MDM 2007 Seminar

Location-Aware Wireless Sensor Networks

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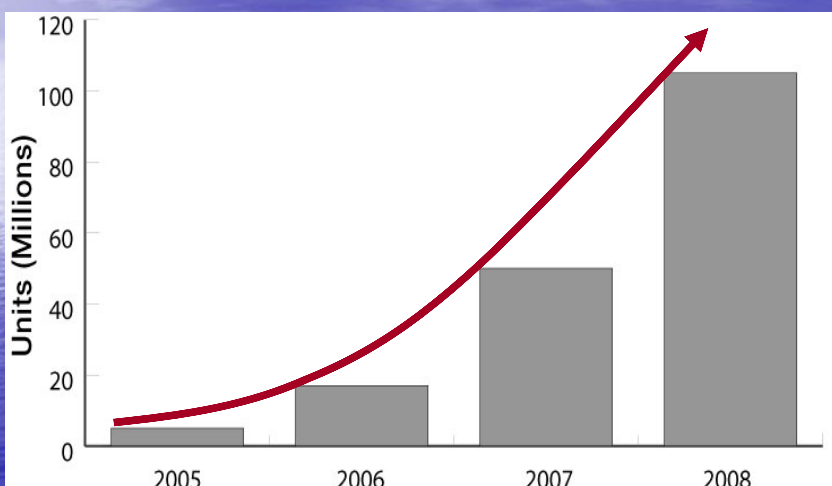
Overview

- Wireless Sensor Networks
- Localization
- Location-Based Routing
  - Routing Protocols
  - Location Services
- Data Management
  - Storage Management
  - Query Processing
- Location Tracking
- Conclusion

Wireless Sensor Network Market Forecast – by Crossbow Technology Inc, 2006



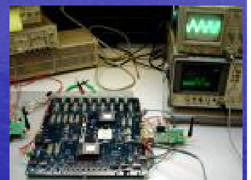
Enabling Technology for WSN

- Sensing
  - Connected to the physical world
- Embedded
  - Small form factor
- Networking
  - Collaborations

Sensor Nodes

- Have the following Components
  - *computation*,
  - *storage*,
  - *communication* and
  - *sensing*
- Powered by *batteries*

UCLA iBadges



BWRC PicoNode

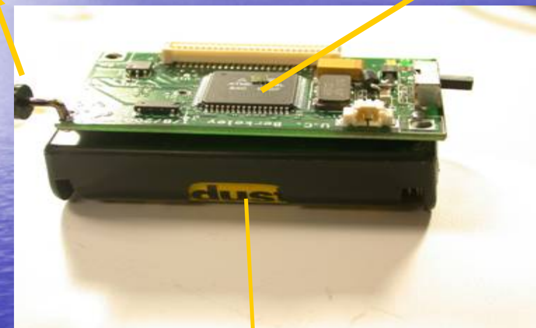
WINS Nodes

Mica Motes

Example: Mica Motes

Radio (<100 kbps)

4MHz 8 bit Atmel *micro-processor*



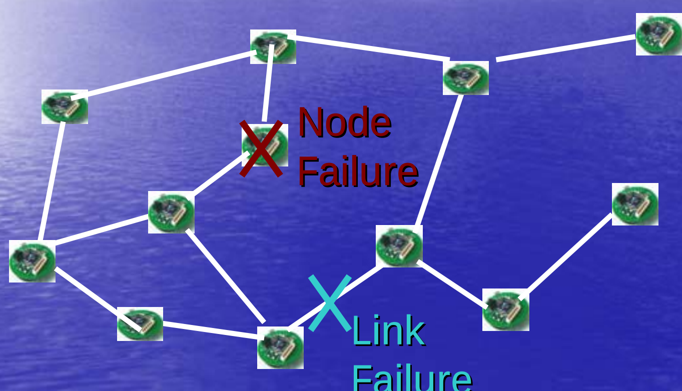
2 AA batteries, 2.5 Ah

Sensors:
temperature
light
humidity …

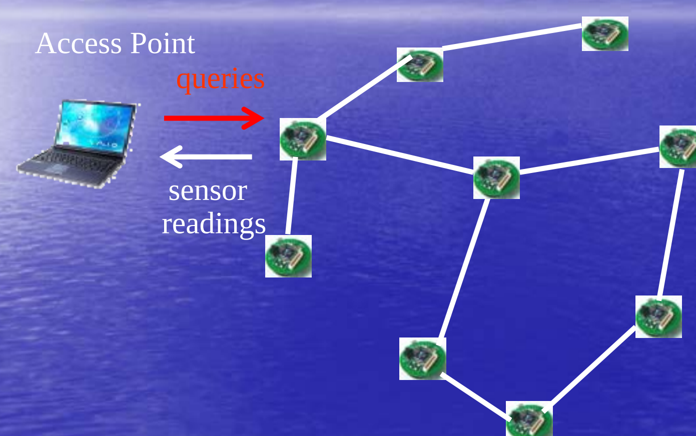
Memory:
512 KB

Sensor network

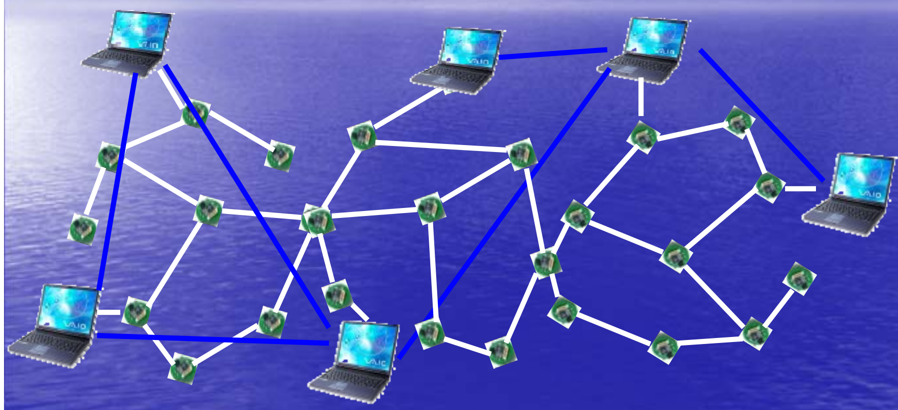
Sensor nodes can form a wireless sensor network, communicated via multi-hop message relays.



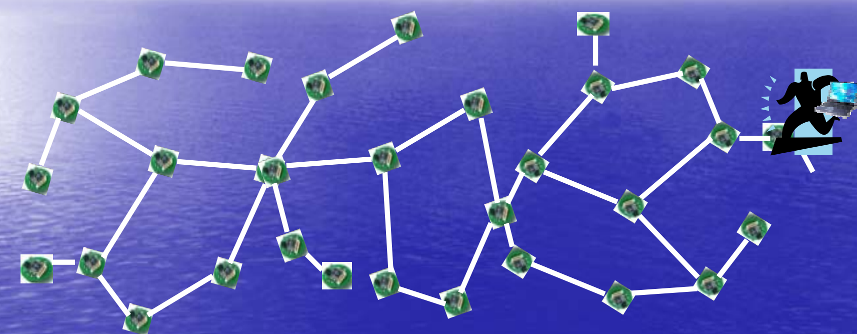
Single Access Point



Multiple Access Points



Mobile Access Points



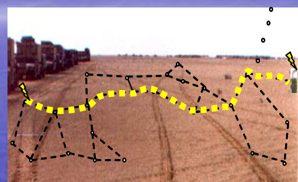
Sensor Networks Applications

Location-Aware Wireless Sensor Networks

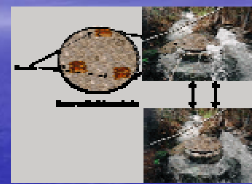
- There is a need for network functionalities designed with emphasis on their spatial property

"Locations" in Sensor Network Applications

Sensor readings at specific location



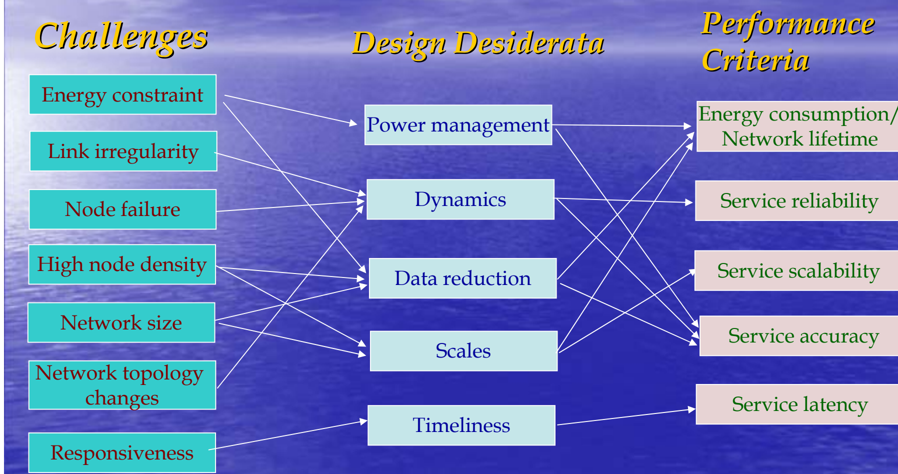
Location (trajectory) of tracked objects



Location of security violation

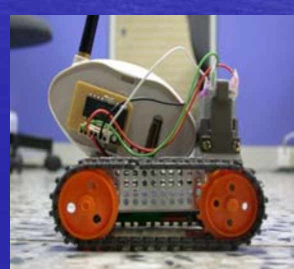
- Many applications are interested in sensor readings and *where readings are from*, instead of specific nodes of these readings

Design Issues



Characteristics

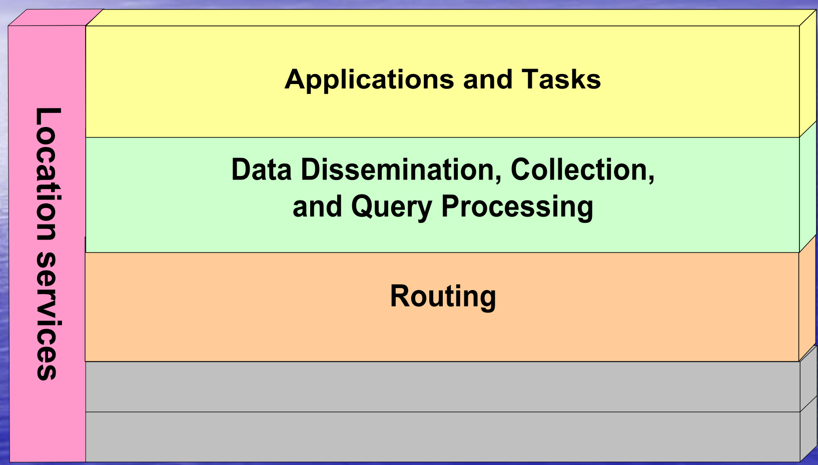
- **Location-awareness**:
  - GPS and localization
- **Communication:**
  - short-range radios & multi-hops transmission
- **Dynamic Network:**
  - Node Mobility
  - Energy Conservation
  - links and node failures



Application Requirements

- Wireless multi-hop communication
- Self-configurable network
- Robustness to failures
- Localized and collaborative operations
- Querying ability
- ...

Layered Architecture



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Location - Representation

[Lee et al., Perv Com Mag.'02]

- Geometric Model
  - 2-D or 3-D coordinates, e.g., the latitude/ longitude pair
  - Compatibility across heterogonous systems
- Symbolic Model
  - Logical, real-world entities
    - Bus stop number, train station name
    - building name, floor, room number
    - Wireless cell ID
  - Coarser location granularity
  - Suitable for LBS applications due to semantics

Location Conversion

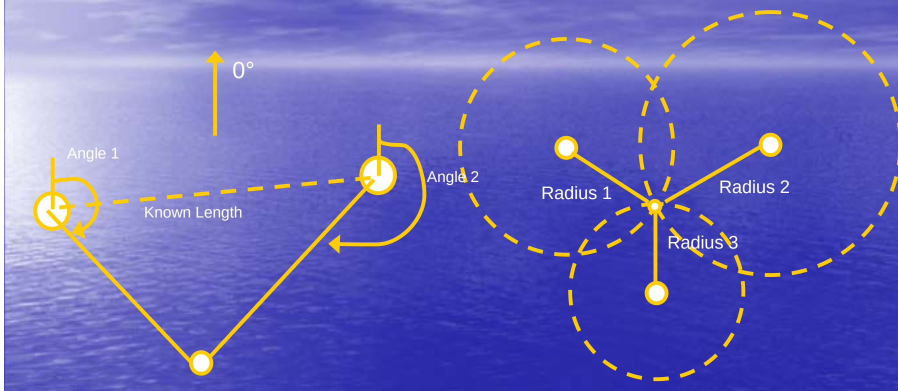
- Location properties of objects
  - Shopping mall: street address
  - University: city name
  - Person's current location: coordinates
- Conversion between heterogeneous (geometric & symbolic) locations
- Recast of location
  - Person on the street: street address
  - Walked into a shopping mall: mapped into floor, store name
  - On a car: bus number, highway route number
  - Returned home: home address

Positioning Techniques

- Triangulation
  - Lateration
  - Angulation
- Scene Analysis
- Proximity

[Hightower & Borriello, IEEE Computer'02]
[Niculescu, IEEE Network]
[Chen & Xiao, MSU TR]

Basic Idea: Triangulation



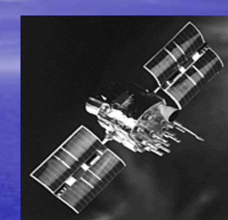
Angulation Lateration

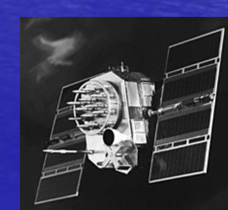
Positioning Systems

- Global Positioning System
  - 24 satellites to compute location of the GPS receiver
  - Outdoor accuracy within 15 meters since May 2000
- Indoor Positioning Systems
  - There are a number of research prototypes providing indoor location information (for pervasive computing)
  - Accuracy varies from centimeters to meters
  - E.g., Active Badge, Active Bat, Cricket, etc.

Global Positioning System [GPS Primer]

- The complete GPS space system includes 24 satellites, 11,000 nautical miles above the Earth.
- Each takes 12 hours to go around the Earth once (one orbit).
- The satellites transmit signals that can be detected by anyone with a GPS receiver.
- We can receive signals, from six of them nearly 100 percent of the time at any point on Earth, to determine our location with great precision.


GPS Block II


GPS Block II

Active Badge [Wand et al., ACM Trans. IS'92]

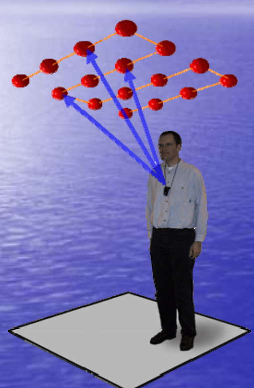
- Locating individuals within a building by determining the location of their Active Badge.
- http://www.uk.research.att.com/ab.html
- Consist of a cellular proximity system that uses diffuse *infrared* technology
- Was developed at Olivetti Research Lab, now AT&T Cambridge.

Active Badge

- The system locates persons wearing active badges
- This small device transmits a unique infra-red signal every 10 seconds.
- Offices are equipped with networked sensors which detect these transmissions.
- The location of the badge (and hence its wearer) can thus be determined on the basis of information provided by these sensors.
- A central server collects this data from fixed infrared sensors around the building, aggregates it, and provides an application programming interface for using the data.

Active Bat [Ward et al., IEEE PC Mag'97]

- http://www.uk.research.att.com/bat/



Bat (7.5cm*3.5cm*1.5cm)
Power: 3.6 V
Lifetime: around 15 months
Unique 48-bit code
Bi-directional 433MHz radio
Two buttons, two LEDs, a speaker, and a voltage monitor

Placed in a square grid, 1.2m apart
Connected by a high-speed serial network
The serial network is terminated by a DSP calculation board

Active Bat

- The Bat System is a 3D ultrasonic location system based on the principle of trilateration
- The system can locate Bats to within 9 cm of their true position for 95 percent of the measurements
- Require a large fixed-sensor infrastructure throughout the ceiling
- Rather sensitive to the precise placement of these sensors.

Cricket [Priyantha et al., Mobicom'00]

- Do not need a sensor Grid
- Use both ultrasonic & radio frequency signals
- Like GPS, mobile devices listen and analyze information from beacons spread throughout the building to determine their locations.
- Location accuracy to a few centimeters; motion angle accuracy to within 3-5 degrees.
- Cricket v2, substantially better than v1
  - has better energy consumption properties
  - has a new software stack based on TinyOS
  - has better support for continuous object tracking

Localization Problem

- In large sensor network systems, sensor nodes need to be able to locate themselves in various environments and on different distance scales.
- The goal is to provide some kind of coordinates to the system and applications.
  - Absolute coordinate
  - Relative coordinate

Localization Algorithms

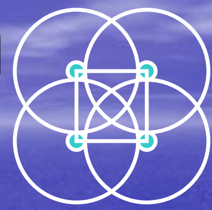
- Centralized [Doherty et al, Infocom'01]
  - Can use global information to improve quality of position estimation
  - Associated cost for collecting topological info.
  - Large computing and communication costs.
- Distributed
  - No single point of failure
  - Load balance
  - Make use of local data
  - Communication limited to small region

Range-based Algorithms

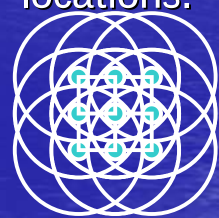
- Widely proposed for wireless sensor networks.
- Key issue is *how to accurately estimate range (e.g., distance)*
- Time-of-arrival (TOA) & Angle-of-arrival (AOA) techniques typically require expensive and energy consuming hardware.
- Received Signal Strength Indicator (RSSI) technology translates signal strength into distance estimates. However, multi-path fading, irregular signal propagation and interference are main challenges.

Centroid Localization

[Bulusu et. al., IEEE PCM 2000]



- Range-free
- Assume a small number of location-aware anchors
- Estimate location by computing the centroid of the audible anchors' locations.
- The granularity of localization becomes finer when increase the overlaps of anchors

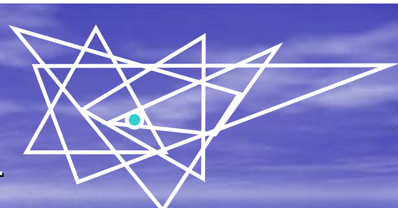


DV-Hop Localization

Niculescu & Nath, GLOBECOM'01]

- Range-free; Assume a small number of location-aware anchors
- All nodes in the network obtain the shortest distance to every anchor
  - Each anchors floods its location with a hop-count to the whole network
  - Hop-count incremented at each hop
  - Each node maintains the minimum hop-count for each anchor
- The system estimates average hop distance based on distance and hop-count among the anchors.
- Use triangulation to estimate location.

APIT Localization



- Range-free
- Assume a small number of location-aware anchors [He et al, MOBICOM03]
- Use the combination of anchor positions to estimate node location
  - Choose three audible anchors to test whether it's inside the formed triangle.
  - Repeat the test till all combination are exhausted or accuracy is achieved.
  - Compute center-of-gravity of intersection to determine its estimated position.

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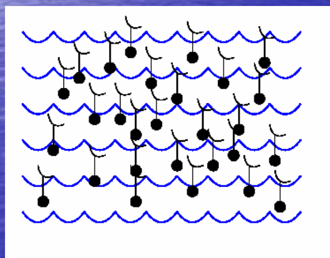
Characteristics of Sensor Networks

- Mobility
- Large number of nodes
- No stable infrastructure



Ocean Sensor Networks

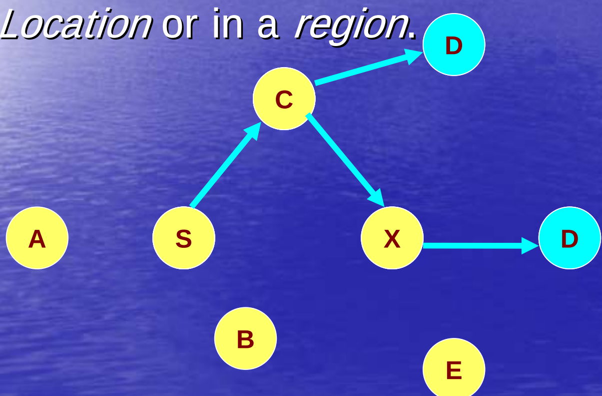
Routing Strategies

- Flooding
- Geographic routing
  - Greedy routing
  - Perimeter or face routing
  - Location services
- Attribute-based routing:
  - Directed diffusion
  - Rumor routing
- Energy-aware routing:
  - Minimum-energy broadcast
  - Energy-aware routing to a region

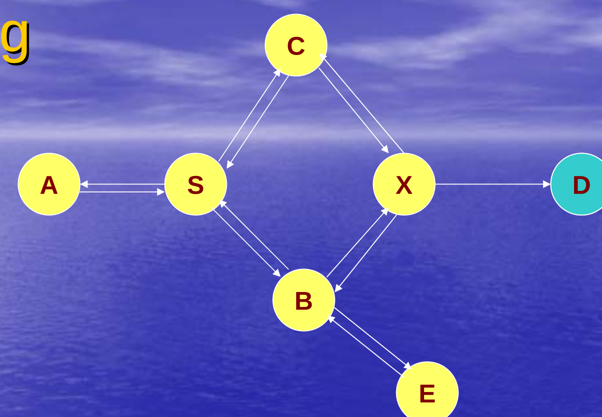
- Mobility
- Large number of nodes
- No stable infrastructure

Problem Formulation

- Given a location-aware sensor network, transmit a packet from source node *S* to a destination node *D* located at/near a *Location* or in a *region*.



Flooding



- Packet will reach every node that is reachable from S, incurring excessive traffic and cost.

Location-Aided Routing (LAR)

- Use physical location information of destination as a guidance to reduce the number of nodes to whom a message (e.g., route request, packet) is propagated.
- Based on flooding in a selected region/path.

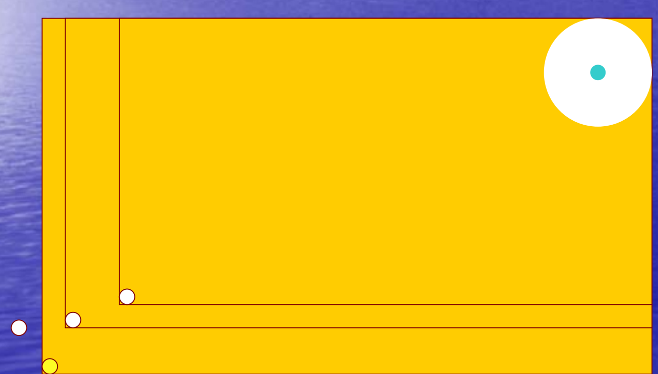
[Ko, MOBICOM98]

Expected and Request Zones

- Expected zone – the region where the message may reach node D (estimated by S)
- Request zone – the region/path sufficient to deliver a message from S to D.
- Key issue – how to determine request zone.

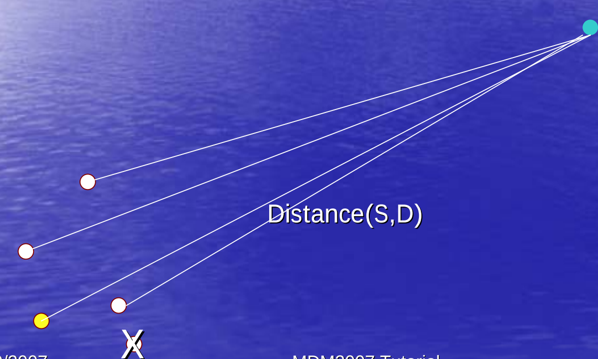
LAR Scheme 1

- Heuristic – the request zone should cover the source node S and the expect zone.



LAR Scheme 2

- Heuristic – Use distance as a greedy function to move towards the destination



Geo-Routing

- *Location* provides a good solution
  - Geographic routing makes packet forwarding decisions based on the position of a packet's destination and next-hop neighbor positions
  - Requires only limited topology information (for only a single hop)
  - Allows nodes to be nearly stateless
- Geo-Routing Protocols for Sensor Networks
  - Greedy Perimeter Stateless Routing (GPSR)
  - Priority-Based Stateless Geo-Routing (PSGR)
  - Trajectory Based Forwarding (TBF)

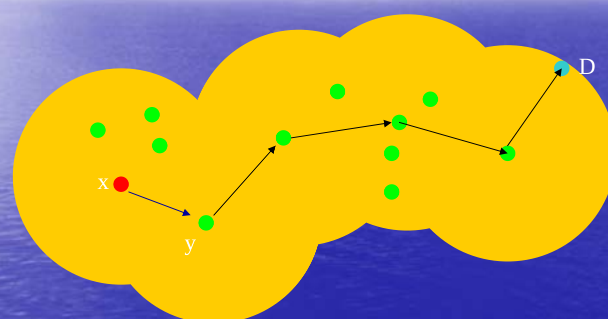
Greedy Perimeter Stateless Routing

- Assumptions [Karp & Kung, MOBICOM00]
  - Source knows its own position
  - Each node knows position of its neighbors by simple beacon message
  - Sources can determine the location of destinations
  - Topologies where wireless nodes are roughly in a plane
- Two packet forwarding modes
  - Greedy Forwarding
  - Perimeter Forwarding

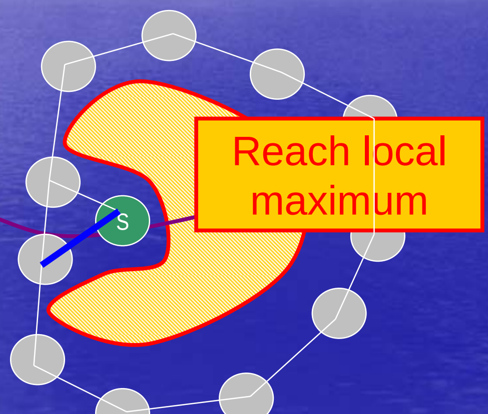
Greedy Forwarding

- Packets are marked by the originator with the destination's location.
- A forwarding node makes a locally optimal, greedy choice in choosing next hop.
  - the locally optimal choice of next hop is the neighbor geographically closest to the packet's destination.
- On a dense network, greedy forwarding approximates to shortest-path routing.

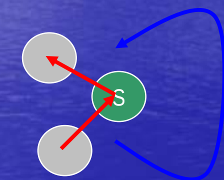
Greedy Forwarding (Illustration)



Communication Void



Perimeter Forwarding

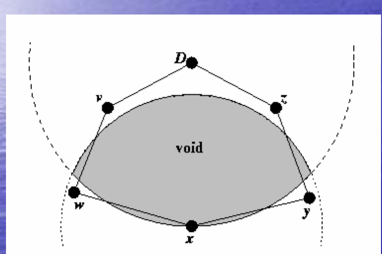


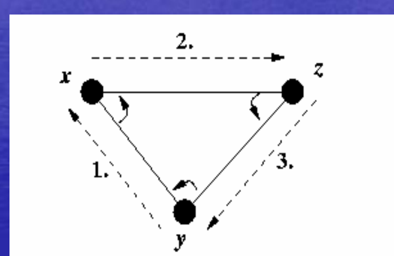
Right Hand Rule:

Each node to receive a packet forwards the packet to the next link counterclockwise about itself from the incoming link

Perimeter Forwarding

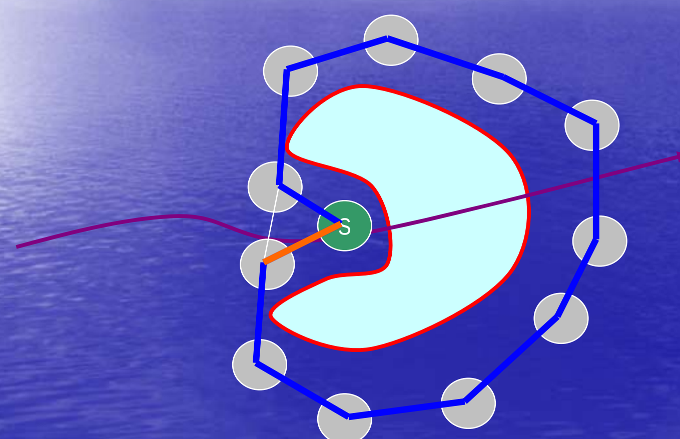
If forward packet using RHR continuously, packet will be forwarded along the perimeter hop by hop, return starting point after a cycle.



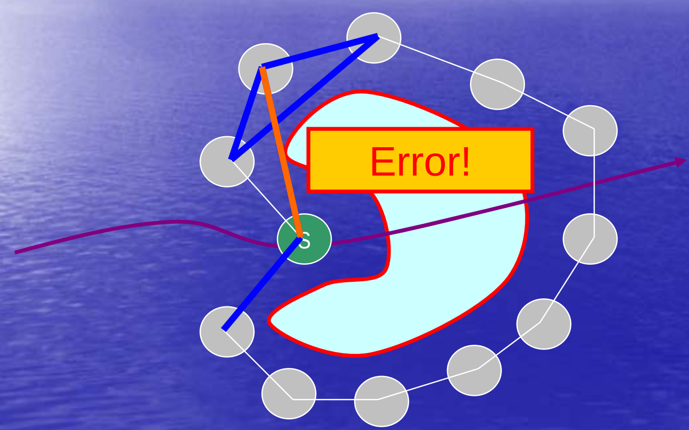


Sequence of edges traversed is called a *perimeter*

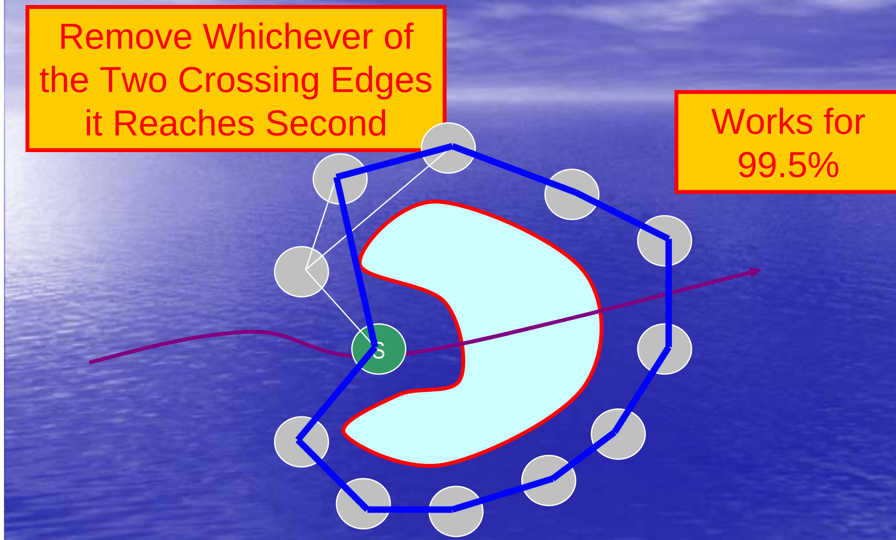
Perimeter Forwarding



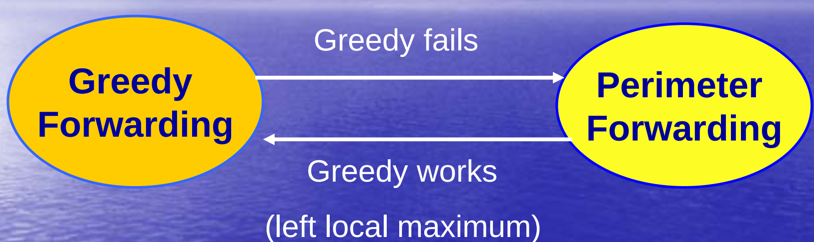
Problem with the Right Hand Rule



The No-Crossing Heuristic



GPSR Routing Modes



- Perimeter forwarding is for recovering from a local maximum.

What happens when *Destination* is not reachable?

- GPSR will forward the perimeter-mode packet until it reaches the corresponding face.
- The packet will tour unsuccessfully around the entirety of the face
- It will reach the node nearest to the destination

Dynamic Sensor Networks

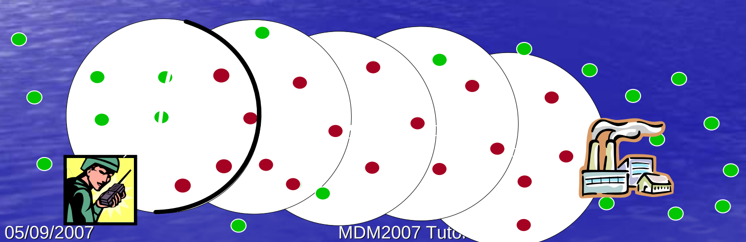
- Wireless sensor networks face network topology transients
  - Possible node failure, movement and energy conservation techniques result in dynamic sensor networks with frequent topology changes.
- Most of geo-routing protocols are stateful, i.e., based on cached location information of neighbor nodes.

PSGR: Priority-based Stateless Geo-Routing [Y. Xu at al, MASS'05]

- Stateful Geo-routing protocols
  - Require states of neighbor nodes for making routing decisions
  - Incurring overhead for dynamic sensor networks
- Truly *stateless* geo-routing protocols are needed for dynamic sensor networks.

Stateless Routing – Volunteer Forwarding

- Probe → Acknowledge → Forward the packet
- Relay node decided by a set of volunteer nodes based on their locations



Technical Issues

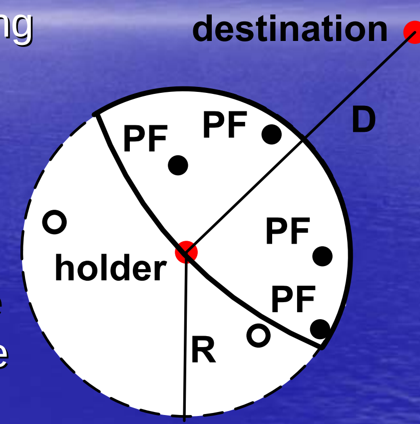
- Communication Collisions
  - Multiple PFs acknowledge the packet holder simultaneously
- Communication Void Problem
  - No PFs inside the forwarding region
- Impact of Transmission Range on Routing Performance

Communication Collisions

- Randomized acknowledgement
- Prioritized acknowledgment
  - Naïve solution:
    - Assign a unique acknowledgement precedence value to each location point, in accordance with a total order relationship.
  - Problem:
    - There is an infinite number of location points

Forwarding Zones

- Divide the forwarding region into forwarding zones.
- Assign Ack precedences to forwarding zones.
- All forwarders in the same zone have the same priority.

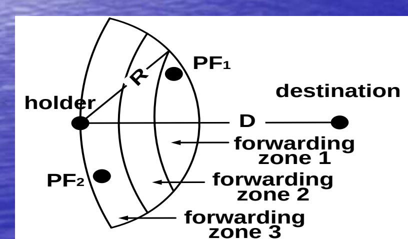


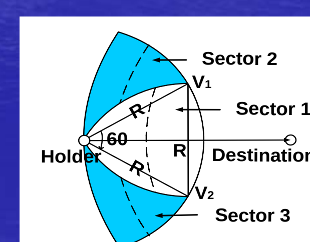
Prioritized Acknowledgement

- Acknowledgement collision has an impact on performance. Thus, the key issue is on-line formation of the forwarding zones.
- Three factors:
  - zone scope
  - zone size
  - acknowledgment timer.

Zone Scope

- The covered area of the forwarding zone
- Heuristic:
  - Distance to the destination (DTD): reduces the number of hops
  - Modified DTD (M_DTD): reduces the ack delay and thus the routing latency

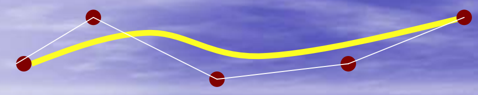




Zone Size and Ack Delay

- Zone Size
  – Zone size is too small → long ack delay
  – Zone size is too large → duplicated ack & delay.
  – Design goal: set the zone size such that only one forwarder in each FZ.
  – Achieved by estimating node density dynamically
- Acknowledgment Delay
  – The time a forwarder waits before it acks.
  – The time should be long enough to accommodate the hop delay, which is obtainable from propagation delay, transmission delay and queuing delay.

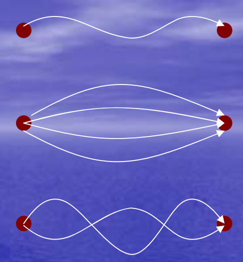
Trajectory Based Forwarding



[Niculescu & Nath, MOBICOM 2003]

- Use a trajectory to guide the packet forwarding.
- A trajectory is established at the source without specifying the intermediate nodes.
- Greedy function based on distance to the trajectory, not to the destination.
- TBF is able to work over a variety of coordinate (positioning) systems.

Applications of TBF



- Unicast Routing
- Multi-Path Routing
- Mobility
- Discovery
- Broadcast
- Multicast

Some Issues in TBF

- How to choose a next hop?
  – Minimum deviation
  – Most forwarding within radius
  – Centroid of feasible set
  – The node with most battery left
  – Random among best three
- How to represent a trajectory?
- How to encode trajectory so nodes can interpret it?

An Issue with Geo-Routing

- The source needs to learn the positions of destination nodes
- Geographic Routing needs a location service!

Possible Designs for a Location Service

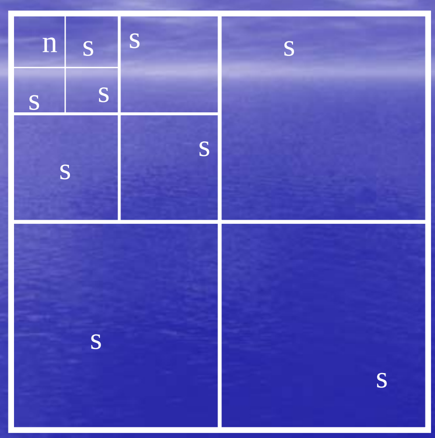
- Flood to get a node's location
  - Excessive messages
- Central static location server.
  - Not fault-tolerant
  - Central server overloaded
- Distributed Location Services
  - Every node acts as server for a few others.
  - Good for load balance and fault-tolerance

Grid Location Service

[Li et al., MOBICOM00]

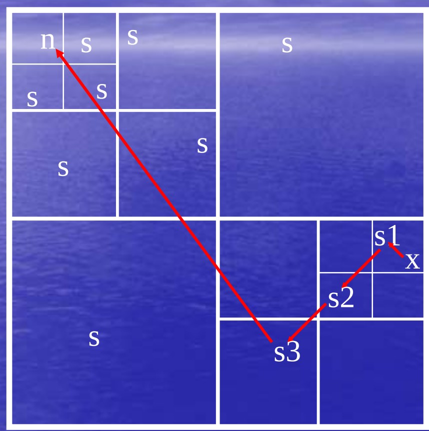
- Organize the space as a hierarchical grid similar to a spatial quad-tree and use distributed sensor nodes as location servers
- Each node has a unique ID, *x*, and several location servers
  - one Location server in each sibling quadrant.
  - the closest successor, the node that has the smallest ID larger than *x*.
- To locate a node *x*
  - Recursively seeking for the closest successor

GLS's Spatial Hierarchy

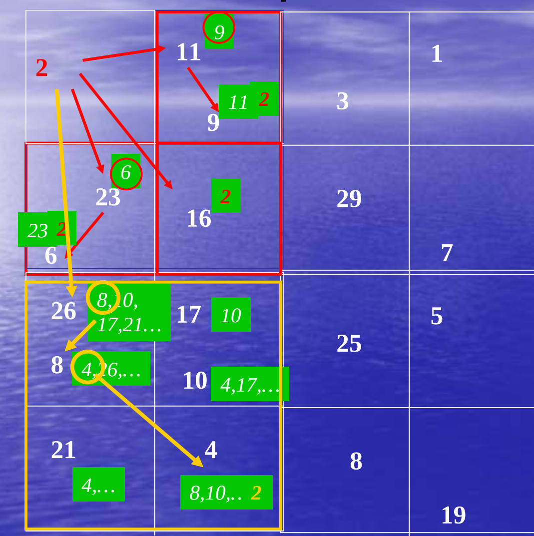


one location server in each sibling quadrant.

Location Lookup

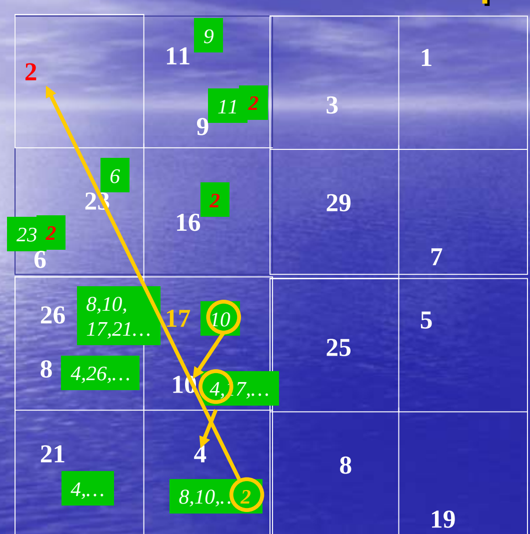


GLS Update



n's successor in each sibling quadrant knows about *n*.

Location Lookup



Node 17 looks for node 2

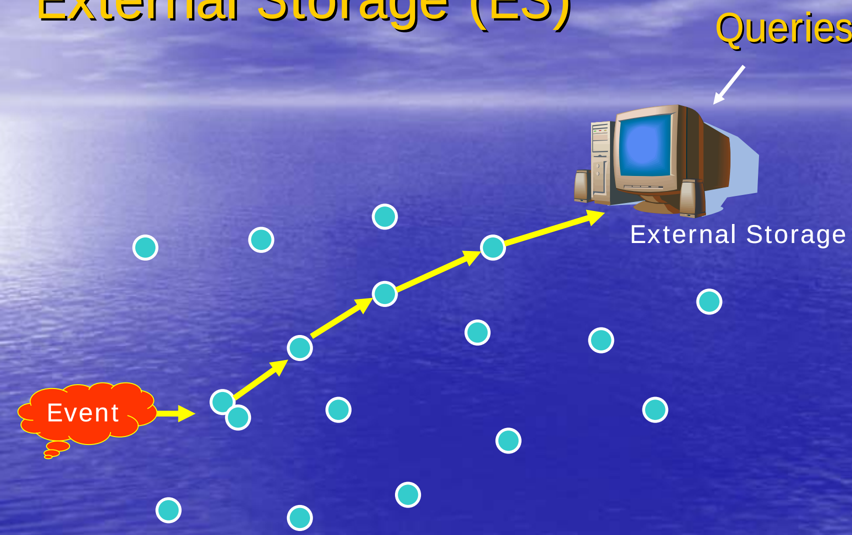
Overview

- Wireless Sensor Networks
- Localization
- Location-Based Routing
  - Routing Protocols
  - Location Services
- Data Management
  - Storage Management
  - Query Processing
- Location Tracking
- Conclusion

Storage Schemes

- External Storage (ES)
  - –Events propagated and stored at an external location (e.g., base station)
- Local Storage (LS)
  - –Events stored locally at the sensor nodes
  - –Queries are flooded to all nodes and the events are sent back

External Storage (ES)

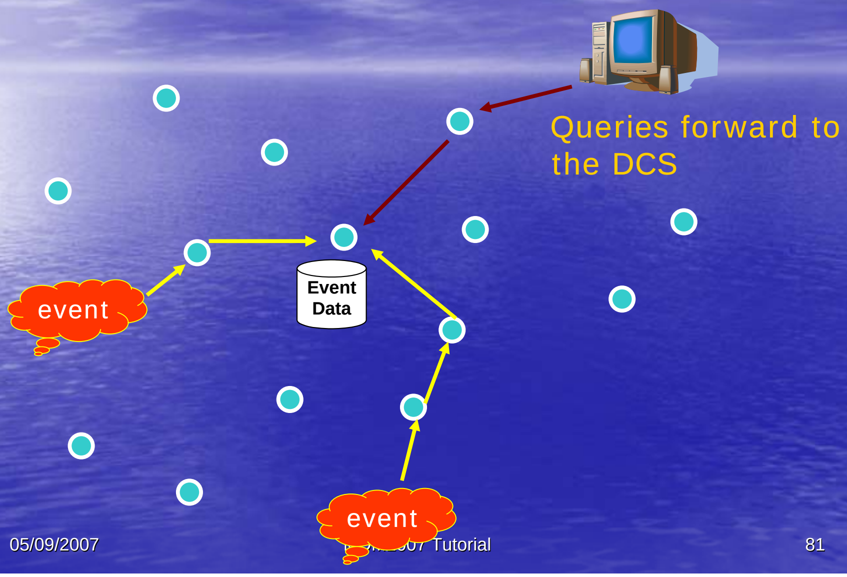


Local Storage (LS)

Data Centric Storage

- Data is stored inside the network
  - – Each attribute or event corresponds to a *location* in space
  - – All data with the same attribute or event will be stored at the same sensor network location
- Queries are directed to the storage node

Data Centric Storage



Assumptions in DCS

- Large Scale networks whose approximate geographic boundaries are known
- Nodes have short range communication and are within the radio range of several other nodes
- Nodes know their own locations
- Communication to the outside world takes place by one or more access points

Why Data centric Storage?

- Energy efficiency
- Robustness
- Scalability

Geographic Hash Tables (GHT)

[Ratnasamy et al, WSNA 2002]

- Based on Geo-Routing
- Similar to DHT in P2P Networks
  - Every node is aware of the hash function
- Hash attributes to specific geographic locations in the network
- Queries are routed to the relevant locations
- Load balanced via hashing

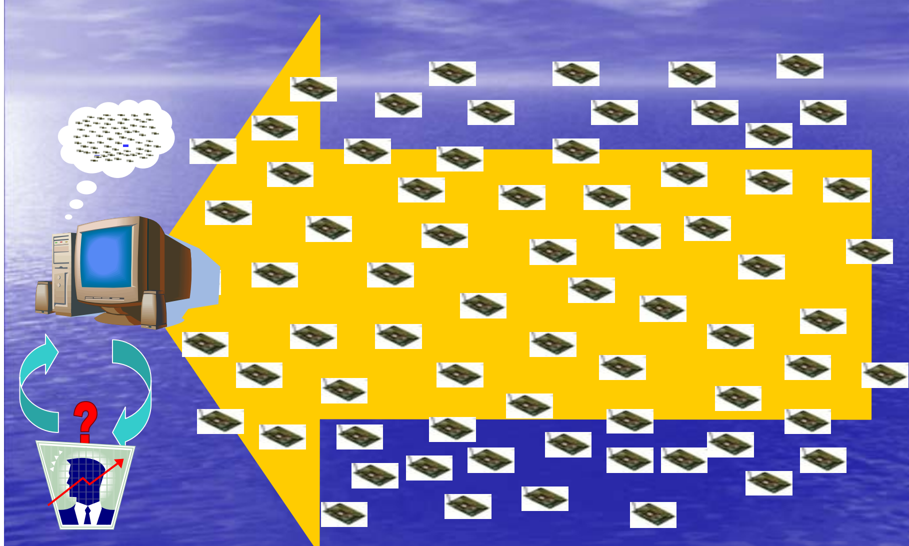
GHT & Geographic Routing

- The nodes associated with an attribute value are the ones that form the perimeter around the hashed location
- One of them is selected as a home node
  - Node closest to the location
  - Determined by going through the cycle
  - Recomputed periodically to allow for changes

Spatial Query Processing

- In most of applications, we are more interested in the sensed data associated with certain *locations* rather than specific sensor nodes.
- Spatial query processing has been extensively studied in the DB community.
- How do we process spatial queries in location-aware WSN?
  - Window Query
  - K Nearest Neighbor Query

External Storage Approach

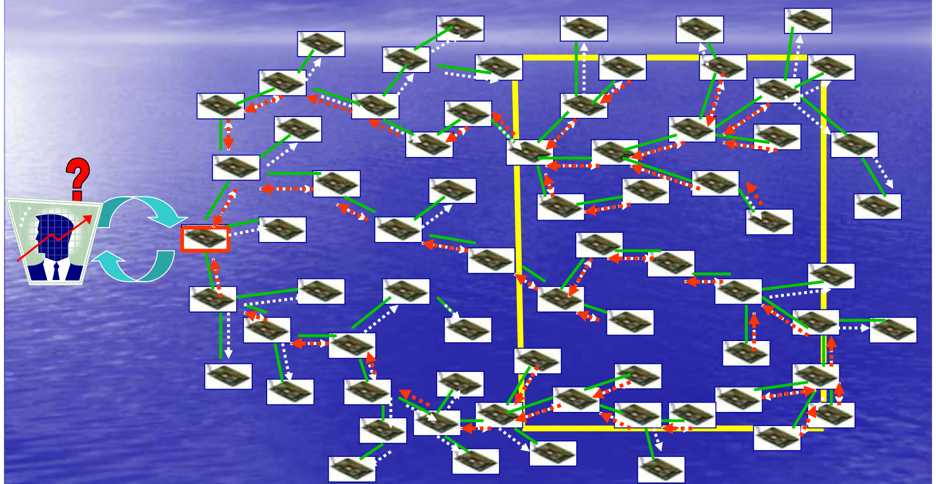


Local Storage Approach

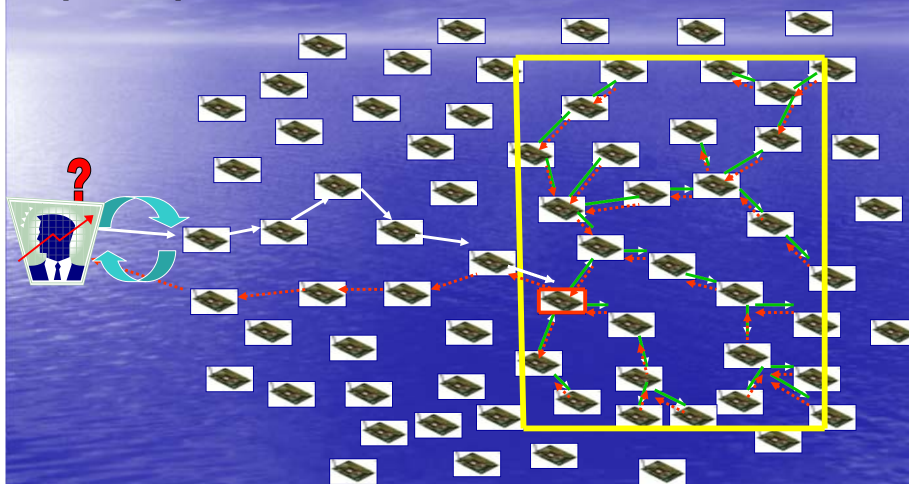
An Execution Plan

1. Forwarding the query toward the specified query window
2. Propagating the query inside the window
3. Collecting and aggregating the data inside the window
4. Returning the query result back to the user

Network Spanning Infrastructure (NSI)



Window Spanning Infrastructure (WSI)



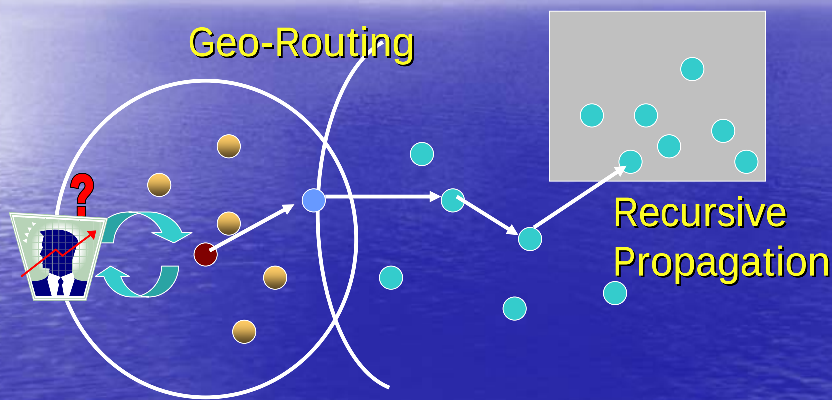
Infrastructure-free Approach

- Infrastructure-based approach
  - E.g., NSI & WSI
  - Susceptible to network topology changes
- Infrastructure-free approach
  - Flooding
  - Recursive propagation
  - Itinerary-based propagation
  - Resilient to the network topology transitions

Geographic and Energy Aware Routing (GEAR) [Yu et. al., UCLA TR 2001]

- Address both of query routing and propagation issues
- Taking energy expense into consideration
- Each node knows its position and remaining energy level
- Each node knows its neighbors' position (beacon) and their remaining energy levels
- Links (Transmission) are bi-directional

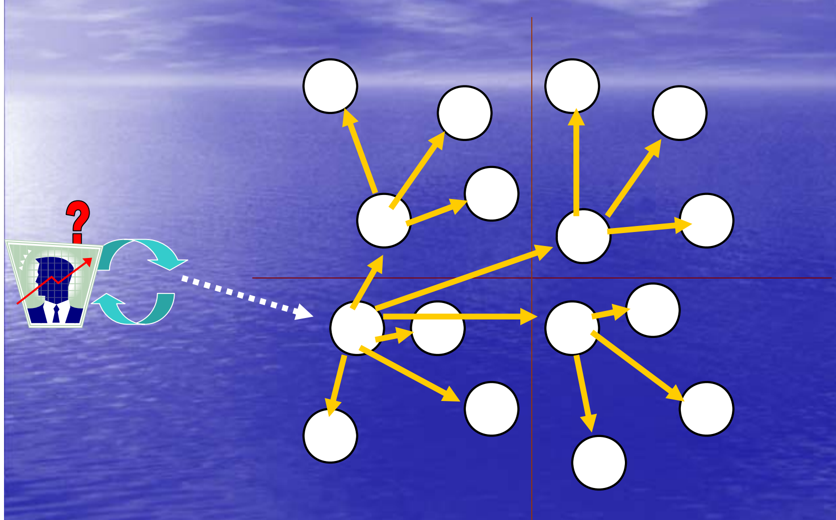
GEAR



Propagate the Target Region

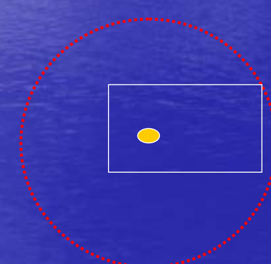
- Node density is high in target region
  - flooding is expensive in terms of energy consumption
  - recursive geographical forwarding
- Node density is low in target region
  - recursive geographical forwarding will not terminate
  - strict flooding

Recursive Propagation

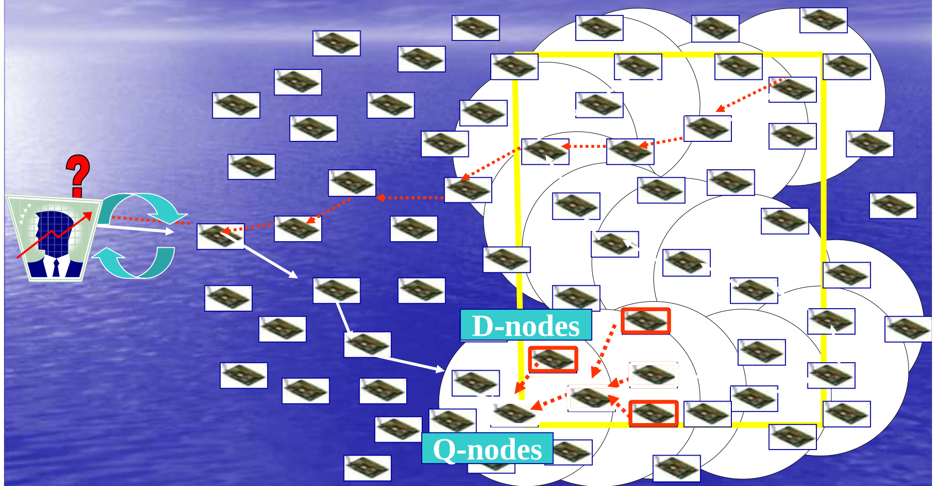


Terminate Condition

- The current node is the only node in sub-region
- The whole sub-region is covered by the radio

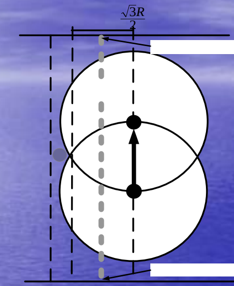


Itinerary-based Window Query Execution (IWQE) [Y. Xu et. al., ICDE05]

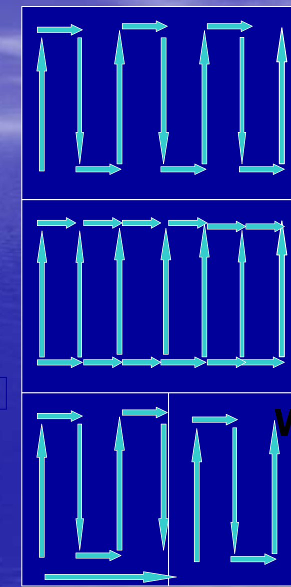


Technical Issues

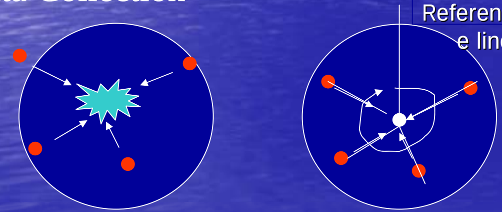
Itinerary Width



Itinerary Routes



Data Collection



Width :

S-II

Missing

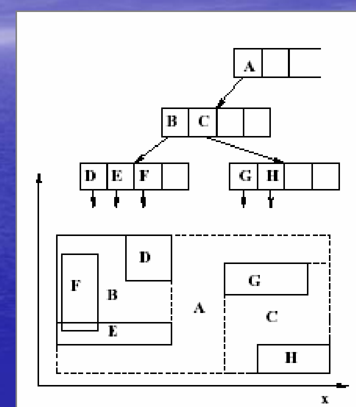
K Nearest Neighbor Queries

- Tree-based query processing
  - Peer tree
- Ad hoc based query processing
  - KPT tree
- Itinerary based query processing
  - IKNN

Peer-Tree

[Demirbas et. al., P2P 2003]

- Distributed index structure based on R-tree
- Designed to support Spatial queries such as window and nearest neighbor queries



KNN Queries on Peer-Tree

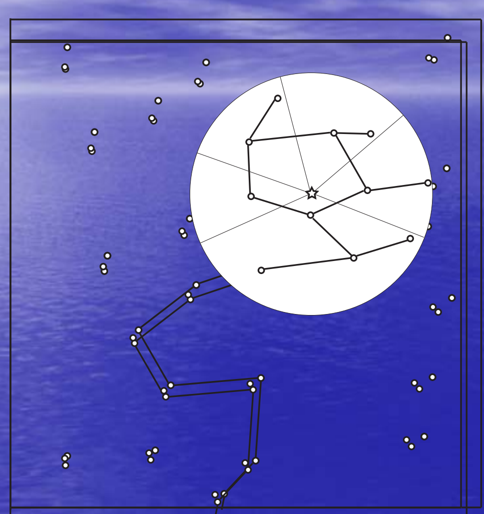
- Query inserted into network to source node nearest to user
- Query forwarded to query root
- Traditional *branch-and-bound* KNN algorithm can run on Peer-Tree
- Results obtained by root are transmitted back to source node

Ad-hoc KNN queries

[J. Winter et. al., MSDN2004, Mobiquitous 2005]

- GPSR will actually find the node nearest to the destination
  - The KNN query is routed to the Nearest Neighbor (home node) of query point
- a bounded search structure (called KPT) constructed around home node
  - Nodes within a bounded region participate in trees rooted at perimeter nodes and receive query from parent

An Illustration



KPT Search Boundary

- Seek minimal spatial search boundary centered at *q* that contains KNN
- Boundary is computed while query travels to home node
- SUMDIST
  - Maintain k nearest locations of forwarding nodes
  - Boundary computed as k-th NN location to *q*
- MHD (Maximum Hop Distance)
  - Maintains largest hop distance on path to home
  - Boundary computed as k * MHD

Deficiency in Existing Solutions

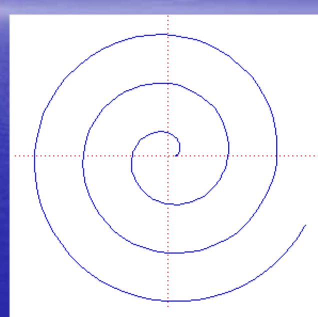
- Sensor network is a dynamic and resource-scared network
  - Centralized approach is too expensive
  - Distributed index approach also involves many update/maintenance overhead.
  - Localized KPT: better than the above twos, but estimating the region is difficult.

Itinerary based KNN query processing (IKNN) [Y. Xu et. al., Sig. Processing]

- Similar to IWQE, query propagation and data collection are performed along an itinerary.
- Does not require an index structure
- Does not estimate a region that encloses KNN
- Query processing automatically stops when KNN are collected

Basic Idea

- IKNN does not have a pre-specified query region. Thus, we consider a new itinerary, called Archimedean spiral.
- The center should be the query point or the node closest to the query point
- The processing stops when KNN are collected



Optimization

- Process the query in *parallel* in order to reduce the latency.
- Parallel threads need to meet periodically to check the partial query result

Overview

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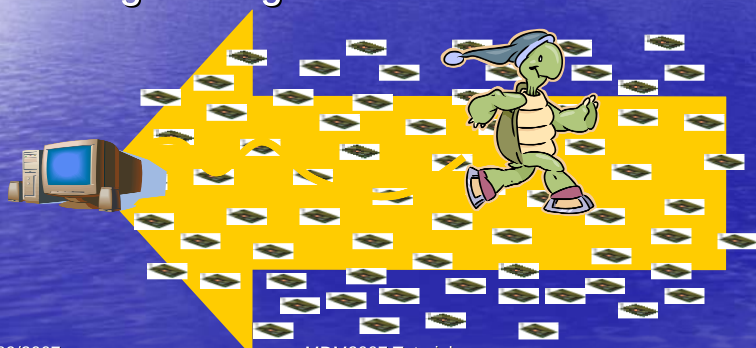
Location Tracking

- Many sensor network applications require monitoring and tracking objects, events and phenomenon
  - E.g., *intrusion detection, animal tracking, etc.*
- Object tracking is considered as a killer app for sensor networks
- *Location* is particularly interested
- Energy efficiency issue is very important for sensor networks

Centralized Approach

- (External) Centric Storage
- Sensor nodes send their readings to the base station periodically or when the readings change.



Prediction Based Monitoring (PREMON)

- Sensors in close proximity are likely to have correlated readings
- Base Station makes a prediction of object location and sends it to the appropriate sensor nodes
- A sensor transmits its reading only when the reading is different from the predicted one
- Trading computation for communication

Dual Prediction

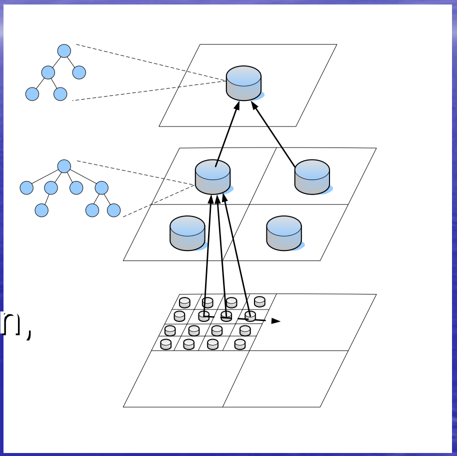
[Y. Xu et. al., Mobiquitous 2004]

- Predict the next move (i.e., location) of objects and wake up the corresponding sensors
- Predictions made at both of Sensor nodes and Base Station
  - Needs location history for prediction, i.e., location history is passed from a sensor node to the next sensor node.
  - Needs to synchronize predictions between nodes and base station
- Sensor node sends detected (actual) location information to base station if prediction is inaccurate

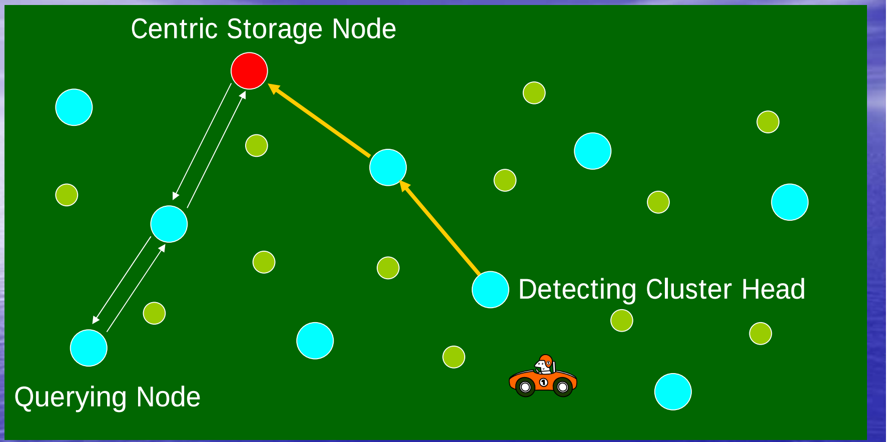
In-Network Mining

[Peng et. al., MDM 2006]

- Accuracy of prediction is key for prediction based object tracking sensor networks
- Use a hierarchical tracking model to facilitate data collection, data mining and prediction



Centralized Approach



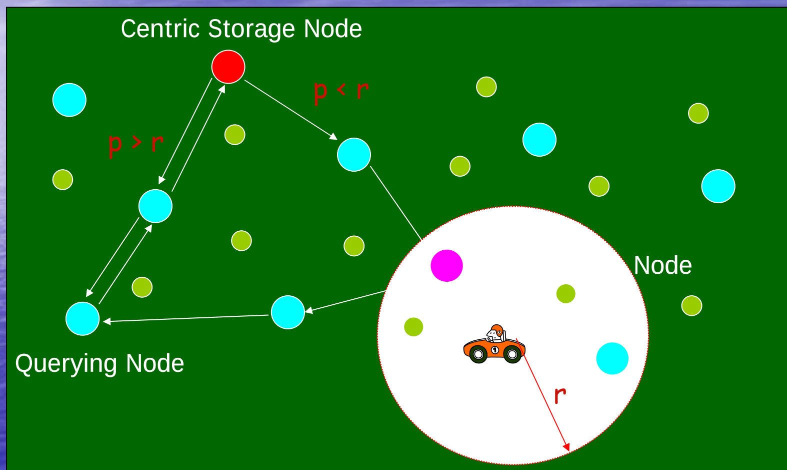
- High-precision location incurs high update cost.
- Not all applications require high-precision location.

Energy-conserving Approximate StoragE (EASE)

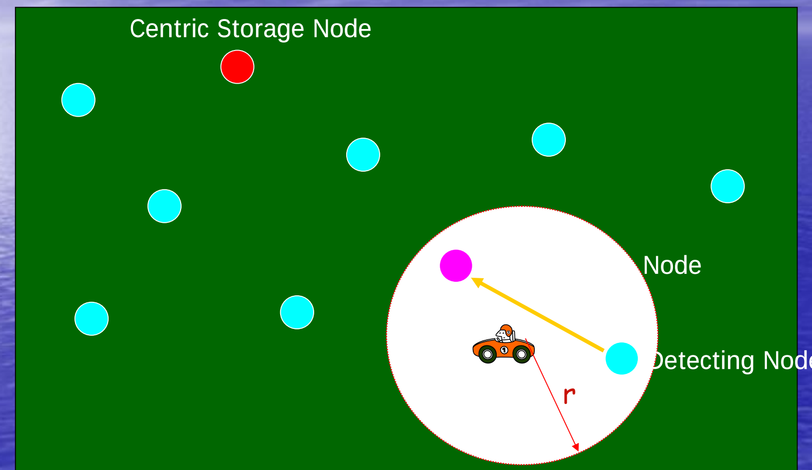
[J. Xu et. al., SECON 2005]

- Maintain two versions of location data:
  - High-precision data at local storage node
  - Low-precision data at centric storage node, bounded by certain error (referred to as approximation radius)
- Role of centric storage node
  - Storage server of error-bounded low-precision data
  - Index server of current local storage node (changes as the object moves)

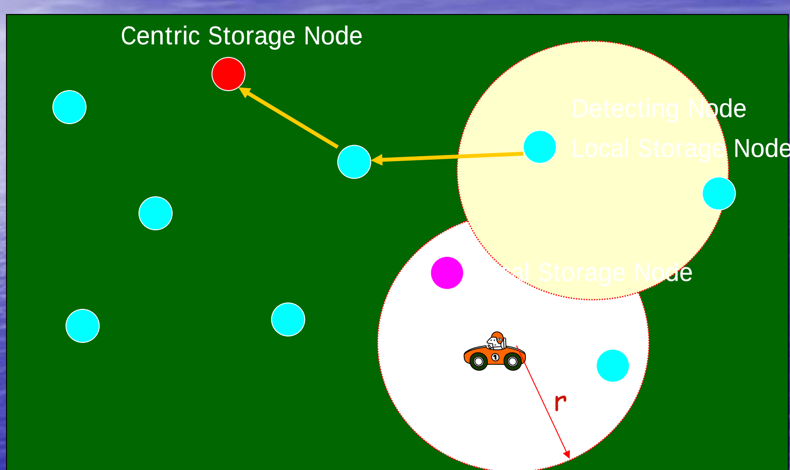
Energy-conserving Approximate StoragE (EASE)



Updating Protocol – Local Update



Updating Protocol – Remote Update



Conclusion

- Wireless sensor networks have attracted a lot of research interests
- There is a need for network functionalities designed with emphasis on their spatial/location property
- Reviewed existing works in localization, geo-routing, spatial query processing and location tracking
- Research effort is still need to realize location-aware wireless sensor networks

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