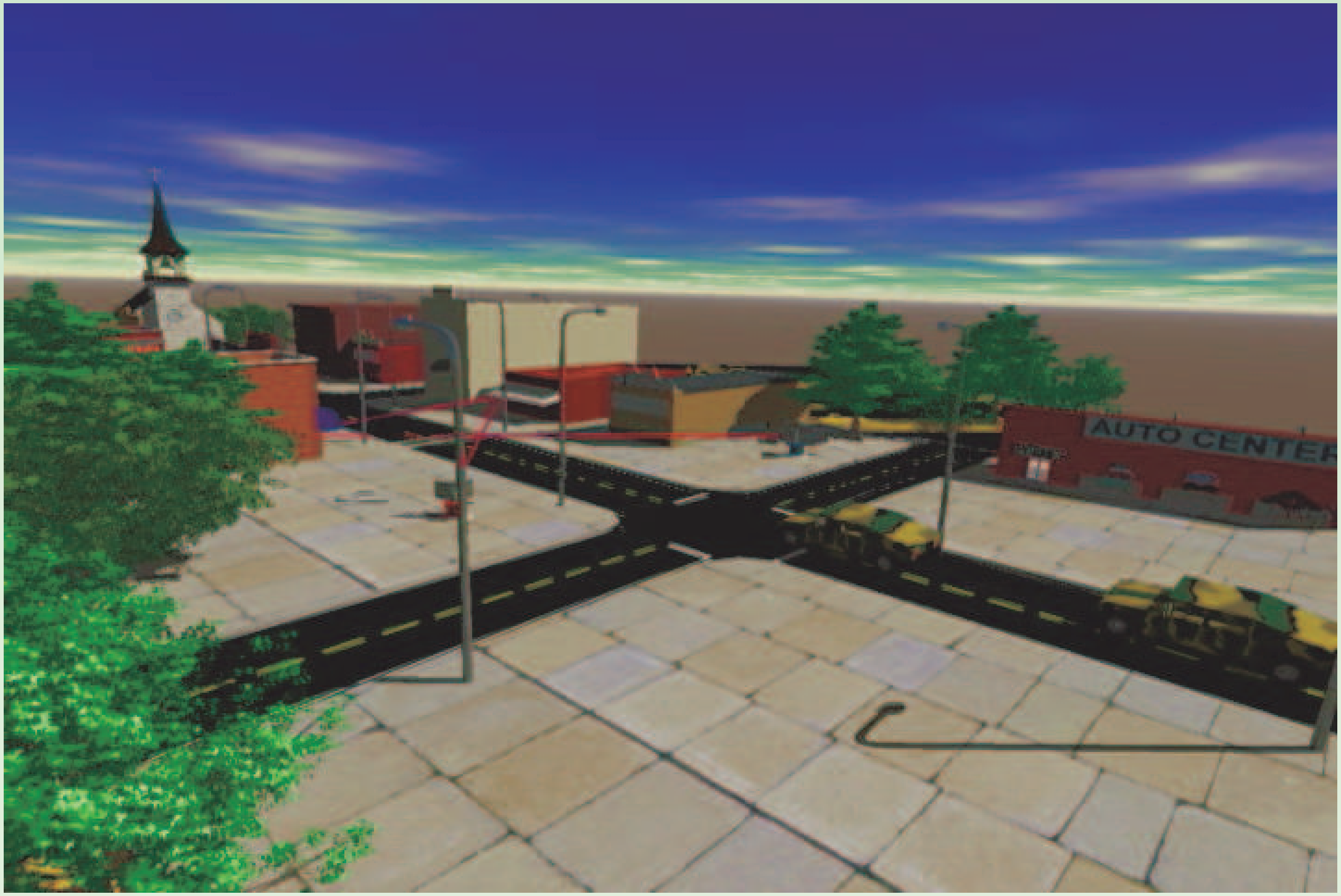
An Interdisciplinary Project

- Modeling
  - Multipath, clutter, sensors, target motion
- Signal processing
  - Detection, Imaging
- Estimation
  - Tracking
- Data fusion
  - Measurement-to-track association, sensor fusion
- Optimization
  - Scheduling waveforms, transmitters

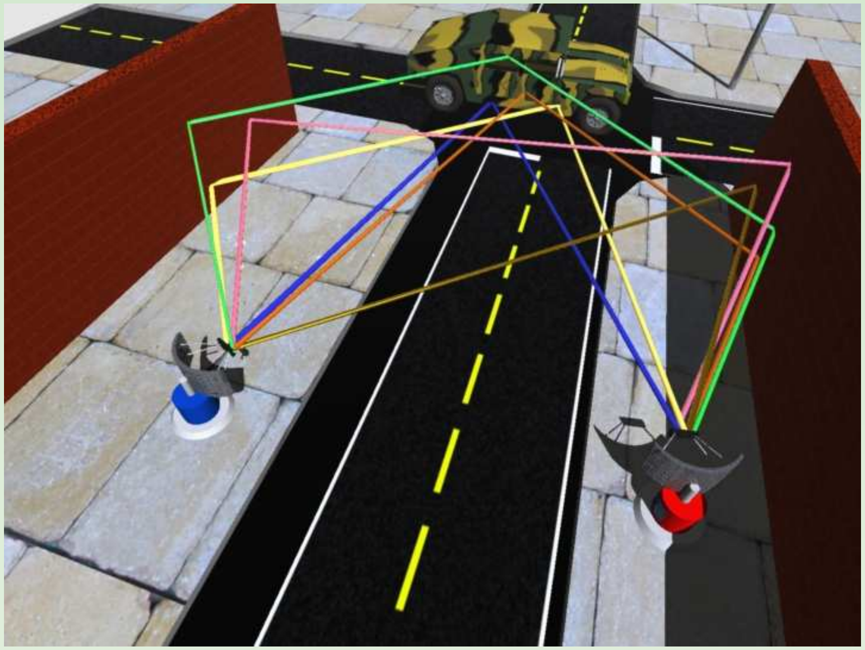
Ongoing work

Multitarget-Multisensor Tracking in an Urban Environment

Application Scenario

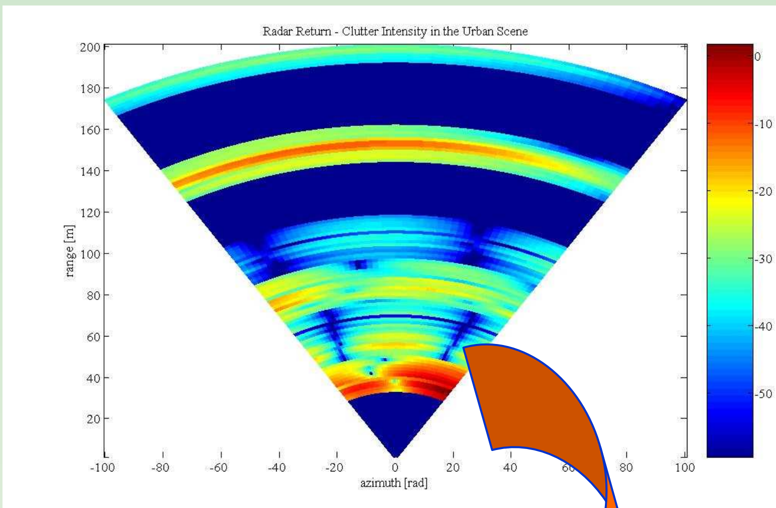


Multipath Model

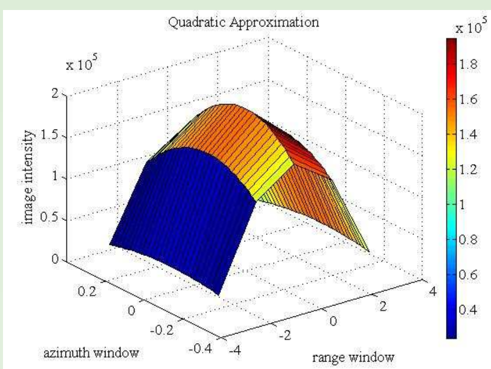


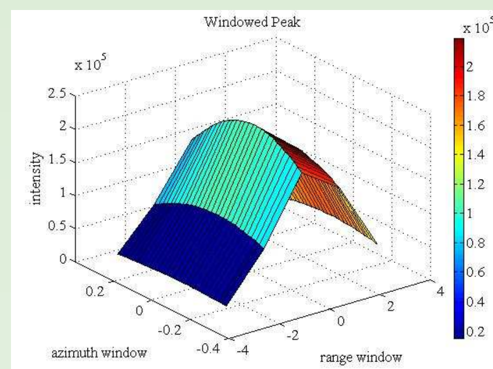
- Consider 6 paths
  - tx → target → rx
  - tx → wall → rx
  - tx → target → wall → rx
  - tx → wall → target → rx
  - tx → wall → wall → rx
  - tx → wall → target → wall → rx
- Use geometry to calculate intersection points
- Received signal is a summation of reflected signals

Detection & Imaging



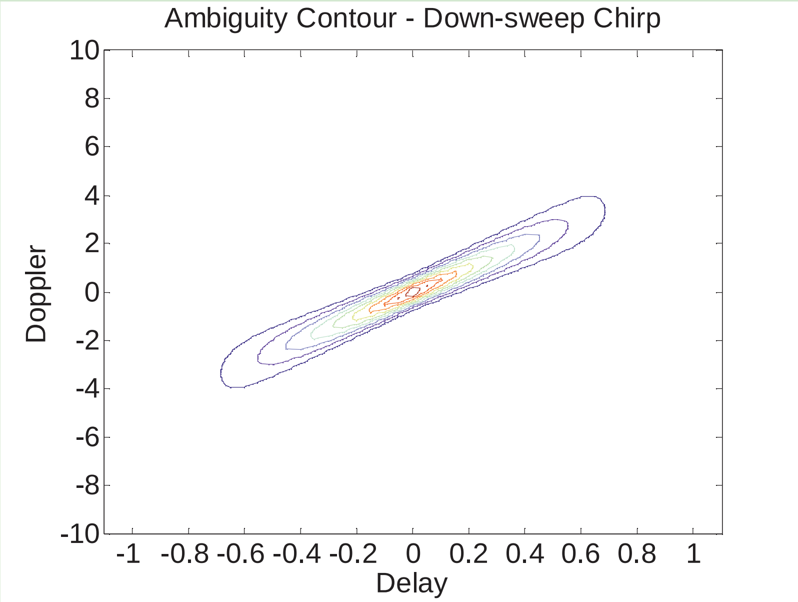
- Matched-filter
- Peak finding
  - (r_{max}, θ_{max})
- Curve fitting
  - Quadratic fit
    - $R_{k,m}(\omega)$

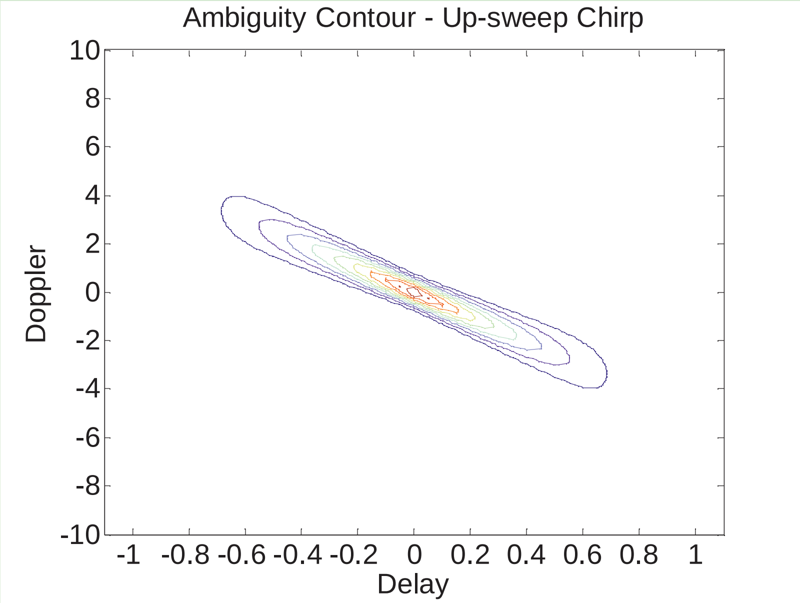




Waveform Library

- Waveform diversity for better target discrimination



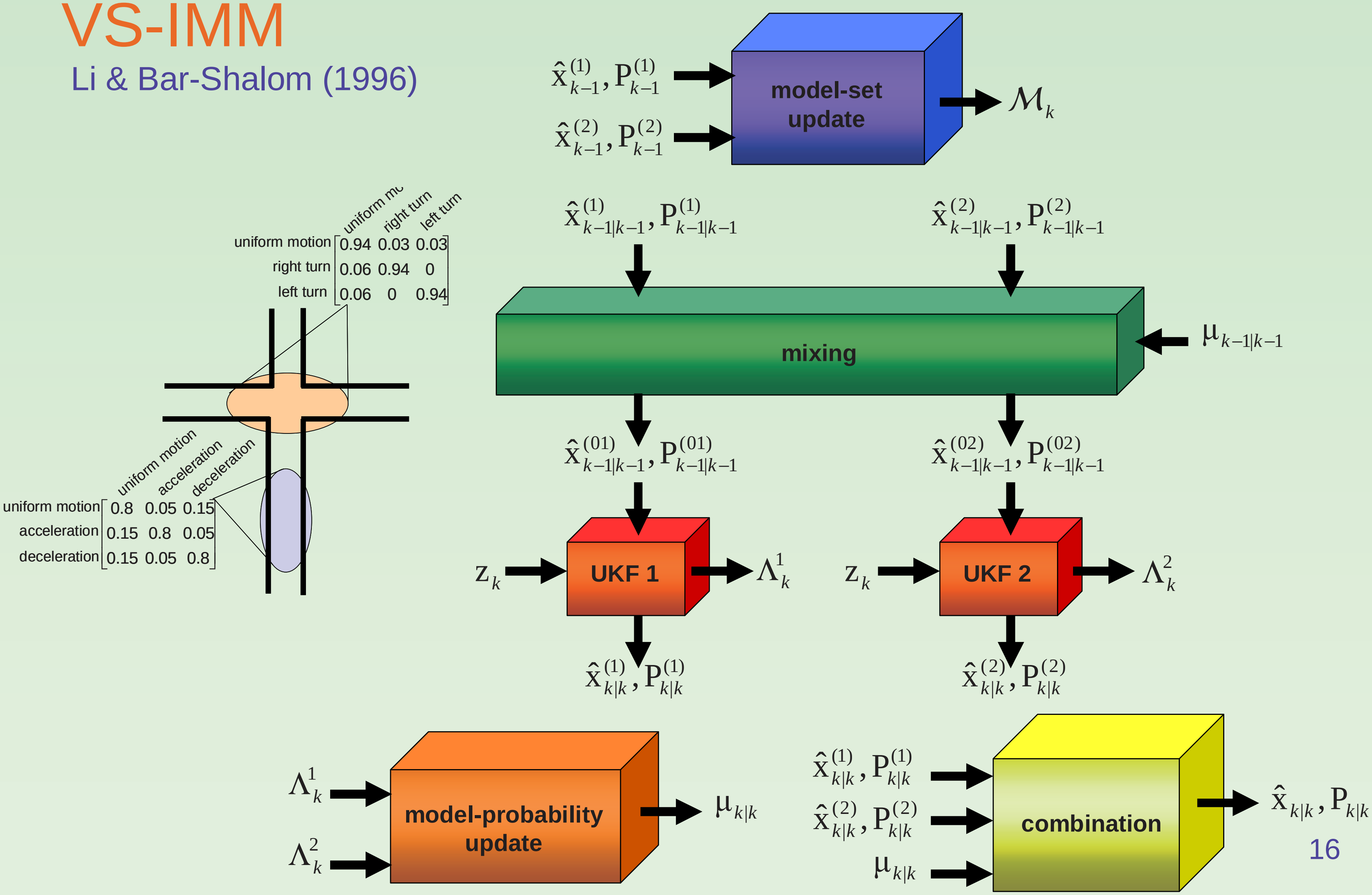


  – Doppler information used in imaging and/or in tracker state (velocity, acceleration estimation)

The Tracker

VS-IMM

Li & Bar-Shalom (1996)



The Tracker - UKF Julier & Uhlmann (1996)

- No linearization (EKF)
- No Monte Carlo sampling (PF)
- State distribution represented by Gaussian through deterministic *sigma-points*
- Posterior mean and covariance accurate up to second order of Taylor expansion for any nonlinearity

The Tracker - LMIPDA Mušicki et al. (2004)

- Integrated target existence concept
  - Modeled as a Markov chain

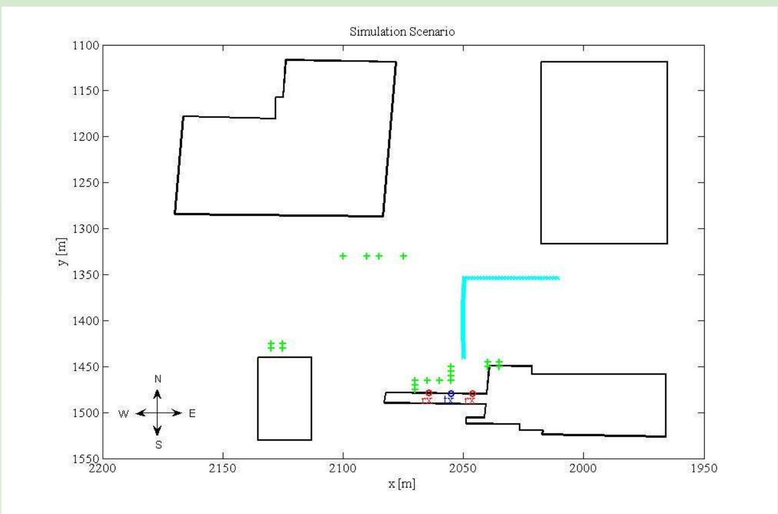
$$\psi_{k|k-1} = p_{11}\psi_{k-1|k-1} + p_{21}\left(1 - \psi_{k-1|k-1}\right)$$

- Converts single target tracking in clutter into multitarget tracking in clutter
  - Modifies clutter density according to predicted measurement density of other tracks
  - Number of operations is linear with number of tracks and measurements
  - Negligible performance loss compared to JPDA

The Devil is in the Details

- Signal sampling rate?
- Detection threshold?
- Process noise?
- Motion model set?
- Motion-model transition probabilities?
- Initiation threshold?
- Clutter density?
- And many other “big” details...

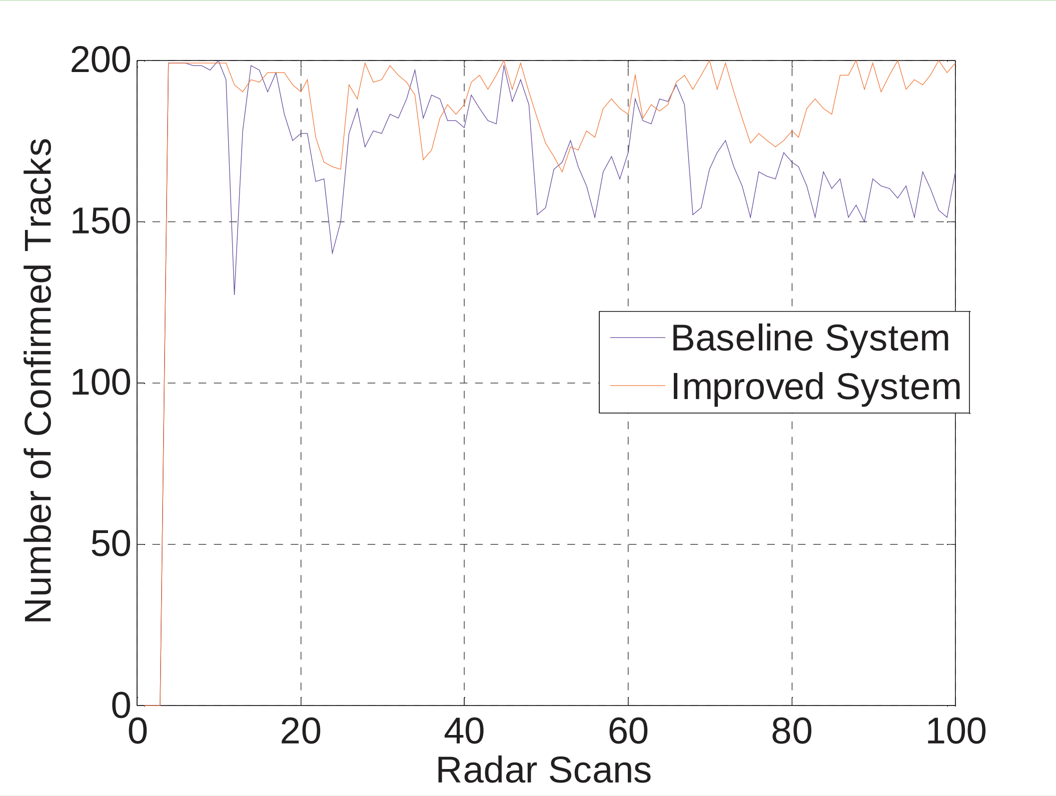
Simulation Setup



- Baseline system
  - 1 tx, 1 rx
  - Up-sweep chirp
  - UKF
- Improved system
  - 1 tx, 2 rx
  - Up and down chirp
  - VS-IMM

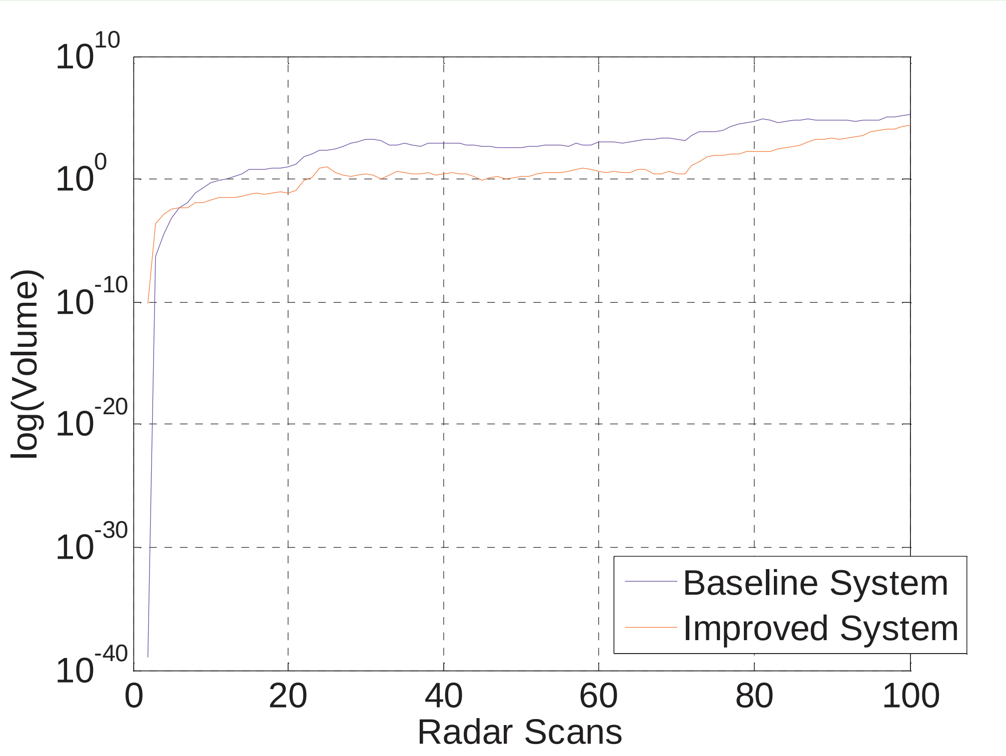
Simulation Results

- 9% increase in confirmed tracks



Simulation Results

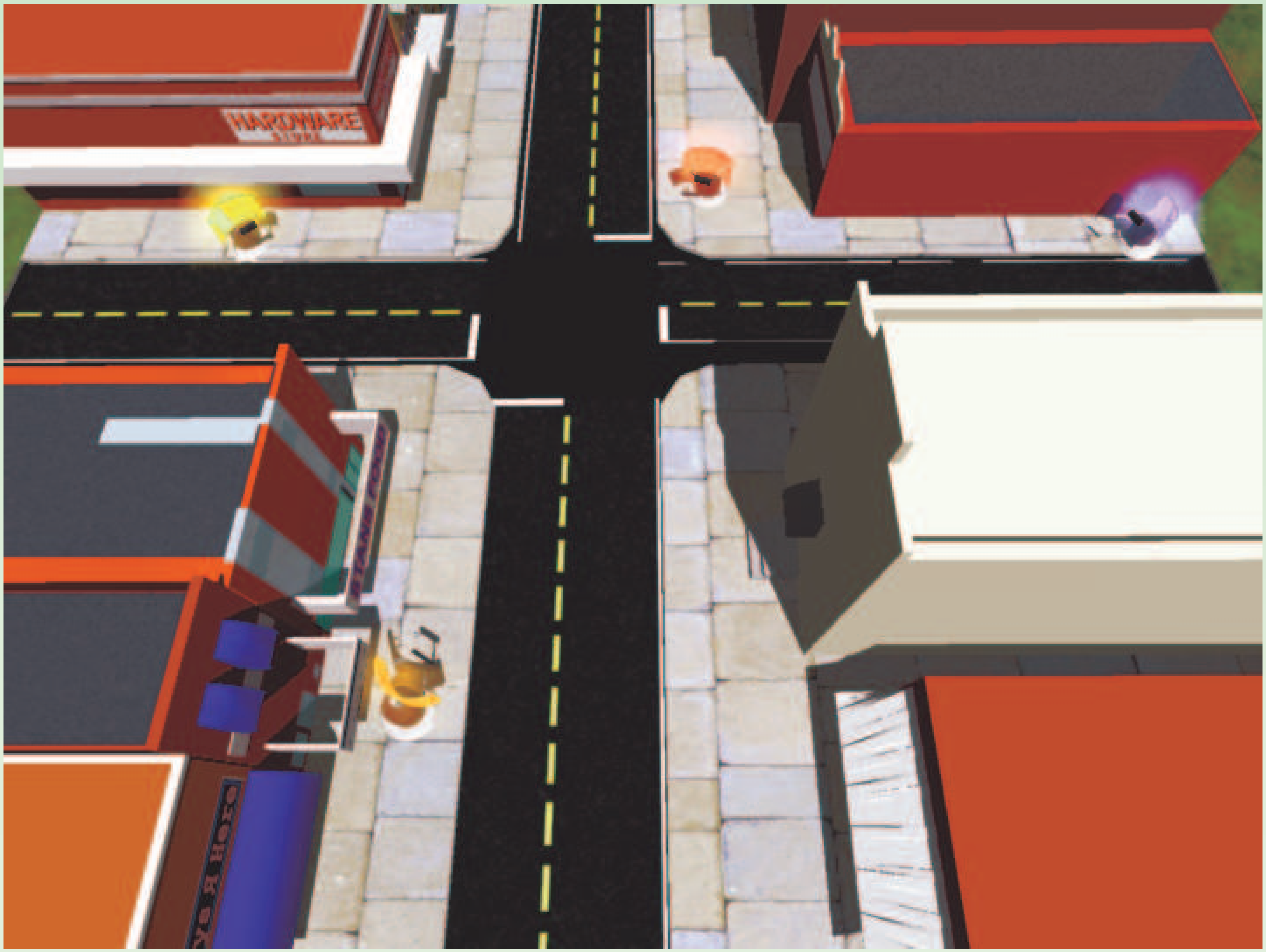
- 10x reduction in uncertainty ellipse volume



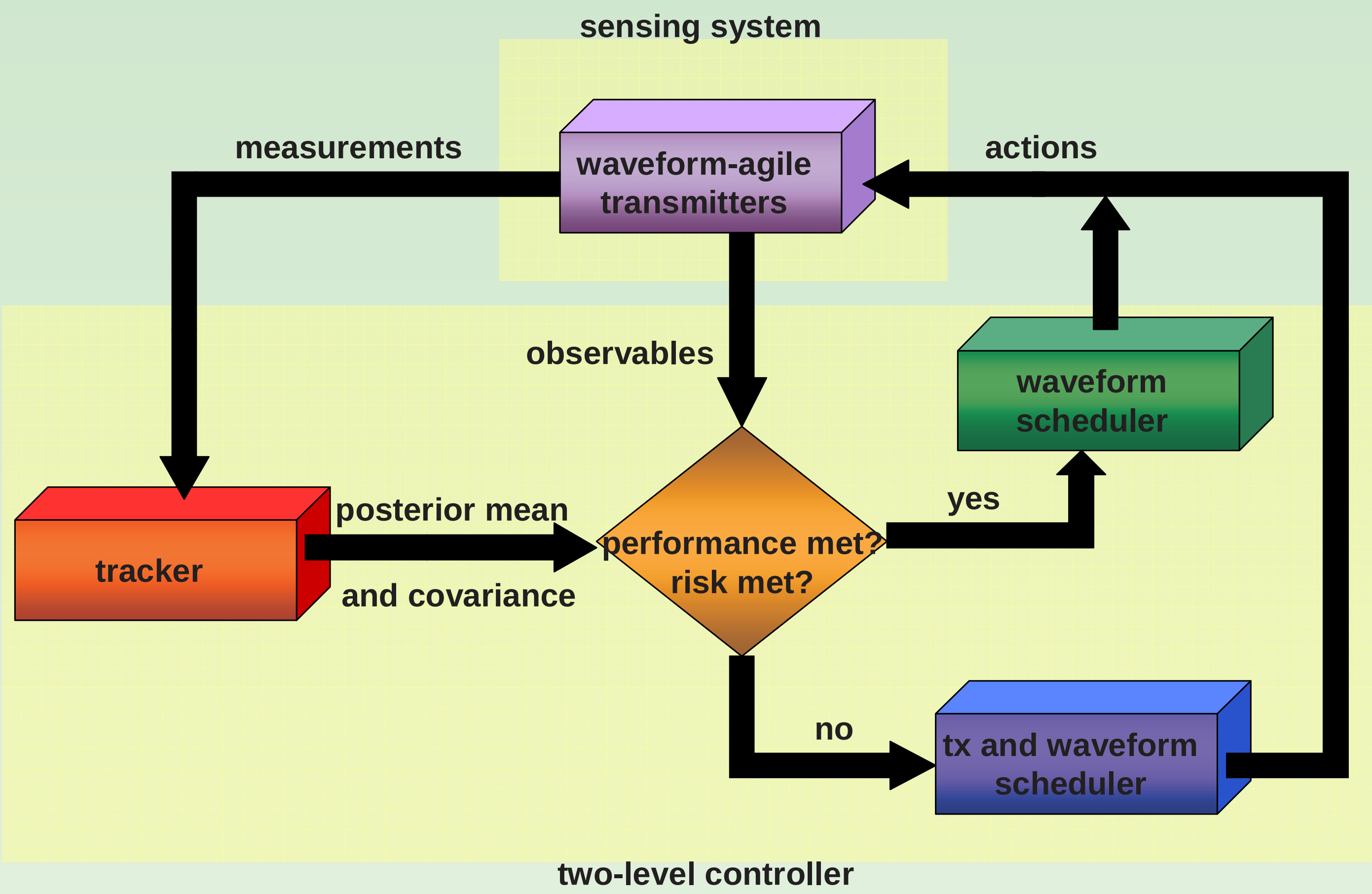
Future work

Adaptive Sensing in an Urban Environment: Closing the Loop

Application Scenario



Two-Level Controller



Motivation

- Waveform-agile transmitters in hostile environment
  - If active for too long, radar may be located
  - Non-myopic scheduler
    - Optimizes performance over larger time horizon
    - Computationally expensive
    - Executed only if certain conditions are met
  - Myopic scheduler
    - Optimizes performance over 1 step ahead only
    - Used every time, unconditionally

Partially Observable Markov Decision Process (POMDP)

- Tuple $\langle \mathcal{X}, \mathcal{A}, \mathcal{T}, \mathcal{C}, \mathcal{Z}, \mathcal{O} \rangle$

  $\mathcal{X}$: finite set of states

  $\mathcal{Z}$: finite set of observations

  $\mathcal{A}$: finite set of actions

  $\mathcal{C}: \ \mathcal{X} \times \mathcal{A} \rightarrow \Re$: one-step cost function

  $\mathcal{T}(\mathrm{X}' \mid \mathrm{X}, \mathrm{a})$: state transition law, $\mathrm{X}, \mathrm{X}' \in \mathcal{X}, \ \mathrm{a} \in \mathcal{A}$

  $\mathcal{O}(\mathrm{z}' \mid \mathrm{z}, \mathrm{a})$: observation law, $\mathrm{z}, \mathrm{z}' \in \mathcal{Z}$

- Objective: minimize cost function

POMDP Formulation

- For every time-step *k*, define:

$$\mathrm{X}_k = [S_k, \mathrm{u}_k, F_k]^\mathrm{T}, \quad \mathrm{X}_k \in \mathcal{X}$$

S_k : states of T_k targets

F_k : filter state

u_k : activation status of $N \times \Omega$ sensing options

$$\mathrm{u}_k = \begin{bmatrix} u_k^{(1,1)} & \cdots & u_k^{(1,\Omega)} \\ \vdots & \ddots & \vdots \\ u_k^{(N,1)} & \cdots & u_k^{(N,\Omega)} \end{bmatrix}$$

$u_k^{(n,\omega)} = 1 \Rightarrow$ waveform ω $(\omega = 1,\ldots,\Omega)$ is sent by nth transmitter $(n = 1,\ldots,N)$

POMDP Formulation

- System state: $\mathrm{x}_k = [S_k, \mathrm{u}_k, F_k]^{\mathsf{T}}, \quad \mathrm{x}_k \in \mathcal{X}$
  - Targets states

$$S_k = \left[\mathrm{x}_k^{(1)}, \ldots, \mathrm{x}_k^{(T_k)}\right]^{\mathsf{T}}$$

$$\mathrm{x}_k^{(t)} = [x_k, \dot{x}_k, y_k, \dot{y}_k], \quad t = 1, \ldots, T_k$$

  - UKF filter state

$$F_k = \left[\hat{\mathrm{x}}_k^{(1)}, \ldots, \hat{\mathrm{x}}_k^{(T_k)}, \mathrm{P}_k^{(1)}, \ldots, \mathrm{P}_k^{(T_k)}\right]^{\mathsf{T}}$$

$$\hat{\mathrm{x}}_k^{(t)} = E\left\{\mathrm{x}_k^{(t)} \middle| \mathrm{z}_k\right\}, \quad \mathrm{z}_k \in \mathcal{Z}, \quad t = 1, \ldots, T_k$$

$$\mathrm{P}_k^{(t)} = E\left\{\left(\mathrm{x}_k^{(t)} - \hat{\mathrm{x}}_k^{(t)}\right)^2 \middle| \mathrm{z}_k\right\}, \quad \mathrm{z}_k \in \mathcal{Z}, \quad t = 1, \ldots, T_k$$

POMDP Formulation

- State dynamics

$$X_{k+1} = f(X_k, a_k, w_k) = \left[f^{tgt}\left(x_k^{(1)}, w_k^{(1)}\right), \ldots, f^{tgt}\left(x_k^{(T_k)}, w_k^{(T_k)}\right), f^{s}(a_k), f^{f}\left(\hat{x}_k^{(1)}, P_k^{(1)}\right), \ldots, f^{f}\left(\hat{x}_k^{(T_k)}, P_k^{(T_k)}\right) \right]^{T}$$

w_k represents randomness in state transition

$$a_k = \begin{bmatrix} a_k^{(1,1)} & \cdots & a_k^{(1,\Omega)} \\ \vdots & \ddots & \vdots \\ a_k^{(N,1)} & \cdots & a_k^{(N,\Omega)} \end{bmatrix}$$ is the action matrix

$a_k^{(n,\omega)} = 1 \Rightarrow$ nth transmitter is active and sends waveform ω

$\sum_{\omega=1}^{\Omega} a_k^{(n,\omega)} = 0 \Rightarrow$ nth transmitter is idle

$$u_{k+1} = f^{s}(a_k)$$

Action Constraints

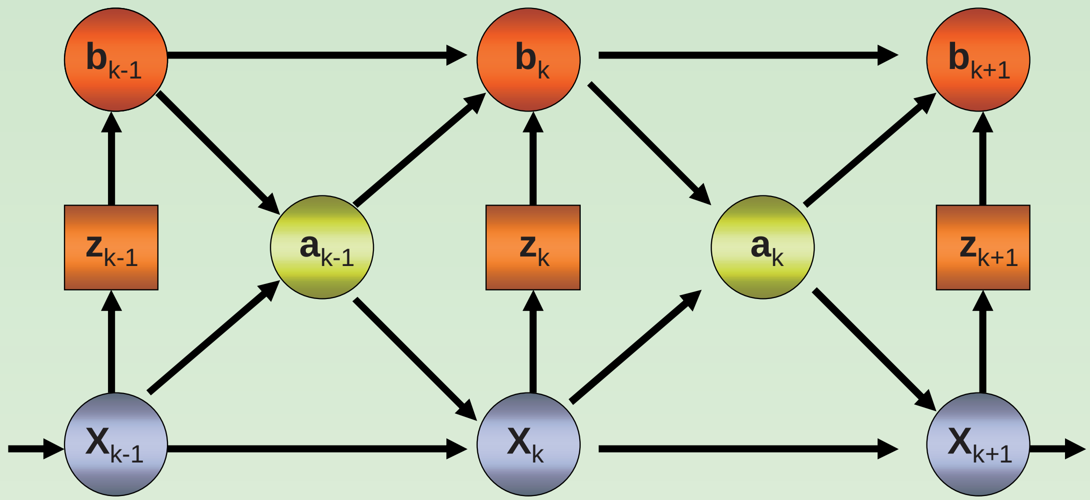
- Each transmitter can only send 1 waveform:

$$\sum_{\omega=1}^{\Omega} a_k^{(n,\omega)} = 1, \quad n = 1, \dots, N$$

- Each transmitter is active for no more than c_{th} scans:

$$\sum_{\omega=1}^{\Omega} \sum_{k=H-c_{th}}^{H} a_k^{(n,\omega)} - c_{th} \le 0, \quad n = 1, \dots, N$$

POMDP Evolution in Time



- State not directly observable
  - POMDP keeps track of belief-state $\mathbf{b}_k$
    - Tracker output, scheduler input
    - Posterior distribution over set of states given observation and action history
      - Posterior mean and covariance

POMDP Policy

- Wish to find optimal stationary policy π^*
- Mapping from belief state to action

$$\mathrm{a}_k = \pi(\mathrm{b}_k)$$

- Action incurs immediate cost

$$\rho(\mathrm{b}_k, \mathrm{a}_k) = \sum_{t=1}^{T_k} \int_{\mathrm{X}_k \in \mathcal{X}} \left\{ \left[\left(x_k^{(t)} - \hat{x}_k^{(t)} \right)^2 + \left(y_k^{(t)} - \hat{y}_k^{(t)} \right)^2 \right] \mathrm{b}_k \right\} d\, \mathrm{X}_k$$

Solving the POMDP

- Q-value approximation
  - (H-k)-step Q-value of action a_k

$$Q_{H-k}(\mathrm{b}_k,\mathrm{a}_k)=\rho(\mathrm{b}_k,\mathrm{a}_k)+E\left\{J^*_{H-k-1}(\mathrm{b}_{k+1})\middle|\mathrm{b}_k,\mathrm{a}_k\right\}$$

- Bellman's optimality principle

$$J_H\left(p_0,\pi^*\right)=\min_{\mathrm{a}\in\mathcal{A}}\{Q_{H-k}(\mathrm{b}_k,\mathrm{a}_k)\}$$

  - For H large

$$\pi^*(\mathrm{b}_k)=\arg\min_{\mathrm{a}\in\mathcal{A}}\{Q_H(\mathrm{b}_k,\mathrm{a})\}$$

The Road Ahead

- Fall 2007
  - Complete DARPA project
    - Waveform scheduling: round-robin vs. myopic
    - Investigate time dedicated to surveillance
    - Submit paper
  - Study POMDPs

The Road Ahead

- Spring 2008
  - Two-level scheduler implementation
    - Non-myopic transmitter scheduler
    - Myopic waveform scheduler
    - Integration with tracking system
    - Submit paper
  - Finalize dissertation

The End

Thank you!