Distributed Tracking in Sensor Networks

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Motivation

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- Original DARPA Distributed Sensor Networks (DSN) program focused on tracking as application

- Tremendous advances in sensors, processors, and communication over last 20 years

TRSS Node

Crossbow

Ember

Sensoria

Dust, Inc.

- Need distributed tracking algorithms to fully exploit potential of sensor networks

Outline

- Tracking in sensor networks
- Distributed tracking issues
- Distributed estimation – single target tracking
- Distributed data association – multiple target tracking
- Research areas and conclusions

Tracking Problem in Sensor Networks

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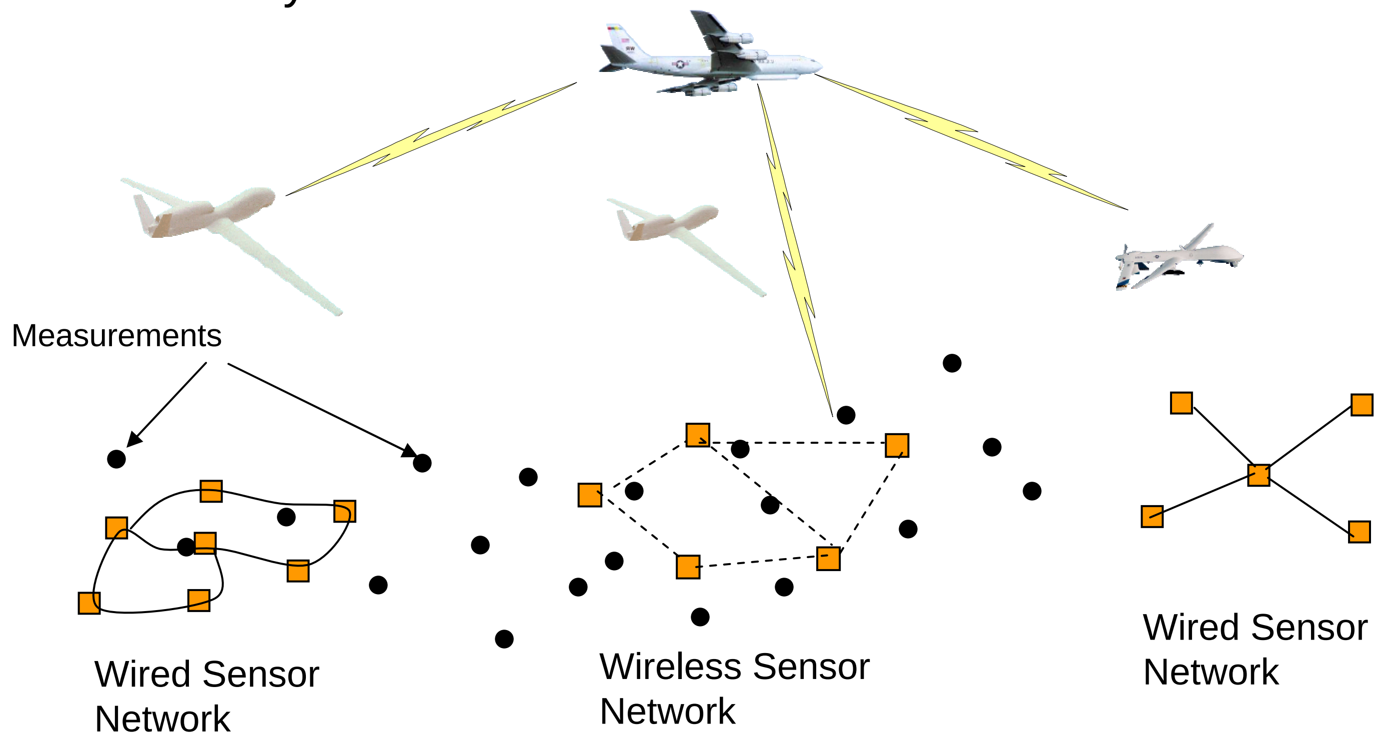
- Estimate state – where are targets
- Associate measurements (for non-cooperative targets)
  - How many targets
  - Where did they come from



Large Sensors versus Small Sensors

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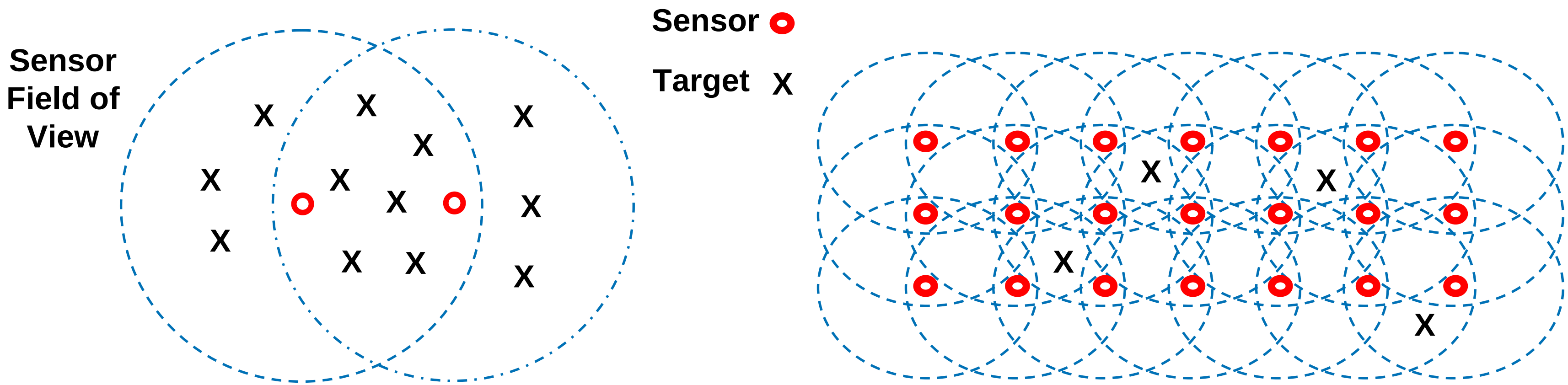


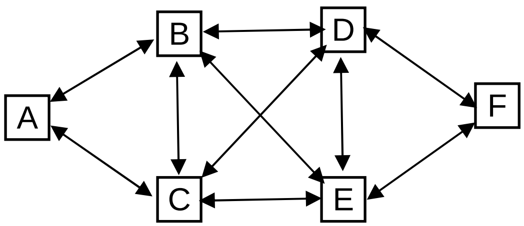
- Large sensors
  - Small number of sensors with large field of view
  - Target density > sensor density
  - Long target residence time in FOV
  - Energy basically unconstrained
  - Example: Cooperative Engagement Capability (CEC)
- Small sensors
  - Large number of sensors with small field of view
  - Sensor density > target density
  - Short target residence time in FOV
  - Energy constrained
  - Example: Unattended Ground Sensors (UGS)

Distributed Tracking

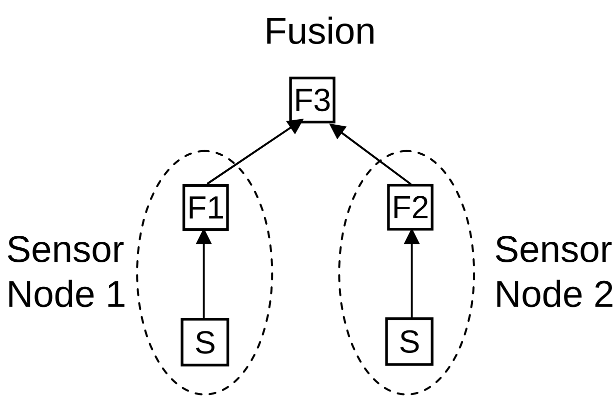
- Advantages over centralized tracking
  - Reduce communication bandwidth
  - Distribute processing load
  - Increase robustness and survivability
- General technical issues
  - Estimation – avoid double counting of information
  - Association – maintain consistent track identities (numbers), e.g., Common Operating (Tactical) Pictures, Single Integrated XX Picture
- Issues specific to small sensors
  - Energy consumption (for sensing and processing)
  - Communication bandwidth

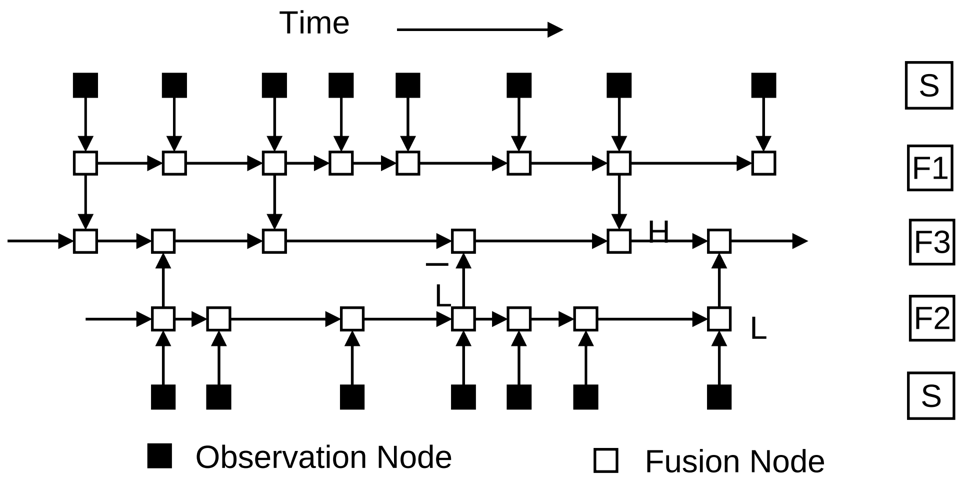
Multiple Information Paths

- Multiple information paths are common in distributed architectures
  - Multiply connected sensor network – obvious



  - Hierarchical network – not so obvious



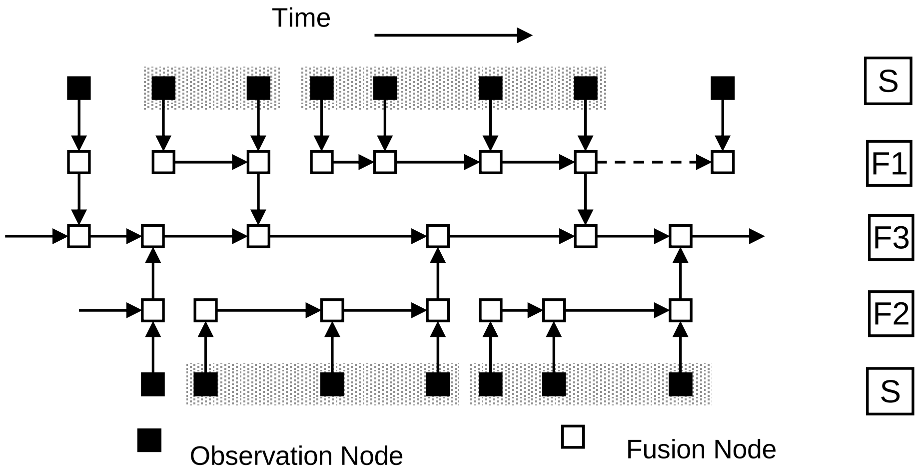


Approaches to Avoid Double Counting

- Maintain information pedigree to identify and remove common information
  - Require more communication and processing

$$p(x \mid Z_1 \cup Z_2) = C^{-1} \frac{p(x \mid Z)\, p(x \mid Z_2)}{p(x \mid Z_1 \cap Z_2)}$$

- Design architecture to ensure single fusion path for each measurement
  - Pseudo-measurements or tracklets, decentralized Kalman filters



Distributed Data Association

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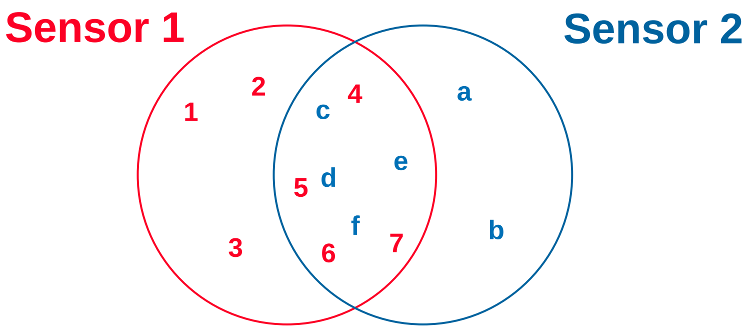
- Given tracks from each sensor node, what is total number of targets?



- Association problem complicated by
  - Processing imperfection and communication latency – same data may give different results
  - Sensor biases
- Important problem in net-centric operations, e.g., Single Integrated Air Picture (SIAP)

Approaches for Distributed Data Association

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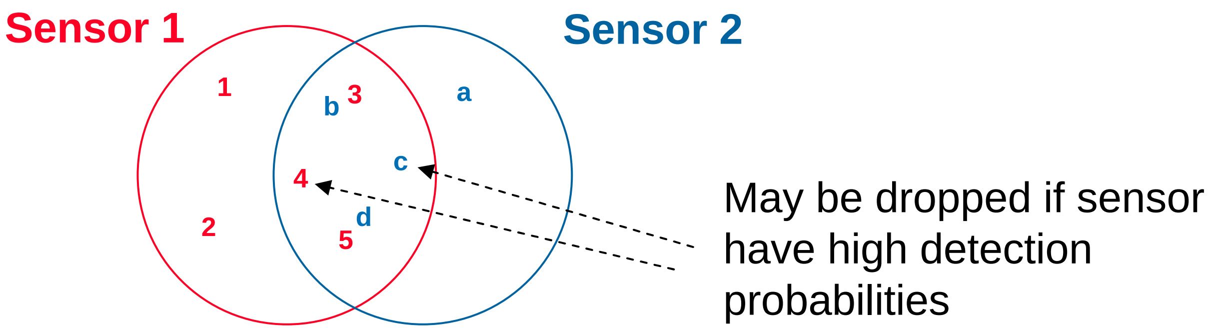
- Optimal assignment
  - Select assignment to minimize cost, e.g., sum of chi-squared distances between tracks
  - Consider detection probability of each sensor in associating unpaired tracks



- Association responsibility
  - Each measurement is associated to tracks by sensor with reporting responsibility
  - Other nodes accept association decisions
  - CEC approach

Tracking with Networks of Small sensors

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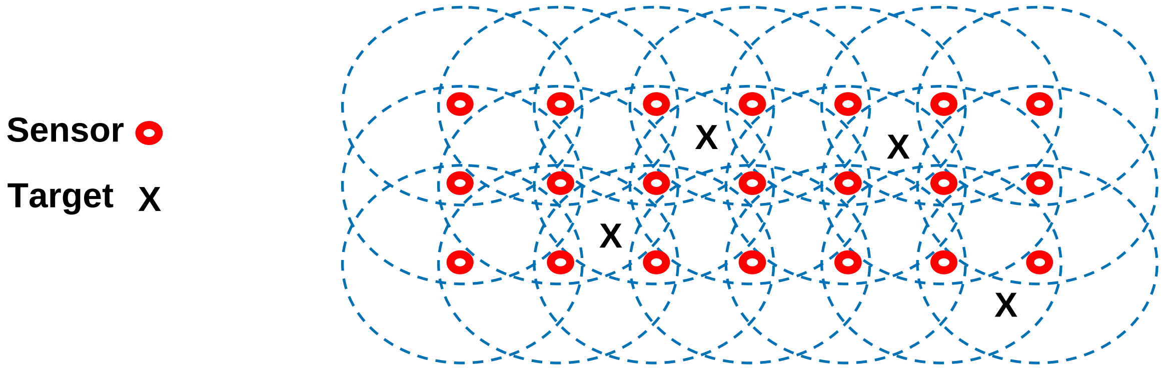

- Characteristics
  - Large number of small sensors with small field of view
  - Sensor density > target density
  - Each sensor may observe target for short time
  - Sensors may be inactive most of the time
  - Communication may require more energy than sensing and processing
- Tracking issues
  - Centralized processing at fixed location may not be practical
  - More measurements may not be better than fewer measurements with energy constraints

Tracking Single Target

- Same problem as tracking widely separated multiple targets – data association is not an issue
- Need to reduce communication bandwidth and energy consumption

- Basic steps in tracking
  - Prediction

$$P(x(t_k) \mid Z_{k-1}) = \int P(x(t_k) \mid x(t_{k-1}))P(x(t_{k-1}) \mid Z_{k-1})dx(t_{k-1})$$

    - No communication is needed

  - Update

$$P(x(t_k) \mid Z_k) = C^{-1}P(z(t_k) \mid x(t_k))P(x(t_k) \mid Z_{k-1})$$

    - Requires communication of sensor measurement

Reducing Communication Cost in Update

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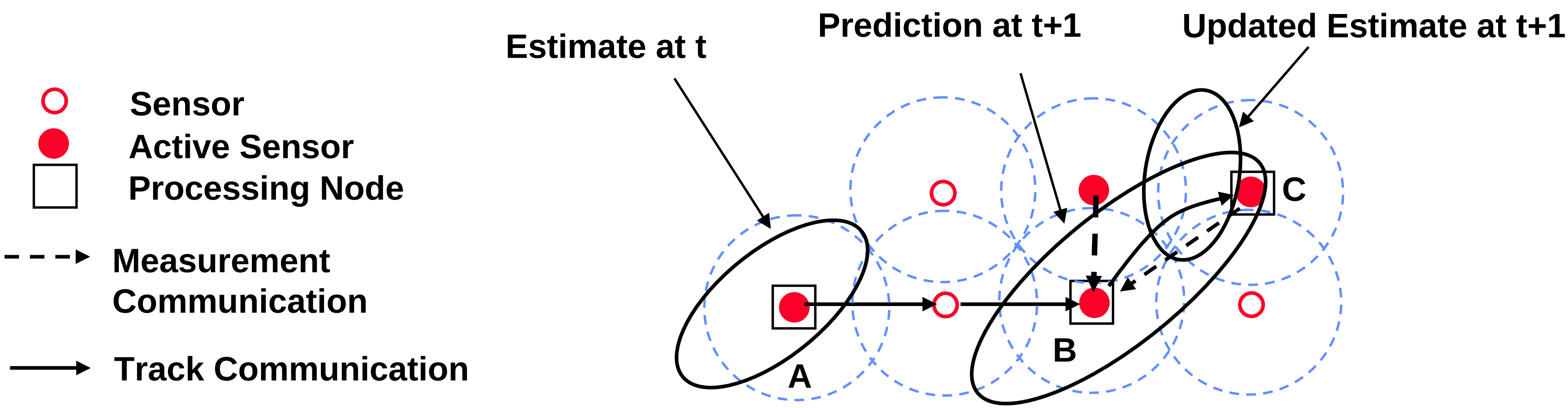
- Reduce number of measurements
  - Many redundant measurements in dense sensor network
  - Little incremental information value from some measurements
  - Will also reduce energy used in processing
- Migrate track processing with movement of target
  - Processing should be close to sensors generating measurements
  - Multi-hop communication not needed
  - Also remove double counting problem
- Still need gateway to communicate results

Migrating Track Processing

- Initiation
  - First sensor to detect target becomes processing node and initiates track
  - Processing node suppresses other neighboring sensors from making more measurements, thus conserving their energy
- Prediction
  - Processing node predicts target state estimate at next measurement time
  - Sensor node whose coverage has most overlap with predicted state is chosen as next processing node
  - Track state is moved to next processing node
- Sensing
  - Processing node selects sensors to generate next measurements and tells other sensors to stay dormant
- Update
  - Observed measurements are sent to processing node to update state estimate

Energy Efficient Distributed Single Target Tracking



A: Processing node after update at t
B: Processing node after prediction at t+1
C: Processing node after update at t+1

- Track state is maintained by only one node at any time
- No need for track fusion or handling of double counting
- Essentially centralized processing with processing node following target
- Multiple processing nodes handle multiple targets

Tracking Multiple Targets

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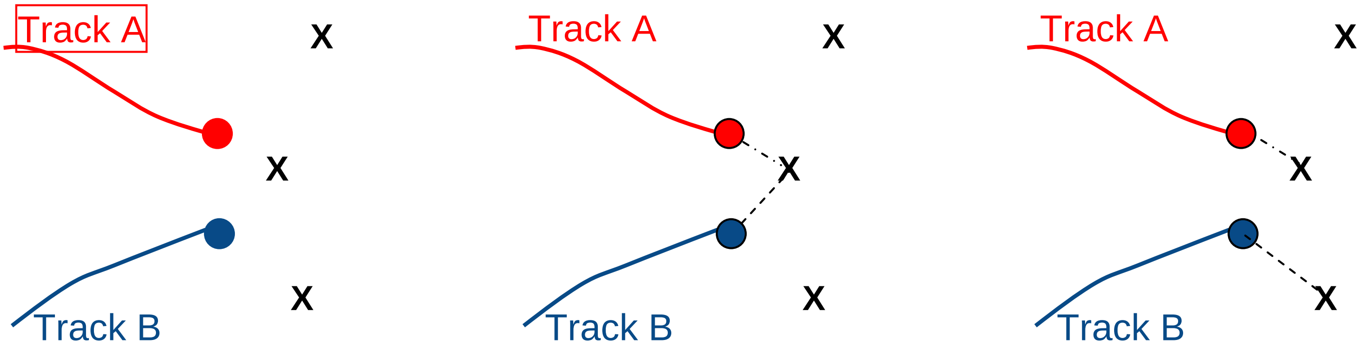
- Association problem
  - Crucial when target density is high relative to sensor error
  - Association is generally computationally intensive
  - Association operations are difficult to distribute or parallelize



Distributed Nearest Neighbor Assignment

Global Nearest Neighbor Assignment

Distributed Processing Architecture

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- Partition sensor nodes into clusters based on need for coordinated data association
- Two level processing architecture
  - State estimation for individual tracks
    - Individual tracks assigned to sensor nodes based upon proximity of sensor nodes to estimated state
    - Some nodes may be responsible for multiple tracks
  - Data association for cluster
    - Nodes within cluster elect a node to be responsible for data association
    - Load balancing may be needed to make sure that “leader” node (cluster processing node) is not overloaded

Cluster Processing Migration in Multi-Target Tracking

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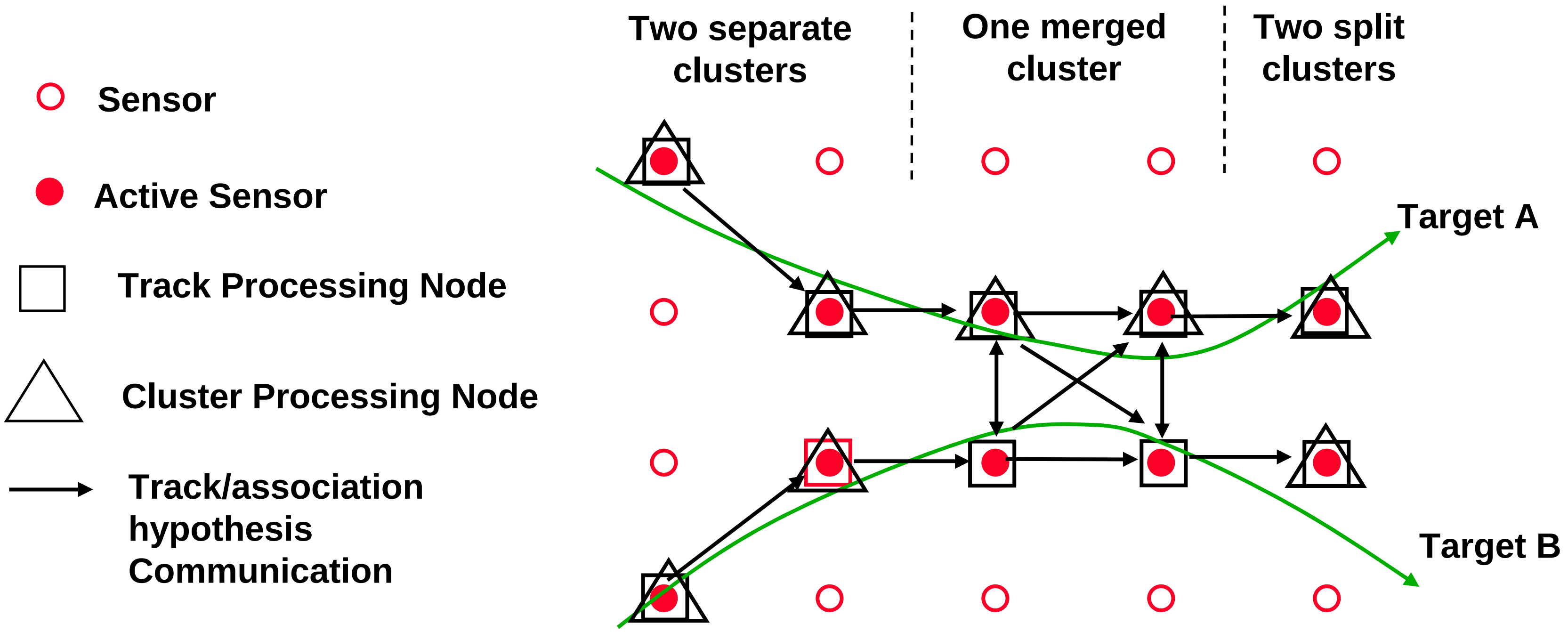
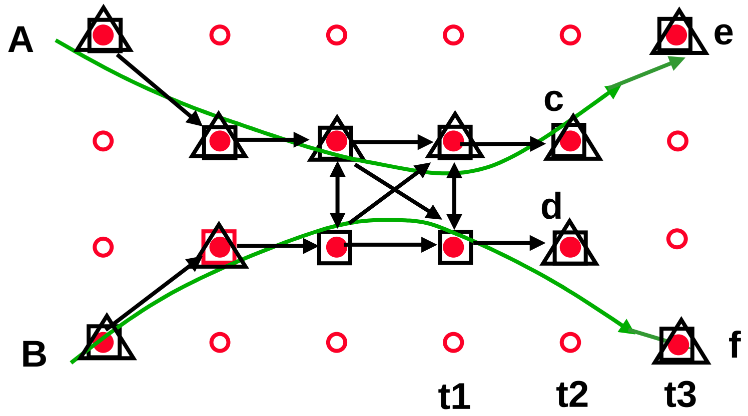


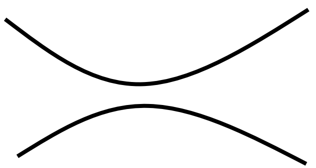
- Parallel processing across clusters
- Centralized processing within cluster
- Cluster processing nodes migrate with cluster
- Track processing nodes migrate with track states

Distributed Multiple Hypothesis Tracking (MHT)

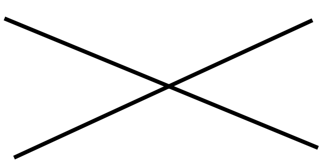
- Multiple hypothesis tracking defers association decision when there is confusion
- Time t1
  - Prob(H1) = 0.7
  - Prob(H2) = 0.3
- Time t2
  - Prob(Track_at_c = A) = 0.7
  - Prob(Track_at_d = B) = 0.7
- Time t3
  - Node e observes feature that associates track with A
  - Prob(Track_at_e = A) = 1.0
  - Information needs to propagate to Node f to update Prob(Track_at_f = B)



Hypothesis H1



Hypothesis H2



Some Distributed Data Association Research

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- Distributed target identity management (Shin, Guibas, Zhao, Liu, Reich)
  - Identity belief matrix to represent identity information of track
  - Distributed algorithm for updating identities across nodes
- Graphical models for distributed data association (Chen, Cetin, Willsky)
  - Zero-scan and N-scan associations
  - Communication sensitive message passing
- Tracking on graphs (Oh, Sastry)
  - Network of binary sensors
  - Hidden state estimation problem solved by Viterbi algorithm
- Distributed multiple target tracking and identity management (Oh, Hwang, Roy, Sastry)
  - Markov Chain Monte Carlo (MCMC) data association
  - Information-theoretic identity management

State-of-the-Art in Distributed Tracking

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- Distributed tracking for large sensor networks has been investigated for over twenty years
  - Significant progress with operational systems such as CEC
  - Many challenging problems still remain
- Distributed tracking technology for large networks are still applicable to small sensor networks but
  - More data is not necessarily better with energy and communication constraints
  - Fusion of data from multiple sensors may become less important
  - Processing should migrate with target
- Small sensor networks have stimulated research in distributed tracking
  - Initial emphasis on single target tracking
  - Recent results address multiple targets and data association
  - More communication with traditional tracking community will be beneficial

Some Research Areas

- Sensor registration (location and other biases)
- Distributed data association that adapts to resource constraints and information content
  - Group versus individual tracking
  - Knowing when situation is too confusing
- Resource management
  - Trade-off between sensing, processing and communicating
  - Information driven and resource constrained
- Cooperative status assessment – detecting sensor failure
- Representations and algorithms to exploit dense networks
- Seamless operation of heterogeneous (large and small) sensor networks
  - Multi-resolution (spatial and temporal) representations
  - Plug and play interfaces
- Challenge problems and MOPs to drive research and evaluate algorithms

Conclusions

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- Tracking is important application for sensor networks
- Distributed tracking is crucial given communication and processing resource constraints
- Two decades of research has addressed distributed tracking for networks of large sensors
- Distributed tracking for networks of small sensors can exploit existing results
- Research is needed to address sensing, processing and communication constraints
- Integration of tracking with resource management is essential