Redes de Sensores Sem Fio

Raquel A. F. Mini

raquelmini@pucminas.br

How Are Protocols Dealing with Energy Restriction?

- Save as much energy as possible
  - Multihop communication
  - Turn off parts of sensor node
  - In-network processing
    - Local Processing
    - Localized Processing (cooperation, negotiation)
    - Data Fusion (aggregation)
- Local energy information
- Global energy information
- Finite energy budget

Protocols use the amount of available energy in the node when they make a decision

Local Energy Information

- Some protocols use the amount of available energy in the node when they make a decision

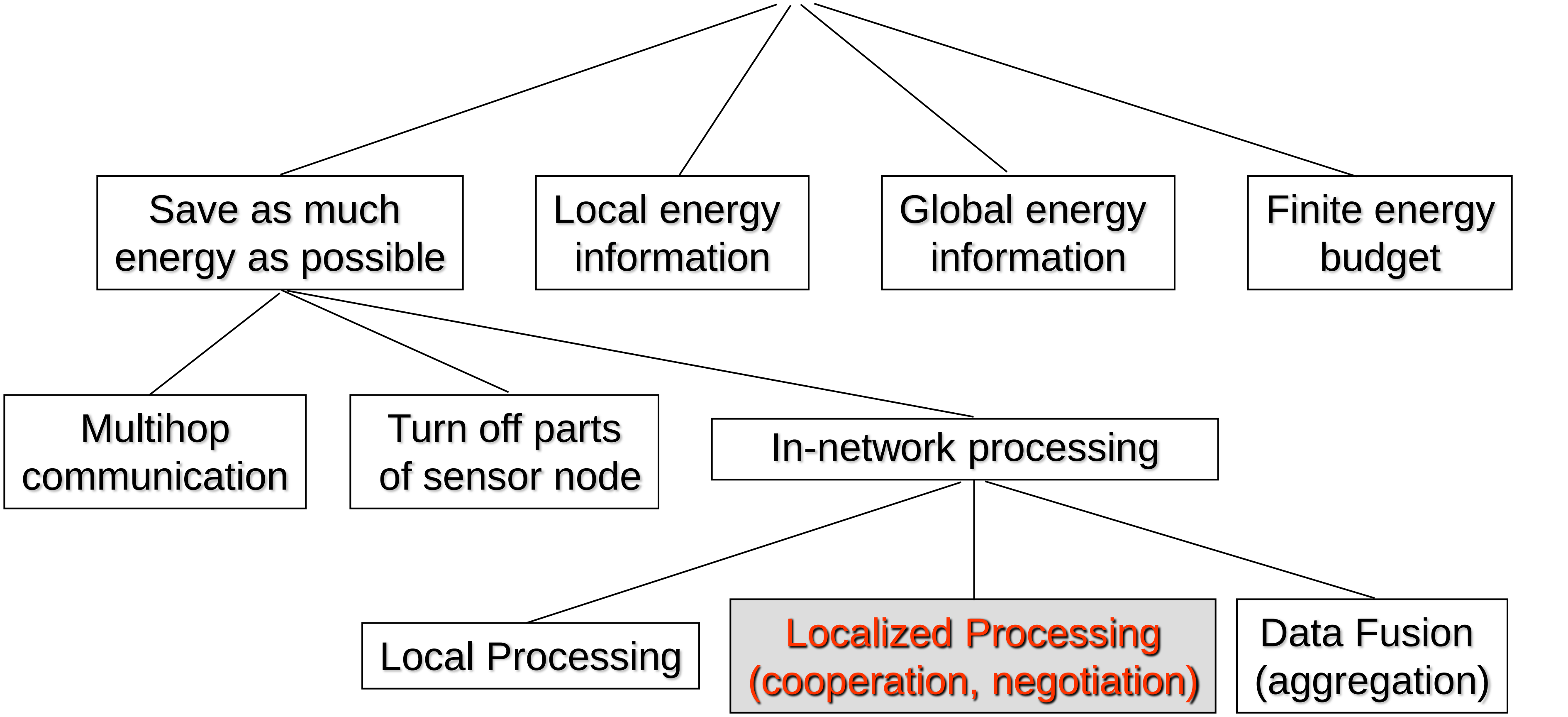
```
if myEnergy < thrEnergy then
   . . .
else
   . . .
```

Local Energy Information

- Sensor Protocols for Information via Negotiation (SPIN):
  - Data negotiation
    - Nodes negotiate with each other before transmitting data
    - Negotiation helps ensure that only useful information will be transferred

Localized Processing

How Are Protocols Dealing with Energy Restriction?



Local Energy Information

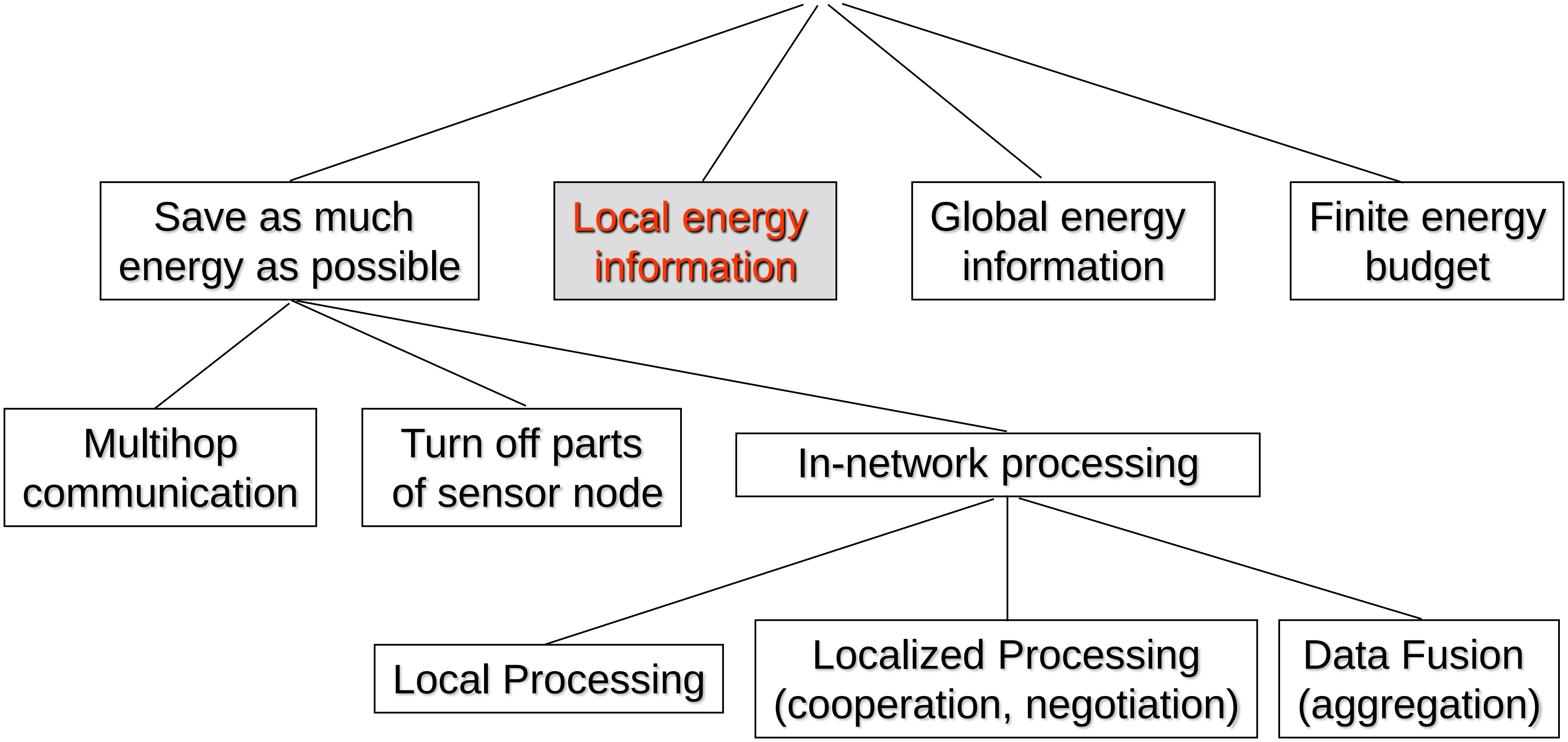
- Sensor Protocols for Information via Negotiation (SPIN):
  - Data negotiation
    - Nodes negotiate with each other before transmitting data
    - Negotiation helps ensure that only useful information will be transferred

Localized Processing

  - Resource management
    - Before data transmission, nodes poll their resources (energy)
    - This allows sensors to cut back on certain activities (*e.g.* forwarding third-party data) when energy is low

Local Energy Information

How Are Protocols Dealing with Energy Restriction?

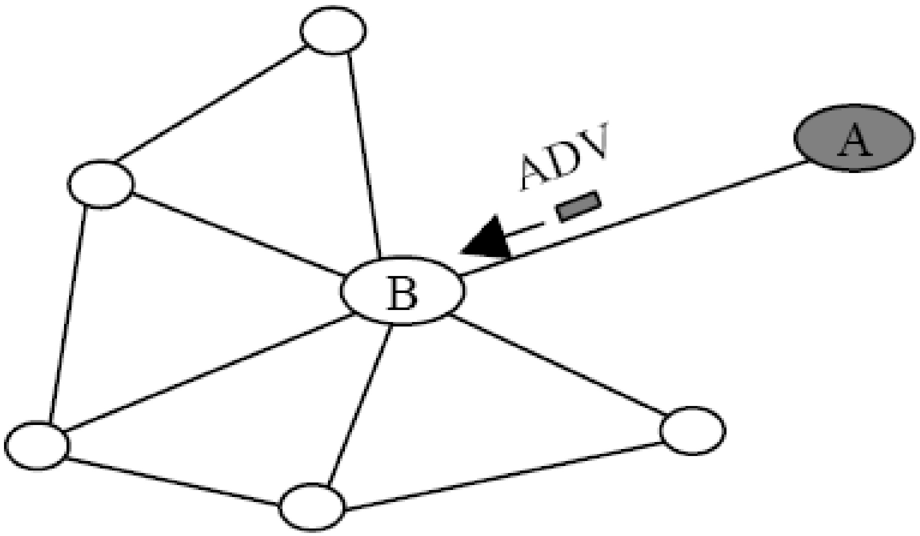


Local Energy Information

- SPIN messages
  - ADV: new data advertisement
  - REQ: request for data
  - DATA: data message

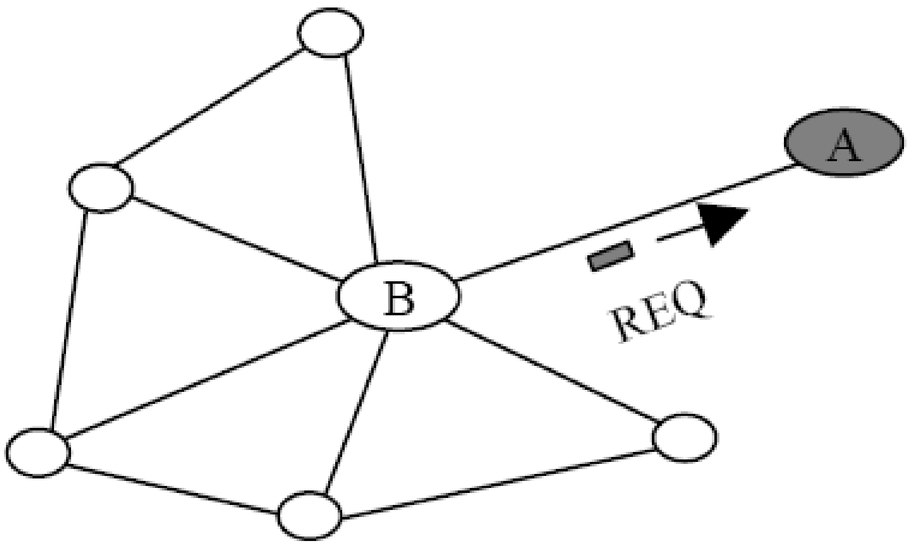
Local Energy Information

- Basic operation of SPIN
  - Node A starts by advertising its data to node B



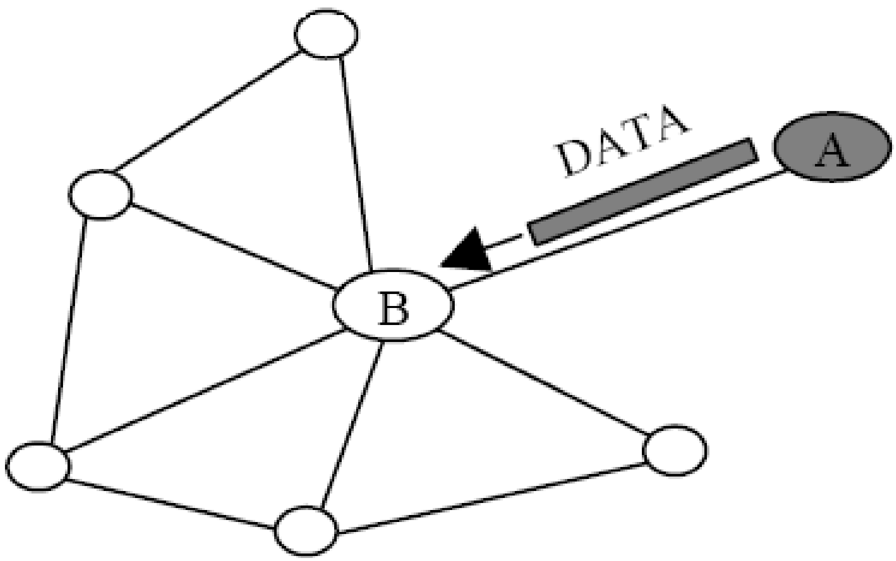
Local Energy Information

- Basic operation of SPIN
  - Node B responds by sending a request to node A



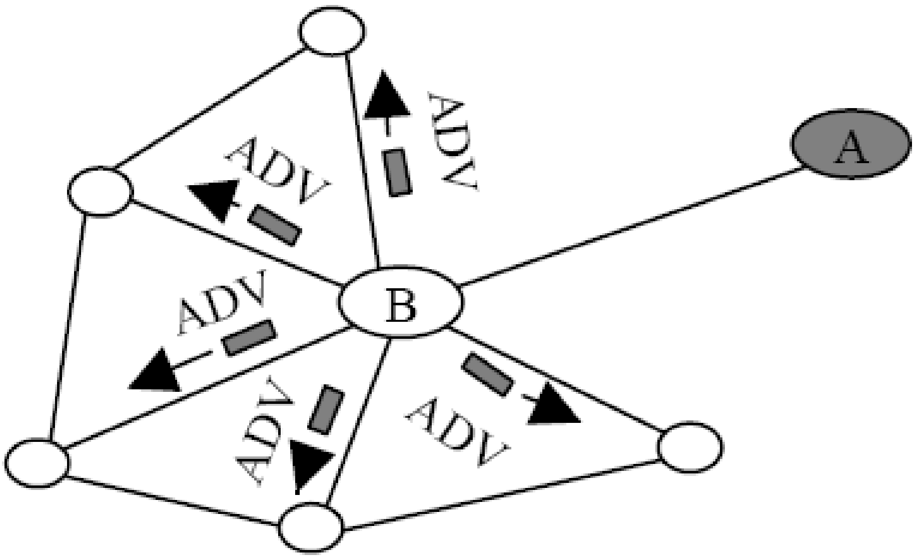
Local Energy Information

- Basic operation of SPIN
  - Node B receives the requested data



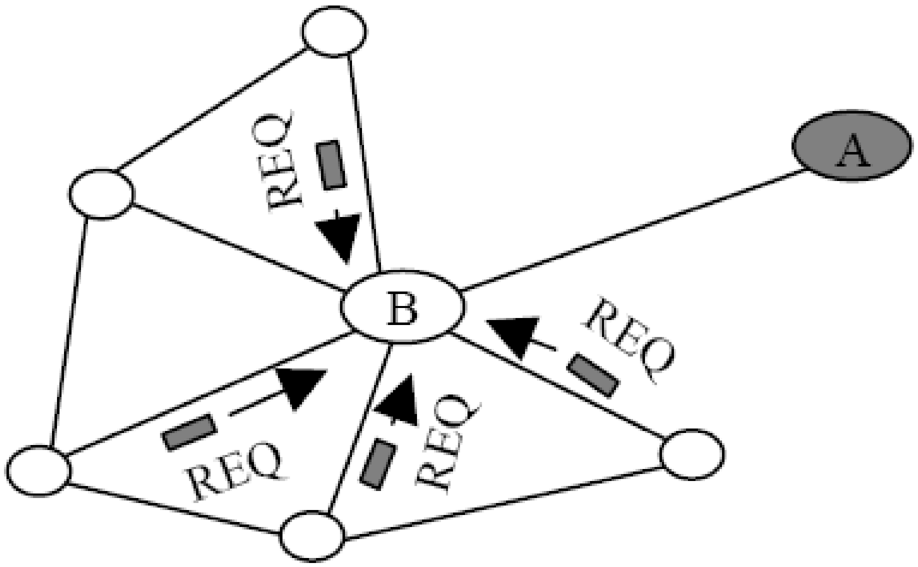
Local Energy Information

- Basic operation of SPIN
  - Node B sends out advertisements to its neighbors



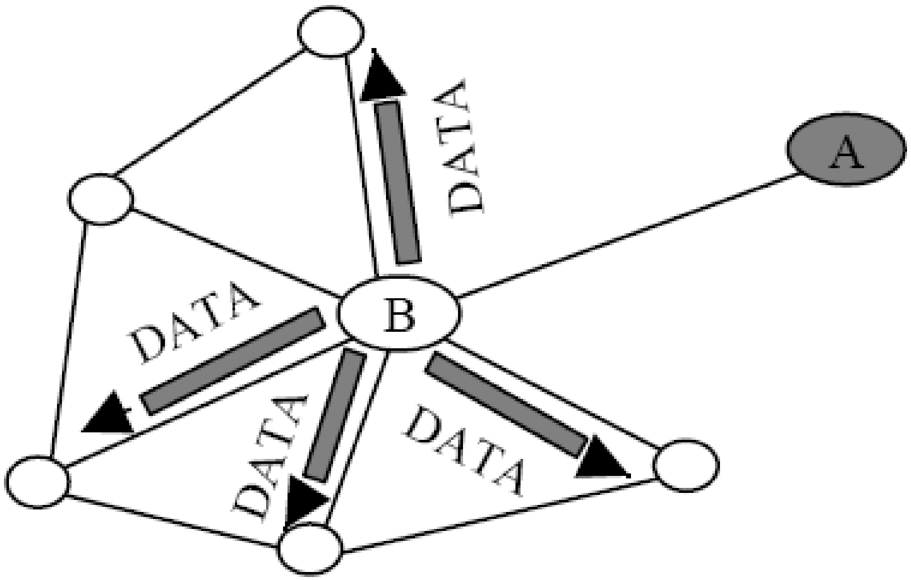
Local Energy Information

- Basic operation of SPIN
  - Neighbors of node B send requests back to B



Local Energy Information

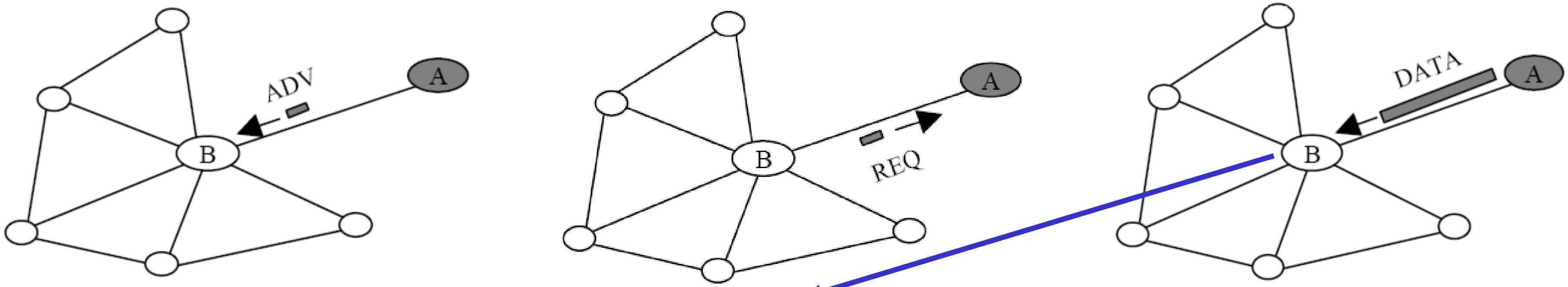
- Basic operation of SPIN
  - Node B sends requested data to its neighbors



Local Energy Information

- Resource management of SPIN:
  - A node will only participate in a stage if it believes that it can complete all the other stages of the protocol without going bellow the low-energy threshold

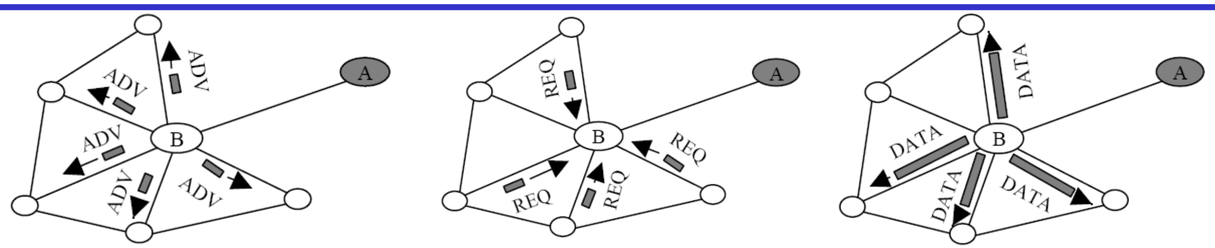
Local Energy Information



Do I have enough energy to participate in the full protocol?

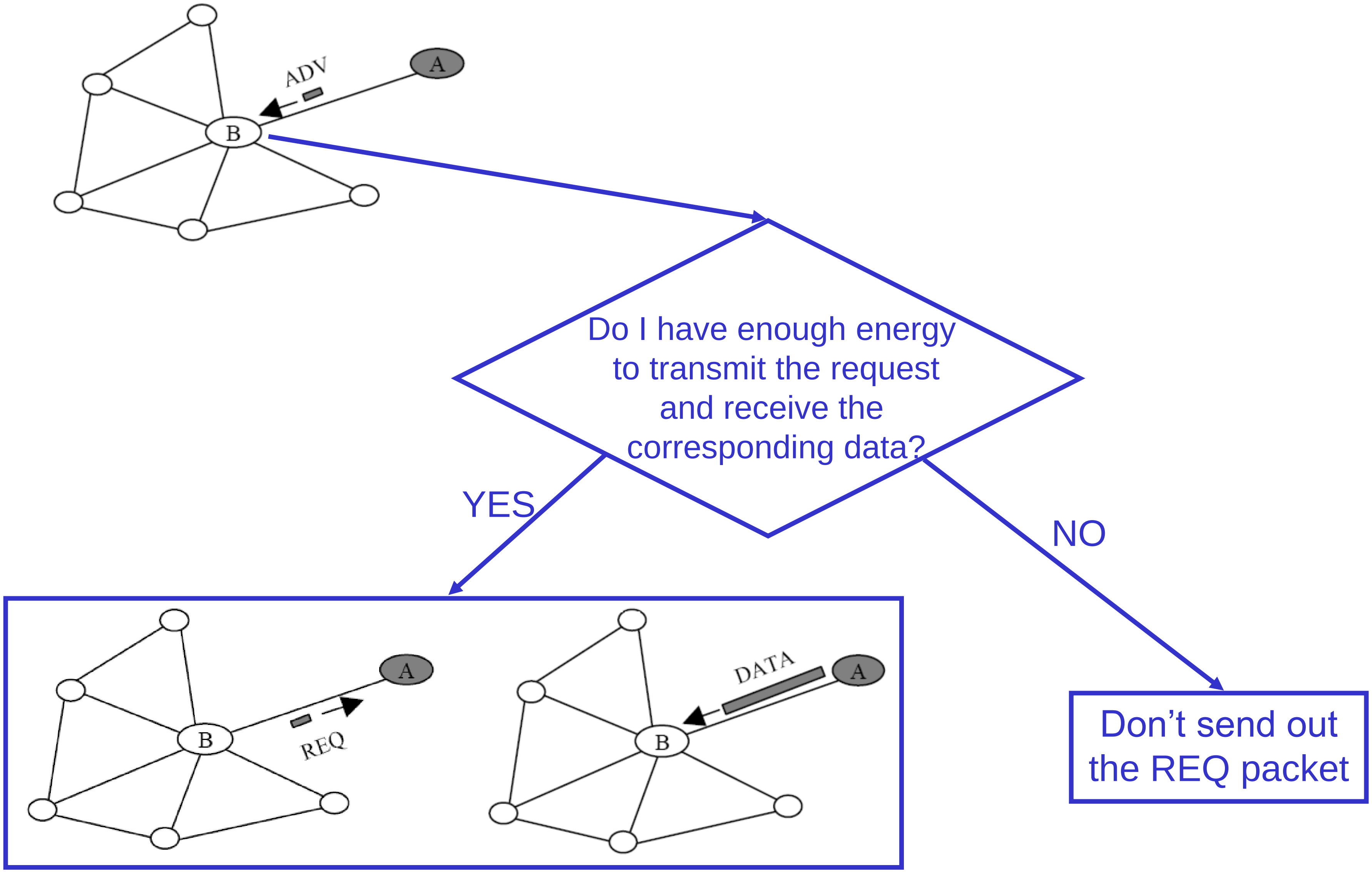
YES

NO



Don’t initiate the three-stage protocol

Local Energy Information



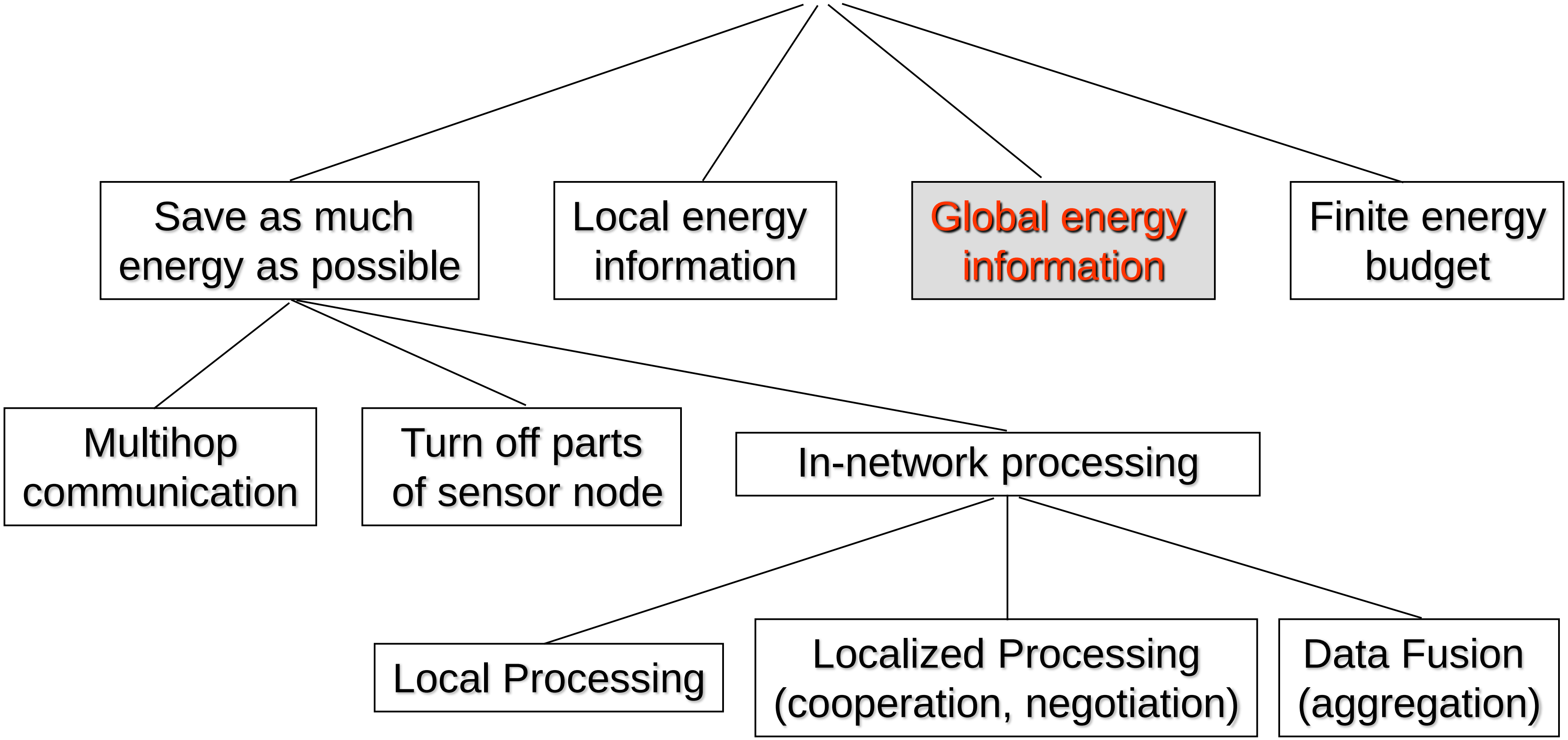
Local Energy Information

- Resource management of SPIN
  - Prevent nodes from ever handling a DATA message bellow a low-energy threshold

Local Energy Information

- In many cases, to look at just the amount of the available energy at a node may either be insufficient or lead to an unacceptable solution
- It would be interesting to evaluate whether an global energy information could provide a better solution

How Are Protocols Dealing with Energy Restriction?

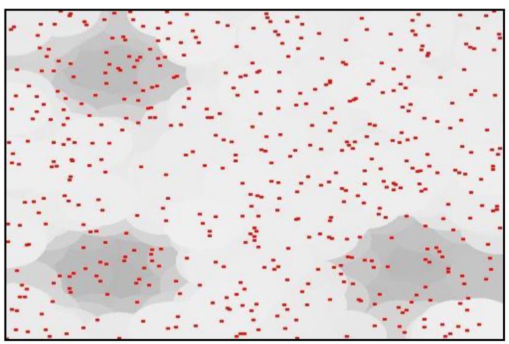


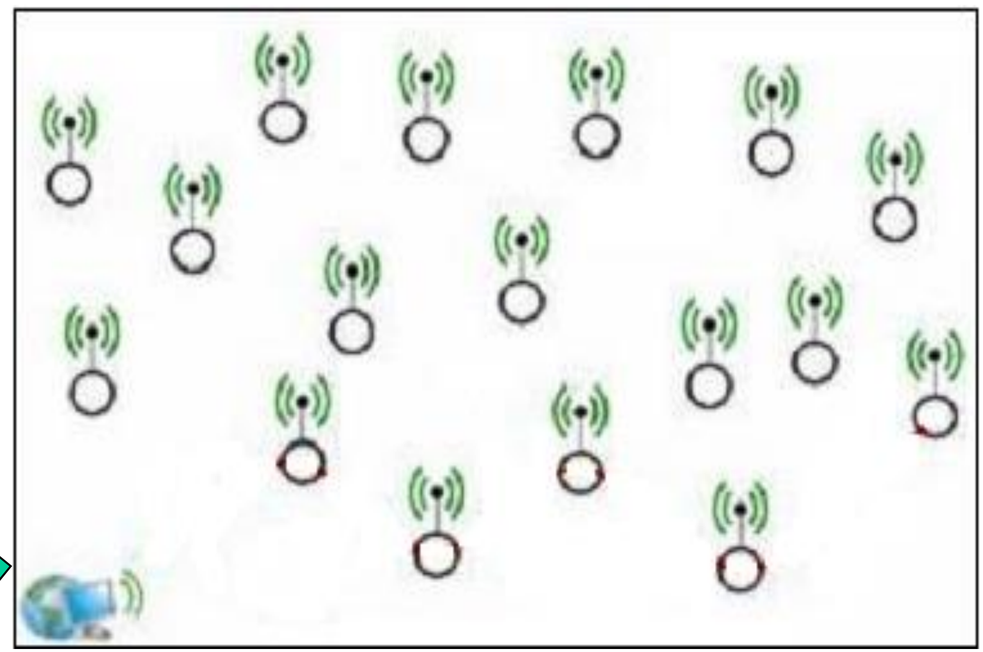
Protocols use the information about the remaining available energy in all nodes of the network

Global Energy Information

- Some protocols use the information about the remaining available energy in all nodes of the network
- This energy information is maintained at the monitoring node and is called **Energy Map**

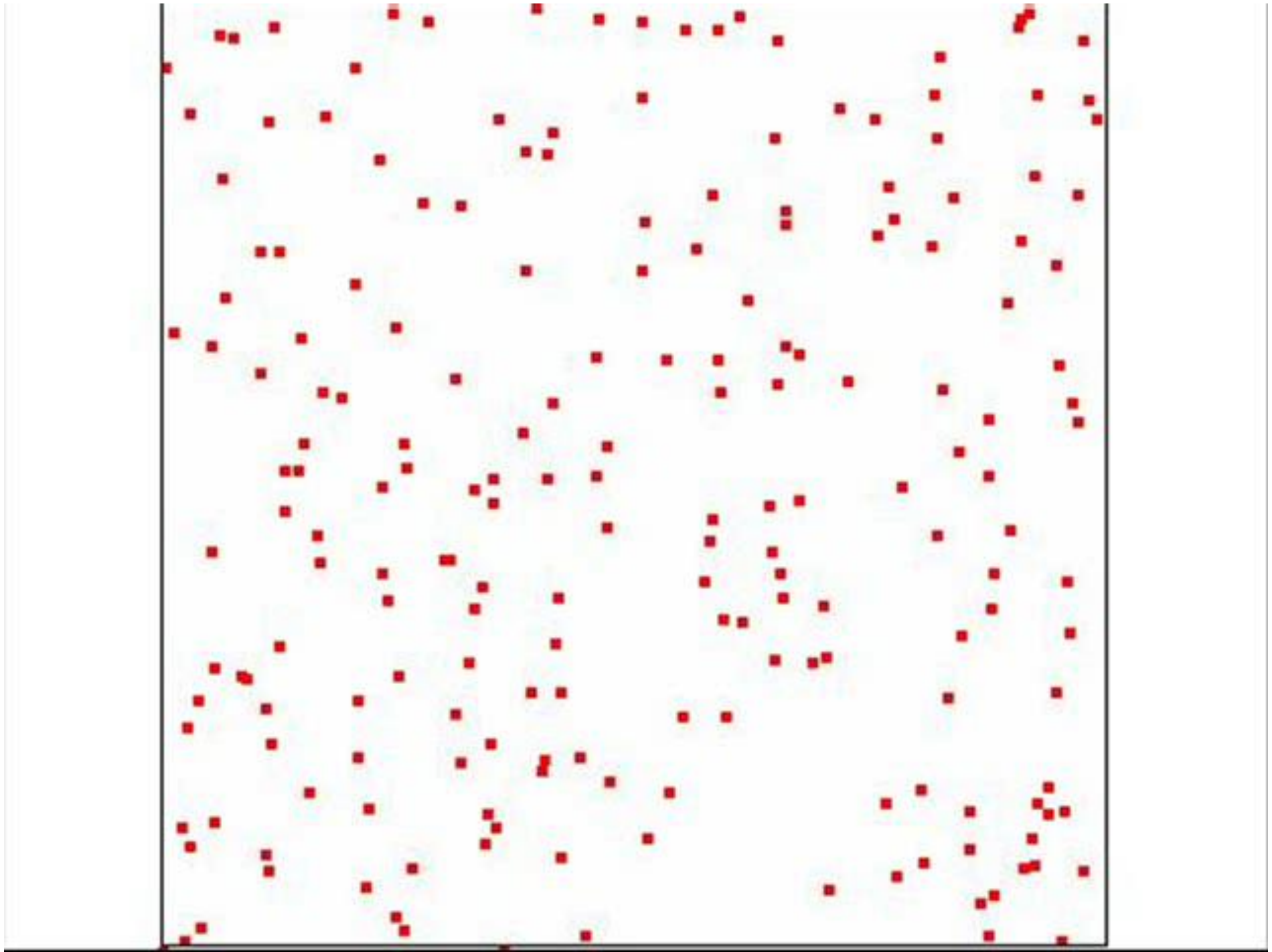
Energy Map





Energy Map

- Energy Map is the information about the remaining available energy in each part of the network



Energy Map

- Construct the energy map of a wireless sensor network
  - Naive
    - Each node sends to the monitoring node only its available energy
  - Prediction-based Energy Map
    - Each node sends to the monitoring node its available energy and the parameters of the model that describes its energy drop
    - The monitoring node uses these parameters to update locally the information about the available energy in each node

- The cost of constructing the energy map must be smaller than the energy saved by using it

Energy Map

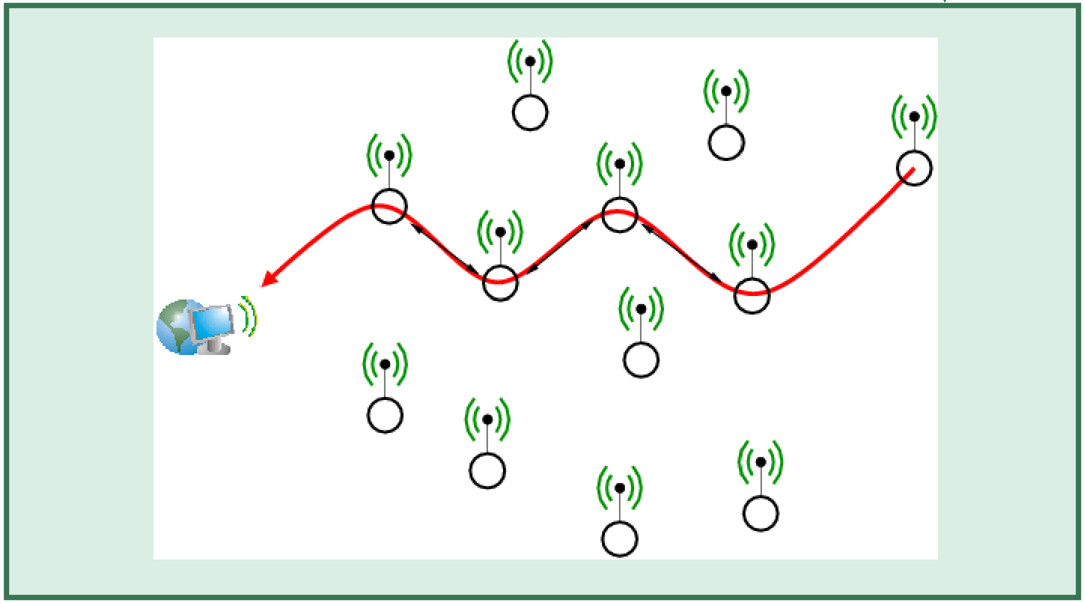
- The Energy Map can help in prolonging the lifetime of the network
  - Identify system failure due to depleted energy
  - Aid in incremental deployment of sensors
  - Choose the best location for the monitoring node
  - Aid routing protocols in the choice of routes that use nodes with more remaining energy
    - Form a virtual backbone based on connecting high energy islands

Energy Map

- The Energy Map can help in prolonging the lifetime of the network
  - Identify system failure due to depleted energy
  - Aid in incremental deployment of sensors
  - Choose the best location for the monitoring node
  - Aid routing protocols in the choice of routes that use nodes with more remaining energy
    - Form a virtual backbone based on connecting high energy islands

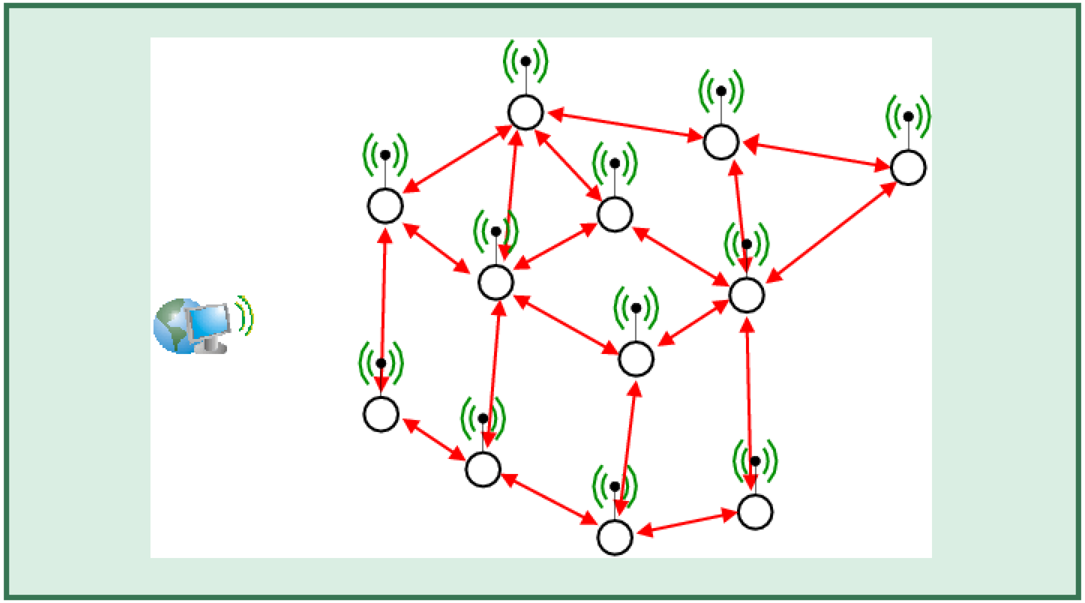
Routing in Wireless Sensor Networks

- Data collection
- Cooperation
- Data Dissemination
  - Unicasting, Multicasting e Broadcasting



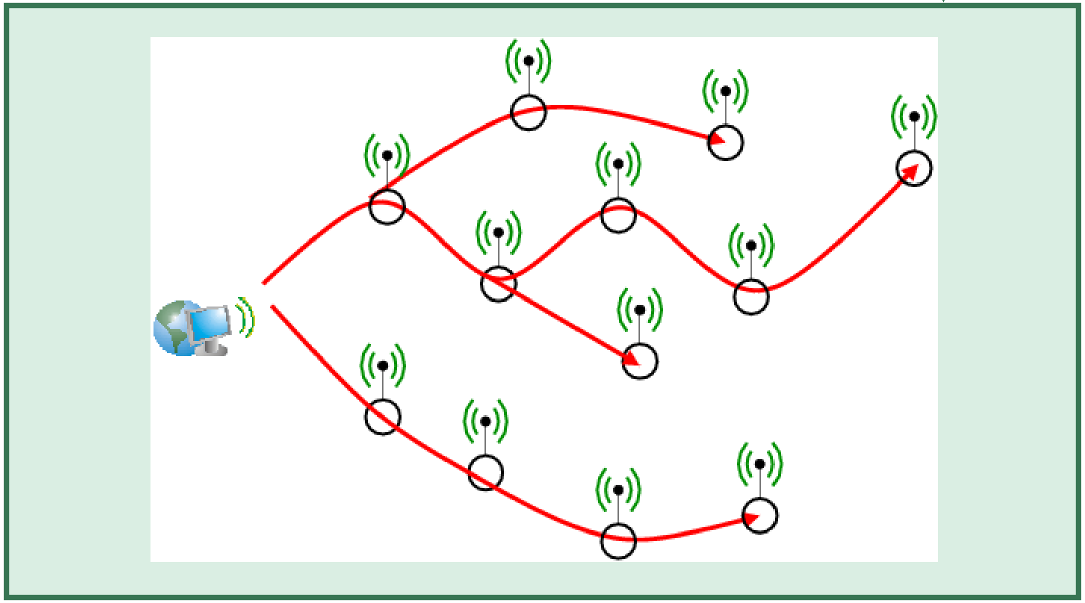
Routing in Wireless Sensor Networks

- Data collection
- Cooperation
- Data Dissemination
  - Unicasting, Multicasting e Broadcasting



Routing in Wireless Sensor Networks

- Data collection
- Cooperation
- Data Dissemination
  - Unicasting, Multicasting e Broadcasting



Data Dissemination using the Energy Map

- Data dissemination protocols can explore the energy map in order to adapt dynamically its dissemination route according to the energy level of sensor nodes

- Data Dissemination Protocols:
  - TBF (Trajectory Based Forwarding)
  - TEDD (Trajectory and Energy-based Data Dissemination)

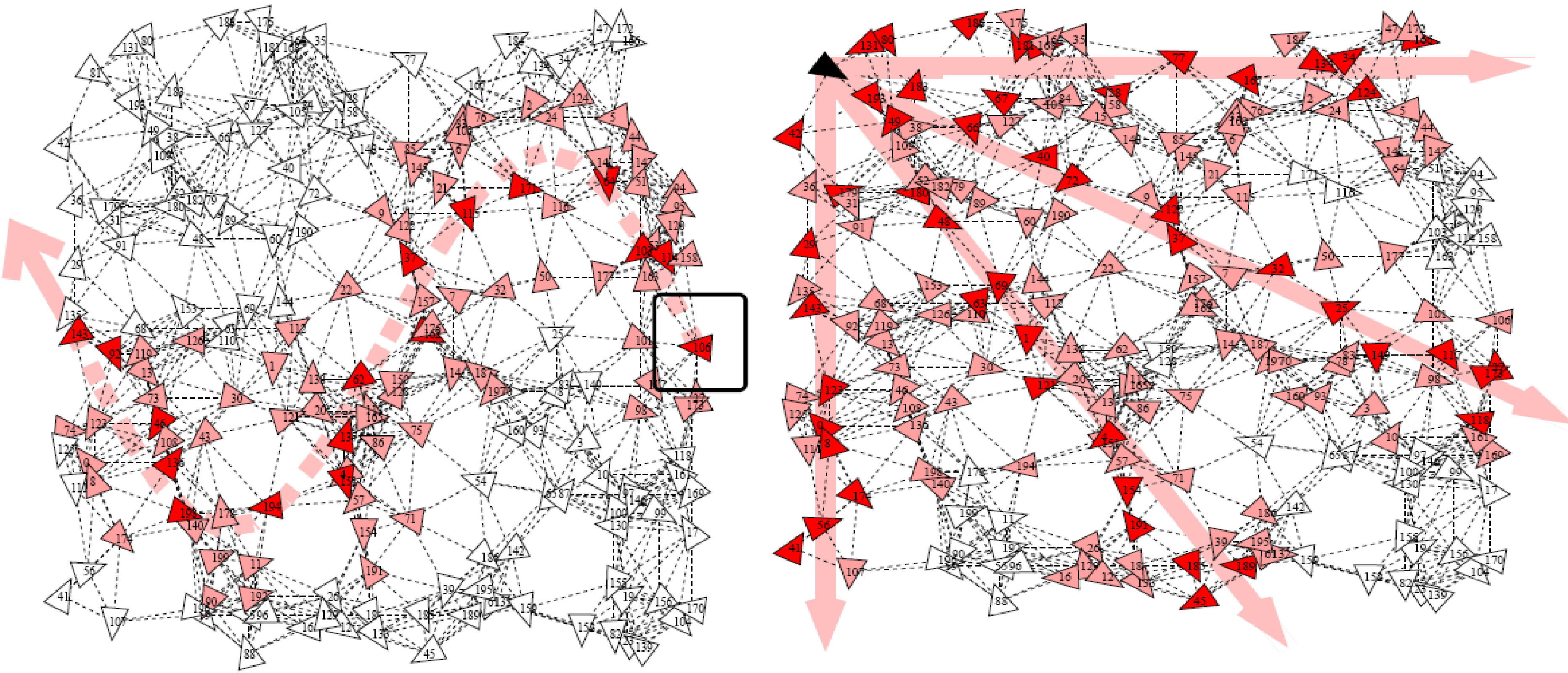
Routing on a Curve

Routing on a Curve

- Trajectory Based Forwarding (TBF)
  - Embed a trajectory in the packet
  - Let the intermediate nodes forward the packets to those nodes that lie more or less on the trajectory

TBF

- Routing technique for large scale, dense wireless sensor networks

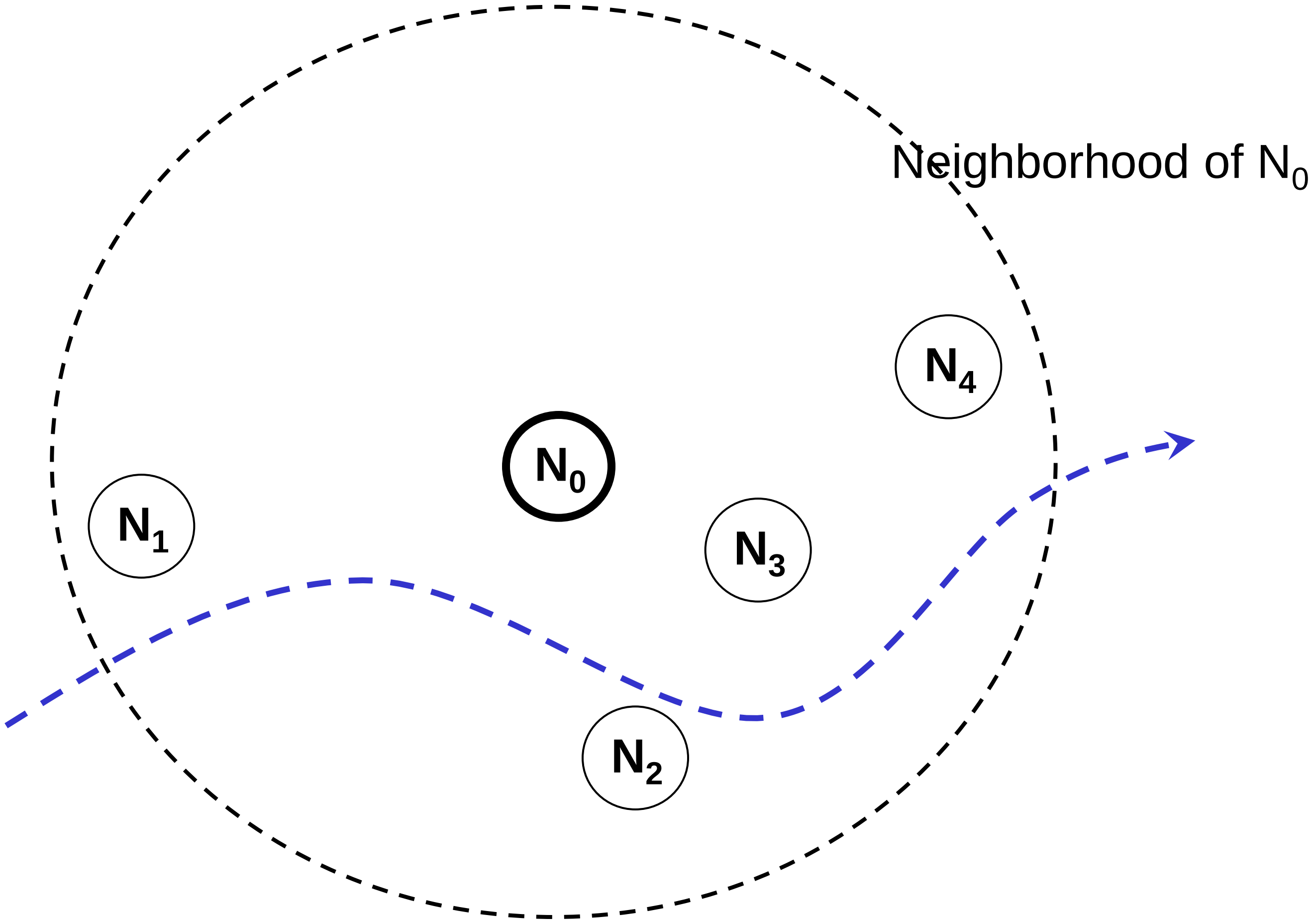


TBF

- As the trajectory does not explicitly encode the nodes in the path, TBF is adaptable to changes in specific nodes that make up the topology
- Supposition:
  - Sufficiently dense network
  - All nodes have to position themselves relative to a coordinate system
  - All nodes have to estimate distance to their neighbors

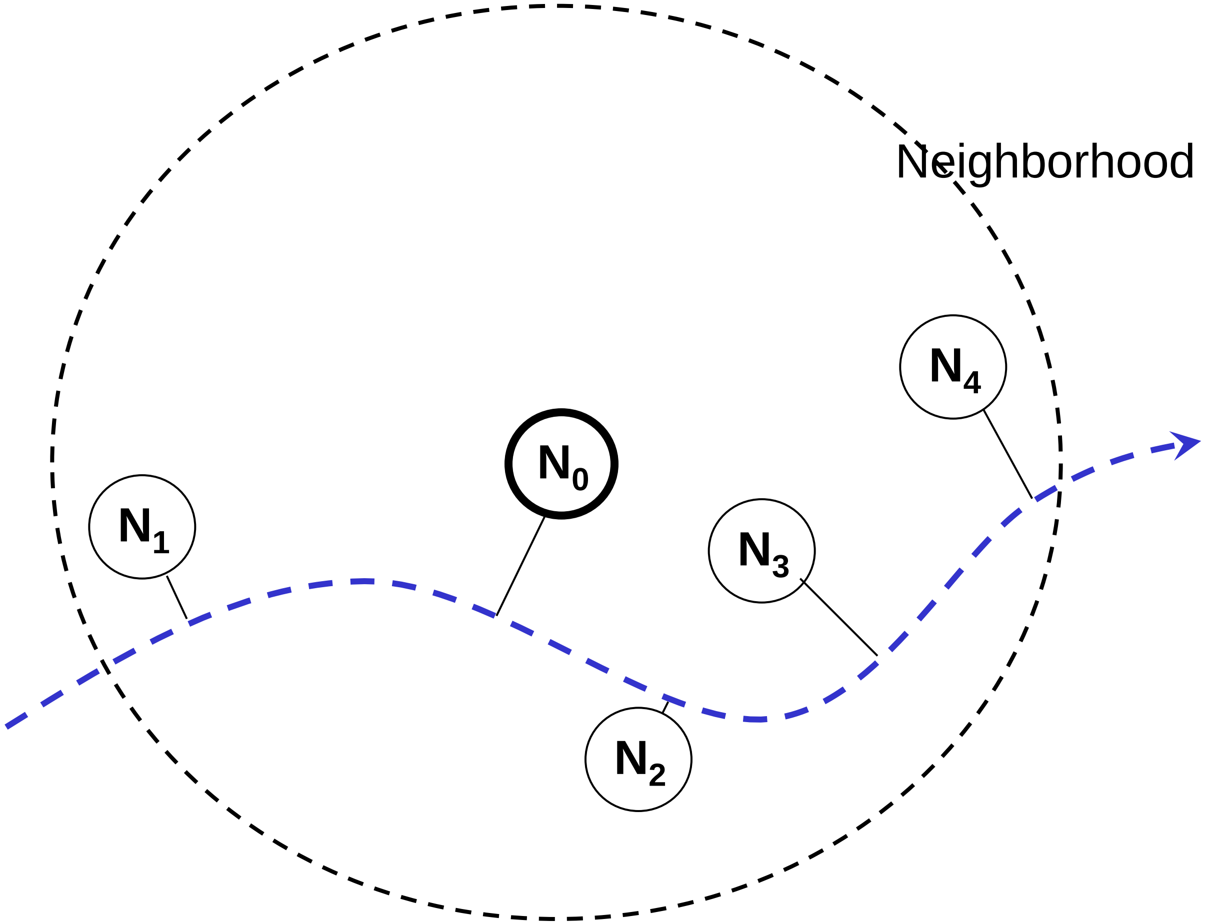
TBF

- N_0 receives the packet with the curve definition



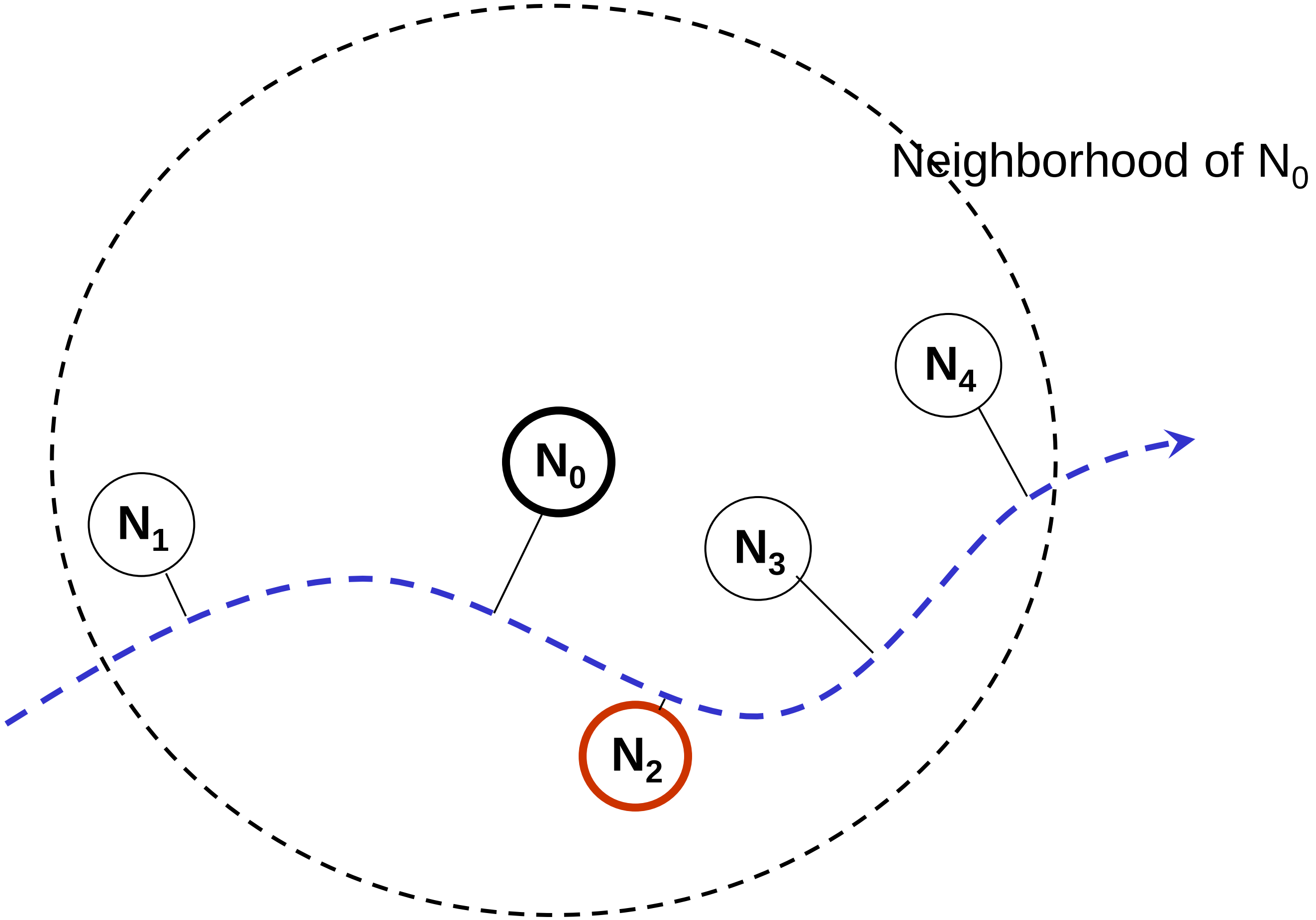
TBF

- Sender-based forwarding technique:
  - N_0 chooses next hop



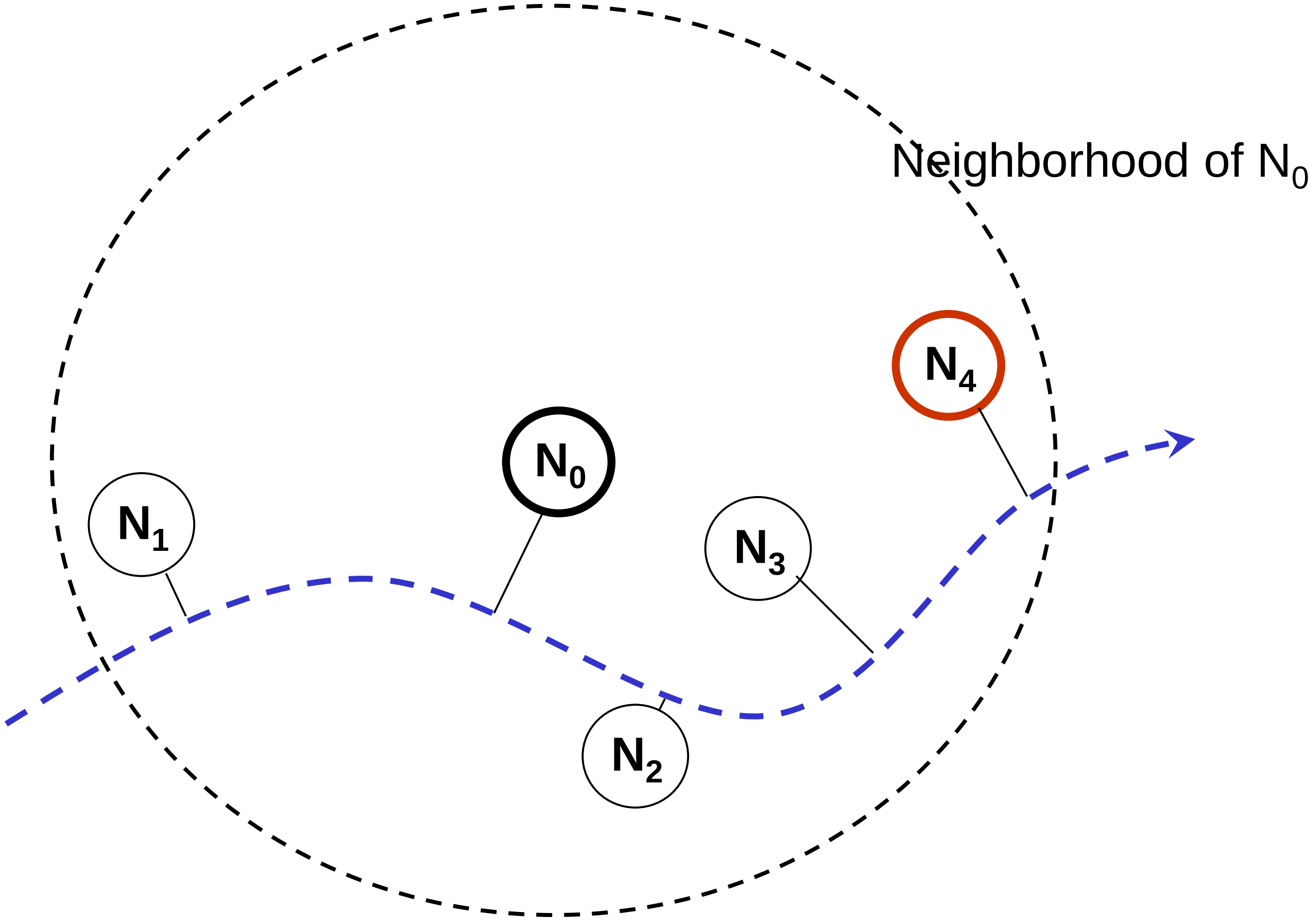
TBF

- Several policies of choosing next hop are possible:
  - Node closest to the curve



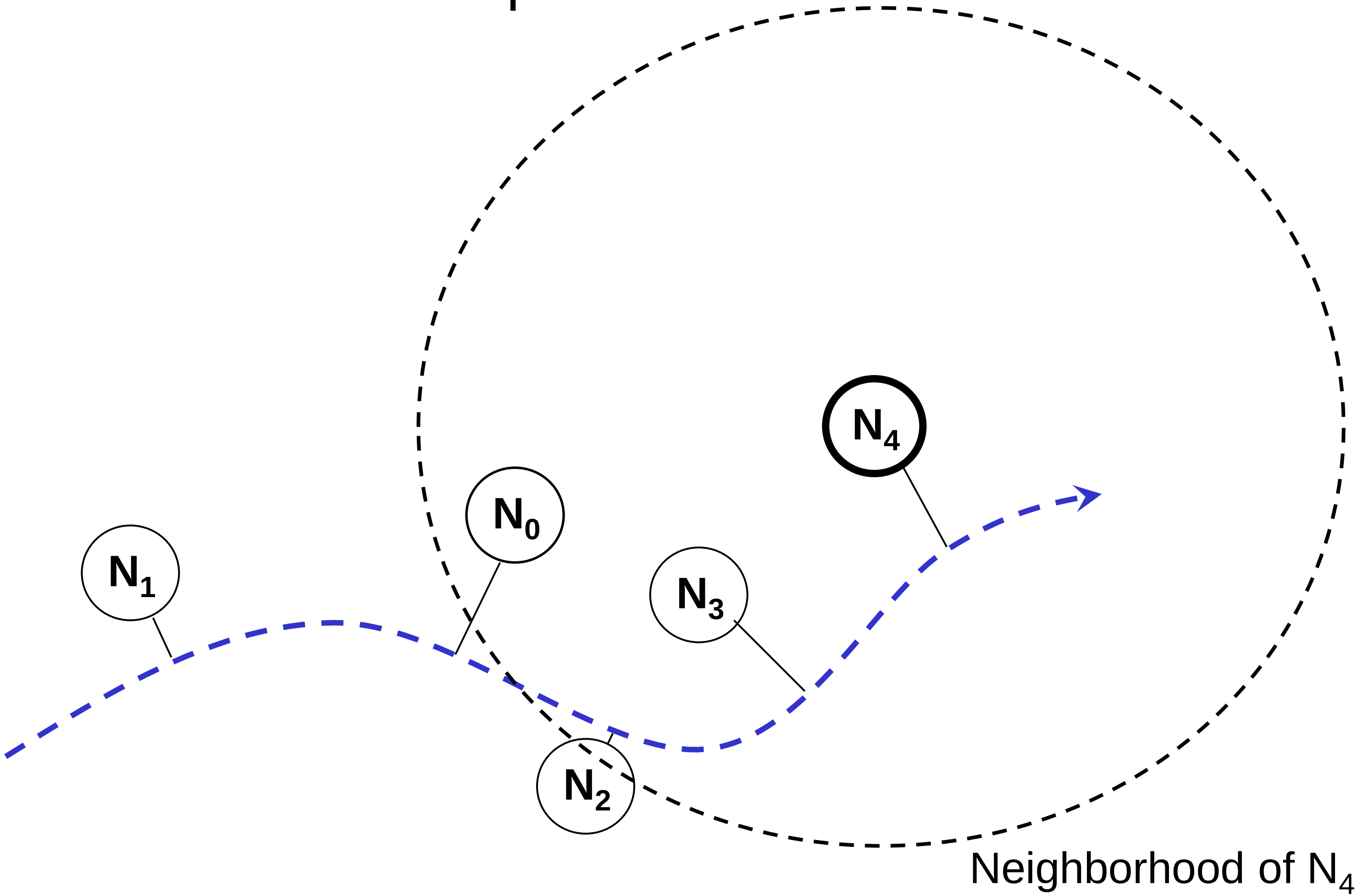
TBF

- Several policies of choosing next hop are possible:
  - Most advancement on the curve

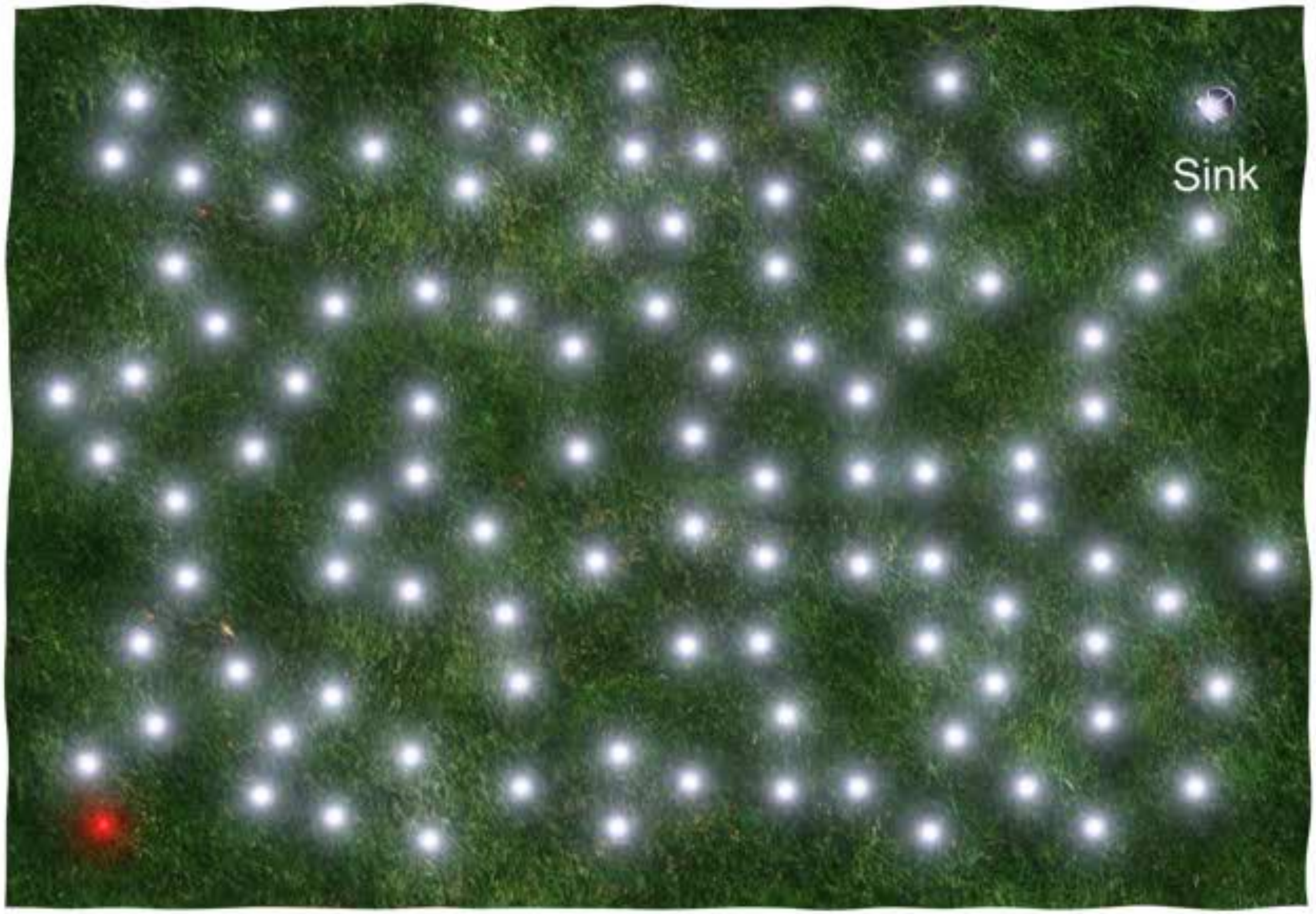


TBF

- Chosen node forwards the packet

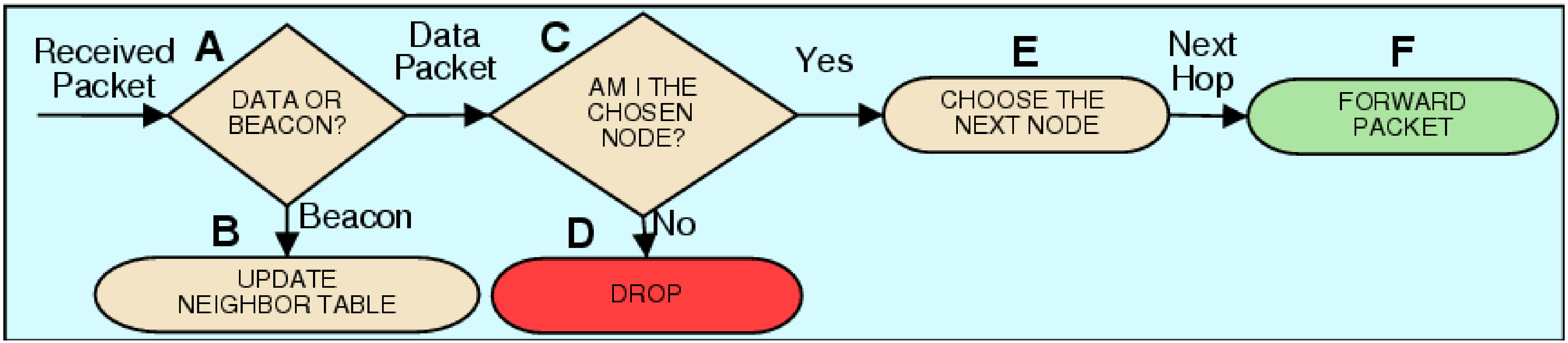


TBF



TBF

- Sender-based forwarding technique



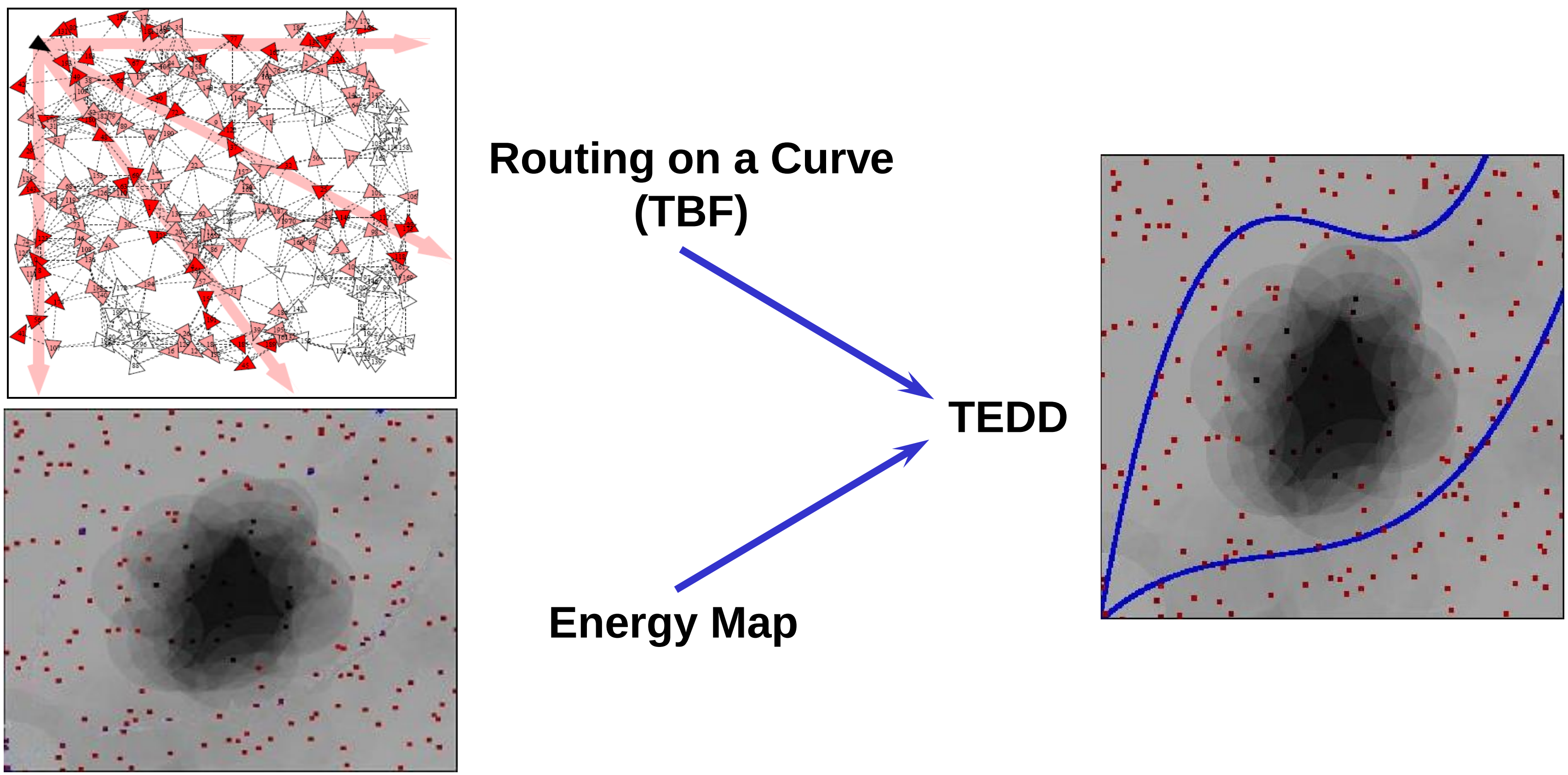
TBF

- Advantages:
  - Compact representation
  - Node independence

- Main drawback:
  - Overhead required to update neighbor tables

TEDD

- Trajectory and Energy-based Data Dissemination (TEDD):
  - A new routing algorithm based on both the **Trajectory Based Forward** algorithm and the **Energy Map**



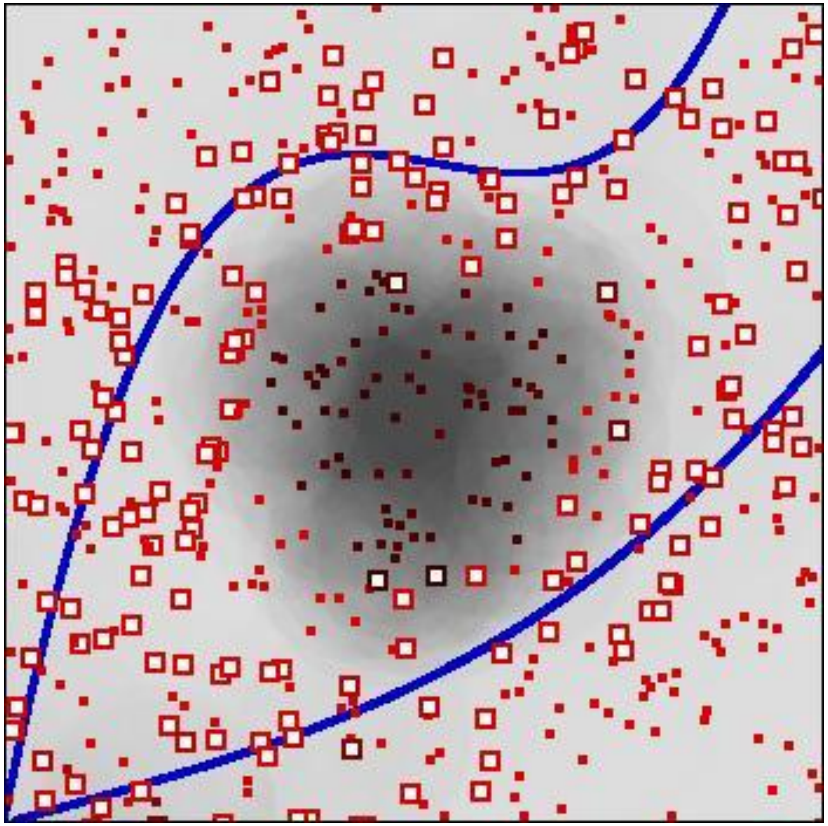
TEDD

- Goal:
  - Combine concepts presented in TBF with the information provided by the energy map to determine routes (or trajectories) in a dynamic fashion based on the energy map of the network
  - Concentrate the energy spent with the routing activity on those nodes that have high energy reserves

TEDD

- Represent and specify trajectories dynamically based on the energy map
- Basic operation:
  - Select a set of nodes in the network that are most suitable for forwarding the packets sent by the sink
  - Find the best set of curves passing through or near these selected points

TEDD

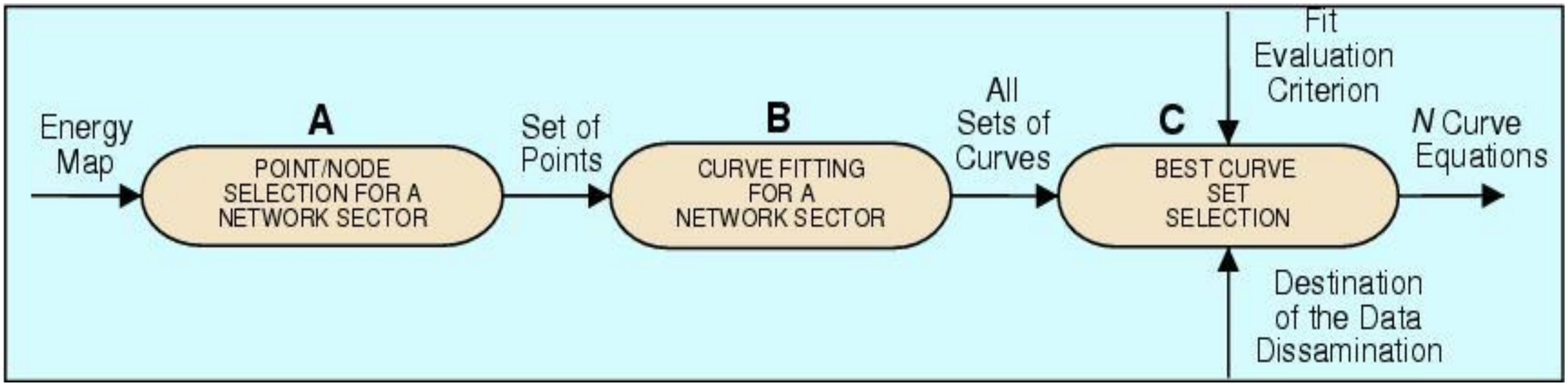


TEDD

- Dynamic trajectory generation:
  - Process of generating trajectories that passes through regions of higher energy reserves and avoids low energy nodes
- Forwarding technique:
  - Receiver-based forwarding technique that diminishes the overhead caused by neighbor table maintenance, presented in other routing algorithms such as TBF

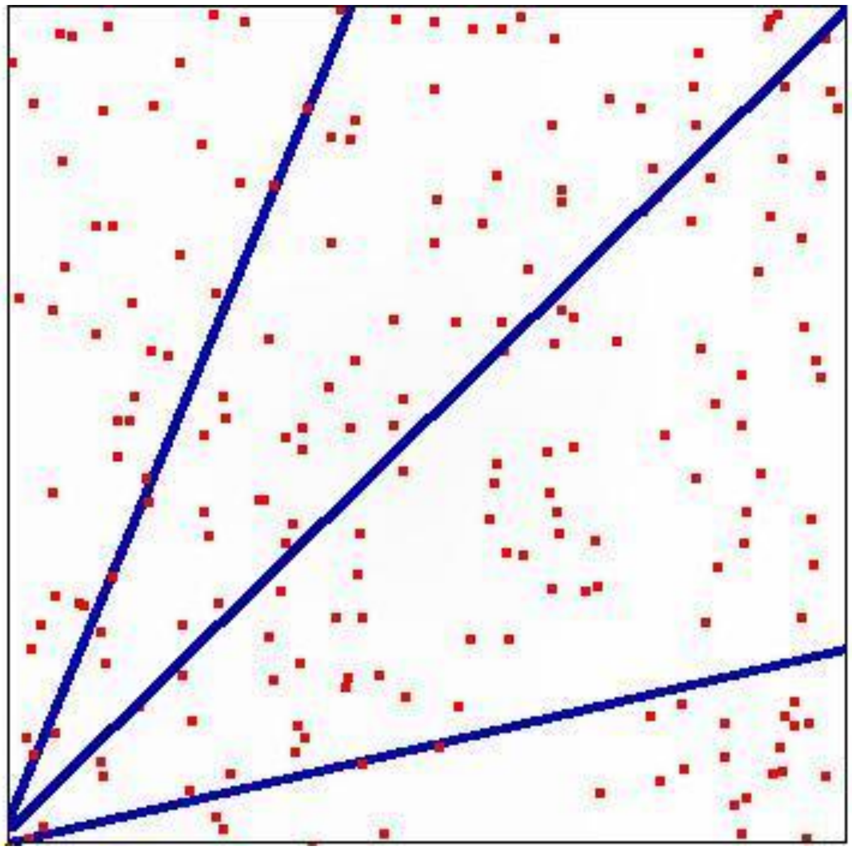
TEDD

- Dynamic trajectory generation



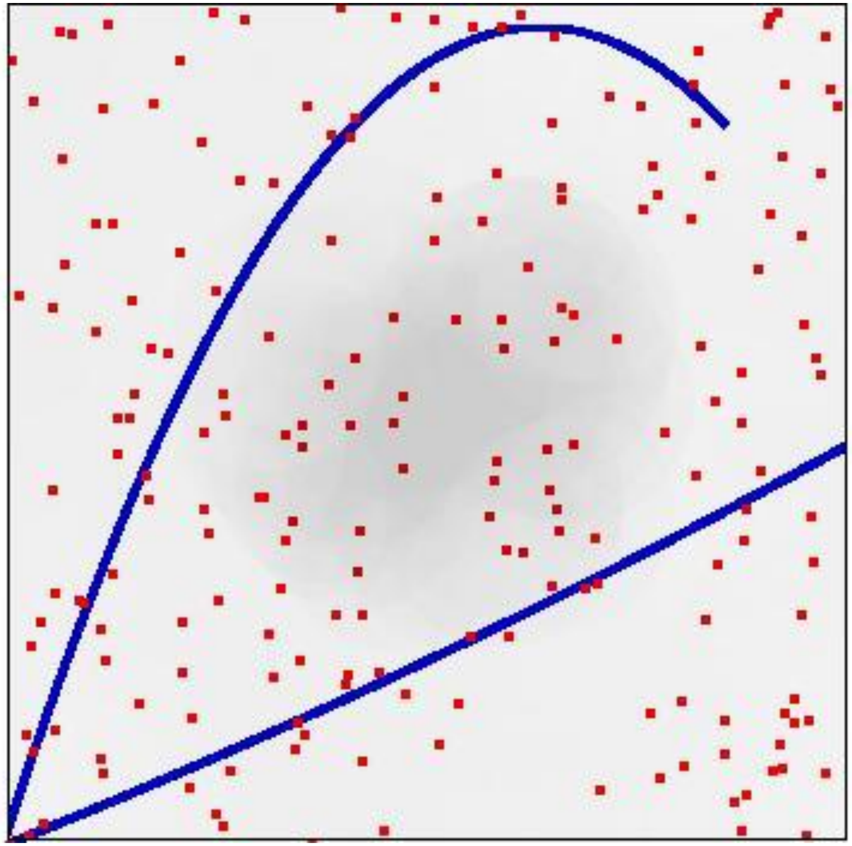
TEDD

- Dynamic trajectory generation



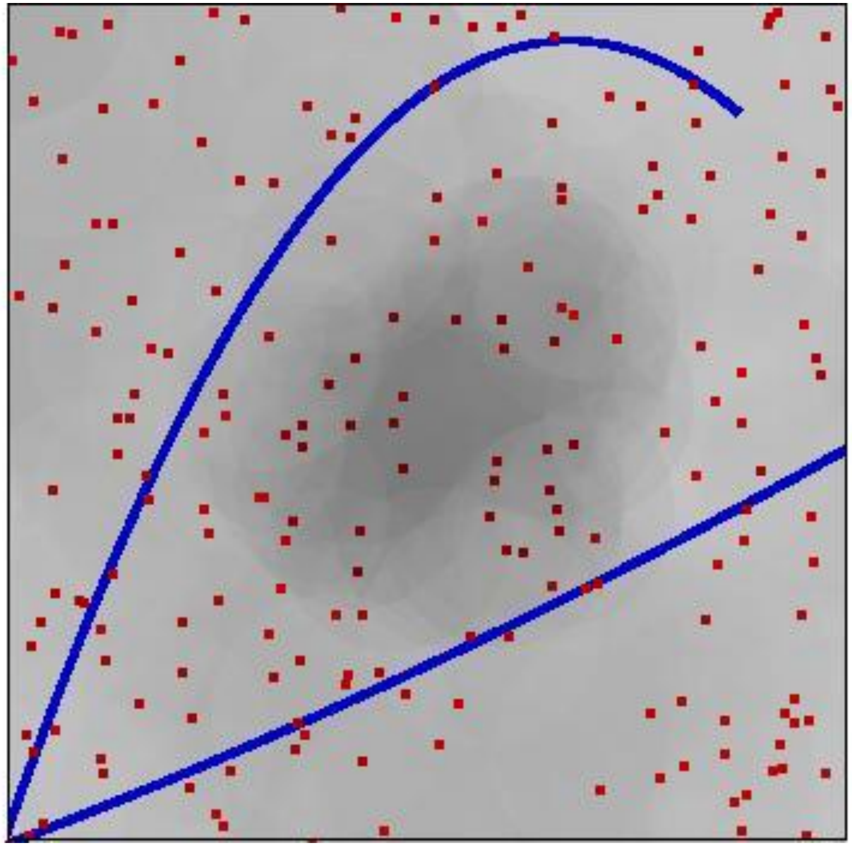
TEDD

- Dynamic trajectory generation



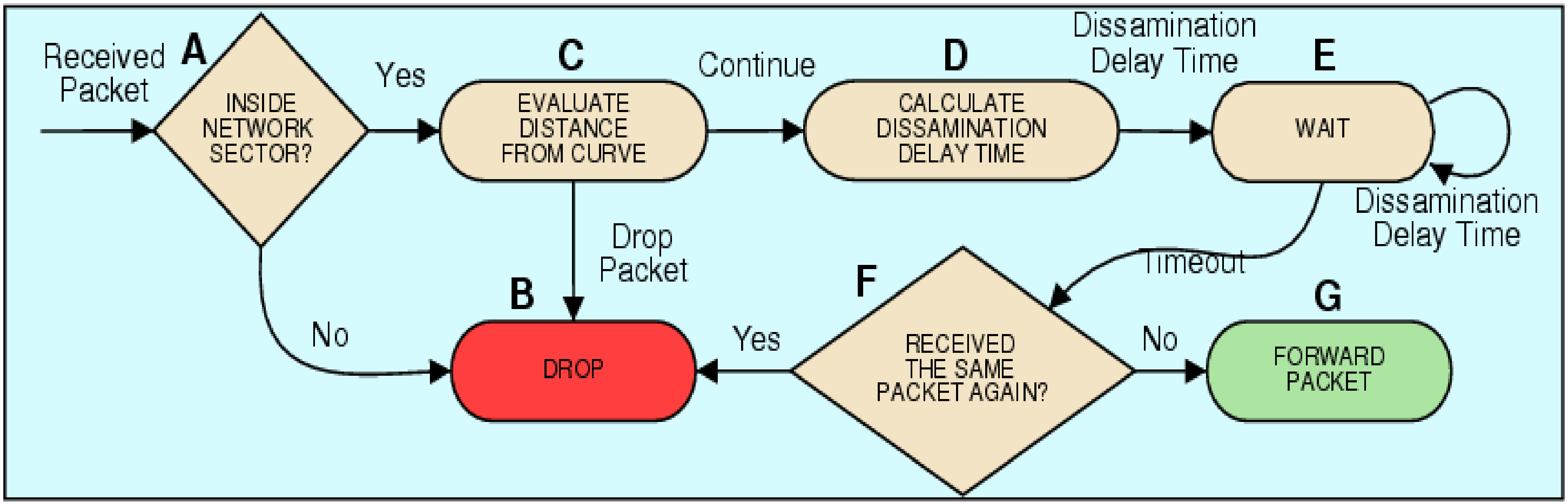
TEDD

- Dynamic trajectory generation



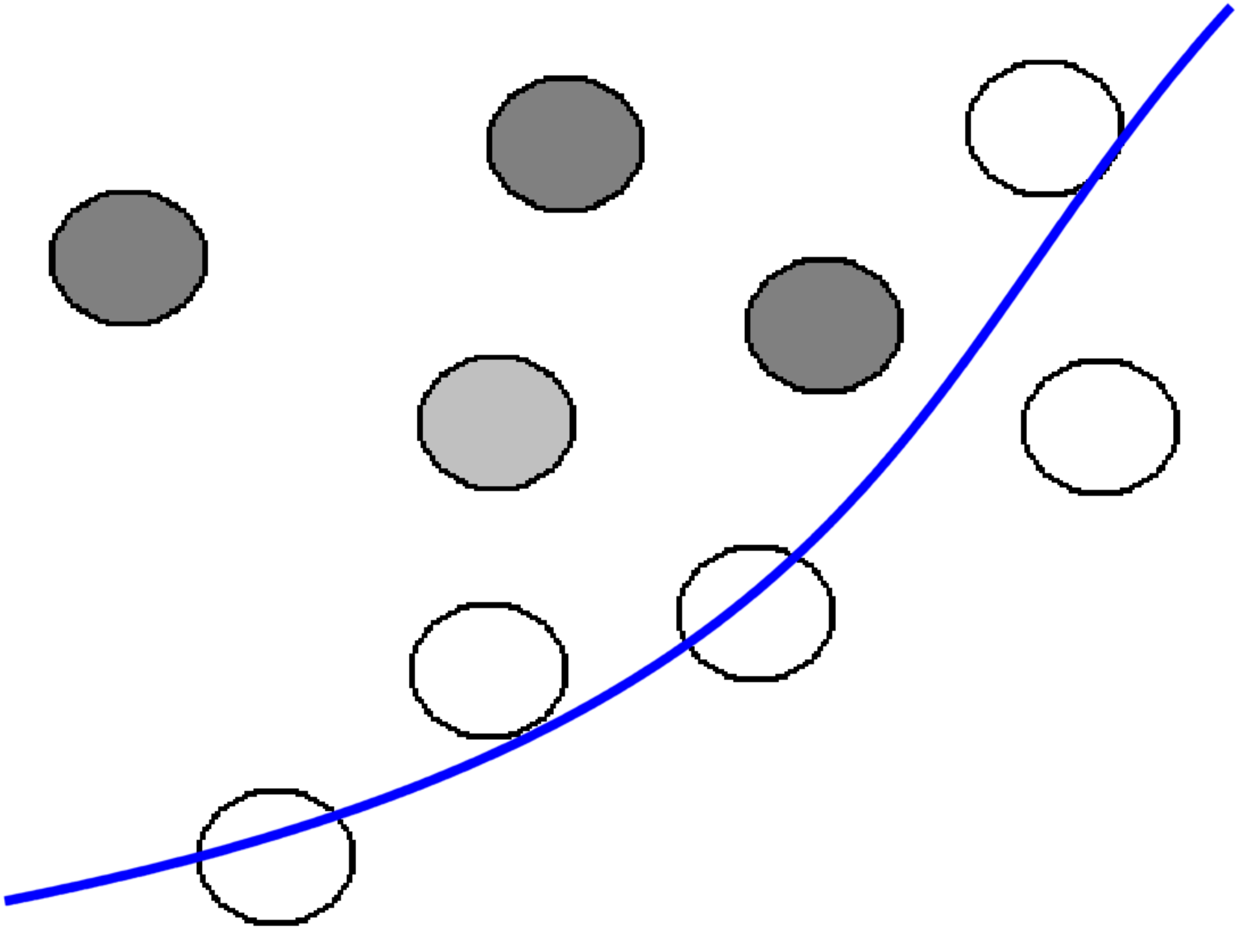
TEDD

- Receiver-based forwarding technique



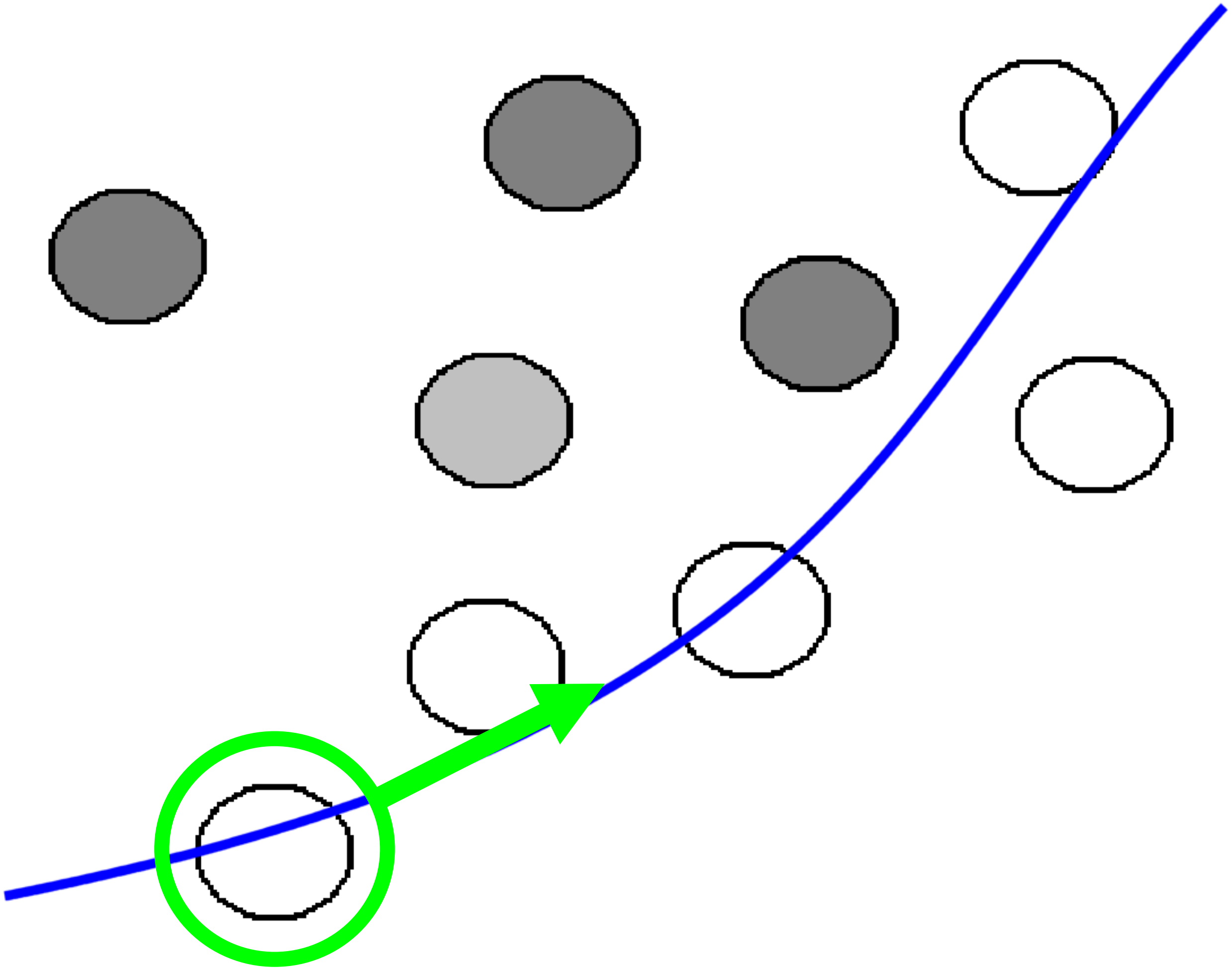
TEDD

- Receiver-based forwarding technique



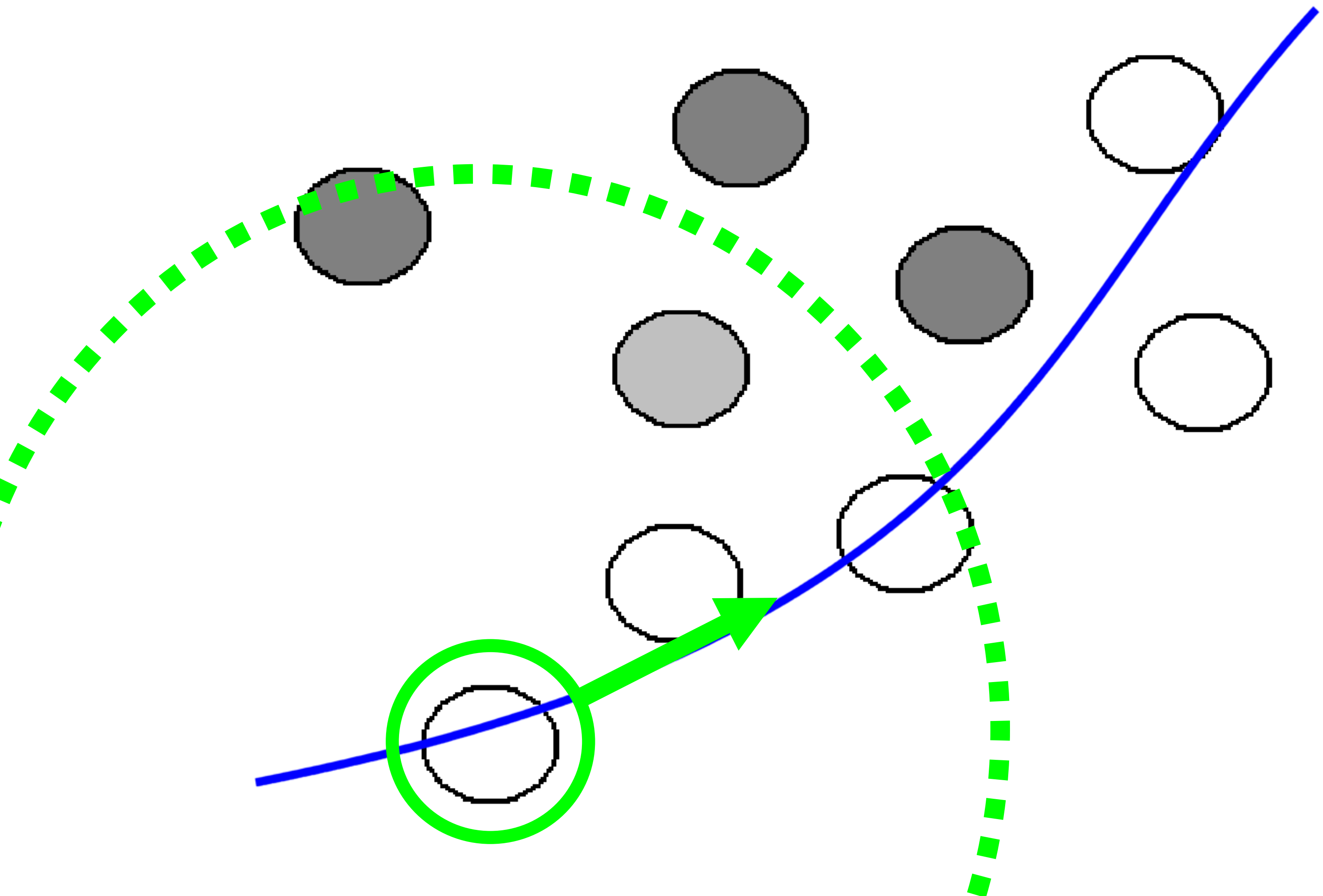
TEDD

- Receiver-based forwarding technique



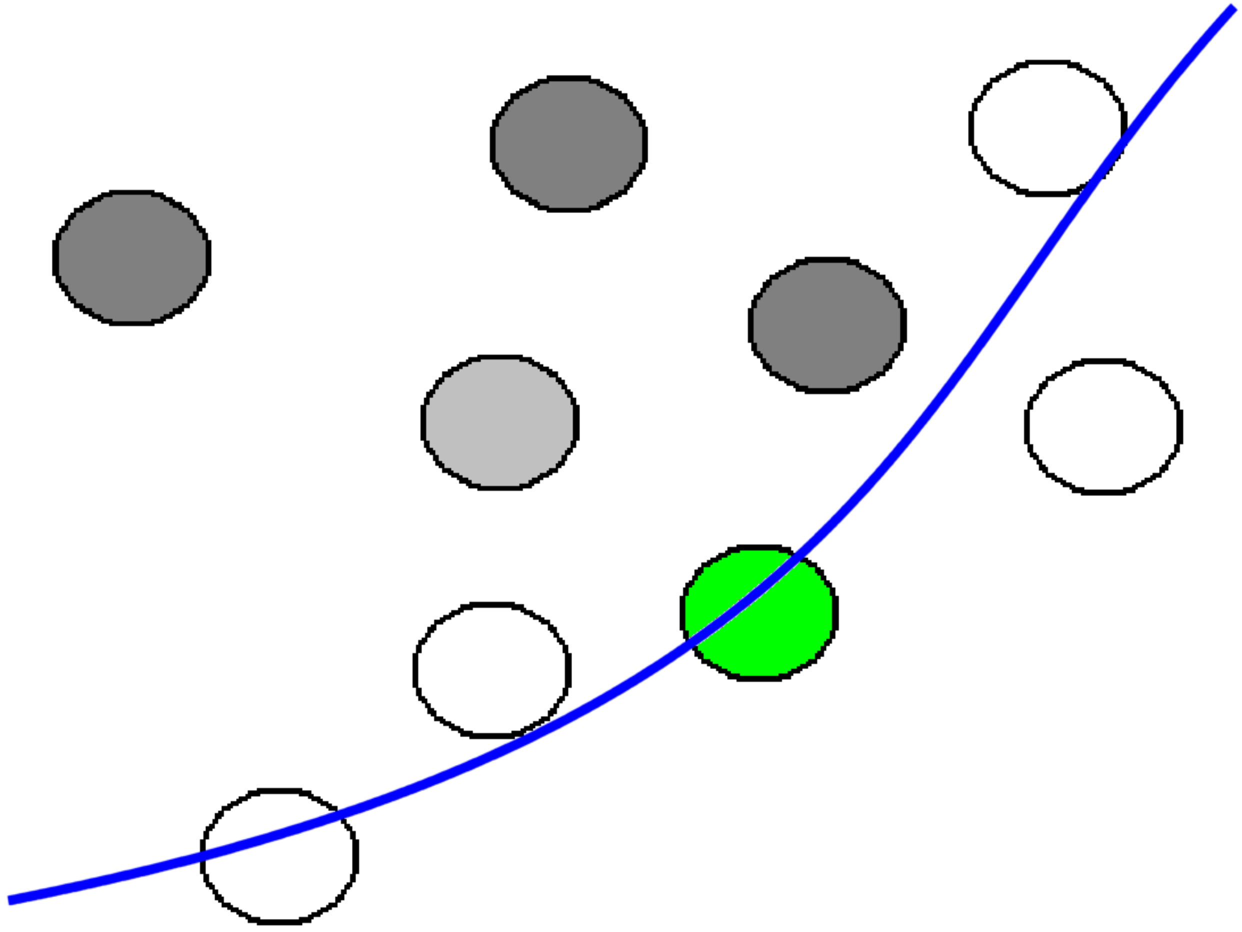
TEDD

- Receiver-based forwarding technique



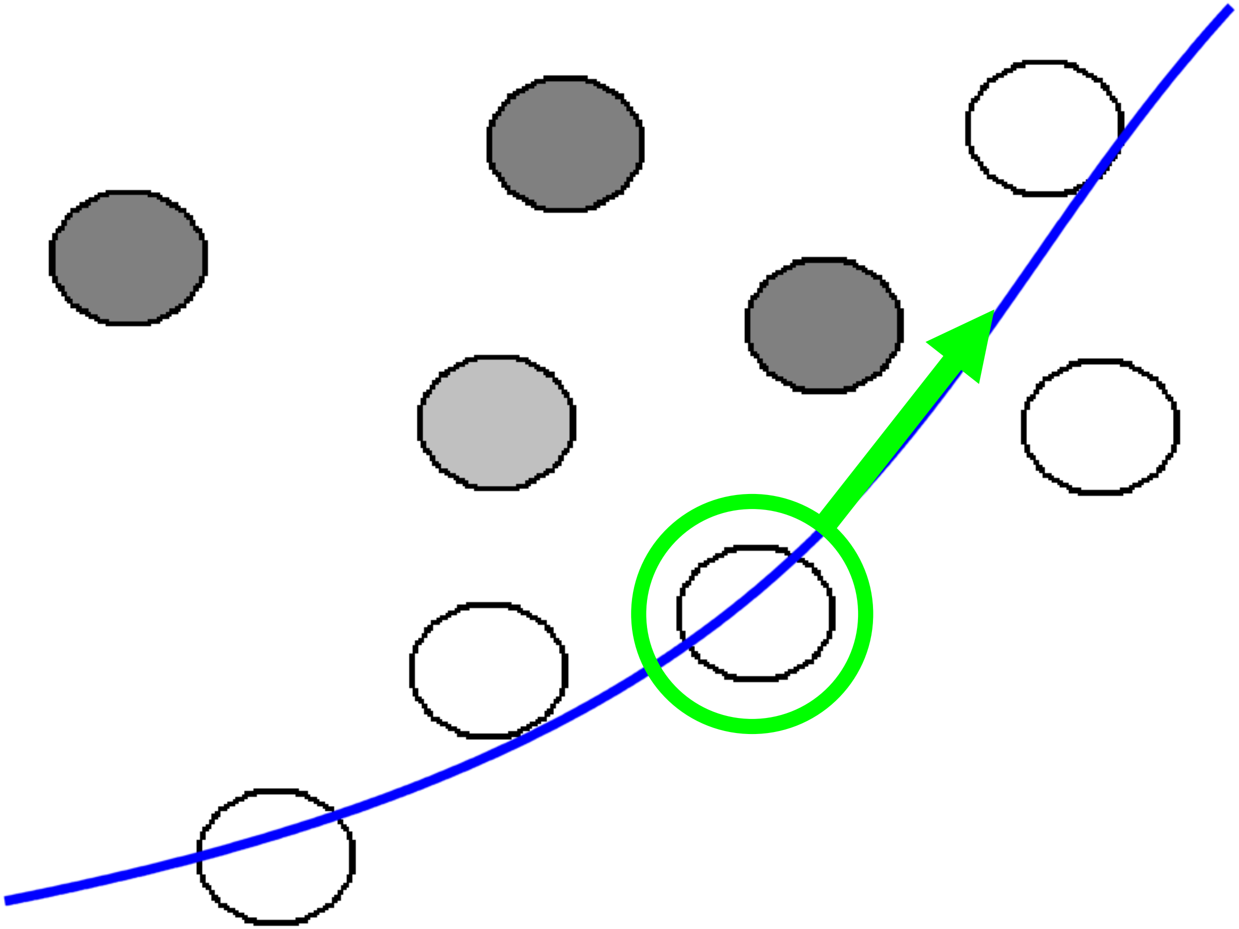
TEDD

- Receiver-based forwarding technique



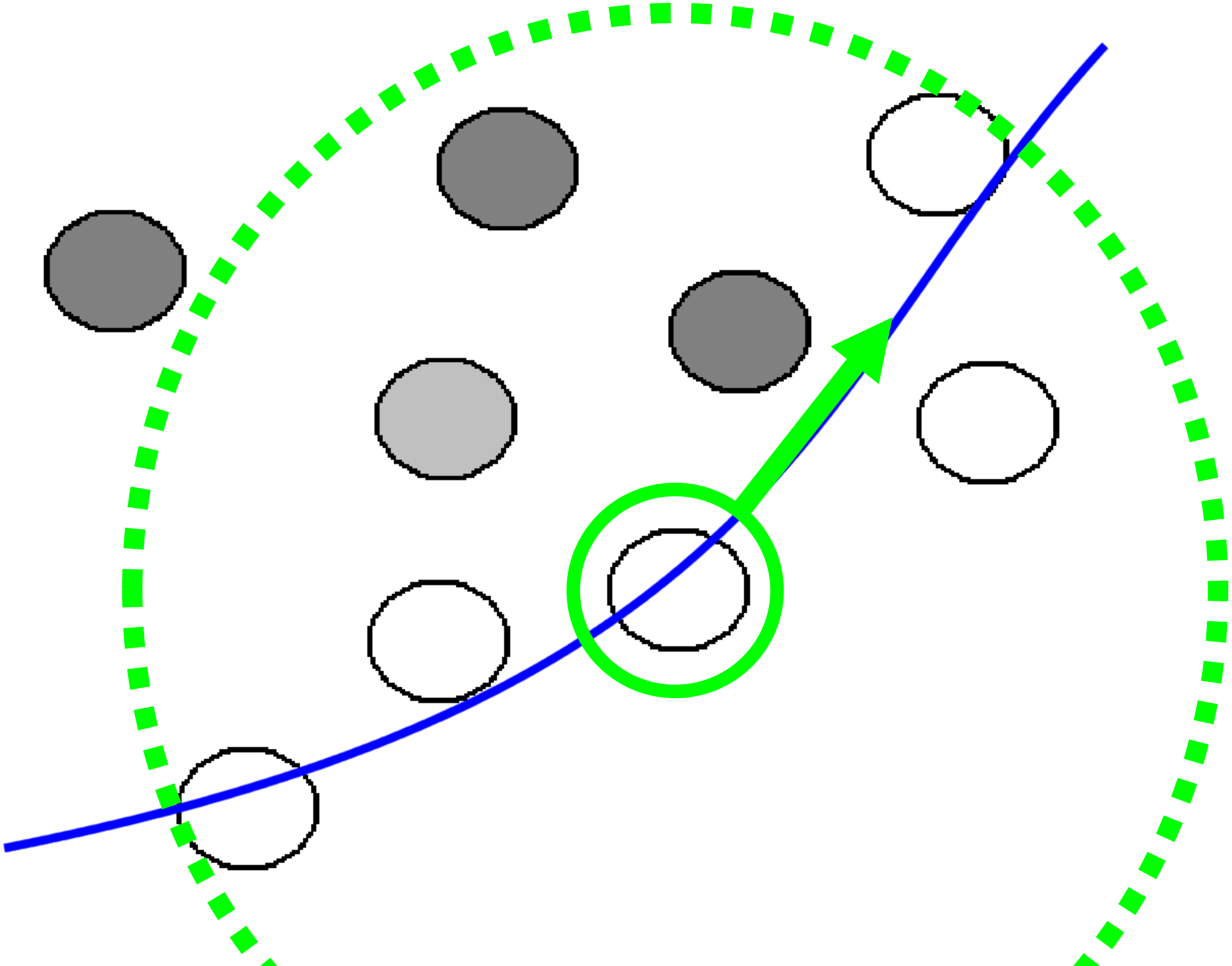
TEDD

- Receiver-based forwarding technique



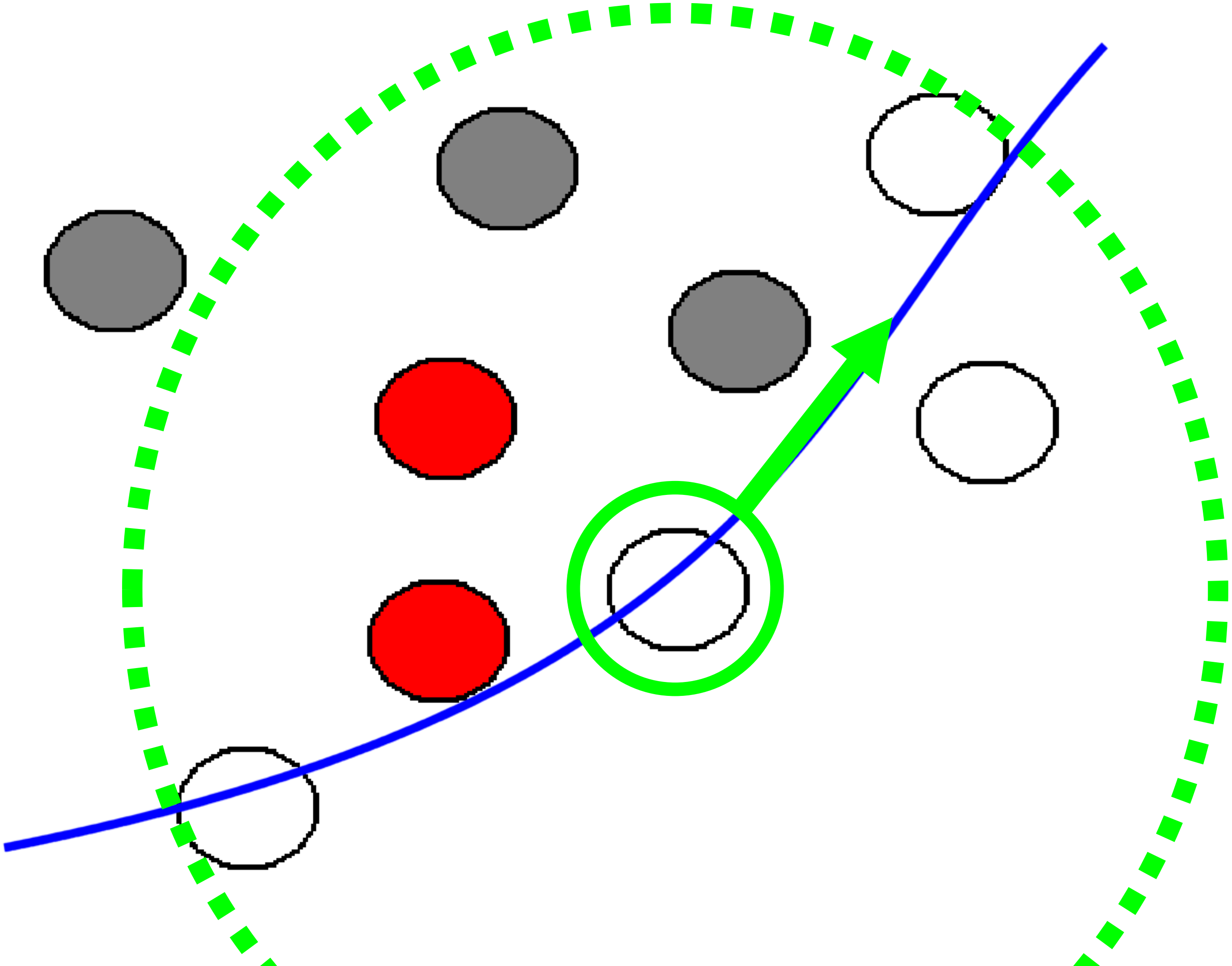
TEDD

- Receiver-based forwarding technique



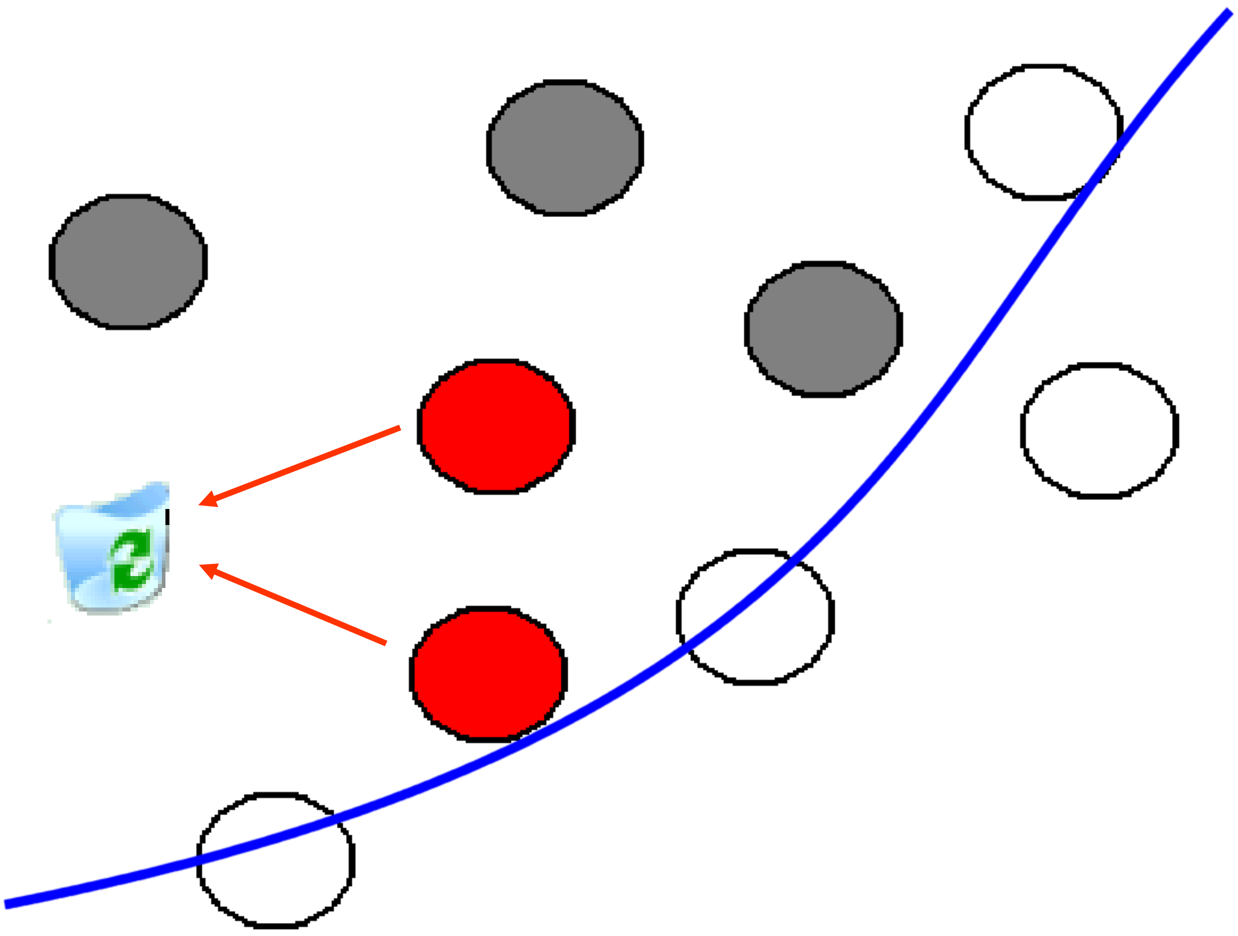
TEDD

- Receiver-based forwarding technique



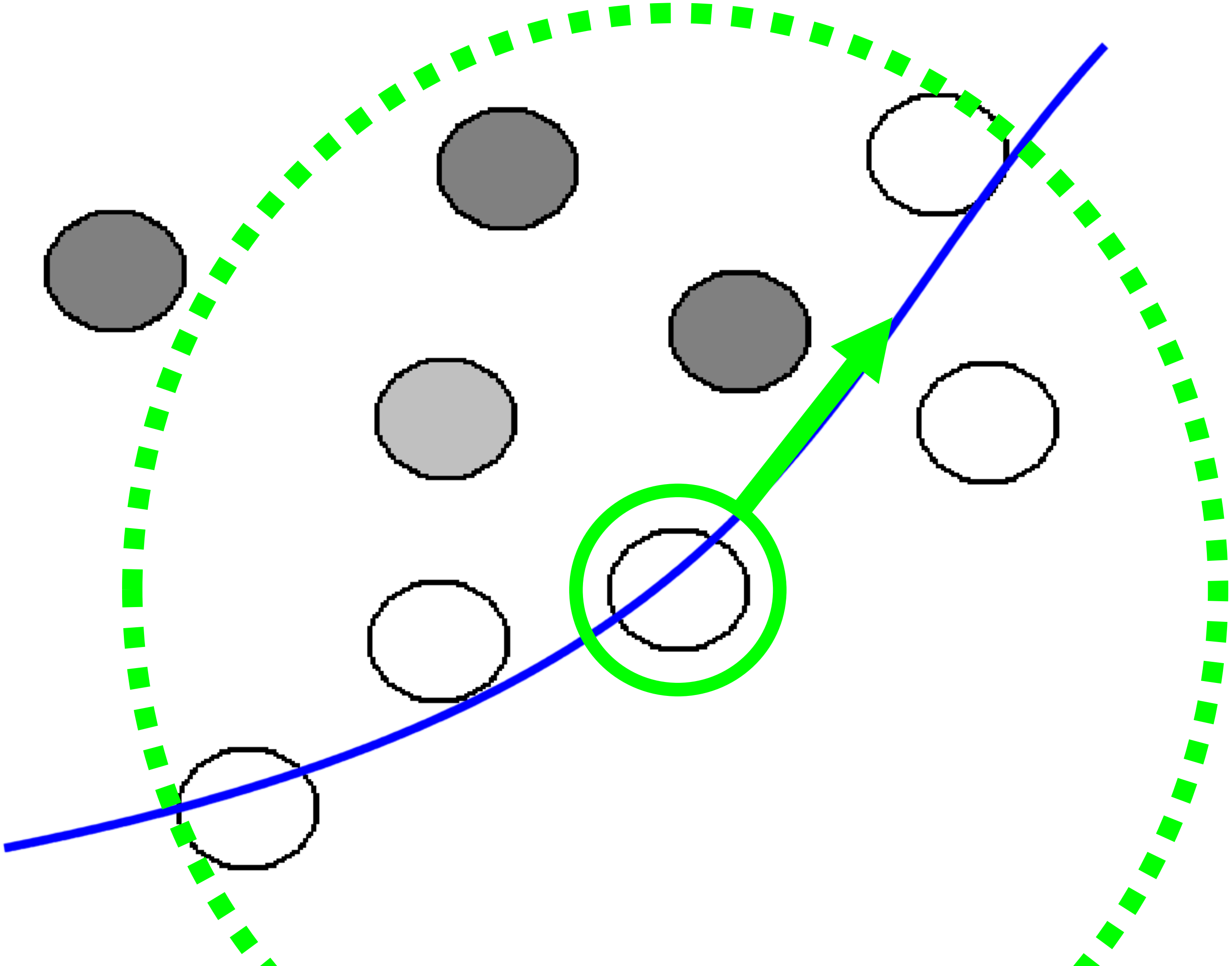
TEDD

- Receiver-based forwarding technique



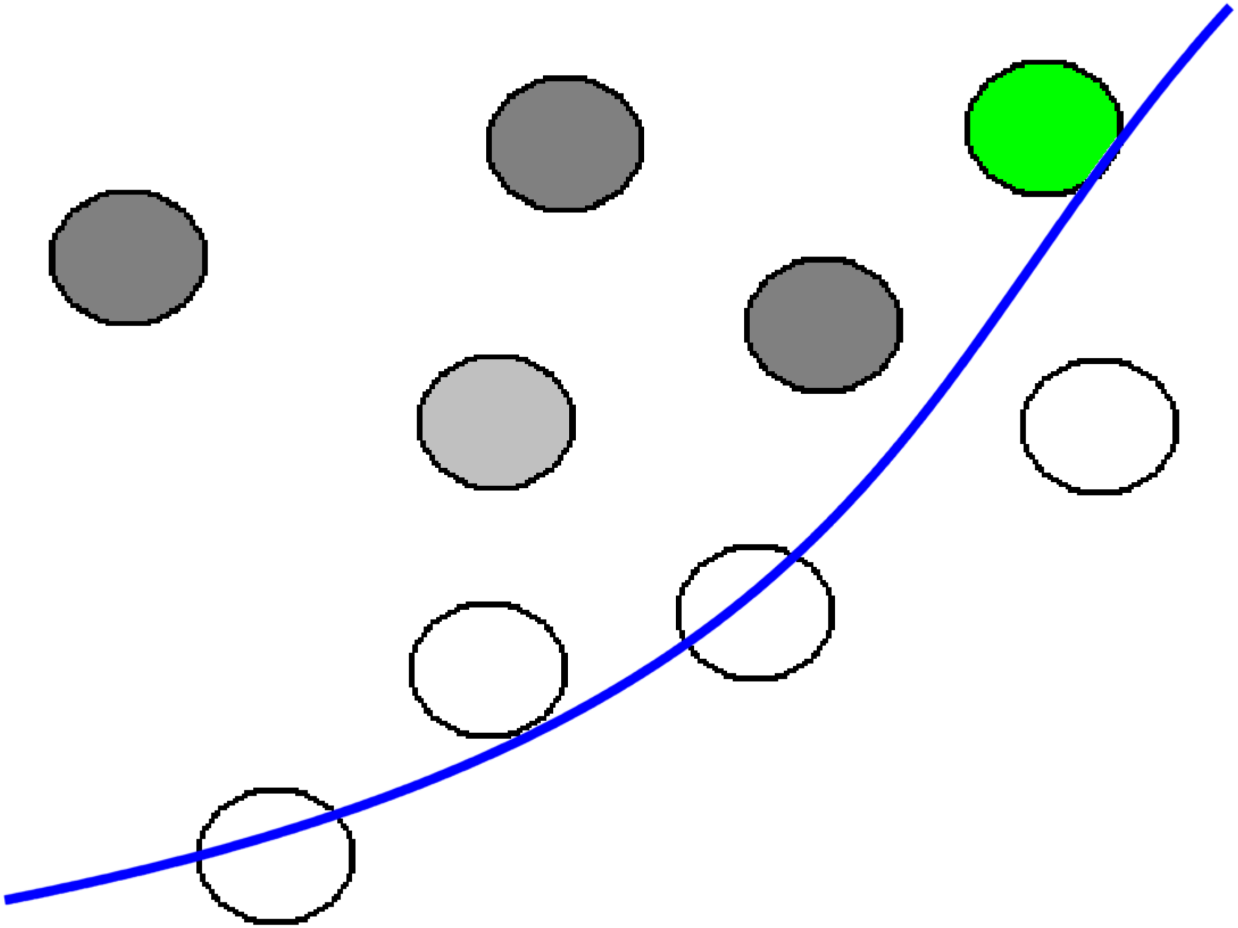
TEDD

- Receiver-based forwarding technique



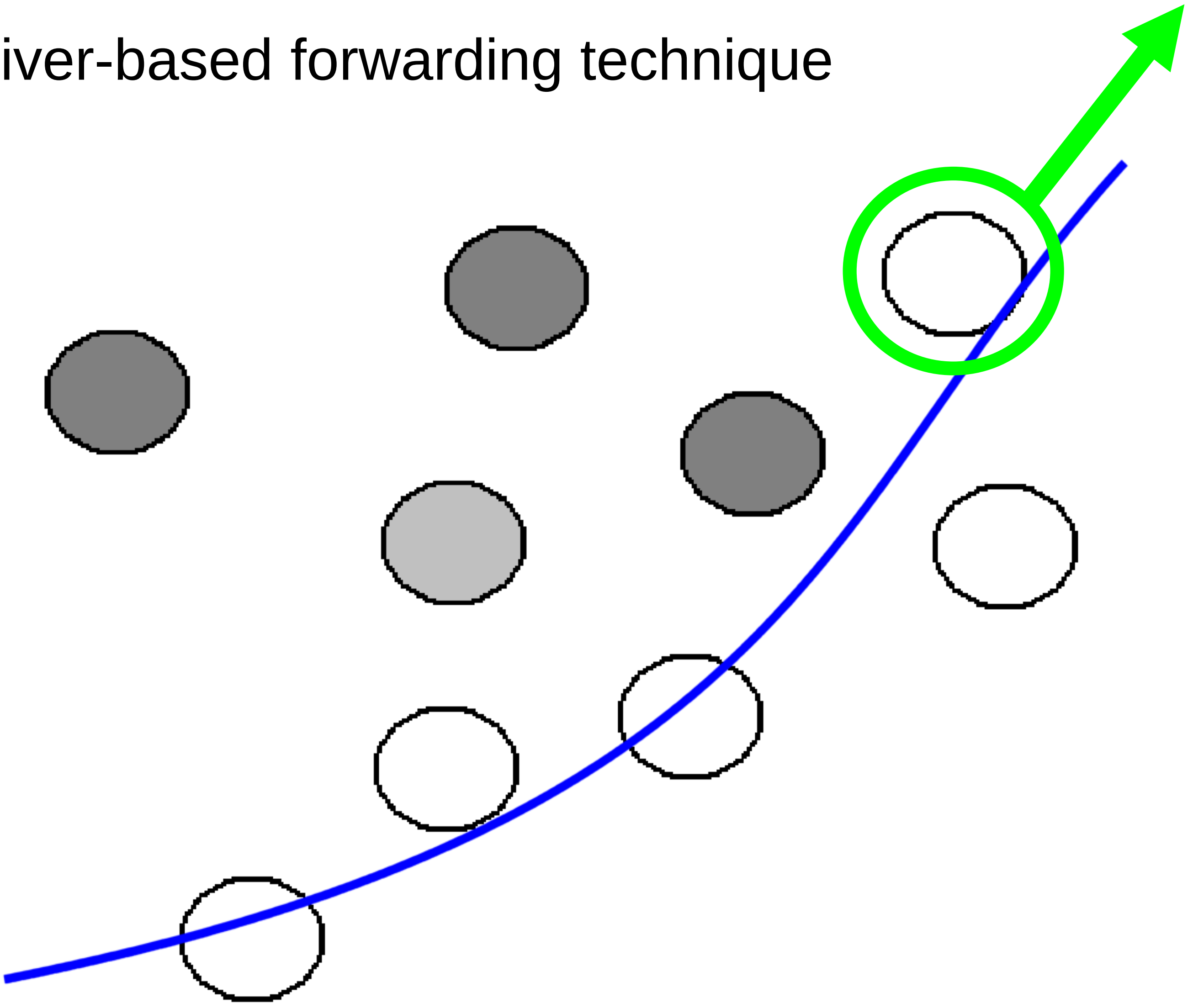
TEDD

- Receiver-based forwarding technique



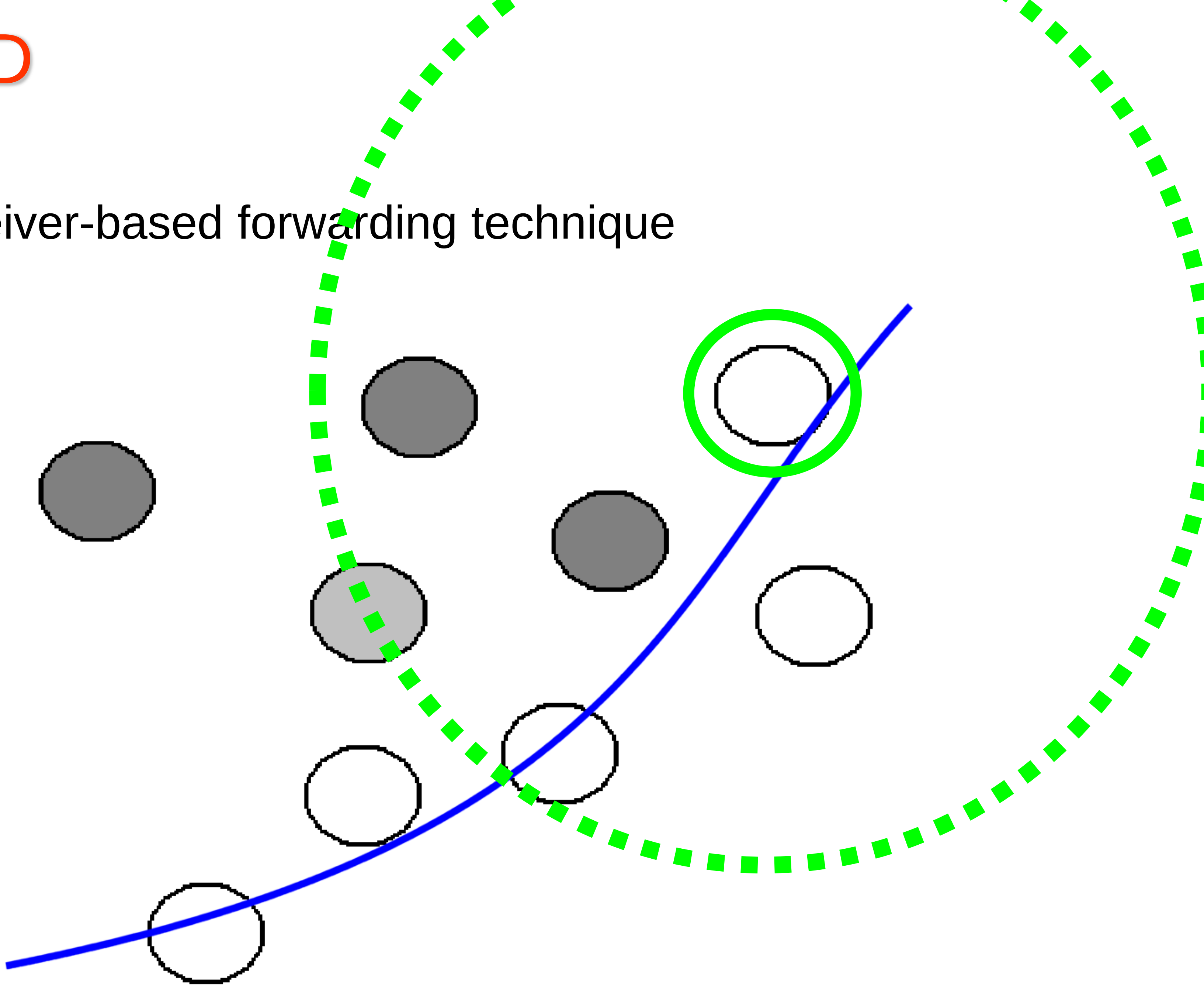
TEDD

- Receiver-based forwarding technique



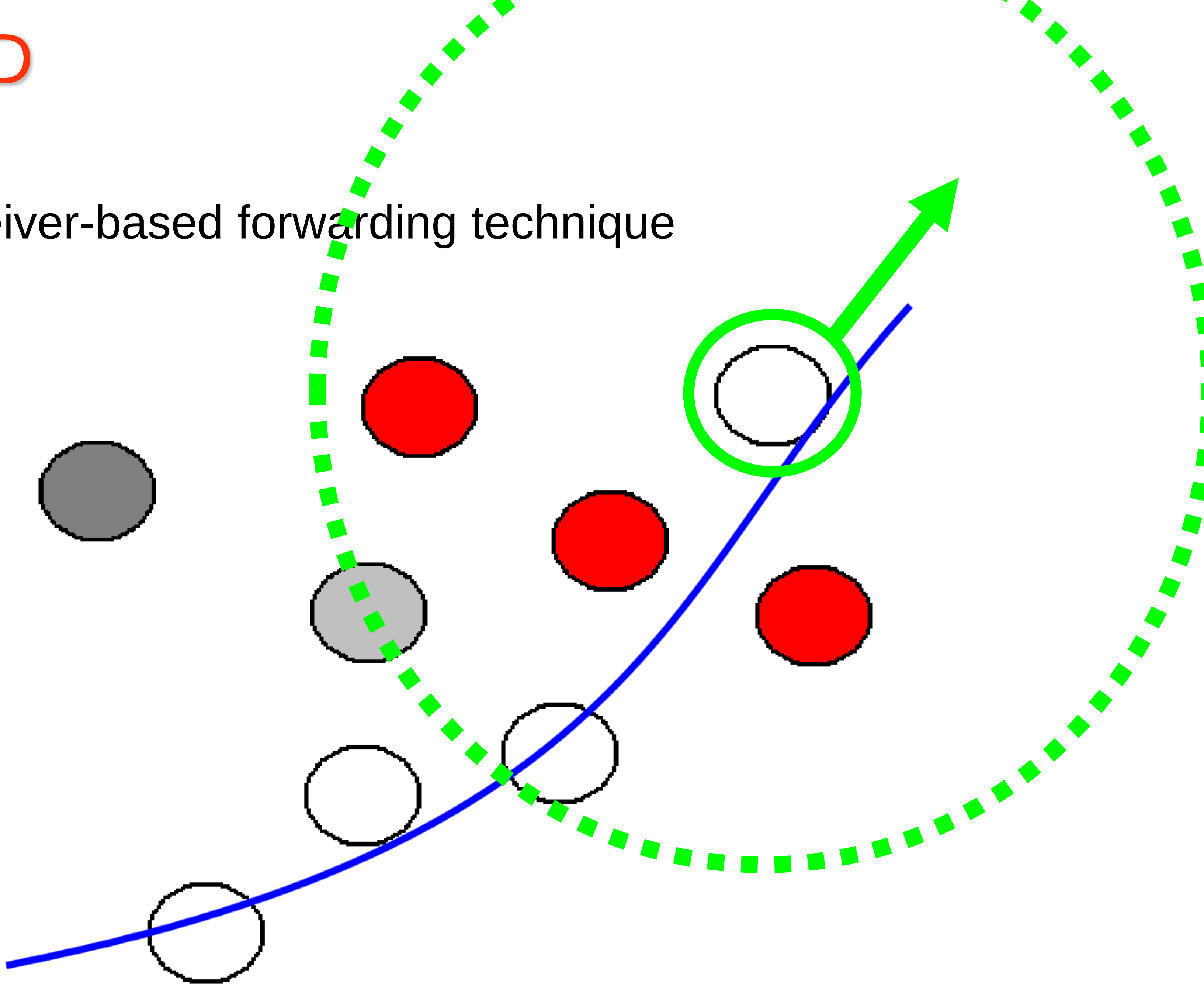
TEDD

- Receiver-based forwarding technique



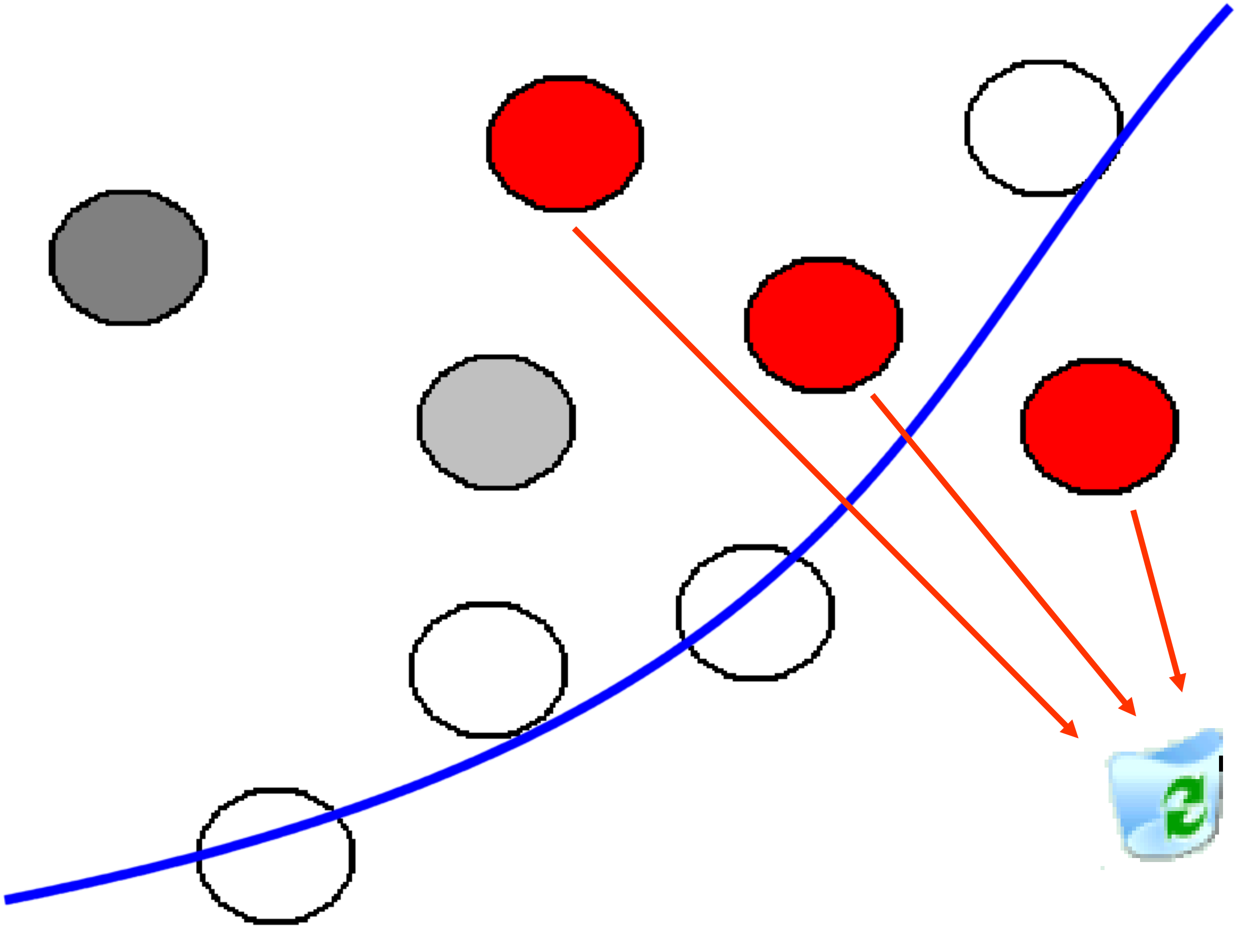
TEDD

- Receiver-based forwarding technique



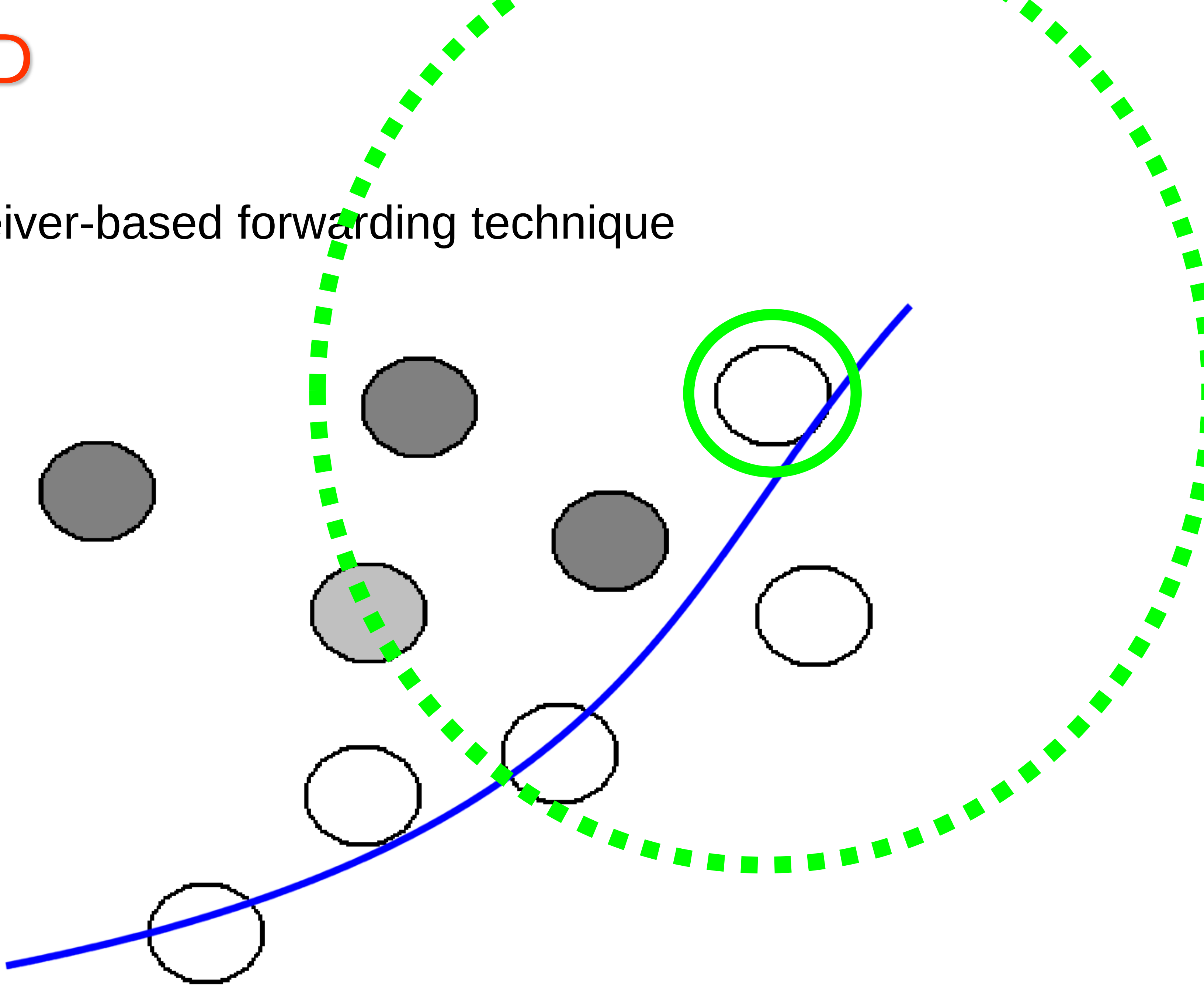
TEDD

- Receiver-based forwarding technique



TEDD

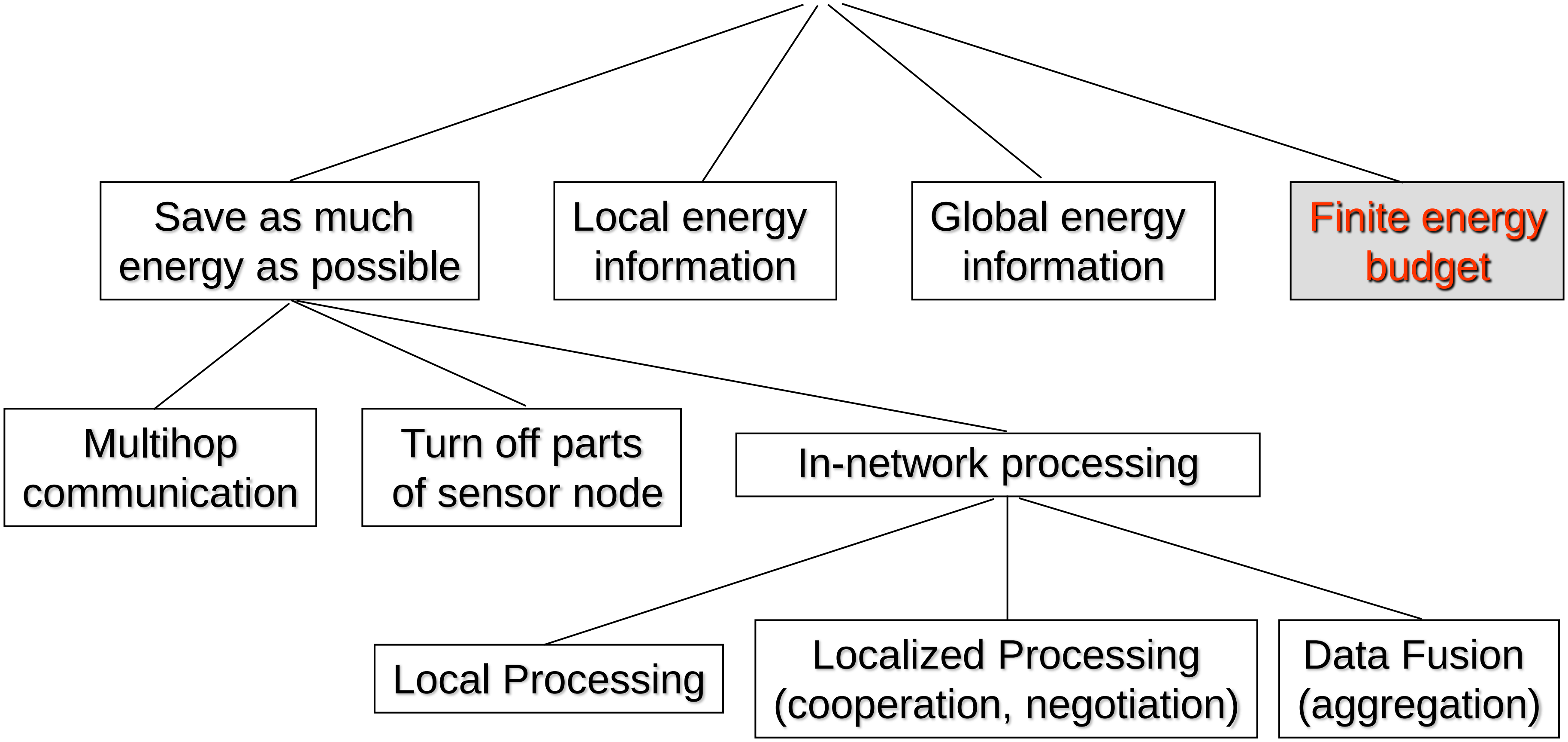
- Receiver-based forwarding technique



TEDD

- Main goal:
  - Avoid the necessity of neighbor tables
- Basic operation:
  - When a node receives a packet, it decides locally whether it should forward it or not, based only on the information contained in the packet
- Characteristics:
  - No particular node is chosen to forward a packet
  - Several nodes can forward the same packet (fault tolerant operation in a dynamic topology environment)
  - It is possible to embed more than one curve in each packet

How Are Protocols Dealing with Energy Restriction?



Protocols have a finite energy budget to spend

Finite Energy Budget

1. The key challenge in the design of wireless sensor network is **maximizing its lifetime**

2. **Energy conservation** is a fundamental issue to extend the network lifetime

3. The **total amount of energy** available in the network is **finite**

What is the best performance a protocol can achieve given that it can spend only a finite amount of energy?

Finite Energy Budget

- It is highly desirable to define the amount of energy each protocol can spend to perform its goal
- We can associate a finite energy budget for each network activity, and ask this activity to achieve its best performance using only its budget
- This is a new way of dealing with network related problems, and should be considered a new paradigm to design algorithms for wireless sensor networks

Finite Energy Budget Paradigm

Finite Energy Budget

- Finite energy budget paradigm have two main steps:

  1. Divide the total energy among all network activities

  2. Decide how each network activity will use its budget

Finite Energy Budget

1. Divide the total energy among all network activities
   - Depends on application features such as:
     - Deployment strategy
     - Communication models
     - Data delivery model
     - Topology
     - Density
     - Dynamism of sensors
     - Phenomena
     - Observers

Finite Energy Budget

1. Divide the total energy among all network activities

Deployment Strategy

Random deployment **X** **Planned deployment**

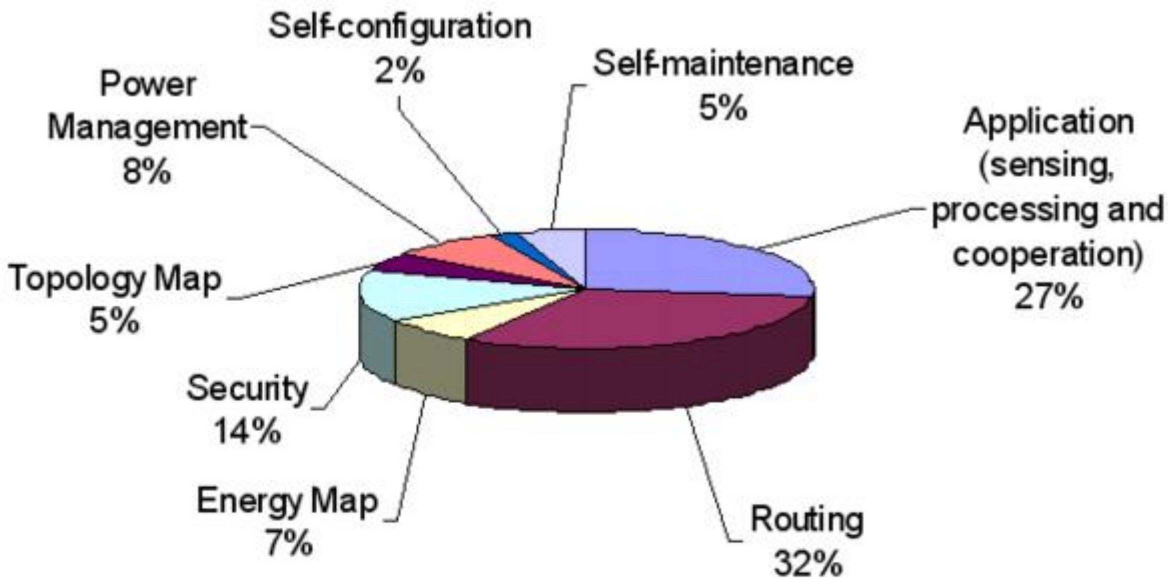
- There is no a priori knowledge of nodes location
- Nodes will need to determine their relative positions and self-organize into a special coordinate system without relying on remote infrastructure such as GPS

- The exact position of each node is carefully studied and known a priori

The self-configuration budget of a planned network will be smaller than the one of a random network

Finite Energy Budget

1. Divide the total energy among all network activities (Example)

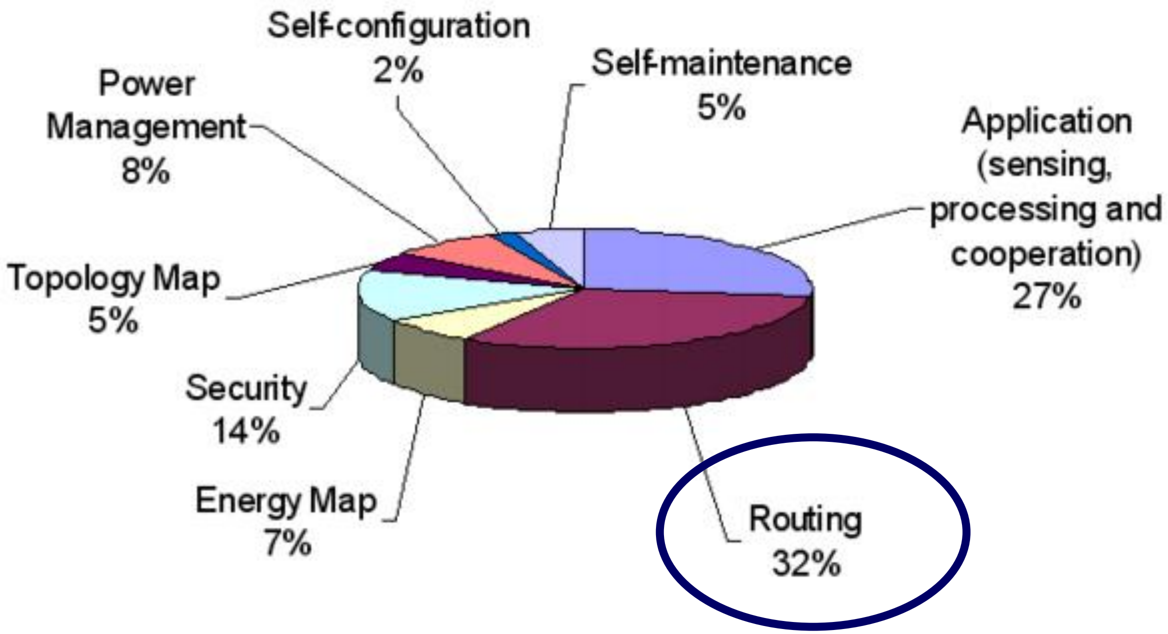


Finite Energy Budget

- Decide how each network activity will use its budget
  - All network activities will have to be designed in order to work under an energy restriction
  - It is necessary to plan the node behavior in order to achieve the best performance spending only a finite amount of energy

Finite Energy Budget

2. Decide how each network activity will use its budget (Example)



Finite Energy Budget

- Decide how each network activity will use its budget (Example)
  - Using up to 32% of the total energy and achieving its best performance, the routing algorithm should make some decisions such as:
    - When/how doing fusion
    - When/how doing compression
    - When drop packets

Finite Energy Budget

- The budget can be negotiated dynamically?
  - Dynamic budget association: transfer energy budget from one activity to another that needs more energy
  - This problem is similar to the dynamic channel allocation in cellular network
    - If an ERB has more channels in relation to its demand for communication in its coverage area, it can yield some channels to another ERB that is with a debit on its demand

Finite Energy Budget

- We can apply the finite energy budget paradigm to a communication decision problem
- Communication decision problems:
  - Decision about performing or not a communication is the most important one
- The finite energy budget is represented by the number of packets each node can transmit

Communication Decision Problems

- The number of packets is used as the metric for energy budget

- Goal:
  - Satisfy a given communication task under the constraint that each node can send no more than a certain number of packets to the monitoring node

Communication Decision Problems

- The moment to send the information packet is decided locally by each node without exchanging information with its neighbors
- This decision should be taken according to a certain probability p
- The value of p determines the frequency in which nodes will send their information and, thus, the amount of energy spent by the given communication task

Communication Decision Problems

- The value of p depends on the following parameters:
  - T_{total}: estimated network lifetime
  - T_{now}: current time
  - P_{total}: number of energy information packets each node can send
  - P_{used}: number of packets the node has already used

- The value of p that maximize the probability of a node sends (P_{total} - P_{used}) packets in (T_{total} - T_{now}) seconds is

$$p = \frac{P_{total} - P_{used}}{T_{total} - T_{now}}$$

Communication Decision Problems

- Each node also knows the error in the data it has to transmit
  - Error between the current information in the sensor node and the one in the monitoring node

- The error between the current information in the sensor node and the one in the sink node will change the value of p in such a way that
  - When the error is small, we should decrease the value of p in order to postpone the sending of an energy packet (we can save energy to be spent when the error is larger)
  - When the error is large, we should increase the value of p in order to force the node to send a new energy information

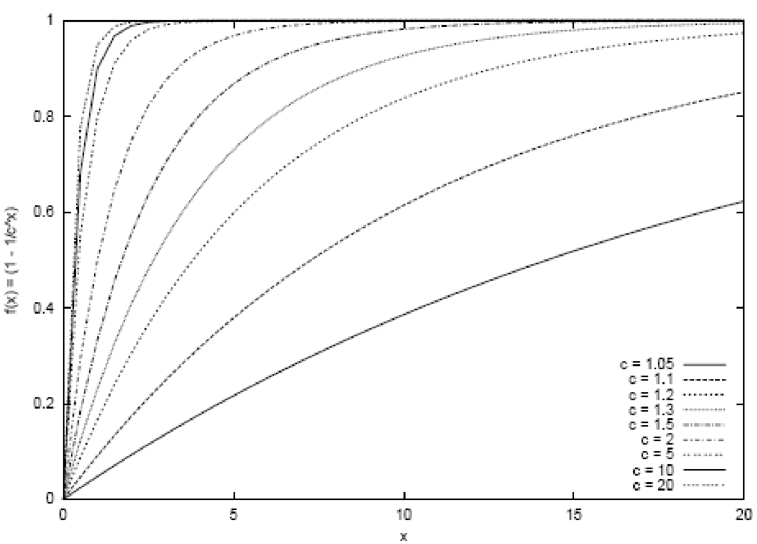
- We redefine the value of p and call it p'

Communication Decision Problems

- Each node will send a packet with probability

$$p' = p \times \left(1 - \frac{1}{c^{error}} \right) + (1-p) \times \left(1 - \frac{1}{c^{max(0, error - k)}} \right)$$

p **is decreased when the error is small, and it is almost unchanged when the error increases**



Communication Decision Problems

- Each node will send a packet with probability

$$p' = p \times \left(1 - \frac{1}{c^{error}}\right) + (1-p) \times \left(1 - \frac{1}{c^{max(0, error-k)}}\right)$$

When the error gets larger, the value of the probability of sending a packet should increase and becomes larger than p

Communication Decision Problems

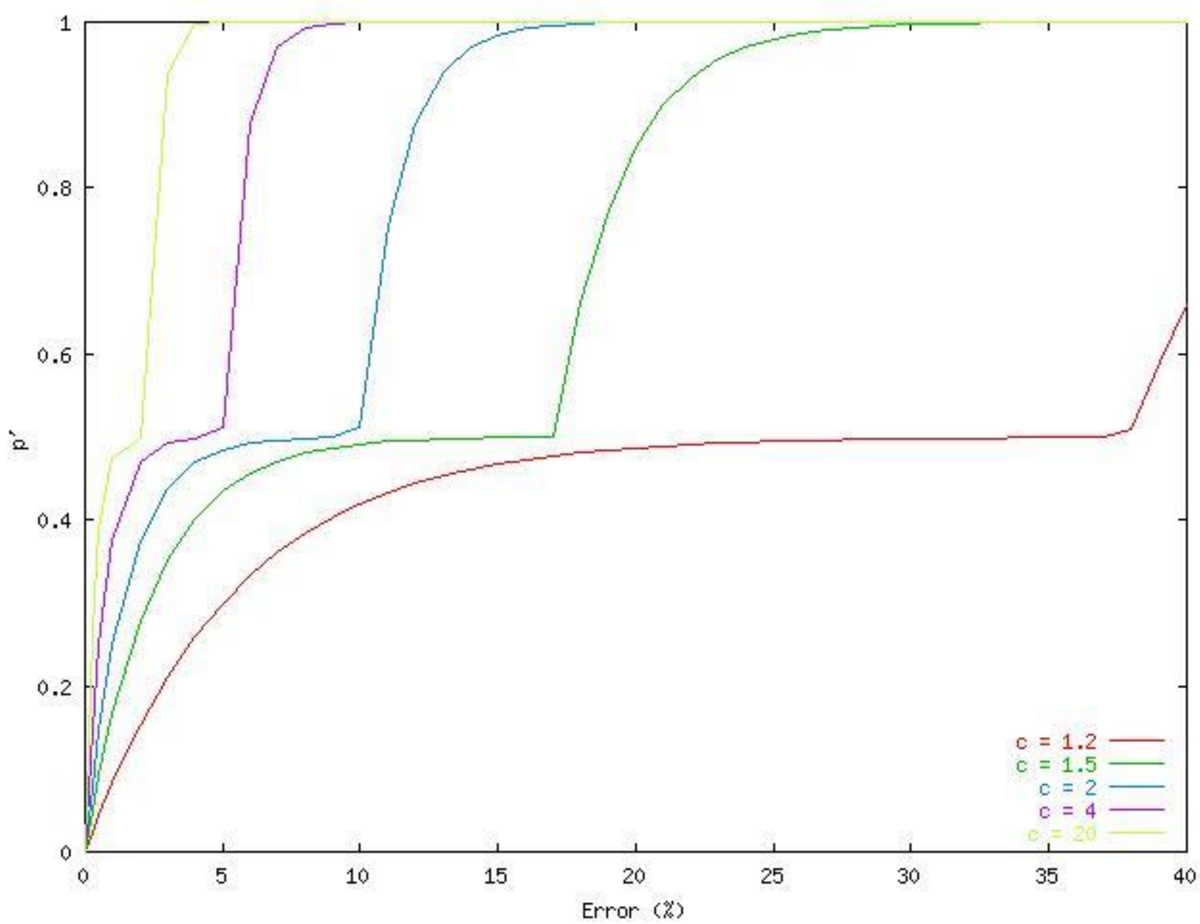
- Each node will send a packet with probability

$$p' = p \times \left(1 - \frac{1}{c^{error}}\right) + (1-p) \times \left(1 - \frac{1}{c^{max(0, error - k)}}\right)$$

The value of (1-*p*) is multiplied by the same function.

Communication Decision Problems

- Using the values of c and k, we can control the shape of the curve that represents the probability of sending a packet

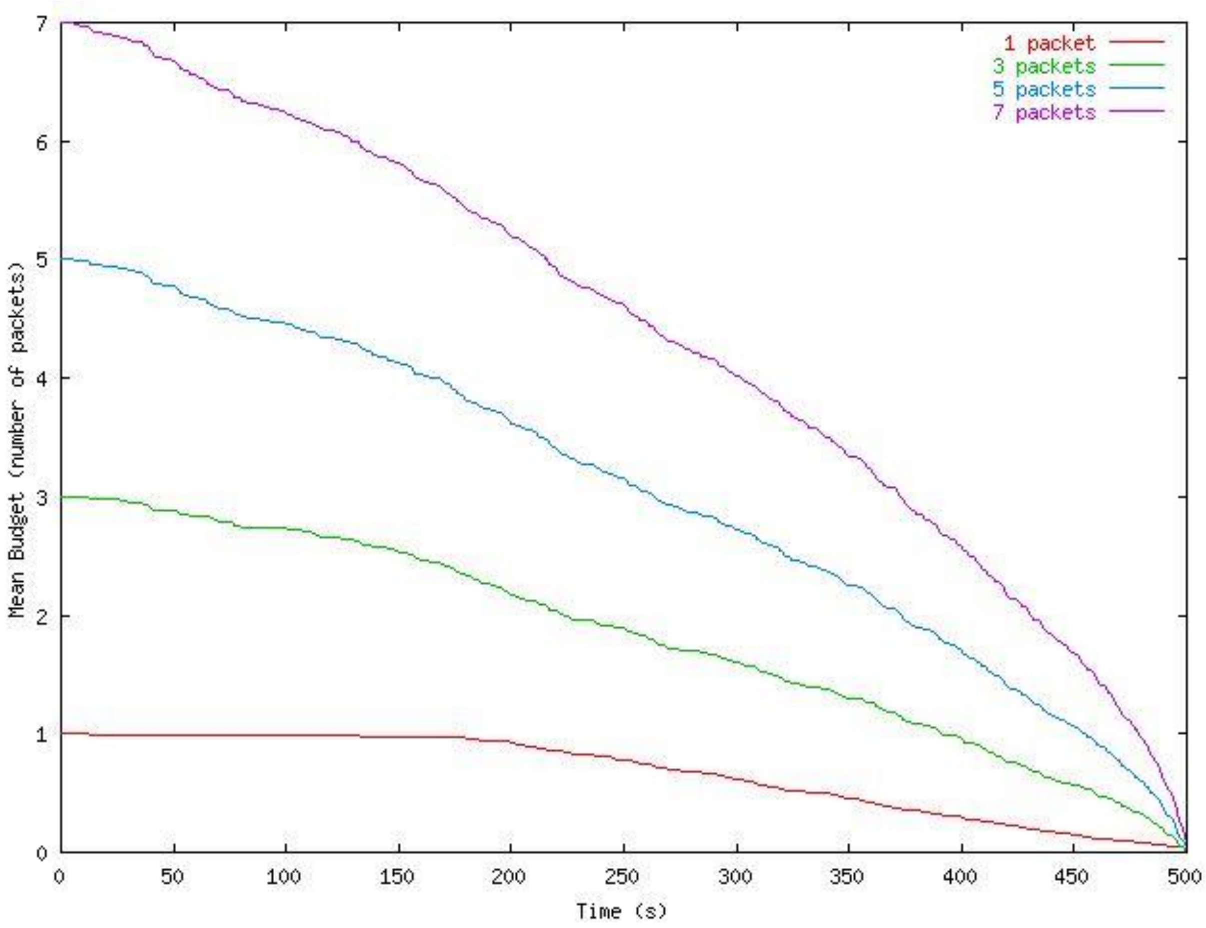


Simulation Results

- Construct the energy map of a wireless sensor network
  - The energy budget is defined in terms of the number of times a sensor node can send its energy information to the monitoring node
  - Communication decision problem: send or not to send the energy information to the monitoring node
- Scenario:
  - Energy consumption of Mica2
  - The monitoring node is positioned at the middle of the field at the position (25,25)
  - Default Values:
    - Number of nodes: 100
    - Initial energy: 100 J
    - Communication range: 15 m
    - Sensor field size: 50 x 50 m^2

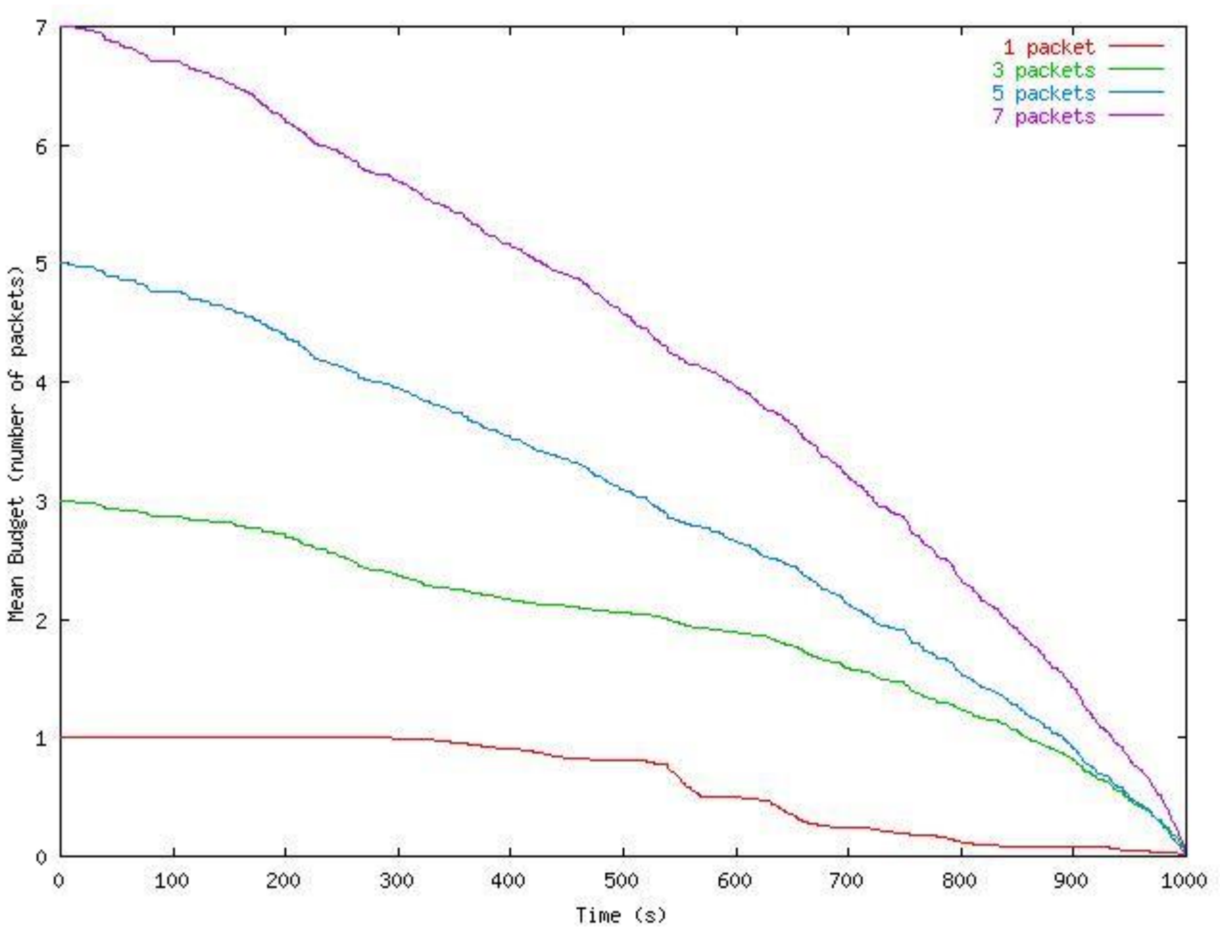
Mean Budget (number of packets)

500 seconds of simulation



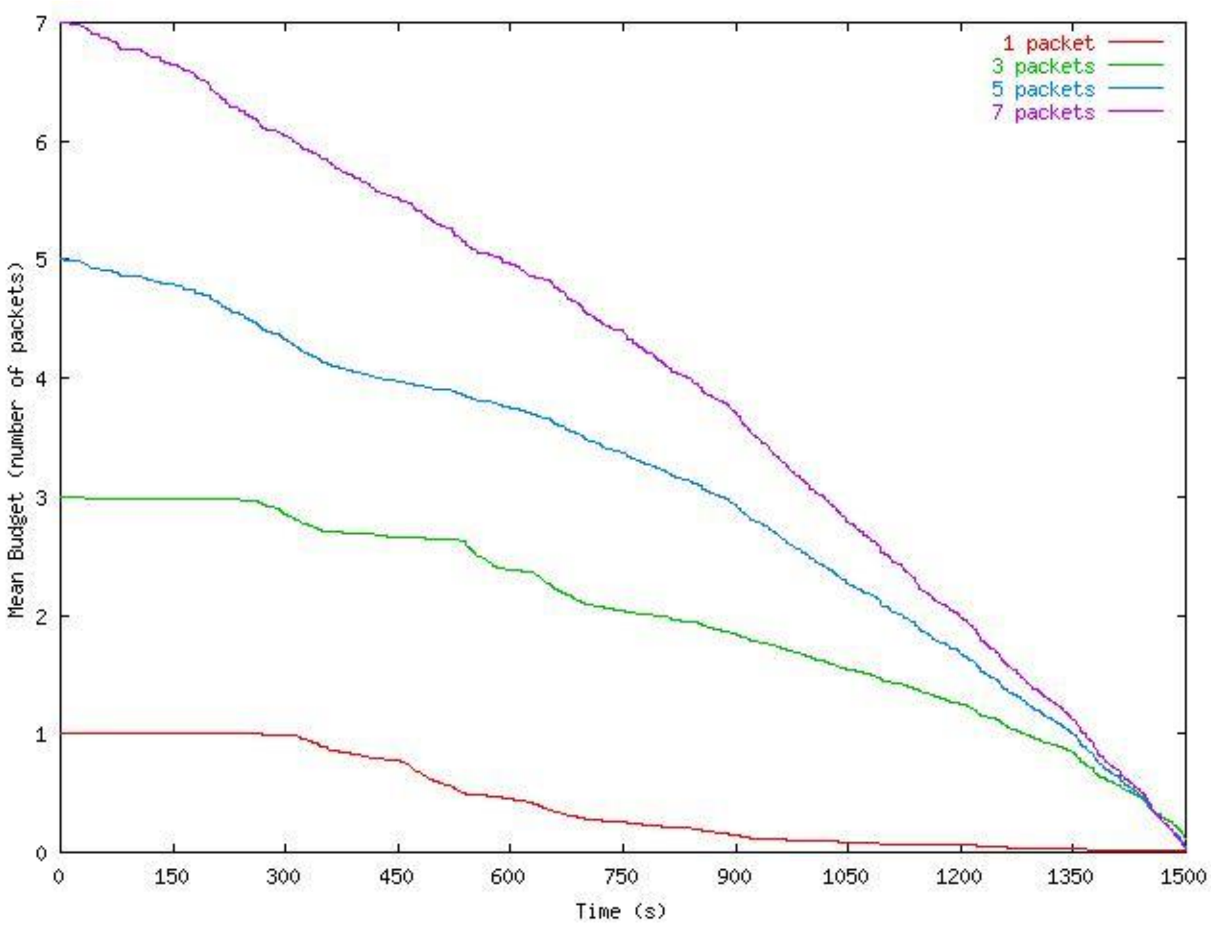
Mean Budget (number of packets)

1000 seconds of simulation



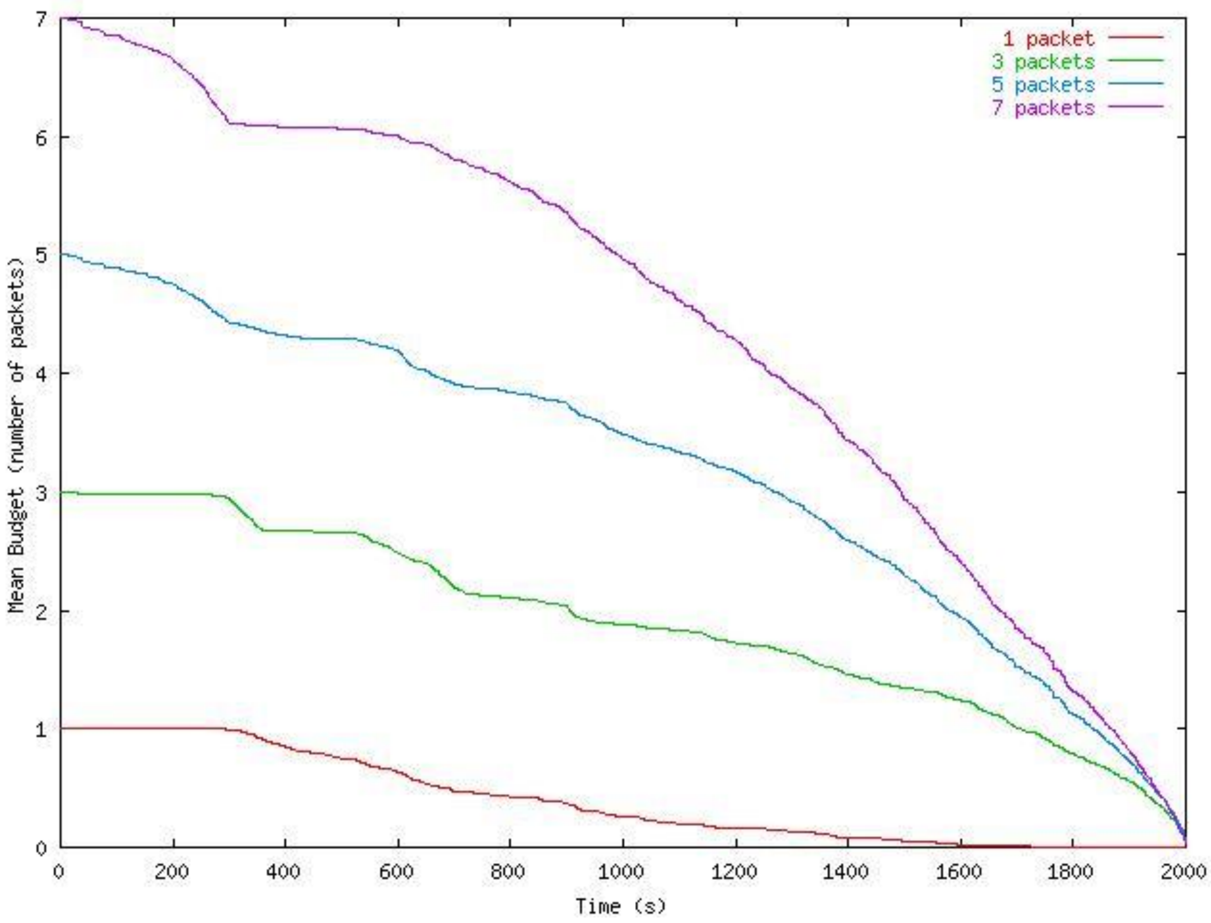
Mean Budget (number of packets)

1500 seconds of simulation



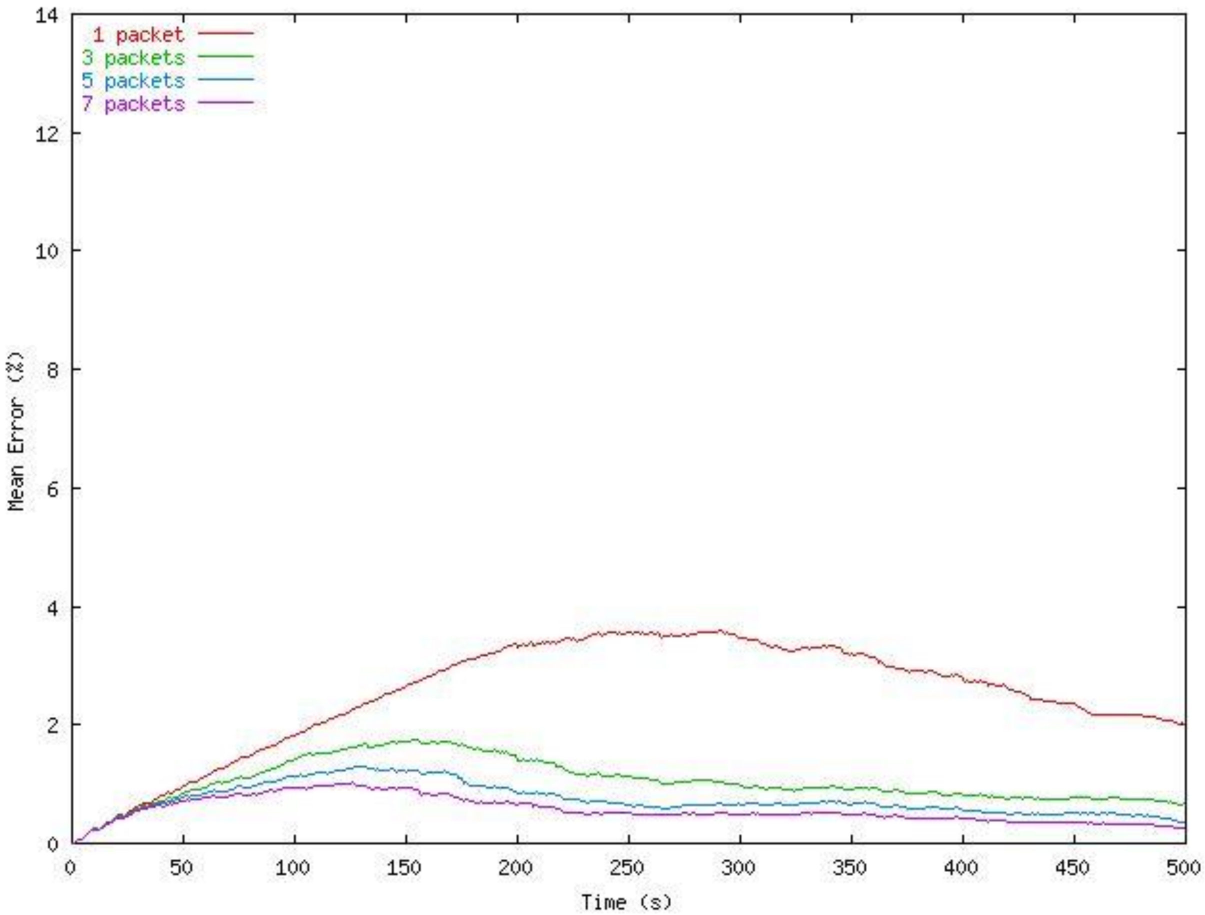
Mean Budget (number of packets)

2000 seconds of simulation



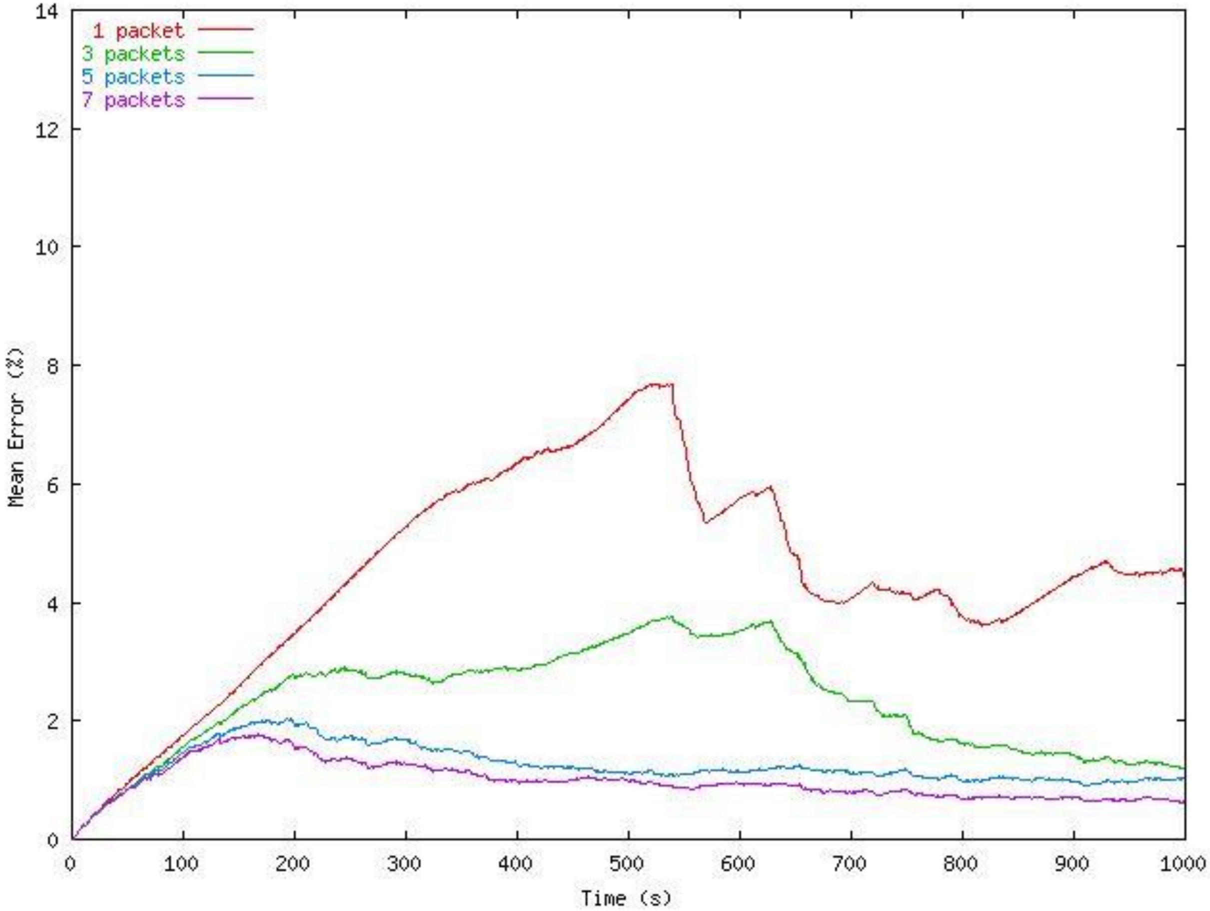
Mean Error (%)

500 seconds of simulation



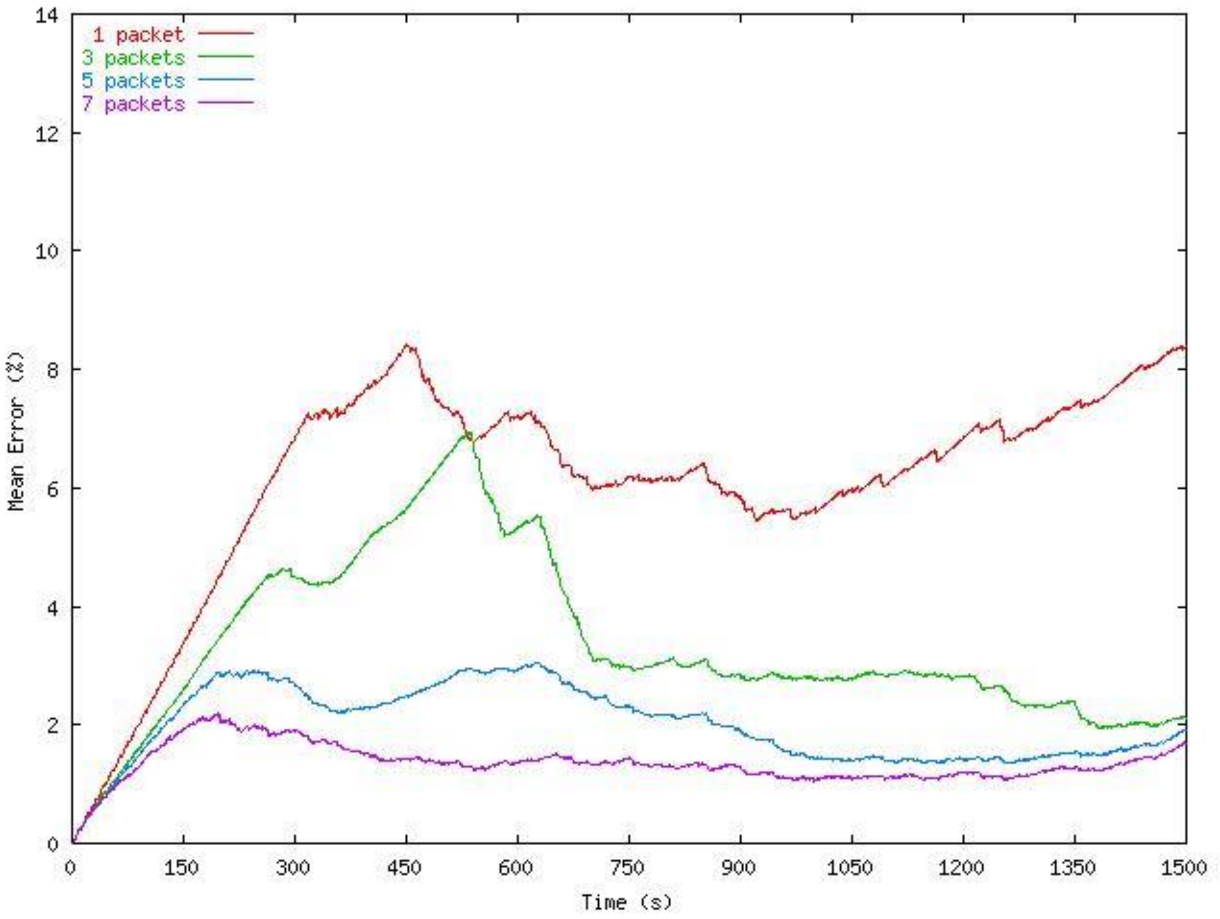
Mean Error (%)

1000 seconds of simulation



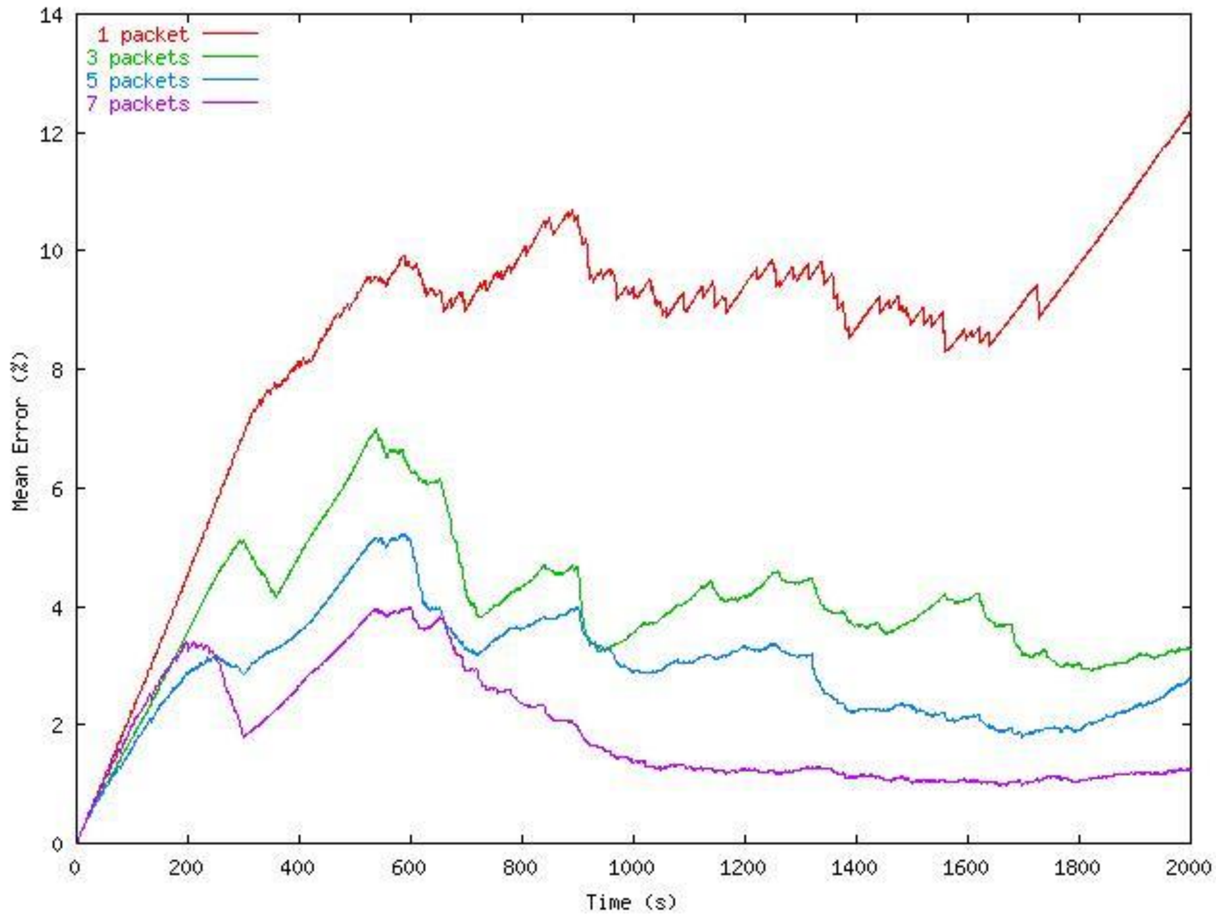
Mean Error (%)

1500 seconds of simulation



Mean Error (%)

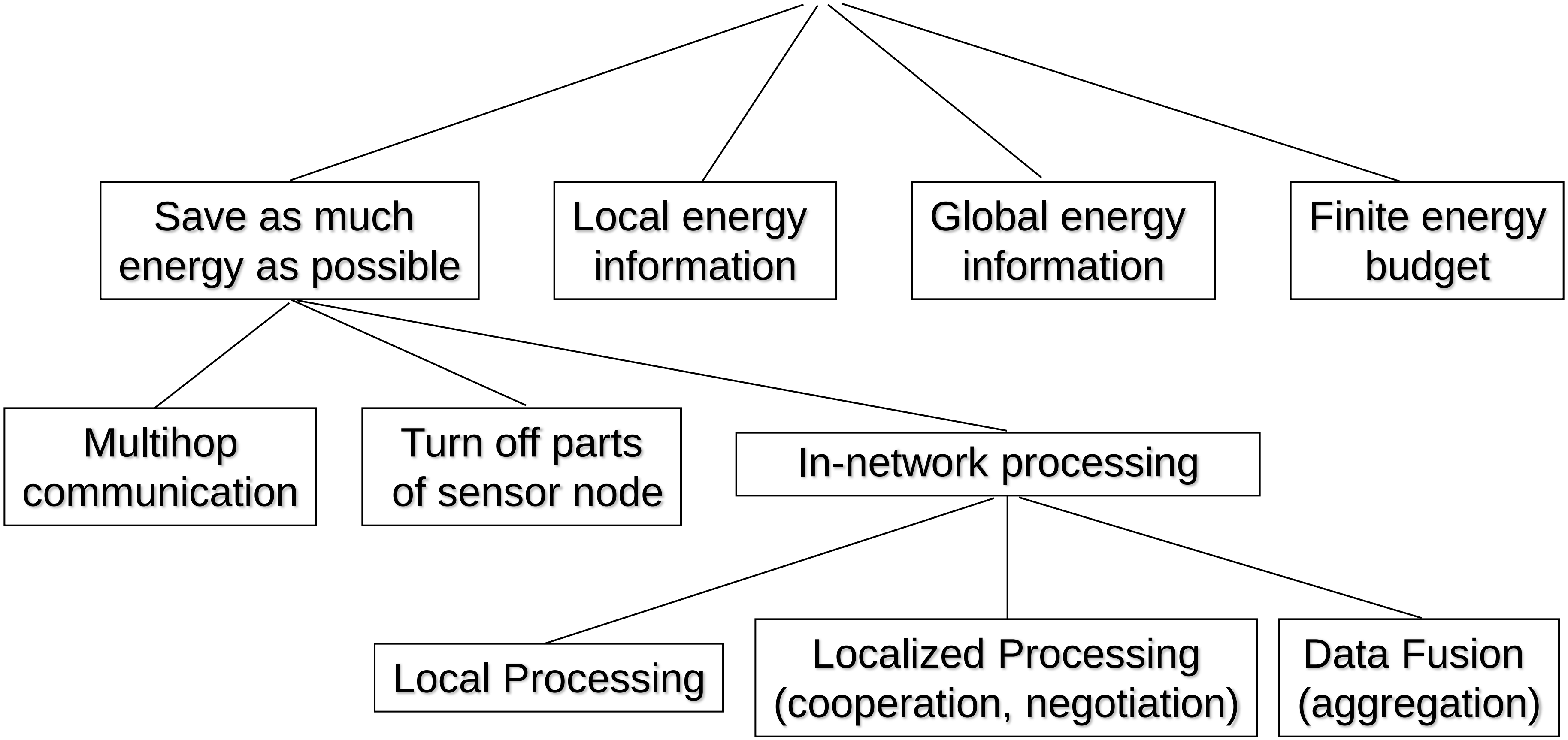
2000 seconds of simulation



Finite Energy Budget: Conclusions

- When we design a network that is very energy restrictive, it would be interesting to determine the energy budget associated with each network activity
- This is a new way of designing solutions for wireless sensor networks
- Finite Energy Budget is a new paradigm for wireless sensor network design

How Are Protocols Dealing with Energy Restriction?



Outline

- Brief overview of wireless sensor networks
- Wireless networking considering energy
- Application design of networked sensor systems considering energy
- Conclusions

Great Duck Island

- Wireless sensor networks applied to real-world habitat monitoring
- Researchers:
  - Alan Mainwaring
    - Computer scientist at the Intel Research Laboratory in Berkeley, California
  - John Anderson
    - Ornithologist at the College of the Atlantic, Bar Harbor

The Project

- Goal:
  - Monitor the Leach's Storm Petrel that is a small and reserved seabird

The Island

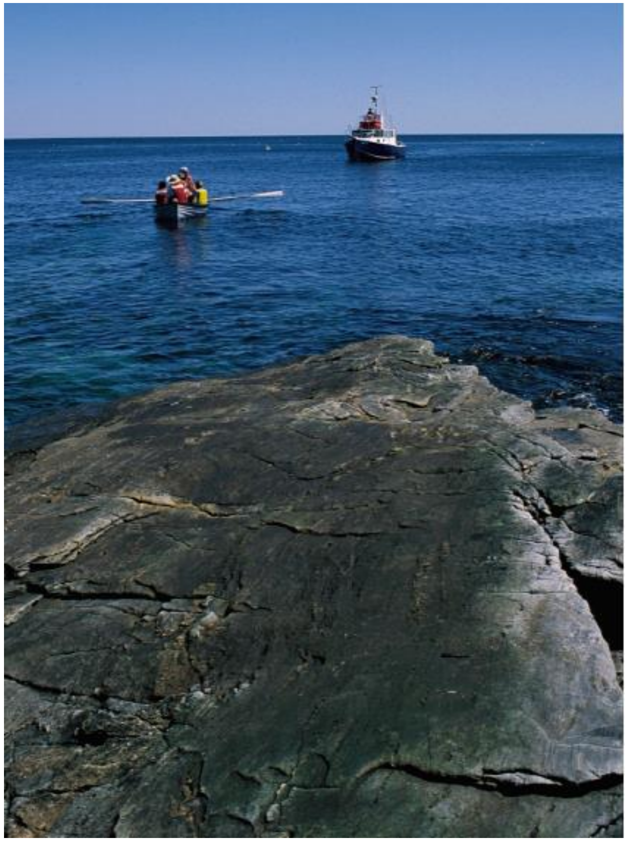
- Desert island sitting 15 kilometers from Bar Harbor, Maine

The Island

- Great Duck Island is located approximately an hour and a half by boat from the northeastern cost of the USA
- 91-hectare island
- No year-round human occupants
- It has a large colony of Leach’s Storm Petrel

The Island

- The access is difficult
- There are lots of rare species
- Controlled visitation



The Petrels

- Have the habit of showing up during bad weather
- Spend much of their lives out on the waters of the South Atlantic, heading north and to shore in the springtime to mate

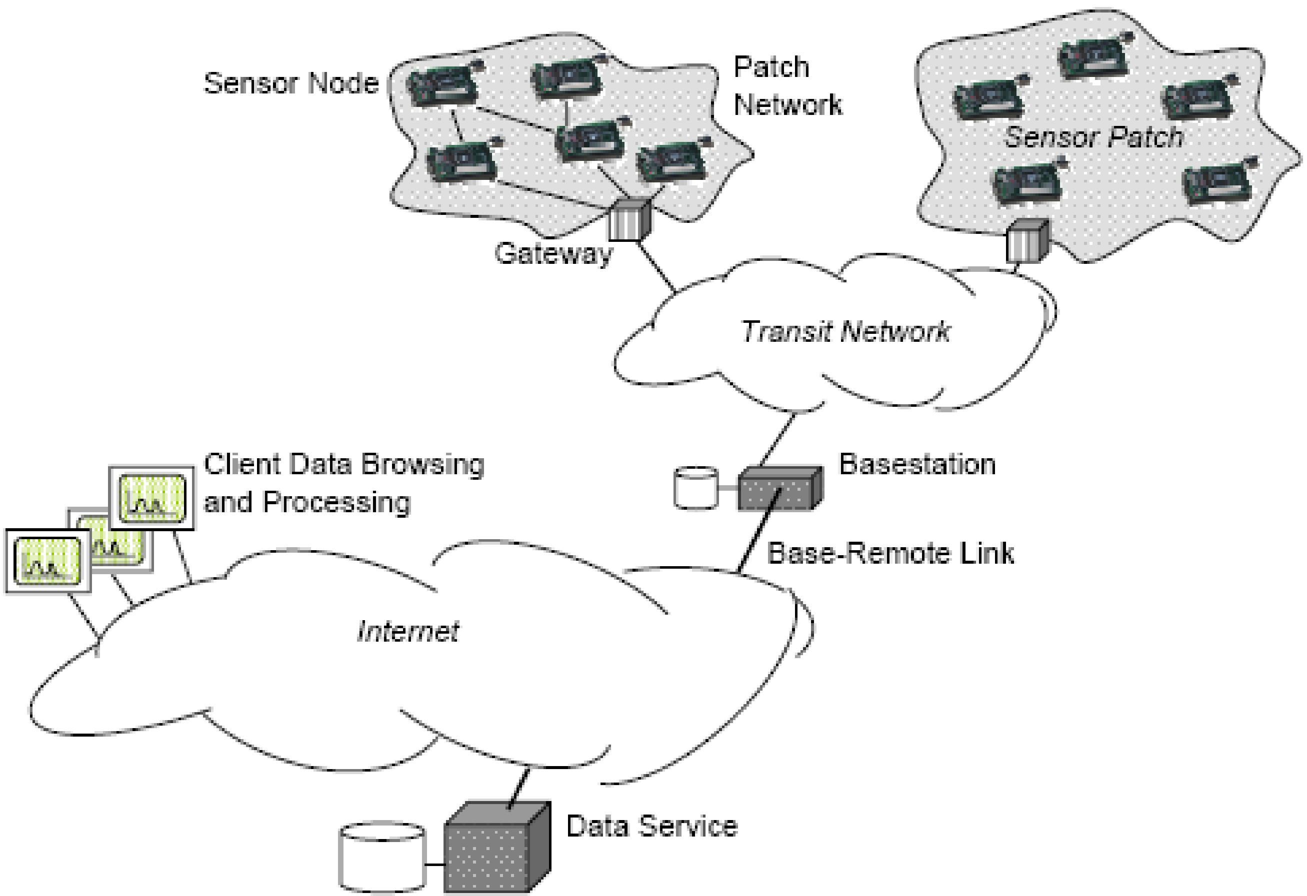
The Petrels

- Once on dry land, the male digs a shallow, narrow burrow
  - 2 to 6 centimeters below ground,
  - 3 to 6 cm across, and
  - 30 cm to 2 meters long
- In the burrow, the female will lay just one egg
- Both parents will occasionally leave the nest to fly back out to deep waters to feed

The Petrels

- Motivation:
  - There’s no good way of looking inside the burrow without causing the creature some distress
  - Some information that is required:
    - How are the conditions down there?
    - How much time do the parents sit on their eggs?
    - Or any of the other things bird scientists want to know…
  - The motes are very helpful because they are small and unobtrusive enough to place inside the burrow

Great Duck Island Architecture



Sensor Nodes

- Distributed system of motes, each having the dual function of data collection and communication
- The motes were built by Crossbow Technology Inc. (www.xbow.com), in San Jose, California

Sensor Nodes

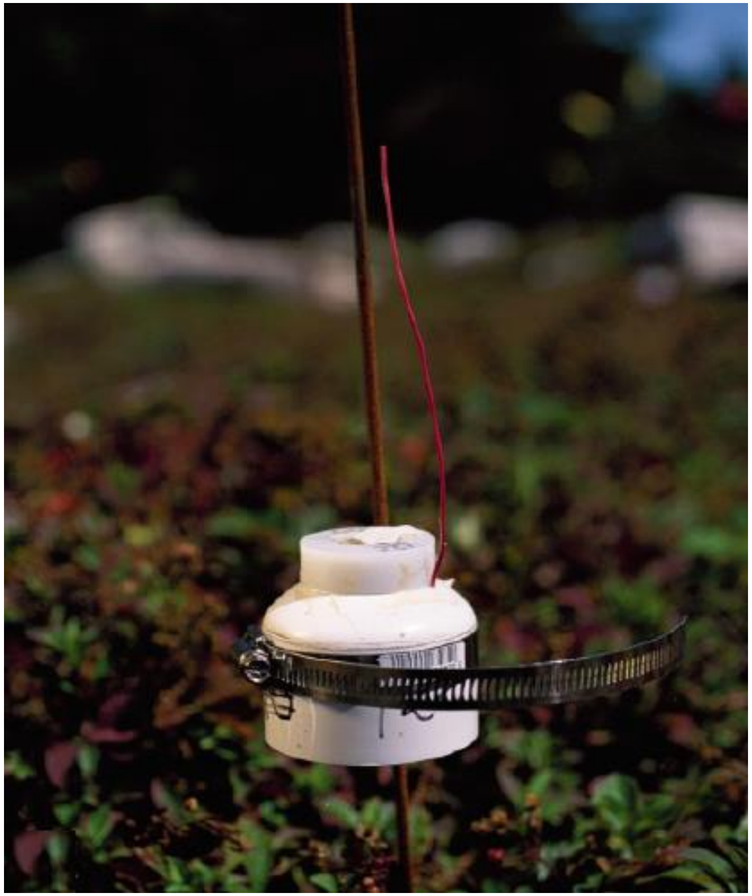
- Initially it was deployed 43 motes running the TinyOS operating system
- The motes have:
  - Microcontroller
  - Low-power radio operating in the unlicensed ISM band
  - Flash and RAM memory
  - Two AA batteries
  - Sensors for temperature, humidity, pressure, ambient light and infrared radiation

Sensor Nodes

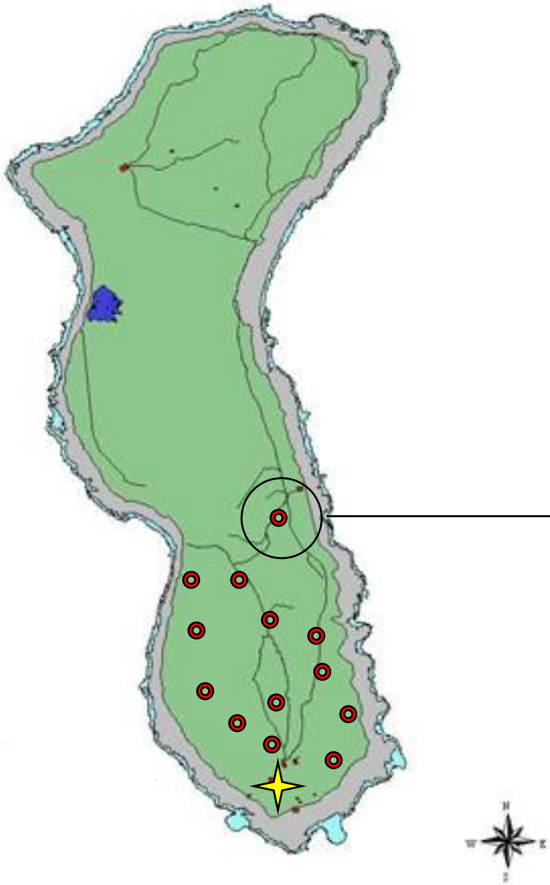
- Some of the motes were buried in the walls of burrows

Sensor Nodes

- Other motes for measuring the weather were placed just outside

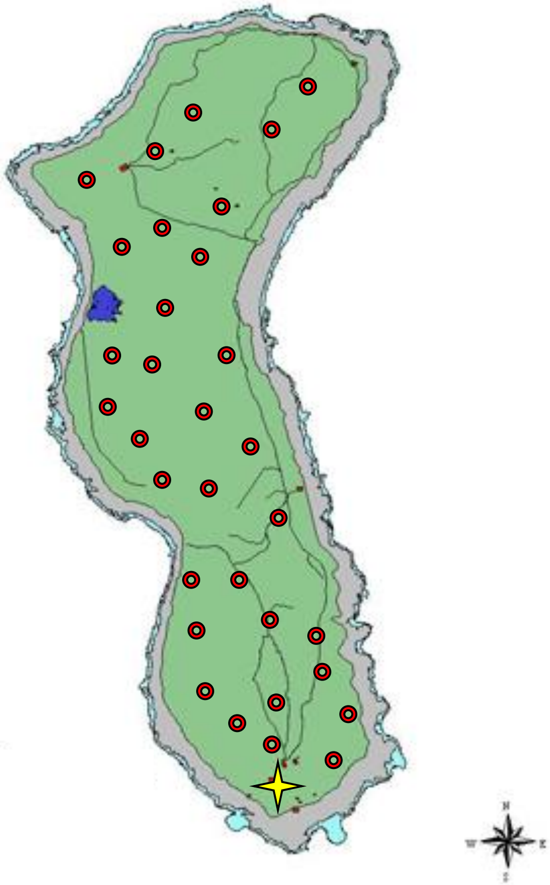


Great Duck Island



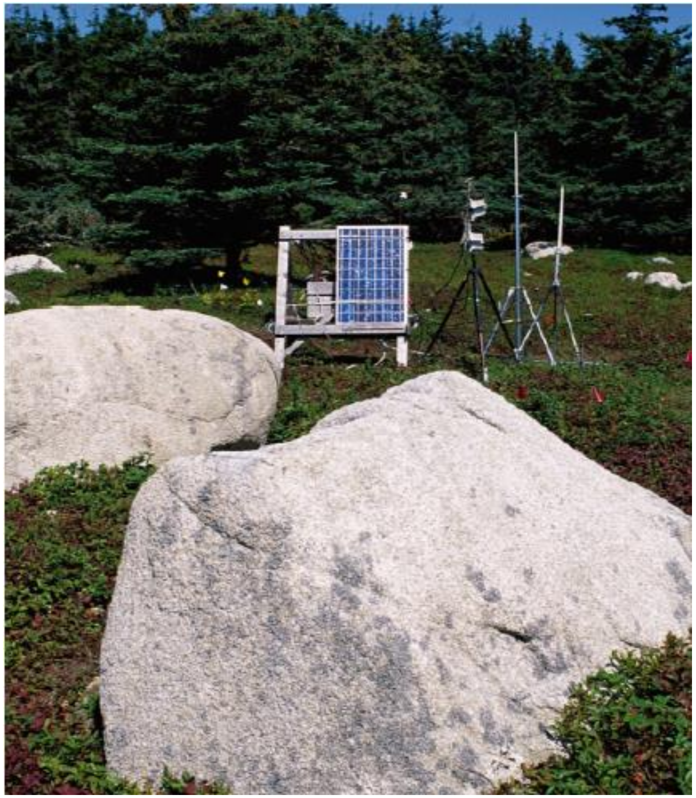
Sensor Nodes

Great Duck Island



Sensor Nodes

- Every 70 seconds, each mote samples its sensors
- The readings are transmitted in a single 36 byte data packet to the gateway mote



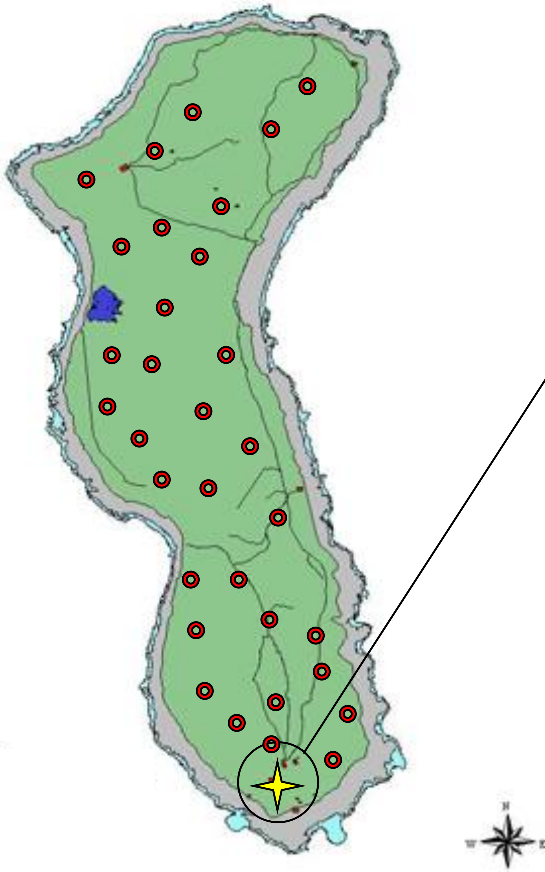
Sensor Nodes

- Data readings are time-stamped with 32-bit sequence numbers and kept in flash memory
- After successfully transmitting the packet of data, the motes entered their lowest power state for the next 70 seconds
- The motes are transmit-only devices
- The expected duty cycle of the application is 1.7%

Sink Node

- Gateway mote relays the data to a solar-powered computer base station located in a small, 114–year–old light-house
- Gateway node ran at a 100% duty cycle and it is powered by a solar cell and rechargeable battery

Sink Node

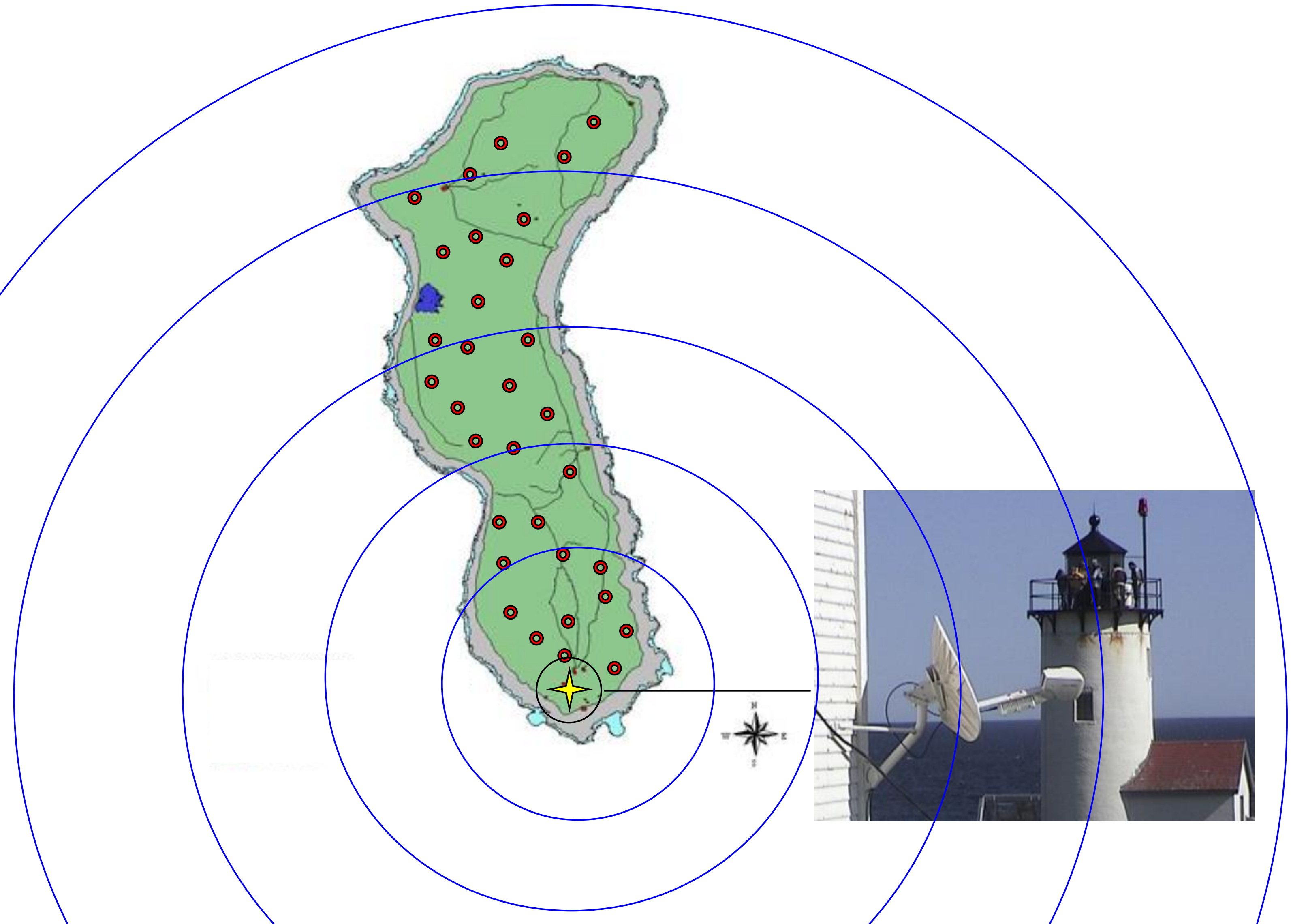


Sink Node

Sink Node

- From the computer base station, data travels by satellite over the Internet to the Intel Research Laboratory in Berkeley, California
- The researchers in California can access the mote data in real time

Sink Node



Experimental Results

- After 123 days of the experiment, it was logged over 1.1 million readings
- Some results:
  - Comparing the readings from a pair of motes, one inside the burrow and one outside, reveals that even when the external temperature changes by 25 °C, the difference inside is less than 2 °C
  - The humidity outside can vary by 80 percent, but in the burrow's interior the change is just half a percent

Experimental Results

- Desired information:
  - Establish the specific sensor readings that correspond to specific states:
    - petrel in burrow
    - egg unattended
    - adult with chick
    - …
  - For how long do the petrels leave their egg unattended?
  - What happens to the egg while the petrels are gone?
  - What kind of environment can the egg withstand?
  - Why do the petrels prefer Great Duck Island instead of similar islands?
  - Why do the petrels nest in only a few select areas on the island?
  - …

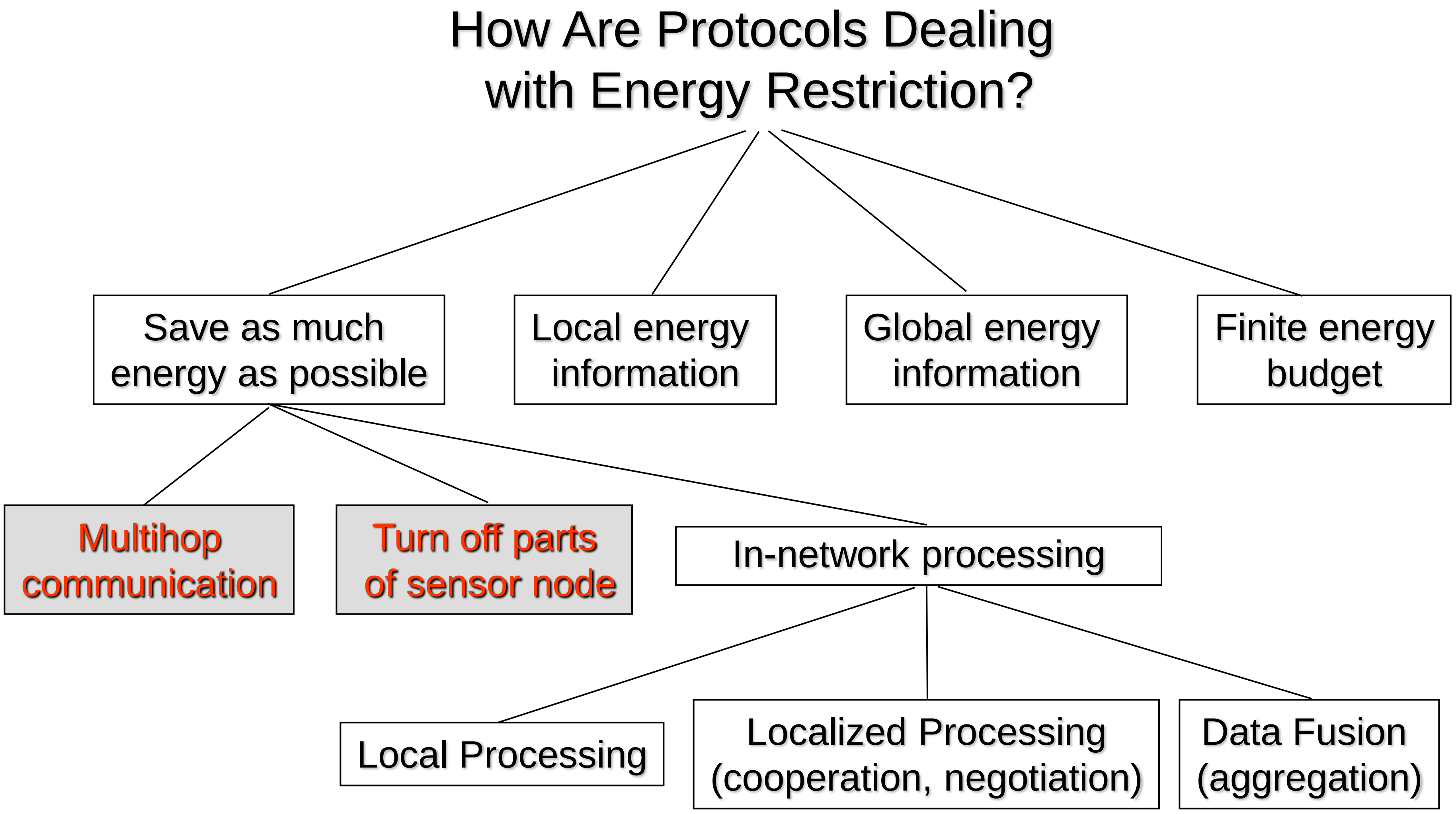
Great Duck Island

- The first project
  - 43 motes
  - Single-hop communication
  - Continuous data delivery model

Great Duck Island

- The second project
  - 190 motes
    - Two-thirds smaller than the predecessors
    - 4 KB of RAM
    - 128 KB of internal flash
    - 512 KB of external flash
  - Multihop communication
  - The operating mode is to spend 99 percent of their time asleep, waking up only to send messages and to listen for signals from other motes
    - Average power consumption 50 μW
    - If CPU, radio and sensors are on, the mote will draw 50 to 100 mW

Great Duck Island



Outline

- Brief overview of wireless sensor networks
- Energy sources for wireless sensor networks
- Sensor node technology from the point of view of energy
- Wireless networking considering energy
- Application design of networked sensor systems considering energy
- Conclusions

Conclusions

- WSN design has many dimensions to consider
  - Energy: should be present in all of them
- Energy-aware techniques are not completely used by real-world applications
- Current capabilities of sensor networks are still underused
- But the future is extremely promising
  - Science: many open research problems
  - Technology: many “engineering” problems to overcome
  - Applications: lots of them