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http://ants.kestrel.edu/

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Outline

- Project Summary
- Challenge Problem Year 2
  - metrics to guide coordination
  - localization
  - implementation details
  - experimental results
- Dynamics of distributed constraint optimization
  - asynchronous algorithm
  - dense graphs
- Plans

Project Summary

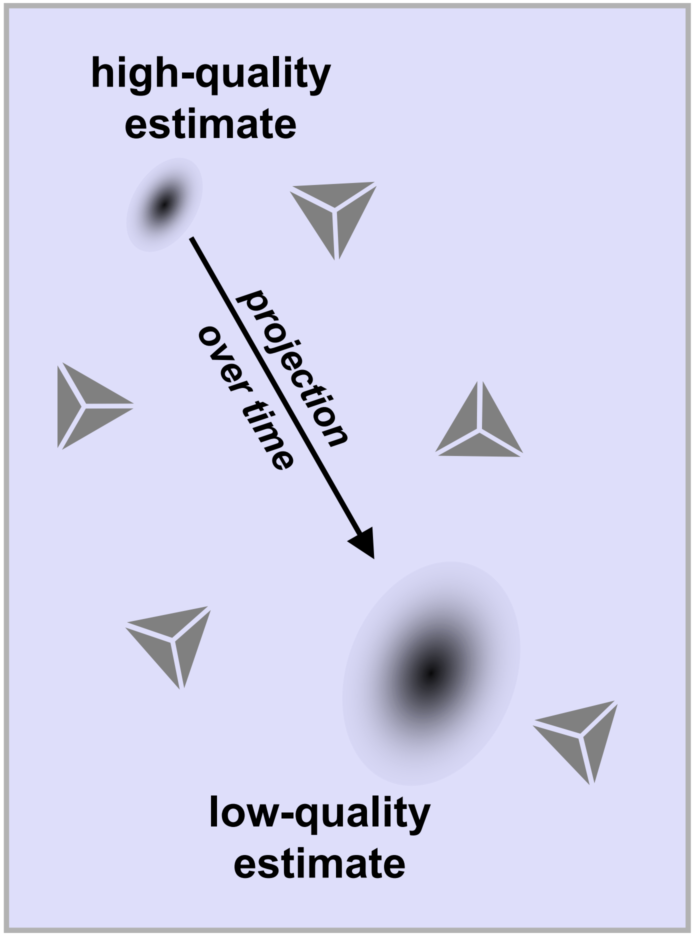
Year 1

- Formulated challenge problem as a distributed constraint optimization problem
  - isomorphic to graph coloring
- Developed distributed, scalable, anytime scheduler
  - soft graph colorer based on an iterative, local-repair algorithm
- Demonstrated scheduler on simulator & hardware
  - single target

Year 2

- Generalized formulation of challenge problem
  - more complex constraints/metrics allow more realistic representation of objectives
- Evaluated scheduler's performance on abstract graph coloring problems
  - scalable, low cost, robust
- Improved performance of distributed scheduler
  - simple stochastic component breaks symmetry to ensure convergence in parallel computations
- Demonstrated scheduler on simulator & hardware
  - multiple targets

Sensor Coordination



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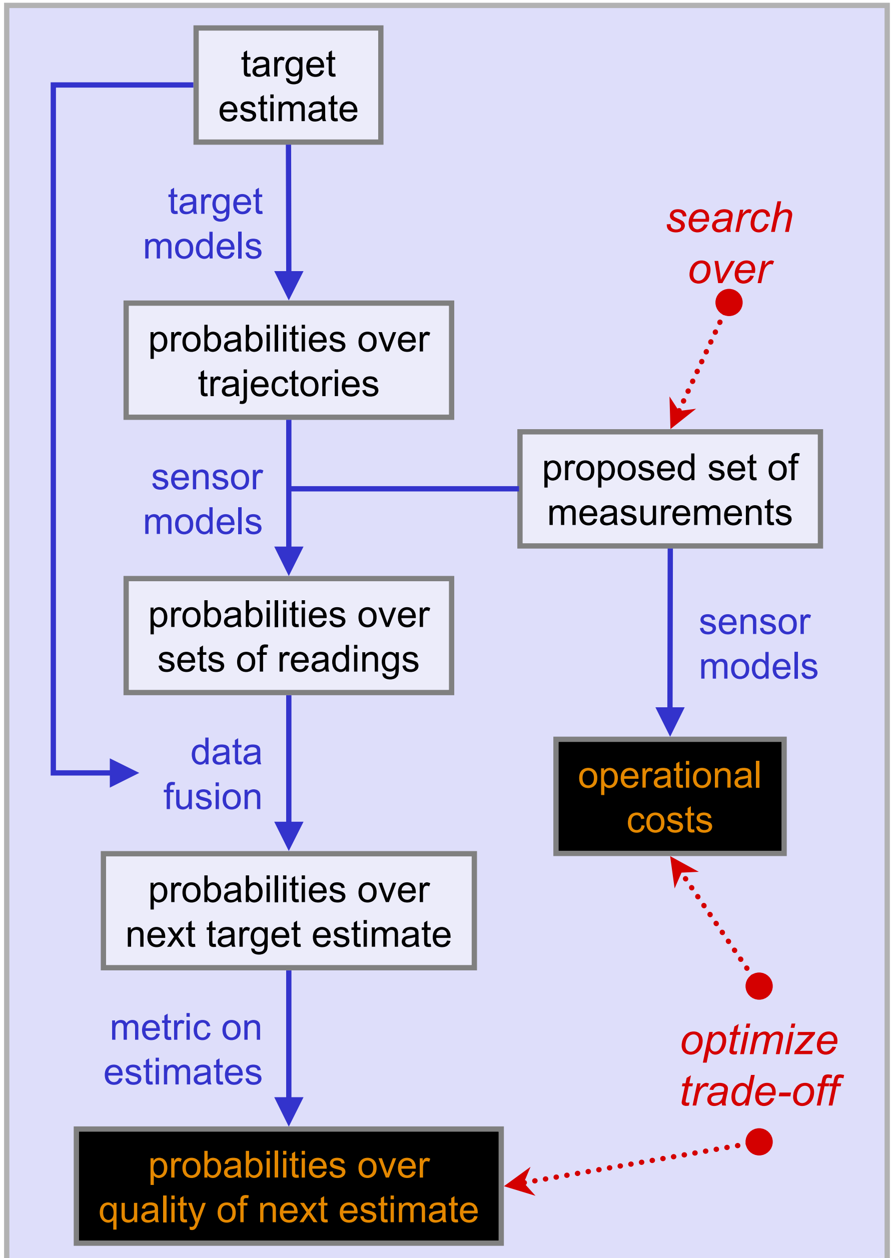
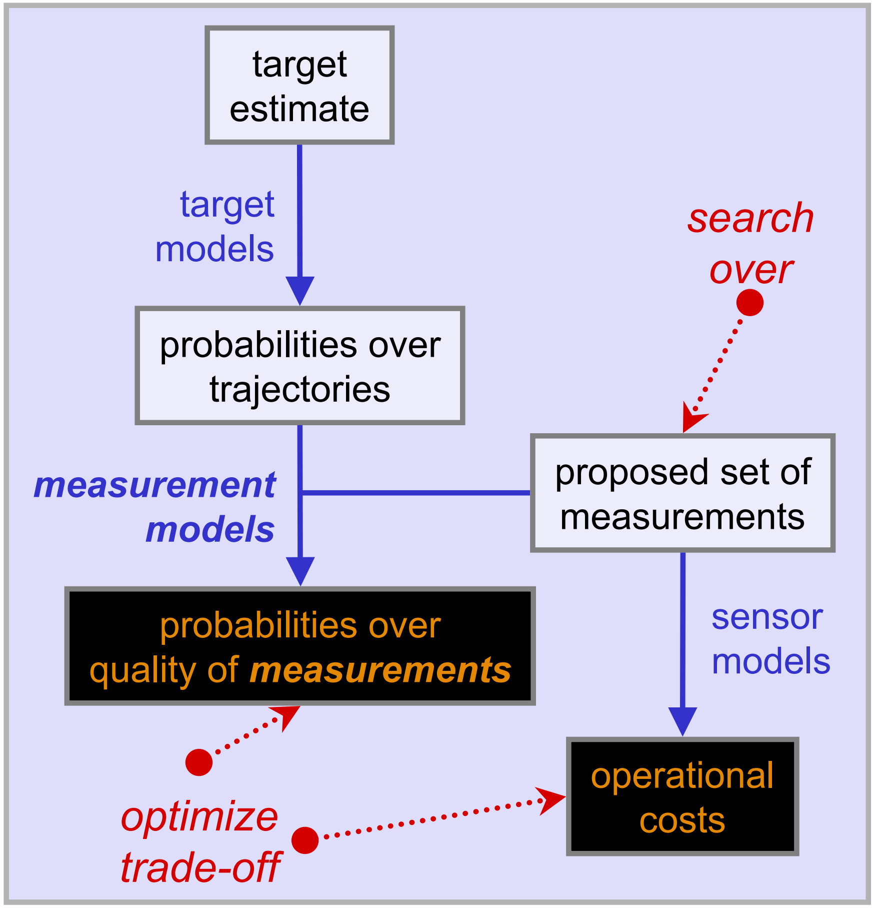
- A *target estimate* represents approximate knowledge about a target
  - probability density function over space of position × velocity
- The *quality* of an estimate reflects its accuracy
  - e.g., standard deviation for normal distributions
- A *target model* predicts a target's future from an estimate
  - probability density function over *trajectories*
  - quality of predictions decreases further into the future
- Estimate quality is maintained by incorporating new measurements
- *Coordination* attempts to optimize the trade-off between quality of estimates and operational costs

Coordination based on Quality of Estimates



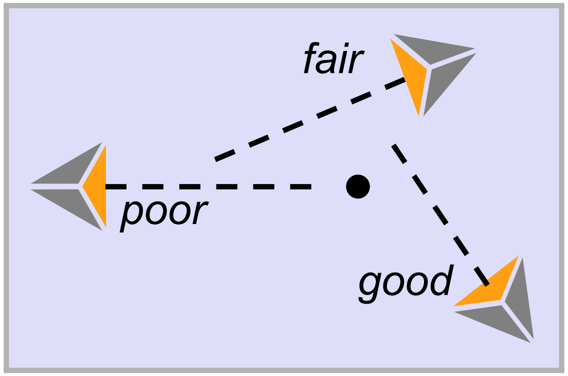
- Given a proposed set of measurements
  - determine expected quality of next estimate
  - determine costs
- Search over sets of measurements
  - optimize expected quality-cost trade-off
- Scalable
  - due to locality of sensor interactions
- But expensive!
  - large search spaces
  - expensive processes at each search node
  - not feasible for real-time, distributed coordination (yet)
- Won't work for BAE tracker
  - no quality metric available

Coordination based on Quality of Measurements

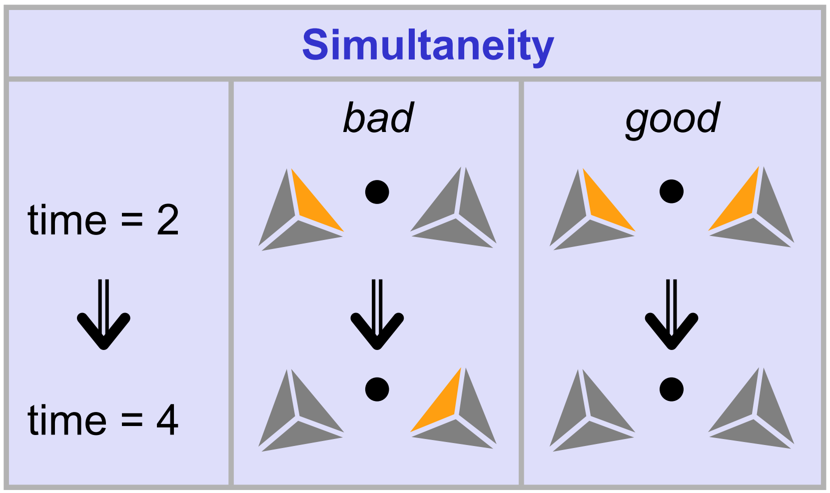


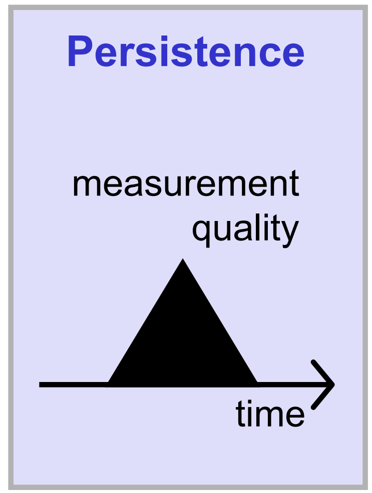
- Heuristic measurement models
  - determine quality of proposed set of measurements with respect to a trajectory
    - details on next slide
  - high-quality measurements assumed to lead to high-quality estimates
- Optimize trade-off between expected measurement quality and costs
- Much cheaper than using quality of estimate
  - presumably not as accurate
  - but will work for BAE tracker
    - no need for metric on estimate quality
    - BAE tracker gives most-likely trajectory

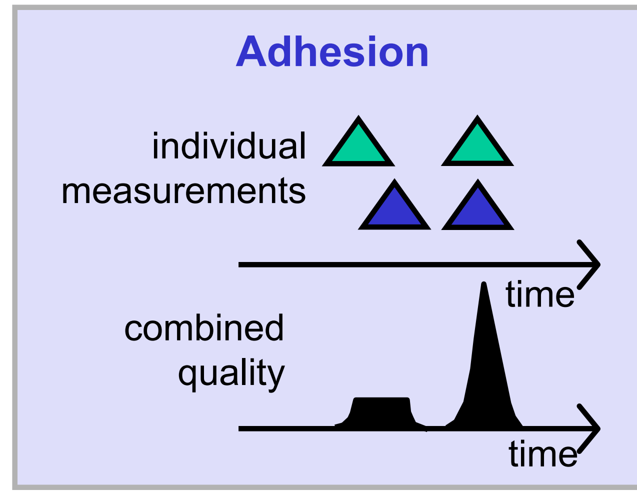
Measurement Metrics (for single target)



- Quality of single measurement derived from signal equation:
  - $s(R,\theta) = K \exp(\theta^2/A)/R^2$
  - $m(s) = \log_2[1+\max(0, (s-s_b)/(s_m-s_b))]$
    - s_m, s_b = maximum, background signals







- Quality of multiple measurements reflects simultaneity

persistence function associates a time window with a measurement

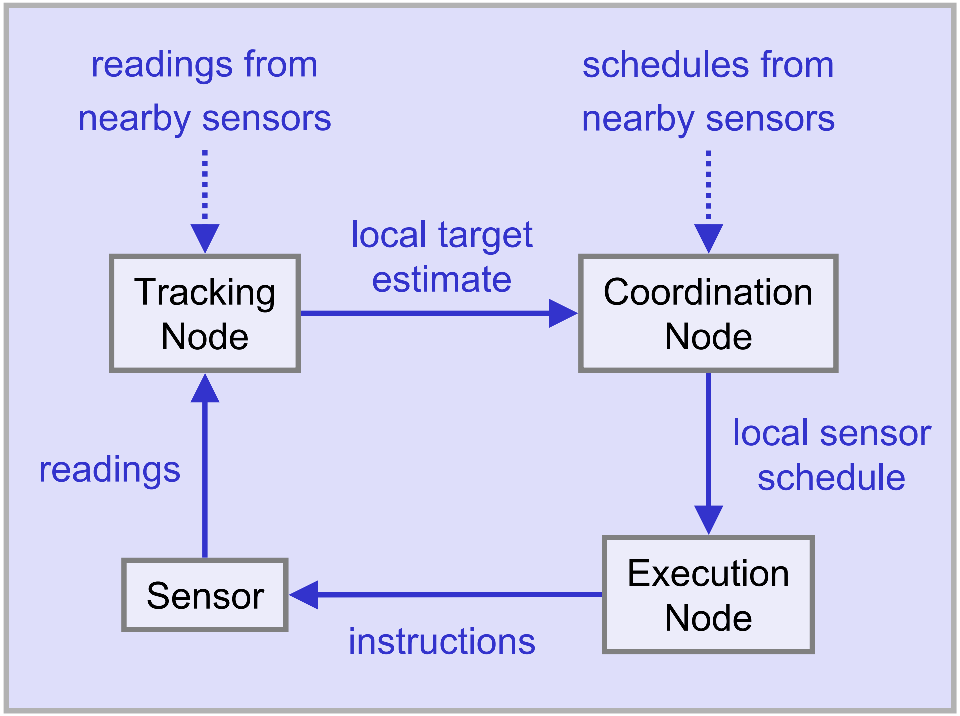
adhesion function combines measurements at every instant based on time windows

- Overall quality with respect to a trajectory
  - integral over time of instantaneous, combined quality

Multiple Targets

- Extend single-target concepts to multiple targets
  - a world state is a finite map from targets to single-target information
  - an estimate is a probability density function over world states
  - a trajectory is a timed sequence of world states
- A measurement may give information about any subset of the targets
  - a quality metric is a finite map from targets to single-target quality metrics
- Interference between targets is possible
  - for the challenge problem hardware $m_G(g) \equiv \max[0, m(g) - \sum_{g' \neq g} m(g')]$
    - where G is the set of all targets and $g, g' \in G$
- Multiple measurements are combined by combining the metrics for each target separately
  - the persistence and adhesion functions are lifted to finite maps

Localization



tightly-coupled: separate threads on same JVM

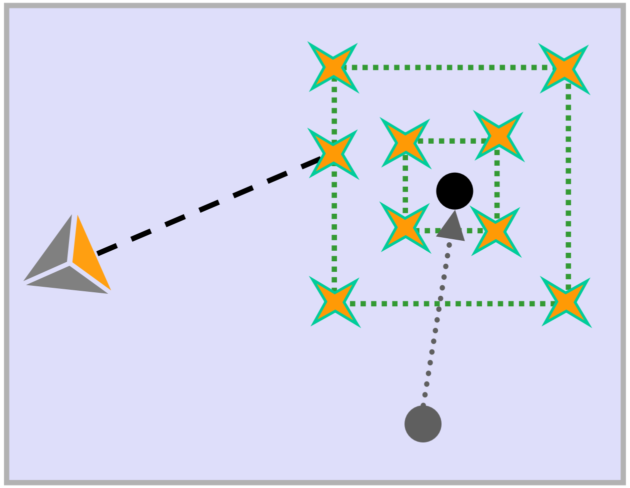
- Fully distributed, homogeneous architecture
  - scalable, robust
  - each sensor has local tracking, coordination and execution nodes
- Coordination occurs via exchange of *schedules*
  - each sensor independently executes its own schedule based on its local, synchronized clock
- Communication latency finessed
  - inter-sensor communication is infrequent
- Adaptation via continual rescheduling
  - convergence? …
- Local coordination metrics
  - assume communication is possible where collaboration is useful

Coordination Nodes

- Stochastic activation
  - periodically, each node randomly decides if it should activate
  - the *activation probability* determines the (mean) fraction of nodes activated
- Local schedule optimized by each activated node
  - given the current, local target estimate;
  - given the schedules that it has received from nearby sensors;
  - it computes a schedule of actions for its sensor
    - optimizes the trade-off between measurement quality and operational costs
  - it broadcasts the schedule (if changed)
- Convergence achieved by suitable activation probability
  - experimentally determined that 0.3 is a reasonable value
    - previously reported experiments with distributed, synchronous graph coloring
    - further experiments on *asynchronous* coloring show similar results
- Anytime process: can be interrupted when schedule is required
  - quality of schedule asymptotically improves over time

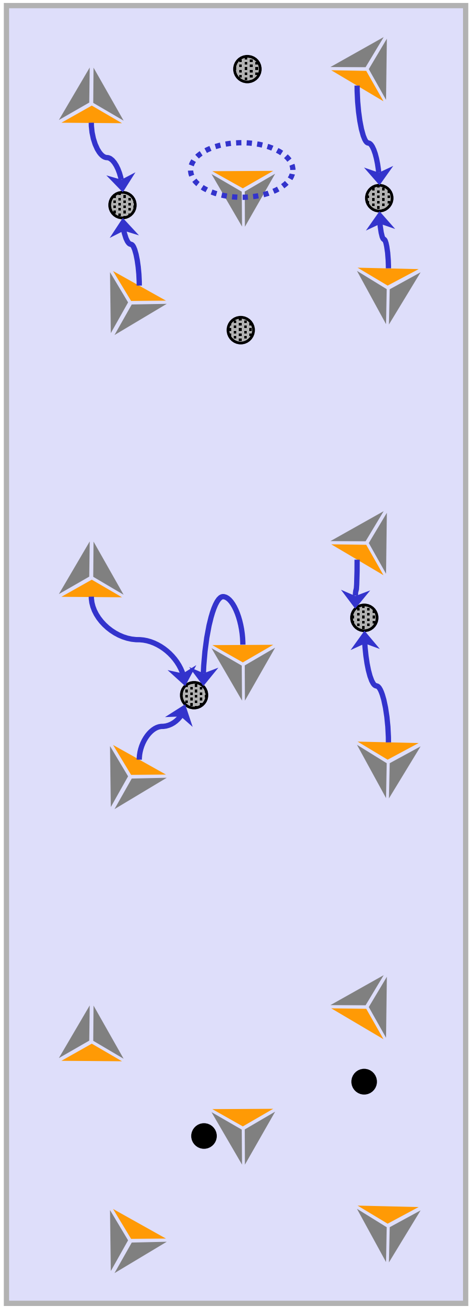
Tracking Nodes

- Each tracking node maintains tracks of nearby targets
  - ideally, we would have a multi-target tracker
  - instead, we tried a few heuristics to adapt BAE’s tracker
  - each tracking node maintains one BAE tracker per target



- Measurement-track association
  - given a measurement, the signal equation is used to try to determine which target might have been illuminated
    - project each target’s position
    - compute theoretical signals at points on a narrow grid around target’s expected position
    - determine if observed signal falls within theoretical range
    - if not, widen grid, up to some limit
  - the measurement is associated with the target that gives the tightest match
    - if none match closely enough, measurement is unassociated …

Track Initiation and Retirement



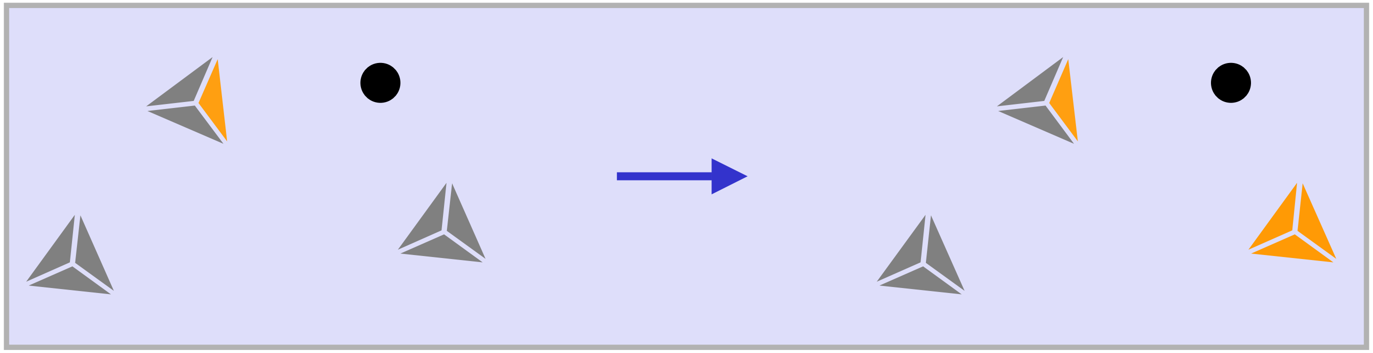
- Tracks initiated from unassociated measurements
  - measurements grouped using clustering
  - new tracks generated from significant groups
- Tracks are retired when they not updated for a certain time

Clustering heuristic

- candidate positions are proposed at various points
- measurement association is attempted for these candidates
- new positions are computed from associated measurements
  - using a χ^2-minimization test
- association retried with the original, unassociated measurements
- this process is repeated until a fix-point is reached

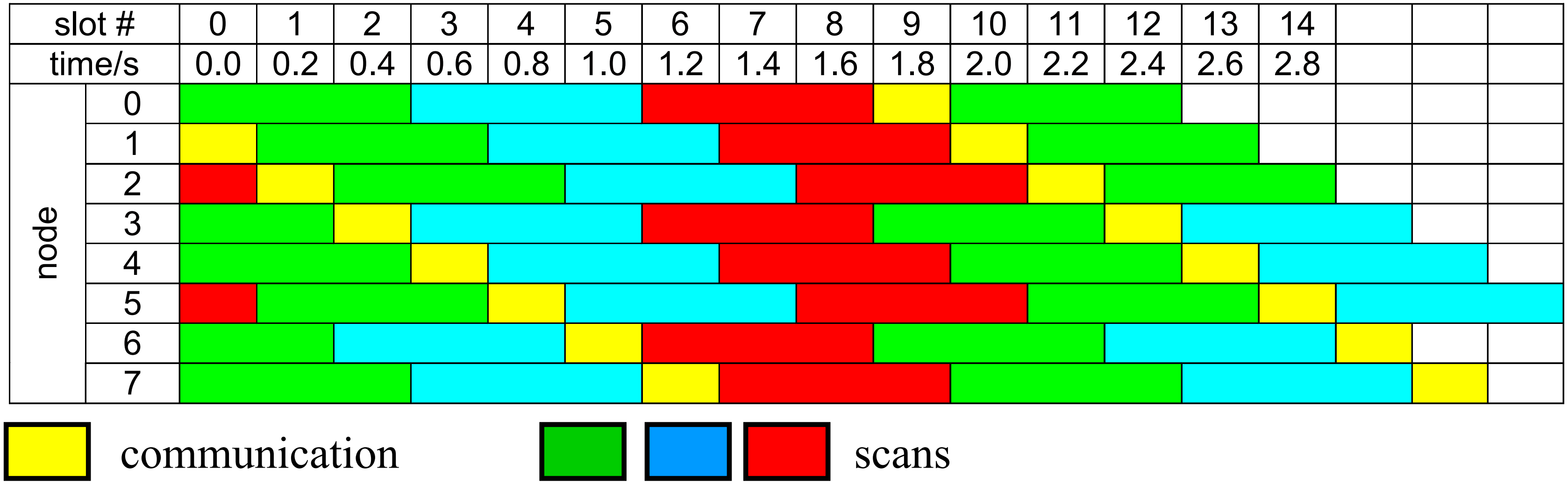
Control-based Supplements

- Cheap but coarse methods to supplement tracking-based method
- Exploit local measurements taken by sensor
  - a sector that gives a strong signal is a good candidate for another measurement
  - compare with signal predictions made during coordination to score tracker
- Use neighbor's measurements for proximity detection
  - allows some sensors to deactivate all sectors
  - simple scheme: a node reactivates if a neighbor that is within 1.5 x (detection range) gets a strong signal.
  - finer scheme: a node reactivates if a neighbor that is within 1.5 x (detection range) gets a strong signal from a sector that looks towards the node.



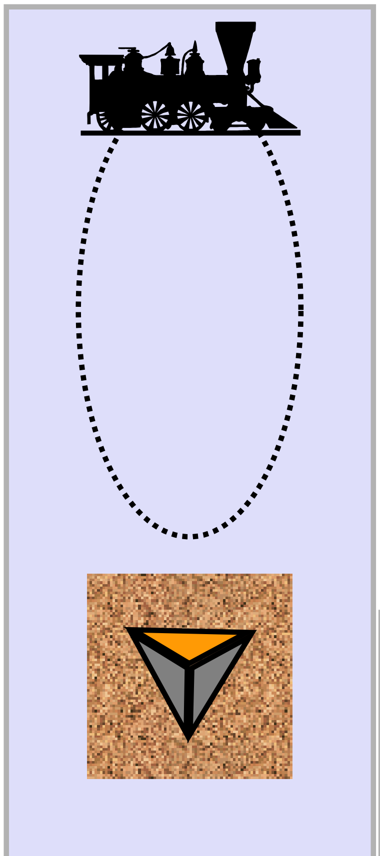
Communication

- Sensor schedule is integrated with a communication schedule
  - periodic schedule
    - 3 scan cycles of duration 0.6 seconds each
      - enough for 3 amplitude-only measurements
      - or 1 amplitude-and-frequency measurement
    - 1 broadcast cycle of duration 0.2 seconds
  - all nodes use the same frequency/channel
  - will need to be generalized for configurations with many more nodes
- Communication optimization
  - compression of multiple messages into single transmission
  - clock synchronization piggy-backed

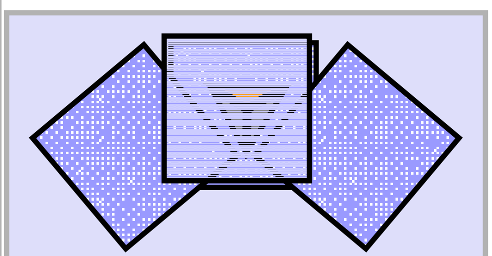


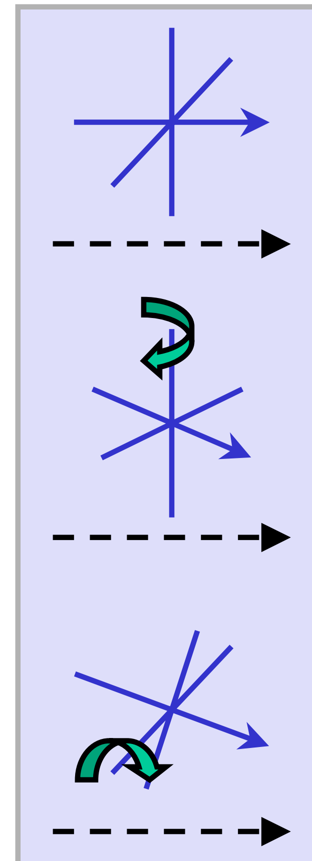
Calibration

- Theoretical signal model: $s(R,\theta) = K \exp(\theta^2/A)/R^2$
- Compare with observed signal
  - amplitude-only measurements every 0.5 seconds



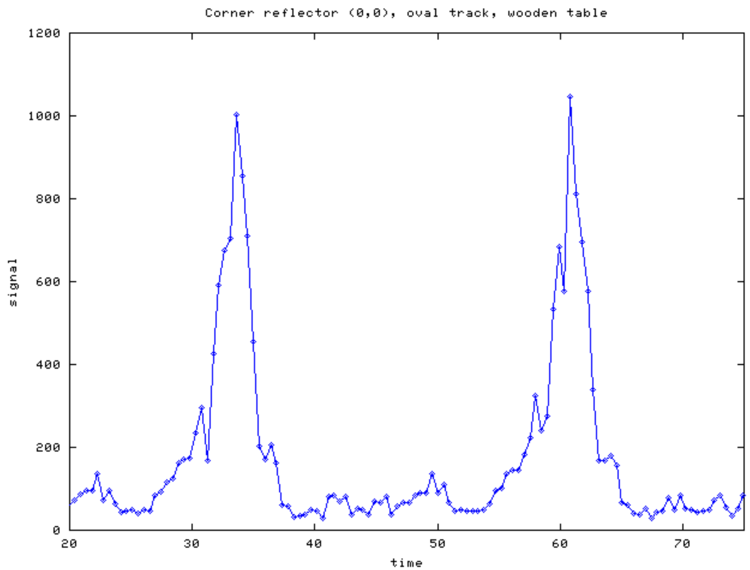
- Sensor raised ~2.5 feet on wooden table
- For some experiments, hood constructed around sensor from radar absorber
- Target moves along oval track
  - length 10 foot
  - width 4 foot
- Orientation of target varied
  - w.r.t. direction of travel

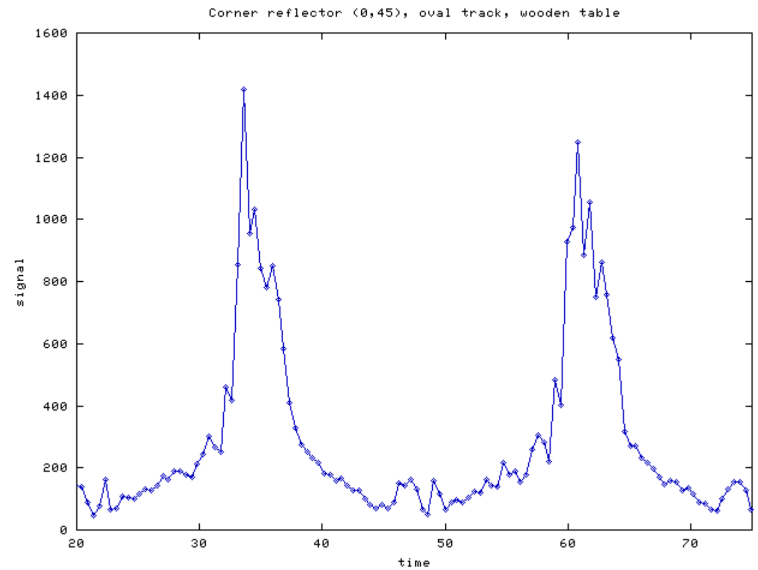


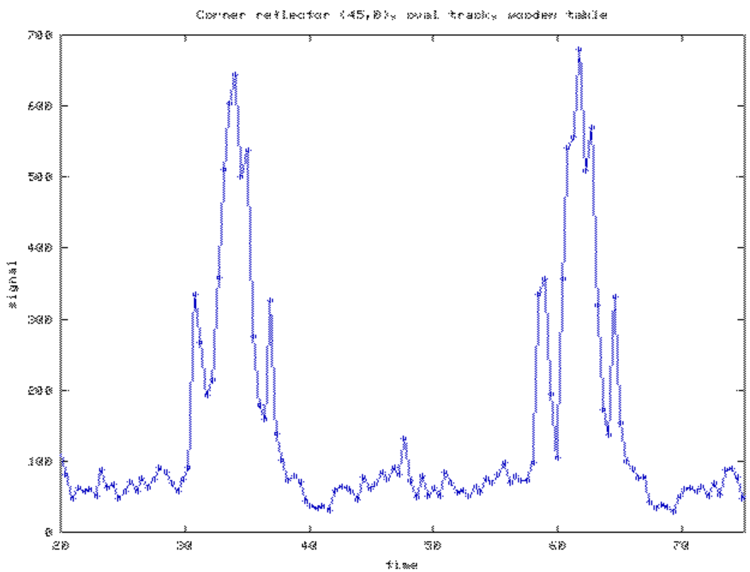


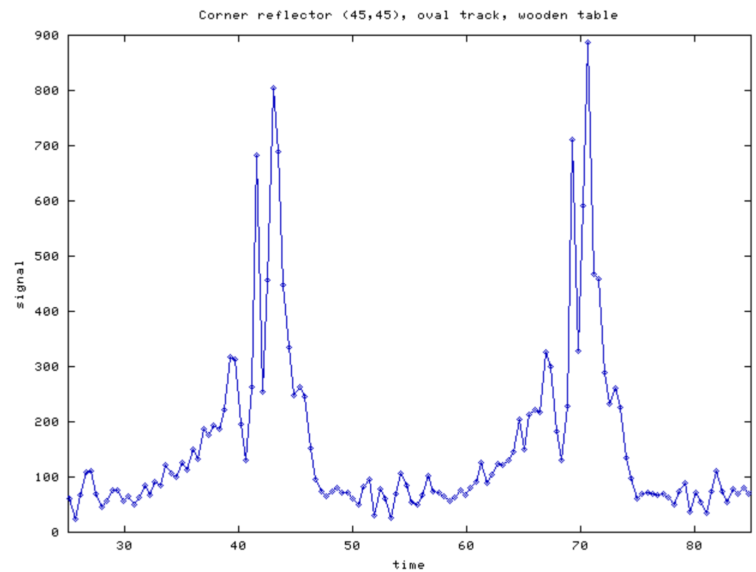
Calibration Results: No Absorber

- Multi-path reflection postulated as major (but not only) source of noise



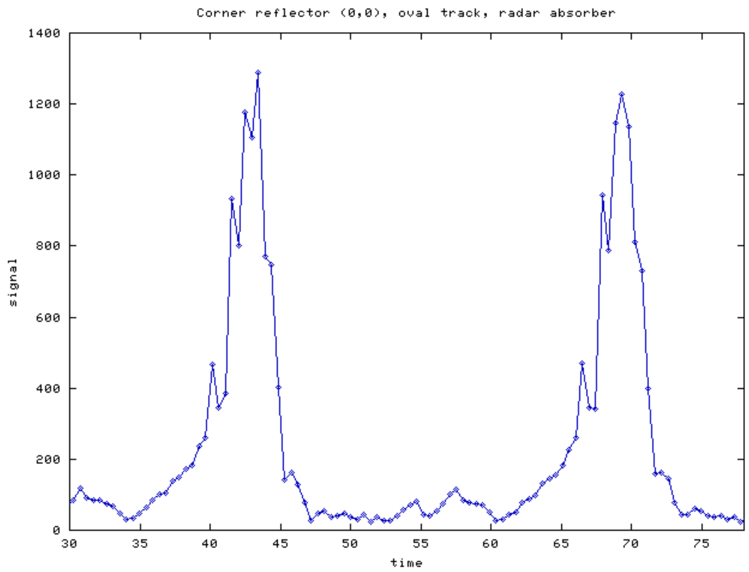


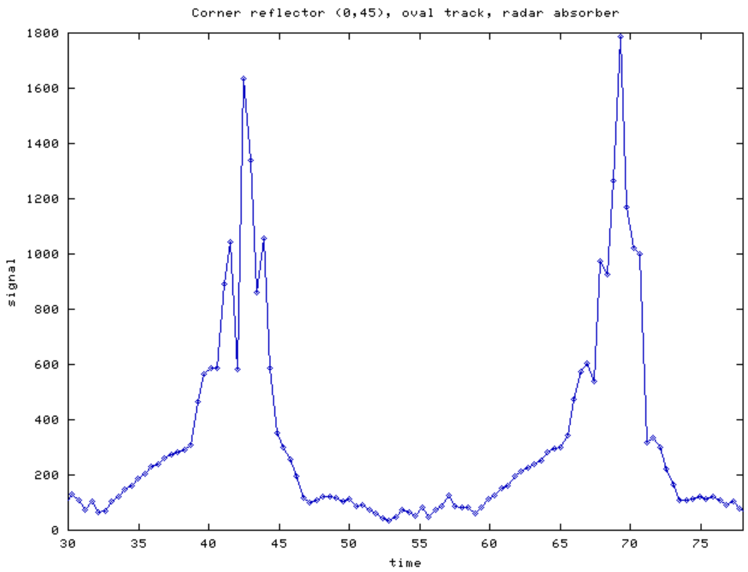


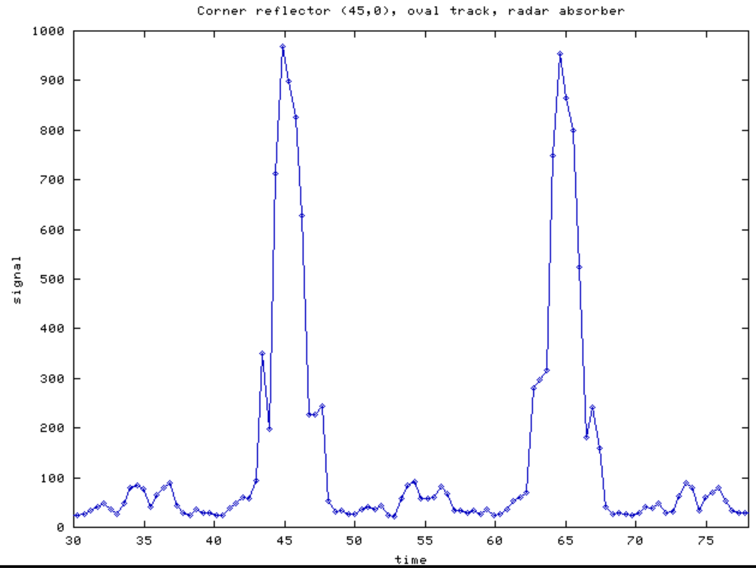


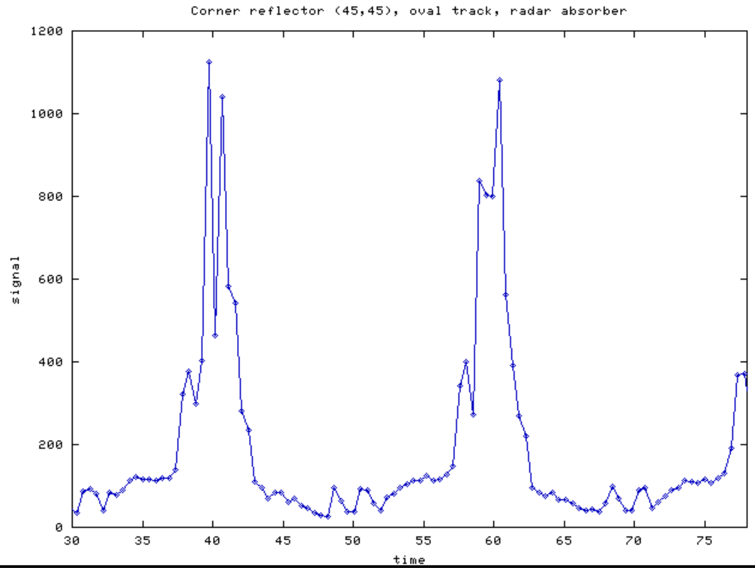
Calibration Results: With Absorber

- Should be no multi-path reflection – target orientation matters



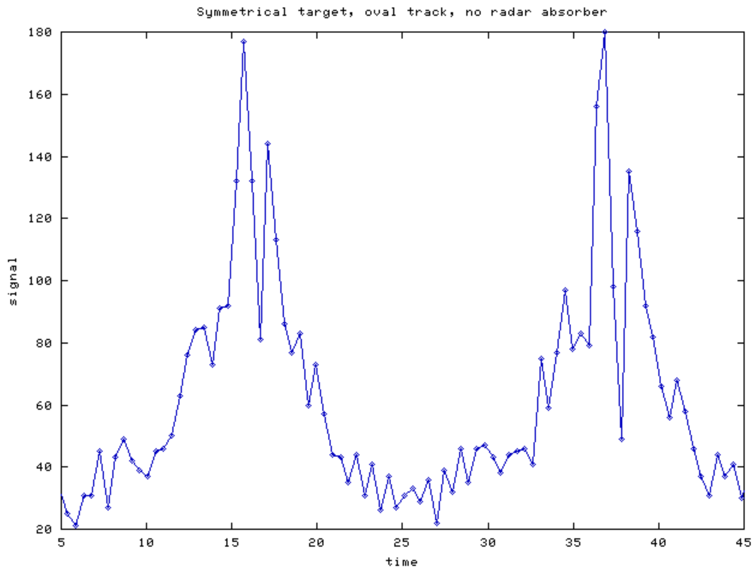


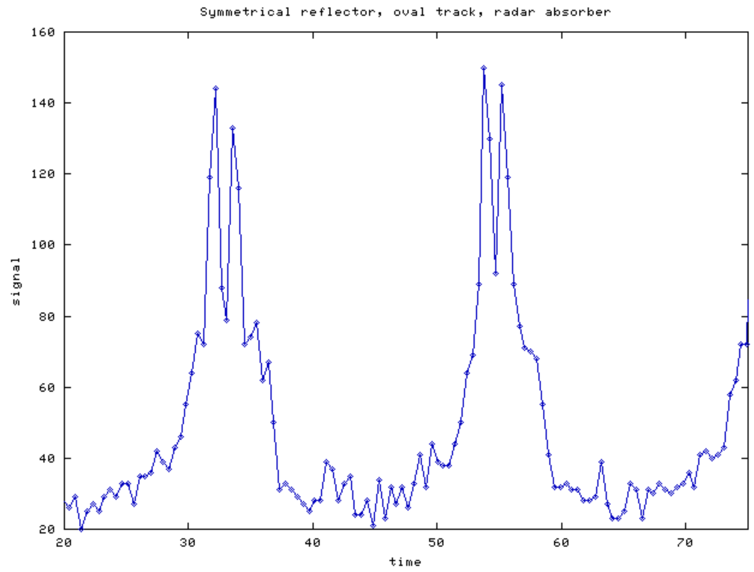




Calibration Results: Spherical Reflector

- Spherical reflector
  - still observe troughs
  - probably due to zero-radial velocity
  - target wobble can also affect signal





In-Situ Calibration

- Measure signal as target moves along known track
  - measure sector 0 on all sensors, then sector 1, then sector 2
- Fit signals to K exp(θ^2/A)/R^γ for each sensor & sector
  - for K, A & γ
- Some sector deliberately unused due to known reflection problems

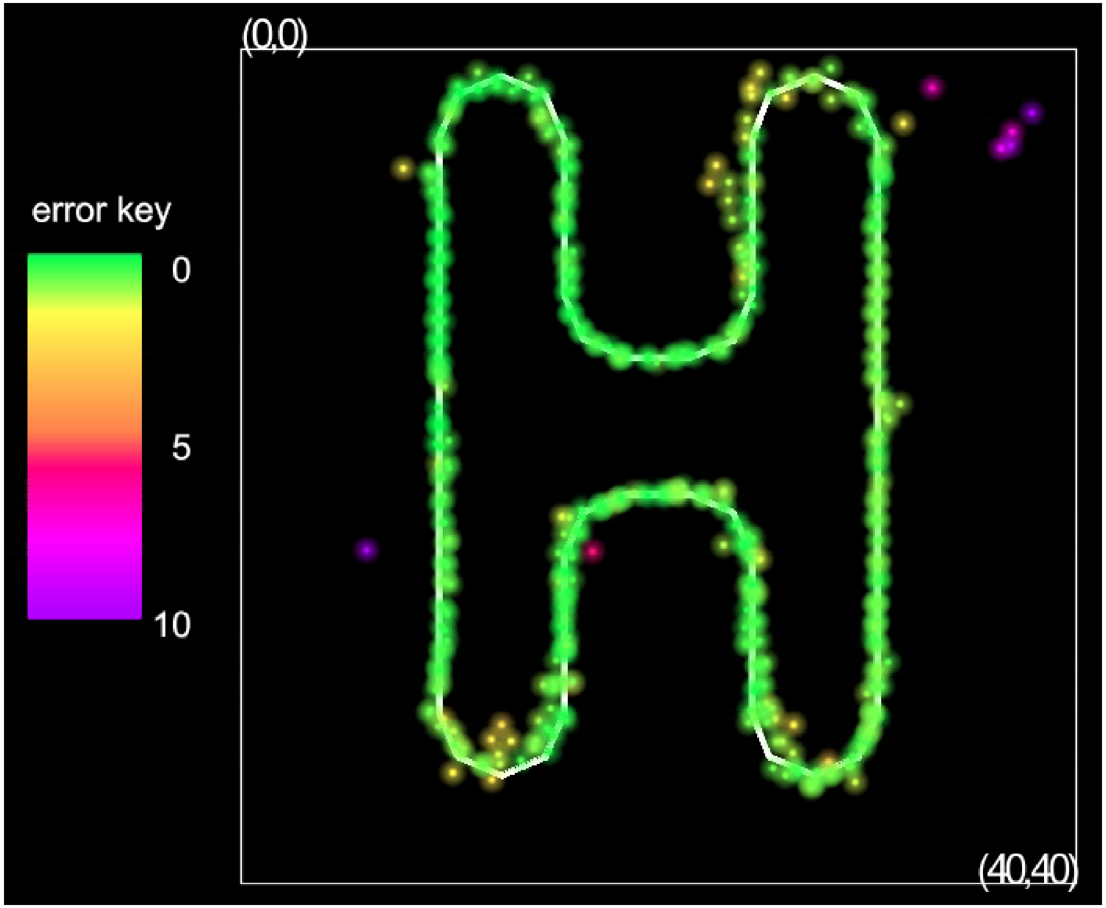
Node	0			1			2			3		
Sector	0	1	2	0	1	2	0	1	2	0	1	2
K/1000	27.1	7.8		12.2	3.5			3.5	13.2	27.0		11.2
A/1000	0.3	1.8		1.4	2.2			1.1	0.9	1.0		1.5
γ	2.0	2.0		2.4	2.0			1.8	2.2	2.4		2.2
Node	**4**			**5**			**6**			**7**		
Sector	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**
K/1000	1.6	32.3		2.1	45.5	88.9	11.8		7.6		17.9	46.1
A/1000	6.5	1.4		6.1	1.1	0.6	1.5		1.5		1.5	1.2
γ	1.5	2.7		1.6	2.9	3.0	2.0		2.0		2.0	2.8

results from Mitre lab.

	K/1000	A/1000	γ
min	1.6	0.3	1.5
mean	21.1	1.8	2.2
max	88.9	6.5	3.0

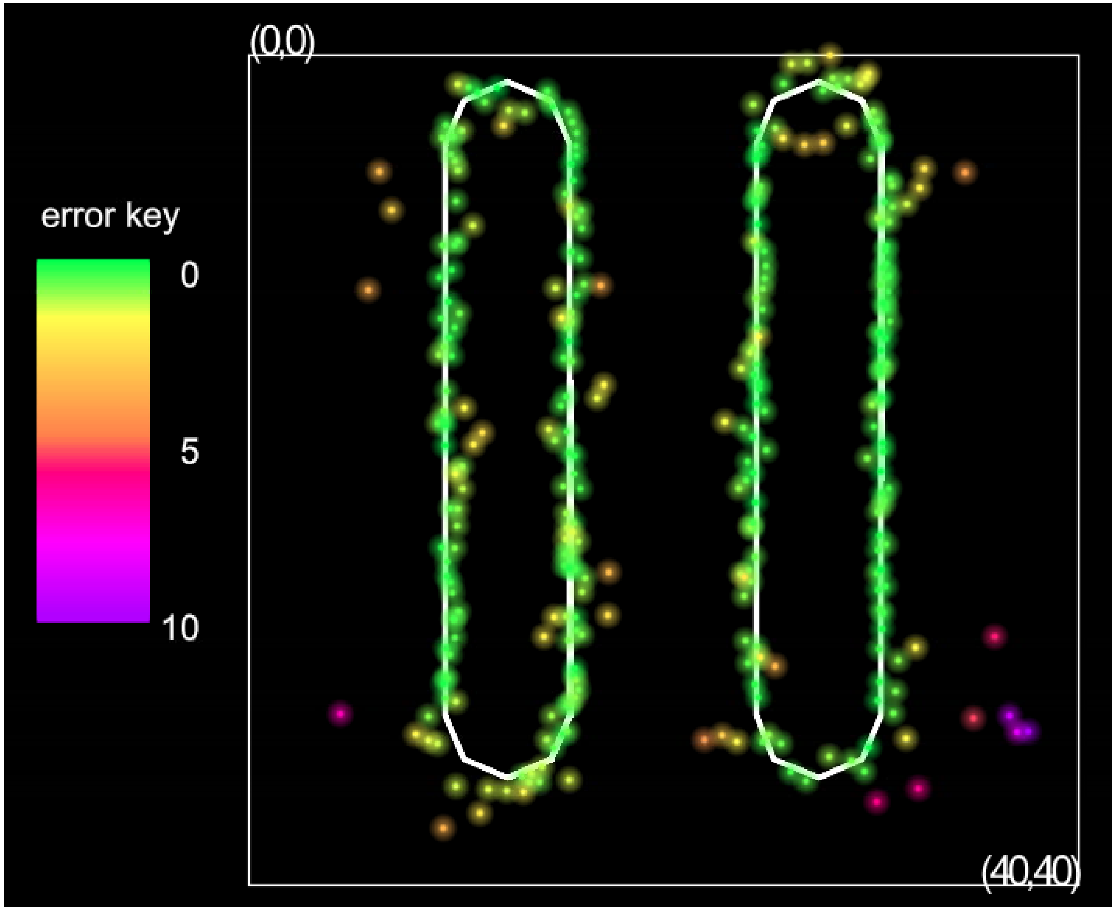
ranges

Results with Simulator: Single Target



- Mean track period = 2.0 seconds
- R.M.S. error = 1.6 feet
  - computed by projecting ground-truth to the time of each track point
  - Y1 result: 3.1 feet
- Mean power usage = 53%
  - should be able to achieve better
  - (beam seconds in RadSim log indicate ~20% usage)
  - Y1 result: 27%
- Communication usage = 0.48 messages per node per second

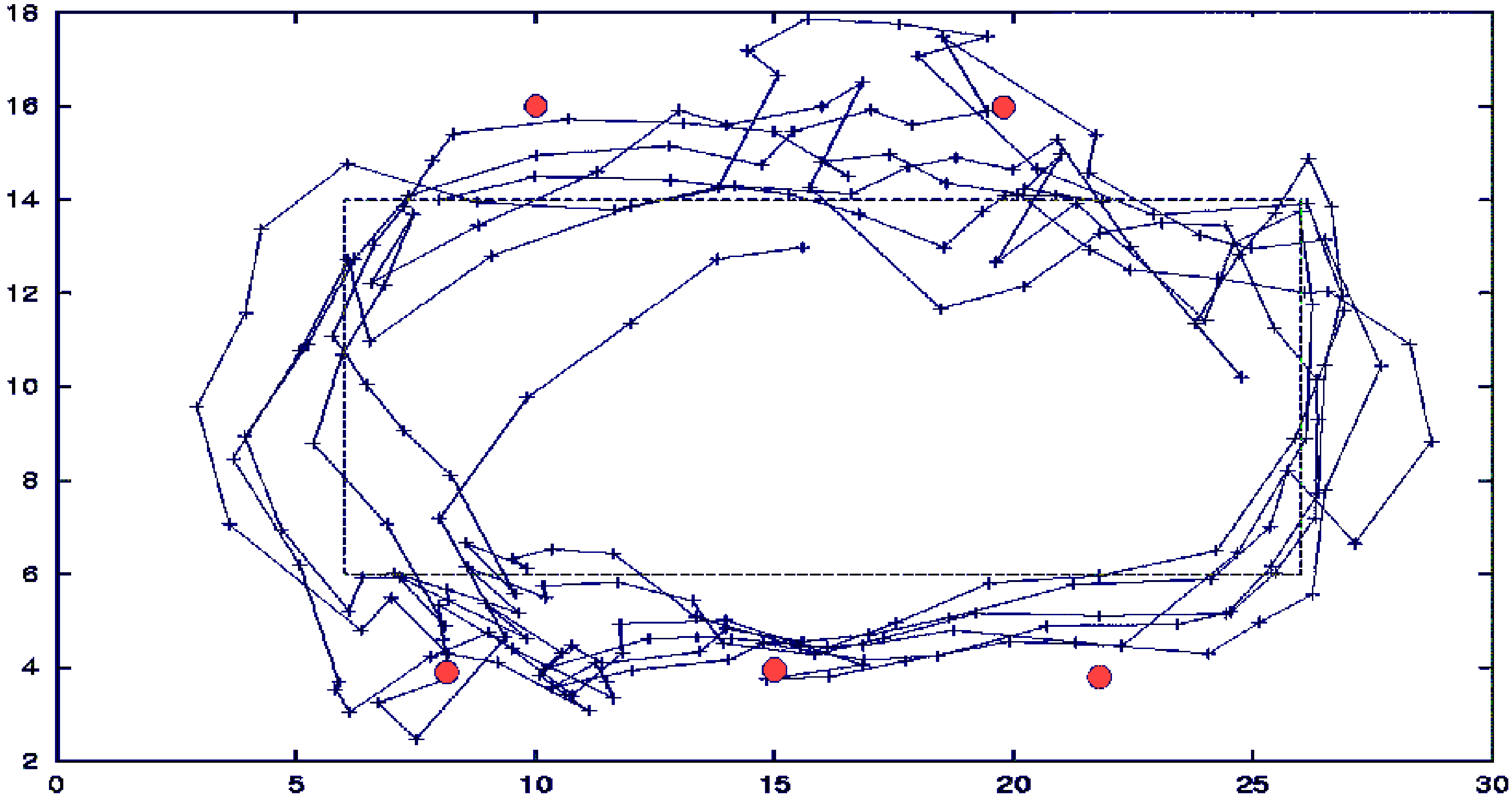
Results with Simulator: Two Targets



- Tracked simultaneously
- Mean track period per target
  - config 1: 1.1 seconds
  - config 2: 2.0 seconds
- R.M.S. error
  - config 1: 2.3 feet
  - config 2: 1.6 feet
  - each track point was assigned to the closer of the ground-truth targets
- Mean power usage
  - config 1: 53%
  - config 2: 61%
- Communication usage
  - config 1: 0.38 messages per node per second
  - config 2: 0.40 messages per node per second

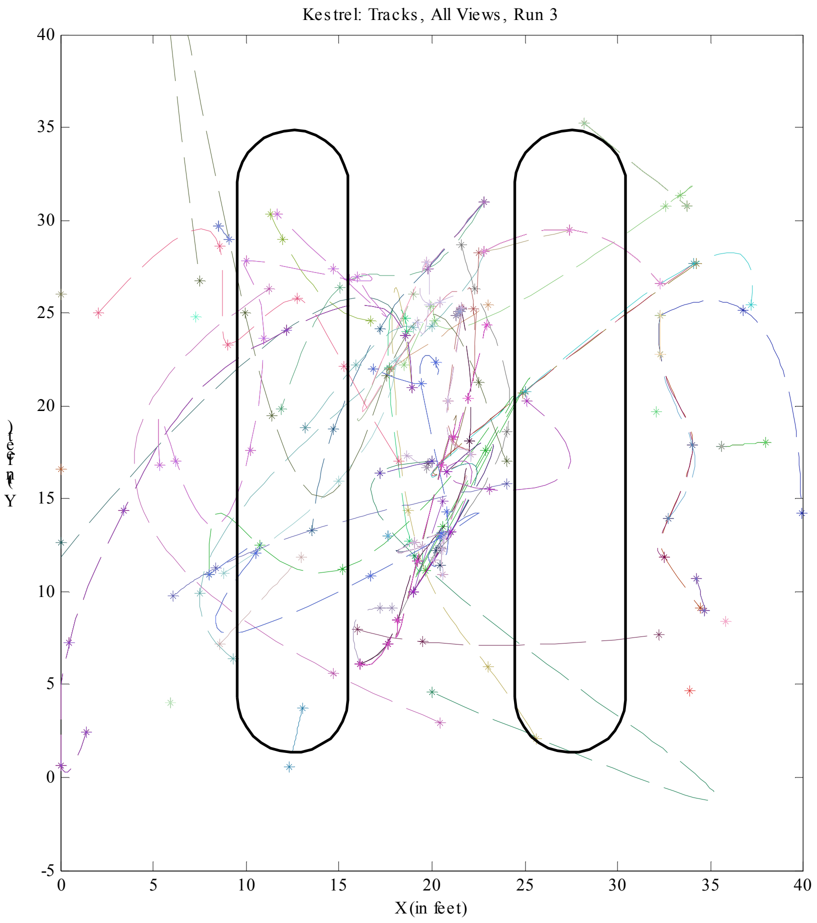
Results with Hardware at Kestrel

- Single target
  - 5 sensors, 400 seconds
  - this is the best performance, not typical



Results with Hardware at Mitre Lab.

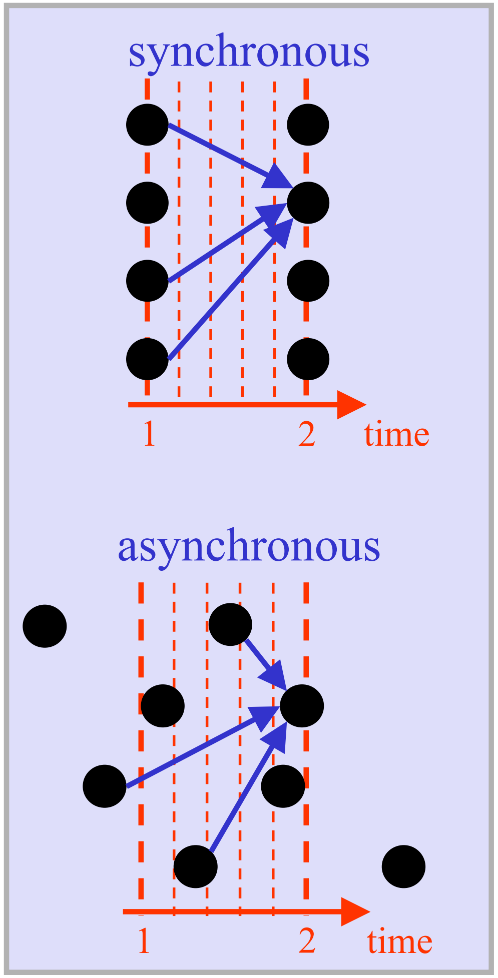
- Mitre experiments
  - 0.31 messages sent per node per second
  - 21.4 bytes sent per node per second
    - not including system headers
  - 64% power usage
    - where 100% = 3 beams
- Tracking poor
  - many, many tracks generated
  - measurement noise interfered with track-measurement association



Dynamics of Distributed Constraint Optimization

- Summary of previous work:
  - distributed graph colouring provides a clean benchmark for experimental assessment of distributed constraint optimization
  - essentially the same as the scheduling algorithm
  - metric being optimized (minimized) is the fraction of edges that are conflicts
    - i.e., that connect nodes of the same color
- Distributed, anytime coloring algorithm
  - each node chooses its own color
  - random initialization
  - stochastic loop in which each node chooses a color that minimizes its conflicts with its neighbors
    - informs its neighbors when its color changes
- Previously reported results for synchronous algorithm on sparse graphs
- What happens under other conditions? …

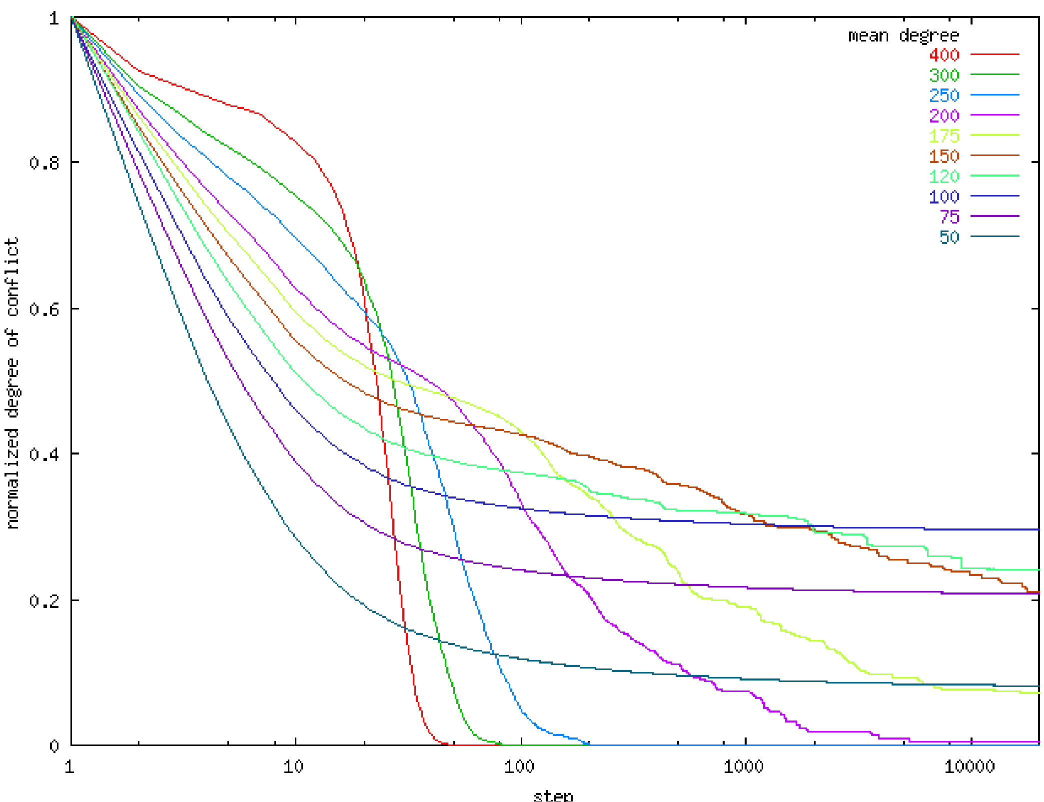
Asynchronous Coloring



- Is strict synchronization needed for coordination?
- Each node updates its color with a mean period P
  - nodes initialized with random phases
  - each node has random jitter in its period, causing relative phase between nodes to drift
- If the communication latency is less than P, each node has *more* up-to-date information than in synchronous coloring
  - improves convergence

Dense Graphs

- Density corresponds to interconnectedness of sensor network
- Generate k-colorable random graphs, given mean degree D
  - randomly assign k colors to N disjoint nodes
  - randomly generate DN/2 edges between nodes of different colors
  - remove colors
  - resulting graph has a chromatic number of no more than k
    - the chromatic number is likely exactly k



- Averages over 20 graphs
  - each 10-colorable
  - mean size ~2000
  - mean degree from 50 to 400
- Fluffy comparison
  - for D=400
  - number of steps for proper coloring ~30
  - activation probability = 0.3
  - equivalent to ~18000 color changes for all 2000 nodes
  - equivalent branching factor b for a back-tracking algorithm

    $b^{2000} = 18000 \Rightarrow b \approx 1.005$
  - don't take too seriously
    - not enough evidence yet

Plans

- Adapt experimental set-up to achieve convincing results on hardware
- Quantify effects of coordination using simulator
  - large scale experiments (e.g., 100 nodes)
  - compare with individual-sensor optimization
- Integrate S.C. tracker
- Extend results on dynamics
  - sparse graphs with local structure
  - compare distributed colorer with sequential colorer on dense graphs
- Develop new theoretical framework
  - position games – add dynamic strategies to games
- Investigate information theory for coordination metrics