 

CS-541
Wireless Sensor Networks

Lecture 7: Routing for Wireless Sensor Networks.

Spring Semester 2017-2018

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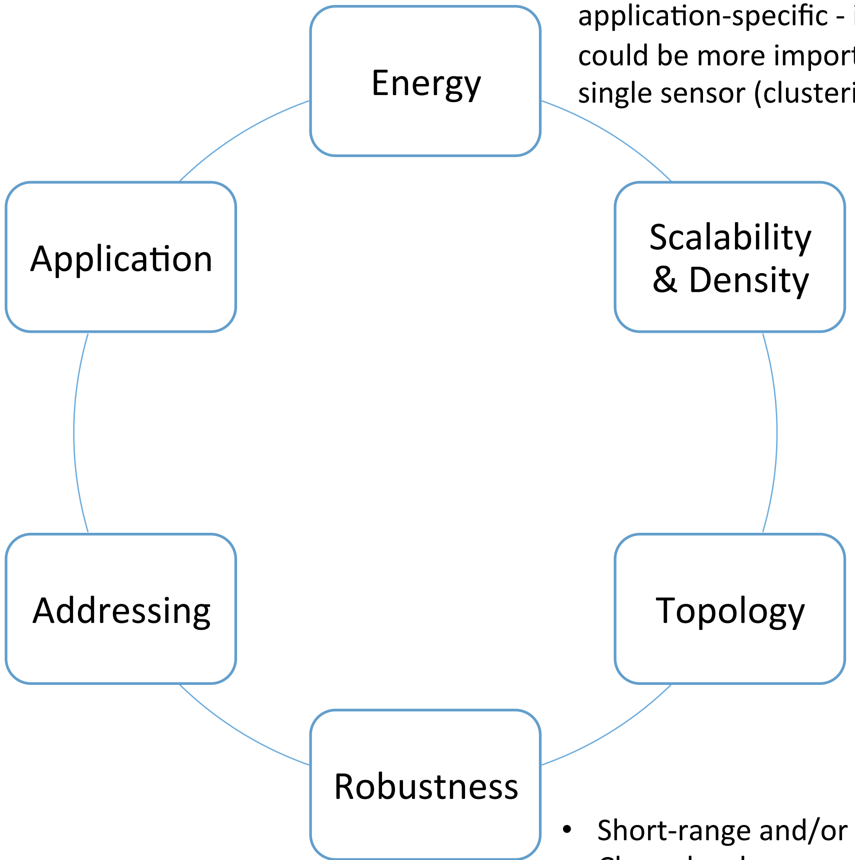
Today's objectives

- Routing Objectives for Wireless Sensor Networks

- Routing Techniques

- Routing in practice & associated services at the transport layer

Routing for Wireless Sensor Networks



- Neighborhood discovery & local information exchange
- Network is more important than the sensor (WSN are application-specific - information from a set of sensors could be more important than the information of a single sensor (clustering or selecting or ***compressing***)

- Periodic monitoring
- Event-driven
- Sometimes also combined, e.g. ***Cyber-physical Systems***
- Different applications need different routing protocols

- Knowledge of the entire topology is not realistic (also because of its changes, due to, e.g. nodes failures or RDC policy)
- Autonomic behavior (self-organizing and optimizing) – from local decisions to converge to a global optimum
- Topology is not network-driven but application driven!
- In-network processing for combining & extracting the important information

- Conventional addressing (e.g. a unique MAC address) is not met in practice
- Addressing is overhead – routing-based on addressing may not work (dynamic topologies and failures)
- Routing that does not rely on unique IDs (***position*** or ***context***)

- Short-range and/or multi-hop
- Cheap hardware – prone to failures
- Unattended and hostile environments (RF harsh)
- Resilient to changes (e.g. the routing paths)

"Wireless Sensor Networks", Ian F. Akyildiz, Mehmet Can Vuran, 2010, Willey, Ch 7

Routing for Wireless Sensor Networks

Classification of routing techniques

Data-centric

- Attribute-based addressing
- Sensor nodes are homogeneous (in terms of sensing modality) OR are clever enough to extract some attributes from different modalities
- The physical phenomenon can be described by more than one sensors..
- Flat architectures
- **Fault-tolerant**

Geographical-based

- Routing decisions are taken with respect to the locations of the sensors
- Localization in the background
- Destination is a geographical location

Topology-driven

- Information available with respect to the network topology
- Associated network metrics (e.g. QoS)
- Proactive or reactive (similar to ad-hoc routing protocols)
- Address-based routing for constructing a specific routing topology (e.g. **tree**)

+Hierarchical approaches (clustering +routing)

Routing for Wireless Sensor Networks

Data-centric

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- Flat architectures
- Fault tolerant

Flooding & Gossiping

SPIN (Sensor Protocols for Information via Negotiation)

Directed Diffusion

Data-centric protocols come as a solution to the addressing limitations in WSN

Routing for Wireless Sensor Networks

Data-centric

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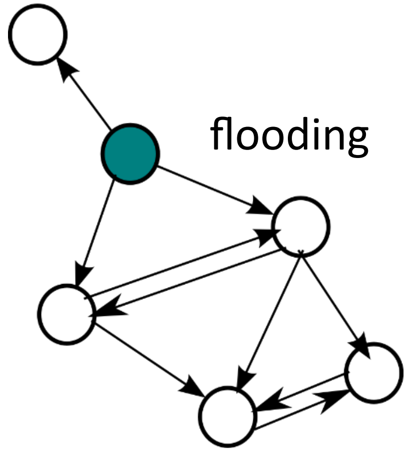
Flooding & Gossiping

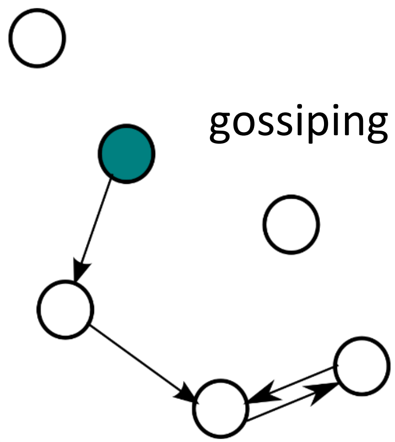
Flooding:

- Blind broadcast of every packet received
- Limiting rebroadcast (time-to-live policy)



Gossiping:

- Random selection of a single neighbor for packet relaying
- Route trace to avoid having rooting loops…



Routing for Wireless Sensor Networks

Data-centric

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Flooding & Gossiping - Problems

Implosion

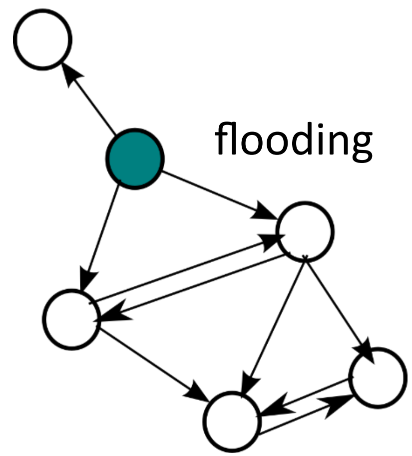
- Always sends data to a neighbor, even it has already received the data from another node
- Density of the network

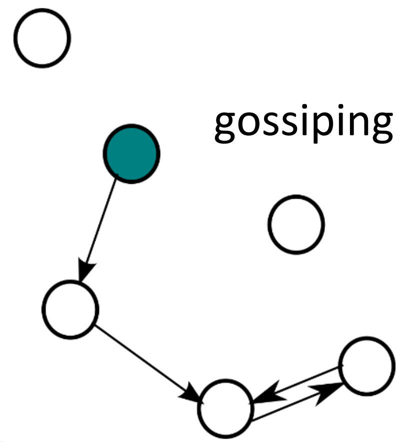
Overlap

- Nodes often cover overlapping areas (e.g. temperature distr.)
- Density and mapping of observed data

Resource blindness

- Amount of energy available is not taken into account





Routing for Wireless Sensor Networks

Data-centric

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SPIN (information via negotiation)

Controlled flooding

A family of routing protocols

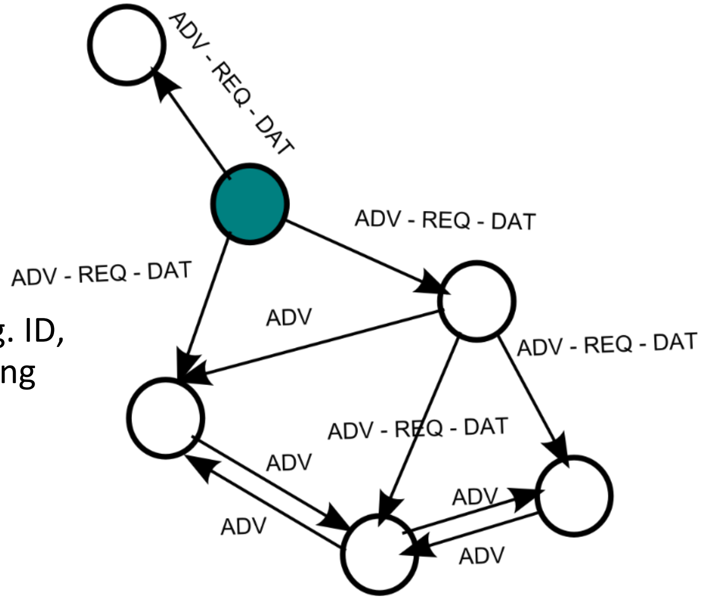
Broadcast information's meta-data (e.g. ID, location, etc) to negotiate before starting transmitting their data. -> ADV

Interested Parties respond with a REQ

DATA packet is sent only to interested parties (multicasting)

Information propagates within the network

No redundant data sent over the network.



Heinzelmann, W. R.; Kulik, J.; and Balakrishnan, H. Adaptive Protocols for Information Dissemination in Wireless Sensor Networks. In *Fifth ACM/IEEE MOBICOM Conference* (August 1999).

Routing for Wireless Sensor Networks

Data-centric

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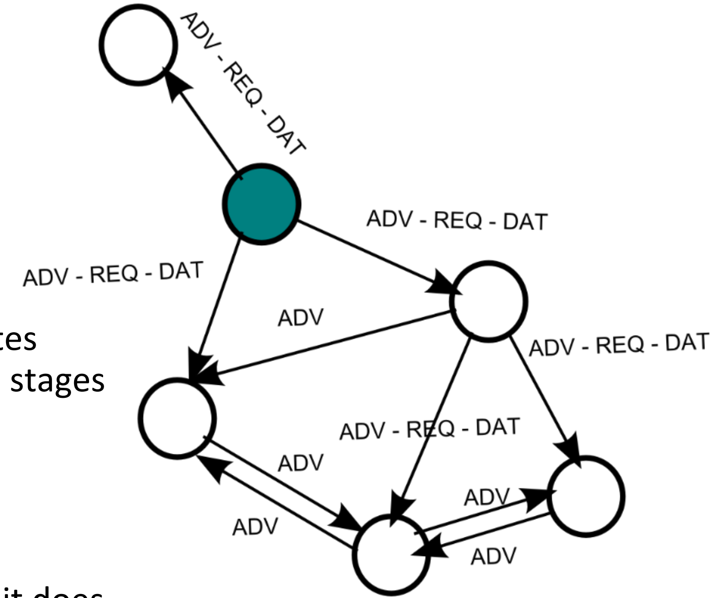
SPIN (information via negotiation) + Energy conservation (resource blindness)

Reduce participation of node when approaching low-energy-threshold

When node receives data, it only initiates protocol if it can participate in all three stages with all neighbor nodes

Nodes with energy below a threshold:

- When node receives advertisement, it does not request the data
- Node still exhausts energy below threshold by receiving ADV or REQ messages



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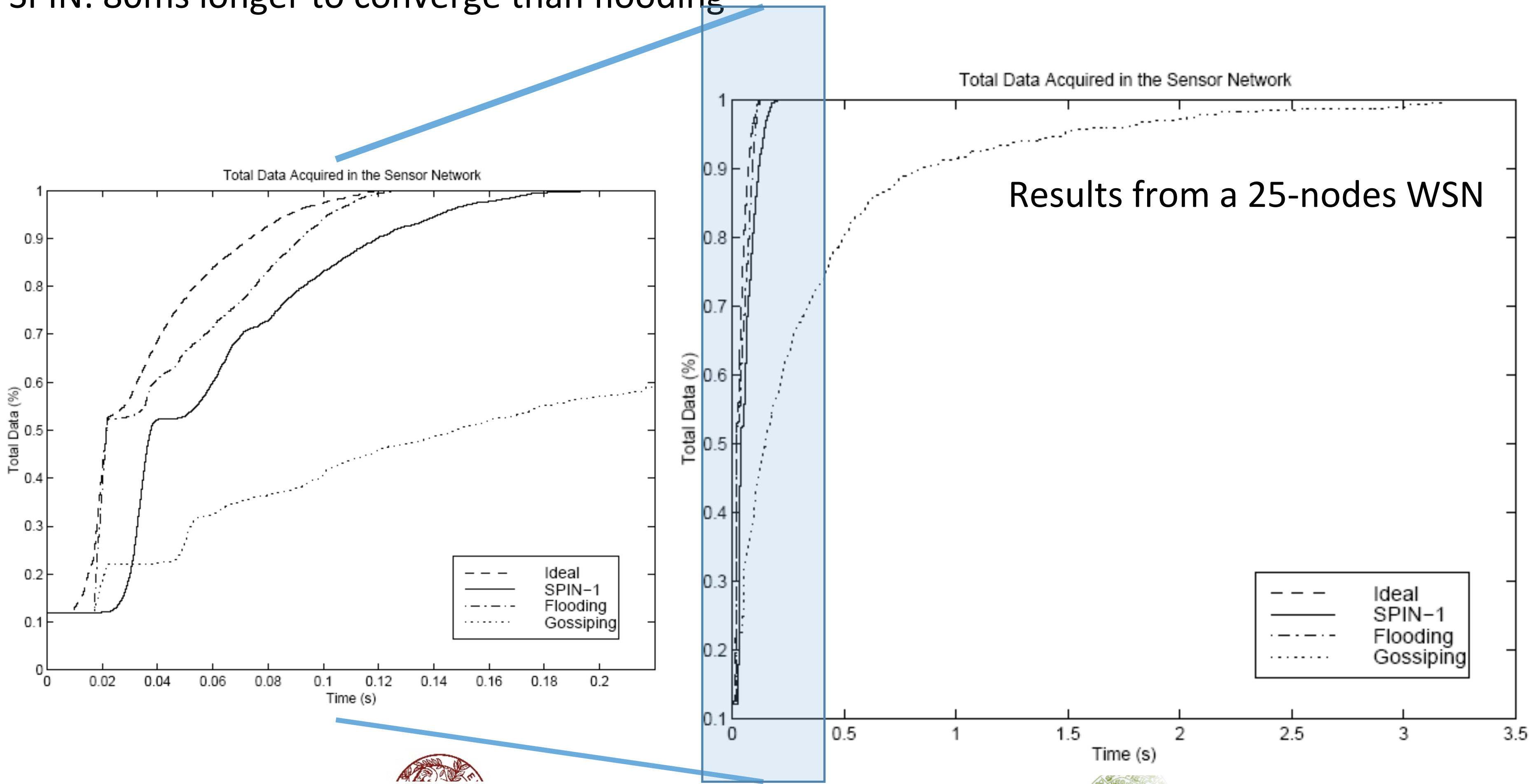
Routing for Wireless Sensor Networks

Gossiping has the slowest convergence, flooding the fastest.
Gossiping: 85% of data in a small amount of time, most spent for the remaining 15% (random choice of neighbor – can be optimized if with the route tracing mechanism)
SPIN: 80ms longer to converge than flooding



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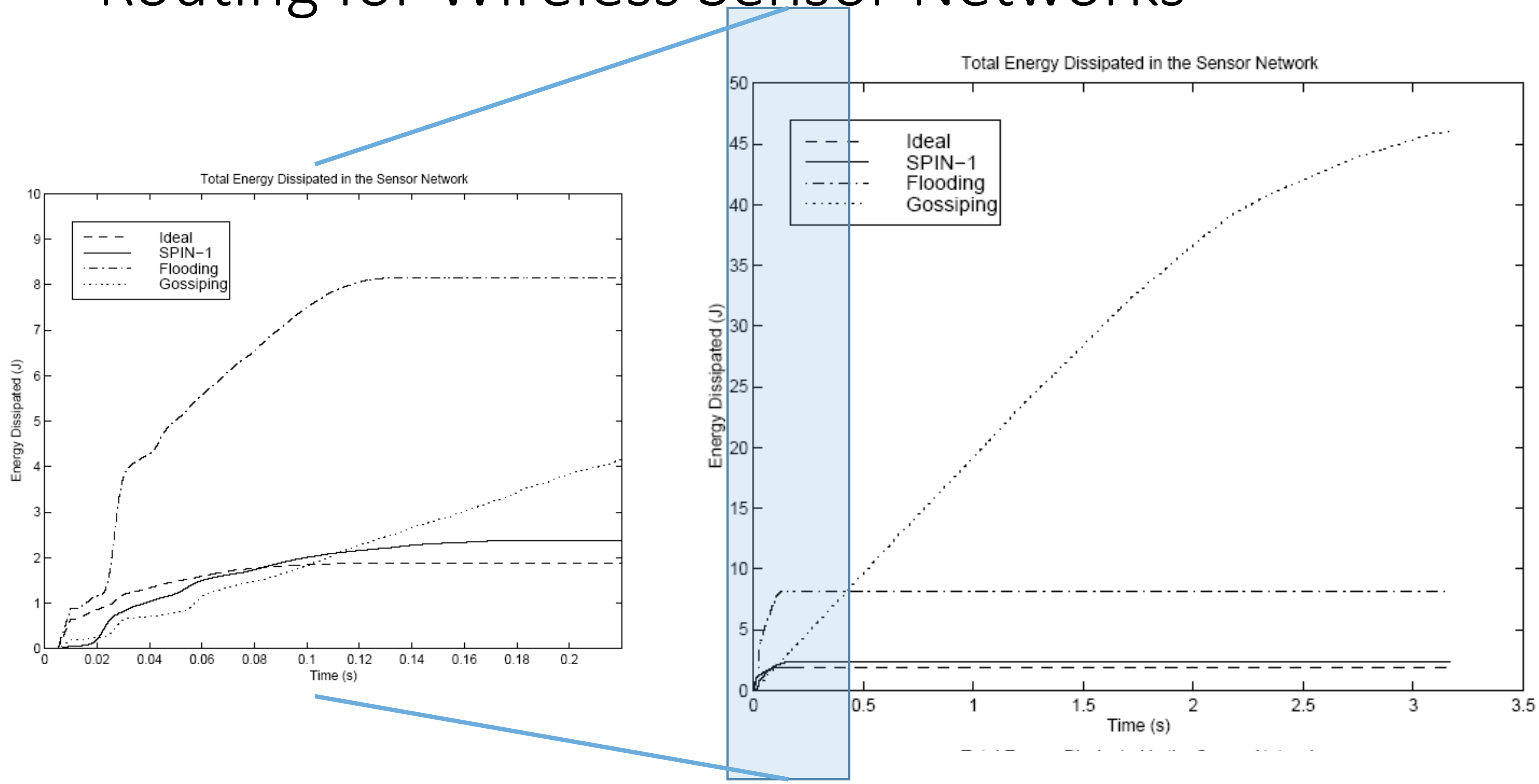
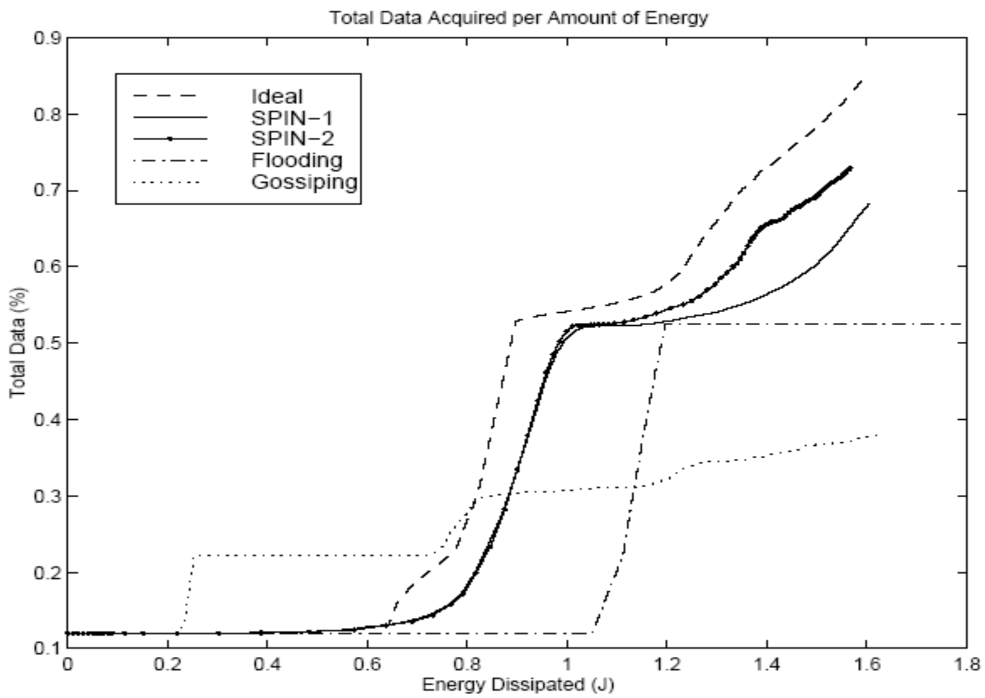
Routing for Wireless Sensor Networks

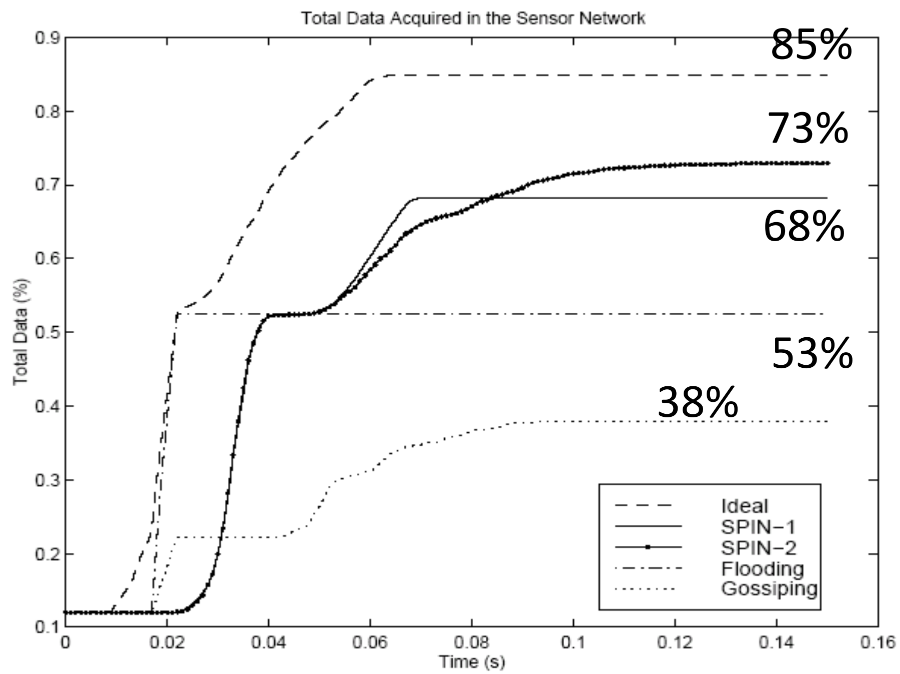


Gossiping does not converge!
Gossiping is the most costly protocol
SPIN 3.5 times less energy than flooding

simulation using ns2 and not modern emulators dedicated for WSN

Routing for Wireless Sensor Networks





Total energy in the system: 1.6 Joule

None cannot deliver 100% of the requested data volume

<0.2 J: none cannot distribute any data
@0.2J: gossiping distributes a small amount of data
@0.5 J: SPIN begins to distribute data
@1.1 J: flooding begins to distribute the data.

SPIN-2: SPIN-EC

Routing for Wireless Sensor Networks

Directed Diffusion

Routing becomes proactive

Data-centric

- Attribute-based addressing
- Sensor nodes are homogeneous (in terms of sensing modality) OR are clever enough to extract some attributes from different modalities
- The physical phenomenon can be described by more than one sensors..
- Flat architectures
- Fault tolerant

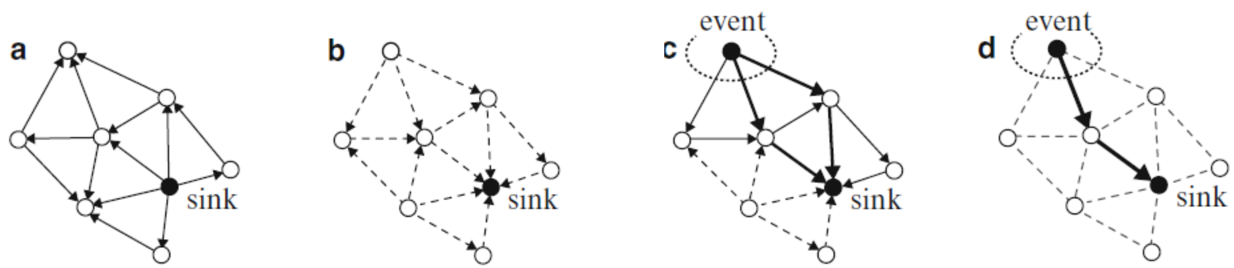
Data flow is initiated from the sink (requests specific information from the sensors)

(a) Interest propagation: exploring for matching data.

(b) Gradient setup: caching the interest message and the trace of the route from which it has been received (**forming a reserved path towards the sink**). Forwarding based on flooding (or optimized, to compensate implosion and/or resource blindness)

(c) Source node: the one that has data / task matching the interest

(d) When data become available, source sends data to sink using the gradient route.



Intanagonwiwat, Chalermek, et al. "Directed diffusion for wireless sensor networking." *Networking, IEEE/ACM Transactions on* 11.1 (2003): 2-16.

Routing for Wireless Sensor Networks

Directed Diffusion

Data-centric

- Attribute-based addressing
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Source node may have more than one gradients -> sink can reinforce the use of a specific path, based on network metrics, e.g.:

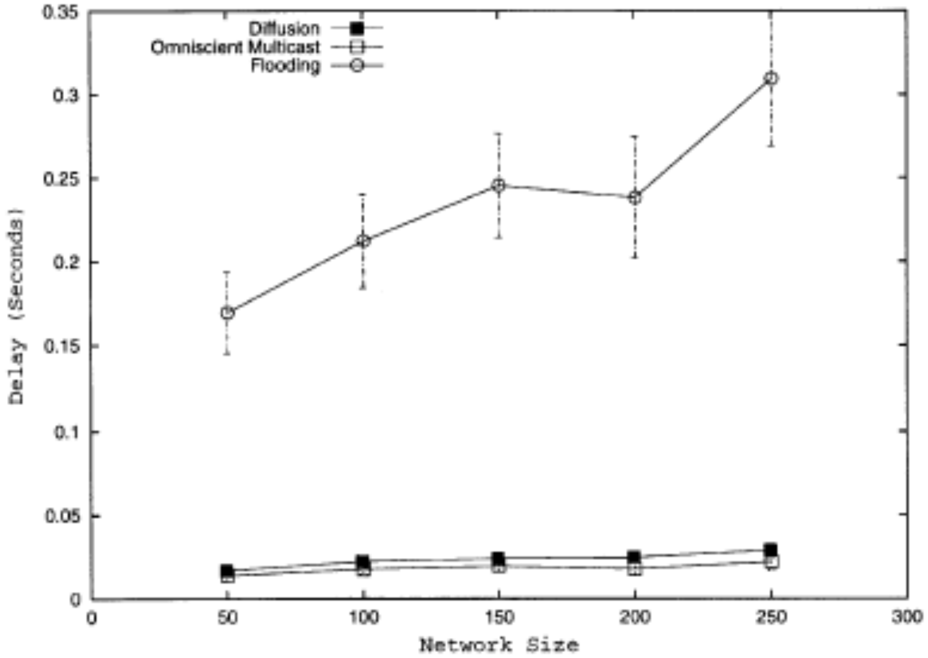
- *Link quality (e.g. SNIR, LQI)*
- Delay

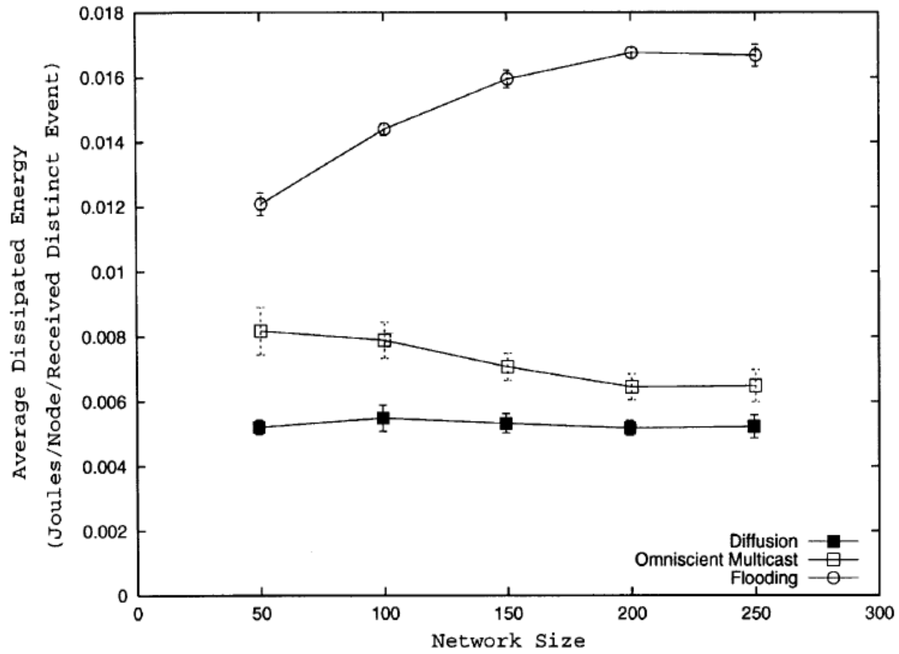
Update the gradients w.r.t. to topology changes & apply negative reinforcement to suppress a routing path OR establish multi-path delivery (e.g. for robustness)

- Variation: ***Push diffusion*** initiated from source nodes (SPIN) + For applications where data need to be initiated from the sensors
- Upon receiving the advertisements, the sink sends reinforcement packets to establish routes between the sources and the sink.

Intanagonwiwat, Chalermek, et al. "Directed diffusion for wireless sensor networking." *Networking, IEEE/ACM Transactions on* 11.1 (2003): 2-16.

Routing for Wireless Sensor Networks





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Routing for Wireless Sensor Networks

Topology-driven

- SAR
- SPEED

- Information available with respect to the network topology
- Associated network metrics (e.g. QoS)
- Proactive or reactive (similar to ad-hoc routing protocols)
- Address-based routing for constructing a specific routing topology (e.g. **tree**)

Routing for Wireless Sensor Networks

Sequential Assignment Routing (SAR)

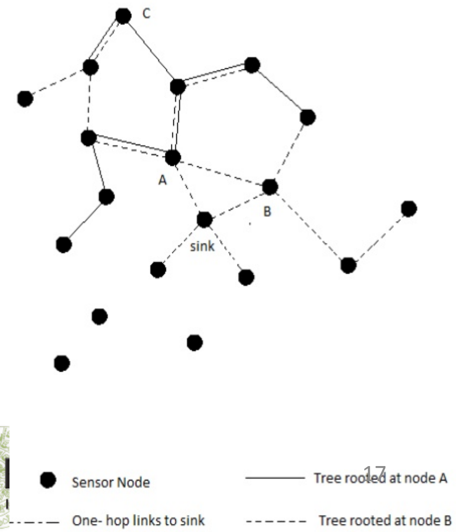
Topology-driven

- Information available with respect to the network topology
- Associated network metrics (e.g. QoS)
- Proactive or reactive (similar to ad-hoc routing protocols)
- Address-based routing for constructing a specific routing topology (e.g. **tree**)

- Quality-of-Service
- Table-driven approach
- Multiple trees for the 1-hop neighborhood of the sink (QoS-metrics)
- Each node specifies two parameters for each path to the sink:
  - **(a) energy resources**
  - **(b) Additive QoS metric:** Each path is also associated with an additive QoS metric (energy and delay)
  - (c) weighted QoS: product of QoS metric and the packet's priority => paths with higher QoS are used for packets with higher priority

(which would be an application area for this metric?)

Establishment of paths based on minimum cost forwarding.
Aggregating cost from hop to hop.



Routing for Wireless Sensor Networks

SPEED

Topology-driven

- Information available with respect to the network topology
- Associated network metrics (e.g. QoS)
- Proactive or reactive (similar to ad-hoc routing protocols)
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- To take into account the spatial correlations
- Packet guaranteed advancement at a given time.
- **End-to-end delay experienced by the packets is proportional to the distance between the source and the destination.**
- Components of SPEED:
  - *neighbor beacon exchange:* location information between neighbors (NeighborID, Position, SendToDelay, and ExpireTime)
  - Delay estimation: time it takes between packet and ACK reception (or moving average)
  - SendToDelay: forwarding using the stateless nondeterministic geographic forwarding (SNGF) algorithm.
  - SNGF forward packets to neighbors that can optimize delay

Routing for Wireless Sensor Networks

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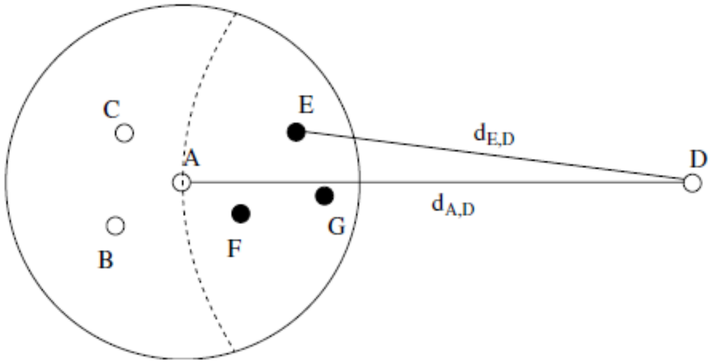
SPEED

A is the sender, D is the destination

Nodes E,F,G are the candidates for forwarding the packet



Selection is made w.r.t.:

$$Speed_A^j(D) = \frac{d_{A,D} - d_{j,D}}{HopDelay_{A,j}} \forall j \in \{E, F, G\}$$

Advancing in distance

A single speed guarantee can be supported in the network. Heterogeneous traffic?

Routing for Wireless Sensor Networks

Geographical-based

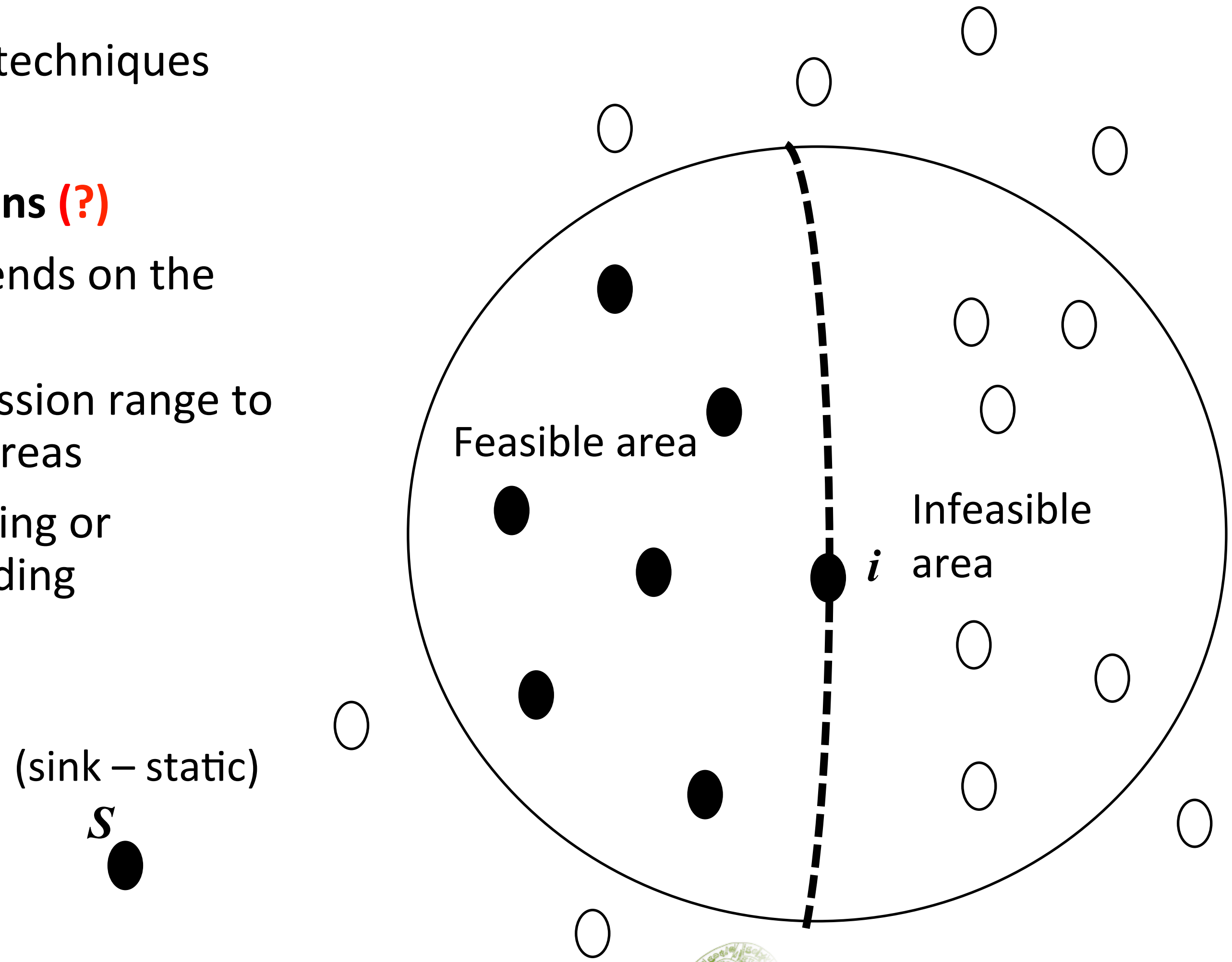
- Routing decisions are taken with respect to the locations of the sensors
- Localization in the background
- Destination is a geographical location
- Virtual coordinates to route messages in the network

- Geographical forwarding techniques
- Planar Graph Techniques

Routing for Wireless Sensor Networks

Geographical forwarding techniques

- Localized: **1-hop decisions (?)**
- Next hop selection depends on the forwarding technique.
- Partitioning the transmission range to feasible and infeasible areas
- Distance-based forwarding or reception-based forwarding



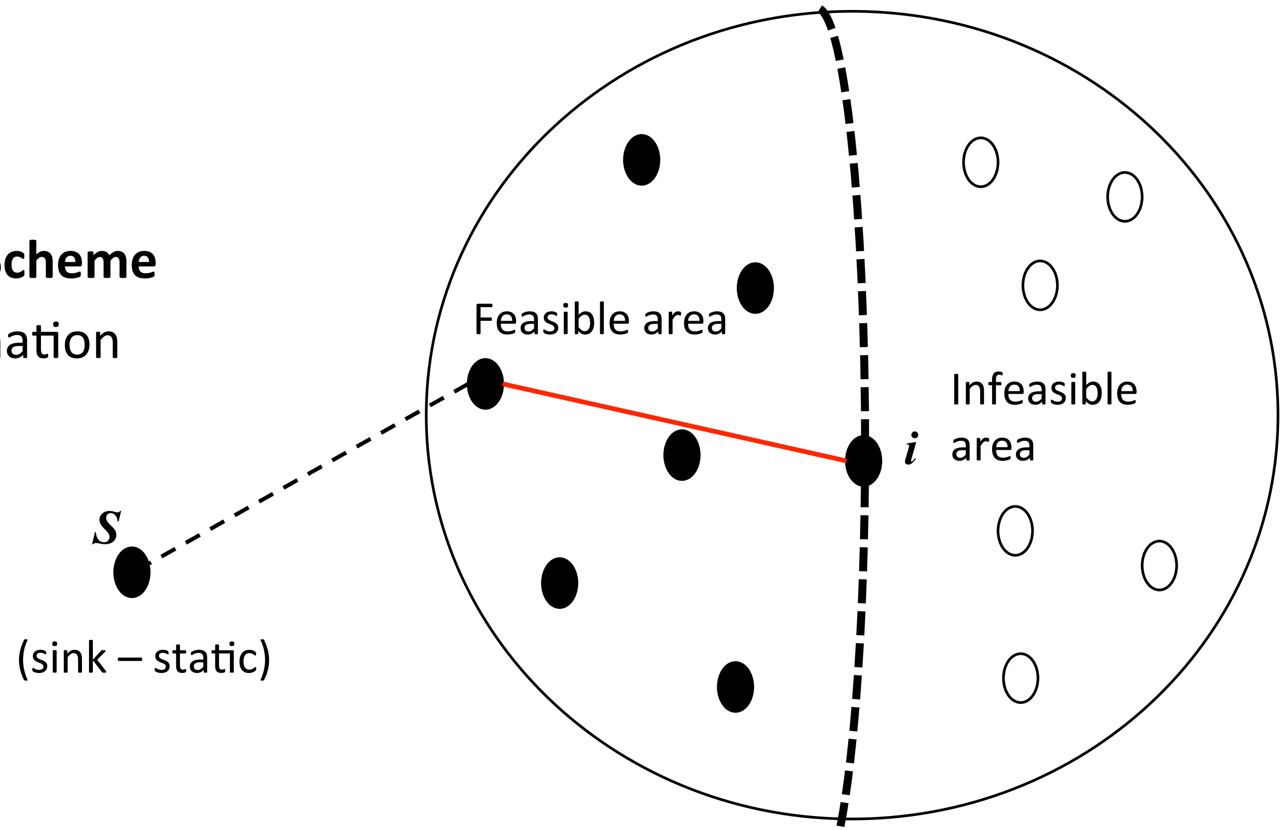
Routing for Wireless Sensor Networks

Geographical forwarding techniques

- Distance-based:

A. Greedy Routing Scheme

Closest to the destination

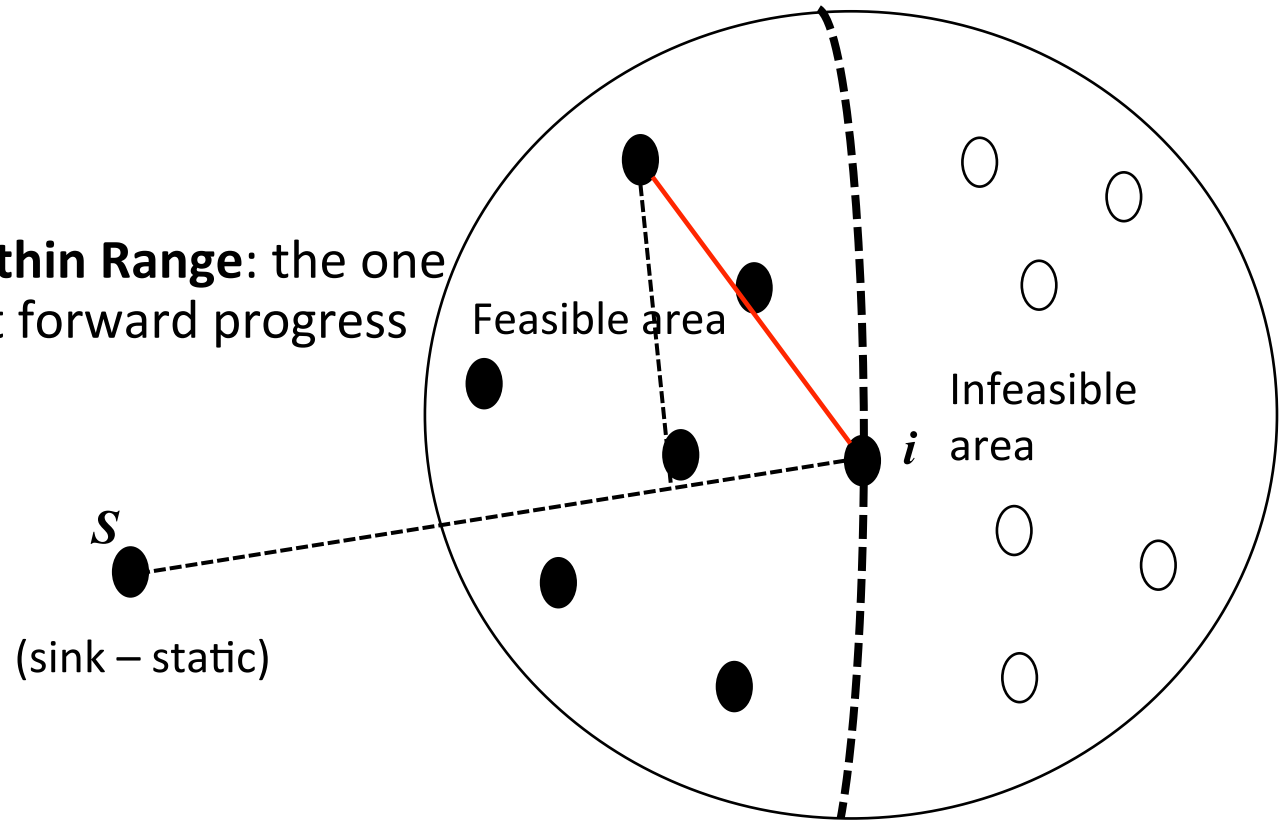


Routing for Wireless Sensor Networks

Geographical forwarding techniques

- Distance-based:

B. Most Forward within Range: the one that allows the most forward progress towards destination



Progress of a 1-hop neighbor (X) within the feasible region: the orthogonal projection of the line connecting X and $\boldsymbol{i}$ onto the line connecting $\boldsymbol{S}$ and $\boldsymbol{i}$.

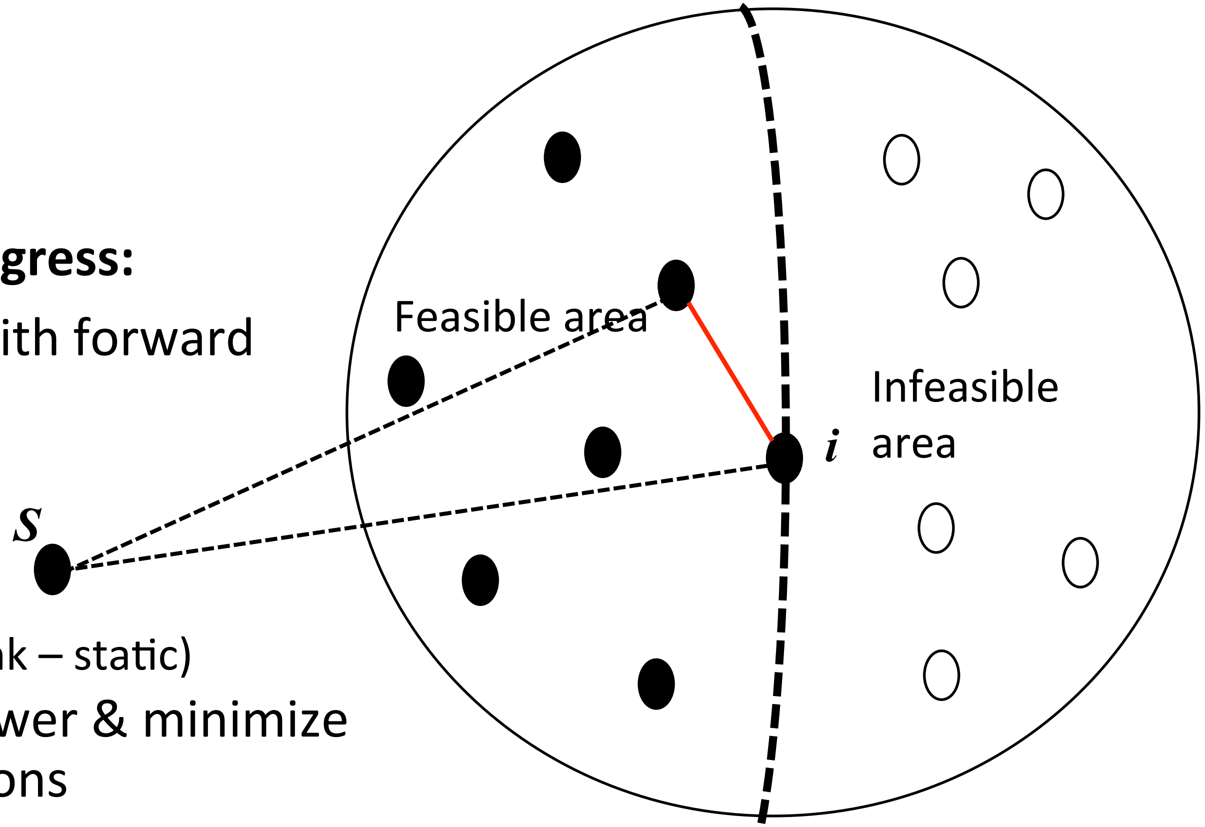
Routing for Wireless Sensor Networks

Geographical forwarding techniques

- Distance-based:

C. Nearest Forward Progress:

The nearest neighbor with forward progress



(adjust transmission power & minimize the possibility of collisions

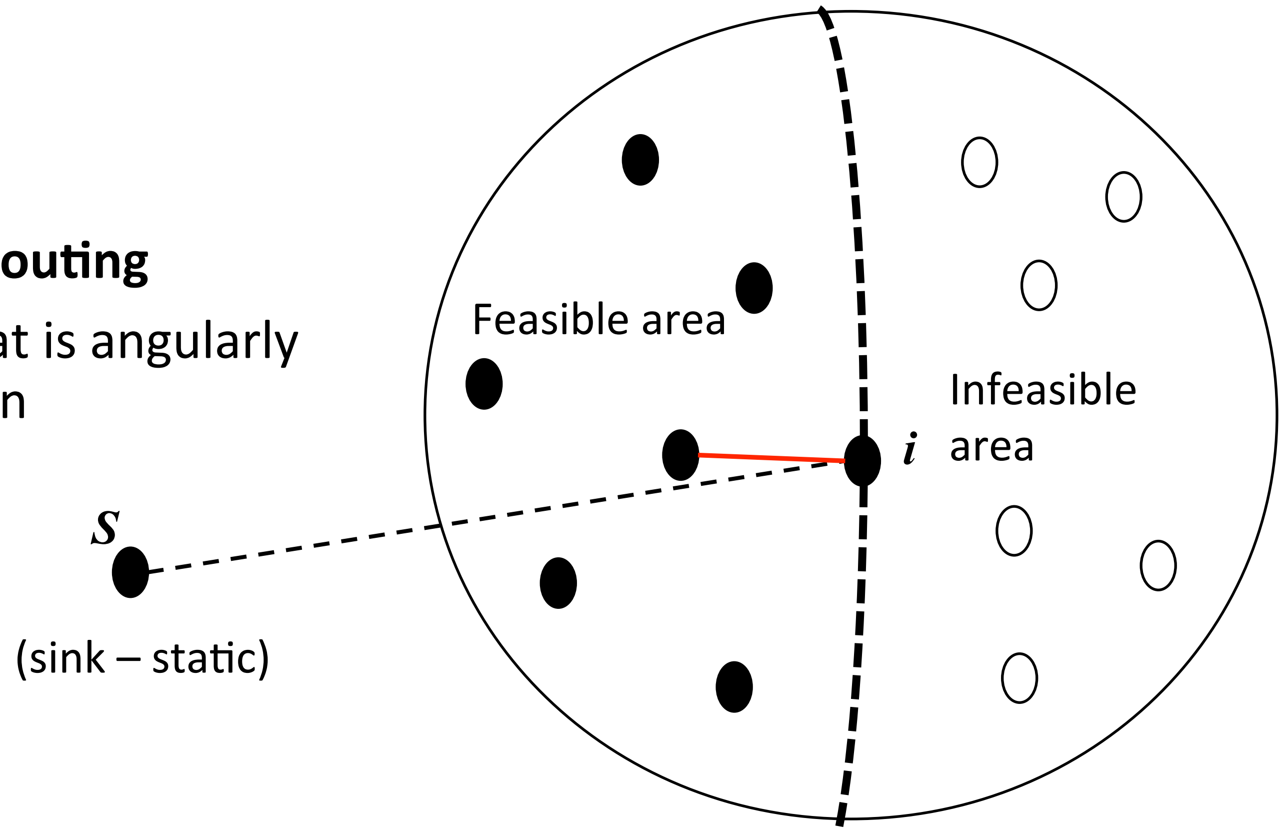
Routing for Wireless Sensor Networks

Geographical forwarding techniques

- Distance-based:

D. Compass-based routing

Choose next hop that is angularly closest to destination



Routing for Wireless Sensor Networks

Geographical forwarding techniques

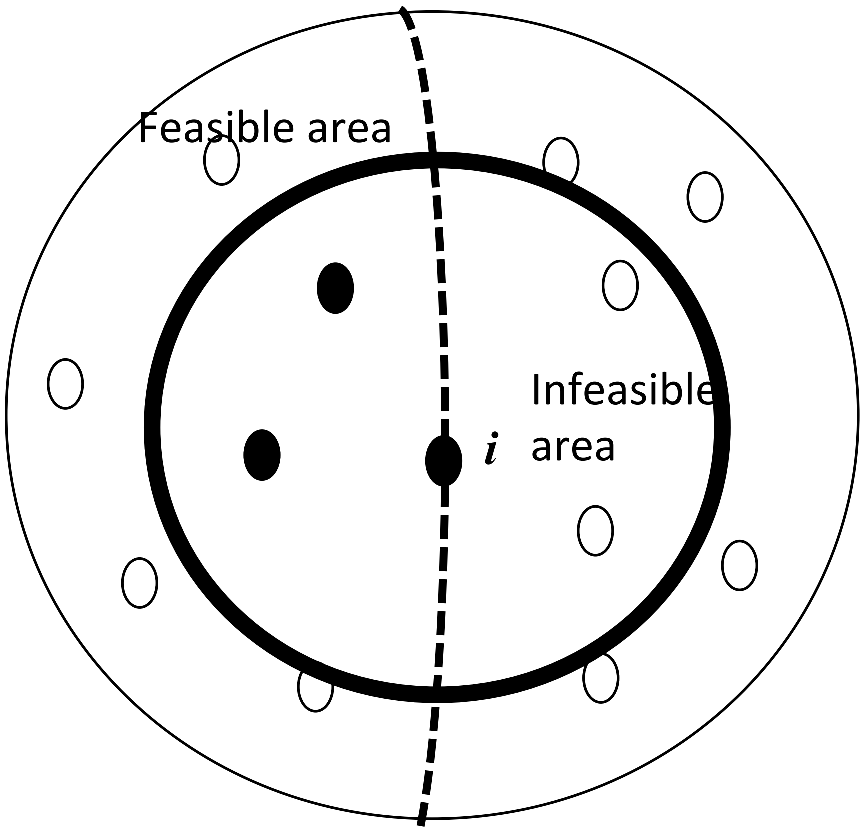
- Distance - Blacklisted:

1-hop located at distance > threshold are blacklisted from the selection process

Why: to increase the chances of delivery – the higher the distance the higher the attenuation…

s

(sink – static)



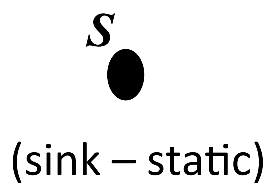
Routing for Wireless Sensor Networks

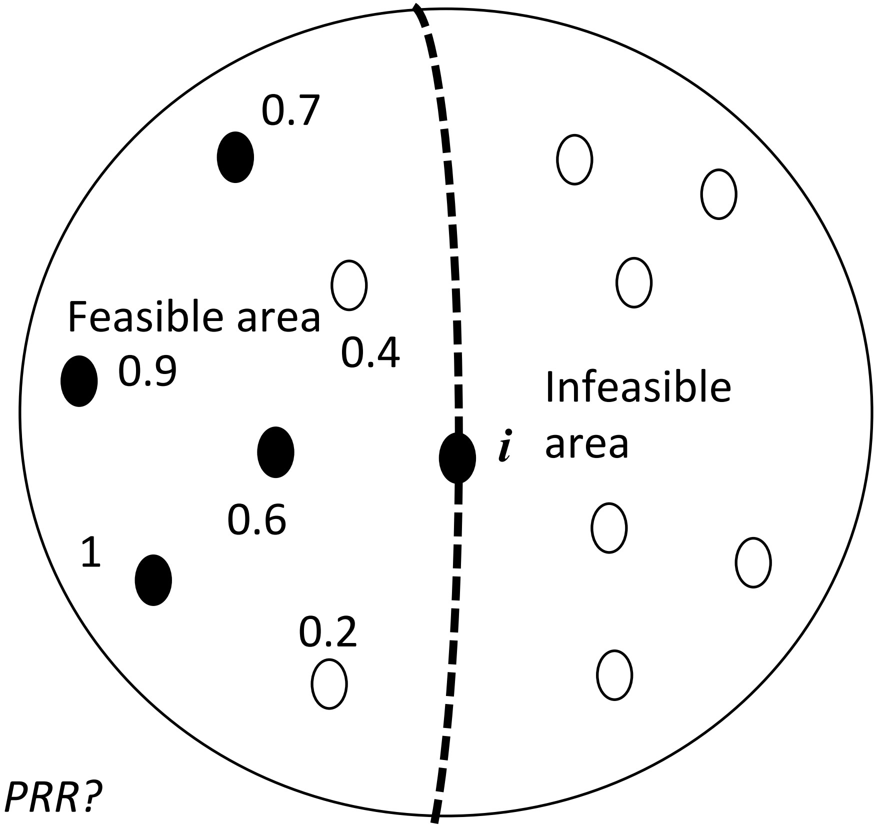
Geographical forwarding techniques

- Reception-based:

- Best-reception within the feasible area
- Blacklisted based on Packet Reception Ratio (i.e. the most reliable) within the feasible area.

Blacklisting can be absolute (i.e. predefined threshold) or relative (i.e. percentage)





e.g. PRR threshold: 0.5

How could the i-th node know the PRR?

Routing for Wireless Sensor Networks

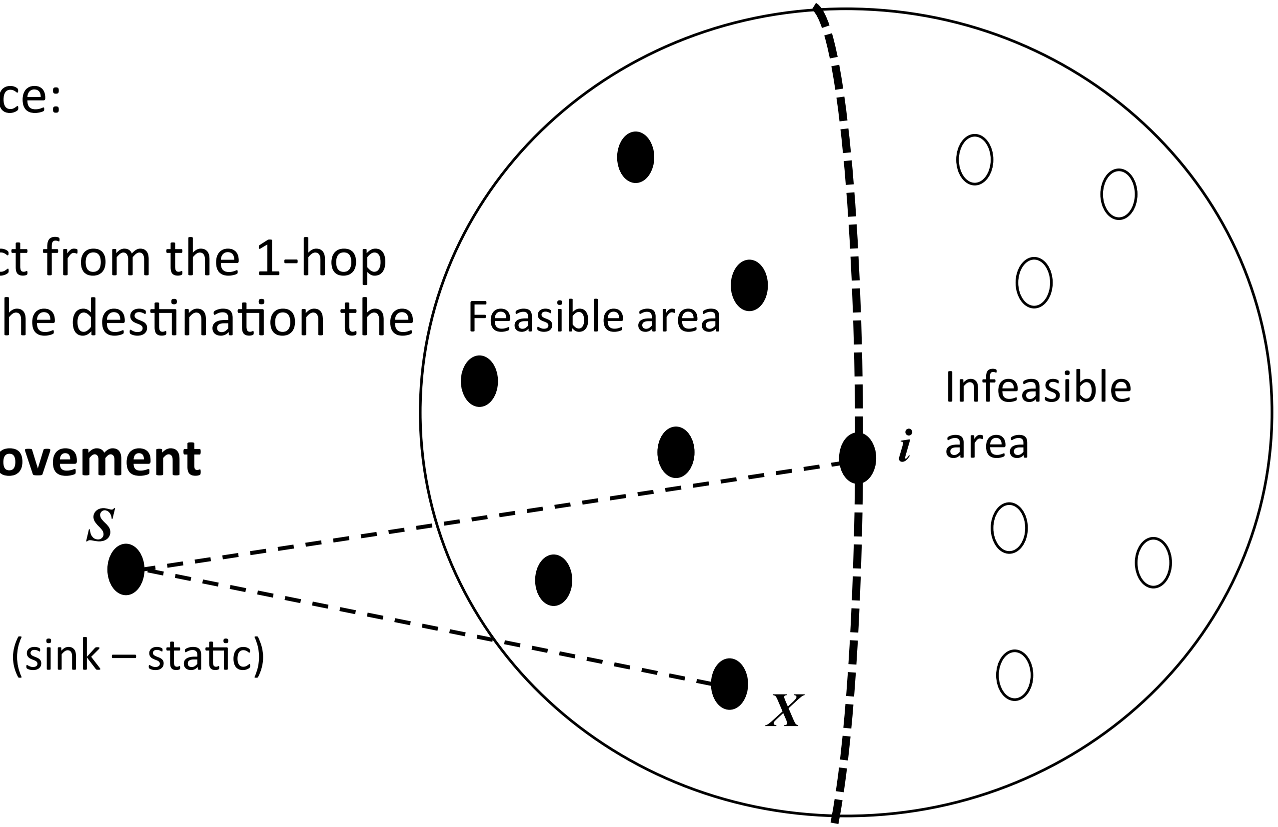
Geographical forwarding techniques

- Reception + Distance:

PRR x Distance: select from the 1-hop neighbors closer to the destination the one that maximizes:

PRR x distance improvement

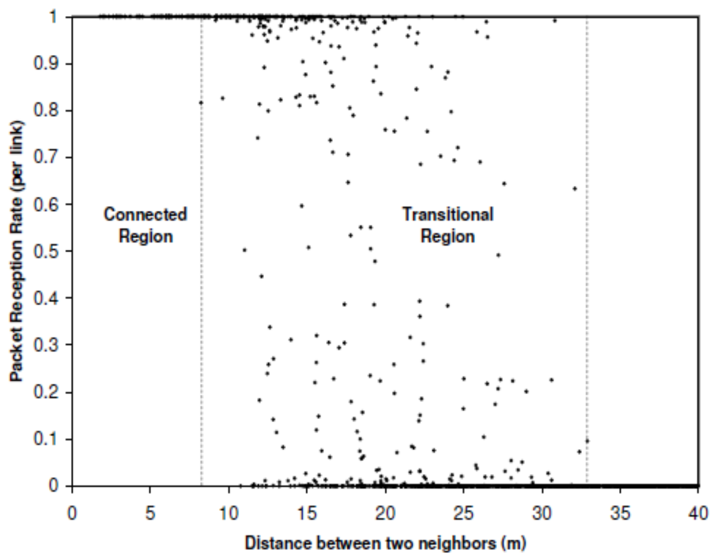
$$1 - d(x,S)/d(i,S)$$

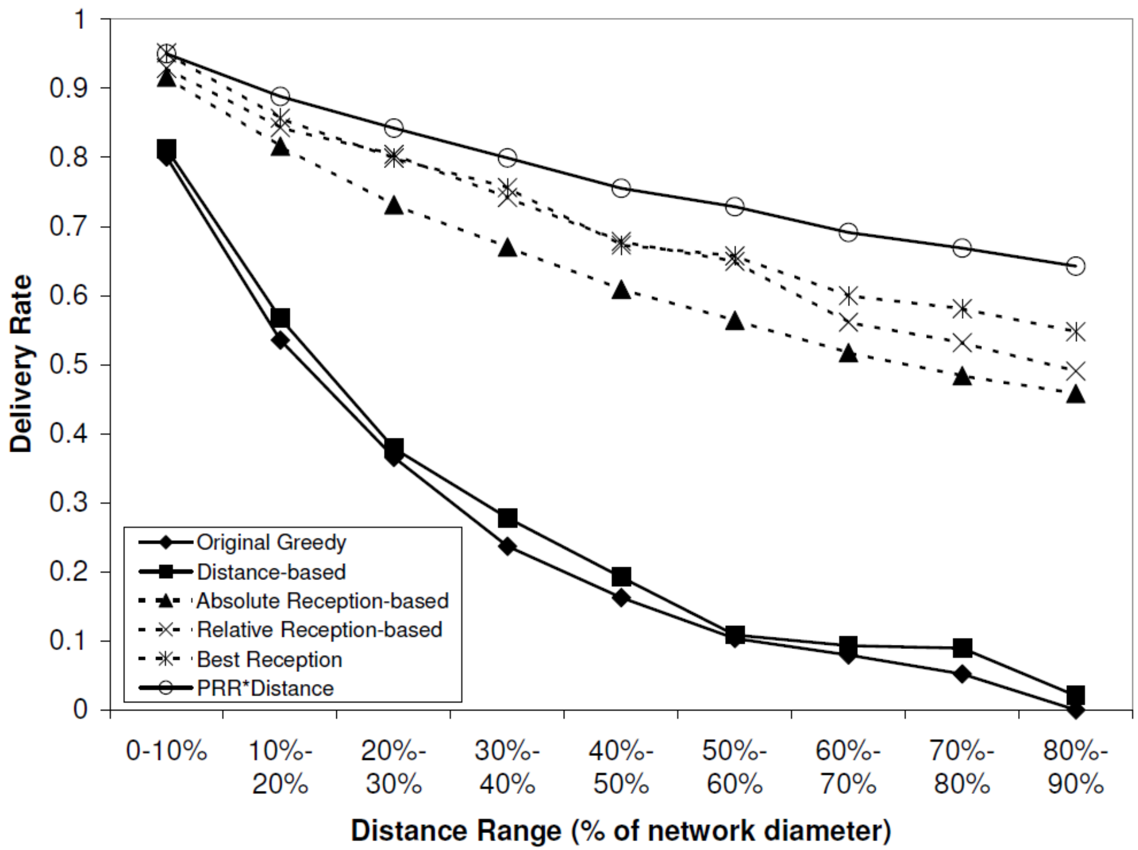


Routing for Wireless Sensor Networks

- Geographical forwarding techniques
- Comparison over noisy and faulty channels (Marco Zúñiga, et al. , 2008)

PRR x distance improvement towards is highly suitable metric for geographic forwarding in **realistic environments** (i.e. considering a realistic PHY model – based on empirical measurements)





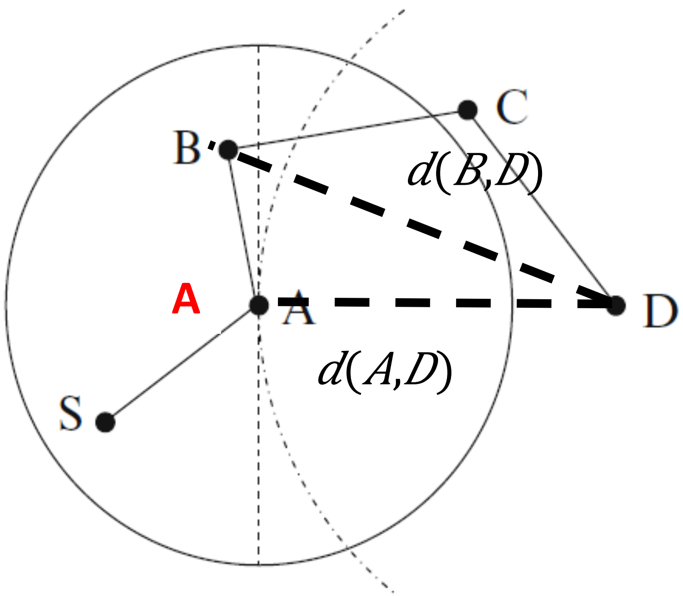
Zamalloa, Marco Zúñiga, et al. "Efficient geographic rou[t] lossy links in wireless sensor networks." ACM Trans. Sensor Networks (TOSN) 4.3 (2008): 12.

Routing for Wireless Sensor Networks

- Geographical forwarding techniques

Succeeds in dense networks

Dead-end: when the packet reaches a node that has no 1-hop neighbor closer to the destination



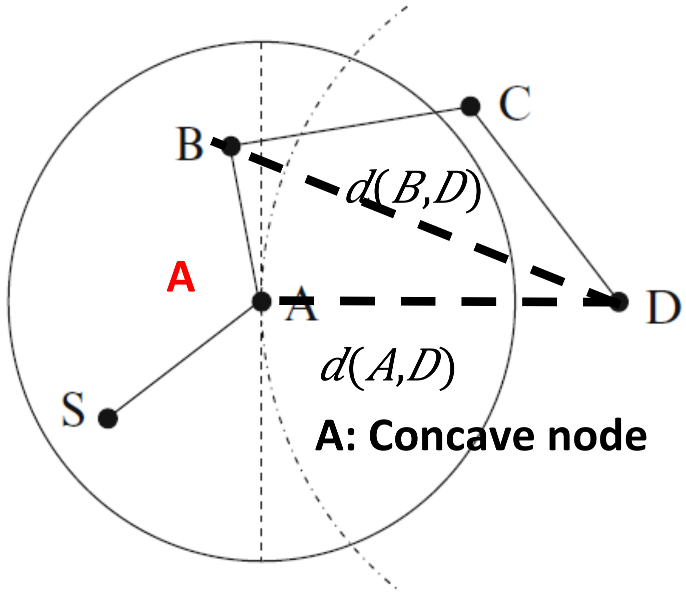
A: Concave node

"Guide to Wireless Sensor Networks", S. Misra, I. Woungang, S. C. Misra, 2009, Springer, Ch 4

Routing for Wireless Sensor Networks

- Geographical forwarding techniques

GEDIR (Geographical distance routing) – applies a greedy forwarding policy (e.g., distance, progress, direction)



The concave node will not forward the message

Handling concave routing decision:

- Drop the packet (packet failure)
- Concave node disconnects itself from the network w.r.t. the specific route and/or message
- Stateless routing: no route trace is kept/travels along with the packet

"Guide to Wireless Sensor Networks", S. Misra, I. Woungang, S. C. Misra, 2009, Springer, Ch 4

Routing for Wireless Sensor Networks

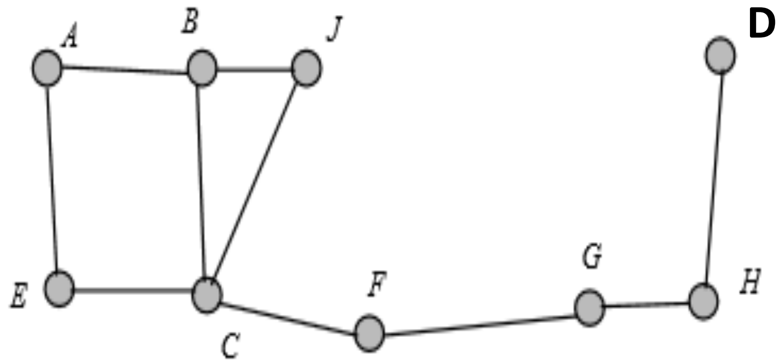
- Geographic forwarding techniques

Alternative GEDIR:

Generating as many copies of the same message as the number of 1st hop neighbors.

Each intermediate node forwards i-th received copy of the same message to the i-th best closest to destination neighbor.

A node becomes concave if the number of copies it receives is larger than the number of 1-hop neighbors.



GEDIR: **A-B-J (pck dropped)**

Xu Lin, Ivan Stojmenovic, Location-based localized alternate, disjoint and multi-path routing algorithms for wireless networks, Journal of Parallel and Distributed Computing, Volume 63, Issue 1, January 2003, Pages 22-32

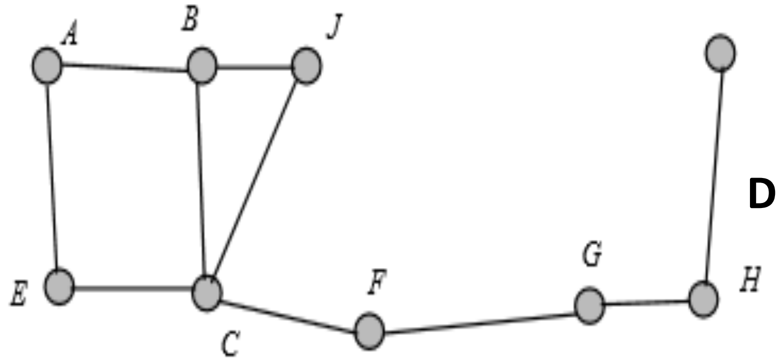
Routing for Wireless Sensor Networks

Which are the silent assumptions made?

- Geographic forwarding techniques

Alternative GEDIR:

Each intermediate node forwards i-th received copy of the same message to the i-th best closest to destination neighbor.



GEDIR: **A-B-J (pck dropped)**
Altr. GEDIR: **A-B-J-B-C-J-C-F-G-H-D**

Temporary loops may be created.

Is J a concave node?

Xu Lin, Ivan Stojmenovic, Location-based localized alternate, disjoint and multi-path routing algorithms for wireless networks, Journal of Parallel and Distributed Computing, Volume 63, Issue 1, January 2003, Pages 22-32

Routing for Wireless Sensor Networks

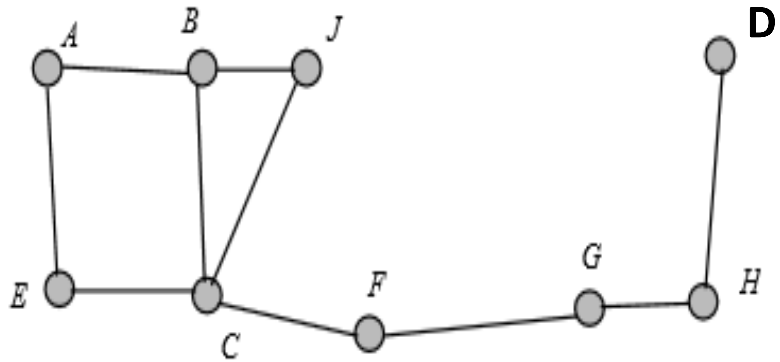
- Geographic forwarding techniques

Is J concave node?

Disjoint GEDIR:

Each interm. node will forward to the **best neighbor among those who never received the same message before**. Then it becomes inactive w.r.t. to that message (drops duplicates).

A node becomes concave if there is no neighbors left to forward the message.



GEDIR: **A-B-J (pck dropped)**
Altr. GEDIR: **A-B-J-B-C-J-C-F-G-H-D**
Disj. GEDIR: **A-B-J-C-F-G-H-D**

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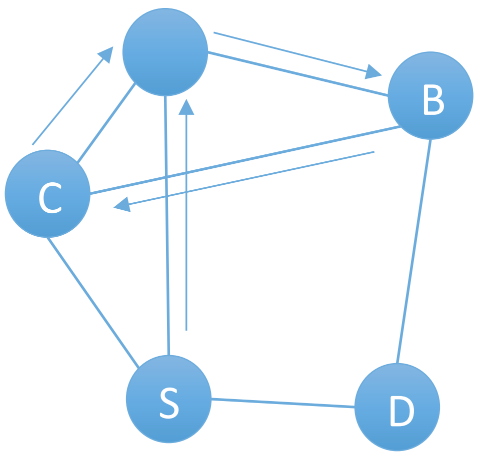
Routing for Wireless Sensor Networks

- Planar graph routing techniques

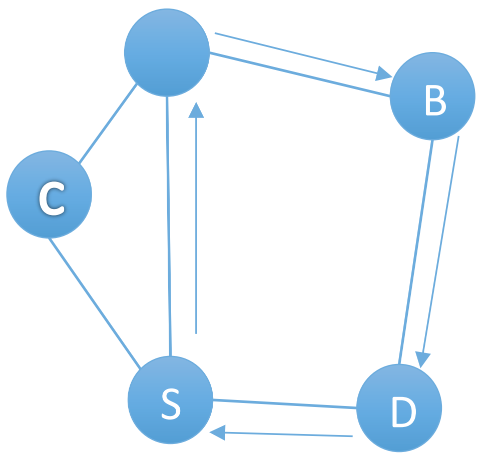
An alternative to geographic forward routing for alleviating the local-minima problem..

Abstracting the network as a graph

Applying locally the left-hand or the right-hand rule. How: find a successor node in clockwise or counter-clockwise order respectively



Non-planar



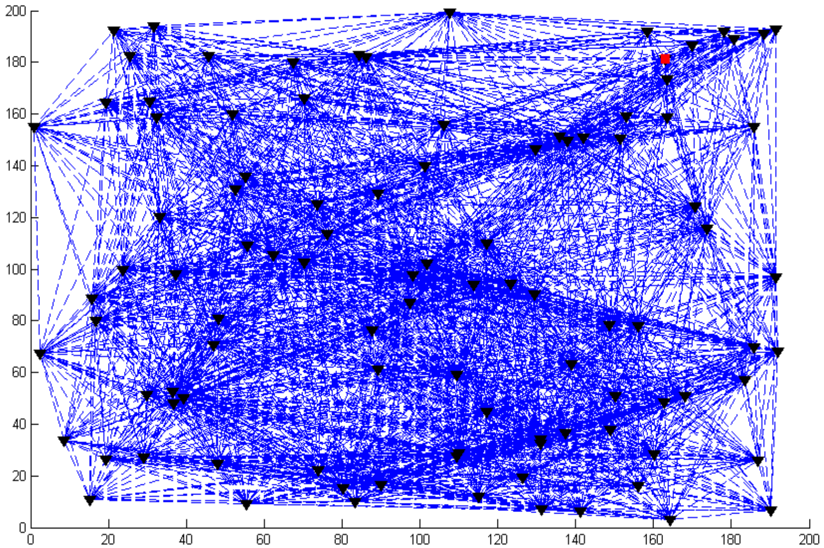
planar

Routing for Wireless Sensor Networks

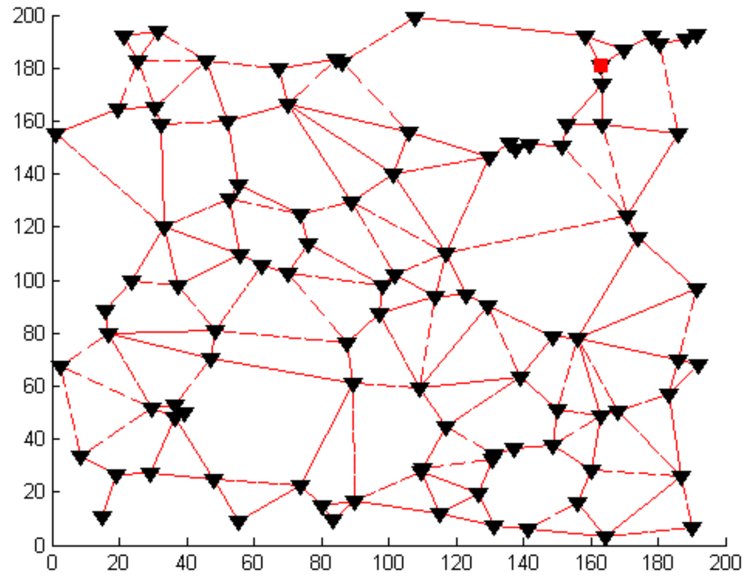
- Planar graph routing techniques

How to make a graph planar:

initial



planar

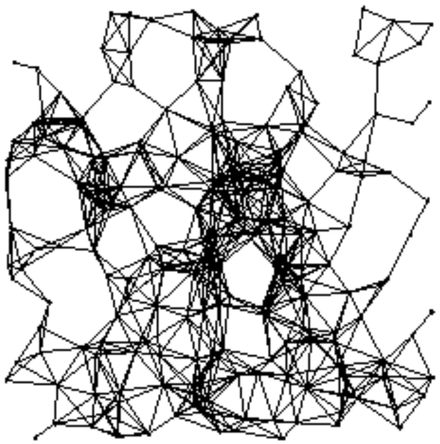


Routing for Wireless Sensor Networks

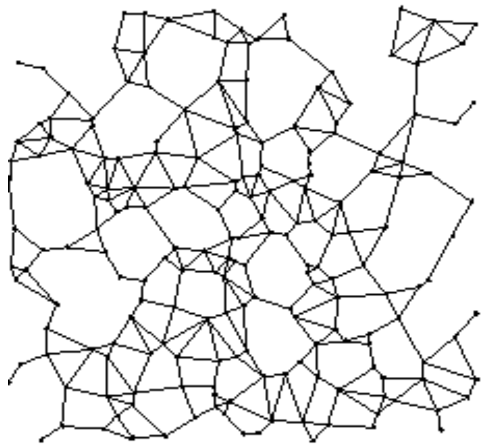
- Planar graph routing techniques

How to make a graph planar (examples):

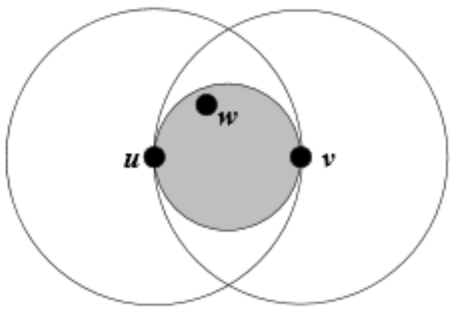
Initial



Gabriel graph (GG)



GG: If max(d(u,w), d(v,w)) < d(u,v) -> uv is not part of the GG

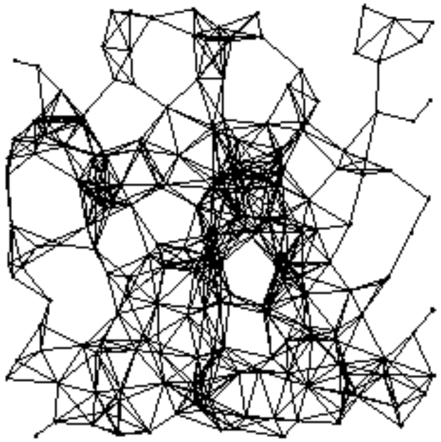


Routing for Wireless Sensor Networks

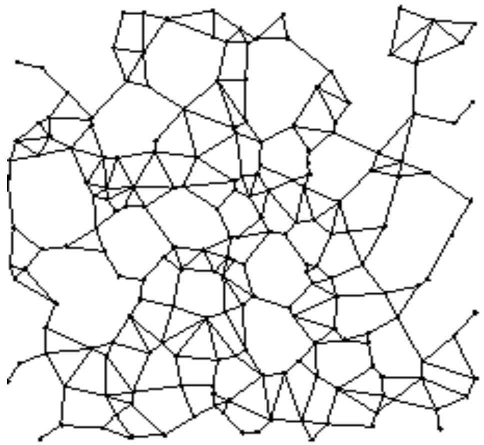
- Planar graph routing techniques

How to make a graph planar (examples cont'):

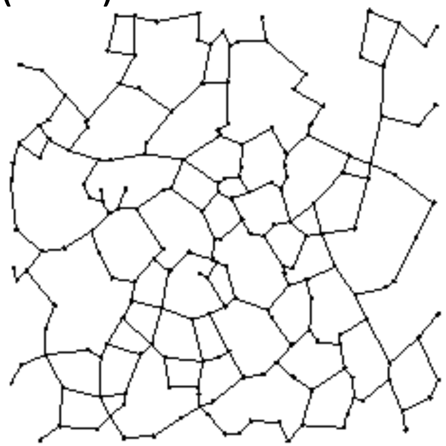
Initial



Gabriel graph



Relative Neighbors graph (RNG)



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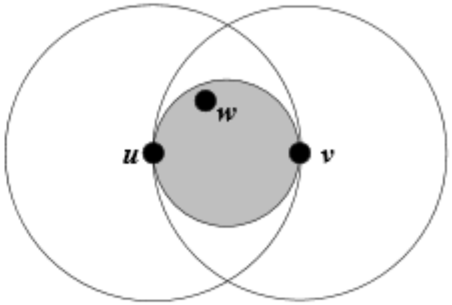
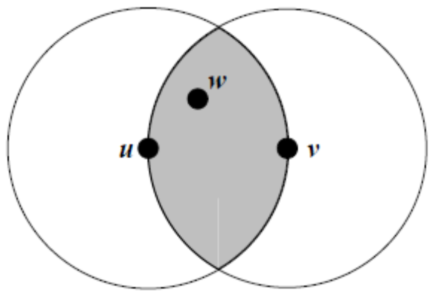


RNG: If w is in the intersection of the u – v range -> uv is not part of the RNG

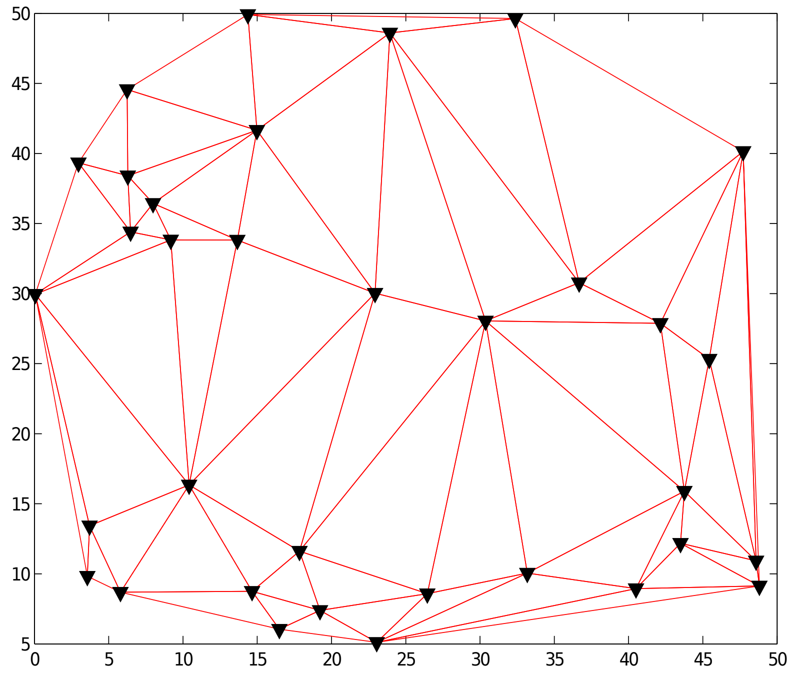


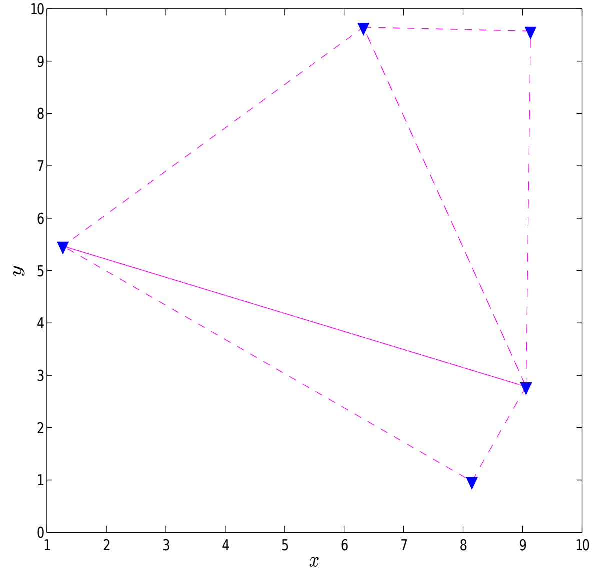
Routing for Wireless Sensor Networks

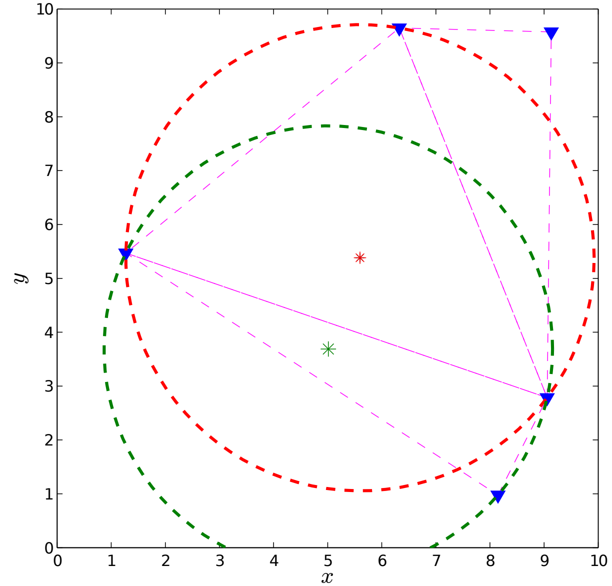
- Planar graph routing techniques

How to make a graph planar (examples cont'):

Delaunay graph







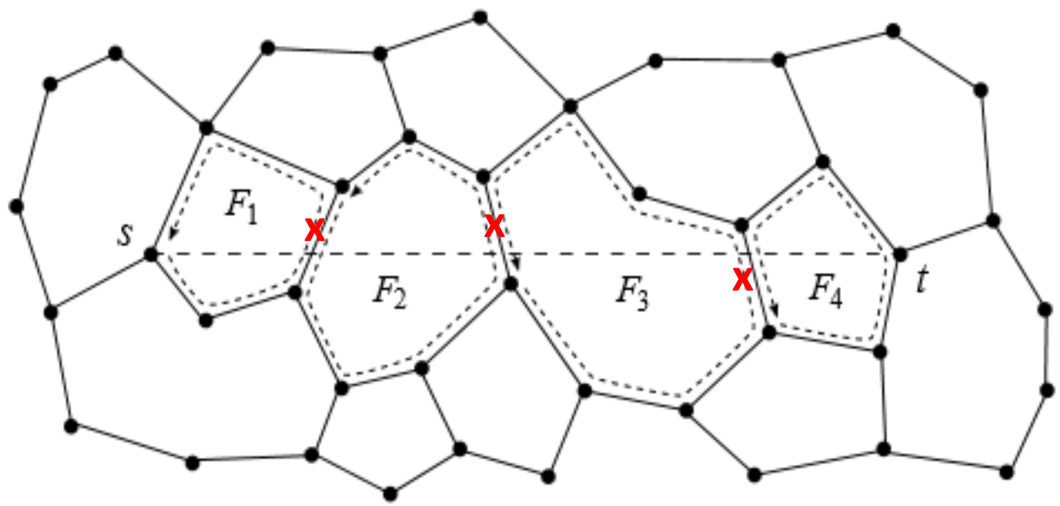
Routing for Wireless Sensor Networks

- Planar graph routing techniques

- Compass Routing II (FACE):

Traverses a sequence of adjacent faces until reaching the destination

Each face is traversed completely in order to determine the edge that intersects the s-t line and is closest to the target.
The message is passed to that endpoint & face changes.

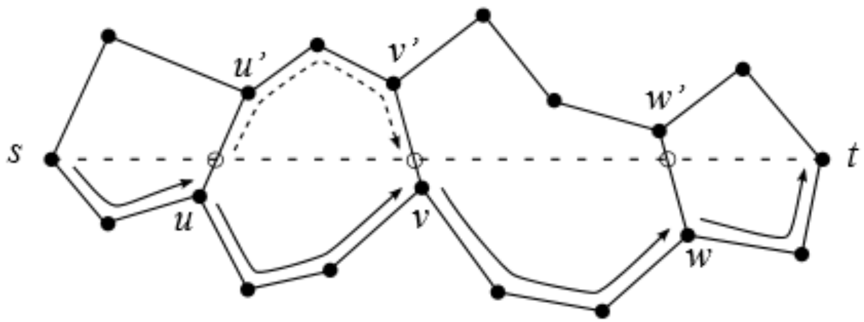


Ruhrup, Stephan. "Theory and practice of geographic routing." *Ad Hoc and Sensor Wireless Networks: Architectures, Algorithms and Protocols* (2009): 69.

Routing for Wireless Sensor Networks

- Planar graph routing techniques

- Face 2:



Avoids the complete traversals and performs the face change before crossing the s-t line.

On each face traversal, a node u checks whether the edge to the next node intersects the s-t-line. If this is the case, then u changes the face and continues traversing the next face.

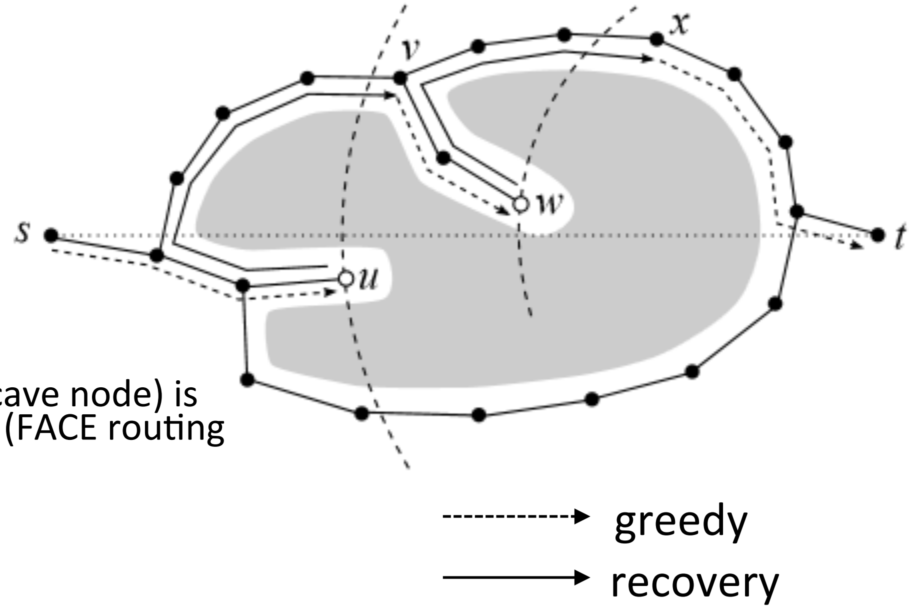
++guarantees delivery on planar graphs
++local position-based rules (**stateless**)

Ruhrup, Stephan. "Theory and practice of geographic routing." *Ad Hoc and Sensor Wireless Networks: Architectures, Algorithms and Protocols* (2009): 69.

Routing for Wireless Sensor Networks

- Planar graph routing techniques

  GPSR: Greedy perimeter stateless routing



Combines greedy + face routing

Greedy & recovery phase: if a local minimum (concave node) is reached, the algorithm switches to recovery mode (FACE routing is applied)

Face: moving along the planar graph edges

Use position where face was entered and destination position to determine when face can be left again, switch back to greedy routing → *keeping a route trace*

Ruhrup, Stephan. "Theory and practice of geographic routing." *Ad Hoc and Sensor Wireless Networks: Architectures, Algorithms and Protocols* (2009): 69.

Routing for Wireless Sensor Networks

- Planar graph routing techniques

In recovery mode you need to know:

- Distance from destination when entering
- First node in recovery mode when entering
- Previous hop

A Combined Greedy/Face-Routing Algorithm
(GFG with sooner-back procedure [15])
Variables: previous hop p, current node u, target t, first edge in recovery mode e_r and distance to target d_r in rec. mode

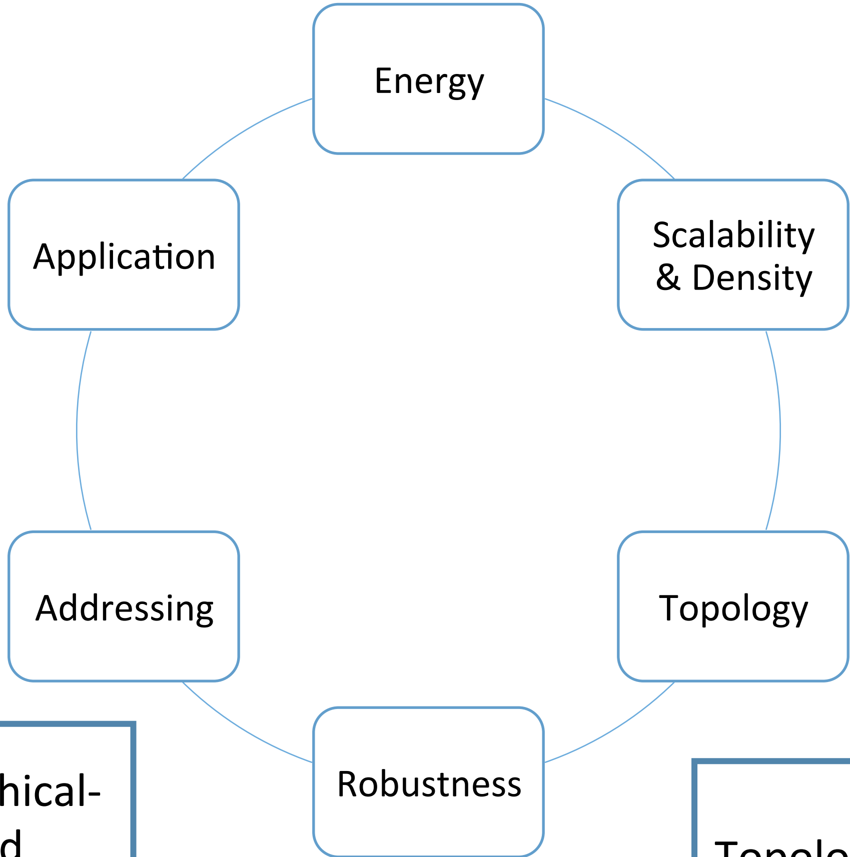
```
if packet in greedy mode
   select next hop v according to the greedy rule
   if no such neighbor exists
      select next hop v in ccw. direction from (u,t)
      switch packet to recovery mode
      store current distance to the destination d_r
         and e_r ← (u,v) in the packet header
   endif
else (packet is in recovery mode)
   if there is a neighbor v with ||v − t|| < d_r
      switch packet to greedy mode
   else
      select next hop v in ccw. direction from (u,p)
      (using only nodes of a GG or RNG subgraph)
      if (u,v) equals the first edge e_r in recovery mode
         drop packet; return
      endif
   endif
endif
forward packet to v
```

Ruhrup, Stephan. "Theory and practice of geographic routing." *Ad Hoc and Sensor Wireless Networks: Architectures, Algorithms and Protocols* (2009): 69.

Routing for Wireless Sensor Networks

- To sum up:
  - Geometric properties and assumptions regarding the communication graph
  - Theoretical analysis of the efficiency vs. real-life constraints (delivery cannot always be guaranteed)
  - Greedy forwarding is still an efficient and robust method for geographic routing in dense networks.
  - To think about: *PRRxdistance + energy over greedy w. recovery phase*

Routing for Wireless Sensor Networks



Data-centric

Geographical-based

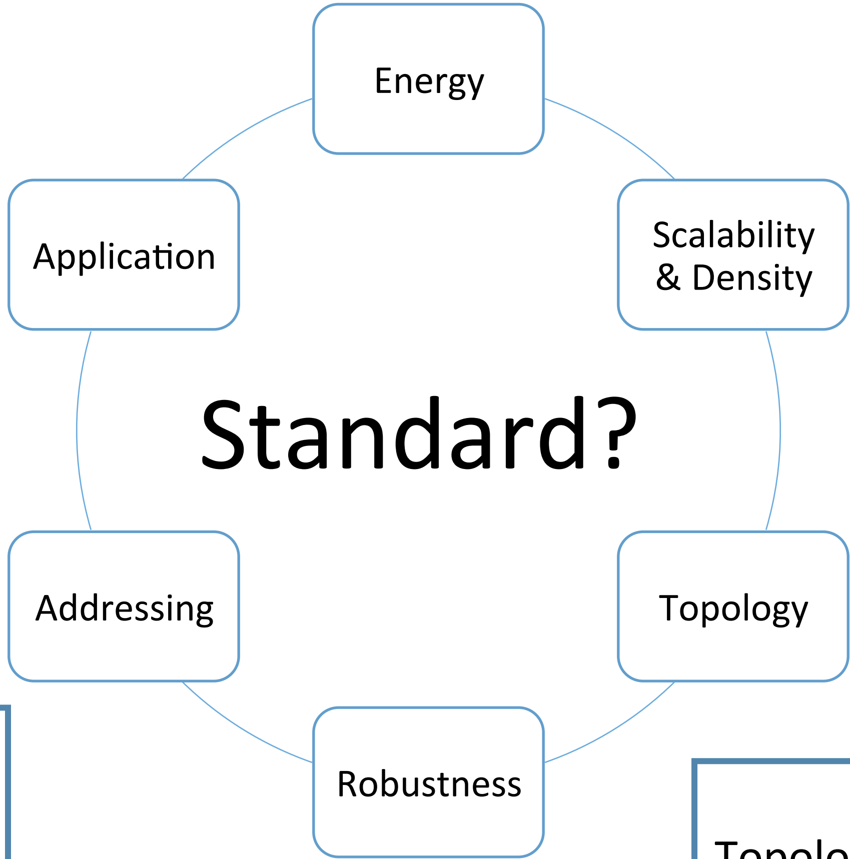
Geographical-based

Topology-driven

"Wireless Sensor Networks", Ian F. Akyıldız, Mehmet Can Vuran, 2010, Willey, Ch 7

Routing for Wireless Sensor Networks

Data-centric



Geographical-based

Geographical-based

Topology-driven

"Wireless Sensor Networks", Ian F. Akyildiz, Mehmet Can Vuran, 2010, Willey, Ch 7

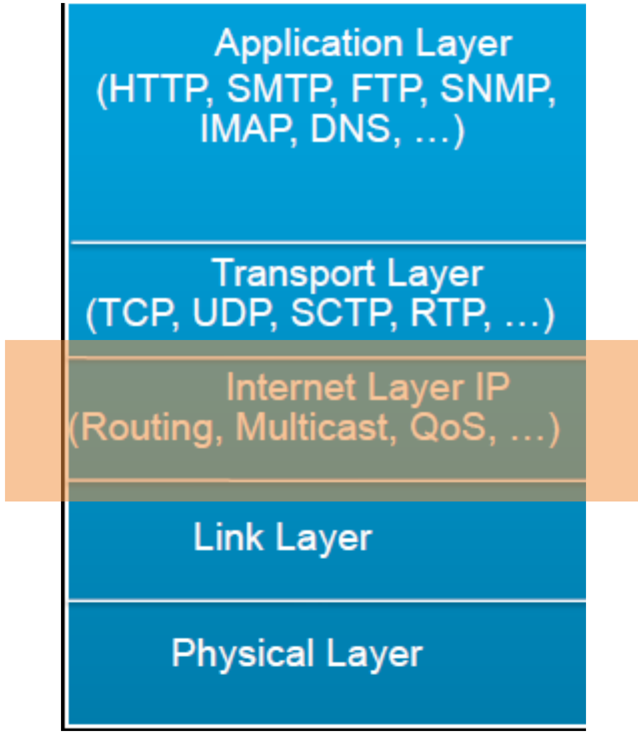
Routing for Wireless Sensor Networks

Routing Standards: IETF Routing protocol for Low-power Lossy Networks (LLN)

- Internet Engineering Task Force: the working groups behind AODV, OLSR, etc.

Rationale: to prevent fragmentation in the sensor networking market by providing an IP-based routing standard

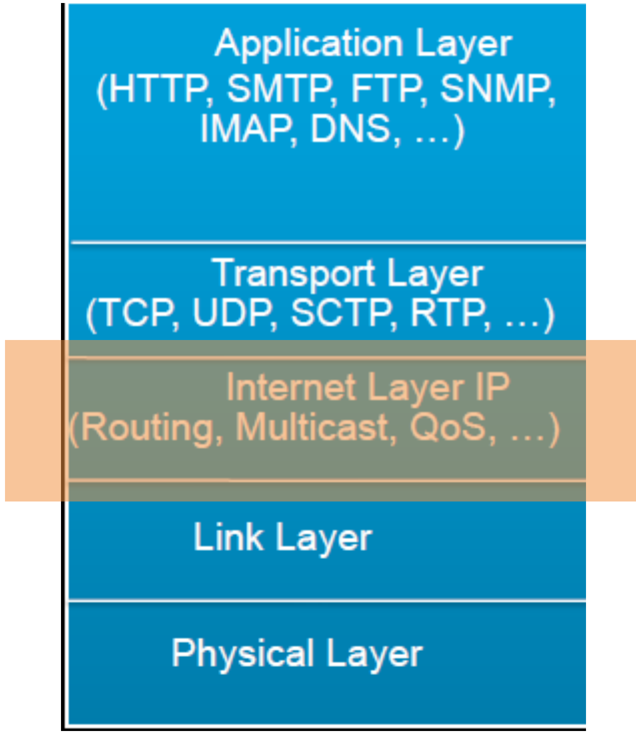
  - Broad industrial support



Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

- **IPv6 routing** over networks with significantly higher packet loss rates than traditional IP routing protocols.
- Extra scalable solutions
- Interoperable w.r.t. to PHY and MAC
- Many-to-one traffic pattern (e.g. sensor nodes to sink node)



Routing in Wireless Sensors

*Uses IP layer for constructing and maintaining a routing tree-> **6LoWPAN***

A set of rules for supporting the implementation of the *μIP* stack in WSN

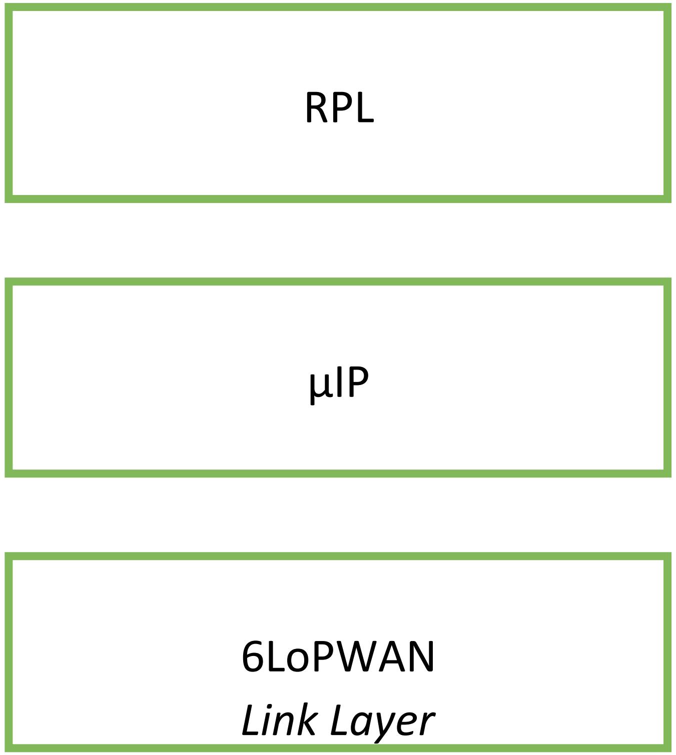
6LoWPAN is not a network protocol!

- Runs on each node – not responsible for MAC functions.
- Compressing the IP headers
- Packet (de)fragmentation

e.g. IPv6: 1280 bytes @ link layer

Maximum capacity of IEEE 802.15.4: 128 bytes

Address resolving & Route discovery



Missing out on heavy functions & stripping packet headers to absolute minimum

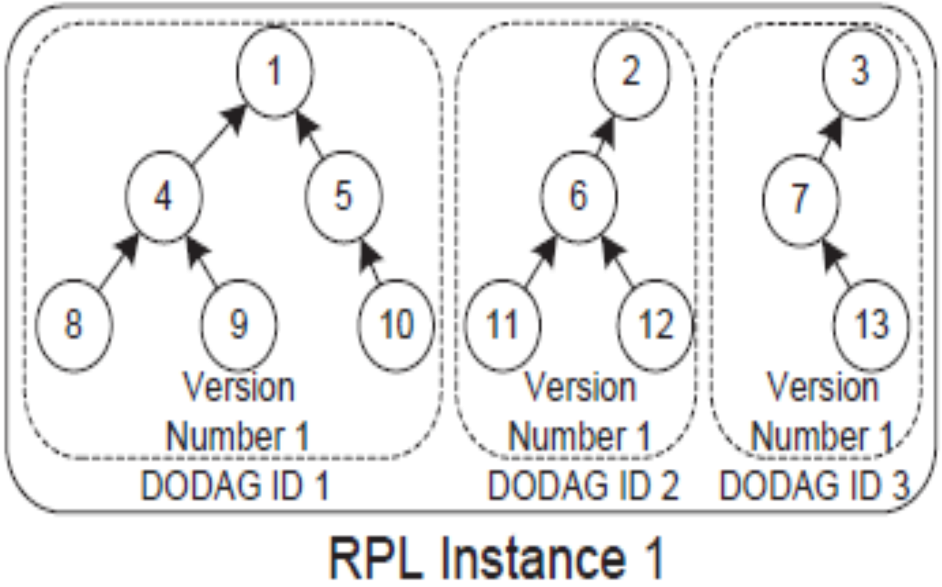
Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

- Routing tree: Destination Oriented Directed Acyclic Graph (DODAG)

Each DODAG is uniquely identified by:

(a) RPL instance ID –independent set of DODAGs for a given scenario (using the same routing criteria)
(b) DODAG ID – root's IPv6 address
(c) DODAG version number – incremented as the DODAG is reconstructed.



Tsvetkov, Tsvetko. "RPL: IPv6 Routing Protocol for Low Power and Lossy Networks." *Sensor Nodes–Operation, Network and Application (SN)* 59 (2011): 2.

Within the same network different instances of RPL (labeled with different IDs)

Routing for Wireless Sensor Networks

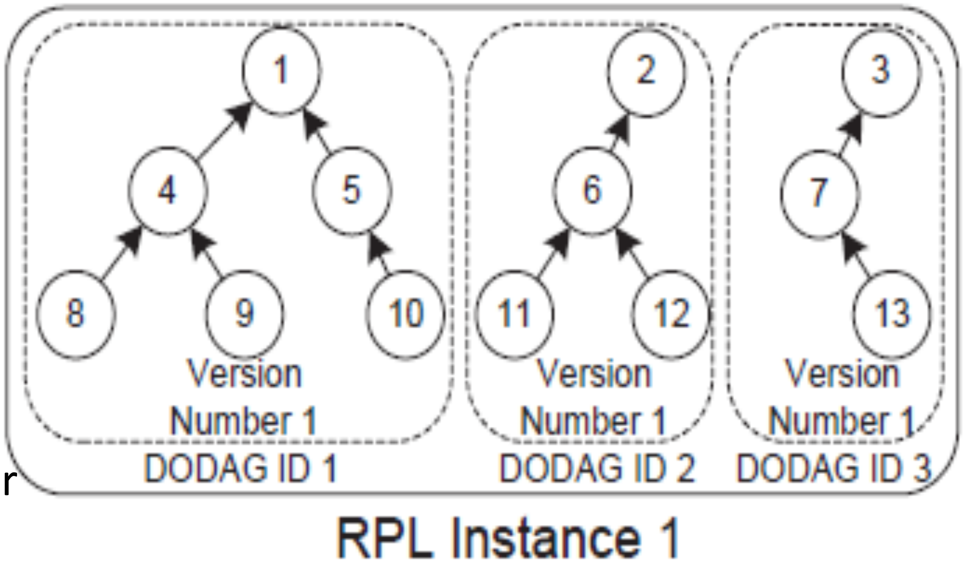
Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

Logical sets of communication:
Candidate neighbors: all reachable nodes (same/different DODAG Versions)

Candidate parents: It includes only neighbor nodes that belong to the same DODAG Version.

When a node stores a neighbor into the parent set, it becomes attached to the given DODAG.

The most preferred next hop taken from the parent set.
A node may belong to more than one RPL Instance. In this case, it must join a DODAG for each RPL Instance.



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Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

4 types of control messages (ICMPv6) for topology maintenance and information exchange

- DODAG Information Object (DIO): Routing control information (Rank of a node, the current RPL Instance, IPv6 address of the root, etc.) – within 1hop neighborhood for topology construction and maintenance.
- Destination Advertisement Object (DAO): Downwards traffic - propagates destination information.
- DODAG Information Solicitation (DIS): on demand requests for DIO messages from a reachable neighbor.
- DAO-ACK: in response to a DAO message.

Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

Distinction between the levels of the tree -> Rank:

A scalar value that represents the relative position of the node w.r.t. other nodes and the DODAG root.

Rank of Root: minimum (0) & increases as we move away from the root.

MinRankIncrease: the minimum difference in ranking between different levels of the tree.

MaxRankIncrease: the maximum allowable difference in ranking between different levels of the tree.

Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

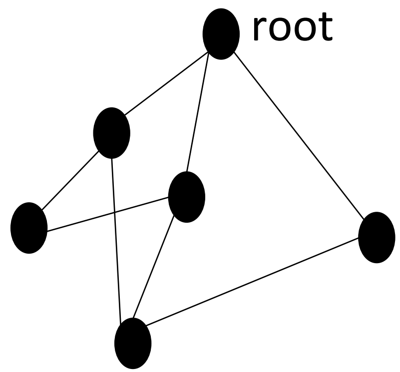
Tree construction:
Root node: sends DIO message. (Rank = 0)

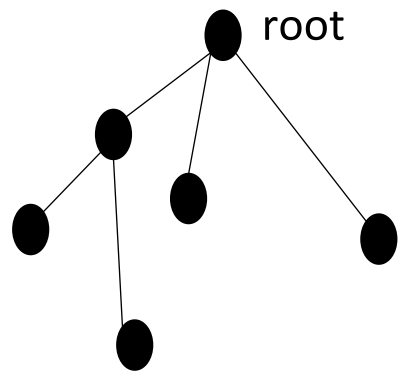
Each node within range: Standby for DIO messages.

Selects parent based on the **Objective Function** and computes its own **Rank**. (Rank is not the same as the Objective Function)

If it is a parent (i.e. there are nodes with a higher rank than its own), it updates the Rank in the DIO message and sends it to all neighboring peers.

Process repeated until reaching a leaf, or when no more nodes are left in range.





Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

How to cope with routing loops

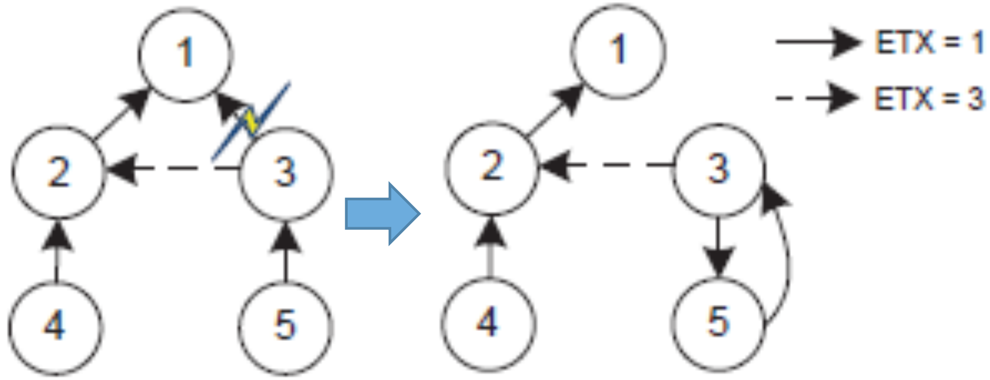
DIOs are sent in the 1st hop neighborhood.

It may happen that child nodes are best next hops.

Each node does not process the DIO messages from nodes with higher Rank than itself

If link fails, then the node in trouble should declare an invalid state, poison its routes, and join the DODAG Version again.

Loop example



Objective Function:
ETX (Expected transmissions count)

Tsvetkov, Tsvetko. "RPL: IPv6 Routing Protocol for Low Power and Lossy Networks." *Sensor Nodes–Operation, Network and Application (SN)* 59 (2011): 2.

Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

How to detect problems

Within data packet: RPL Packet Information field

1. Direction (upwards or downwards)
2. Rank mismatch (between sender and receiver) – packet is not immediately dropped but if it happens again RPL enters the tree route repair mechanism.
3. Forwarding error field (child node): there is no valid route (Rank of the sender and the RPL Instance ID)

→

Root Repairing

↓

Global repair or local repair

Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

Root Repairing / Topology Maintenance

DIO messages are periodically sent – how periodically?

Trickle Timer

T: Timer value. T is in the range [I, I/2]
C: Redundancy counter
K: Redundancy constant
I_{min}: Smallest value of I
$I_{doubling}$: The number of times is doubled before maintaining a constant multicast rate.
I_{max}: Largest value of $I_{max} = I_{min} * 2^{Idoubling}$.
When T fires, if C>K, then send DIO, then upon expiration of I, compute new(I) and T.

Detection of inconsistency => Trickle timer reset
Nodes may increment C if they receive consistent messages

JP Vasseur , IoT Workshop "RPL Tutorial" April 2011

Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

RPL is flexible w.r.t. **objective function for selecting the parent.**

RPL Objective Function: combination of end-to-end metrics & application constraints.

Max/Min Metric s.t. Constraint

Defined by the standard:

Node Metrics	Link Metrics
Node state & attributes object: reflecting the node workload	Throughput
Node energy object	Latency (maximum or over entire route)
Hop count	Link reliability

Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)

RPL is flexible w.r.t. **objective function for selecting the parent.**

RPL Objective Function: combination of end-to-end metrics & application constraints.

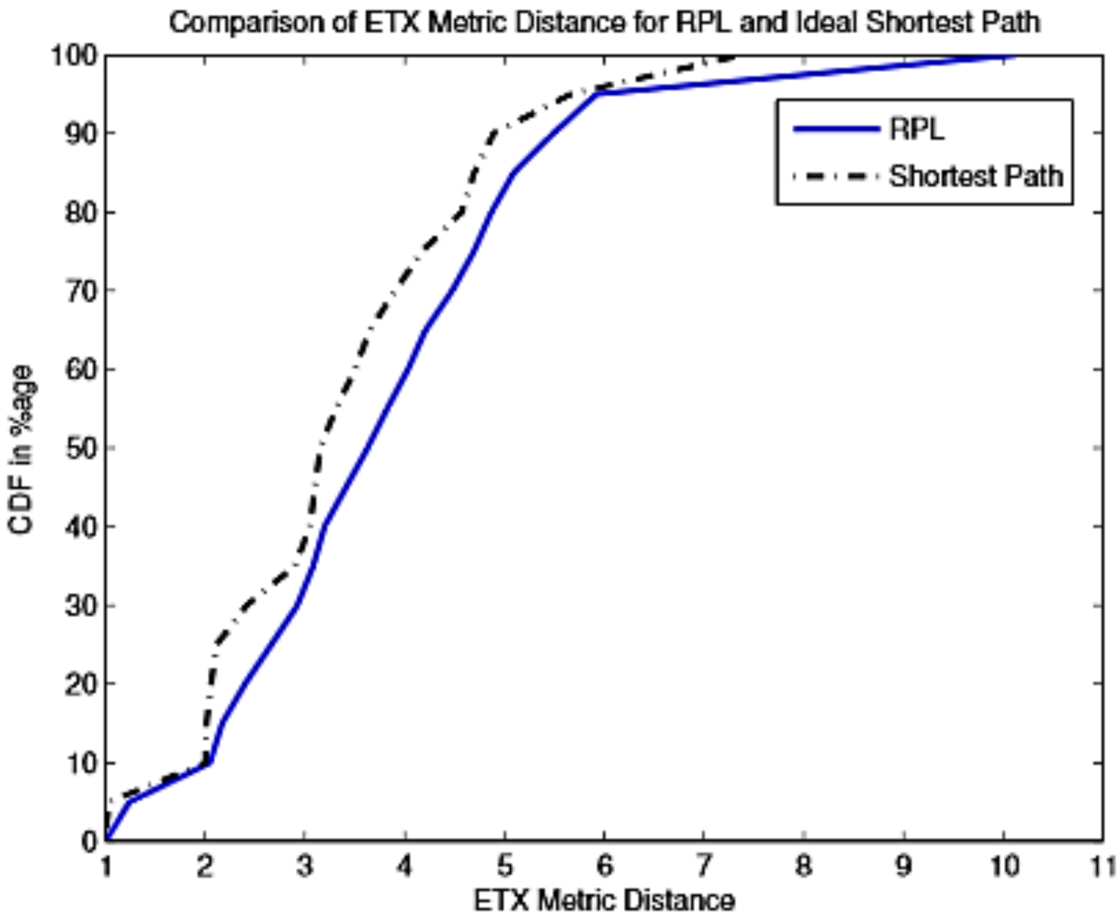
Max/Min Metric s.t. Constraint

Default: hop distance from the root. (OF0)
Popular: ETX: The expected number of transmissions between two neighbors (or between source and destination – additive over path). ETX = 1/PRR
Alternatives: Plenty! E.g:
R-metric: based on the probability that a packet is correctly received in each link of the route (considering backoff & MAC retransmissions) OR
Q-metric: forward load balancing and power consumption during TX & RX

Di Marco, P.; Fischione, C.; Athanasiou, G.; Mekikis, P.-V., "Harmonizing MAC and routing in low power and lossy networks," Global Communications Conference (GLOBECOM), 2013 IEEE , vol., no., pp.231,236, 9-13 Dec. 2013

Routing for Wireless Sensor Networks

Routing Standards: IEFT Routing protocol for Low-power Lossy Networks (LLN)



Oliveira, Jaudelice de, and Joydeep Tripathi. "Performance Evaluation of the Routing Protocol for Low-Power and Lossy Networks (RPL)." *Performance Evaluation* (2012).

Routing for Wireless Sensor Networks

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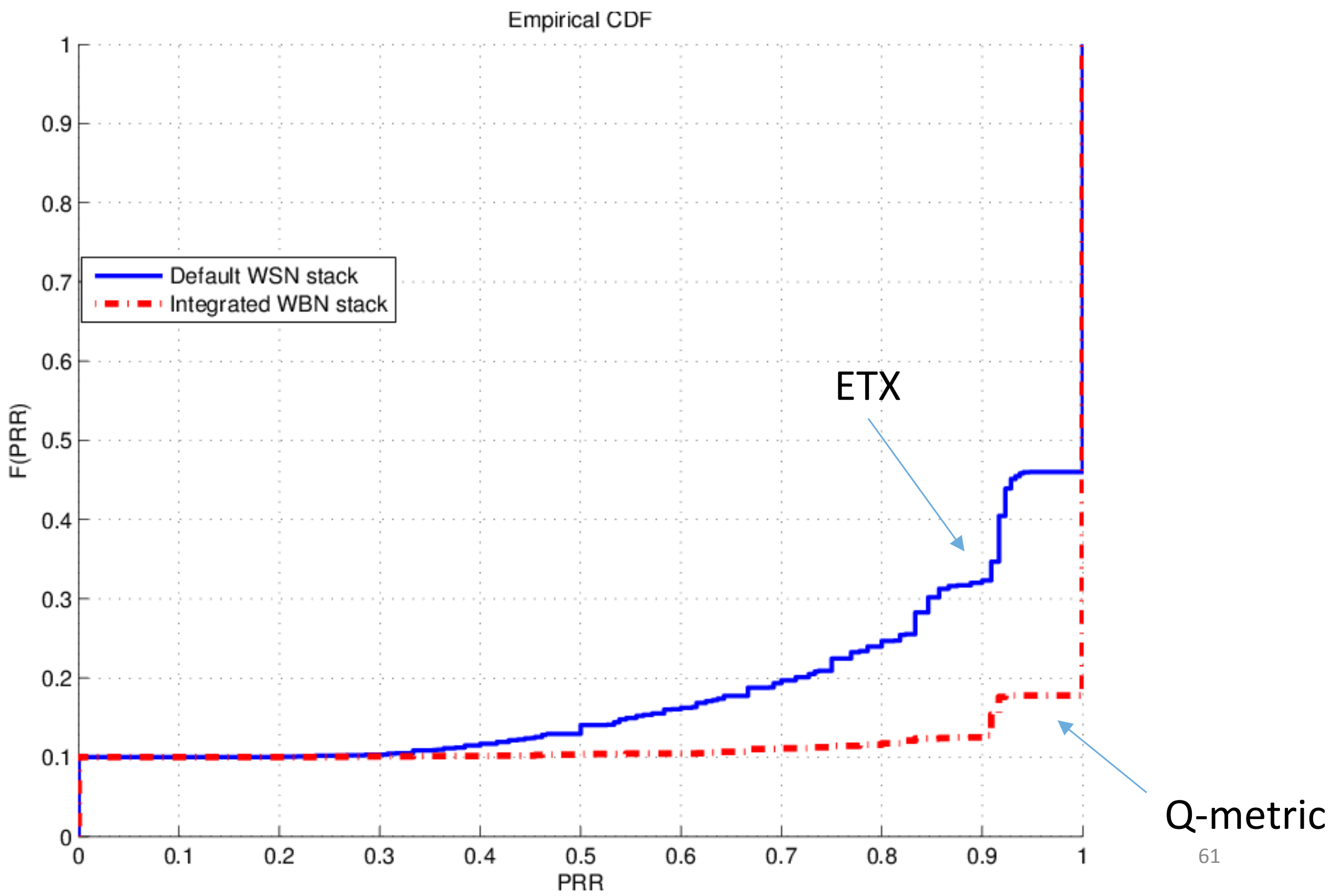

References and Material for Reading

"Guide to Wireless Sensor Networks", S. Misra, I. Woungang, S. C. Misra, 2009, Springer, Ch 4-5

Intanagonwiwat, Chalermek, et al. "Directed diffusion for wireless sensor networking." *Networking, IEEE/ACM Transactions on* 11.1 (2003): 2-16.

Sadagopan, Narayanan, Bhaskar Krishnamachari, and Ahmed Helmy. "Active query forwarding in sensor networks." Ad Hoc Networks 3.1 (2005): 91-113.

Heinzelmann, W. R.; Kulik, J.; and Balakrishnan, H. Adaptive Protocols for Information Dissemination in Wireless Sensor Networks. In *Fifth ACM/IEEE MOBICOM Conference* (August 1999).

"Wireless Sensor Networks", Ian F. Akyildiz, Mehmet Can Vuran, 2010, Willey, Ch 7

"Wireless Sensor Networks: An Information Processing Approach", F. Zhao, L. Guibas, 2004, Elsevier / Morgan Kaufmann – Ch 3

References and Material for Reading

Kemal Akkaya, Mohamed Younis, A survey on routing protocols for wireless sensor networks, Ad Hoc Networks, Volume 3, Issue 3, May 2005, Pages 325-349, ISSN 1570-8705, http://dx.doi.org/10.1016/j.adhoc.2003.09.010.

Rodoplu, Volkan, and Teresa H. Meng. "Minimum energy mobile wireless networks." Selected Areas in Communications, IEEE Journal on 17.8 (1999): 1333-1344.

Marco Zúñiga, et al. "Efficient geographic routing over lossy links in wireless sensor networks." ACM Transactions on Sensor Networks (TOSN) 4.3 (2008): 12.

“Guide to Wireless Sensor Networks”, S. Misra, I. Woungang, S. C. Misra, 2009, Springer, Ch 4-5

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"Wireless Sensor Networks: An Information Processing Approach”, F. Zhao, L. Guibas, 2004, Elsevier / Morgan Kaufmann – Ch 3

Xu Lin, Ivan Stojmenovic, Location-based localized alternate, disjoint and multi-path routing algorithms for wireless networks, Journal of Parallel and Distributed Computing, Volume 63, Issue 1, January 2003, Pages 22-32

Ruhrup, Stephan. "Theory and practice of geographic routing." Ad Hoc and Sensor Wireless Networks: Architectures, Algorithms and Protocols (2009): 69.

Karp, Brad, and Hsiang-Tsung Kung. "GPSR: Greedy perimeter stateless routing for wireless networks." Proceedings of the 6th annual international conference on Mobile computing and networking. ACM, 2000.

References and Material for Reading

Rao, Ananth, et al. "Geographic routing without location information." *Proceedings of the 9th annual international conference on Mobile computing and networking*. ACM, 2003.

Tsvetkov, Tsvetko. "RPL: IPv6 Routing Protocol for Low Power and Lossy Networks." *Sensor Nodes–Operation, Network and Application (SN)* 59 (2011): 2.

Di Marco, P.; Fischione, C.; Athanasiou, G.; Mekikis, P.-V., "Harmonizing MAC and routing in low power and lossy networks," *Global Communications Conference (GLOBECOM), 2013 IEEE* , vol., no., pp.231,236, 9-13 Dec. 2013

Routing Over Low power and Lossy networks (ROLL). RFC6550 Description of Working Group. http://datatracker.ietf.org/wg/roll/charter/, 2011.

Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks. RFC6551 Description of Working Group. http://datatracker.ietf.org/wg/roll/charter/, 2012.

Oliveira, Jaudelice de, and Joydeep Tripathi. "Performance Evaluation of the Routing Protocol for Low-Power and Lossy Networks (RPL)." *Performance Evaluation* (2012).

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