Sensor Networks

Part 4: Networking Challenges and Design

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Networking Challenges and Design Principles

- Localization
- Synchronization
- Coverage
  - Device management and scheduling
  - Connectivity (topology) maintenance
- Routing
- Reliable Data Transport

Localization and Synchronization

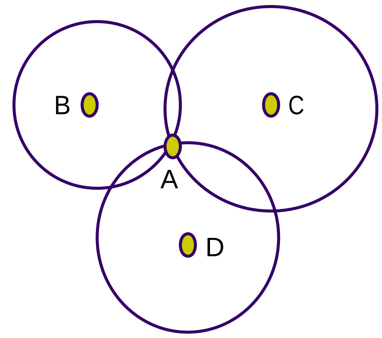
- Accurate localization and synchronization
  - Need to determine where events occur in space
  - Critical for fusion of sensor measurements
  - Important for coordination of communication
- GPS provides one solution
  - Not always available
  - Can be too costly, bulky

Localization

- Most techniques use recursive trilateration/multilateration
- Some nodes are assumed to know their position (through GPS for instance).
- These act as beacons by periodically transmitting their position
- Nodes hearing these beacons use them to estimate their position
- May be an iterative process

Localization

- Fine-grained (timing/signal strength) or coarse-grained (proximity)
- Fine-grained
  - Time of flight
  - Signal strength
  - Signal pattern matching
  - Directionality
- Coarse-grained
  - Centroid of beacons



Trilateration

Localization Challenges

- How many beacons are needed?
  - Provide good coverage, avoid excessive interference
- Where should beacons be placed?
  - Incremental beacon placement
    - Place new beacon in region of maximum (average) localization error
- Controlling beacons
  - Scheduling operation to preserve lifetime

Synchronization

- Metrics
  - Precision
    - Peer dispersion or with reference to external standard
  - Lifetime
    - Ranging from persistent to instantaneous
  - Scope and Availability
    - Geographic span and completeness of coverage
  - Efficiency
    - Time and energy expenditure
  - Cost and form factor

Sensor Network Synchronization

- Fine-grained, persistent timing is important in sensor networks
  - Data fusion
    - detect/estimate the same event
  - Local data processing
    - Eliminate duplicates through timestamping
- Existing network timing protocols inadequate
  - Often conservative in use of bandwidth (e.g., NTP) but neglect cost of listening
  - Heterogeneity of hardware
  - Multiple methods of synchronization should be available
  - Algorithms should be tunable (precision vs. energy)

Coverage

- Measures of coverage
  - Area coverage : fraction of area covered by sensors
  - Detectability : probability sensors detect event
  - Node coverage: fraction of sensors covered by other sensors
  - Maximal breach path : intruder is maximum distance from sensors over entire path
  - Maximum exposure path : minimum distance from sensors over entire path
  - K-coverage : entire sensing region must be within distance K of a sensor

Coverage

- Maintenance
  - Where to position sensors initially?
  - Where to add new sensors?
  - Where to move sensors?
  - When to schedule sensors? (overlapping sensors should not operate at same time)
  - Locate coverage holes, breach areas, best areas.

Coverage – Node Scheduling

- Turn off redundant nodes
  - Extend system lifetime
  - Maintain reliability and coverage/detectability
  - Rotate active sensor set
- Optimal Schedules
  - Possible to find optimal schedules, but
  - Requires global knowledge -> much communication
  - Not robust to changes of network state
- Distributed approaches
  - Topology control: select active routers
  - Sensor mode selection: select active sensors

Topology Control

- Goals
  - Ensure that devices are activated so that all sensors can route data to sink(s)
  - Allow non-selected devices to sleep
  - Rotate active routers to balance energy
  - Ensure robustness: sensor losses do not disconnect the network
- Example protocols:
  - Geographic Adaptive Fidelity (GAF)
  - Span
  - Adaptive Self-Configuring Sensor Network Topologies (ASCENT)
  - Sparse Topology and Energy Management (STEM)

Topology Control Examples

- Geographic Adaptive Fidelity (GAF)
  - Overlay virtual grid over network
  - Activate only one device per cell in grid
- STEM
  - Reactively turn on routers when sensors need to send data
  - Paging channel used to wake up neighbours
  - A wake-up message – tone or beacon

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Sensor Mode Selection

- Goal
  - Select sensing modes (active/inactive, frequency, resolution) to ensure network objectives achieved
    - Example criteria: K-coverage, minimum tracking accuracy, maximum missed detection probability
  - Allow non-selected sensors to sleep
- Example Protocols
  - Probing Environment and Adaptive Sleeping (PEAS)
  - Node Self Scheduling Scheme (NSSS)
  - Coverage Configuration Protocol (CCP)

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Sensor Mode Selection Protocols

- PEAS
  - Goal is to provide consistent coverage and robustness to node failure
  - Nodes send "probe" messages to neighbours
  - If no replies, the node becomes active, otherwise sleeps.
  - Probing range chosen to meet transmission and sensing coverage
- CCP
  - Node determines the intersection points of neighbours' sensing radii and the edge of sensed area
  - If all intersection points are K-covered, node can sleep.

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Joint Sensor Selection and Topology Control

- Find minimum set of sensors and routers to efficiently process a query
- Connected Sensor Cover (CSC)
  - Set of active sensors
  - Each sensor calculates how much coverage it would add and how many additional routers it would require if added to the set
  - Add sensors in greedy fashion to active set
  - Continue until desired level of coverage attained

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Routing

- Routing Challenges
  - Node deployment
  - Time-critical applications
  - Node/link heterogeneity
  - Fault tolerance
  - Scalability
  - Network dynamics – environment and nodes
  - Connectivity and coverage

Routing

- Categories of Routing
  - Data-centric
  - Hierarchical
  - Location-based
  - QoS-aware

Data-centric routing

- Sensor networks can be considered as a virtual database
- Implement query-processing operators in the sensor network
- Queries are flooded through the network (or sent to a representative set of nodes)
- In response, nodes generate tuples and send matching tuples towards the origin of the query
- Intermediate nodes may merge responses or perform aggregation.

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Data-centric routing

- Example protocols
  - Directed Diffusion
  - Sensor Protocols for Information via Negotiation (SPIN)
  - GRAdient Broadcast (GRAB)
  - Rumour Routing
- Protocols can be event-driven or query-driven

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Directed Diffusion

- Protocol initiated by destination (through query)
- Data has *attributes* ; sink broadcasts *interests*
- Nodes receiving the broadcast set up a gradient (leading towards the sink) and cache the interests
- When data are sensed whose attributes match a cached set of interests, a path to sink has been constructed.
- GRAB extends Directed Diffusion by restricting messages to minimum-cost path

Rumour Routing

- Goal is to avoid expensive flooding operations
- Combination of event-driven and query-driven
- Each node:
  - maintains a neighbour list and an event table
  - Adds observed events to event table
  - Generates an agent with some probability
- Agent
  - Long-lived packet that roams network carrying event-list
  - Synchronizes event-list with nodes it traverses
  - Dies after fixed number of hops
- Querying
  - If a node does not know the route for a query, it sends it to a random neighbour
  - Flooding is last resort

Hierarchical Routing

- Organize nodes into clusters
- Cluster head acts as scheduler, router to other clusters, aggregator and processor
- Challenges
  - How do you form clusters initially? How is the cluster head selected?
  - How do you maintain clusters as network state and connectivity changes?
  - How do clusters communicate?

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Protocols

- LEACH
- PEGASIS
- TEEN and APTEEN
- MECN
- SOP
- Sensor Aggregates Routing
- Virtual Grid Architecture Routing
- Hierarchical Power-aware Routing
- Two-tier Data Dissemination

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LEACH

- Low-energy Adaptive Clustering Hierarchy
  - Sensor nodes elect themselves as cluster-heads with some probability
  - Other nodes join cluster based on maximum received signal strength (minimum communication energy)
  - Local cluster-heads used as routers to base station (sink)
  - Cluster-heads create a schedule for their local nodes
  - Cluster-head role changed to balance energy

PEGASIS and TEEN

- PEGASIS
  - No cluster formation
  - Requires that all nodes can directly communicate with base-station
  - Neighbours transmit to each other and take turns transmitting to base-station
- TEEN
  - Time-critical applications
  - Nodes continually sense medium but only send when their sensed attribute changes
  - Cluster-heads determine thresholds for transmission

Location-based Routing

- Sensor nodes addressed according to their locations
- Distance between nodes measured by signal-strength
- Protocols
  - Geographic Adaptive Fidelity (GAF)
  - Geographic and Energy-aware Routing (GEAR)
  - Greedy Other Adaptive Face Routing (GOAFR)

Geographic Adaptive Fidelity

- Network divided into fixed zones that form a virtual grid
- Inside each zone, nodes collaborate (topology control and sensor selection)
- Handling mobility
  - Nodes estimate leaving time of a zone
  - Notifies neighbours

Reliable Data Transport

- Transport layer design is difficult because of application-specific nature of sensor networks
- Networking layers tend to become fused (particularly transport and application)
- Goal: design customizable transport layer
- Provide the primitives for reliable transport
- Allow the network designer the flexibility to use them according to the application needs.
- Example: PSFQ (Pump slowly, Fetch Quickly)

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