A Comprehensive Framework for Dependable Nomadic Computing

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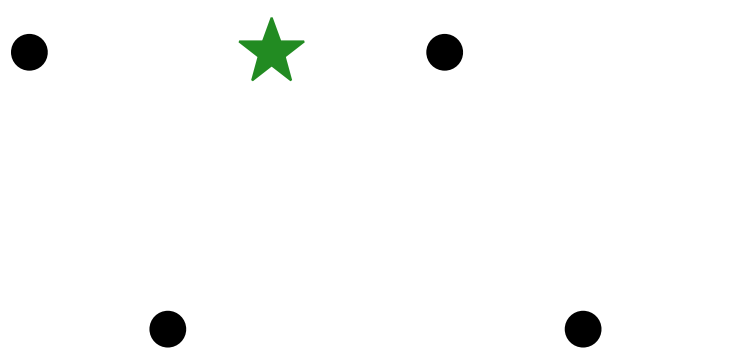
Dependable Nomadic Systems

- Nomadic systems pose many problems
  - Localization (Sextant, [Mobihoc 2005])
  - Programming Model (MagnetOS, [MobiSys 2005])
  - Routing (SHARP, [Mobihoc 2002])
  - Path Selection (DPSP, [Mobihoc 2001])
  - Simulation (SNS, [WSC 2003, TOMACS 2004])
  - ...
- Need to figure out the location of nodes in order to provide novel location-based services
- Need a new programming model for performing long-lived computations in mobile networks

Challenges in Localization



Hardware

- Expensive
- Power Consuming

Infrastructure

- Initial setup required
- Not always available

Modeling

- Irregular wireless coverage area
- Introduces error

Sextant Approach

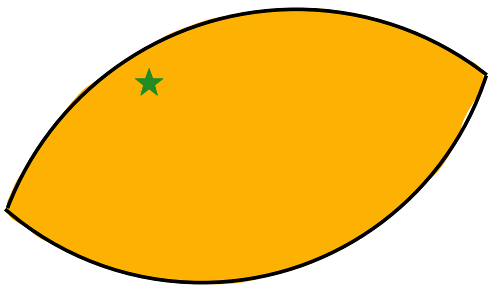
- Extract geometric constraints
- Disseminate them transitively
- Solve in a distributed manner

Sextant Approach

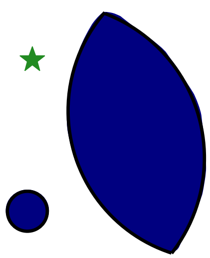
Contributions

- Unified Node and Event localization
- Accurate
  - Negative as well as positive information
  - Explicit representation
- Practical
  - Constraint extraction
  - Deployed on MICA-2 motes, laptops and PDAs

Sextant Approach



Positive constraint



Negative constraint

Contributions

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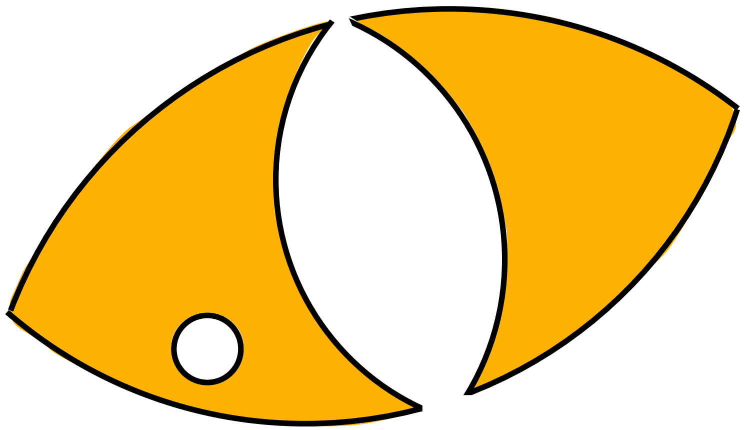
Sextant Approach



- Need not be convex
- May have holes
- May have disconnected components

Contributions

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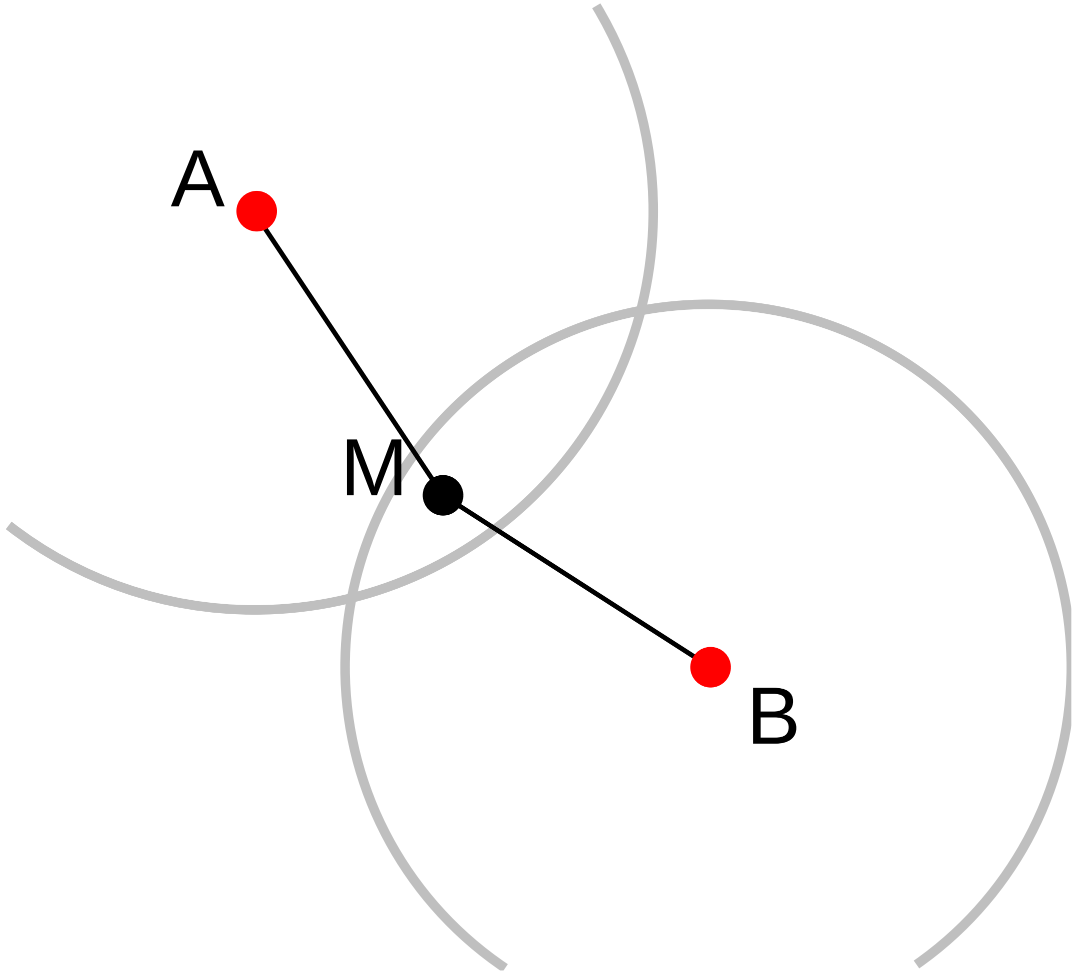
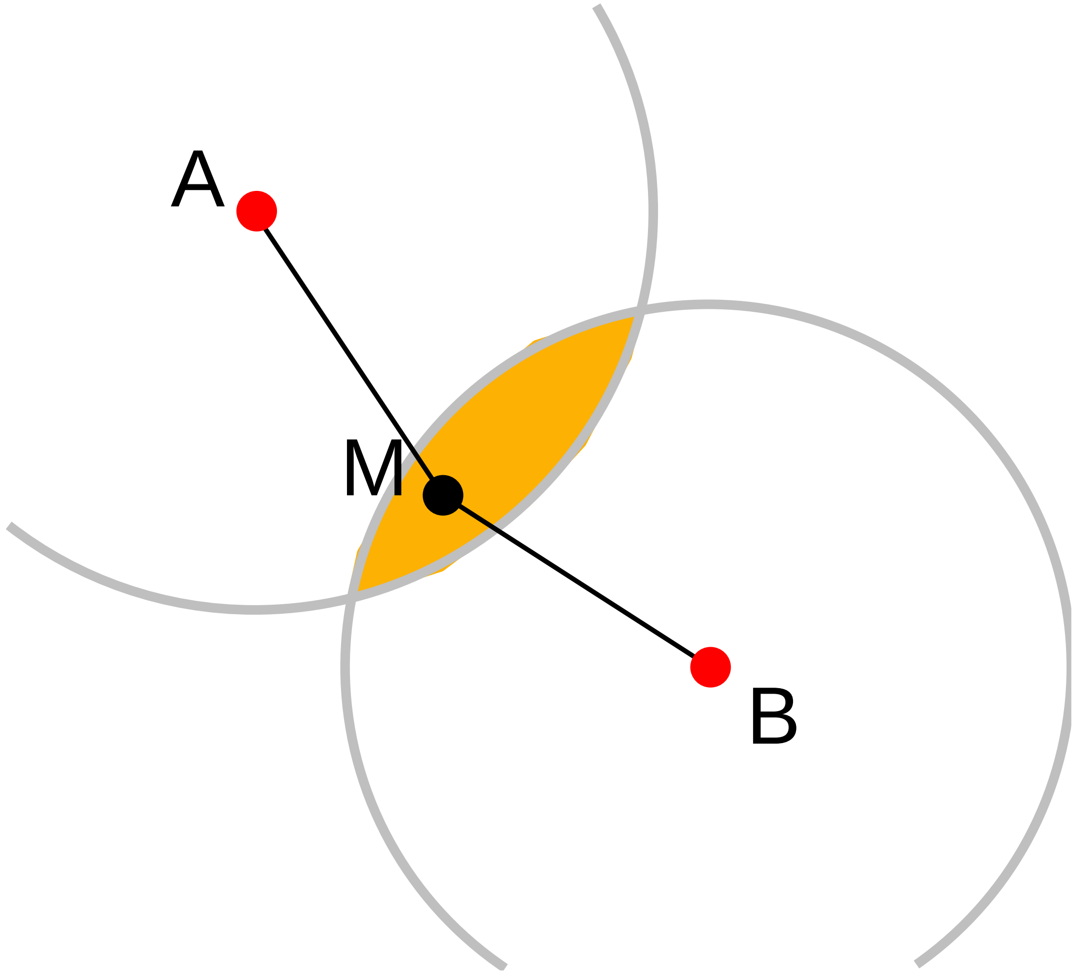
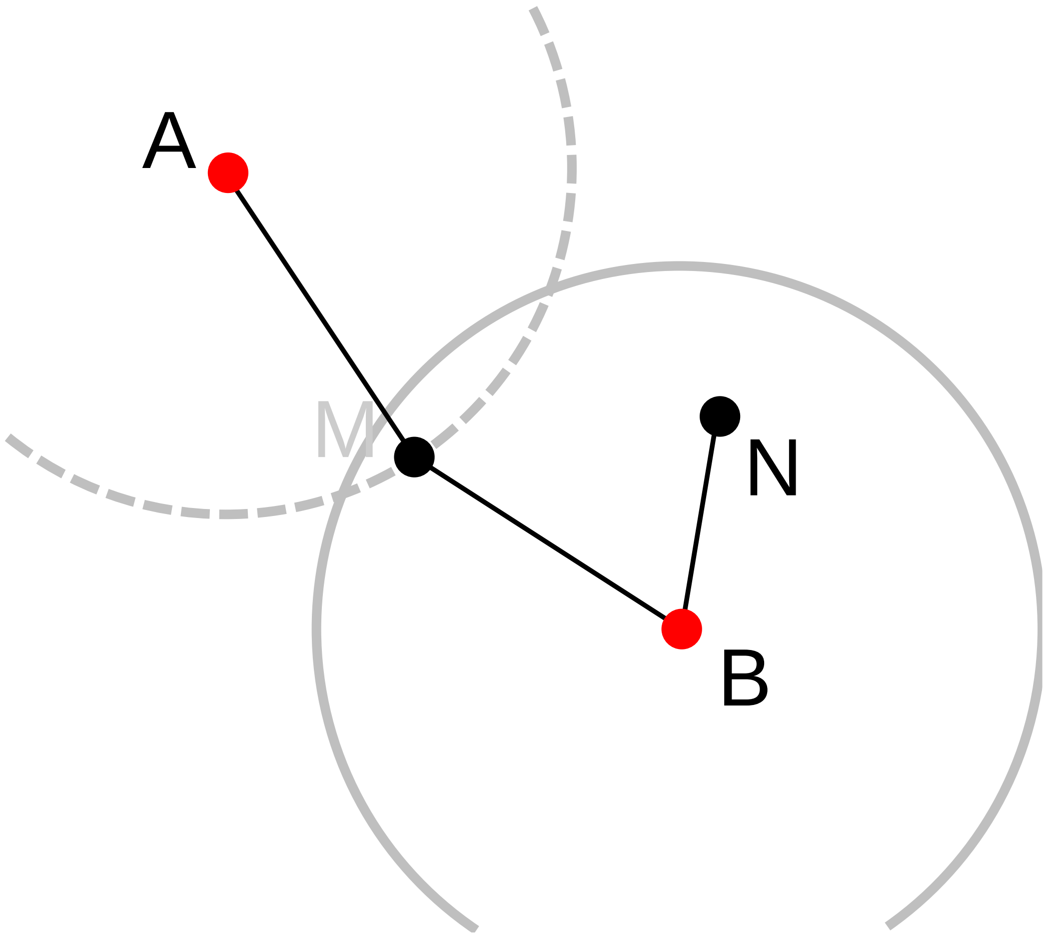


Positive Information

Node Localization

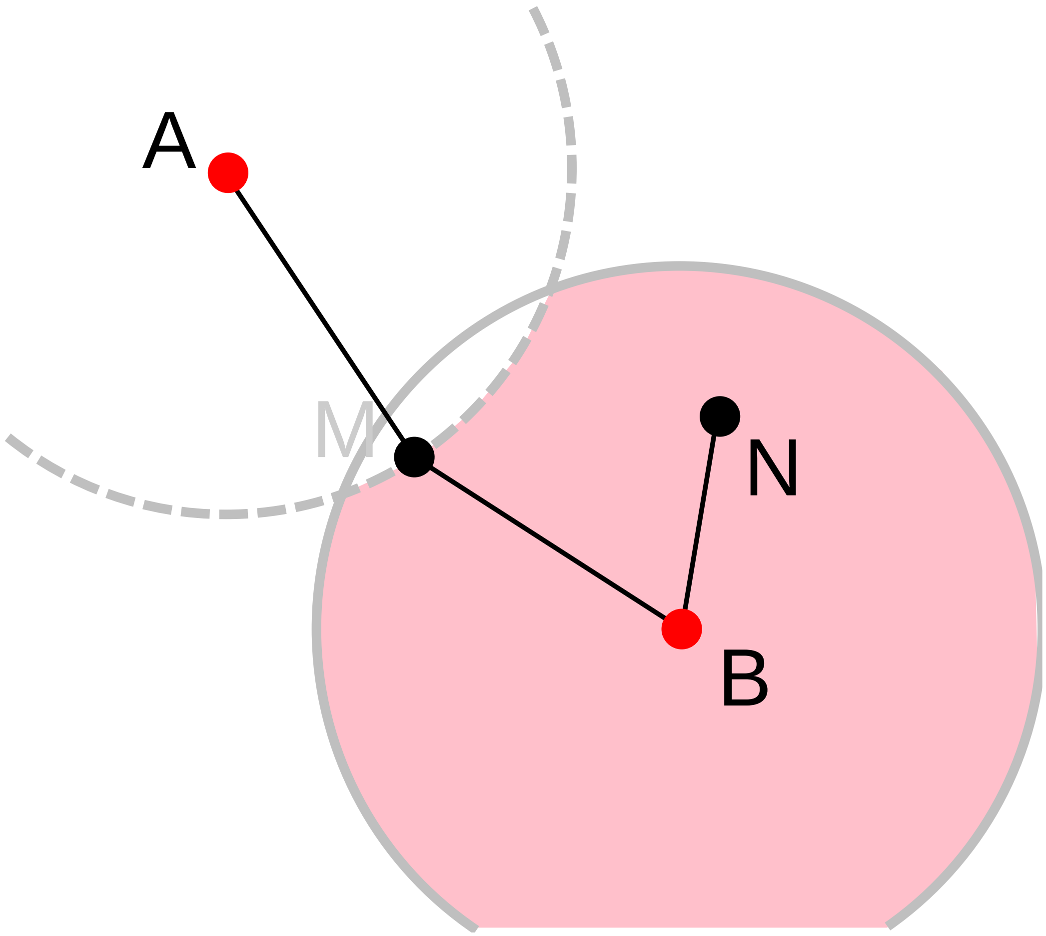


Intersection of Positive Information

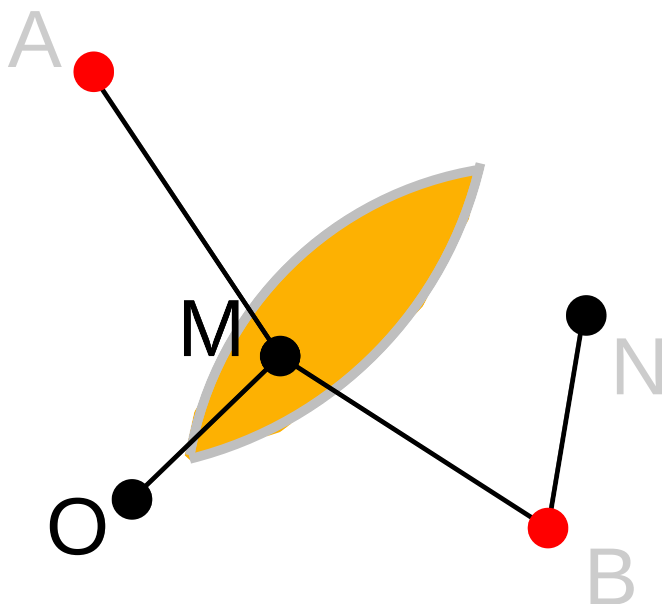


Negative Information

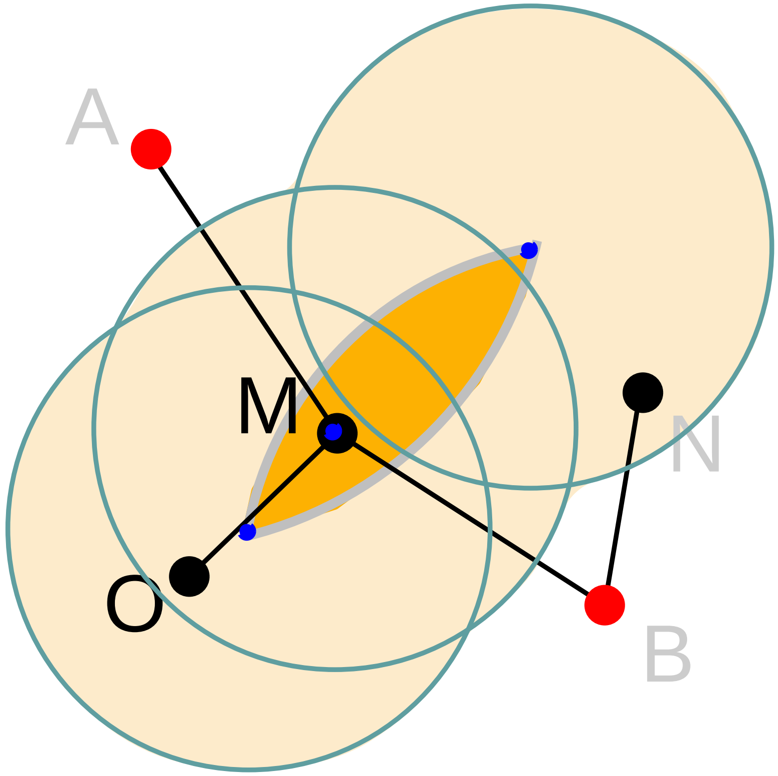
Node Localization



Subtraction of Negative Information



Transitive Dissemination of Positive Information



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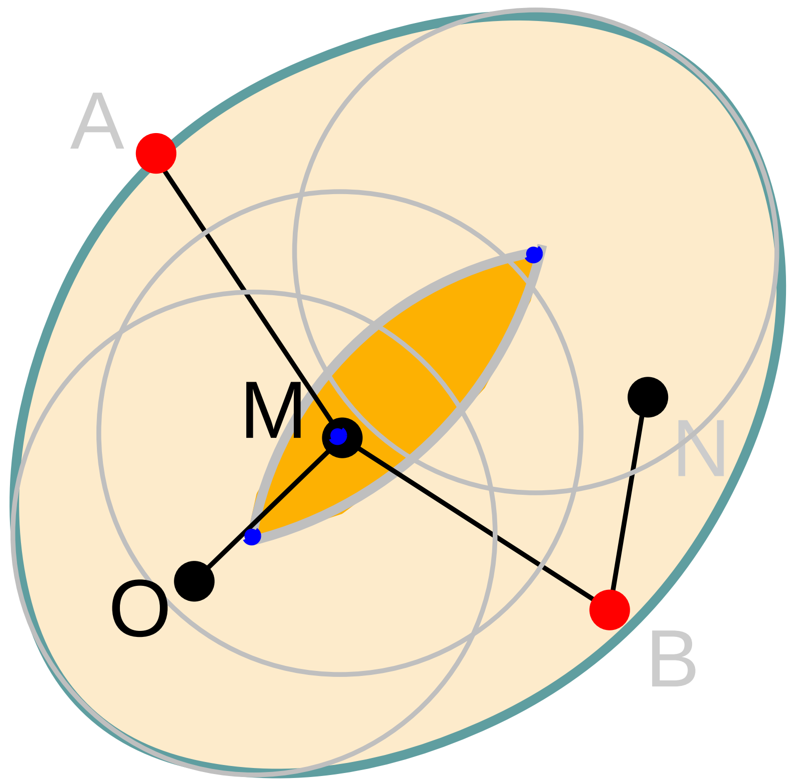

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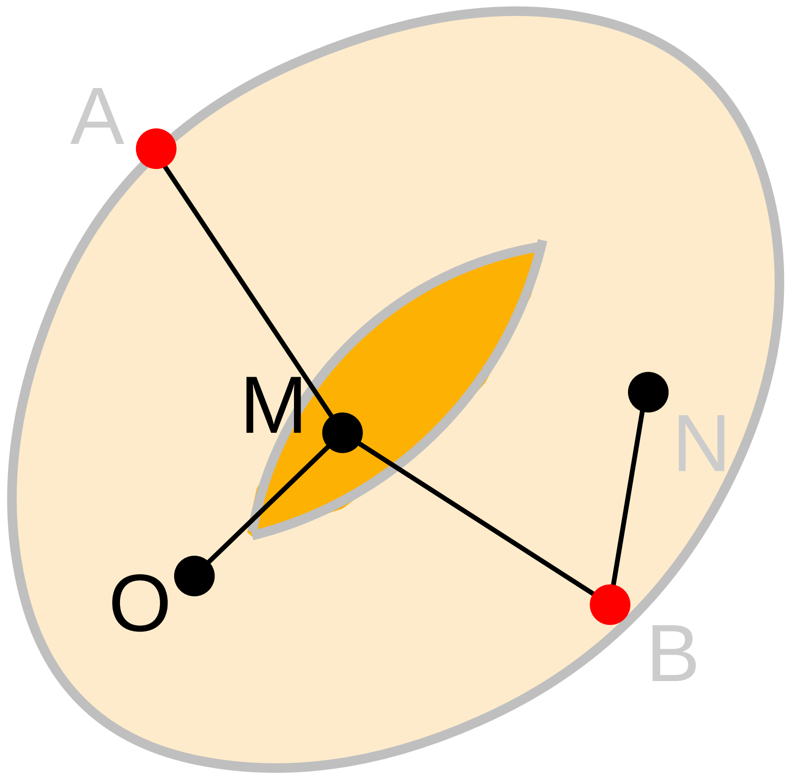

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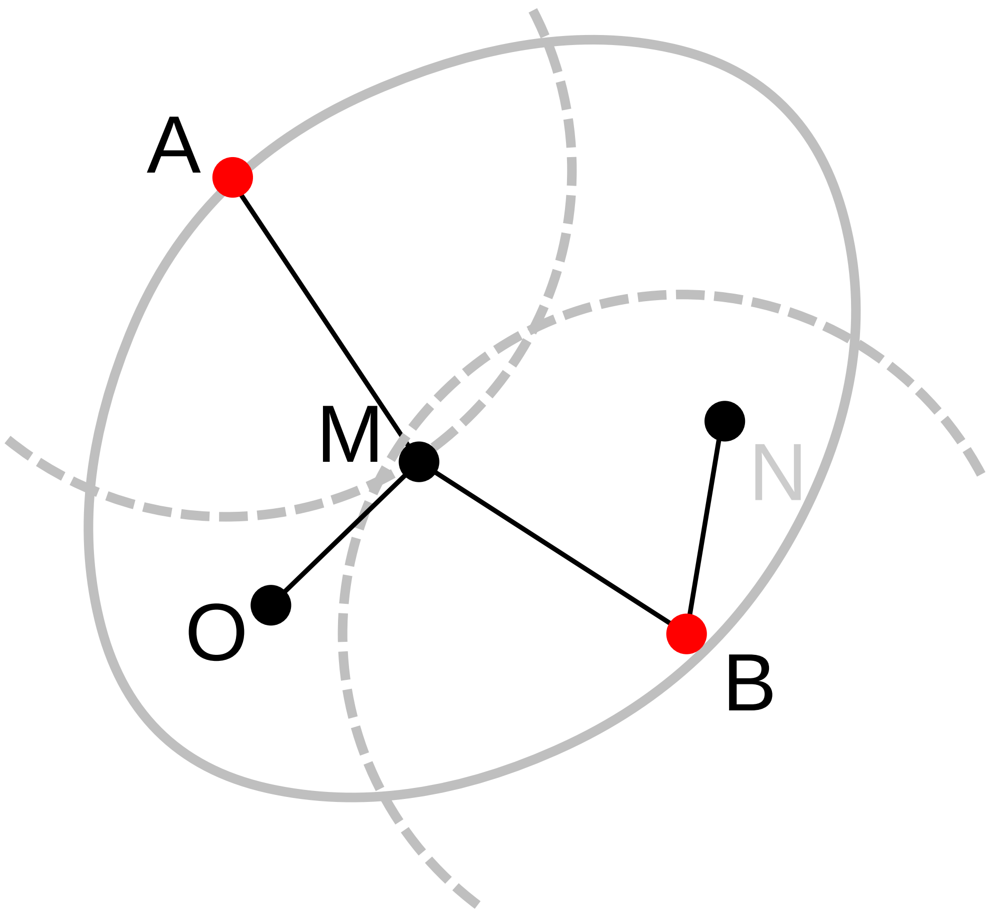
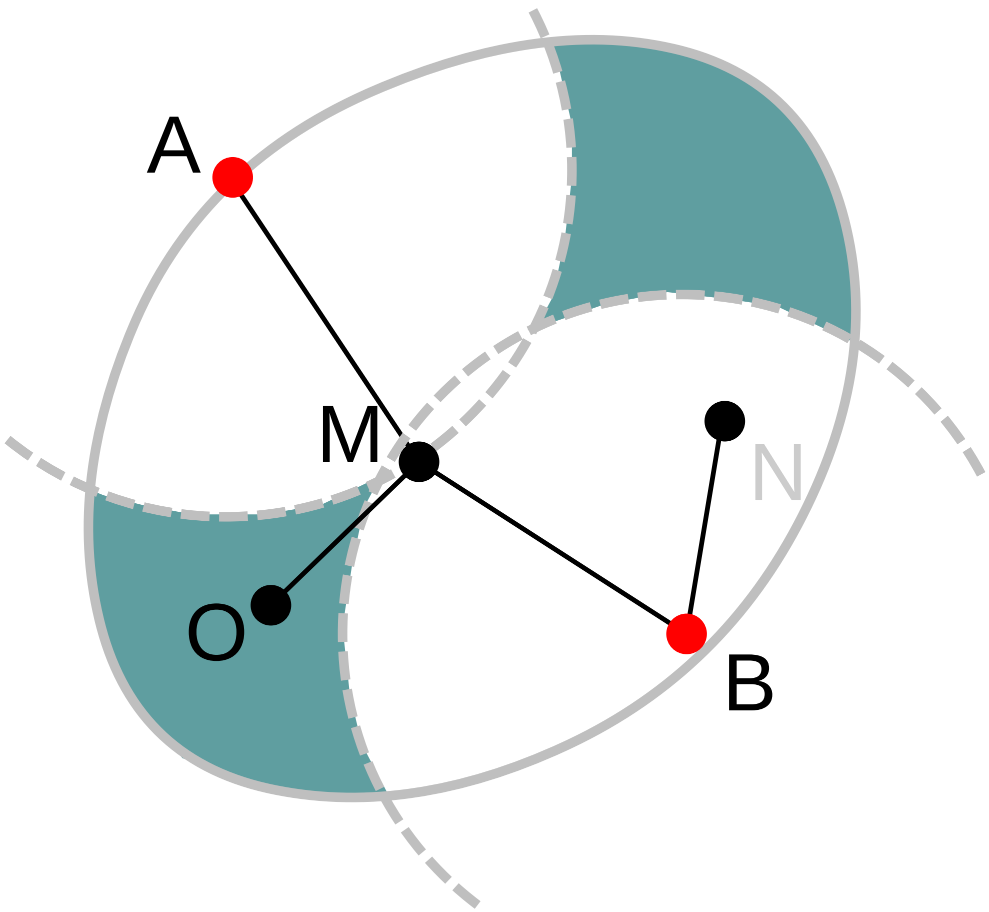


Combining Positive and Negative Information



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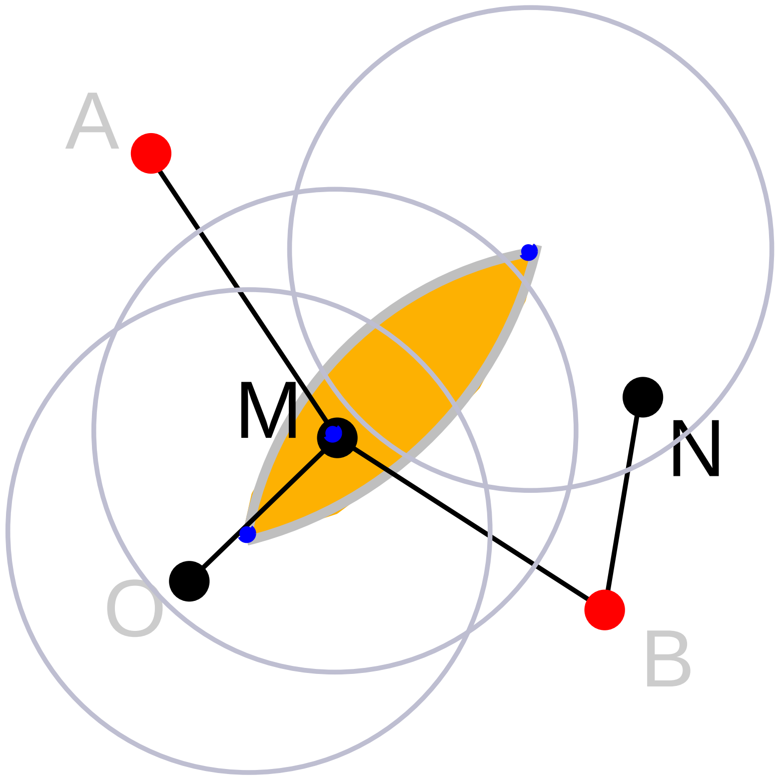
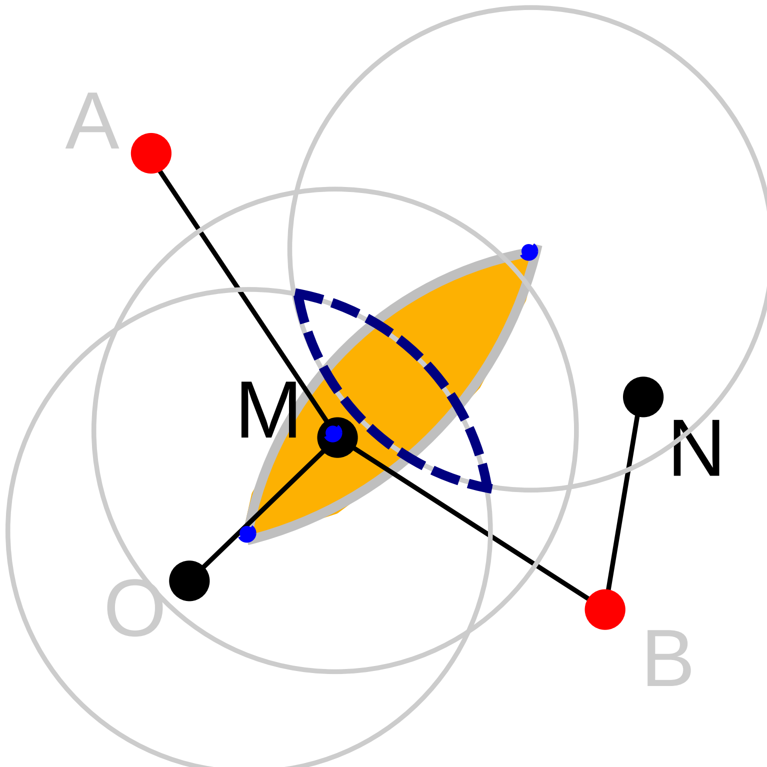


Transitive Dissemination of Negative Information

Node Localization



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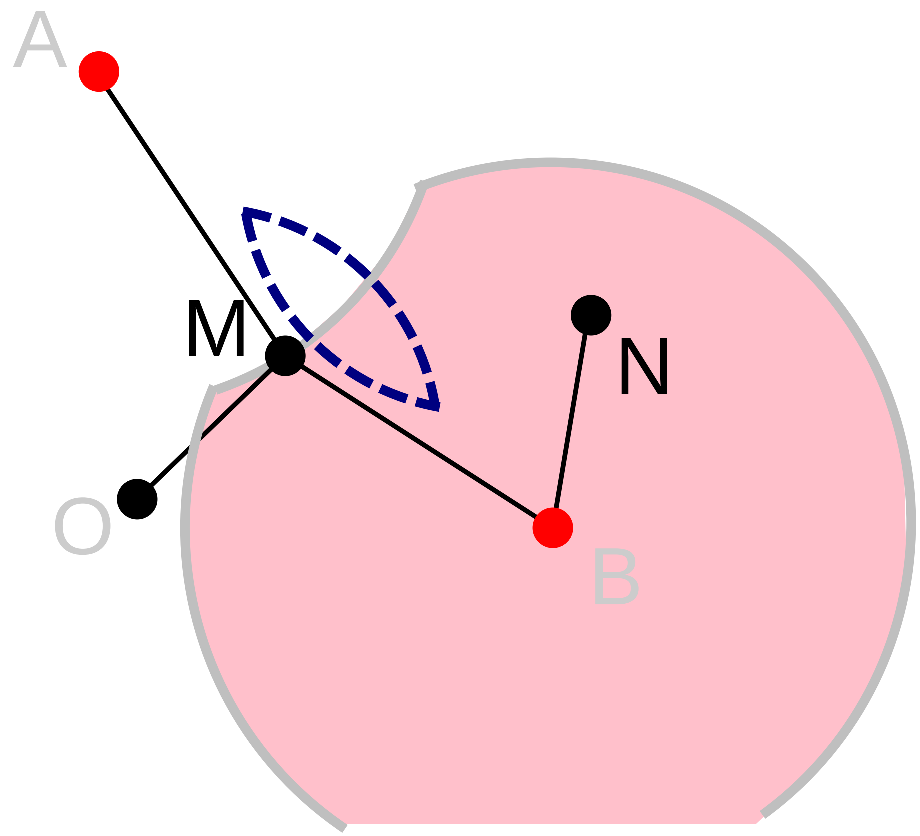
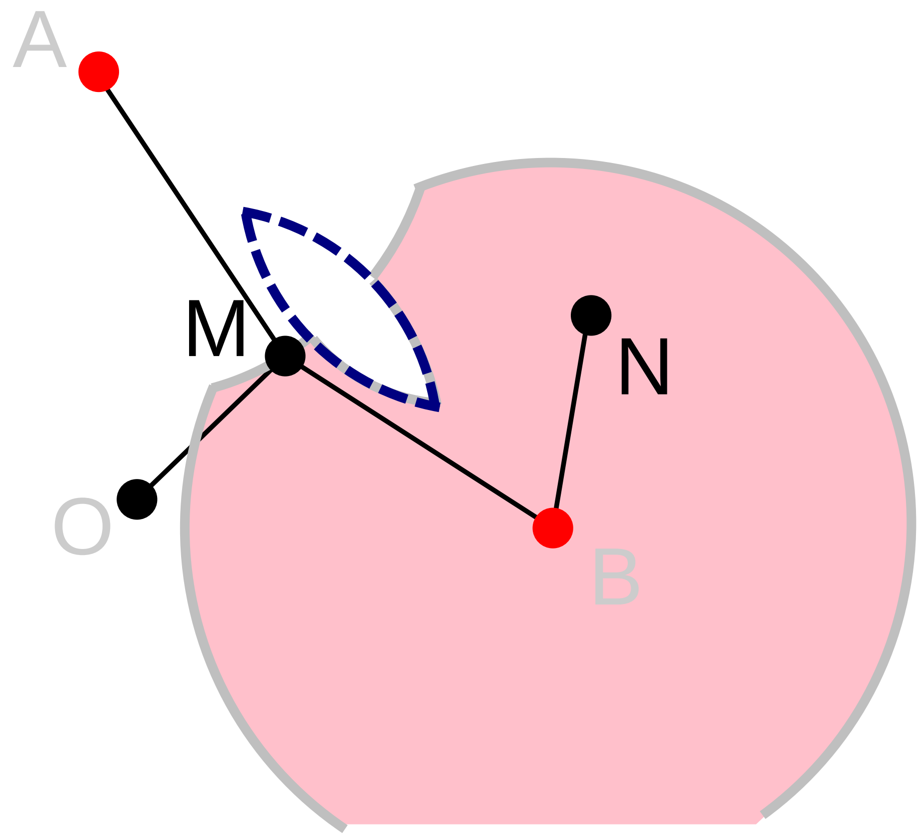
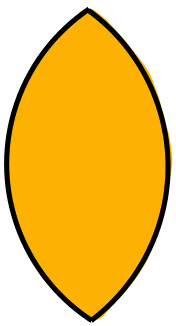


Refining Location Estimates



Refining Location Estimates

Sextant Approach



Polygons with Bézier boundaries

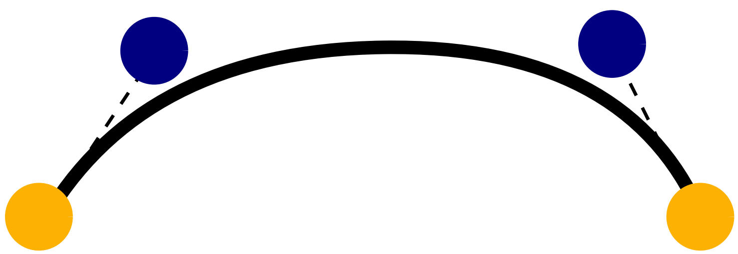
Each Node x

- Location Estimate: $\mathcal{E}_x$
- Positive Constraint: $\mathcal{P}_x$
- Negative Constraint: $\mathcal{N}_x$
- Set of positive constraints: Γ_x
- Set of negative constraints: Θ_x

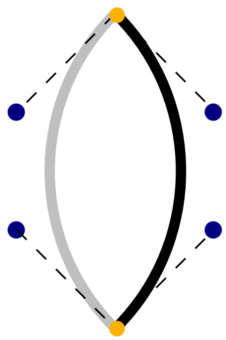
Invariant

$$\mathcal{E}_x = \bigcap_{p \in \Gamma_x} p \setminus \bigcup_{n \in \Theta_x} n$$

Sextant Approach



Bézier curve



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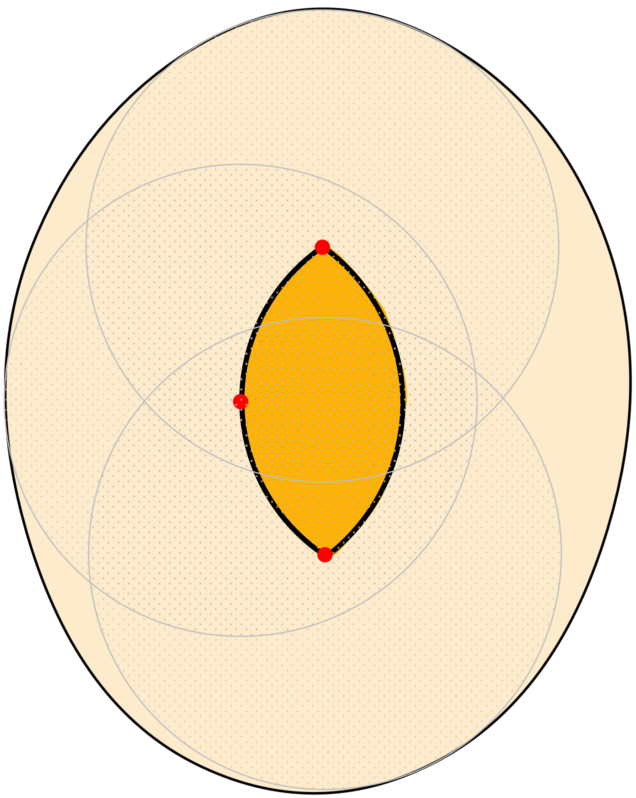

Union of circles in $\mathcal{E}_x$

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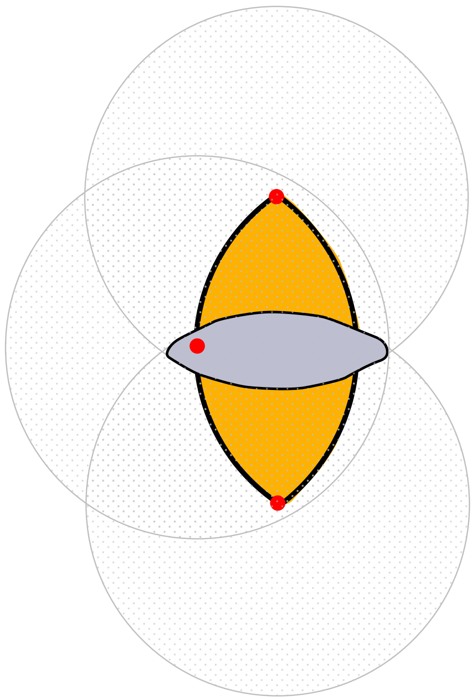

Intersection of circles in $\mathcal{E}_x$

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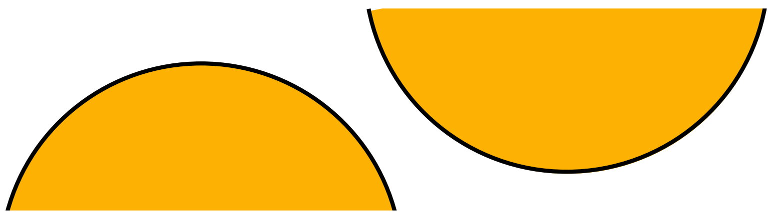
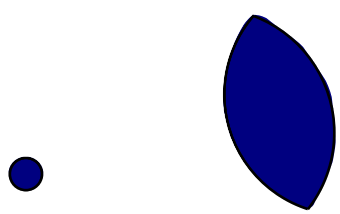


Γ_x: learned from wireless neighbors



Θ_x: learned from wireless non-neighbors

Each Node x

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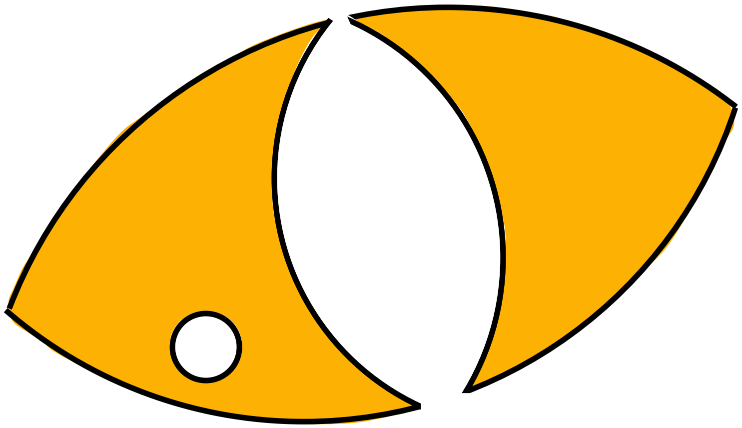

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Event Localization

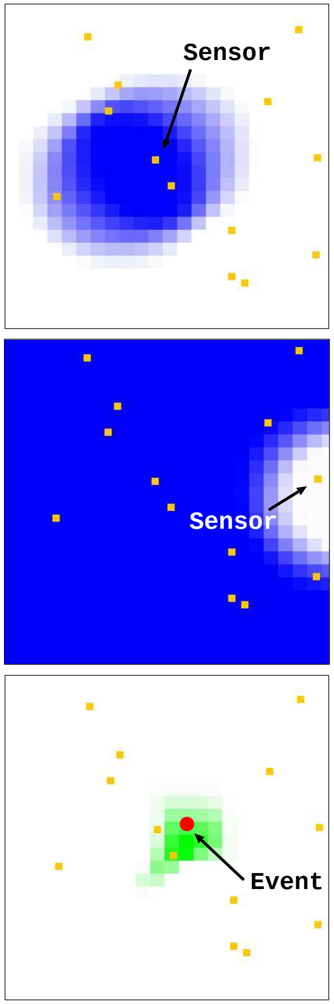
Similarity to Node Localization

- Constraints from sensing hardware vs. wireless radio
- Boolean sensed/not-sensed signal vs. boolean connectivity

Differences from Node Localization

- Annotate resultant areas with probabilities

Event Localization



Bayesian Probability

Positive Contribution

Sensor somewhere in $\mathcal{E}$ detects event; probability event in grid $\mathcal{G}_i$.

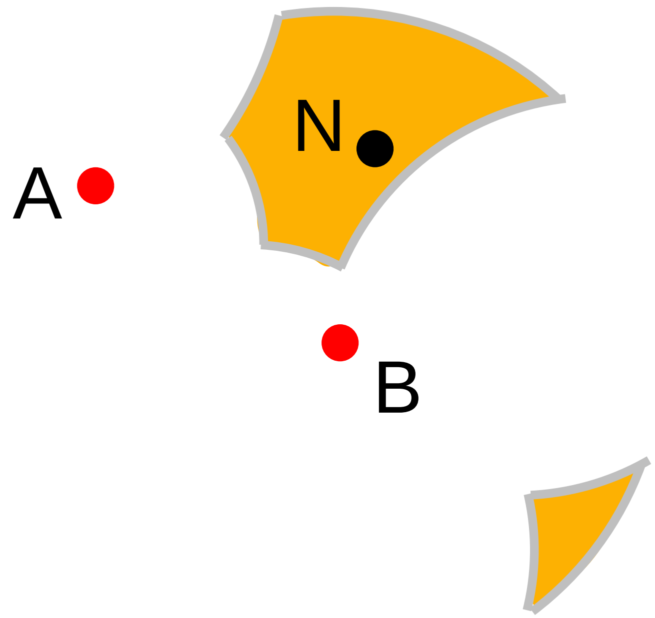
Negative Contribution

Sensor somewhere in $\mathcal{E}$ does not detect event; probability event in grid $\mathcal{G}_i$.

Solution

Product of positive and negative contributions from sensors sensing and not-sensing the event.

Feedback



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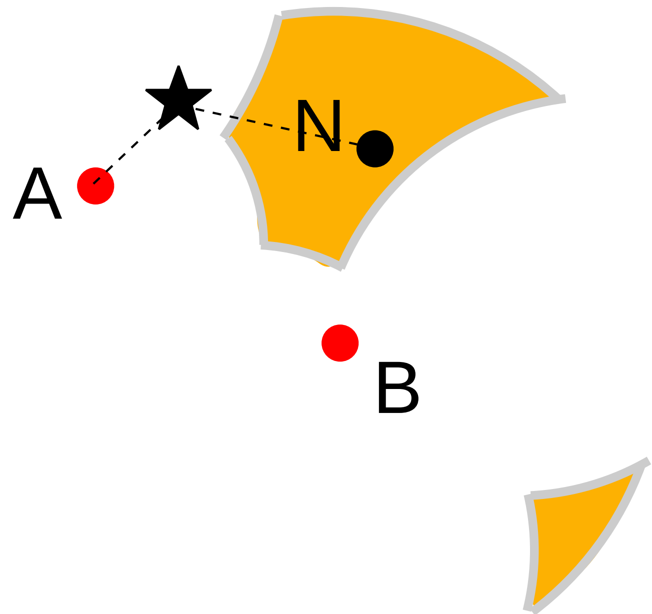

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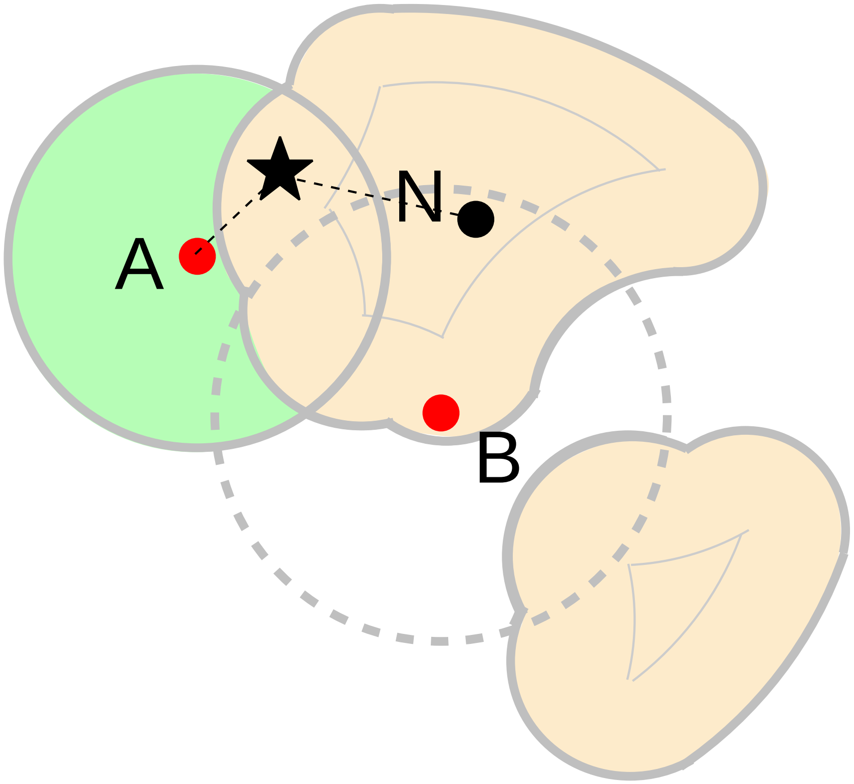

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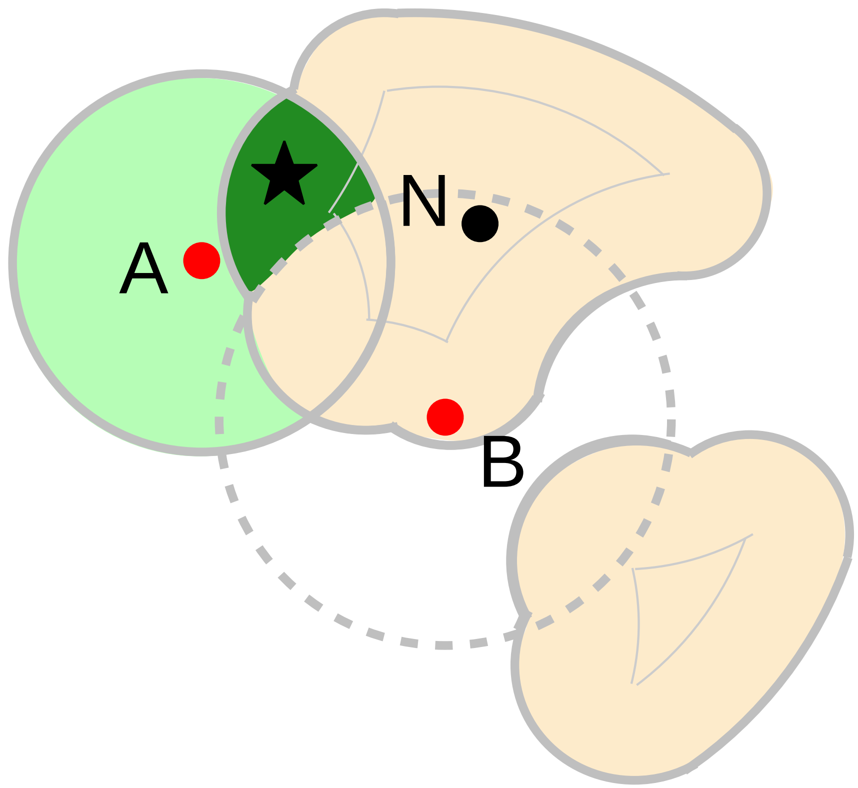

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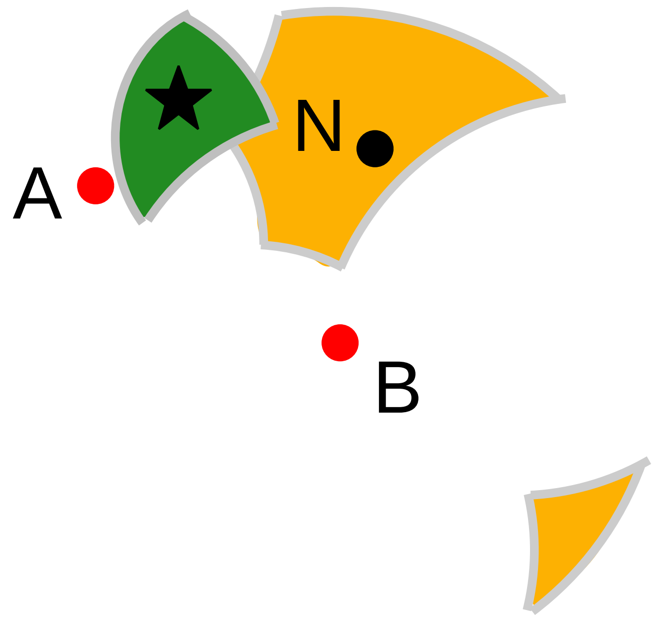

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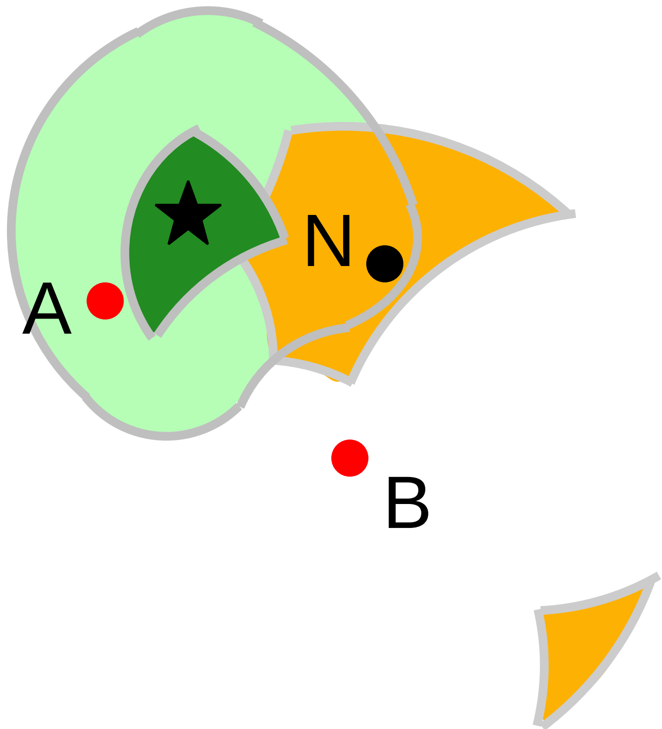
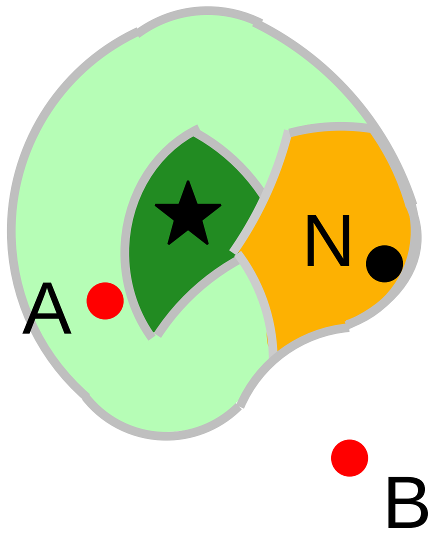


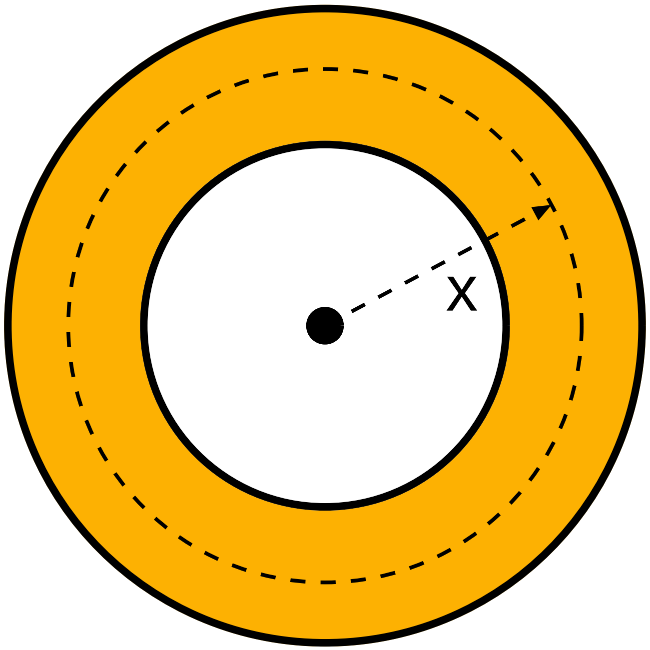
Events as a Source of Constraints

Feedback



Events as a Source of Constraints

Optimizations



Annulus for range x

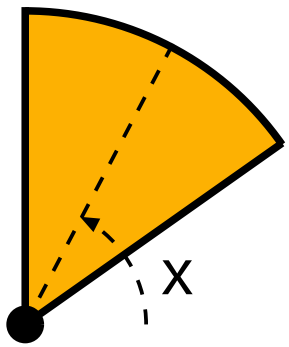
Wireless Hardware

- Range Measurements
- Angle of Arrival

Sensor Hardware

- Event Distance
- Directional Sensors

Optimizations



Sector for angle x

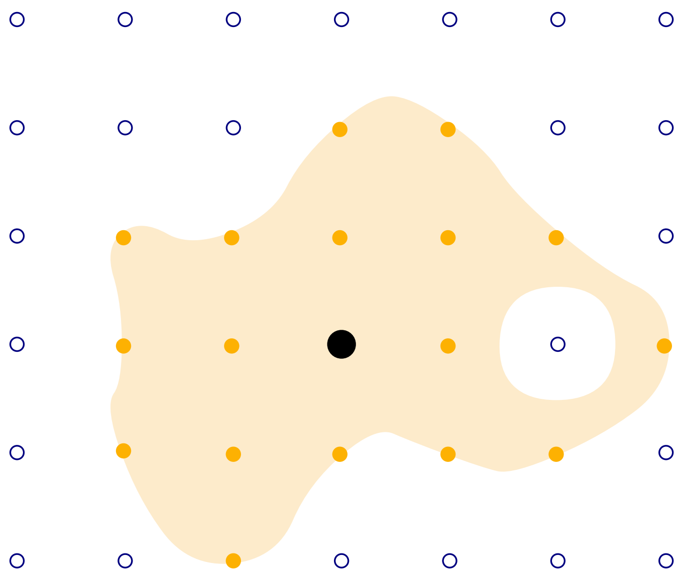
Wireless Hardware

- Range Measurements
- Angle of Arrival

Sensor Hardware

- Event Distance
- Directional Sensors

Modeling



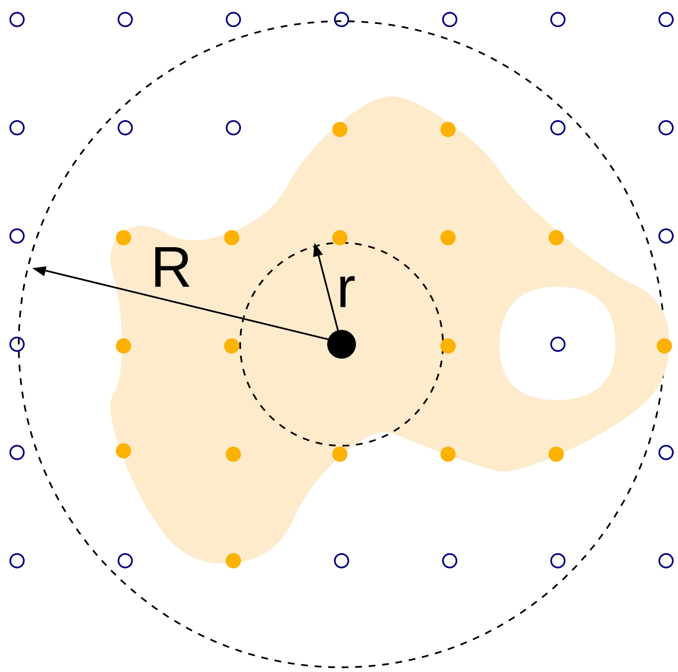
Wireless coverage area is non-convex and has holes

Wireless Radio

Boolean packet-received / packet-not-received.

- All reachable nodes $\leq R$ away
- All unreachable nodes $\geq r$ away

Modeling



Wireless Radio

Boolean packet-received / packet-not-received.

- All reachable nodes $\leq R$ away
- All unreachable nodes $\geq r$ away

Protocol

Neighborhood Discovery

- Nodes transmit periodic beacons
- Threshold beacon reception required for boolean connectivity

Gossip

Disseminate constraints as long as they are useful

- Positive information – used only at first hop
- Negative information – used within the first few hops

Validation of Node Localization

Implementation

- Implemented on MICA-2 motes, laptops and PDA
- About 2kB of storage per node
- About 80kB data transmitted per node until convergence

Setup

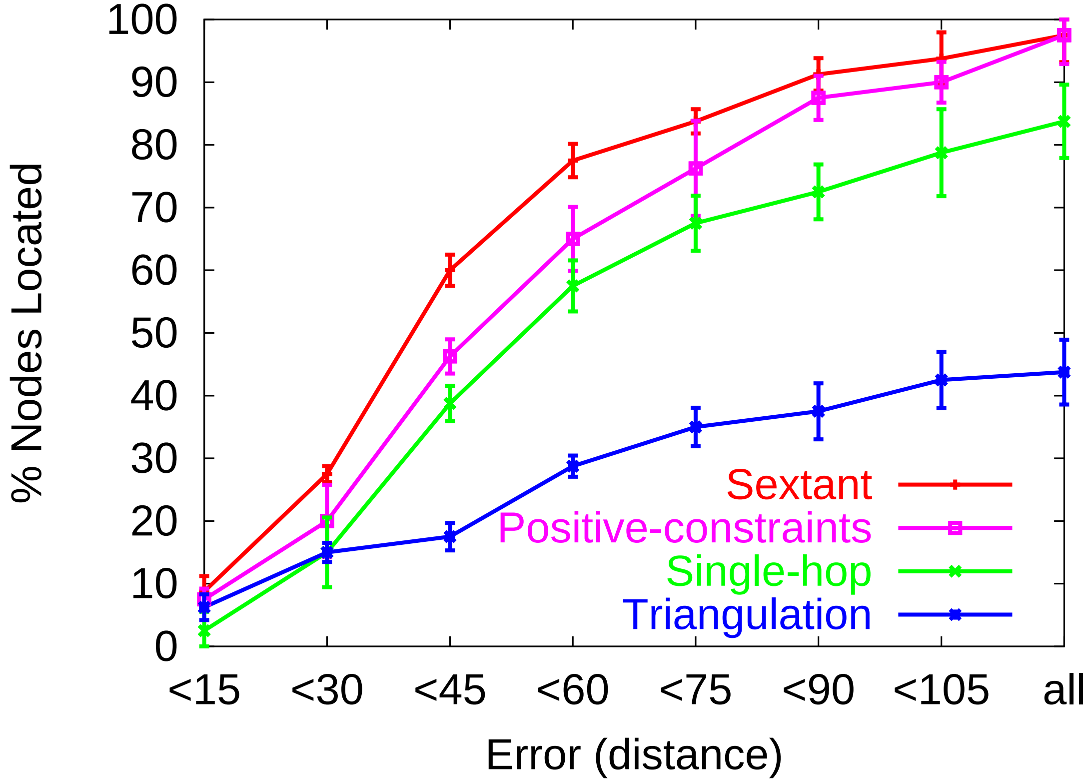
- 50 MICA2 motes placed in a grid pattern
- Landmarks chosen at random
- 80% packet reception threshold chosen for connectivity

Validation of Node Localization

Comparing Node Localization

- **Triangulation** – Centroid of neighbor nodes
  - GPSLess
- **Single-hop** – No transitive dissemination
  - Active Badge, Cricket, GPSLess, Localization Using Moving Target
- **Positive-constraints** – No negative information
  - APS, Convex position estimation, N-hop Multilateration, Robust Positioning
- **Sextant**

Validation of Node Localization

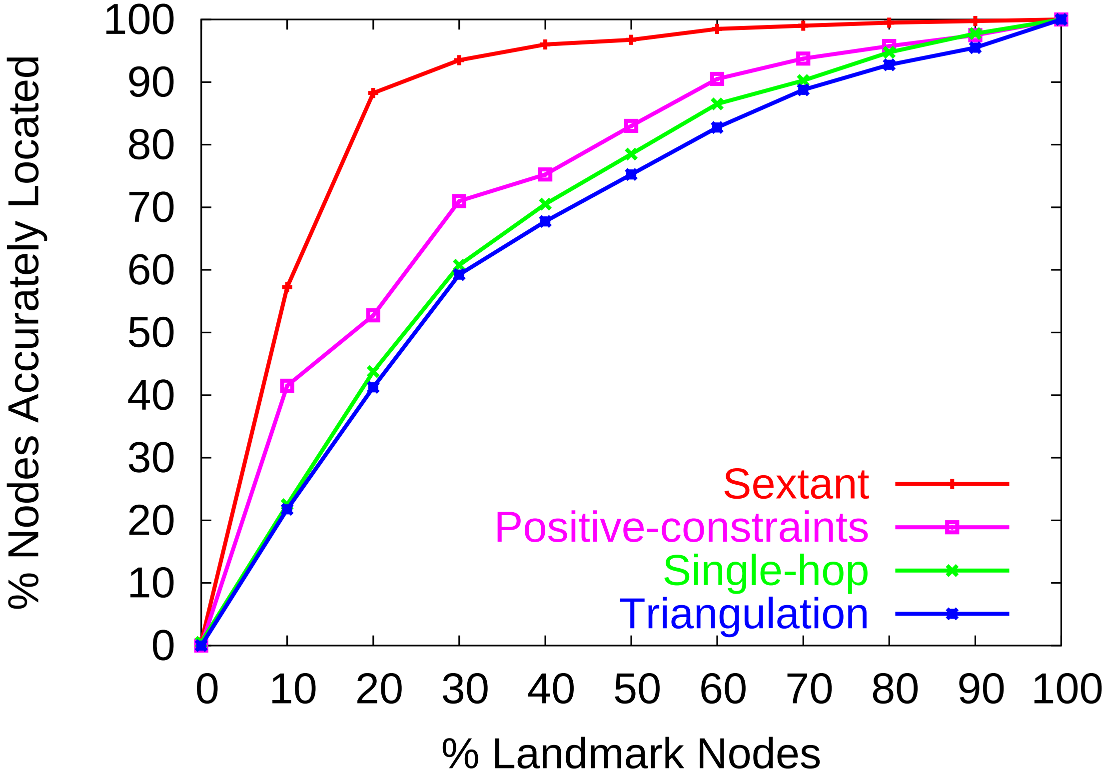


Node Localization

- Accurate
- Efficient
- Scalable

Sextant locates more nodes accurately

Validation of Node Localization

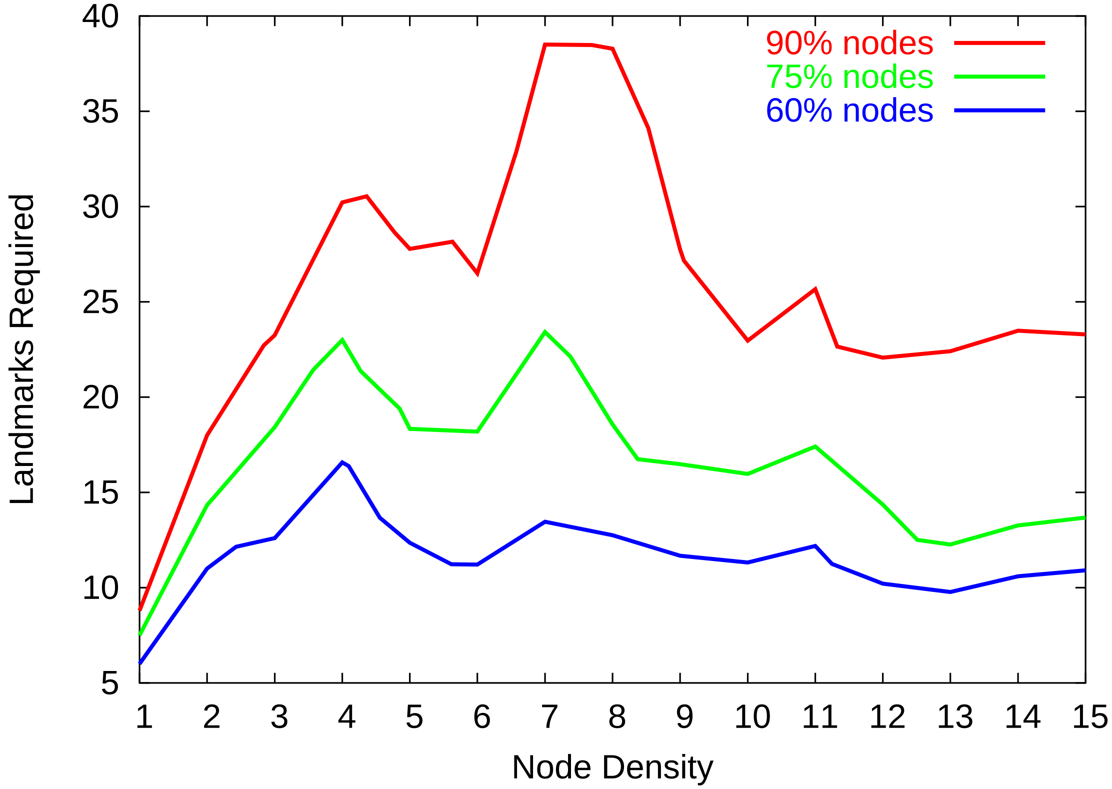


Node Localization

- Accurate
- Efficient
- Scalable

Sextant requires few landmarks

Validation of Node Localization



Sextant requires fixed landmark density

Node Localization

- Accurate
- Efficient
- Scalable

Validation of Event Localization

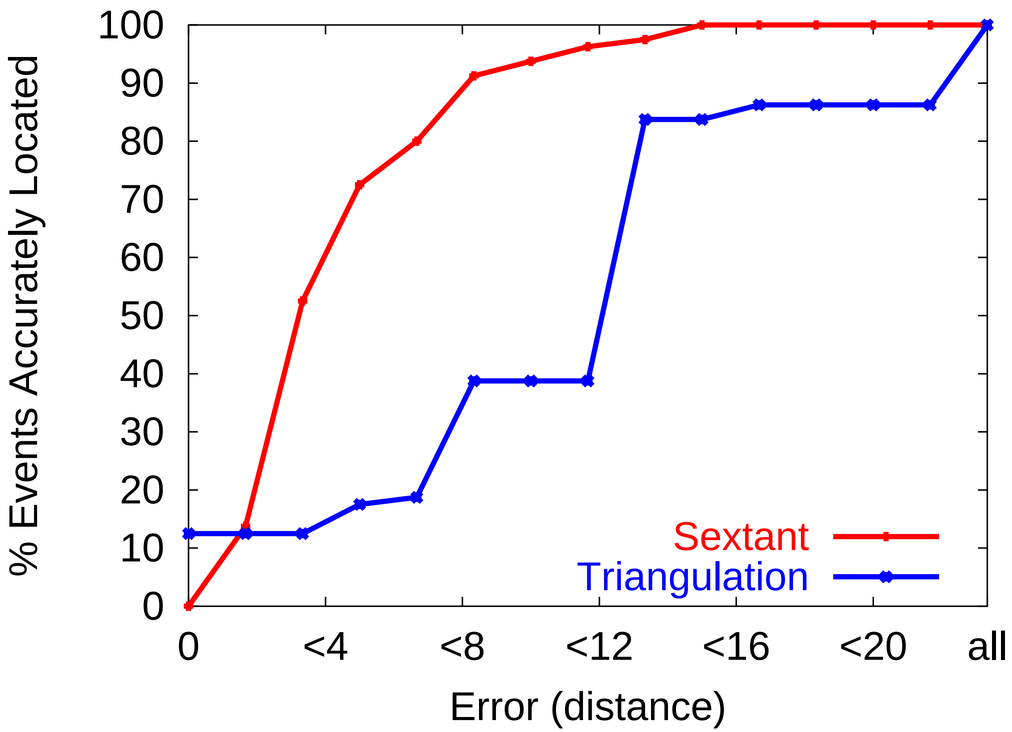
Setup

- 50 MICA2 motes placed in a grid pattern
- Event is a flash of light
- Appreciable change in analog value triggers sensor

Comparing Event Localization

- **Triangulation** – Centroid of sensors reporting the event
  - Acoustic Ranging
- **Sextant**

Validation of Event Localization



Event Localization

- Accurate
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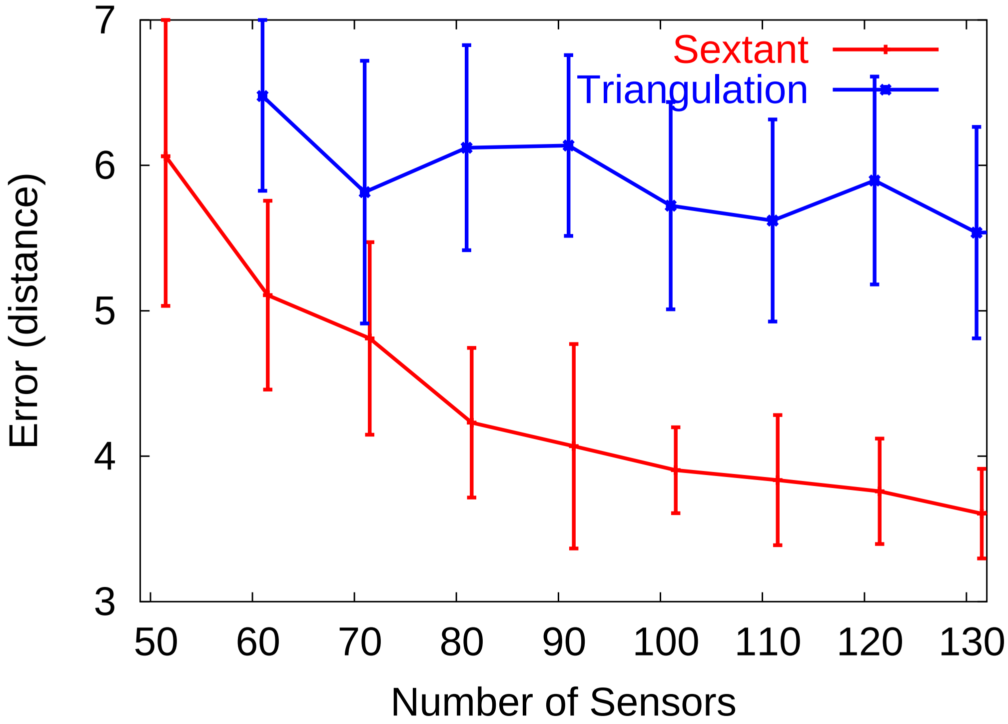
Sextant locates more events accurately

Validation of Event Localization

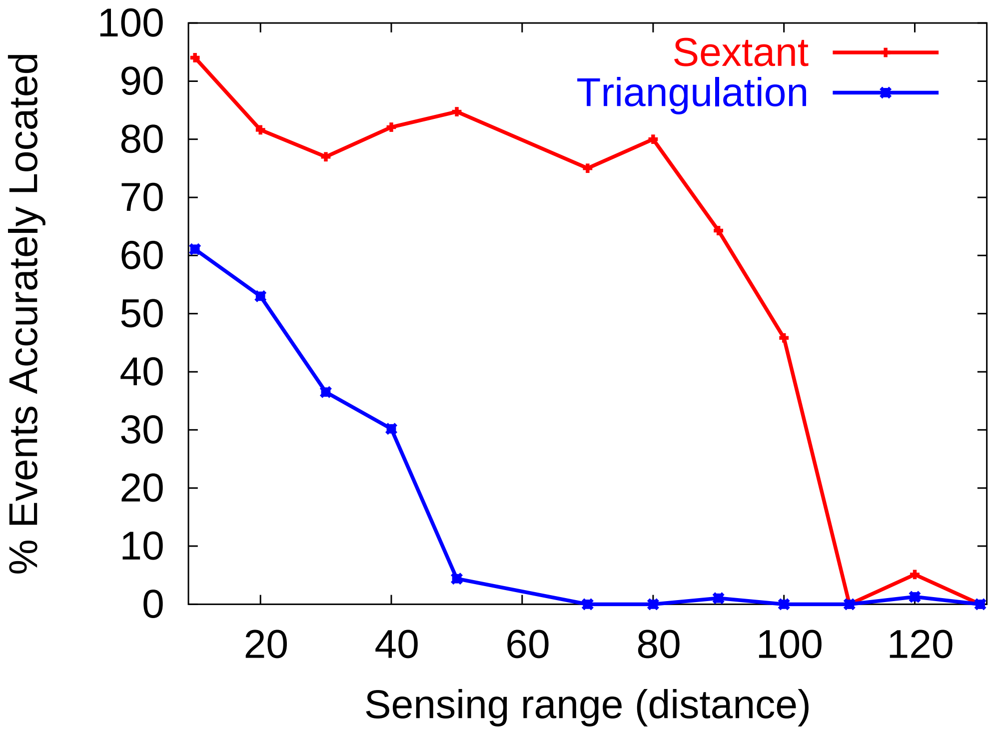


Accuracy improves with nodes

Event Localization

- Accurate
- Efficient
- Robust

Validation of Event Localization



Sextant independent of sensing range

Event Localization

- Accurate
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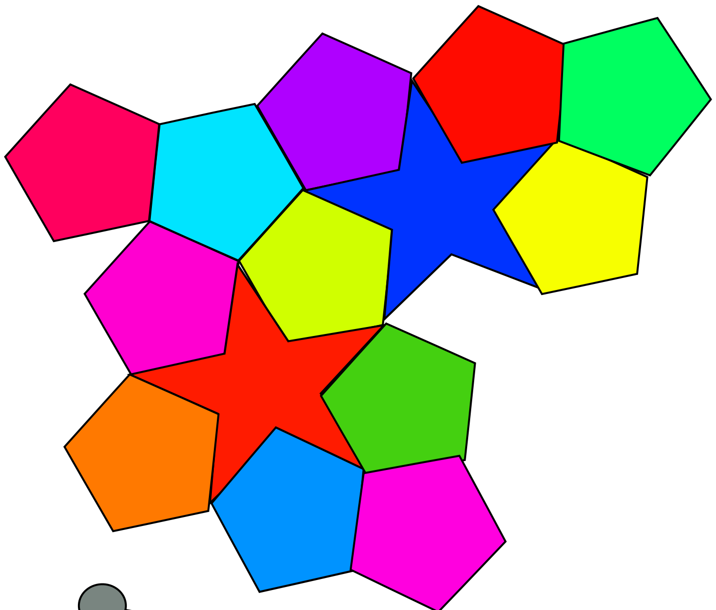
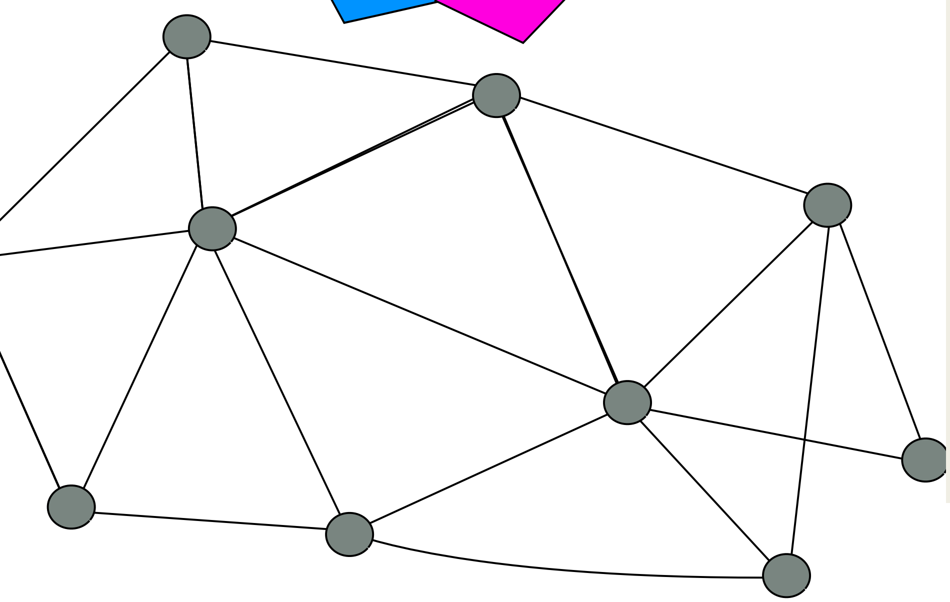
Programming Model for Ad Hoc Networks

- Current state of the art is to view the network as a system of systems
  - Forces all applications to implement their own mechanisms for state migration
  - Tedious, error-prone
  - Multiple applications may conflict
- Fundamental problem stems from lack of an arbiter
  - Need a system layer to perform resource mediation

MagnetOS Approach

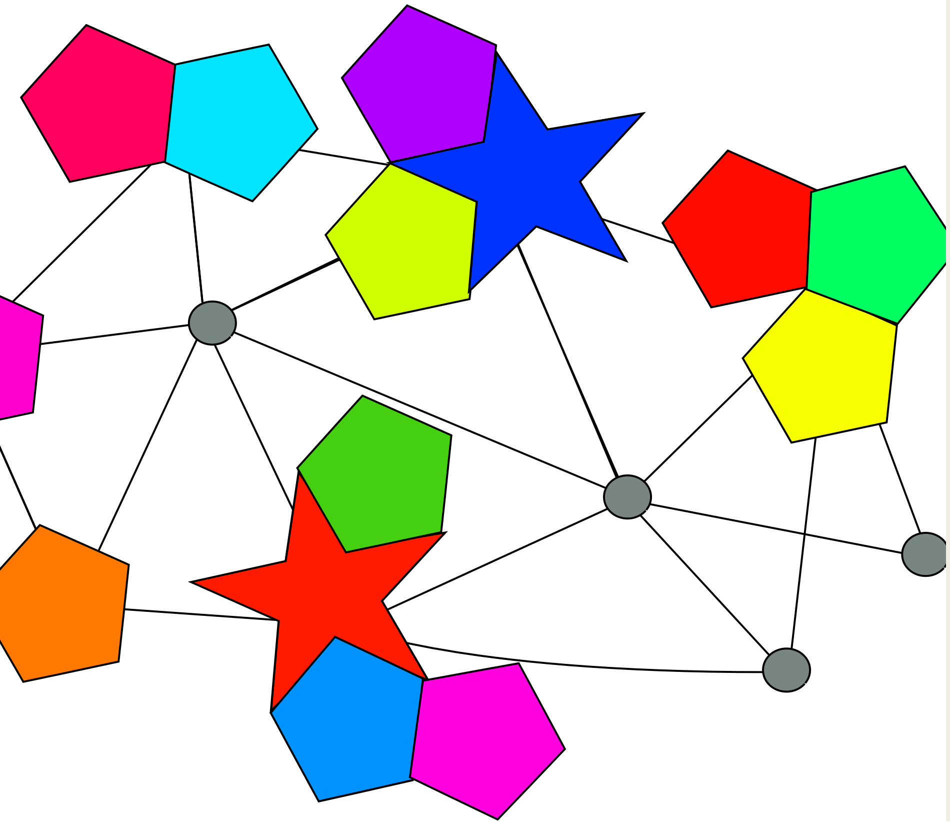




Contributions

- Programmer writes monolithic application for a single JVM
- MagnetOS statically partitions the application into communicating objects
  - Objects can reside anywhere in the network
- MagnetOS dynamically finds a good placement of objects on nodes in the network
  - Energy efficiency is the key goal

MagnetOS Approach



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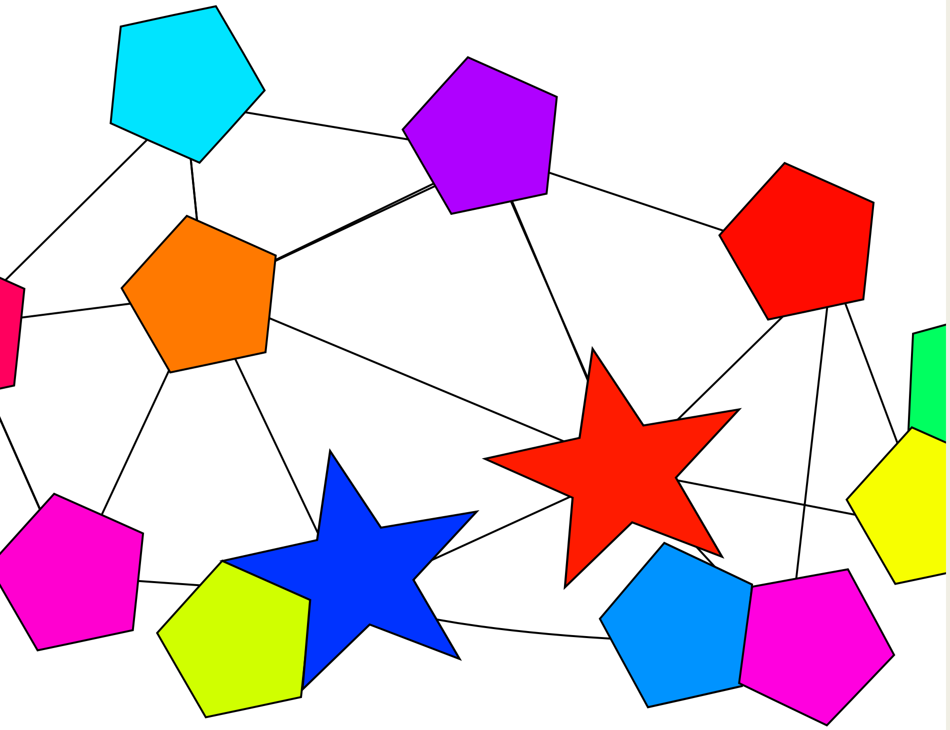

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MagnetOS Implementation and Status

- Implemented most of the system
  - Static rewriter (50K loc)
  - Space-optimized JVM for x86 and StrongARM (30K loc)
  - Dynamic runtime (25K loc)
- Working on adding transparent replication
  - Based on message logging
  - Driven initially by programmer annotations

Summary

- Sextant is a localization framework that achieves high accuracy and scalability
  - Explicit representation of regions using Bézier curves
  - Conservative and comprehensive extraction of negative as well as positive constraints
  - Transitive dissemination of constraints
  - Use of events to refine node location
- Sextant is practical
- MagnetOS simplifies programming mobile systems
  - Many new directions based on transparent rewriting

http://www.cs.cornell.edu/People/egs/sextant/
http://www.cs.cornell.edu/People/egs/magnetos/

Related Work

Positive Information

- **GPS-Free** '01: Capkun, Hamdi and Hubaux
- **APS** '01: Niculescu and Nath
- **Convex Position Estimation** '01: Doherty, Pister and Ghaoui
- **Robust Positioning** '02: Savarese, Rabay and Langendoen
- **N-hop Multilateration** '02: Savvides, Park and Srivastava
- **APS-AoA** '03: Niculescu and Nath
- **Mere Connectivity Localization** '03: Shang, Ruml, Zhang and Fromherz
- **Connectivity-Based Positioning** '04: Bischoff and Wattenhofer
- **Unit Disk Approximation** '04: Kuhn, Moscibroda and Wattenhofer
- **Virtual Coordinates** '04: Moscibroda, O'Dell and Wattenhofer

Related Work

Single-Hop

- **Active Badge** '92: Want, Hopper, Falcão and Gibbons
- **GPS-Less** '00: Bulusu, Heidemann and Estrin
- **RADAR** '00: Bahl and Padmanabhan
- **Cricket** '00: Priyantha, Chakraborty and Balakrishnan
- **RF-Based Location Tracking** '04: Lorincz and Welsh
- **VORBA** '04: Niculescu and Nath
- **Localization Using a Moving Target** '04: Galstyan, Krishnamachari, Lerman and Pattem

Related Work

Event Localization

- **Fine-grained Localization** '01: Savvides, Han and Srivastava
- **Collaborative Processing** '03: Zhao, Liu, Guibas and Reich
- **Acoustic Ranging** '04: Sallai, Balogh, Maroti and Ledeczi
- **Countersniper** '04: Simon, Maroti, Ledeczi et al.
- **Entity Tracking** '02: Brooks, Griffin and Friedlander
- **Energy-Efficient Surveillance** '04: He, Krishnamurthy, Stankovic et al.