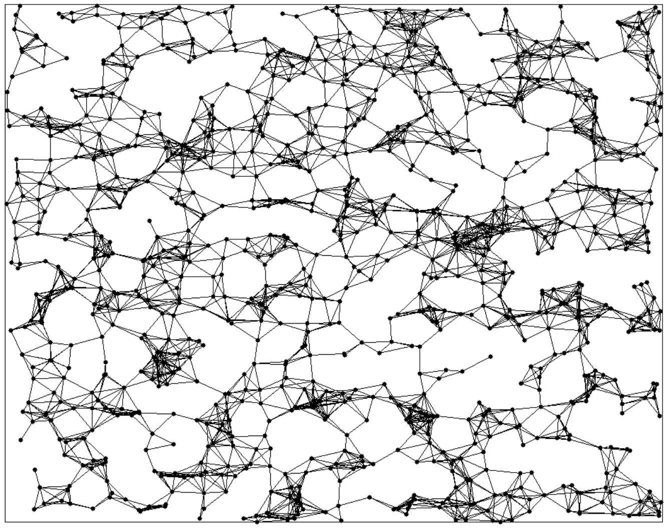
An Introduction to Wireless Sensor Networks



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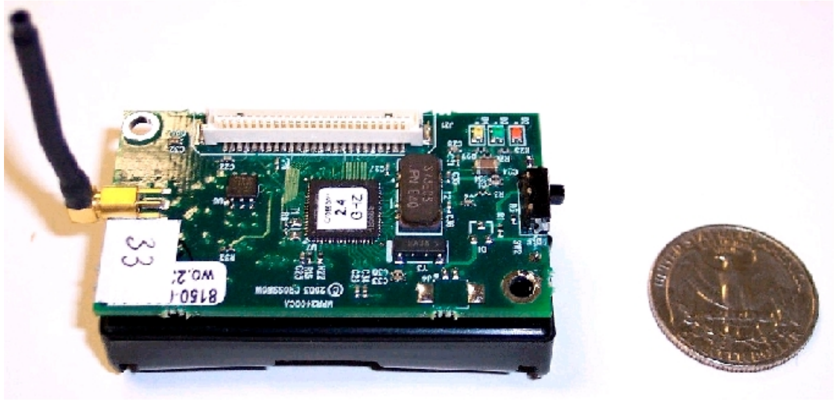
Tutorial Presented at the Second International Conference on Intelligent Sensing and Information Processing (ICISIP), Chennai, India, January 2005.

Overview

Wireless Sensor Networks (WSN)

- The “many - tiny” principle: wireless networks of thousands of inexpensive miniature devices capable of computation, communication and sensing

- Their use throughout society “could well dwarf previous milestones in the information revolution”: U.S. National Research Council Report, 2001.



Berkeley Mote (MICAz MPR 2400 Series)

Timeline

- 1970’s: Wired sensors connected to central location
- 1980’s: Distributed wired sensor networks
- 1993: LWIM project at UCLA
- 1999-2003: DARPA SensIT project: UC Berkeley, USC, Cornell etc.
- 2001: Intel Research Lab at Berkeley focused on WSN
- 2002: NSF Center for Embedded Networked Sensing
- 2001-2002: Emergence of sensor networks industry; startup companies including Sensoria, Crossbow, Ember Corp, SensiCast plus established ones: Intel, Bosch, Motorola, General Electric, Samsung.
- 2003-2004: IEEE 802.15.4 standard, Zigbee Alliance.

Wireless Sensor Networks (WSN)

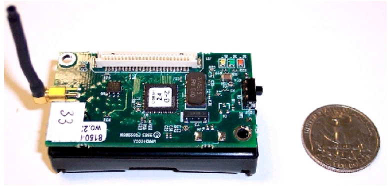
- Provide a bridge between the real physical and virtual worlds

- Allow the ability to observe the previously unobservable at a fine resolution over large spatio-temporal scales

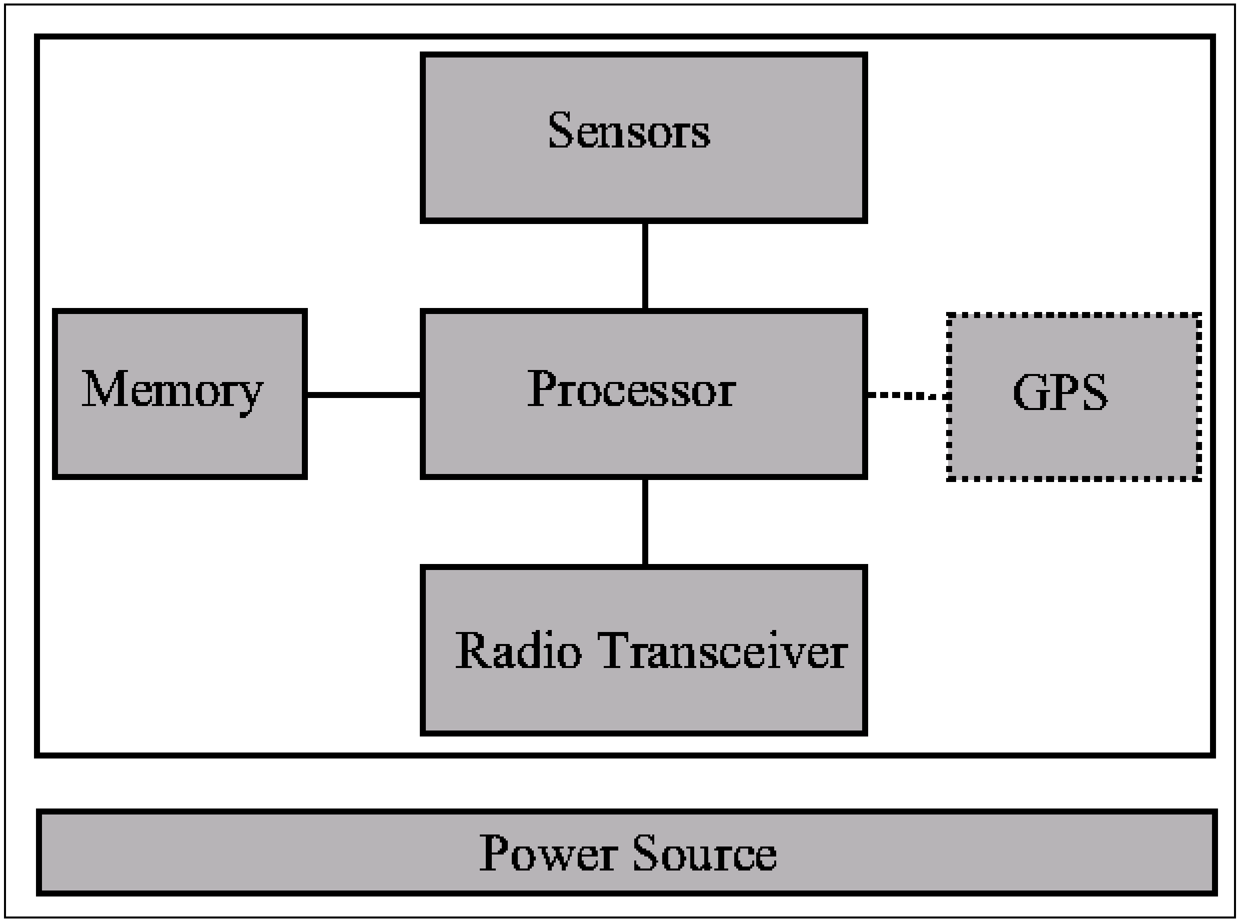
- Have a wide range of potential applications to industry, science, transportation, civil infrastructure, and security.

Some Sample Applications

- Habitat and Ecosystem Monitoring
- Seismic Monitoring
- Civil Structural Health Monitoring
- Monitoring Groundwater Contamination
- Rapid Emergency Response
- Industrial Process Monitoring
- Perimeter Security and Surveillance
- Automated Building Climate Control



Basic Components of a WSN Node



Challenges

- Energy Efficiency
- Responsiveness
- Robustness
- Self-Configuration and Adaptation

Challenges (contd.)

- Scalability
- Heterogeneity
- Systematic Design
- Privacy and Security

Outline for the Rest of the Tutorial

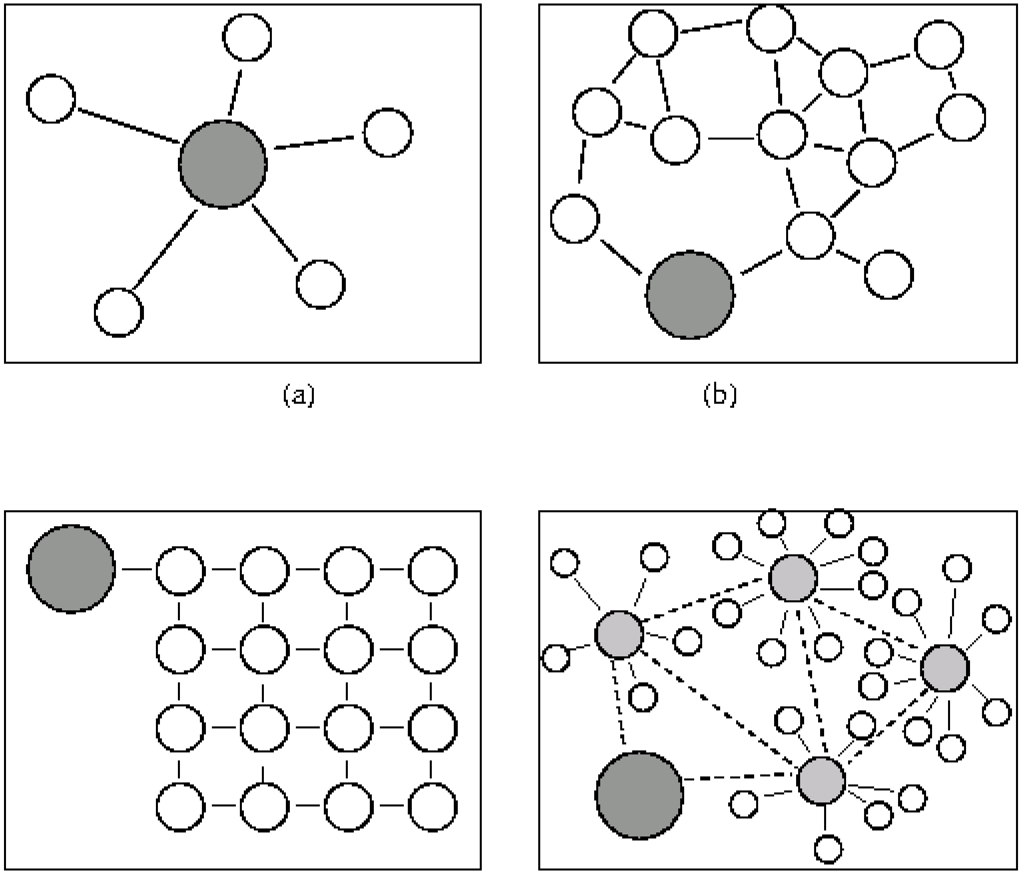
- Deployment
- Localization
- Time Synchronization
- Wireless Link Characteristics
- Medium Access
- Sleep Based Topology Control
- Routing
- Data Centric Networking
- Transport

Deployment

Deployment Issues

- Structured versus Randomized Deployment
- Overdeployed versus Incremental Deployment
- Connectivity and Coverage Metrics of Interest

Network Topologies



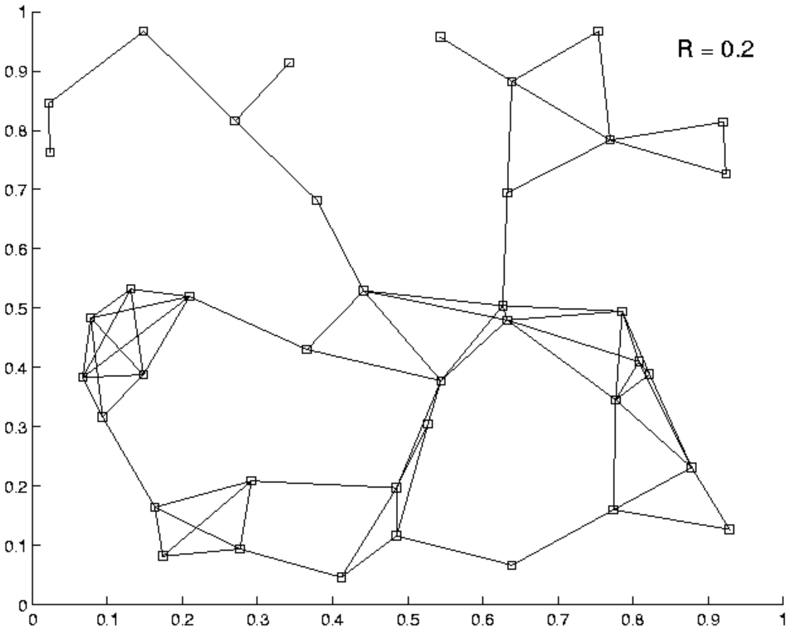
(a) (b)

(c) (d)

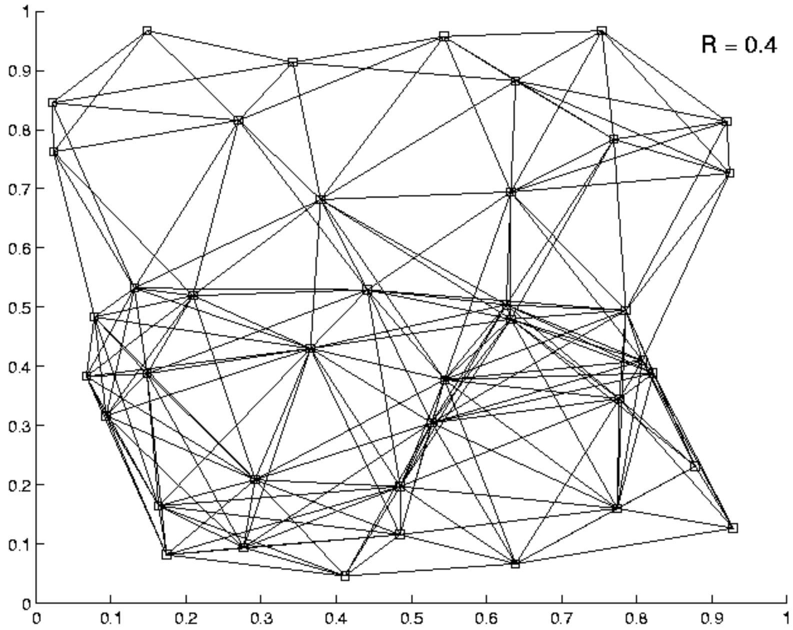
Random Graph Models

- For some applications, WSN nodes could be scattered randomly (e.g. from an airplane)
- Random Graph Theory is useful in analyzing such deployments
- The most common random graph model is G(n,R): deploy n nodes randomly with a uniform distribution in a unit area, placing an edge between any two that are within Euclidean range R.

Geometric Random Graph G(n,R)



sparse

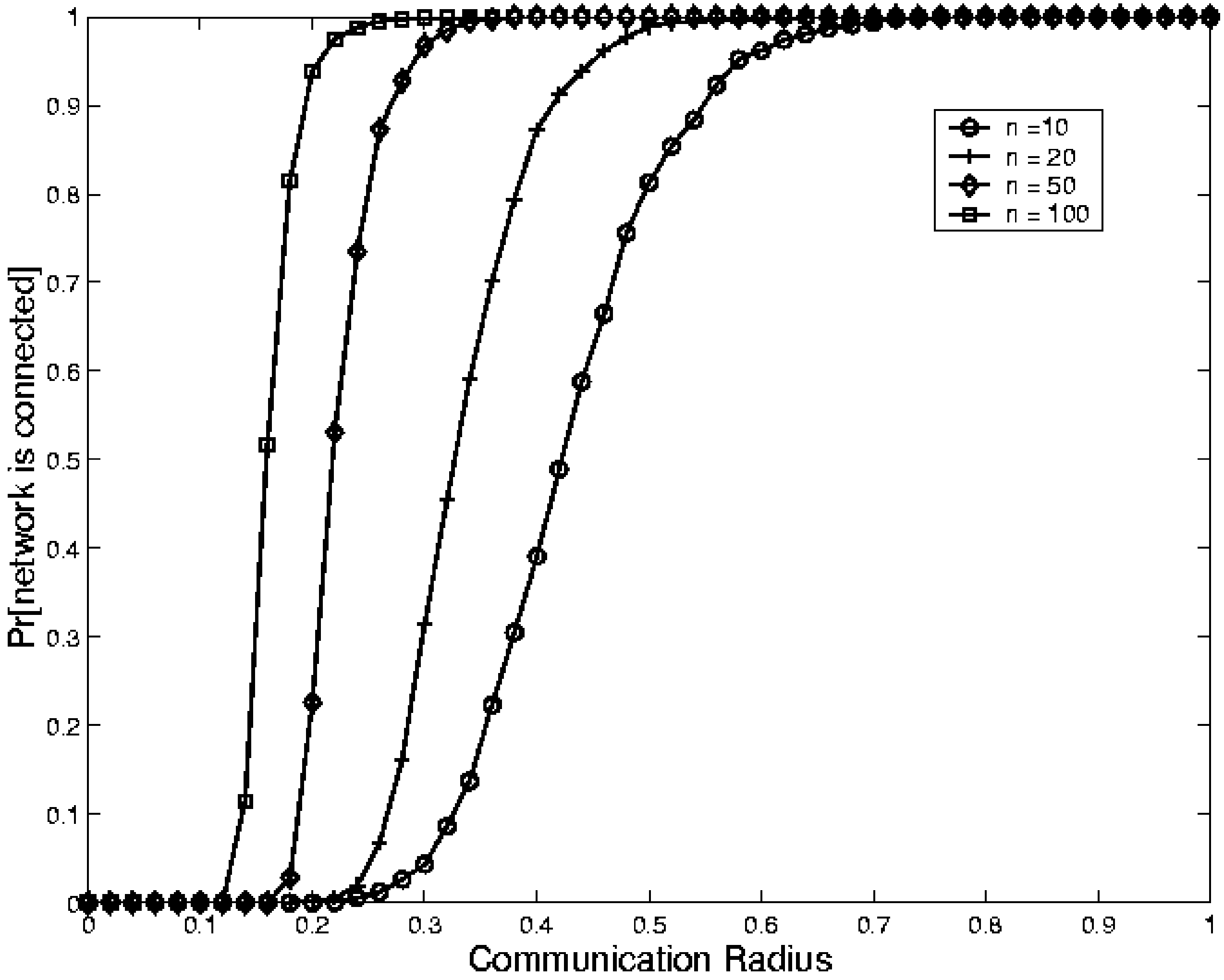


dense

Some Key Results

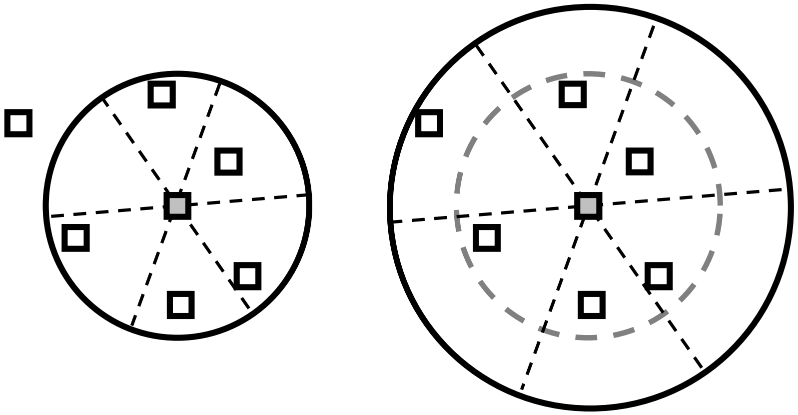
- All monotone graph properties have an asymptotic critical range R beyond which they are guaranteed with high probability *(*Goel, Rai, and Krishnamachari *'04)*
- The critical range for connectivity is $O(\sqrt{(\frac{\log n}{n})})$ (Penrose '97, Gupta and Kumar '98)
- The critical range to ensure that all nodes have at least k neighbors also ensures k-connectivity w.h.p. (Penrose '99)

Connectivity in G(n,R)



Power Control

- Provides a degree of flexibility in configuring the network connectivity after deployment.
- Must carefully balance several factors, including connectivity, energy usage, and interference.



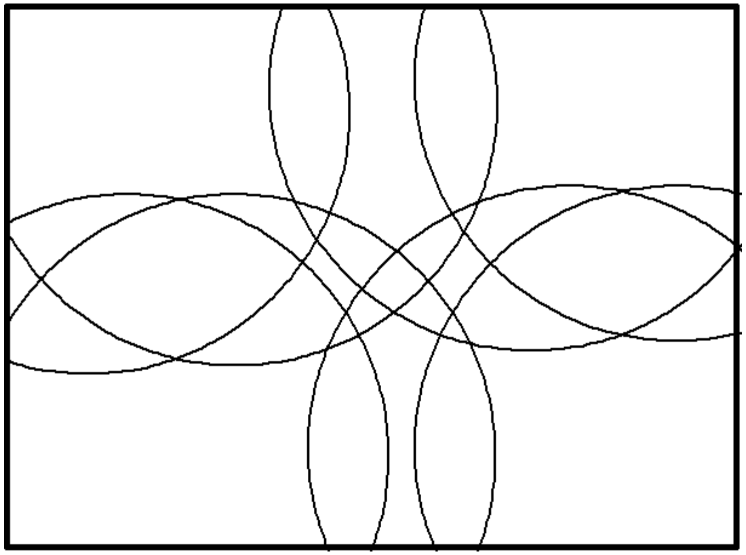
- The CBTC (Li *et al.* '01) provides a distributed rule for global connectivity: increase power until there is a neighbor within range in every sector of angle $\alpha \leq 5\pi/6$

Coverage Metrics

- Much more application specific than connectivity.
- Some that have been studied in particular detail are:
  - Path observation metrics: An example of this is the maximal breach distance, defined as the closest any evasive target must get to a sensor in the field (Meguerdichian *et al.* ‘99)
  - K-Coverage: ensure that all parts of the field are within sensing range of K sensors (e.g. Wang *et al.* ‘03)

Key Results on K-Coverage

- A field is K-covered if and only if all intersection points between sensing circles are at or inside the boundary of K+1 sensing circles. (Wang *et al. '03*)
- If a region is K-covered by n sensors, they also form a K-connected graph if their communication range is at least twice the communication range. (Wang *et al. '03*)



A 2-covered region

Localization

Localization Issues

- Location information necessary/useful for many functions, including measurement stamps, coherent signal processing, cluster formation, efficient querying and routing.

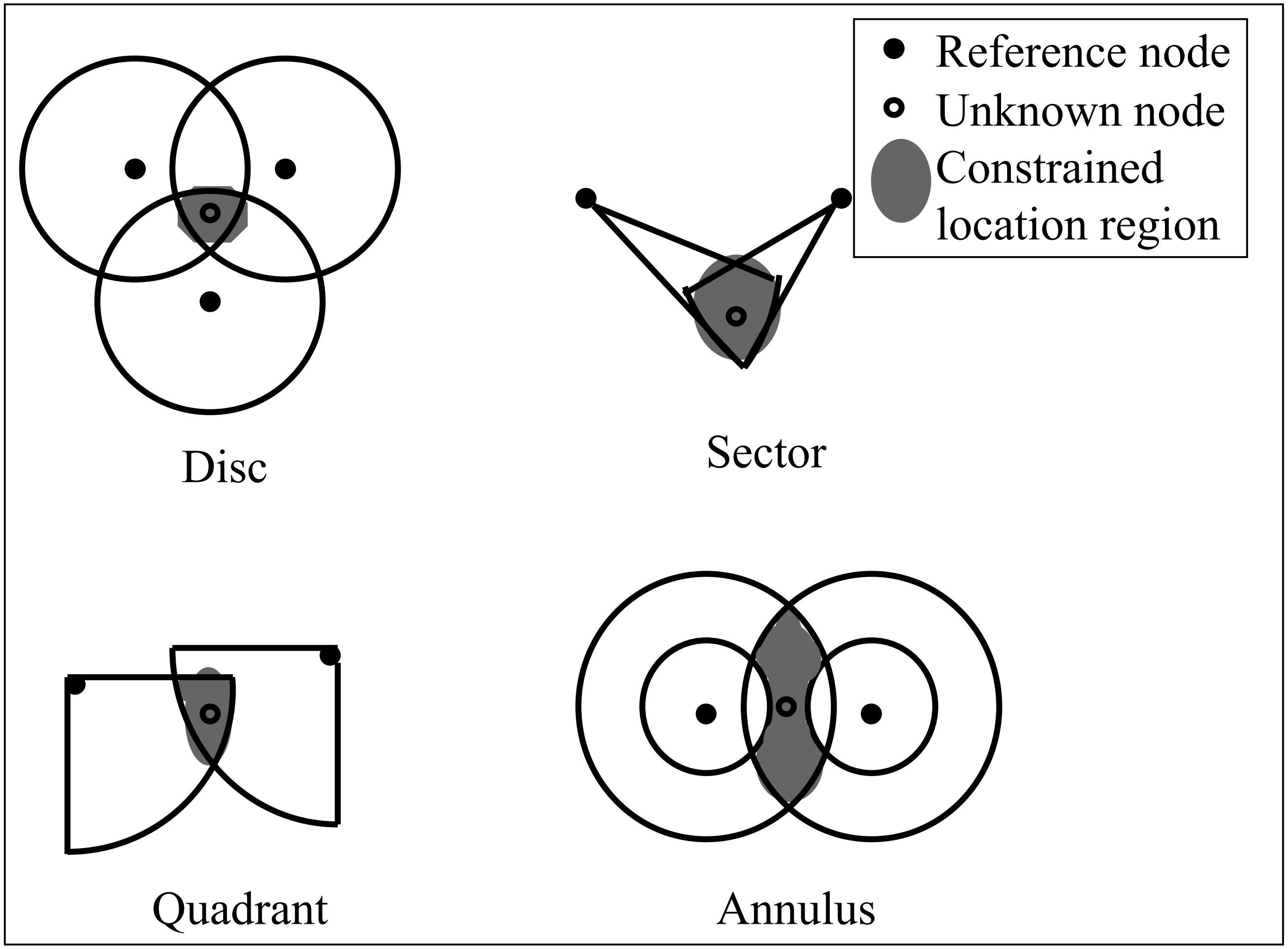
- Key Questions:
  - What to localize?
  - When to localize?
  - How well to localize?
  - How to localize?

Coarse Grained Node Localization

Several techniques provide approximate solutions for node localization based on the use of minimal information:

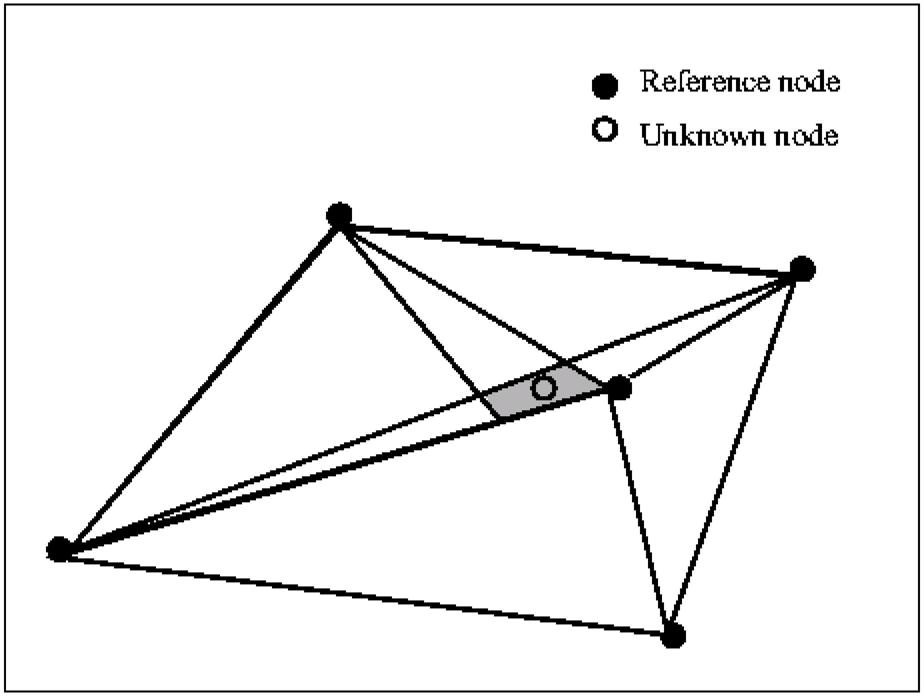
- Proximity
- Centroids
- Geometric Constraints
- APIT
- Identifying Codes

Geometric Constraints



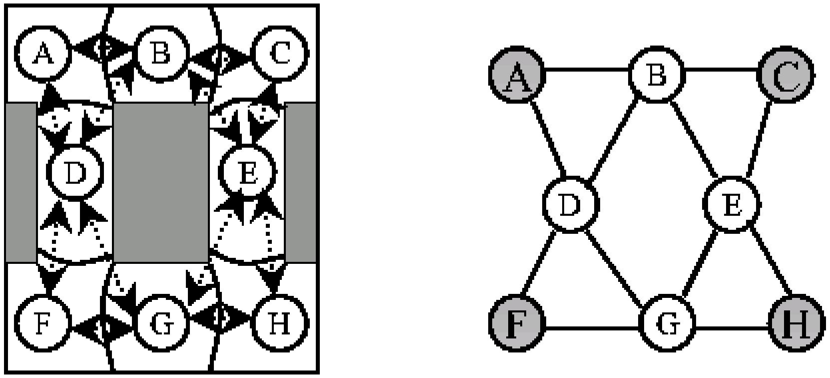
(Doherty, Pister and Ghaoui '01)

Approximate Point in Triangle (APIT)



(He, Huang, *et al.* *‘03*)

ID-Codes



Node Locations

Connectivity Graph

Transmitters A, F, C, H provide unique IDs for all node locations

V:	A	B	C	D	E	F	G	H
ID:	A	A,C	C	A,F	C,H	F	F,H	H

(Ray *et al.* *'03*)

Fine-Grained Node Localization

- Basic Approach: Ranging
  - ranging using radio signal strengths (m-level accuracy)
  - ranging using time difference of arrival (cm-level accuracy over short distances)

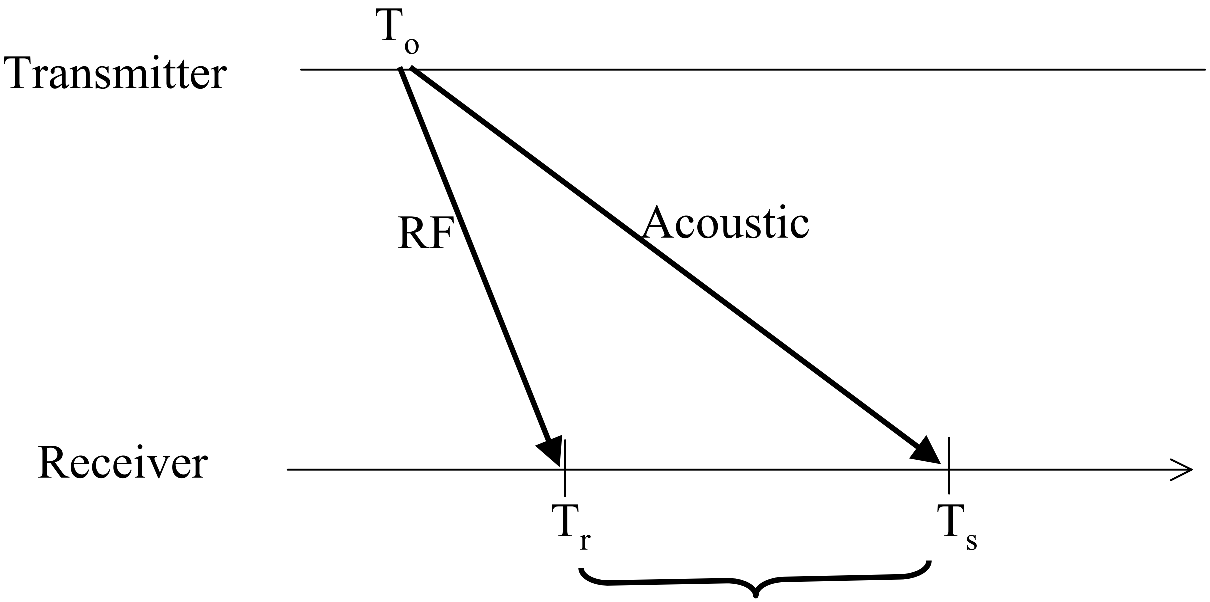
- Position estimation is then an MMSE problem:

$$E_j = R_{i,j} - \sqrt{}\,((x_i-x_j)^2+(y_i-y_j)^2)$$

Find (xi,yi) to minimize $\Sigma\,(Ej)^2$

- Angle of arrival techniques are particularly useful in conjunction with ranging

Time Difference of Arrival



T_o

Transmitter

RF

Acoustic

Receiver

T_r

T_s

Distance $\cong (T_r - T_s) \cdot V_s$

Fine-Grained Node Localization (contd.)

- Pattern matching techniques such as RADAR (Bahl and Padmanabhan, ‘00) require pre-training of signal strengths at different locations in the environment.

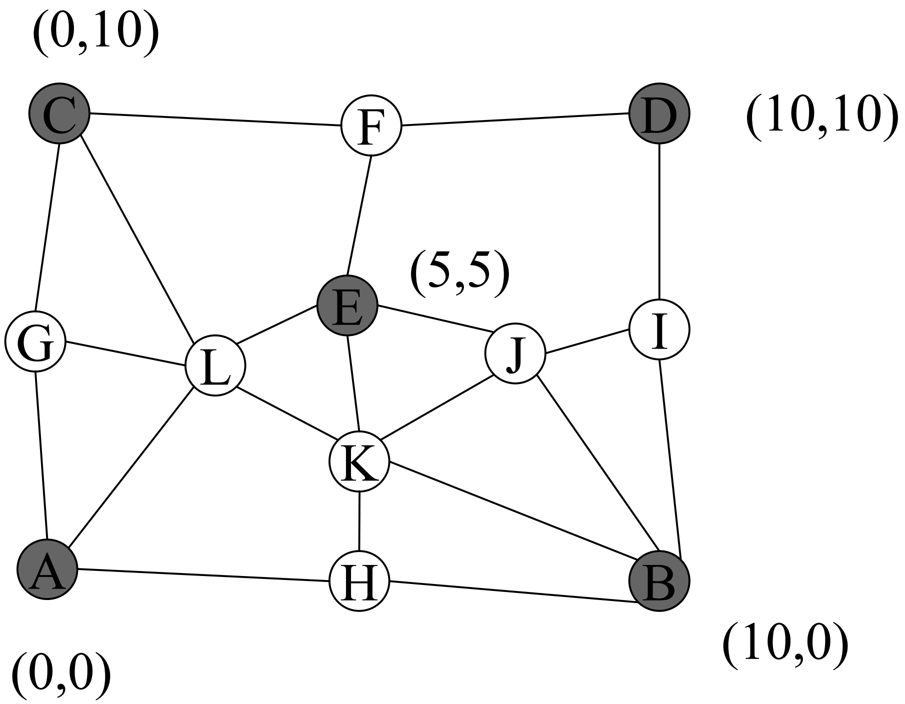
- Ecolocation (Yedavalli *et al.* ‘04) is based on sequence decoding.
  - Record the received signal strengths at different reference nodes from a given unknown node, and order these into a sequence
  - Return as the unknown node’s location the location that “best matches” the measured sequence

Network Localization

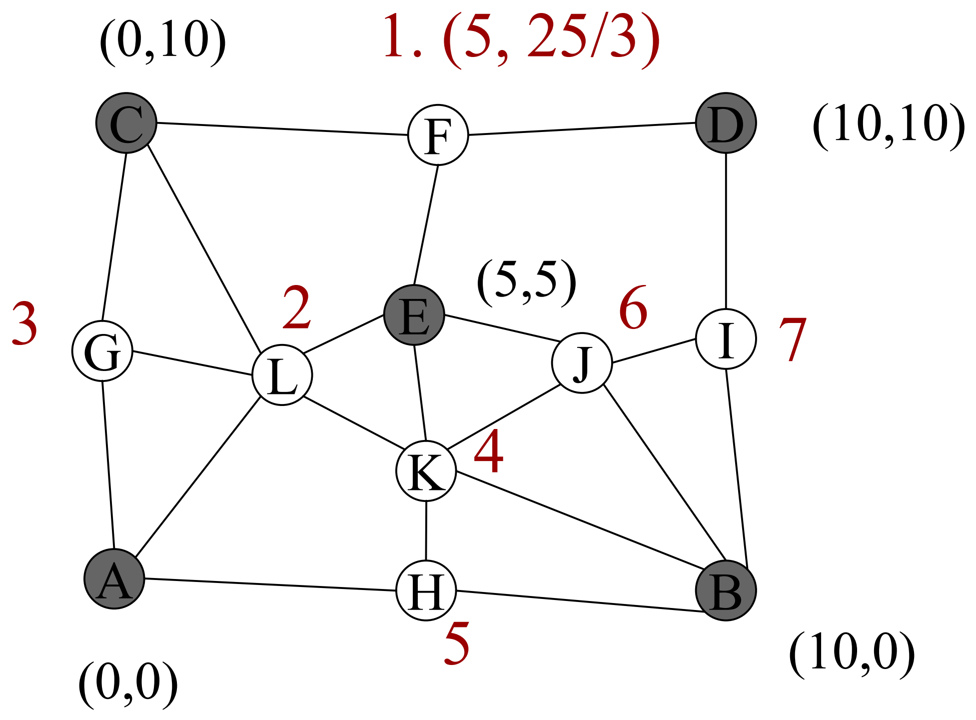
- Different from node localization. Few reference nodes and several networked unknown nodes.

- Several approaches:
  - Constraint satisfaction/optimization (centralized)
  - Joint estimation using ranging estimates (centralized)
  - Multihop distance estimation (distributed)
  - Iterative localization (distributed)
  - Potential fields (distributed)

Iterative Localization



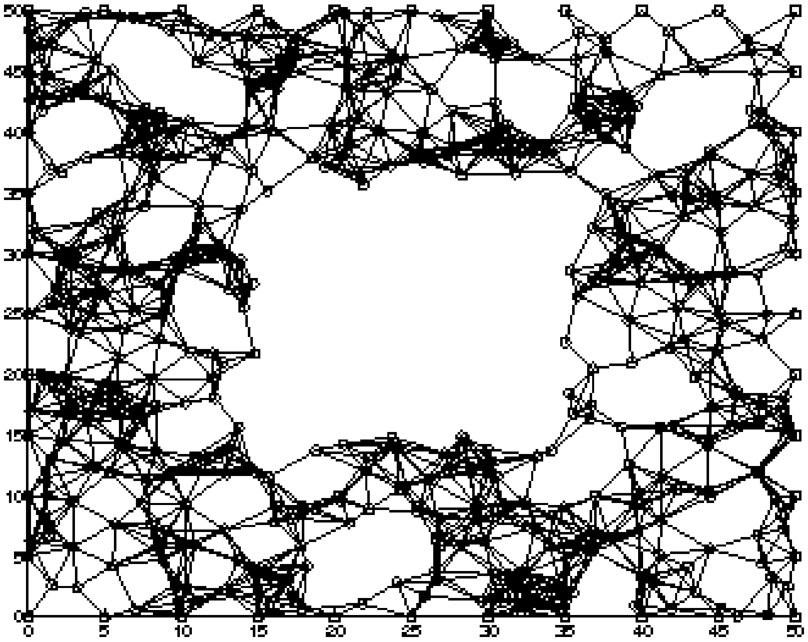
Iterative Localization



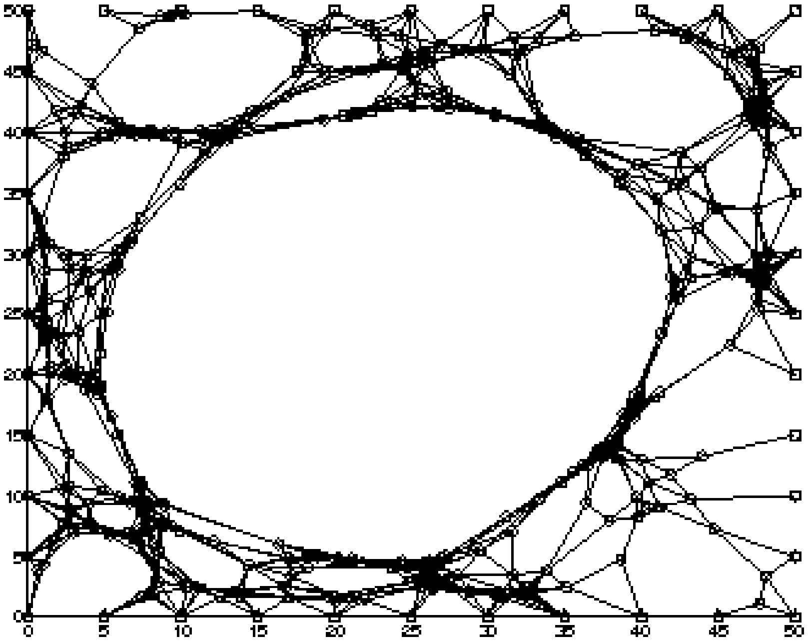
Reference-less Localization

- What if there are no reference nodes with known locations?
- Three-step solution (Rao ‘03):
  - 1. If all boundary nodes have known locations, use iterative centroid calculations
  - 2. If boundary nodes do not have known locations, use pairwise hop-counts to get approximate locations and apply step 1.
  - 3. If nodes are not aware of boundary, use a flood to identify boundary nodes and apply step 2.
- The solution provides only a relative map, useful for geographic routing

Illustration of Reference-less Localization



Correct locations



Localization assuming only known boundary nodes

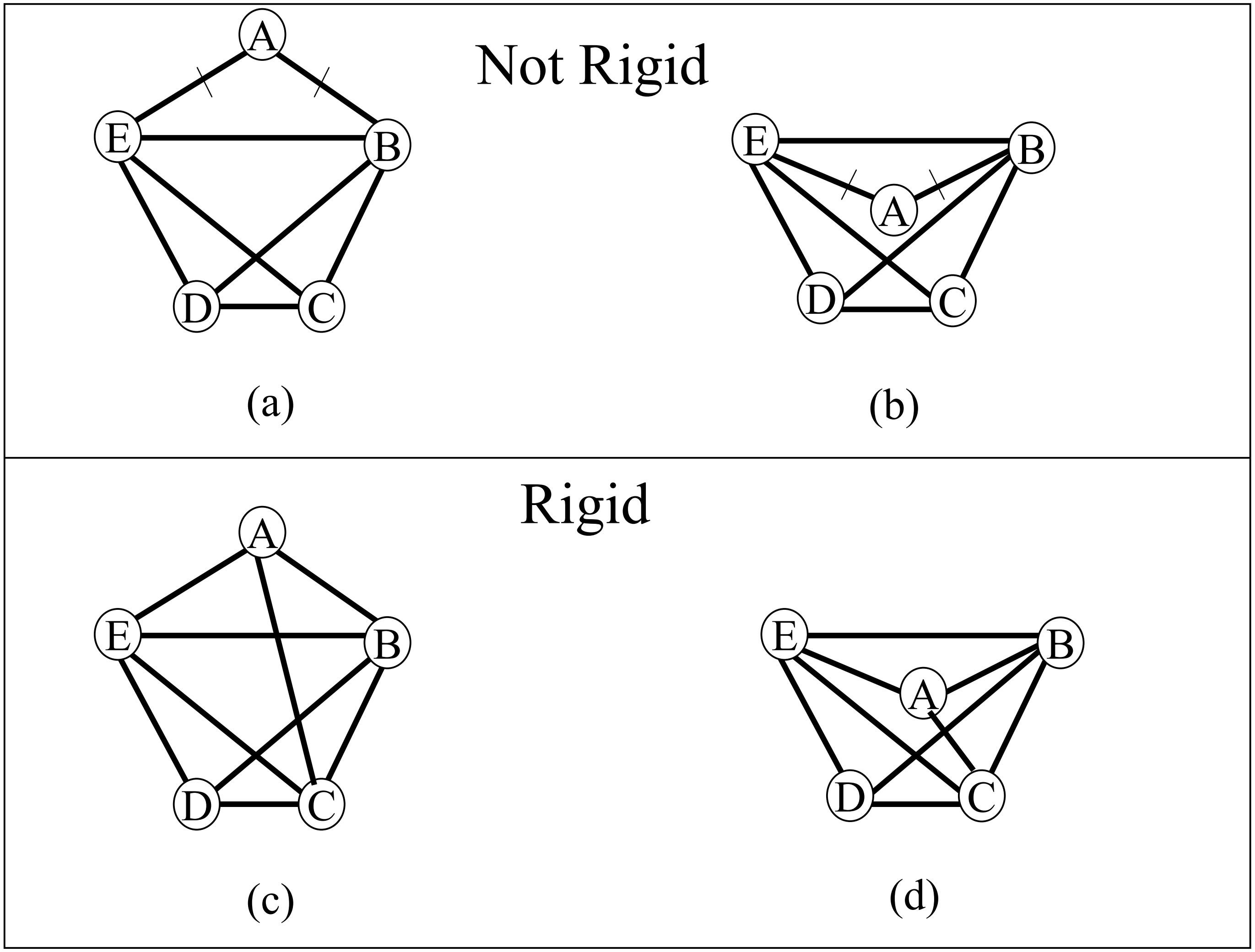
Rigidity and Unique Localization

- The network is said to be *uniquely localizable* if there exists a unique assignment of (x,y) coordinates to all nodes that is consistent with the available positions and distance estimates in a network.

- Let G_N be the grounded graph, i.e. the network graph augmented with distance-labelled edges between all pairs of reference nodes.

- Theorem: A network is uniquely localizable if its grounded graph is *globally rigid.* (Eren *et al.* ‘04)

Global Rigidity

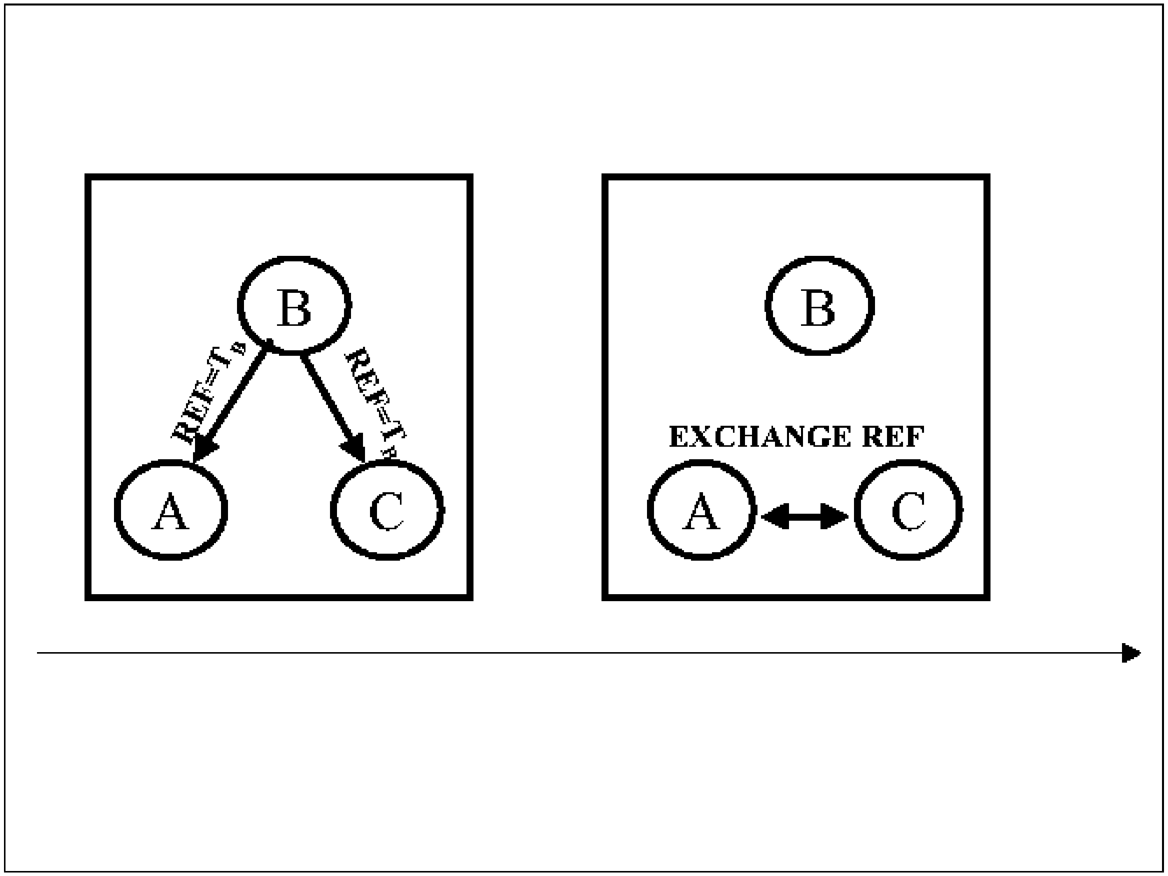


Time Synchronization

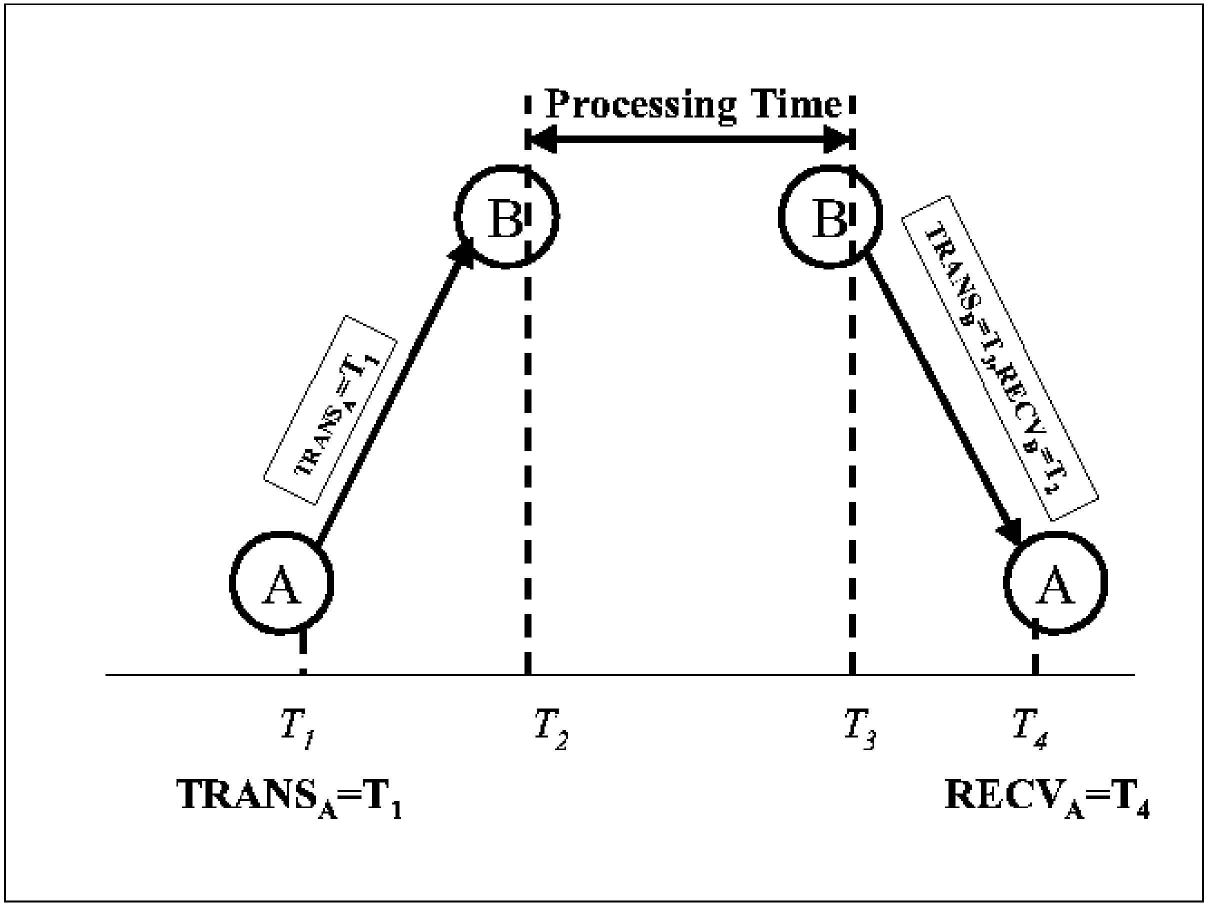
Synchronization Techniques

- Receiver Broadcast Synchronization: multiple receivers synchronize to the same broadcast (Elson, Girod, and Estrin ‘02)
- Timing-Sync Protocol for Sensor Nets (TPSN): traditional sender-receiver synchronization (Ganeriwal, Kumar and Srivastava ‘03)
- FTSP: Multiple time stamping at sender and receiver for each packet to mitigate processing time jitter. Possible to synchronize nodes to within 1µs. (Maroti *et al.* ‘04)

Reference Broadcast Synchronization



TPSN



$$T2 = T1 + \Delta + d$$

$$T4 = T3 - \Delta + d$$

$$\Delta = \frac{(T2 - T4) - (T1 - T3)}{2}$$

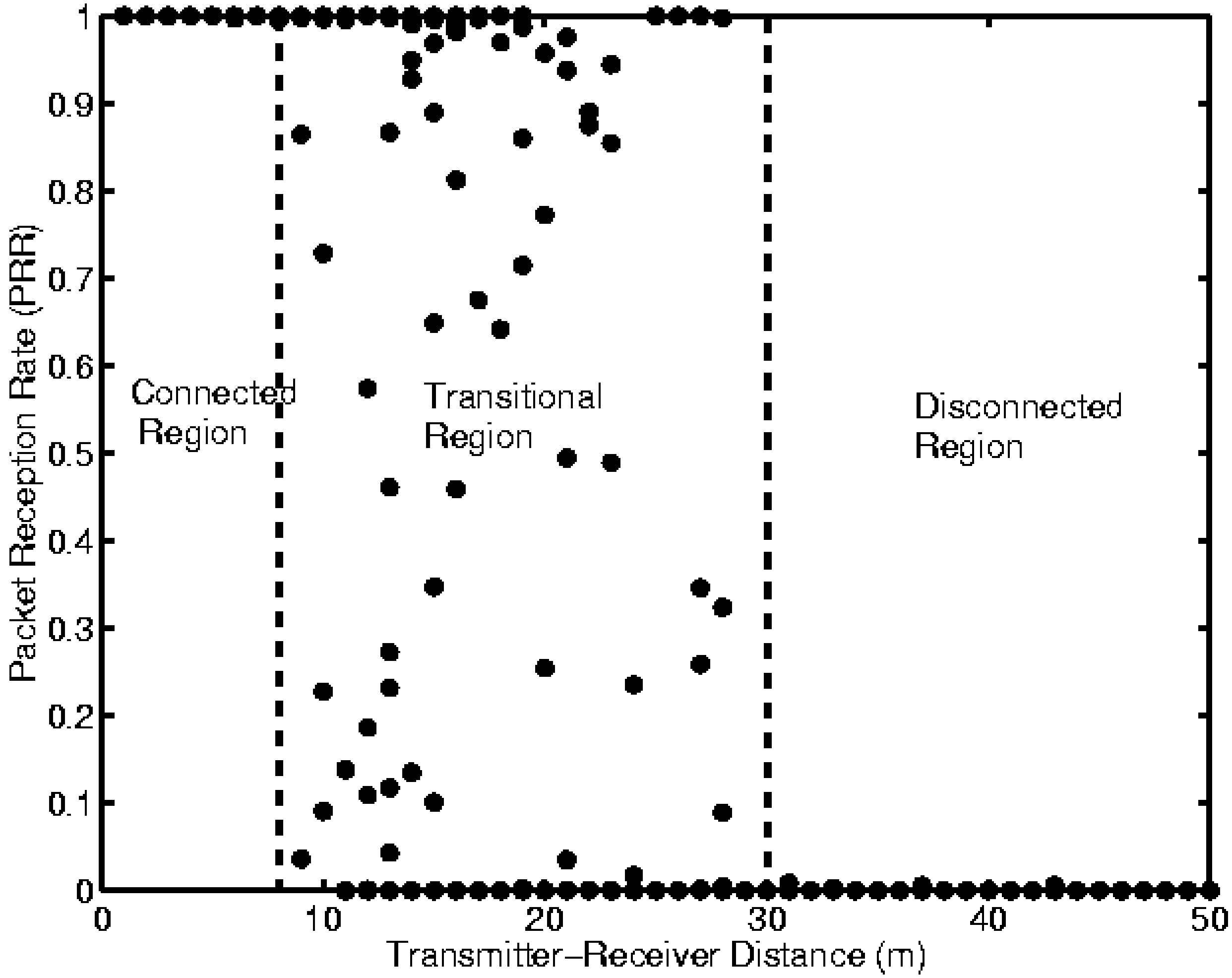
$$d = \frac{(T2 + T4) - (T1 + T3)}{2}$$

Wireless Link Characteristics

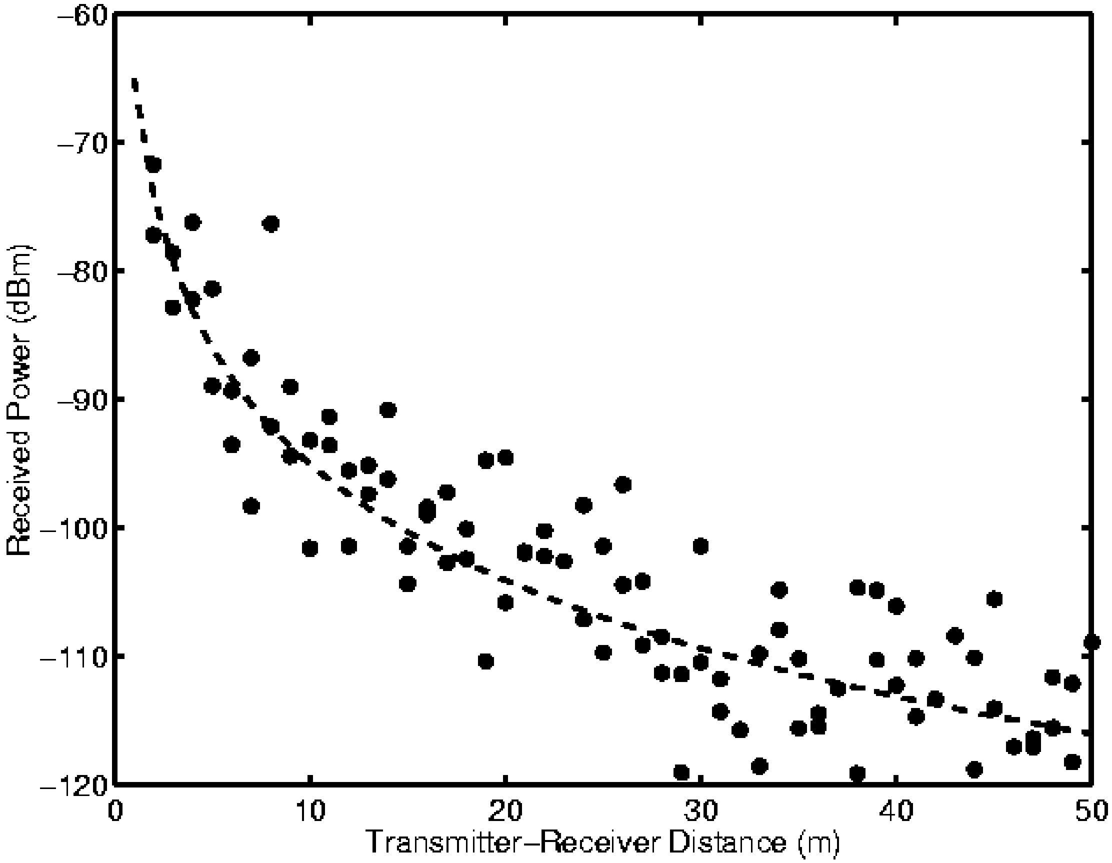
Empirical Observations

- Early studies all assumed a simple perfect-connectivity-within-range model for simulations and analysis.
- A number of empirical studies suggest this can be very misleading (Ganesan ‘02; Zhao and Govindan ‘03; Woo, Tong and Culler ‘03).
- A better characterization is that links fall into three regions: connected, transitional and unconnected. The transitional region will contain a large number of unreliable links.

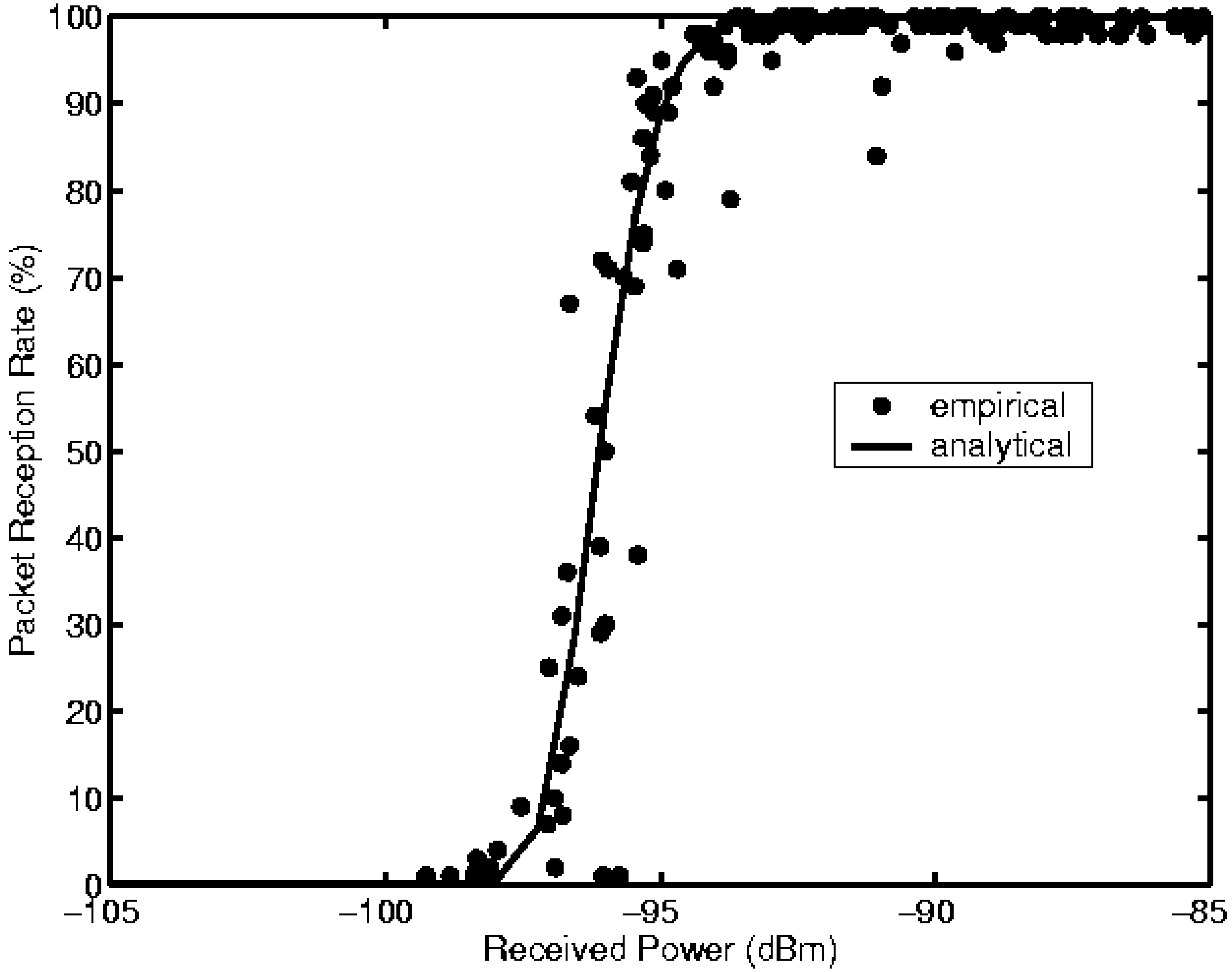
Link Regions



Received Signal Strength



Radio Reception



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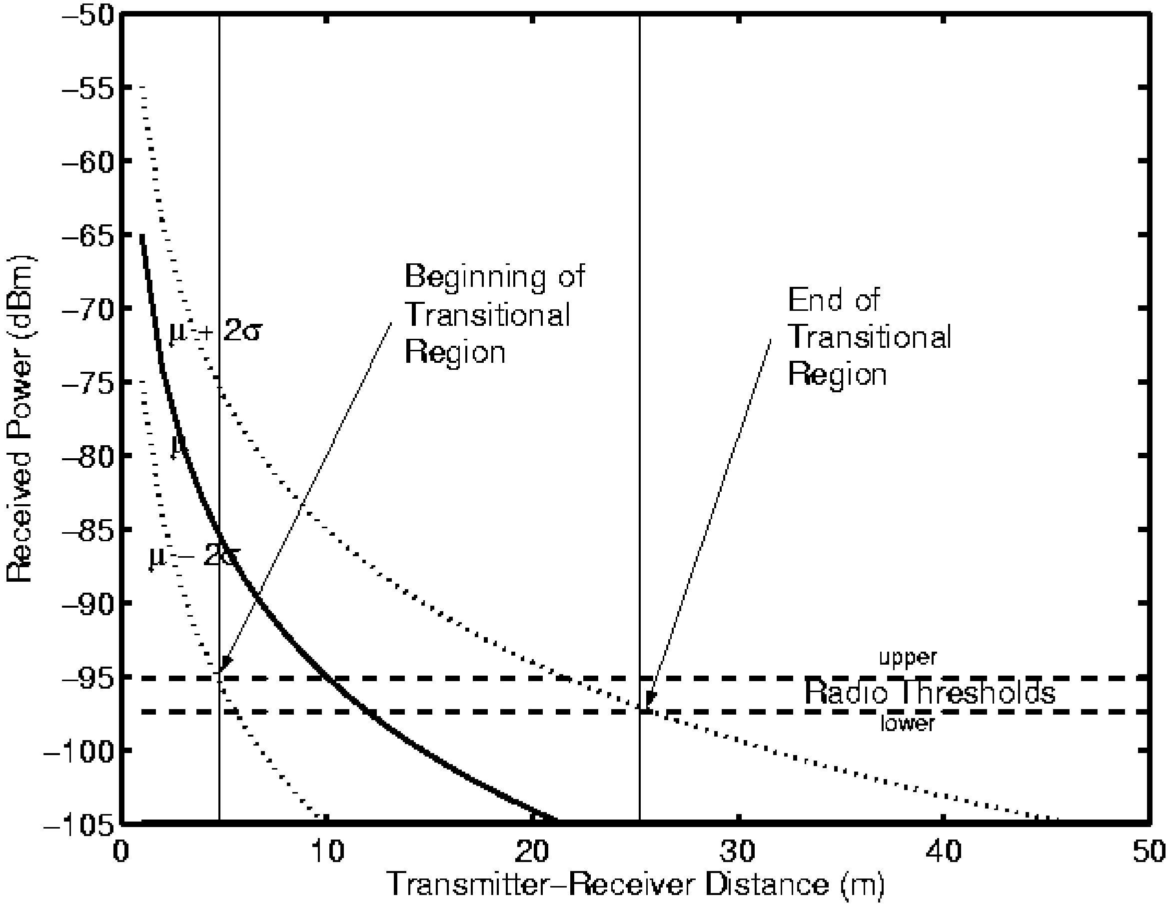
Explanation for Link Regions

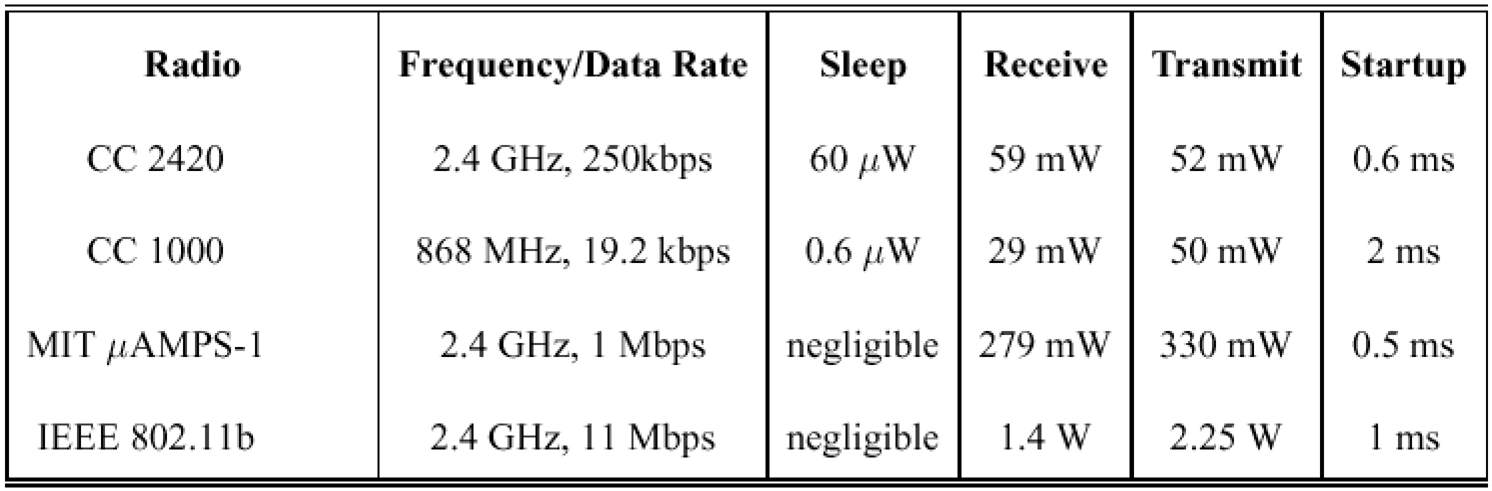


(Zuniga and Krishnamachari '04)

Link Quality Assurance

- Blacklisting: Identify neighbors with poor link quality (weak/highly variable/asymmetric links) and eliminate them from neighbor table (Woo, Tong and Culler ‘03, Gnawali *et al.* ‘04).
- Blacklisting can be implemented using a global threshold or using a local rule like blacklisting all but the top k links.
- Blacklisting provides reliable link quality at the risk of providing a disconnected topology.

Radio Energy Characteristics



Radio	Frequency/Data Rate	Sleep	Receive	Transmit	Startup
CC 2420	2.4 GHz, 250kbps	60 μW	59 mW	52 mW	0.6 ms
CC 1000	868 MHz, 19.2 kbps	0.6 μW	29 mW	50 mW	2 ms
MIT μAMPS-1	2.4 GHz, 1 Mbps	negligible	279 mW	330 mW	0.5 ms
IEEE 802.11b	2.4 GHz, 11 Mbps	negligible	1.4 W	2.25 W	1 ms

(compiled from various sources)

- Transmit and Receive/Idle energy costs are typically the same for most radios. Sleep is the only energy efficient mode.
- Startup times and costs vary from radio to radio, but can be quite significant.

Medium Access

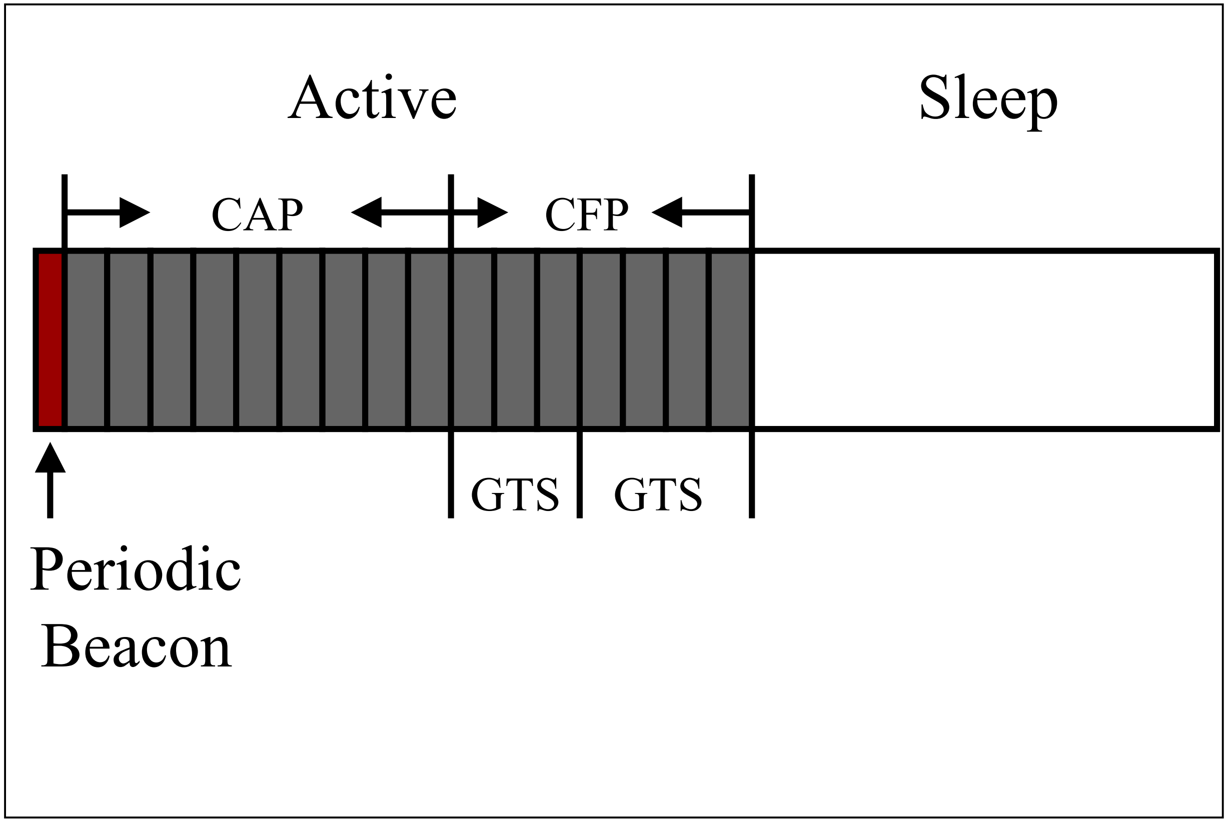
Issues

- Unlike traditional MAC protocols, WSN schemes must also incorporate sleep modes during radio inactivity, to maximize energy efficiency.
- Two main classes of protocols: contention based and contention free
- Contention based protocols offer low complexity and more flexibility, though not suited for heavy traffic conditions.

IEEE 802.15.4 (for Low Rate Low Power WPAN)

- 16 channels in the 2450 MHz band, 10 channels in the 915 MHz band, and 1 channel in the 868 MHz band
- Over-the-air data rates of 250 kb/s, 40 kb/s, and 20 kb/s
- Star or peer-to-peer operation
- Allocated 16 bit short or 64 bit extended addresses
- CSMA/CA channel access and allocation of guaranteed time slots, ACKS
- Energy detection (ED) and Link quality indication (LQI)

IEEE 802.15.4 MAC (beacon-enabled mode for star topology)



B-MAC

B-MAC Components	ROM	RAM
Basic B-MAC	3046	166
Basic B-MAC LPL	4092	170
Basic B-MAC LPL ACK	4386	172
Basic B-MAC LPL ACK RTS/CTS	4616	277

A highly configurable MAC protocol implemented on TinyOS/Motes (Polastre, Hill and Culler ‘04)

Many independent components that can be turned off if not needed for a particular application

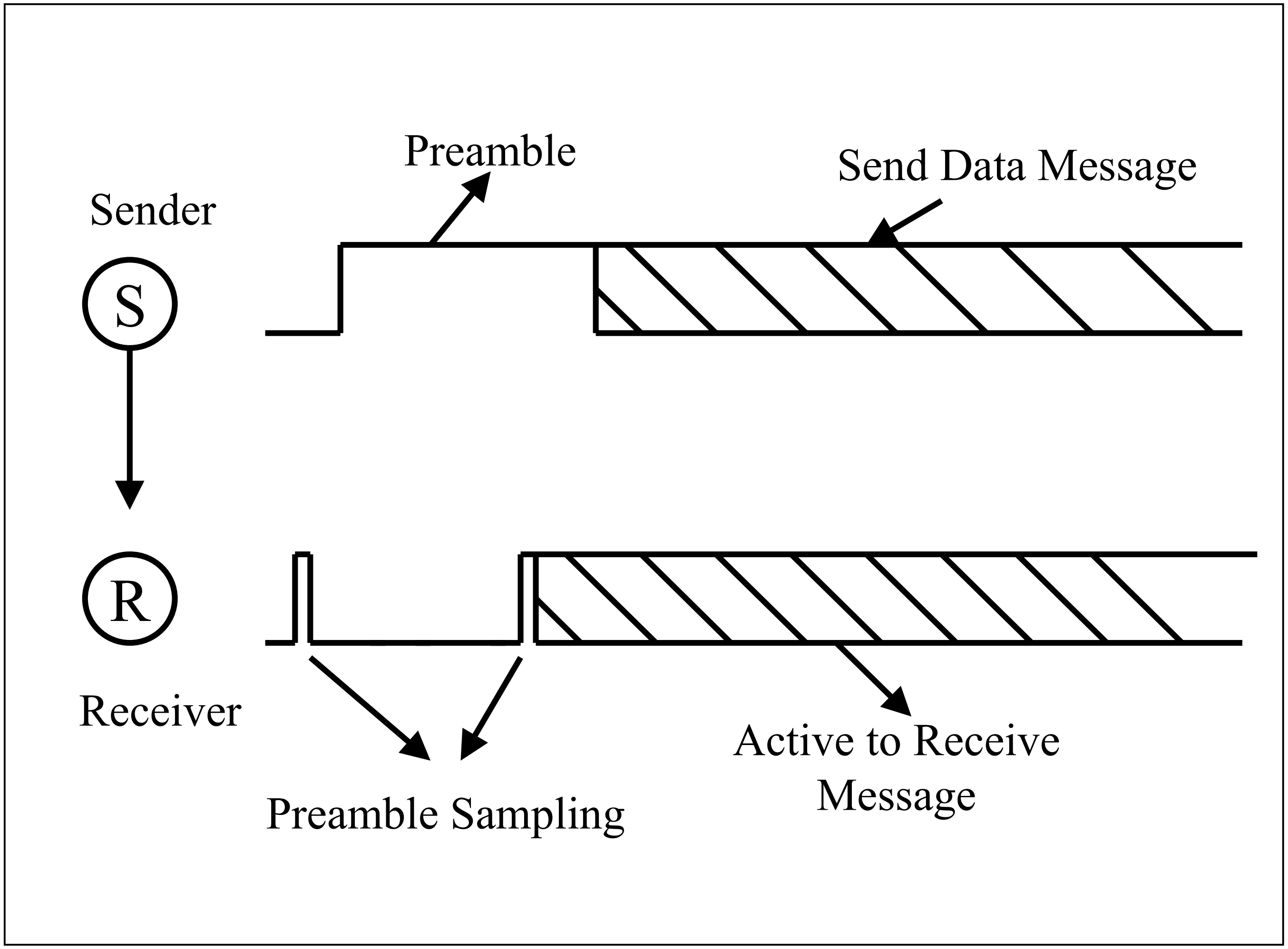
Energy-Efficient Contention-based MAC

- Low Power Listening / Preamble Sampling: wake up the radio only when needed to transmit, and periodically to check for preamble from transmitter. No synchronization necessary.

- S-MAC/D-MAC: periodic sleep-wake duty cycle, adapted for higher traffic, adjusted to minimize delay.

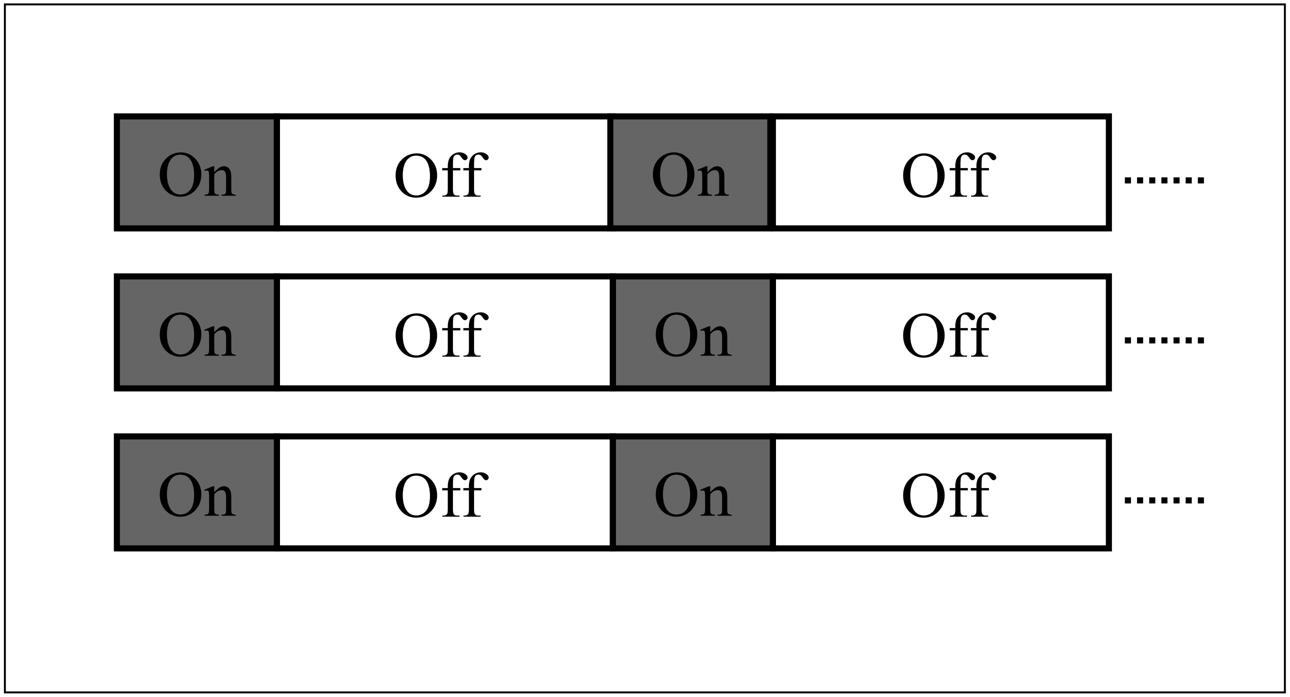
- Asynchronous: use a periodic schedule but not synchronized across nodes. Useful for highly dynamic scenarios.

Preamble Sampling



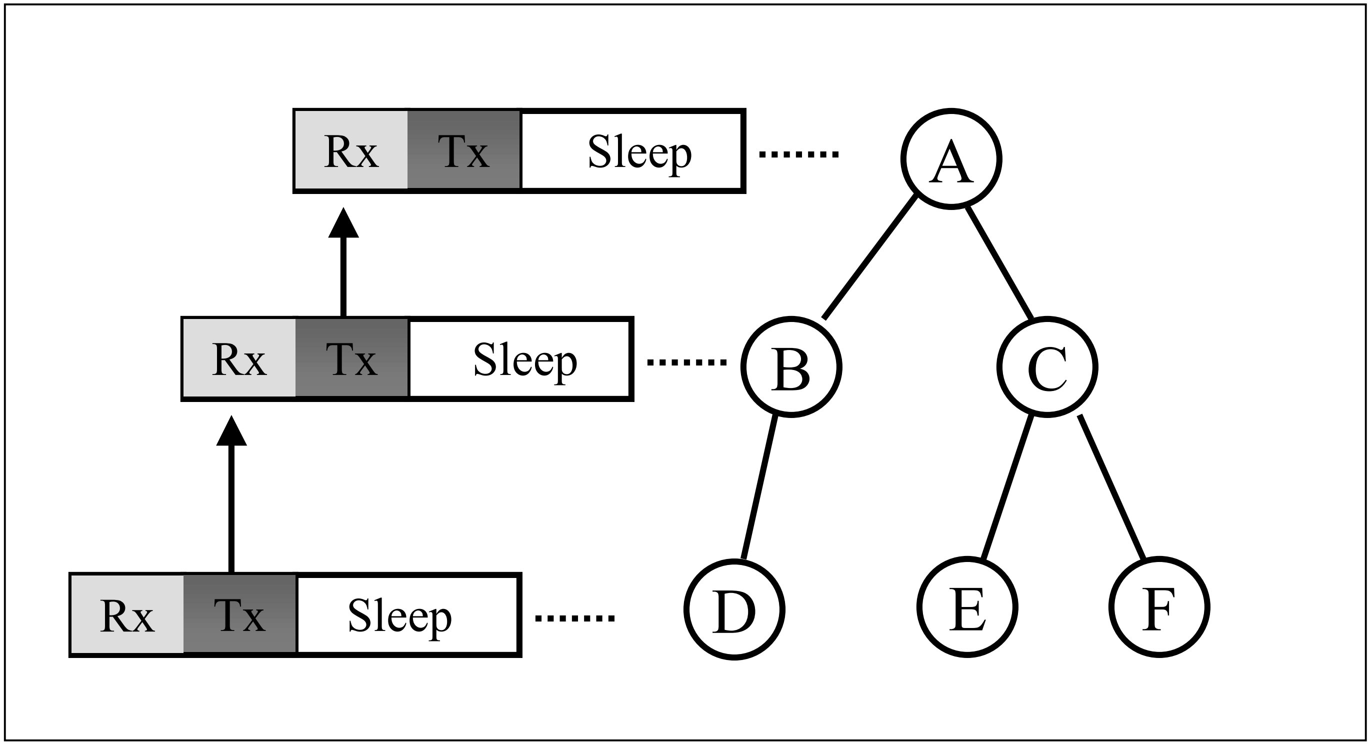
(El Hoiydi '02; Hill and Culler '02)

S-MAC Schedule



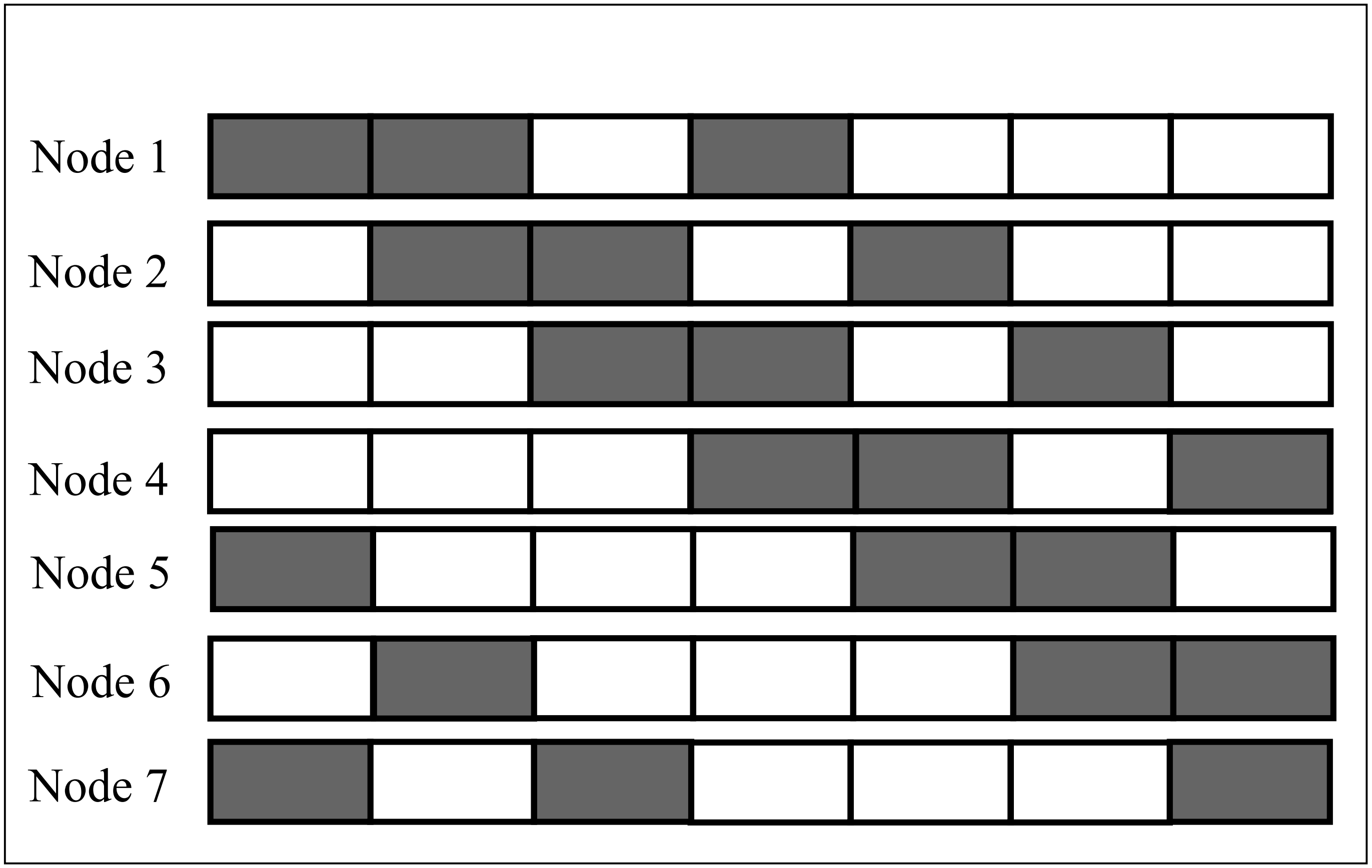
(Ye, Heidemann and Estrin '02)

D-MAC



(Lu, Krishnamachari and Raghavendra ‘04)

Asynchronous Schedule



Node 1	▨	▨	□	▨	□	□	□
Node 2	□	▨	▨	□	▨	□	□
Node 3	□	□	▨	▨	□	▨	□
Node 4	□	□	□	▨	▨	□	▨
Node 5	▨	□	□	□	▨	▨	□
Node 6	□	▨	□	□	□	▨	▨
Node 7	▨	□	▨	□	□	□	▨

(Zheng, Hou and Sha ‘03)

Sleep-based Topology Control

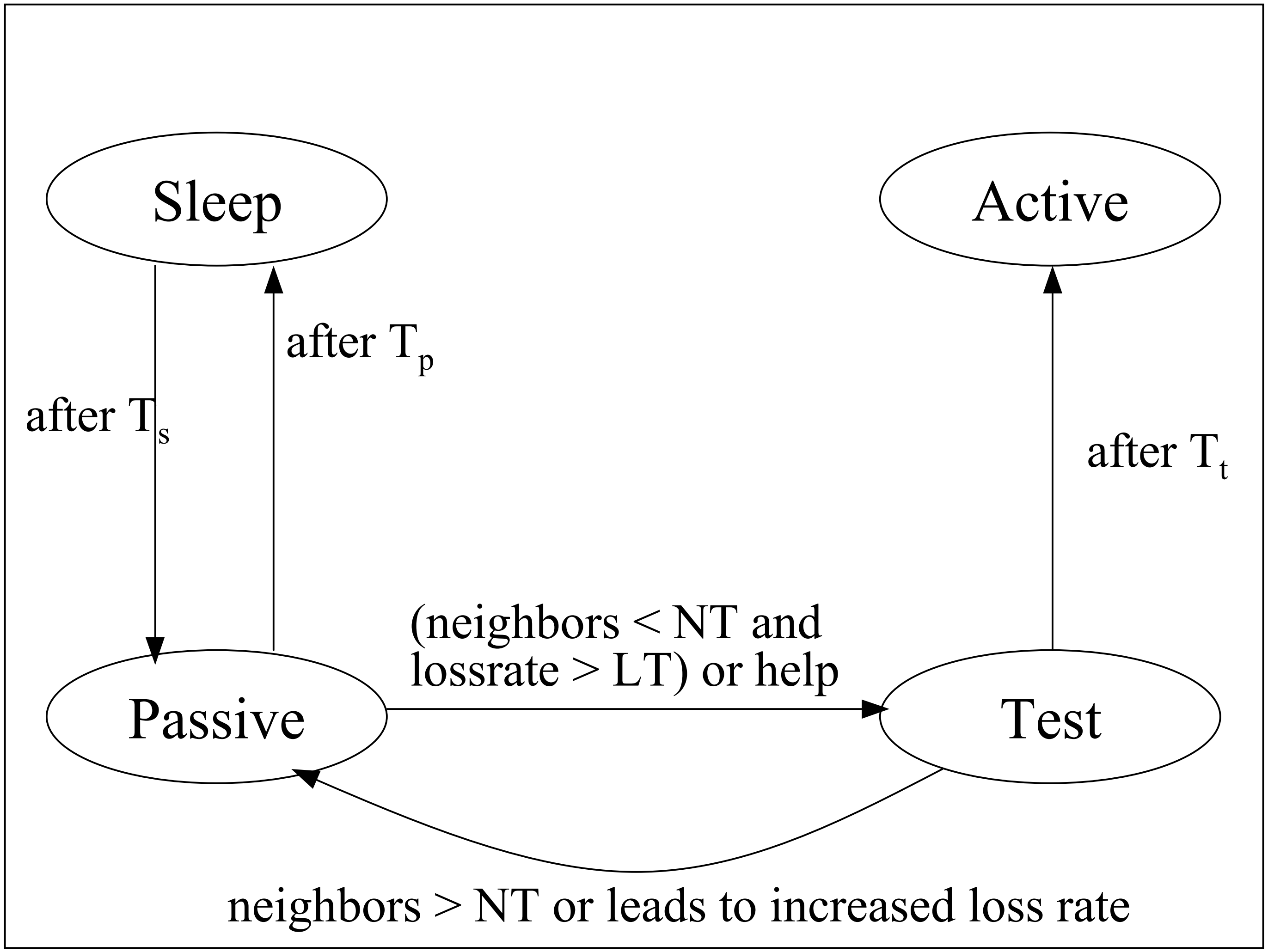
Sleep-based Topology Control

- If network is over-deployed initially, then excess nodes must be kept in sleep mode until necessary for coverage/connectivity (due to failures of other nodes). This is the function of topology control.
- Operate over a much longer time scale than sleep modes for medium access protocols.
- Are typically implemented in a distributed fashion through the use of a finite state machine with states including sleep, active and test modes. Different protocols use different timers and conditions for switching between modes.

Topology Control for Connectivity

- BECA (Xu, Heidemann and Estrin ‘00): Nodes switch to active mode when there is routing traffic present for them to participate in.
- GAF (Xu, Heidemann and Estrin ‘00): Geographically organized clusters with one active node in each cluster.
- ASCENT (Cerpa and Estrin ‘02): Nodes switch to active mode if the number of active neighbors falls below some threshold, or if measured loss rates are high.
- SPAN (Chen *et al.* ‘01): nodes activate to become coordinators to ensure that any pair of neighboring nodes can communicate directly or through a coordinator node.

State Transitions in ASCENT



Techniques Incorporating Coverage

- PEAS (Ye *et al. '03*): Randomized wakeup with adaptive sleeping, tunable coverage ensures that there is at least one active neighbor within range R_p
- Sponsored Sector (Tian and Georganas '03): Nodes are activated if they determine that their own coverage area is not fully covered by neighboring nodes.
- CCP (Wang *et al. '03*): An integrated protocol using intersections to determine K-coverage.
- LDAS (Wu *et al.*): Probabilistic coverage by ensuring that a constant number (5-11) of active neighbors are awake within range.

Routing

Overview

WSN Routing can be made robust and efficient by incorporating different types of local state information:

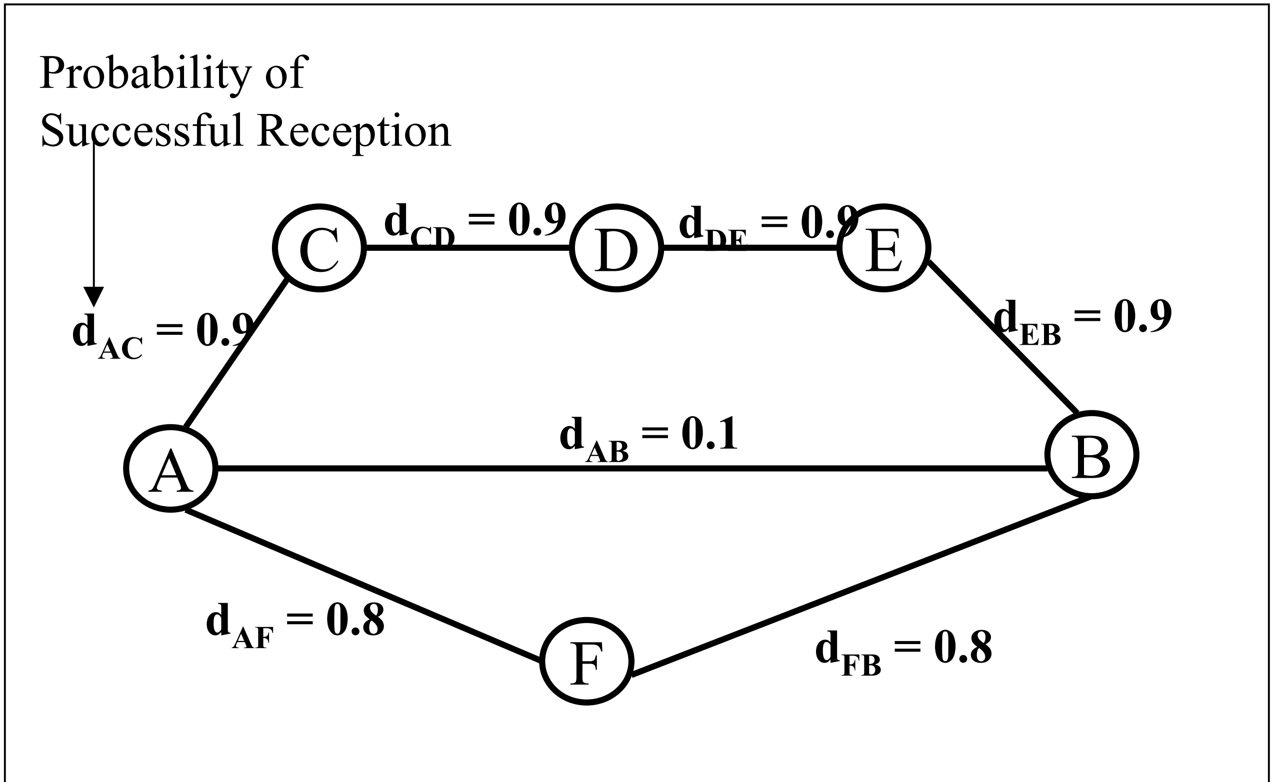
- Link quality
- Link distance
- Residual energy
- Position information

Robust Routing

- Given the unreliable and time varying wireless links, it is very important to provide robust delivery of information.

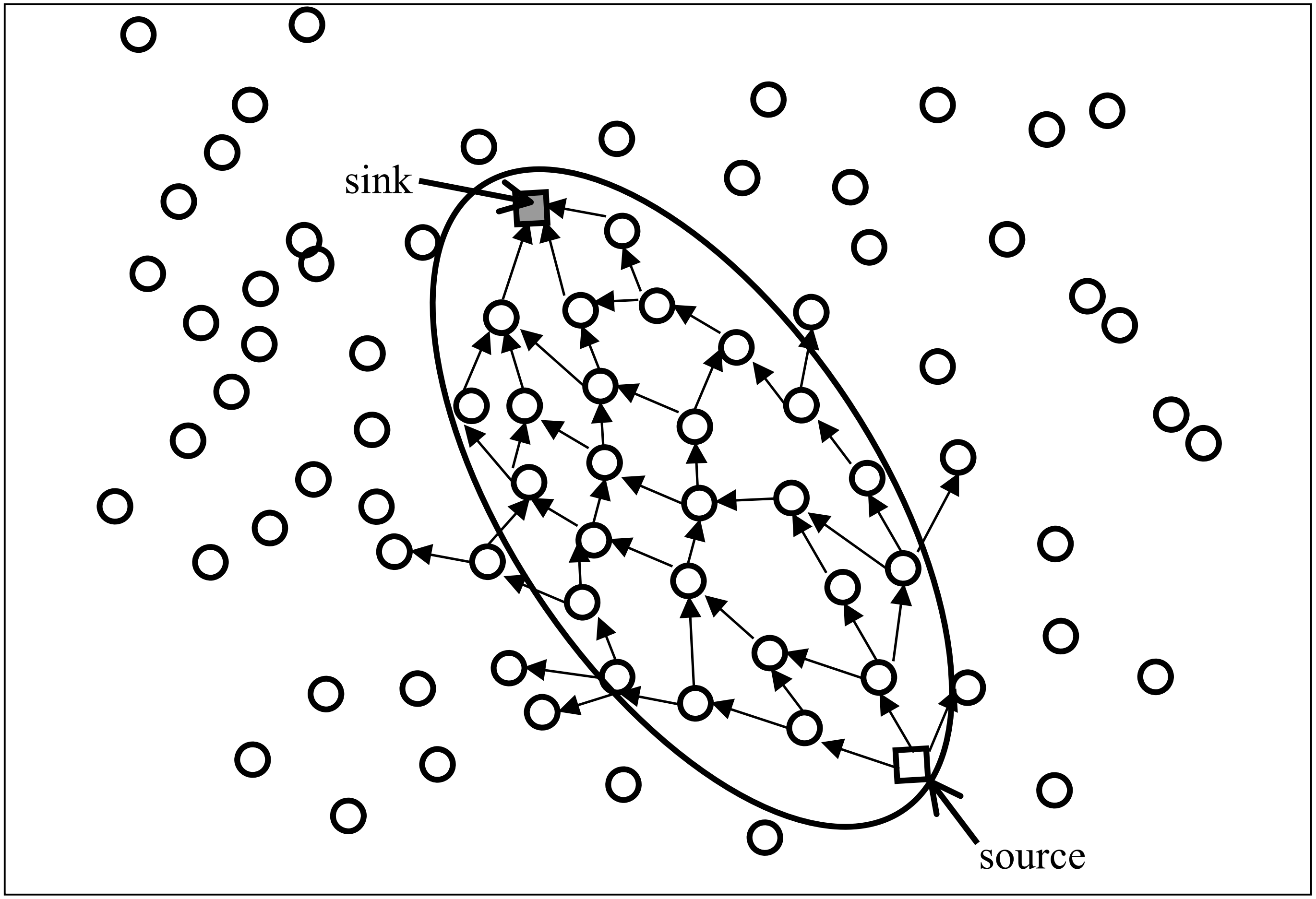
- There are several approaches to providing robustness:
  - use of appropriate link quality metrics (e.g. ETX, De Couto *et al.* ‘03)
  - multipath routing (e.g. GRAB, Ye *et al.* ‘03)
  - wireless diversity-based routing techniques (e.g. ExOR, Biswas and Morris ‘04)

The ETX Metric

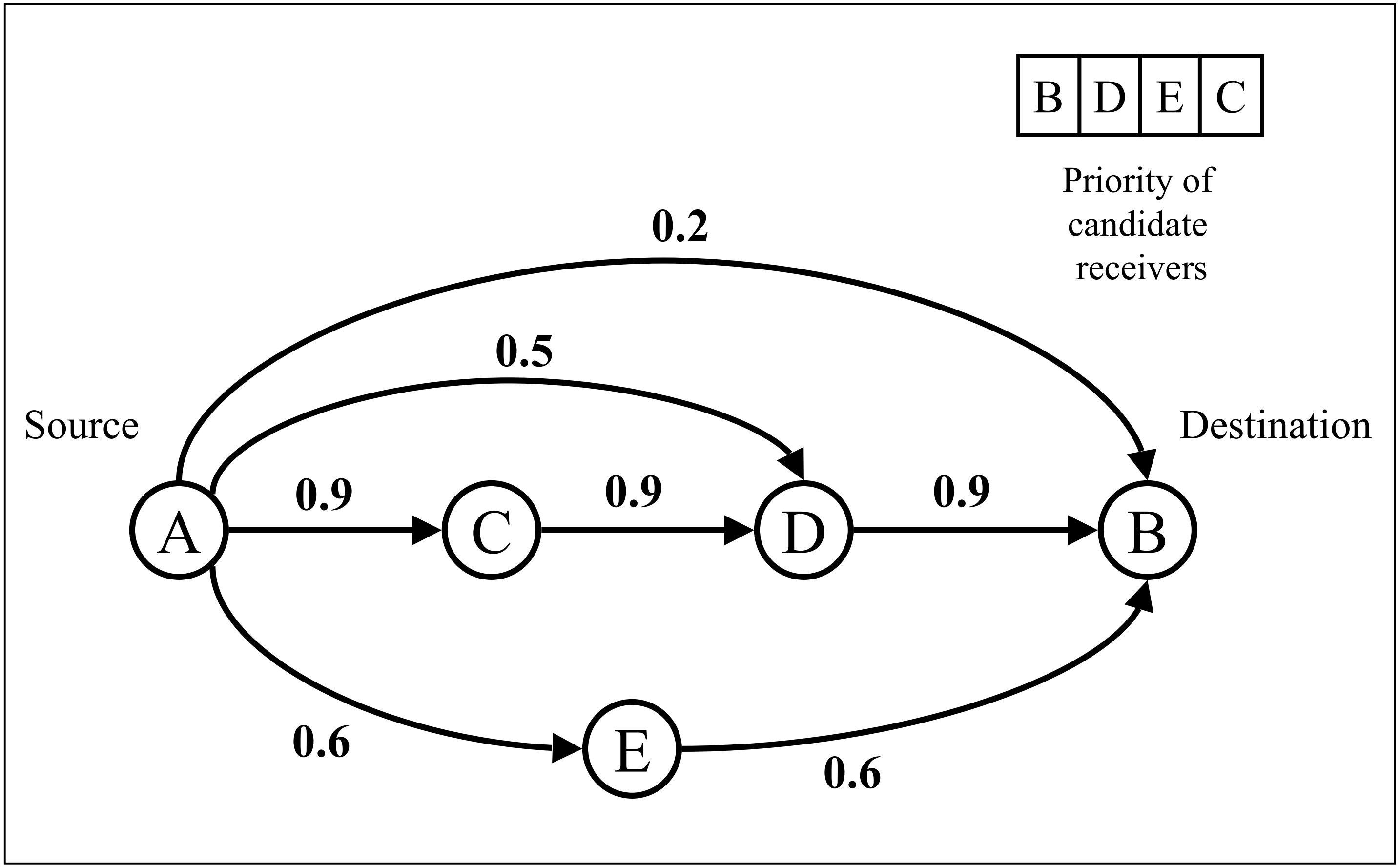


Expected Number of Transmissions, ETX = $1/(d_f.d_r)$

Mesh Multipath Routing



Extremely Opportunistic Routing (ExOR)



Energy Efficient Routing

- Key link metrics for energy efficiency include transmission cost T, residual energy R, and initial energy E
- General Formulation (Chang and Tassiulas '00):

$$c_{i,j} = T_{i,j}^{a} R_{i}^{-b} E_{i}^{c}$$

- Optimization formulations can also be used to determine efficient network flows given a number of constraints.

Flow Optimization Formulations

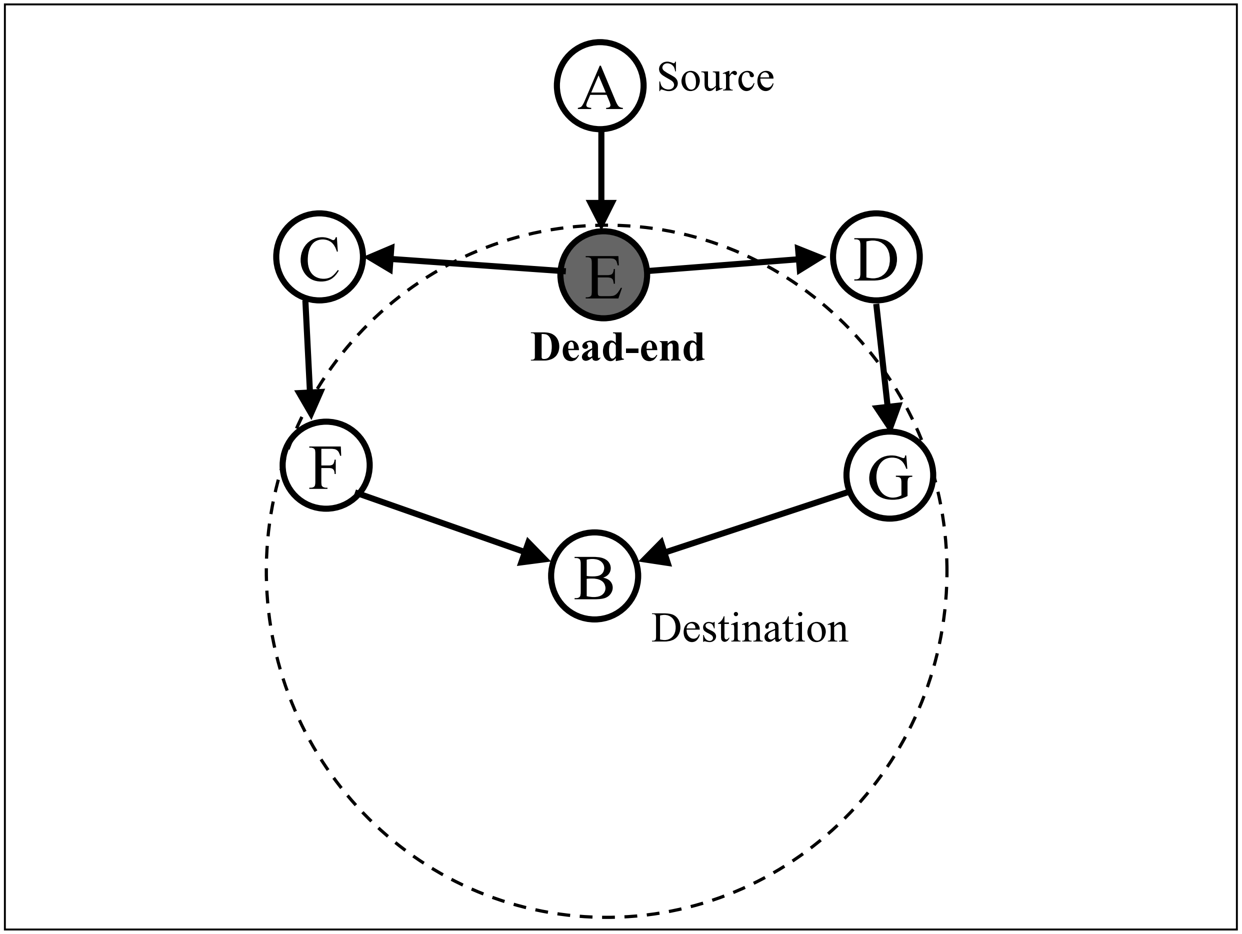
$$
\begin{aligned}
\max \quad & \textstyle\sum_{j=i}^{n} f_{i,n+1} \cdot T \\
\text{s.t. } \forall \mathrm{i} \neq (\mathrm{n}+1), \quad & \sum_{j=1}^{n+1} f_{ij} - \sum_{j=1}^{n} f_{ji} \geq 0 && (a) \\
& (\sum_{j=1}^{n+1} f_{ij} \cdot C_{ij} + \sum_{j=1}^{n} f_{ji} \cdot R) \cdot T \leq E_i && (b) \\
& \sum_{j=1}^{n+1} f_{ij} + \sum_{j=1}^{c} f_{ji} \leq B_i && (b)
\end{aligned}
$$

Over a given interval, maximize total data obtained at the sink node, subject to per-node constraints on (a) flow conservation, (b) available energy, and (c) available bandwidth.

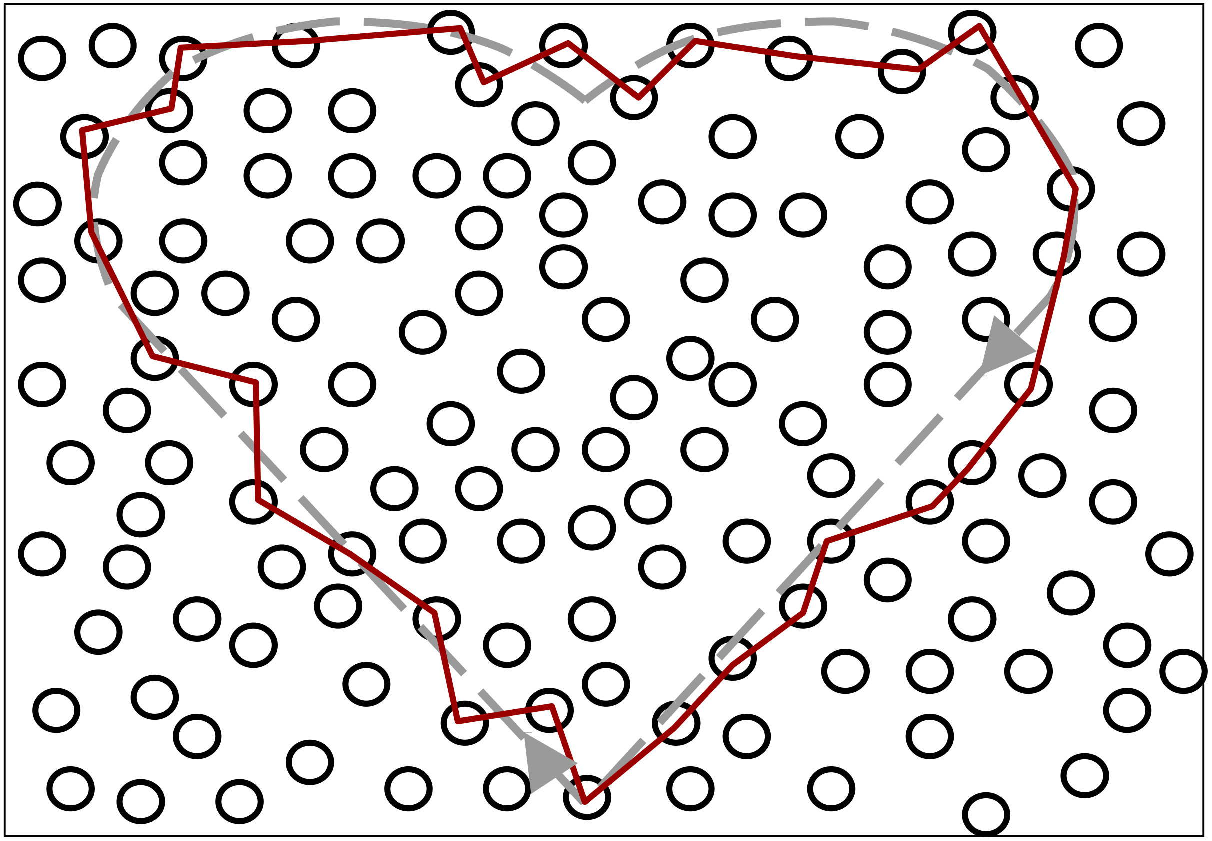
Geographic Routing

- Geographic routing techniques are of interest in WSN where there is ready availability of position information.
- In the basic greedy geographic technique, the packet is forwarded at each step to the neighbor whose position is closest to destination (Finn ‘87)
- Greedy forwarding, however, is susceptible to problem of dead-ends (Bose *et al.* ‘99, Karp and Kung ‘00)
- Trajectory based forwarding allows packets to traverse arbitrary paths (Niculescu and Nath ‘03)

Dead-end with Greedy Geographic Forwarding



Trajectory Based Forwarding

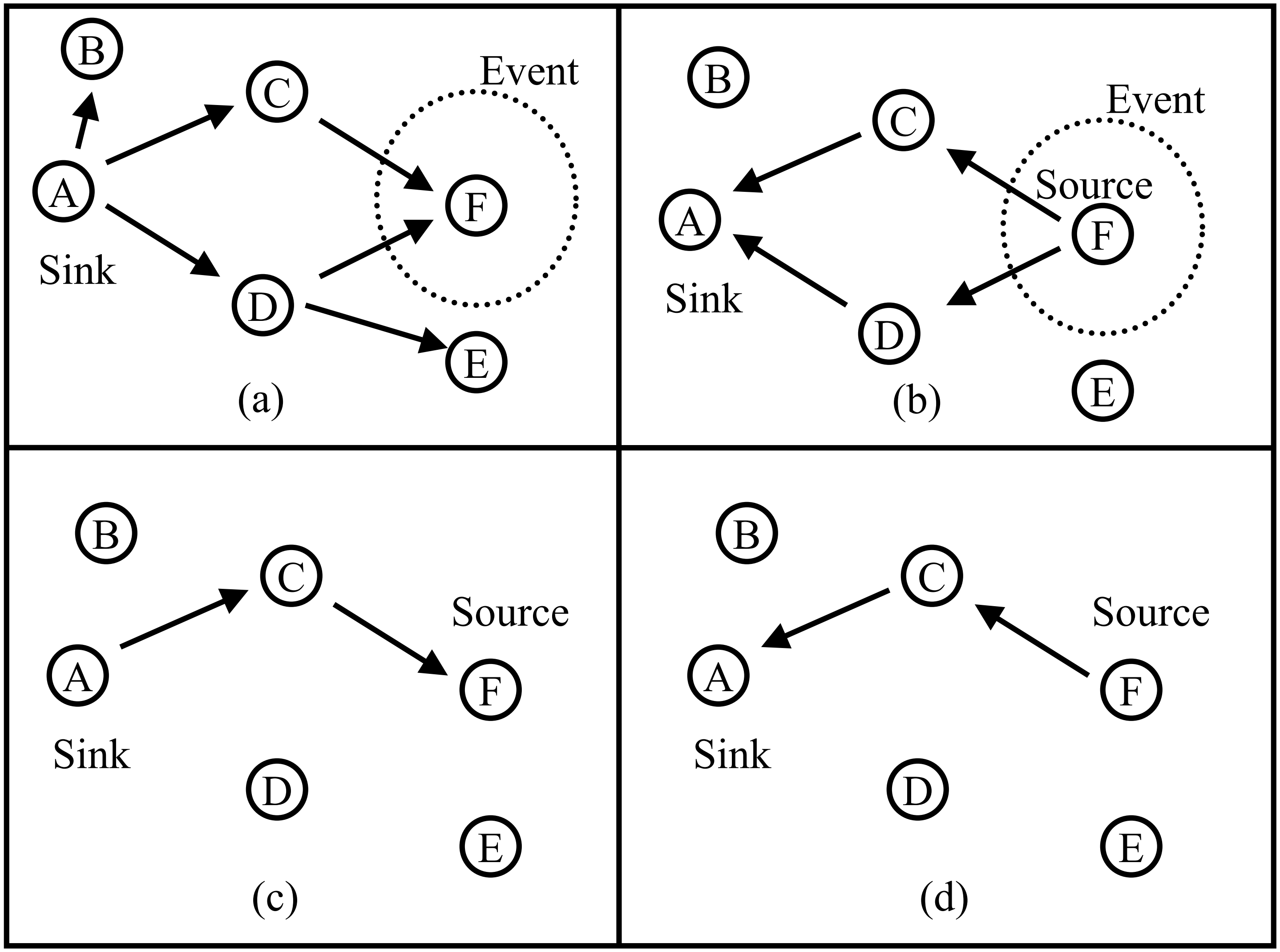


Data Centric Networking

Data-Centric Operation

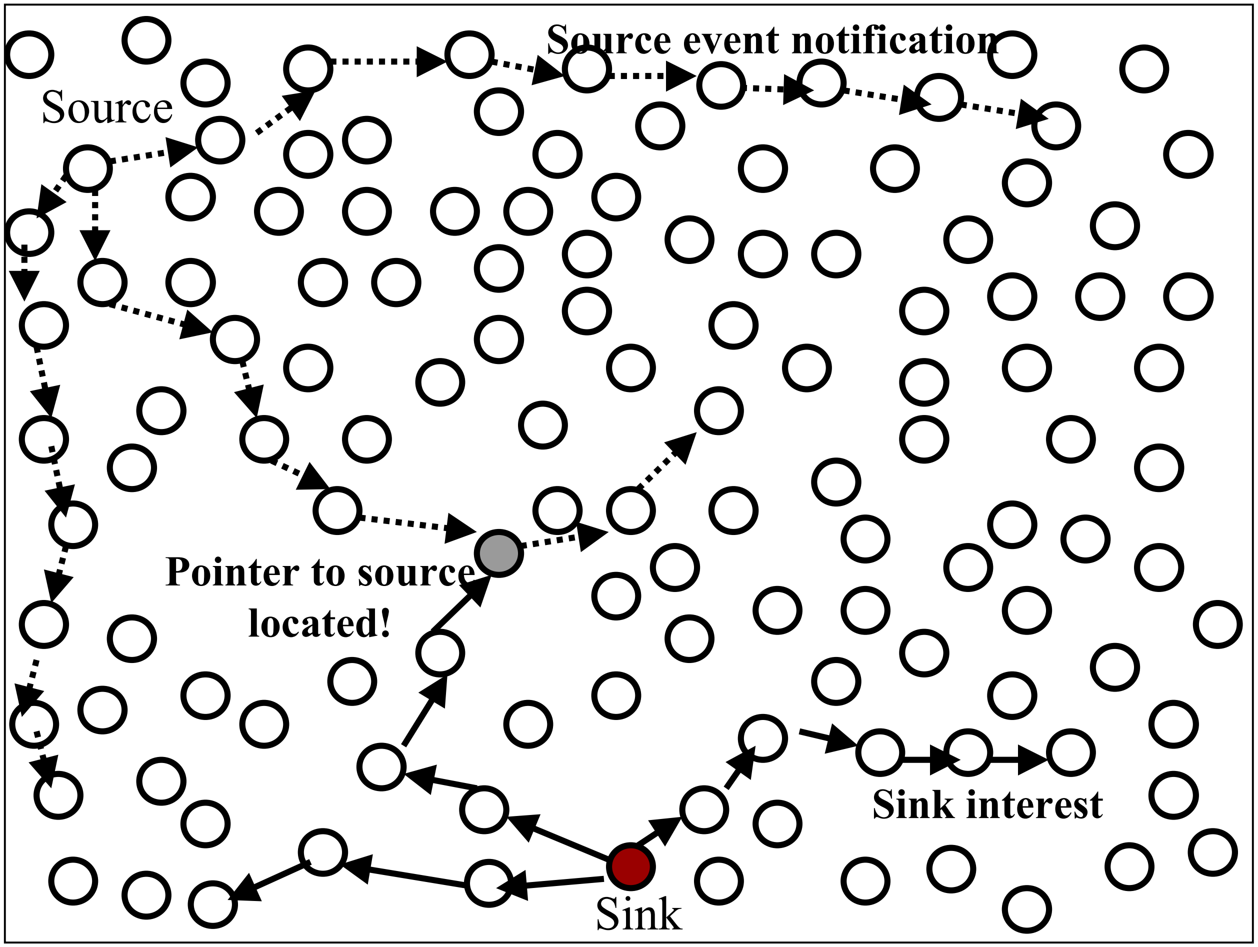
- Uniquely appropriate to sensor networks because of their application-specific nature
- Data centric routing, storage, and querying techniques are based on application-level content names instead of network address.
- Twin advantages:
  - lower overhead due to removal of address indirection,
  - greater energy savings by allowing easier in-network processing (including refinement, aggregation and compression)

Directed Diffusion Routing



(Intanagonwiwat, Govindan, Estrin '00)

Rumor Routing

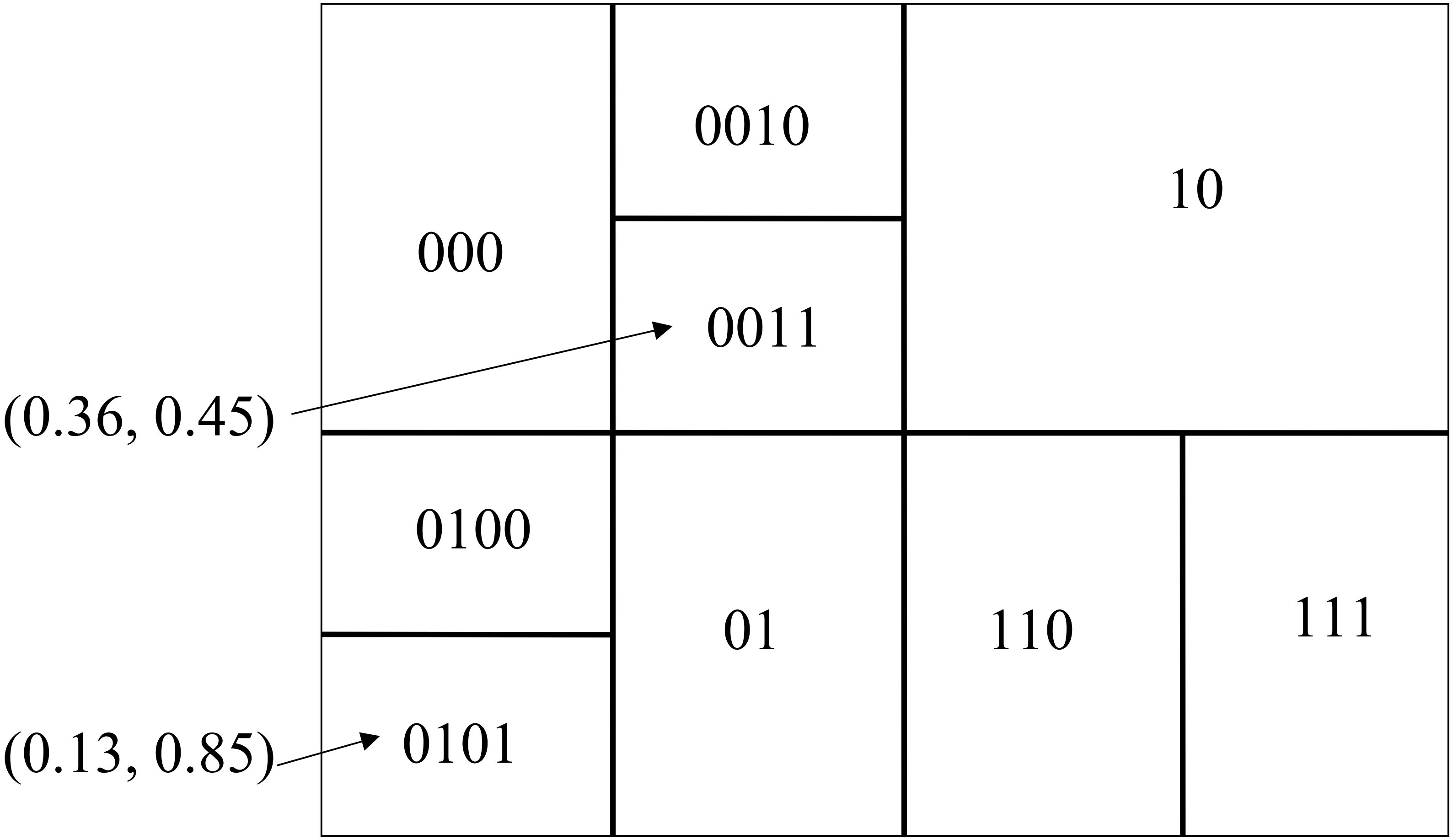


(Braginsky and Estrin '02)

Data-Centric Storage

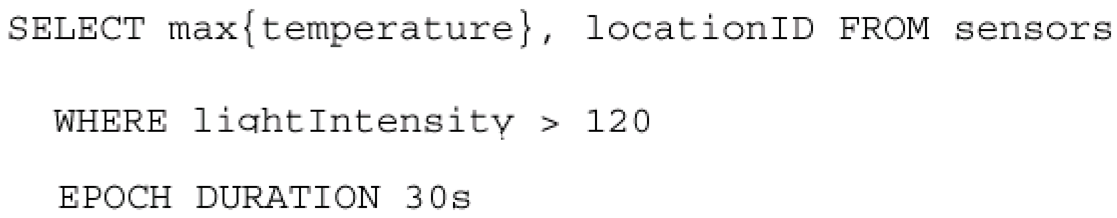
- Store sensor measurements within the network in an organized manner to allow for efficient retrieval.
- The GHT mechanism (Ratnasamy *et al*. ‘03) hashes event names to a unique geographic location for storage and retrieval.
- The DIM mechanism (Li *et al.* ‘03) hashes multidimensional ranges to a unique binary code, and binary codes to a unique geographic zone for storage and retrieval.

DCS for Multidimensional Range Queries (DIM)



The Database Perspective

- Treat the sensor network as a distributed database.
- Can then use a simple SQL-like language to query and task the WSN. E.g. TinyDB/TinySQL (Madden *et al.* ‘02)



```
SELECT max{temperature}, locationID FROM sensors
  WHERE lightIntensity > 120
  EPOCH DURATION 30s
```

- Allows for easy in-network aggregation and optimization of query plans

Transport

Key Issues

- Many transport-level QoS guarantees are essential in WSN: reliable delivery, priority delivery, delay guarantee, energy efficient delivery, fairness, application-specific quality of gathered information, etc.

- Challenges include channel loss, bandwidth limitation, interference and congestion, bursty traffic, buffer size and computational constraints.

Transport Design Parameters

- Rate Control
- Scheduling Policy
- Drop Policy
- MAC backoff
- Use of explicit notification messages
- ACKS

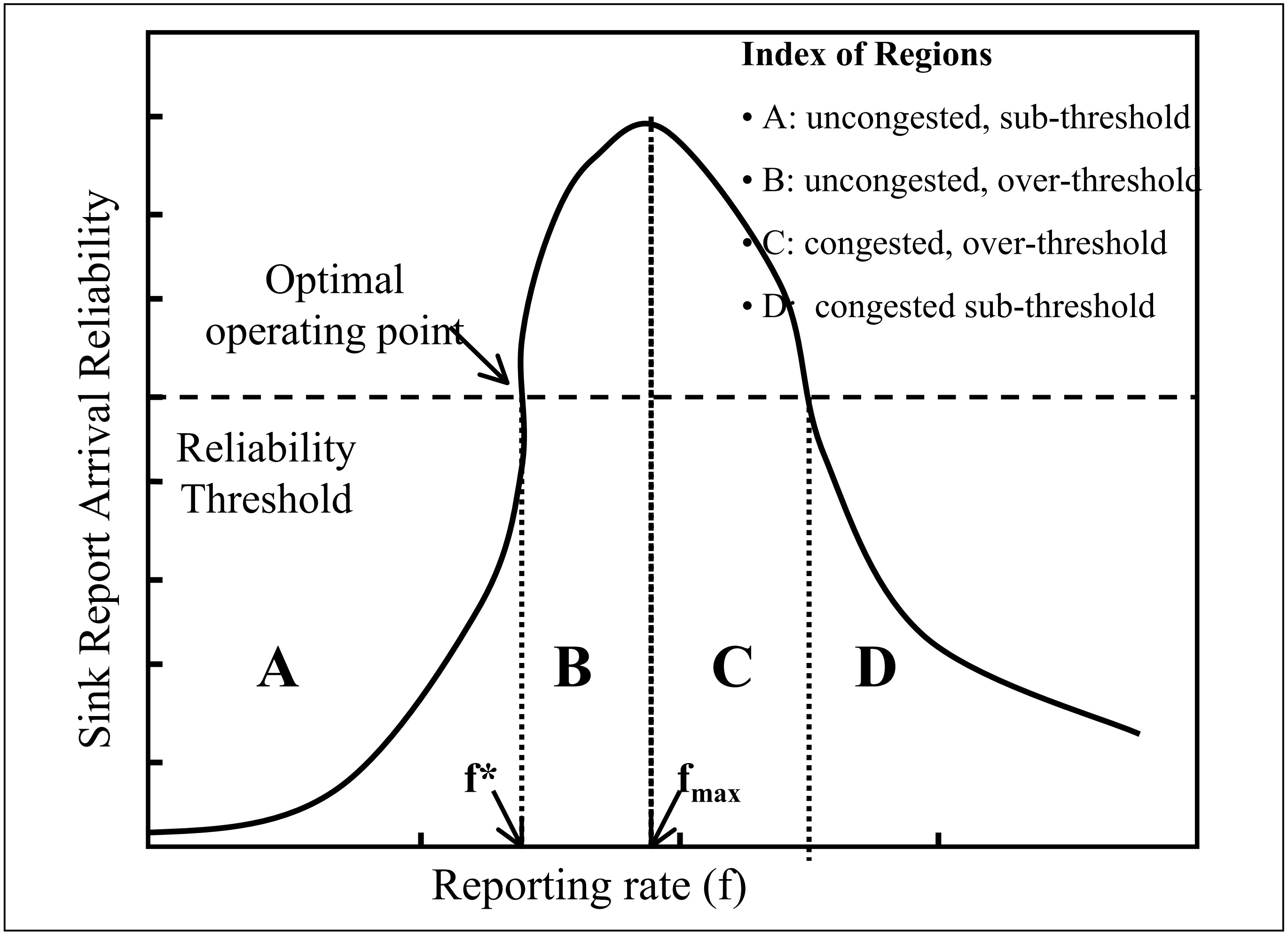
Transport Techniques for WSN

- PSFQ (Wan, Campbell and Krishnamurthy ‘02), RMST (Stann and Heidemann ‘03) : advocate the use of message sequencing and hop-by-hop NACKs for reliable message transfer.

- ARC (Woo and Culler ‘01), CODA (Wan, Eisenman, Campbell ‘03): open loop rate control based on hop-by-hop back-pressure

- ESRT (Sankarasubramaniam, Akan and Akyildiz ‘03): closed loop rate control based on application-specific feedback from sink

ESRT


Index of Regions
• A: uncongested, sub-threshold
• B: uncongested, over-threshold
• C: congested, over-threshold
• D: congested sub-threshold
Optimal operating point
Reliability Threshold
A
B
C
D
f*
f_{max}
Sink Report Arrival Reliability
Reporting rate (f)

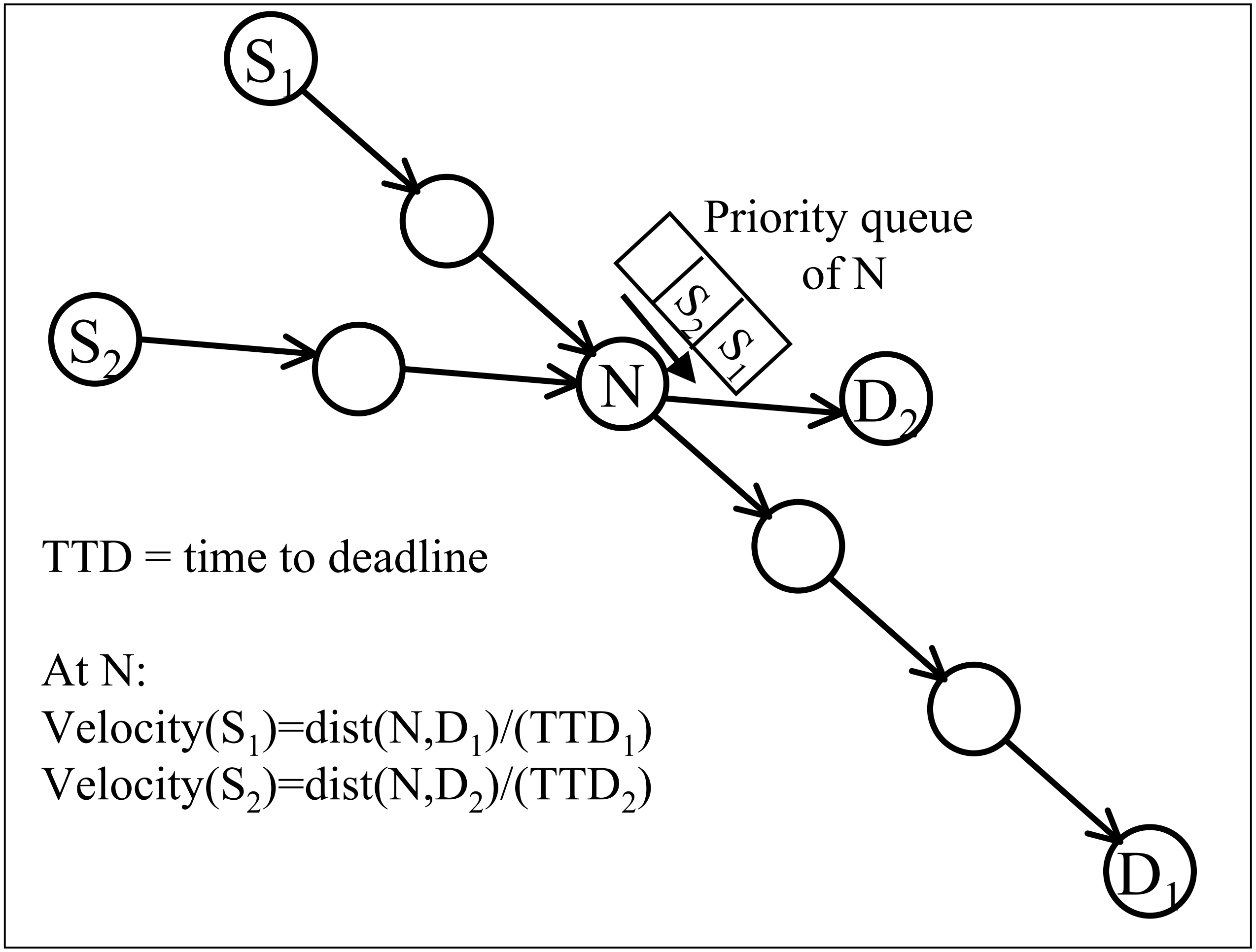
Real Time Transport

- SPEED (He, Stankovic, *et al. '03)*: each node estimates expected speed of packet delivery through each neighbor. A speed threshold is used to decide whom to forward the packet to, or if the packet should be dropped.

$$v_{i,j} = \frac{L_i - L_j}{t_{i,j}}$$

- VMS (Lu *et al.* '02*)*: A velocity is calculated dynamically for each packet at each intermediate location, given a deadline. Scheduling is monotonic with velocity

Velocity Monotonic Scheduling



TTD = time to deadline

At N:
$\text{Velocity}(S_1)=\text{dist}(N,D_1)/(TTD_1)$
$\text{Velocity}(S_2)=\text{dist}(N,D_2)/(TTD_2)$

Other Topics

Further Topics

- Asymptotic network capacity
- Hardware and software tools
- Tracking point targets and diffuse phenomena
- Programming, middleware, and systematic design
- Security issues and protocols

Conclusions

Conclusions

- WSN are a widely applicable, major emerging technology.
- They bring a whole host of novel research challenges pertaining to energy efficiency, robustness, scalability, self-configuration, etc.
- These challenges must be tackled at multiple levels through different protocols and mechanisms.
- Existing partial solutions offer much hope for the future, but much work remains to be done.

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