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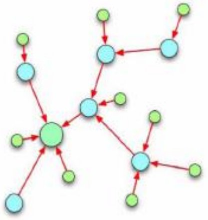

Wireless Sensor and Actuator Networks:

Technologies, Analysis and Design

Communication Protocols for WSANs

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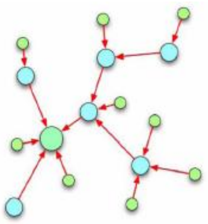
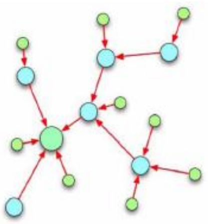
http://www.robertoverdone.org



Outline

1. **Energy Efficiency**
2. **MAC: Basics**
3. **Routing: Basics**



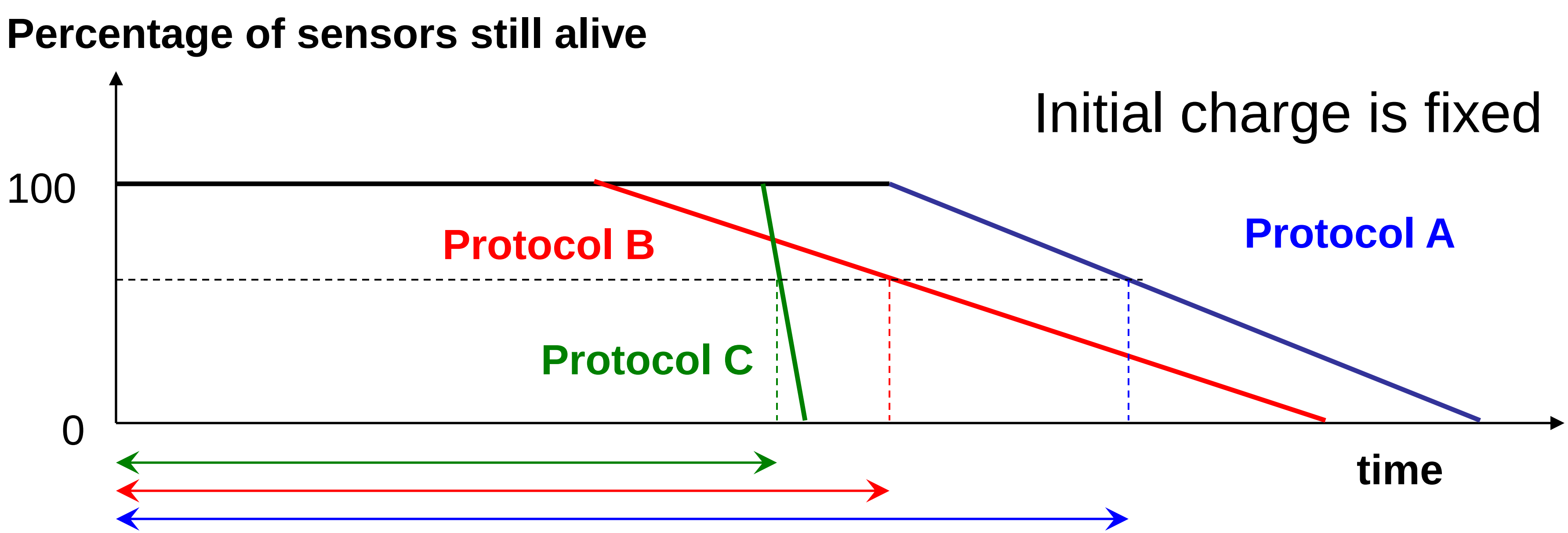
Section 1
Energy Efficiency

Network Lifetime
LEACH
Relation Between Connectivity and Network Lifetime
Simulations
Communication Protocols and Energy Efficiency

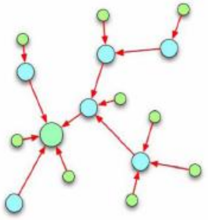
Network Lifetime

Network Lifetime Definition 1

Network lifetime can be defined as the interval of time (possibly measured in *rounds*), started with the first transmission in the wireless network,
ending when the percentage of nodes that have not terminated their residual energy falls below a specific threshold, which is set according to the type of application
(it can be either 100% or less).



One protocol does not fit all.

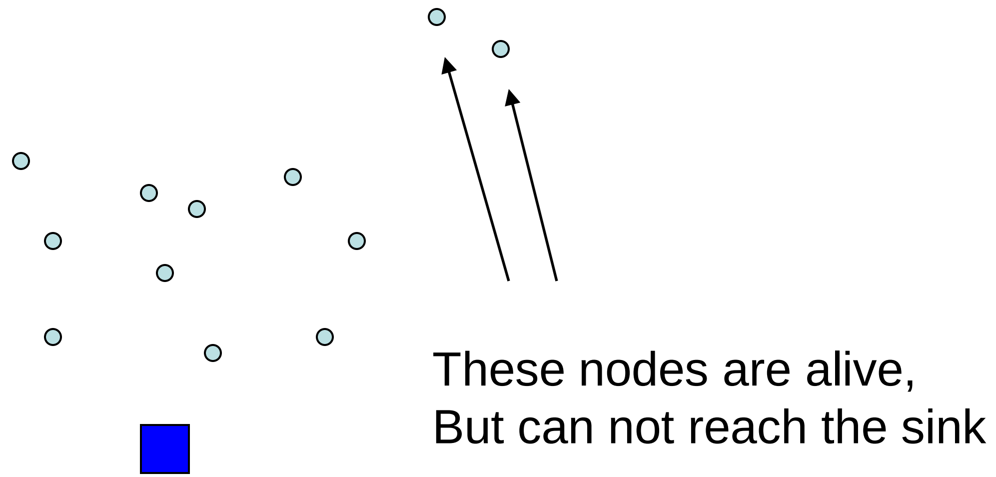


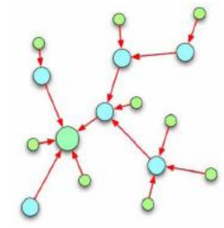
Network Lifetime

Network Lifetime Definition 2

Network lifetime can be defined as the interval of time (possibly measured in *rounds*), started with the first transmission in the wireless network, ending when the percentage of nodes **still reachable** in the network falls below a specific threshold, which is set according to the type of application (it can be either 100% or less).

This definition also considers connectivity issues



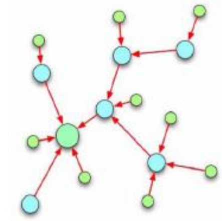


Network Lifetime

Network Lifetime Definition 3

Network lifetime can be defined as the interval of time (possibly measured in *rounds*), started with the first transmission in the wireless network,
ending when the percentage of **reports from nodes**, averaged over a time window, falls below a specific threshold, which is set according to the type of application
(it can be either 100% or less).

This definition also considers QoS issues.



Network Lifetime

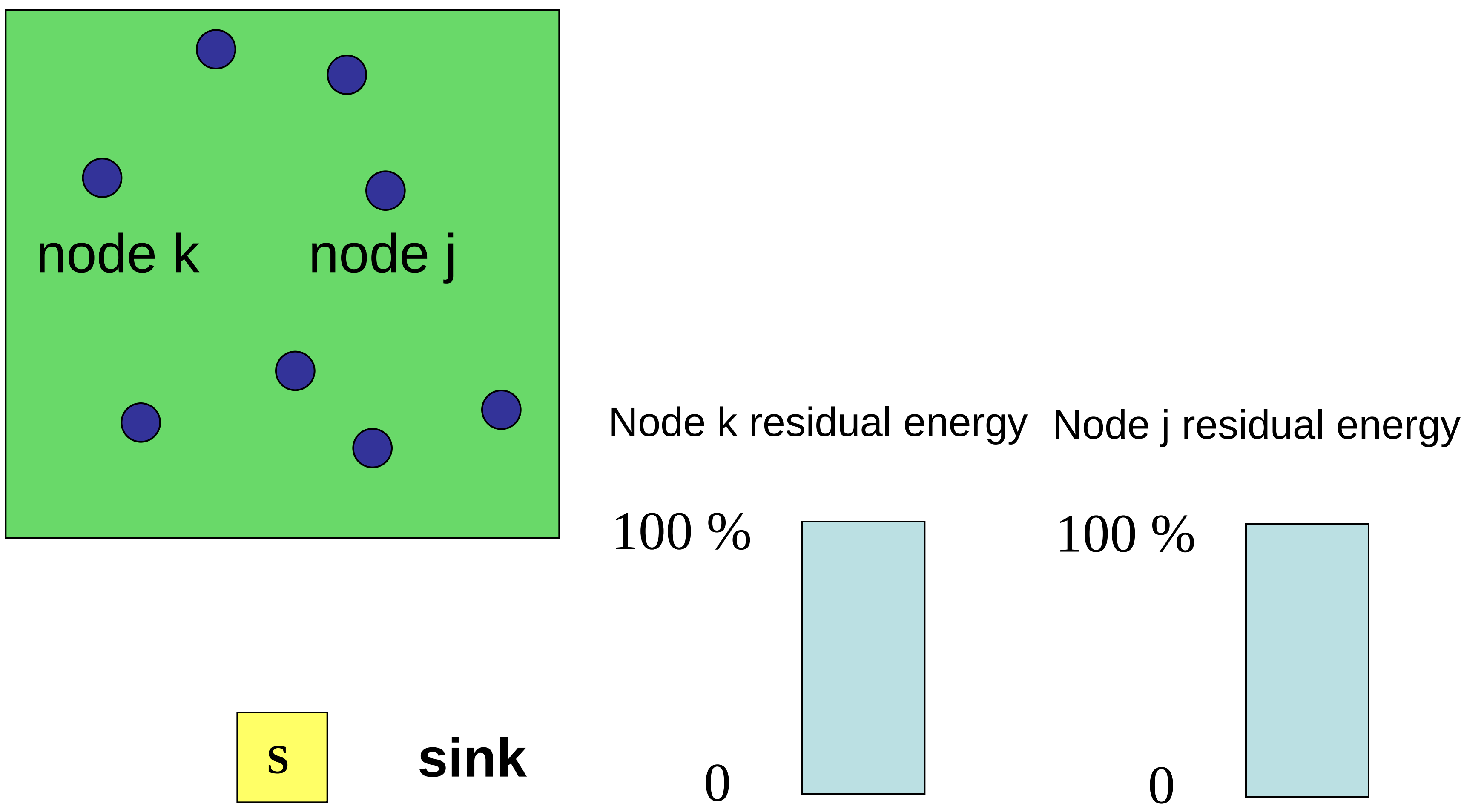
Network Lifetime Definition 4

Network lifetime can be defined as the interval of time (possibly measured in *rounds*), started with the first transmission in the wireless network, ending when the **spatial random process estimation error** falls below a specific threshold, which is set according to the type of application.

This definition also considers QoS issues.

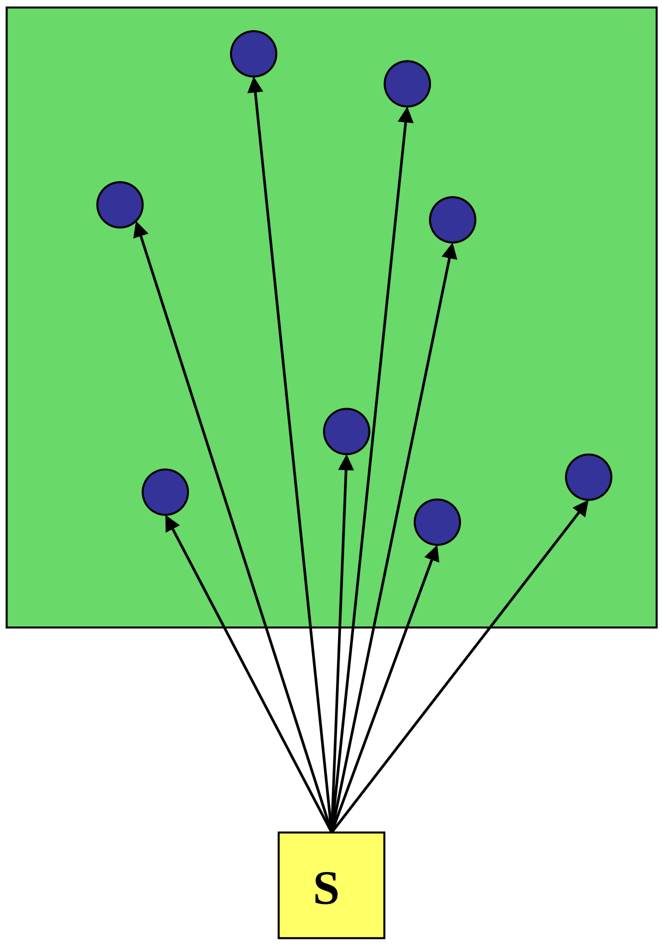
$$\varepsilon = p^2 + (1-p)\beta\zeta/\rho$$

Example of Communication Protocol: LEACH *

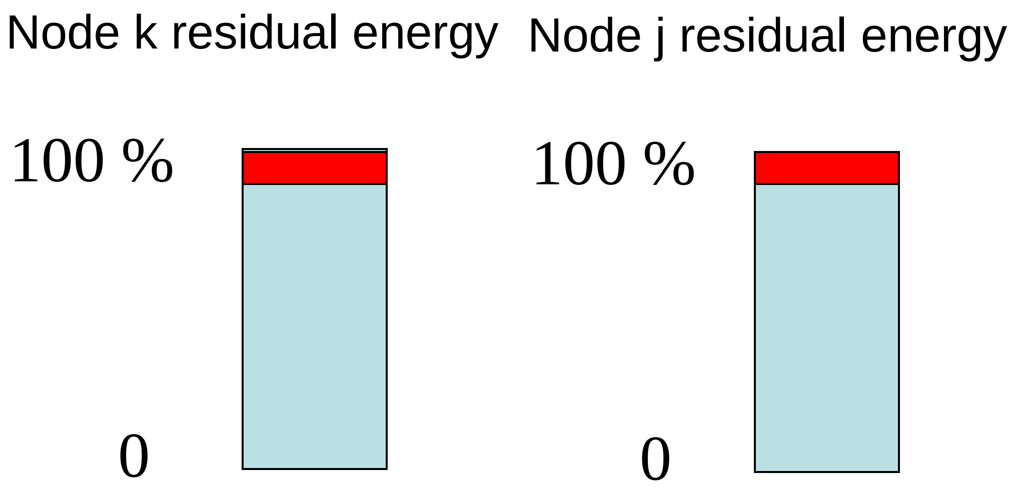


* C.S. Raghavendra et alii, “*Wireless Sensor Networks*”, Kluwer, 2004

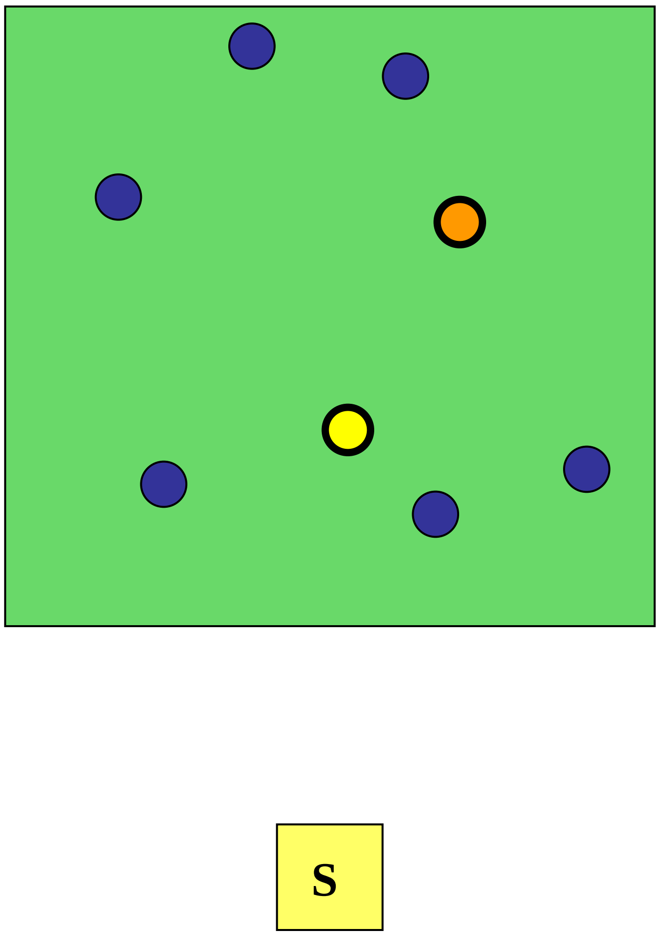
Example of Communication Protocol: LEACH



START packet

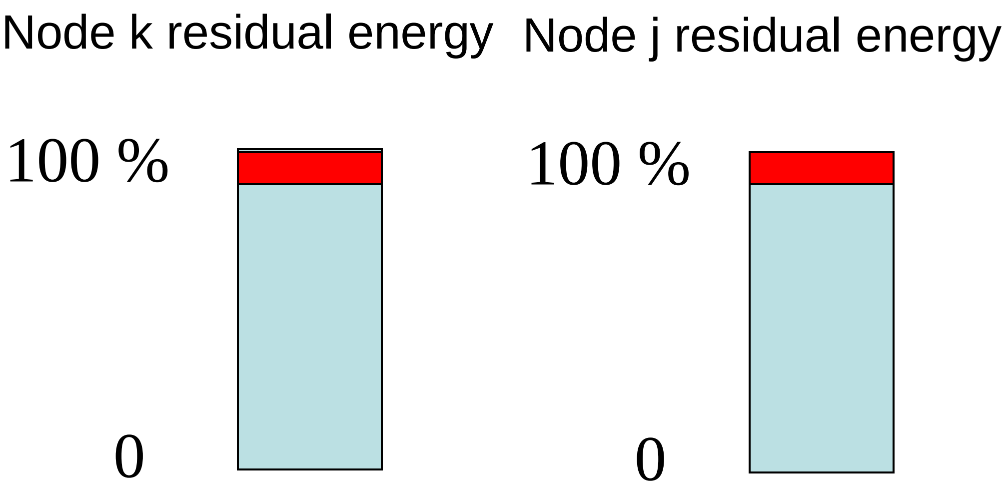


Example of Communication Protocol: LEACH

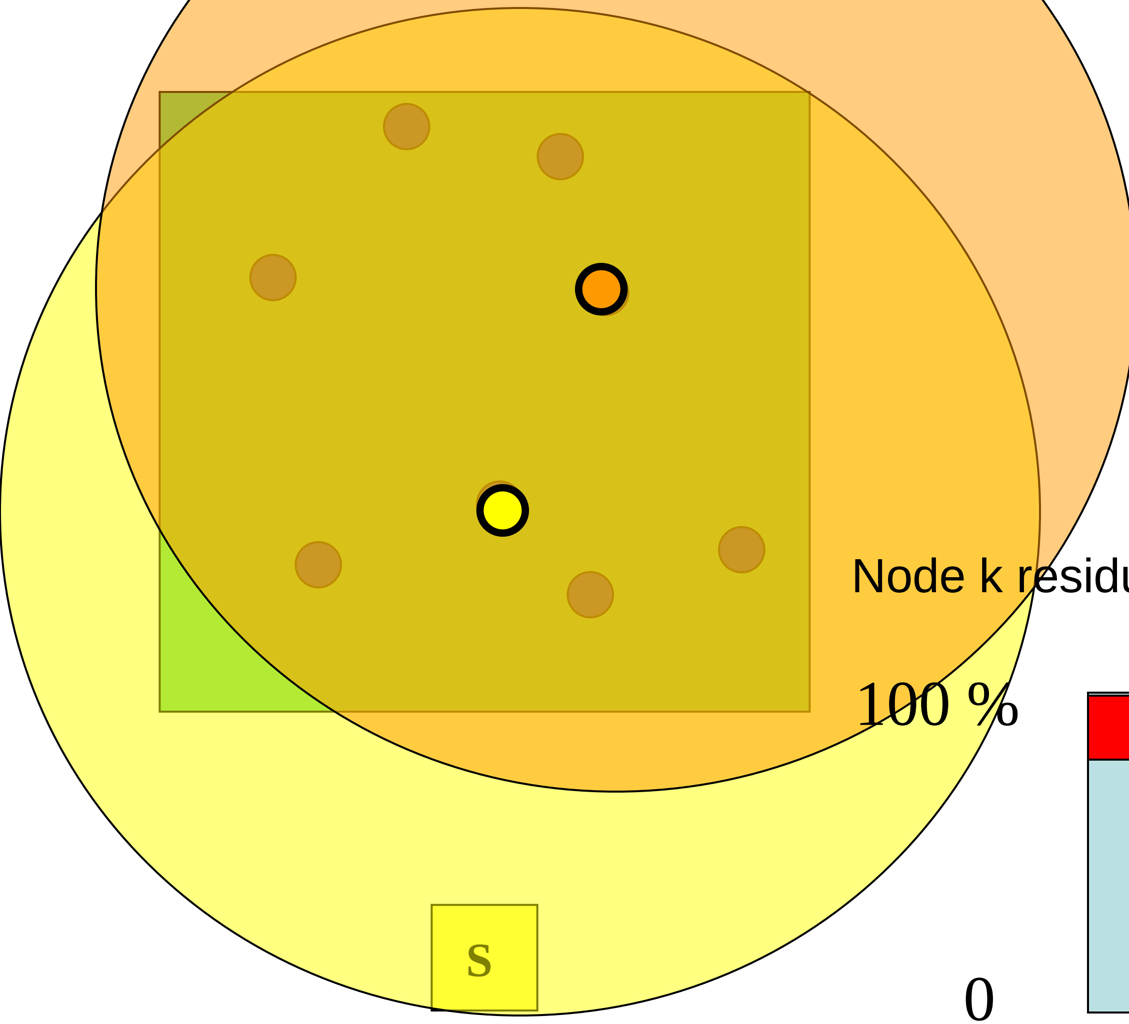


Cluster Head self-election

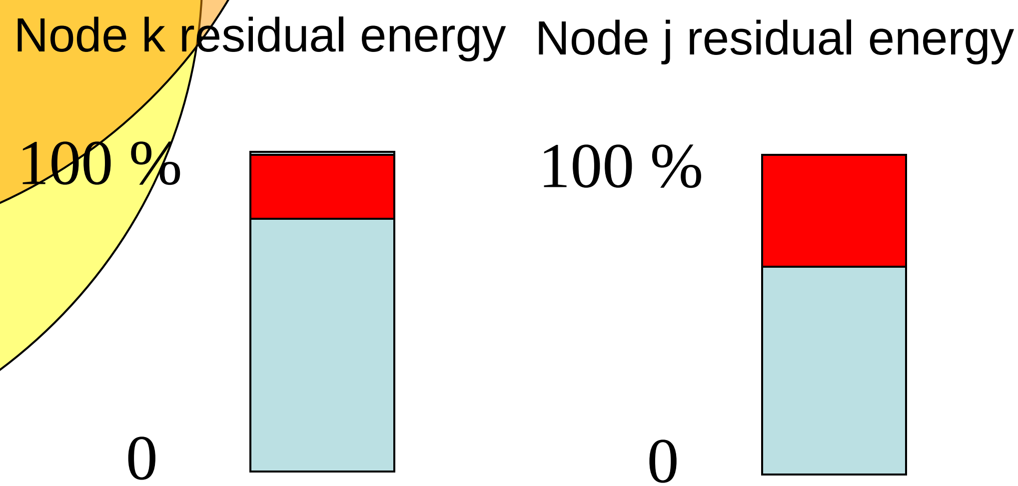
- Uncoordinated
- Based on residual energy



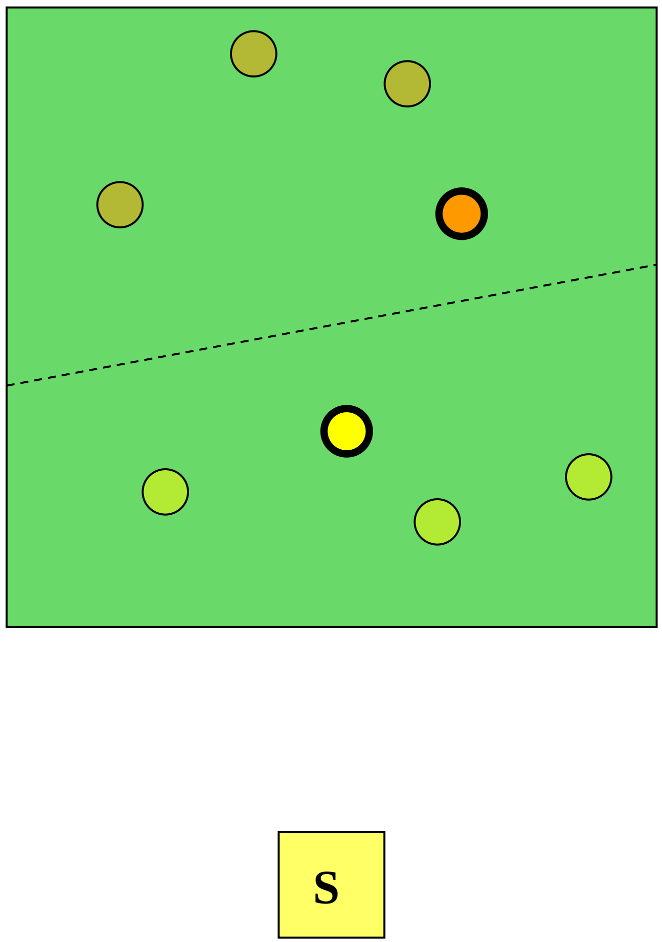
Example of Communication Protocol: LEACH



Broadcast packet(s)

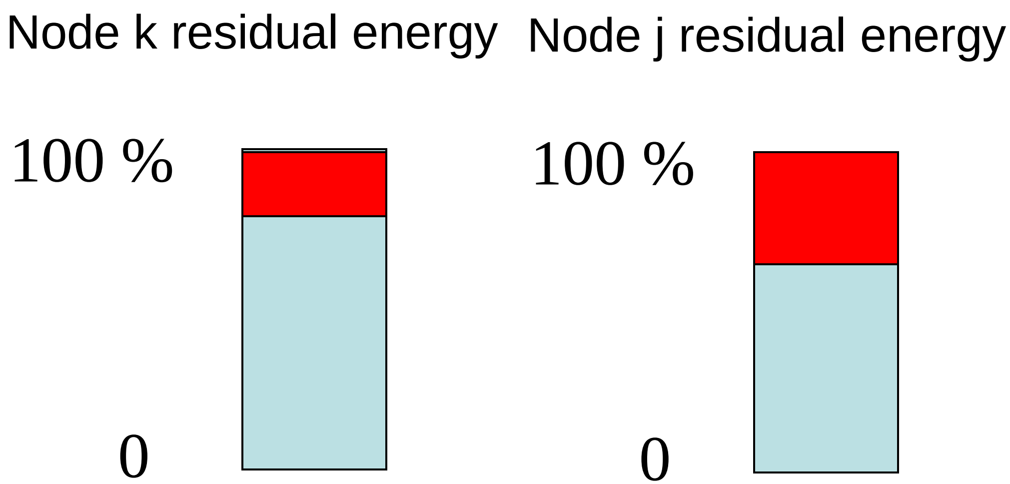


Example of Communication Protocol: LEACH B *



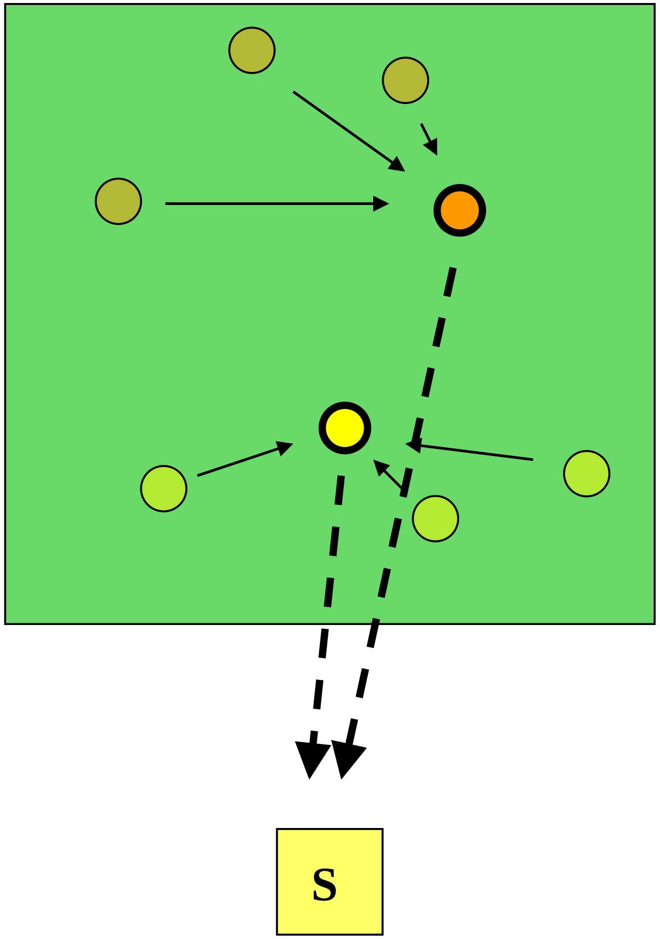
Cluster formation

- Uncoordinated
- Minimum <u>TOTAL</u> Loss



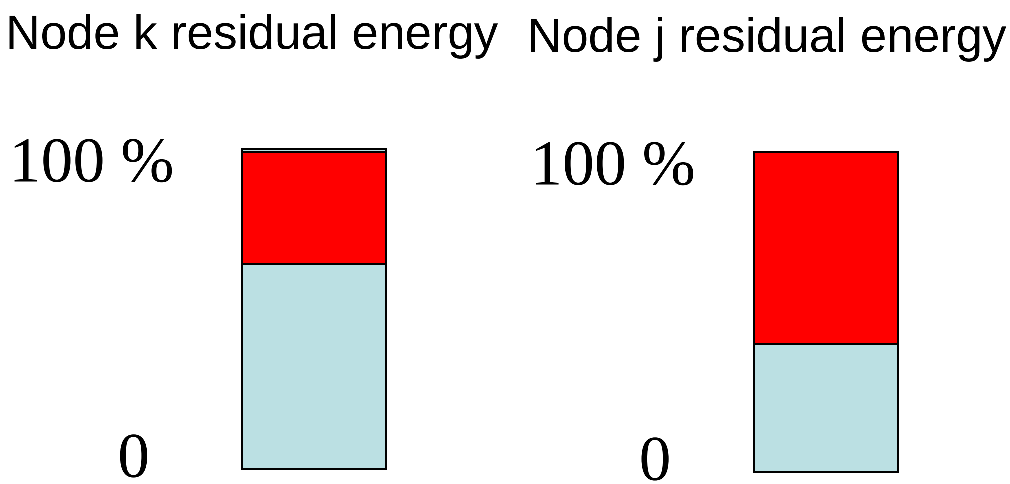
* De Pedri, Zanella, Verdone, IEEE AINS 2003.

Example of Communication Protocol: LEACH B

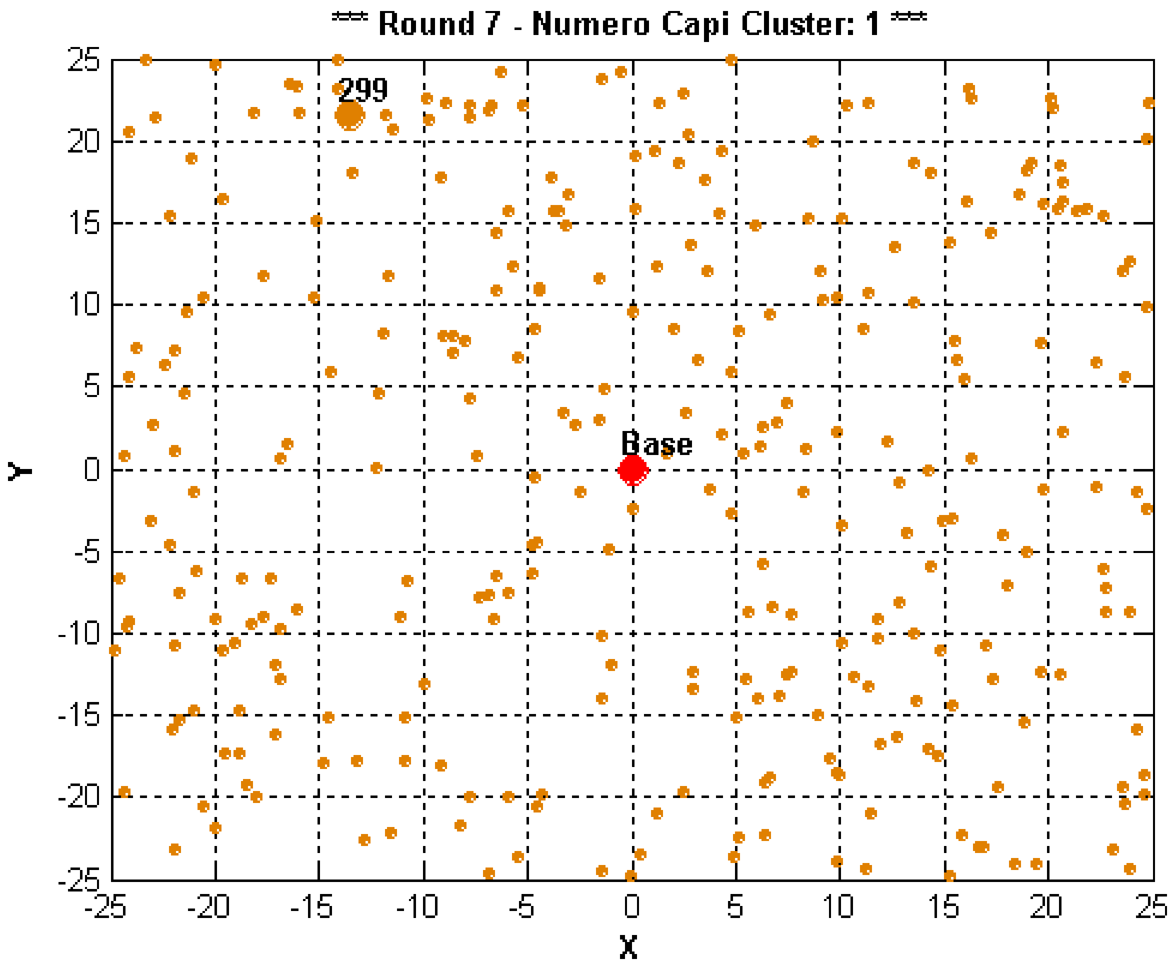


Data transmission

- Two hops



Example of Communication Protocol: LEACH

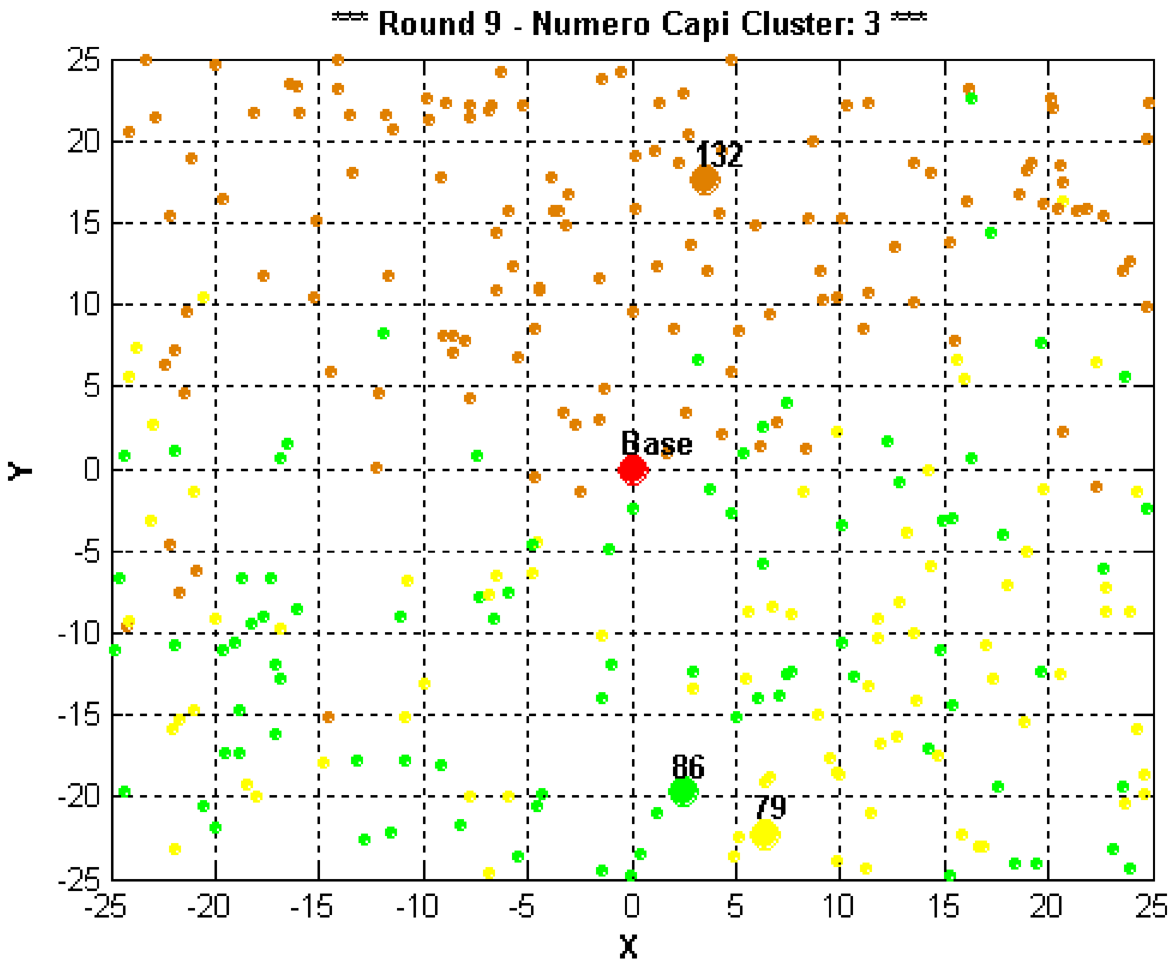


300 nodes

$P_{CH} = 0.01$

$\sigma = 5$

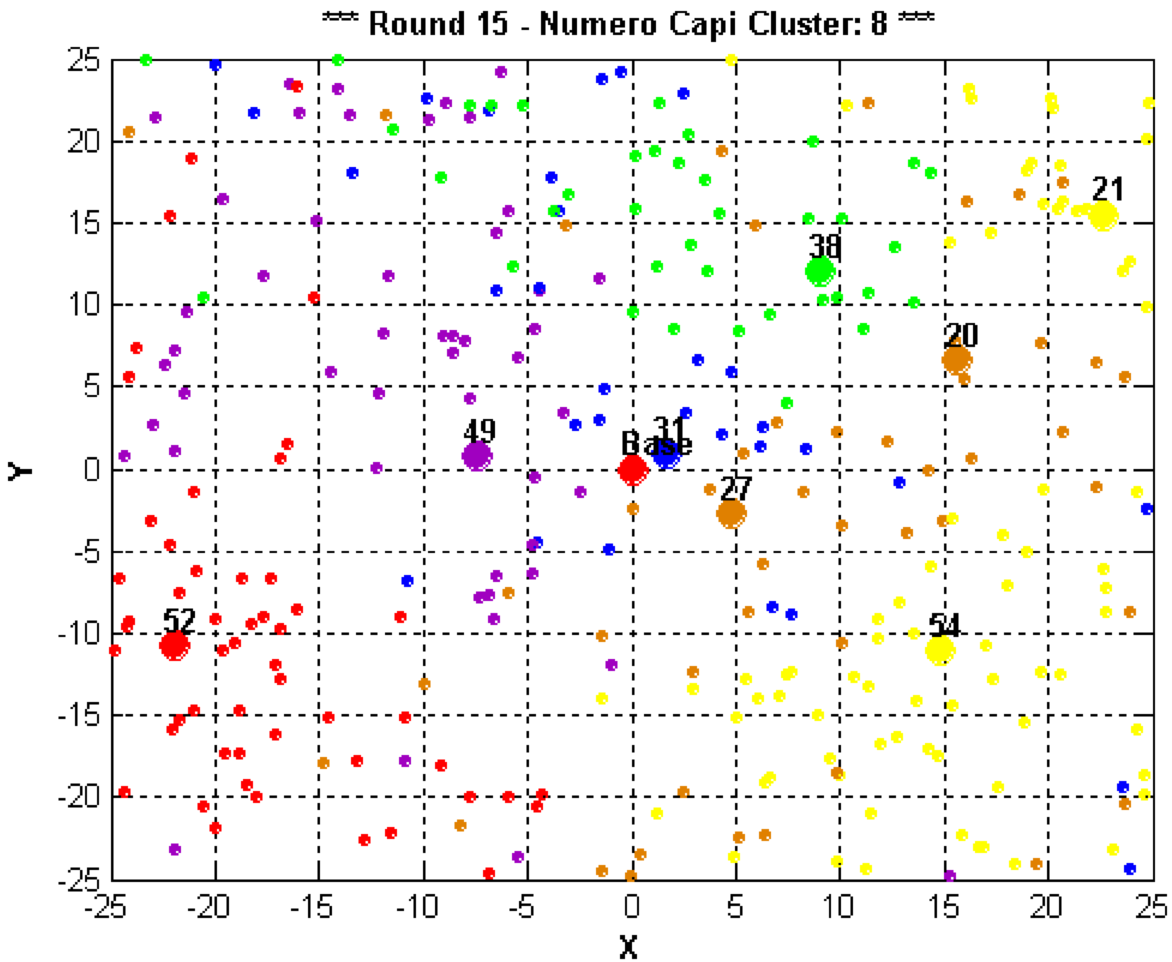
Example of Communication Protocol: LEACH



300 nodes
$P_{CH} = 0.01$

$\sigma = 5$

Example of Communication Protocol: LEACH



300 nodes
$P_{CH} = 0.01$

$\sigma = 5$

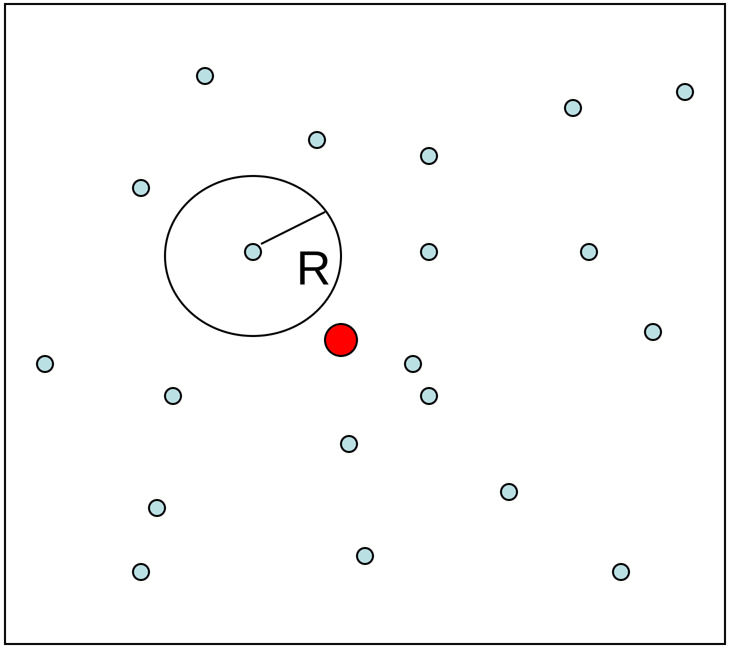
Summing-Up

Clusters are a simple way to organise a WSN.

Being cluster-head is very energy consuming.
The role of cluster-head must be rotated very often.
The network topology is thus very dynamic.
Packet loss rate has large variance.

Simulation Examples / 1

L = 50 m

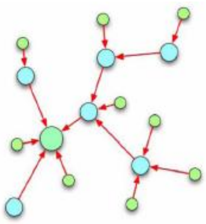


Initial charge: 1 Joule

IEEE802.15.4 MAC
LEACH

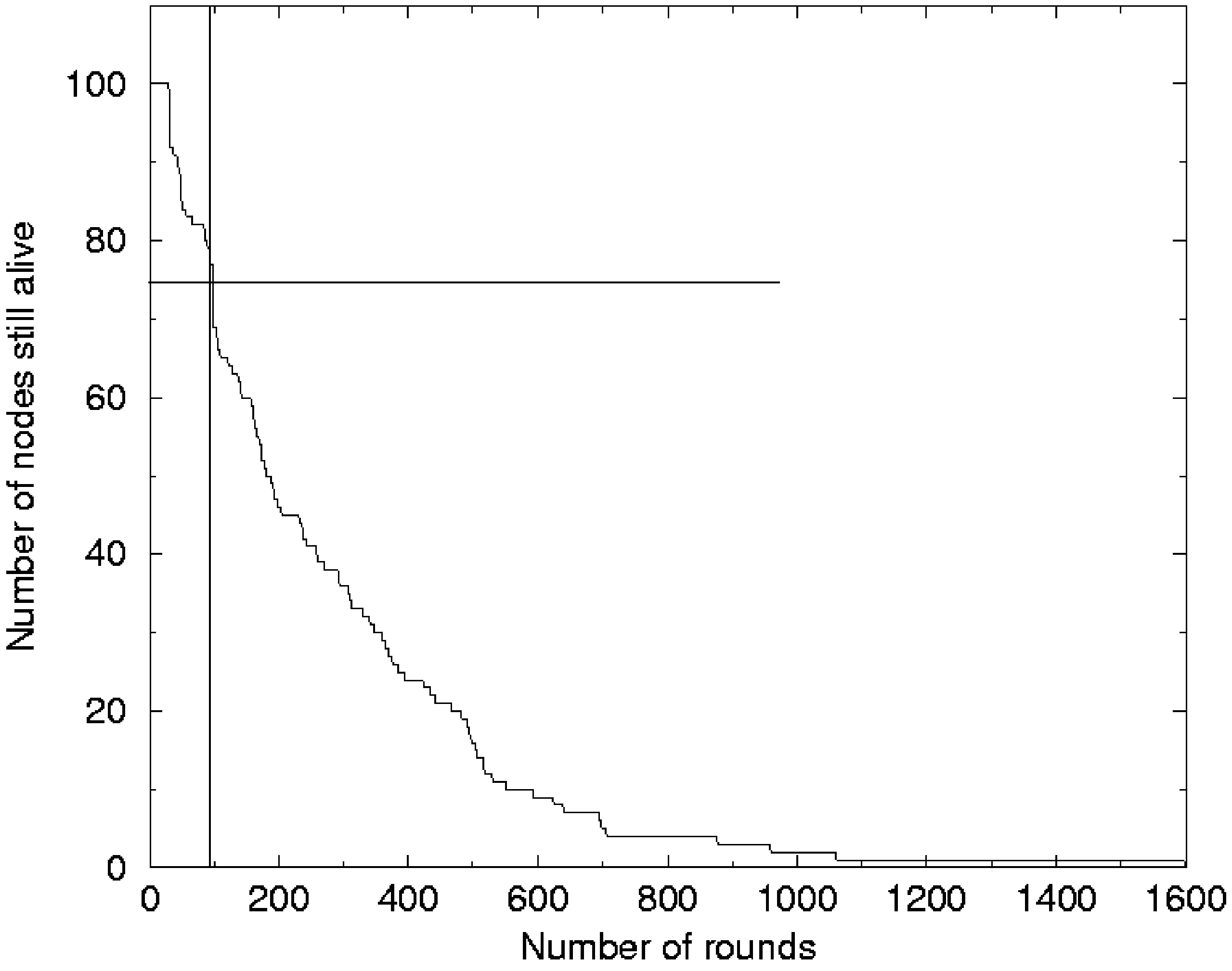
R = Ideal transmission range approx 54 m
$\sigma = 3.5$

n = 100 nodes



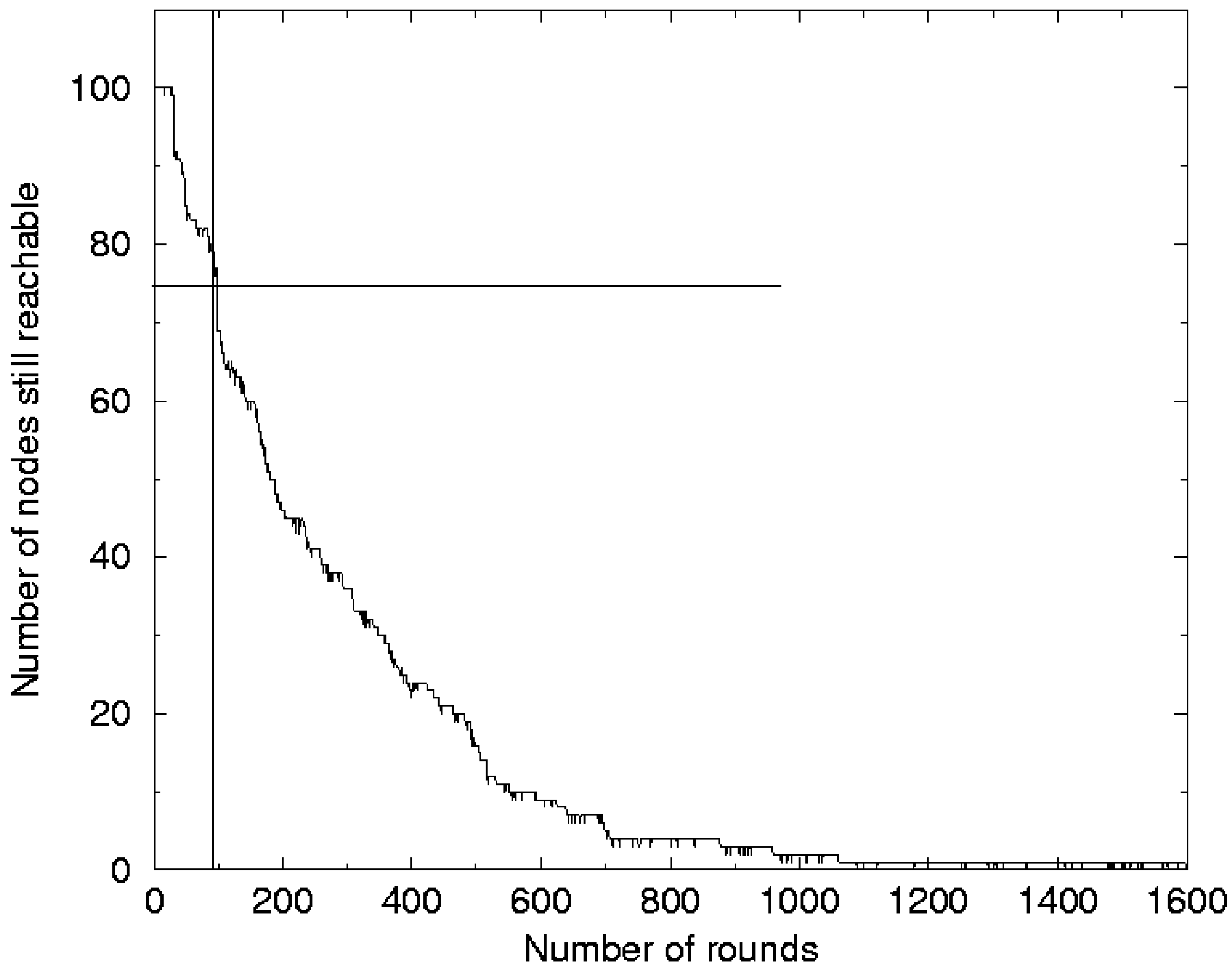
Simulation Examples / 1

Network Lifetime Definition 1



Simulation Examples / 1

Network Lifetime Definition 2



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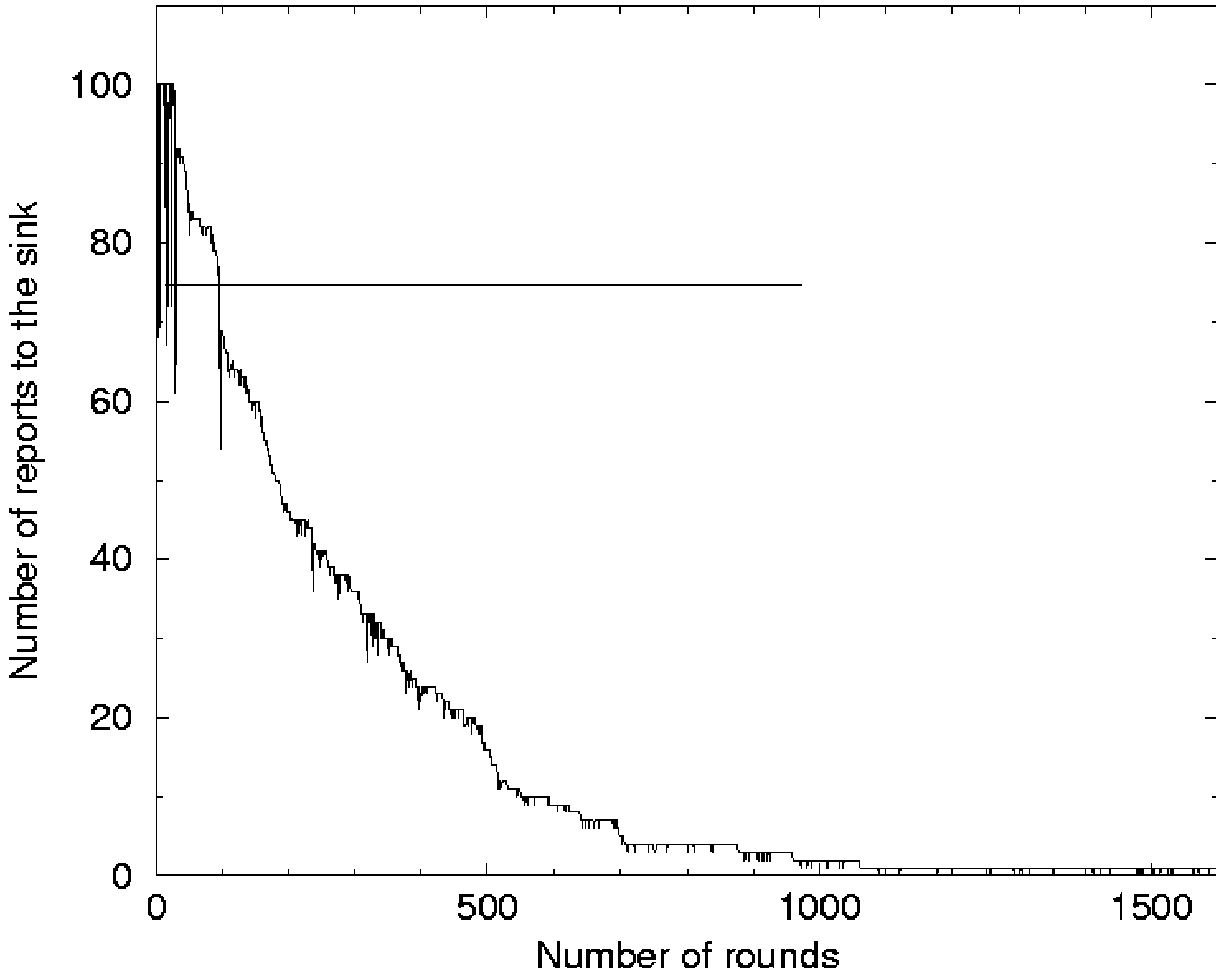
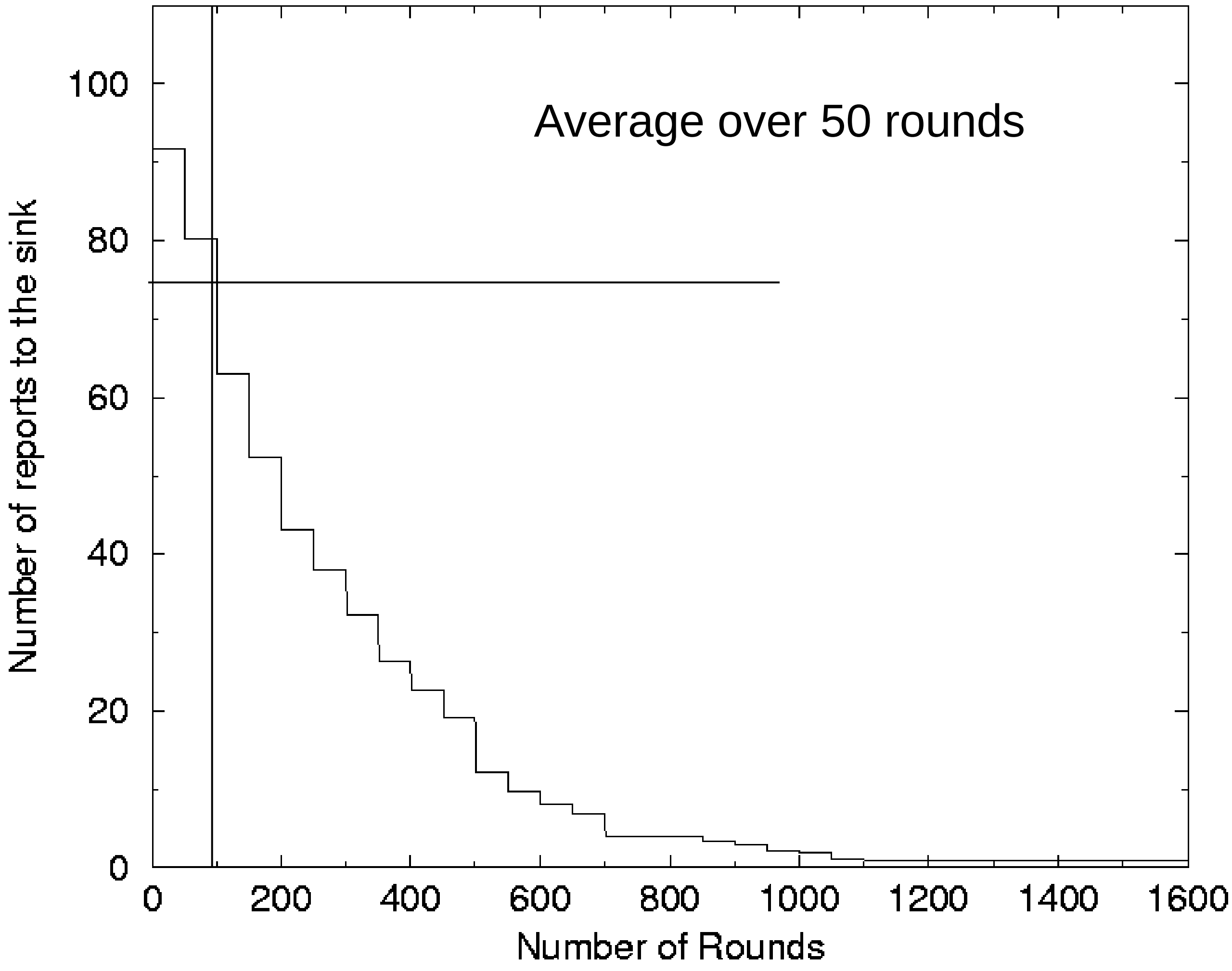
Simulation Examples / 1

Network Lifetime Definition 3



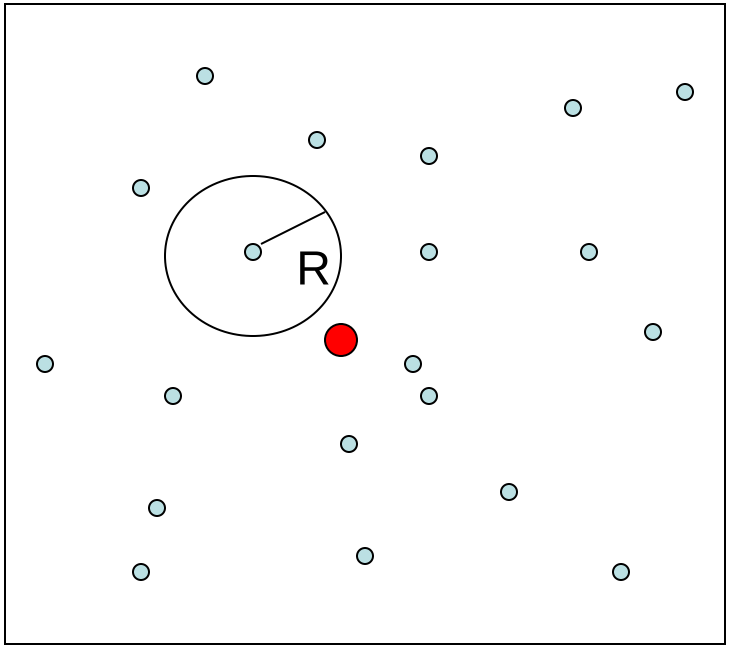
Simulation Examples / 1

Network Lifetime Definition 3



Simulation Examples / 2

L = 50 m



Initial charge: 1 Joule

IEEE802.15.4 MAC
LEACH

R = Ideal transmission range approx 54 m
σ = 3.5

n = 500 nodes

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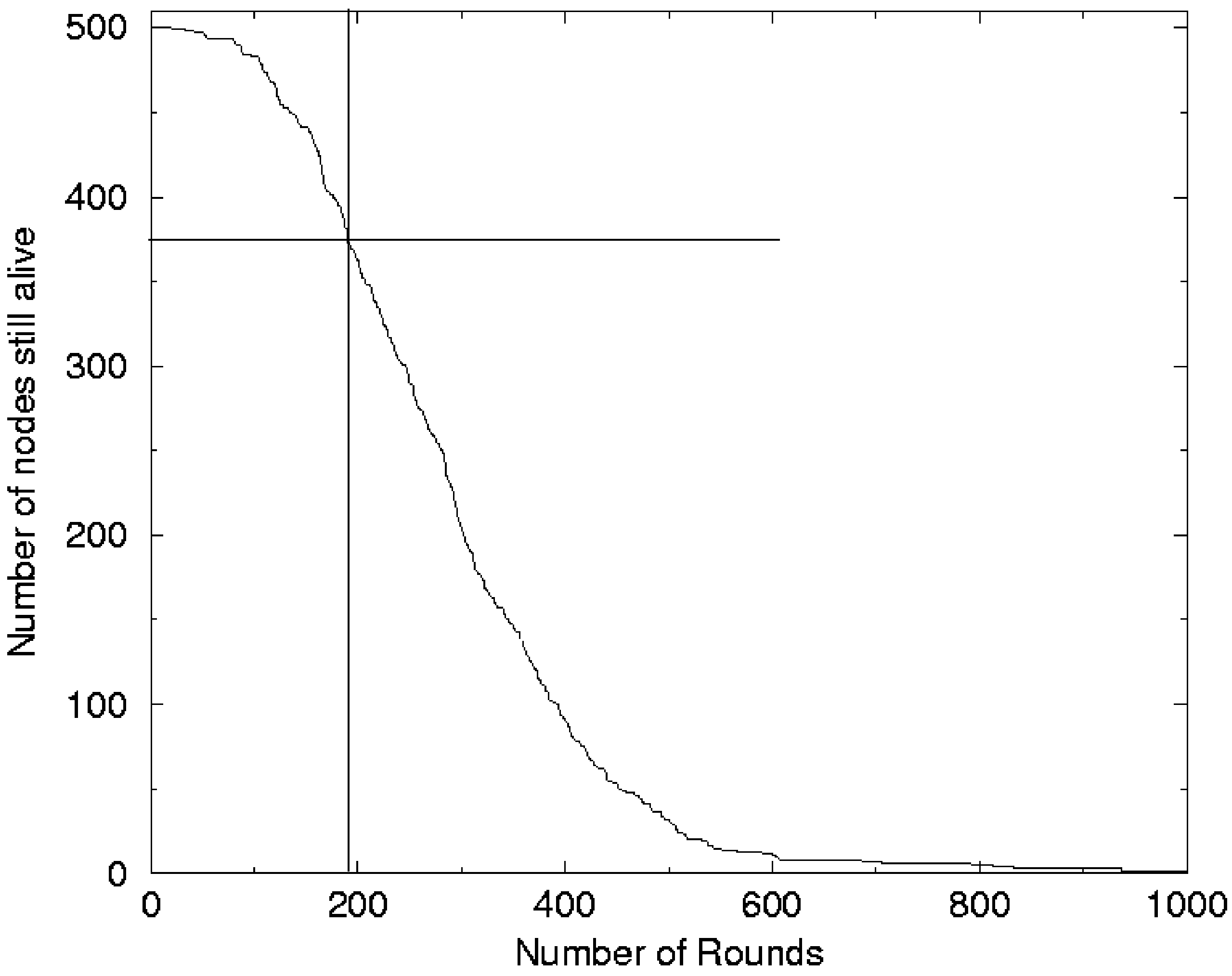
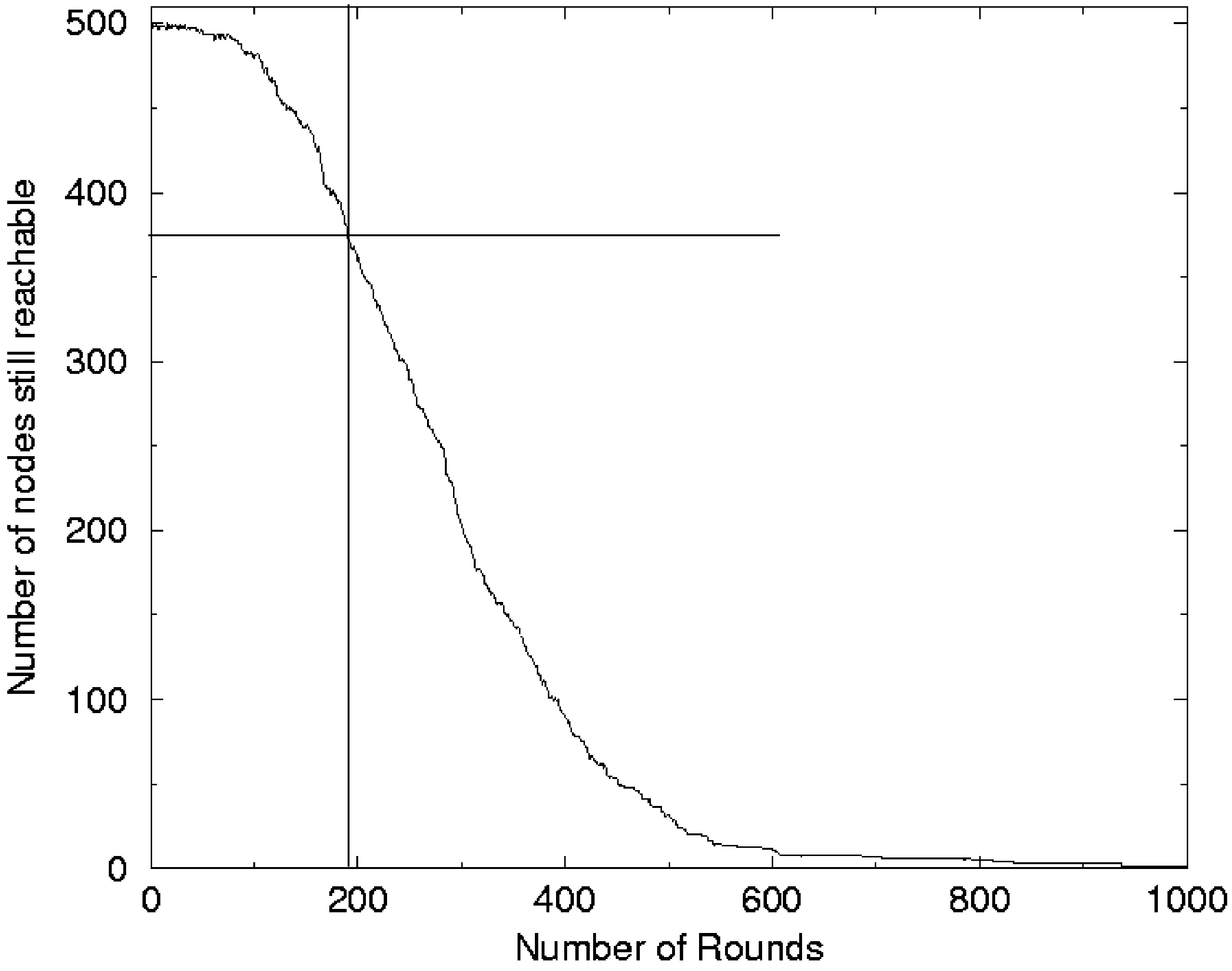
Simulation Examples / 2

Network Lifetime Definition 1



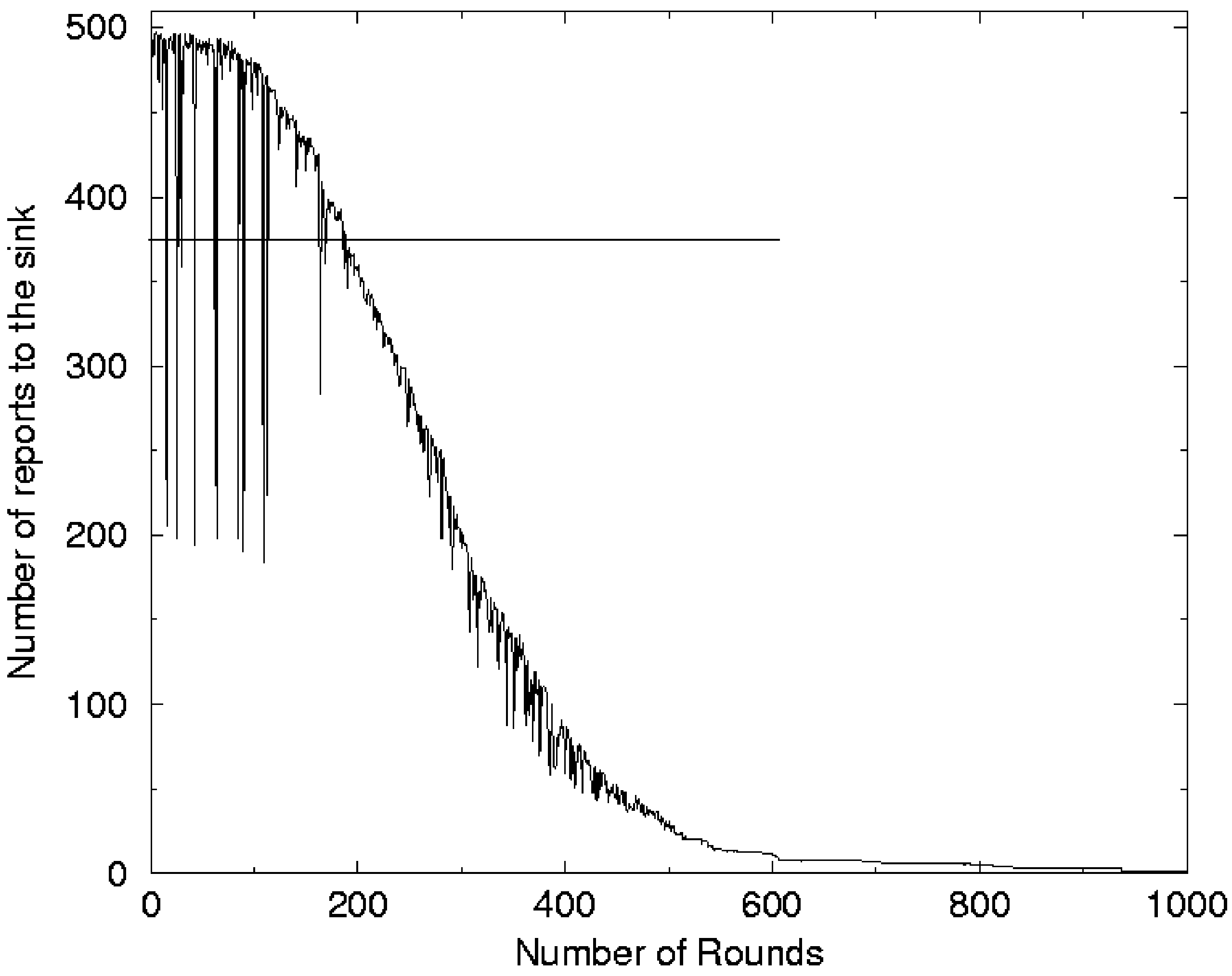
Simulation Examples / 2

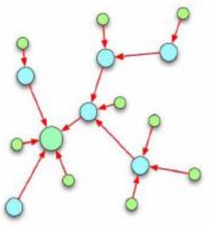
Network Lifetime Definition 2



Simulation Examples / 2

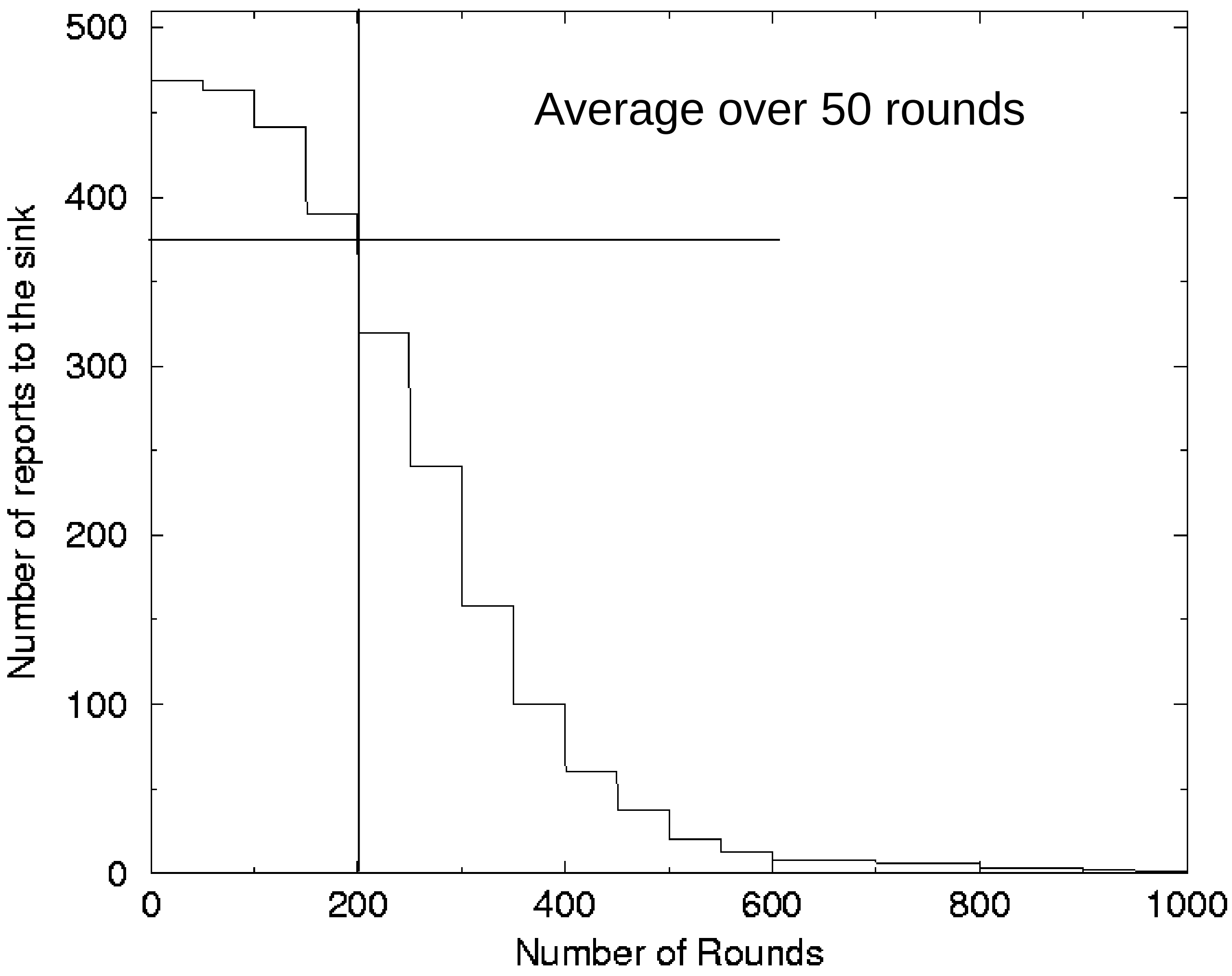
Network Lifetime Definition 3



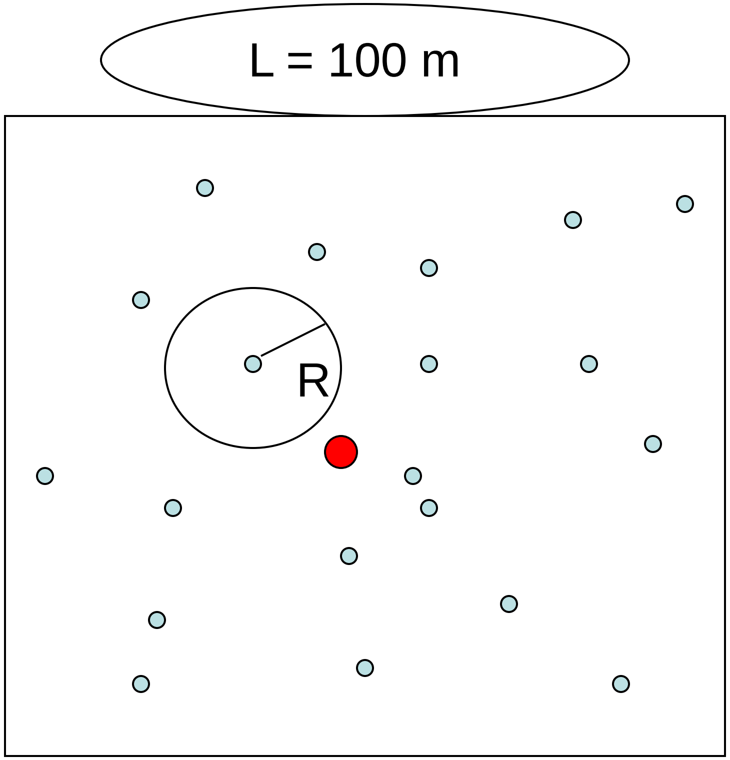


Simulation Examples / 2

Network Lifetime Definition 3



Simulation Examples / 3



Initial charge: 1 Joule

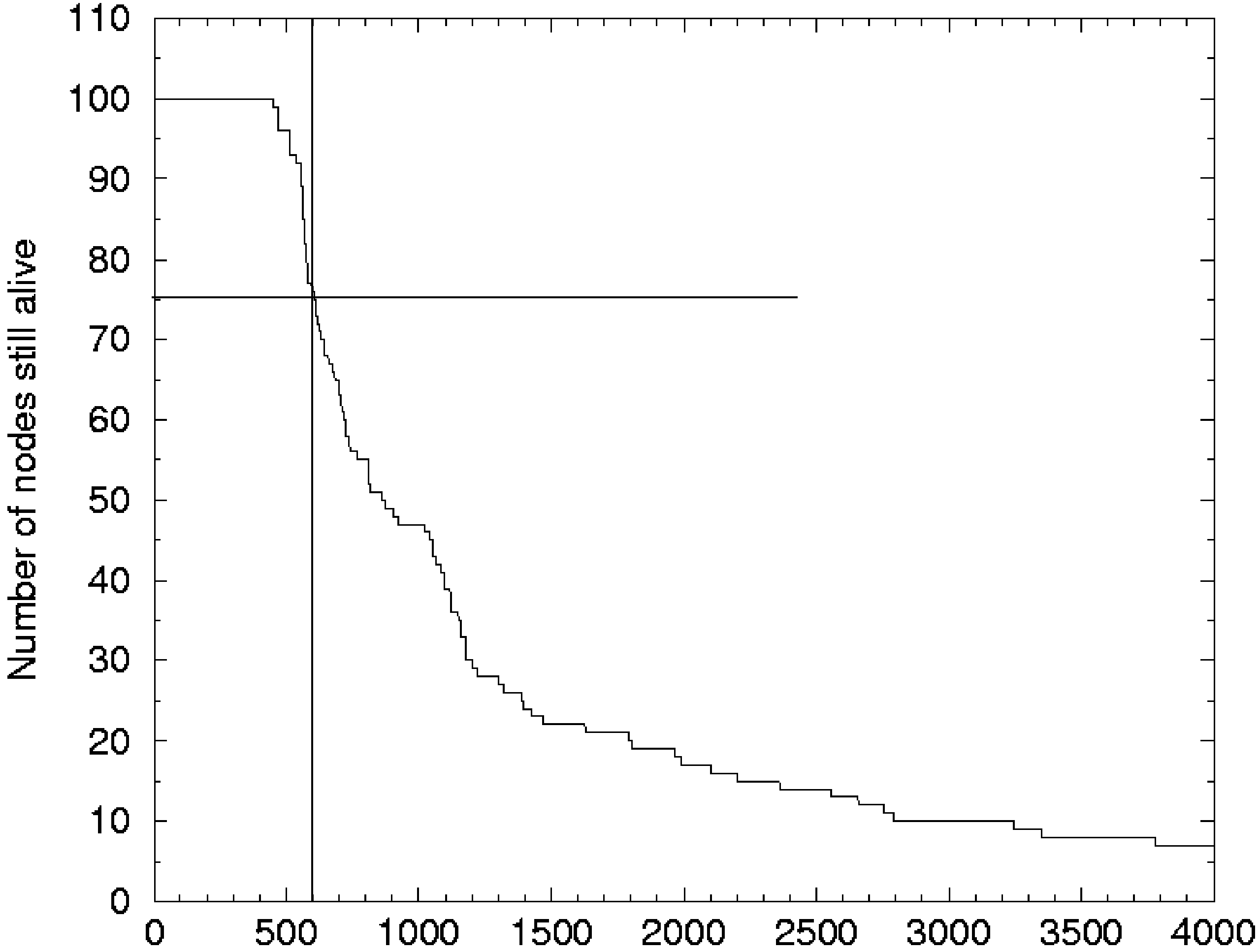
IEEE802.15.4 MAC
LEACH

R = Ideal transmission range approx 54 m
$\sigma = 3.5$

n = 100 nodes

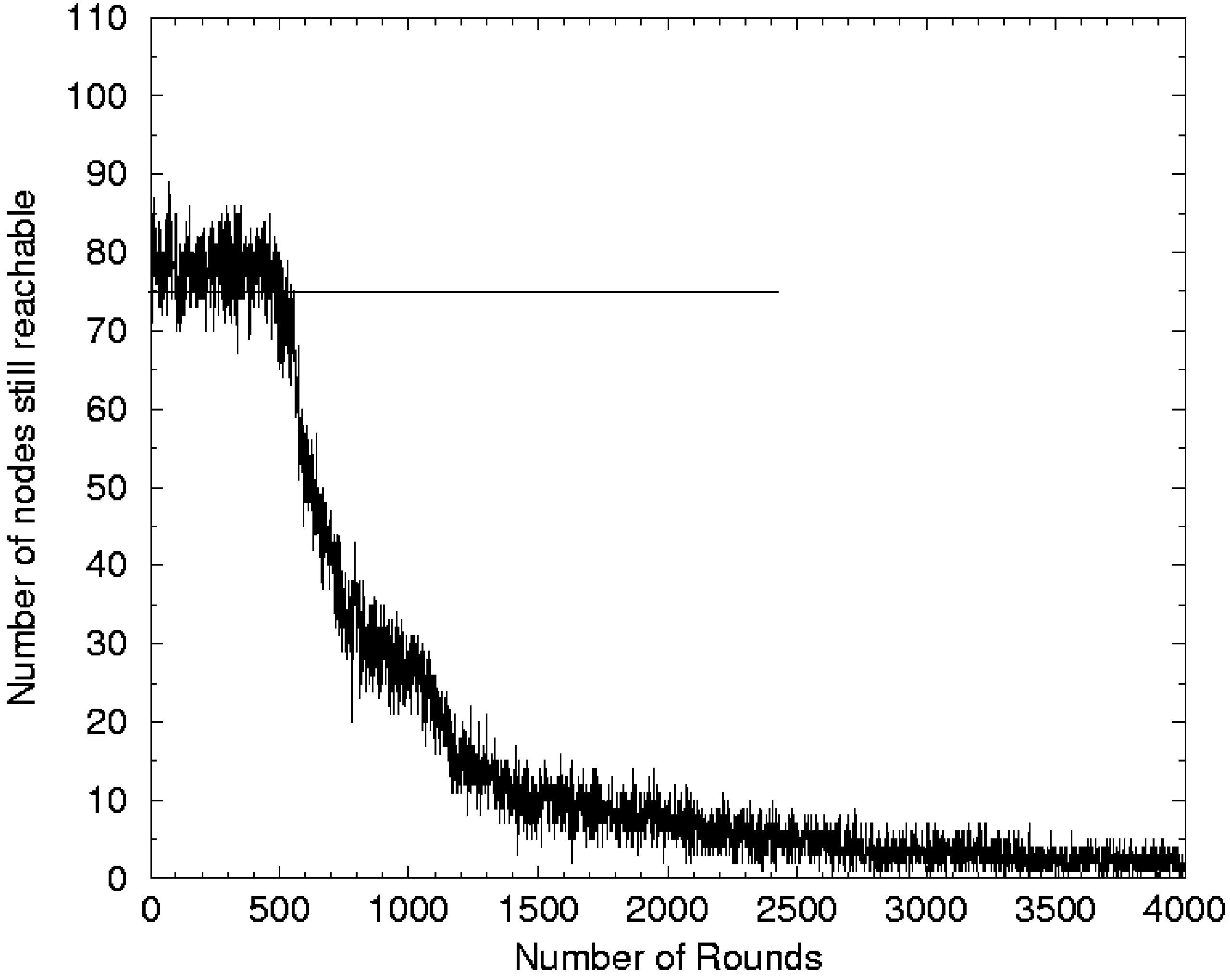
Simulation Examples / 3

Network Lifetime Definition 1



Simulation Examples / 3

Network Lifetime Definition 2



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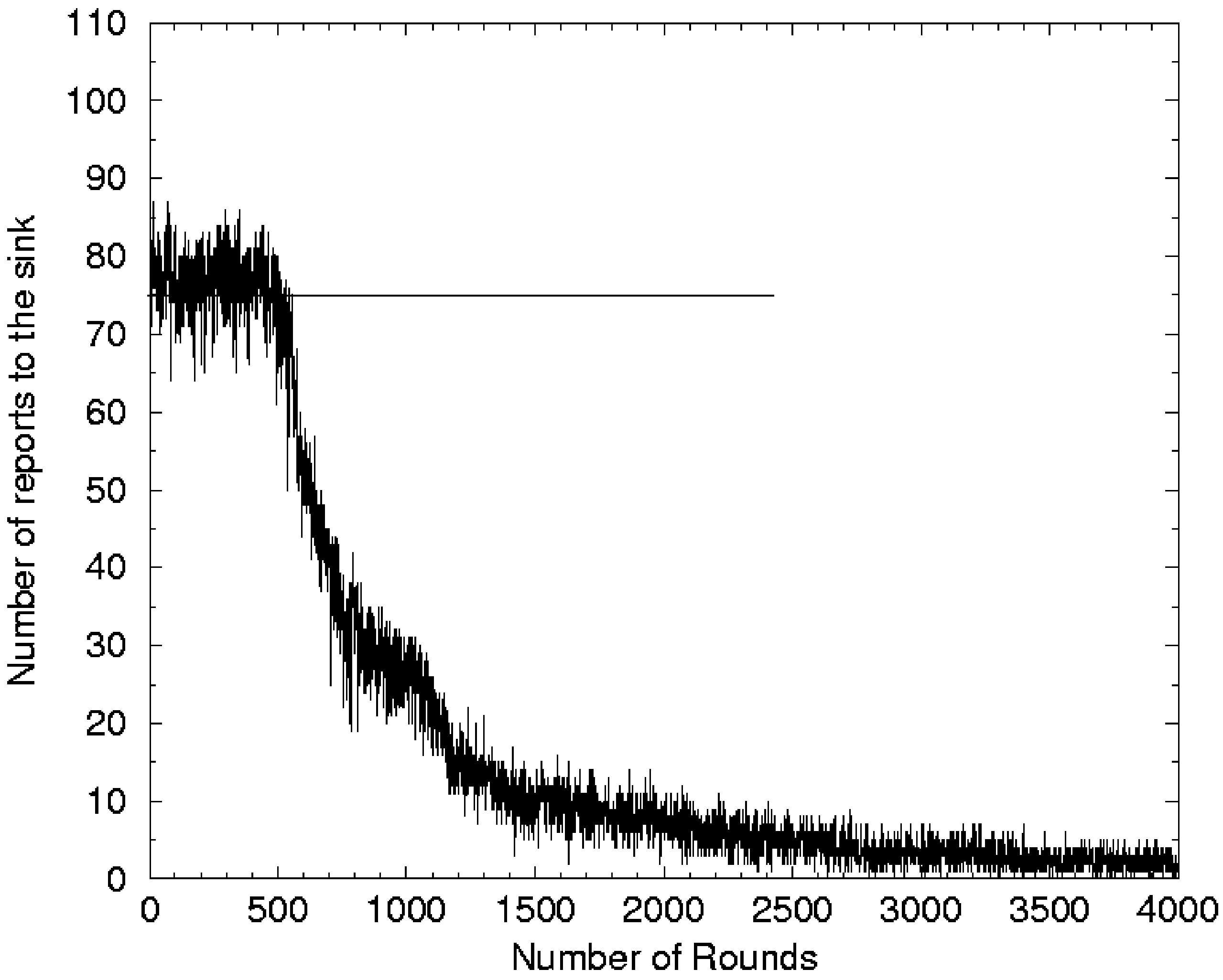
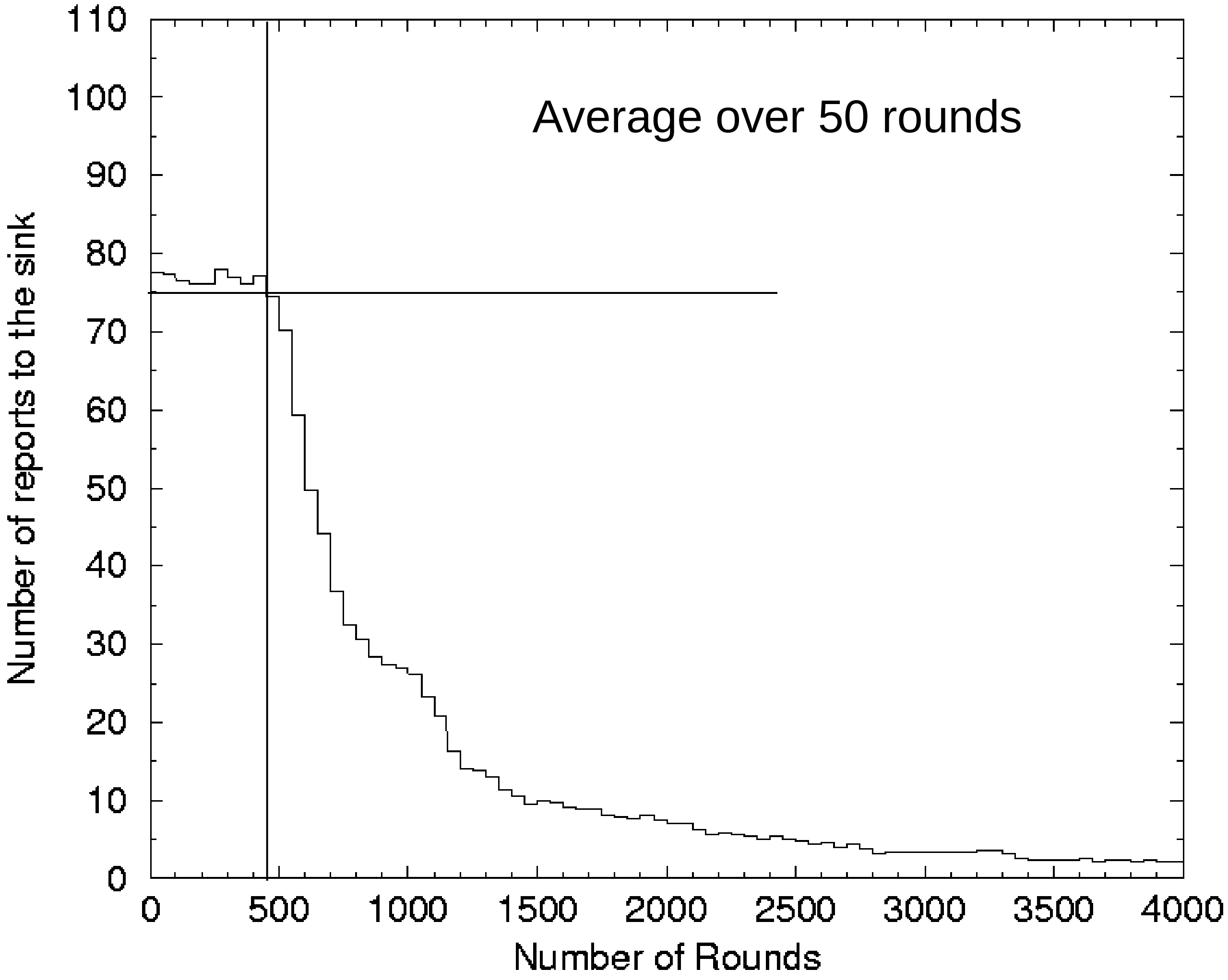
Simulation Examples / 3

Network Lifetime Definition 3



Simulation Examples / 3

Network Lifetime Definition 3



Communication Protocols and Energy Efficiency

Collisions:

happen when a node is within the transmission range of two or more nodes that are simultaneously transmitting so that it does not capture any frame

energy drained in the transmission and reception of collided frames is wasted

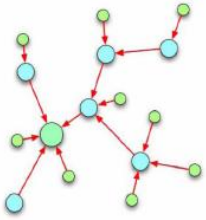
due to the large impact of collisions on protocols performance, MAC/Routing protocols should features technique to reduce or even avoid them

Overhearing:

happens when a node drains energy receiving irrelevant packets or signals (irrelevant packets may be for example unicast packets destined to other nodes)

overhearing such irrelevant unicast packets can be avoided through a filtering based on the packet’s destination addresses

therefore a node that is not concerned with the transmission may switch off its radio to avoid overhearing unneeded transmissions



Communication Protocols and Energy Efficiency

Overhead:

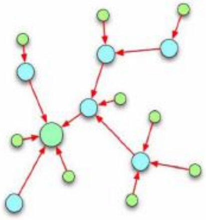
- protocol overhead may result in energy waste when transmitting and receiving irrelevant control packets
- for example, RTS/CTS exchanges induce high overheads in the range of 40% to 75% of the channel capacity, because data frames are typically very small in sensor networks

Idle Listening:

- happens when a node does not know when it will be the receiver of a frame
- node keeps its radio on while listening to the channel waiting for potential data
- amount of energy wasted whilst the radio is on is considerable even when it is neither receiving nor transmitting frames:

Section 2
MAC: Basics

MAC Protocols: Preliminaries
Random Access



MAC Protocols for WSNs: Preliminaries

Collision less protocols (e.g. TDMA, SMACS)
require overhead to schedule transmissions

Convenient if the network environment/topology is stationary or slowly varying

Collision prone protocols (e.g. CSMA)
require retransmission strategies → latency increases

Convenient if the network environment/topology is highly dynamic

$T_R << T_{COH}$	Collision less	→	T/FDMA
$T_R > T_{COH}$	Collision prone	→	CSMA

T_R might range from 10^{-5} to 10^{+5} seconds.

MAC Protocols for WSNs: Preliminaries

What might affect network dynamism?

- Wireless channel fluctuations. — T_{COH} is in the order of secs.
- Mobility of nodes. — T_{COH} is in the order of 10-100 msecs.
- Changes in the topology due to re-clustering mechanisms at NET. — T_{COH} is in the order of T_R.
- Changes in the topology due to random/uncorrelated sleep intervals at PHY.

The coherence time of the network environment/topology should be estimated according to the application and other layers. Then, comparison with round duration will drive the selection of protocols. CSMA family of protocols is often the choice.

Random Access: ALOHA and CSMA

ALOHA

S- ALOHA

CSMA

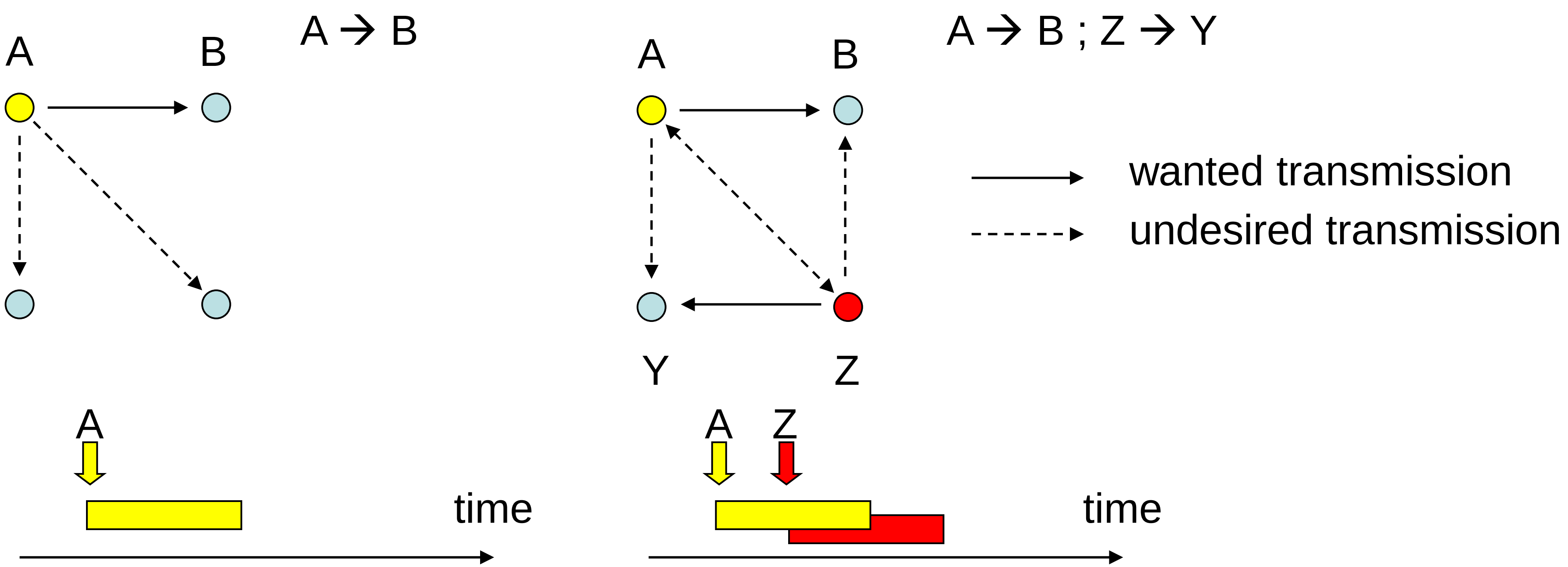
CSMA/CD

CSMA/CA

CSMA/CA with RTS/CTS

ALOHA

Whenever a node has a packet in the data link layer buffer, it broadcasts it.
Collisions (i.e. partial or total overlap between packet transmissions by separate sources) may occur, with probability P_{collA}
In an interference-limited environment, packet losses (i.e. events of packets not captured by the receiver because of C/I below capture threshold) may occur, with probability $P_{lossA} < P_{collA}$.



ALOHA

IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. COM-25, NO. 1, JANUARY 1977

The Throughput of Packet Broadcasting Channels

NORMAN ABRAMSON, FELLOW, IEEE

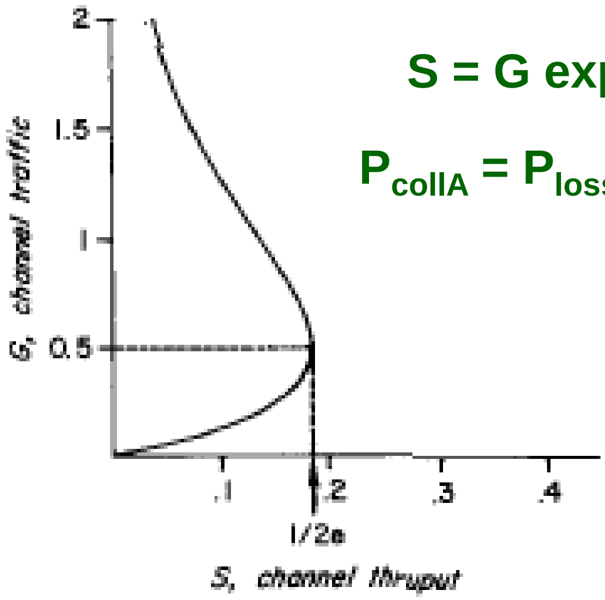


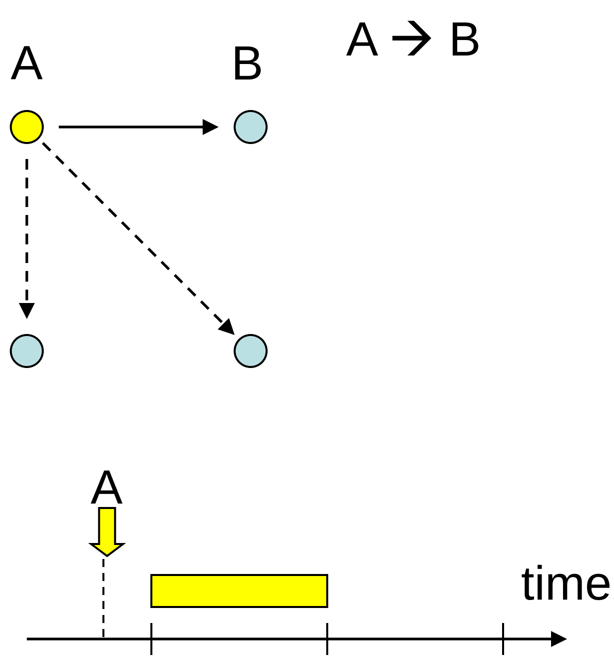
Fig. 3. Channel throughput versus channel traffic for an ALOHA channel.

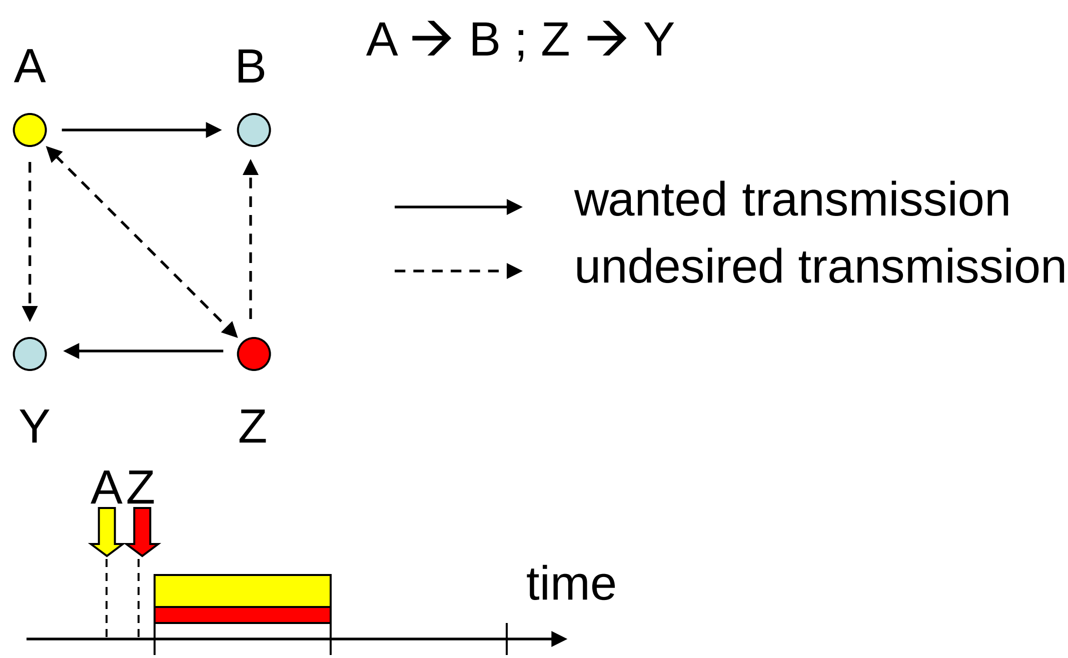
$$S = G \exp(-2G)$$

$$P_{collA} = P_{lossA} = 1 - S/G = 1 - \exp(-2G)$$

S-ALOHA

Time is slotted. Whenever a node has a packet in the data link layer buffer, it broadcasts it starting from instant when next slot initiates.
Collisions (i.e. total overlap between packet transmissions by separate sources) may occur, with probability P_{collSA}
In an interference-limited environment, packet losses (i.e. events of packets not captured by the receiver because of C/I below capture threshold) may occur, with probability $P_{lossSA} < P_{collSA}$.





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S-ALOHA

IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. COM-25, NO. 1, JANUARY 1977

The Throughput of Packet Broadcasting Channels

NORMAN ABRAMSON, FELLOW, IEEE

$$S = G \exp(-G)$$

$$P_{collSA} = P_{lossSA} = 1 - S/G = 1 - \exp(-G)$$

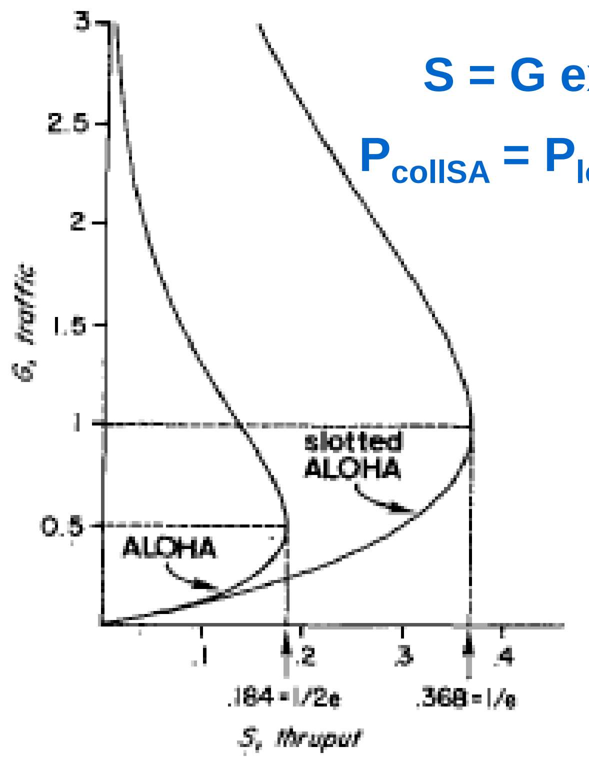
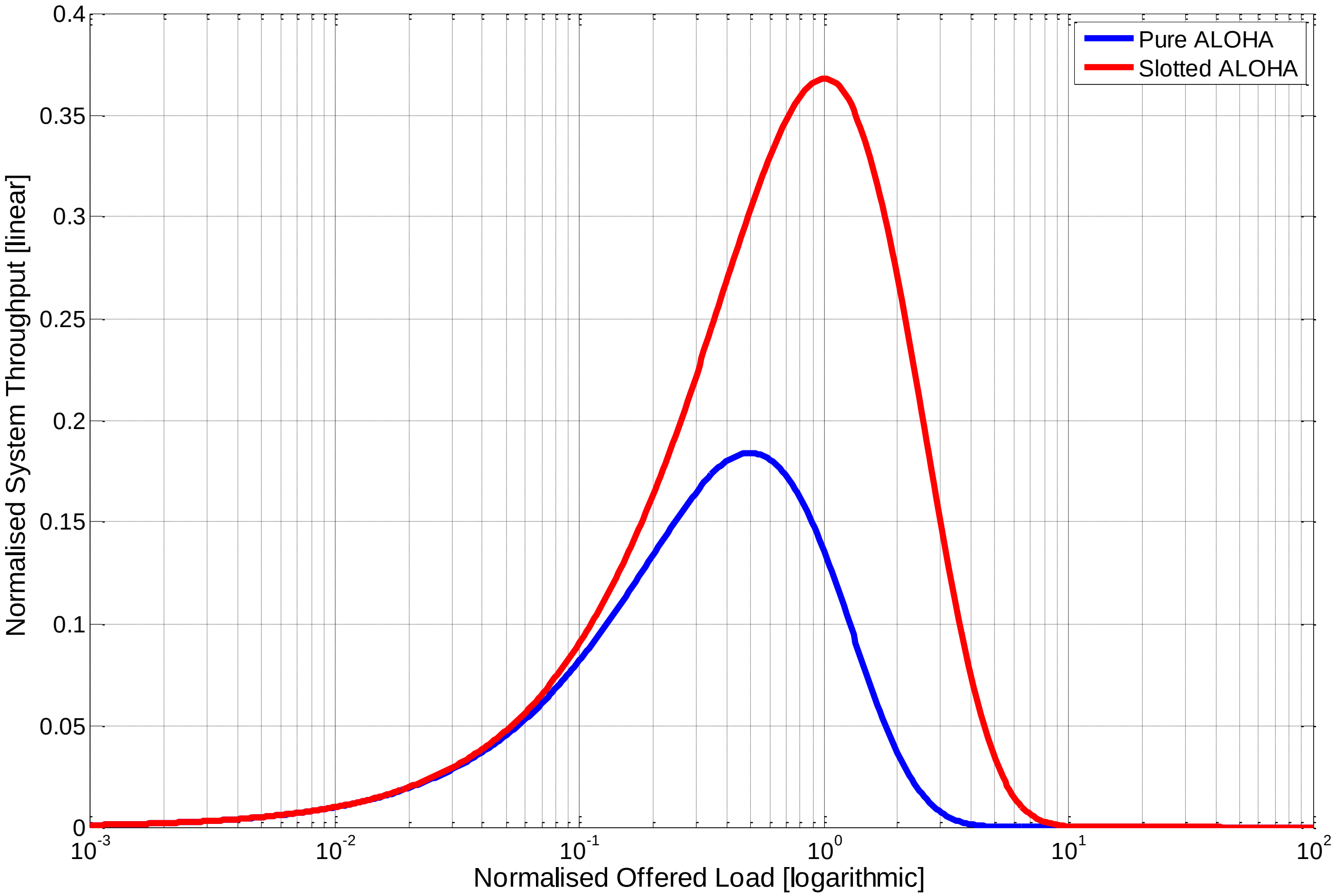


Fig. 4. Traffic versus throughput for an ALOHA channel and a slotted ALOHA channel.

S-ALOHA


Pure ALOHA
Slotted ALOHA
Normalised System Throughput [linear]
Normalised Offered Load [logarithmic]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

(In)Stability of S-ALOHA

With reference to figure on next slide:

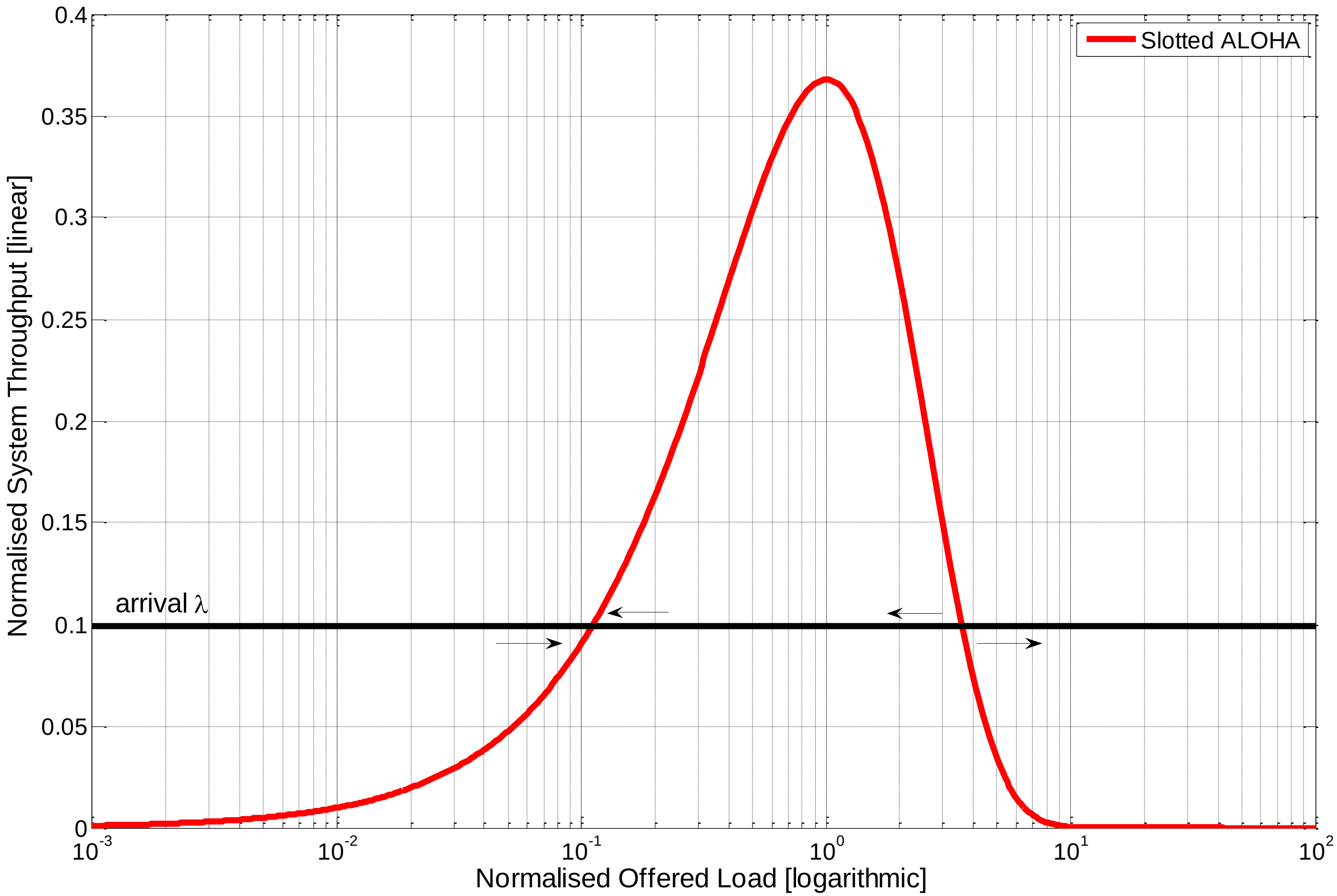
Conditionally stable point:

- for a given arrival rate λ, the system stabilises at point (G_1,S); this means that packets arrive at the same rate as they leave;
- small increase in G_1, increases throughput and hence makes packets leave faster than they arrive; this makes traffic to go back to G_1;
- same applies for small decrease in G_1; therefore, small changes bring system back to point (G_1,S).

Instability:

- large increase in G_1 beyond G_2, decreases throughput and hence makes packets leave slower than they arrive; this decreases throughput further;
- ALOHA system enters catastrophic state (with probability one);
- stable throughput of ALOHA is hence zero!

(In)Stability of S-ALOHA



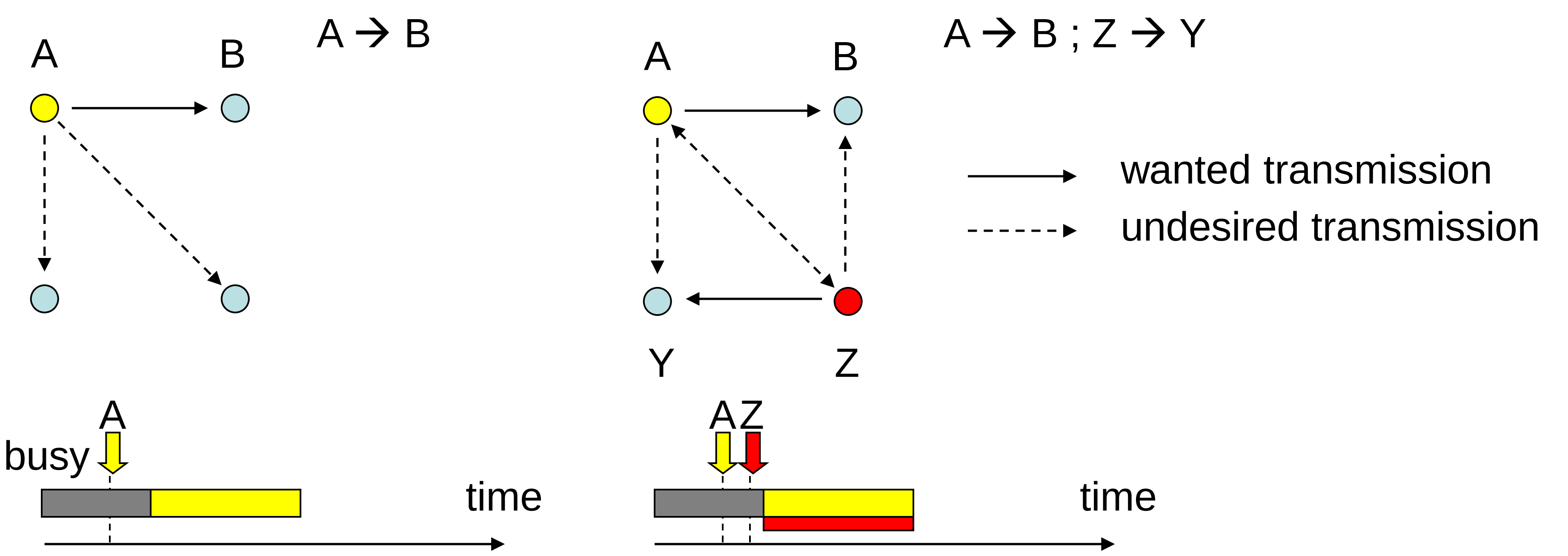
CSMA (Carrier Sensing MA)

Whenever a node has a packet in the data link layer buffer, it starts sensing the carrier. When it detects the channel is free, it broadcasts the packet.

Collisions may occur if two nodes stop sensing the carrier simultaneously, with probability P_{collC}

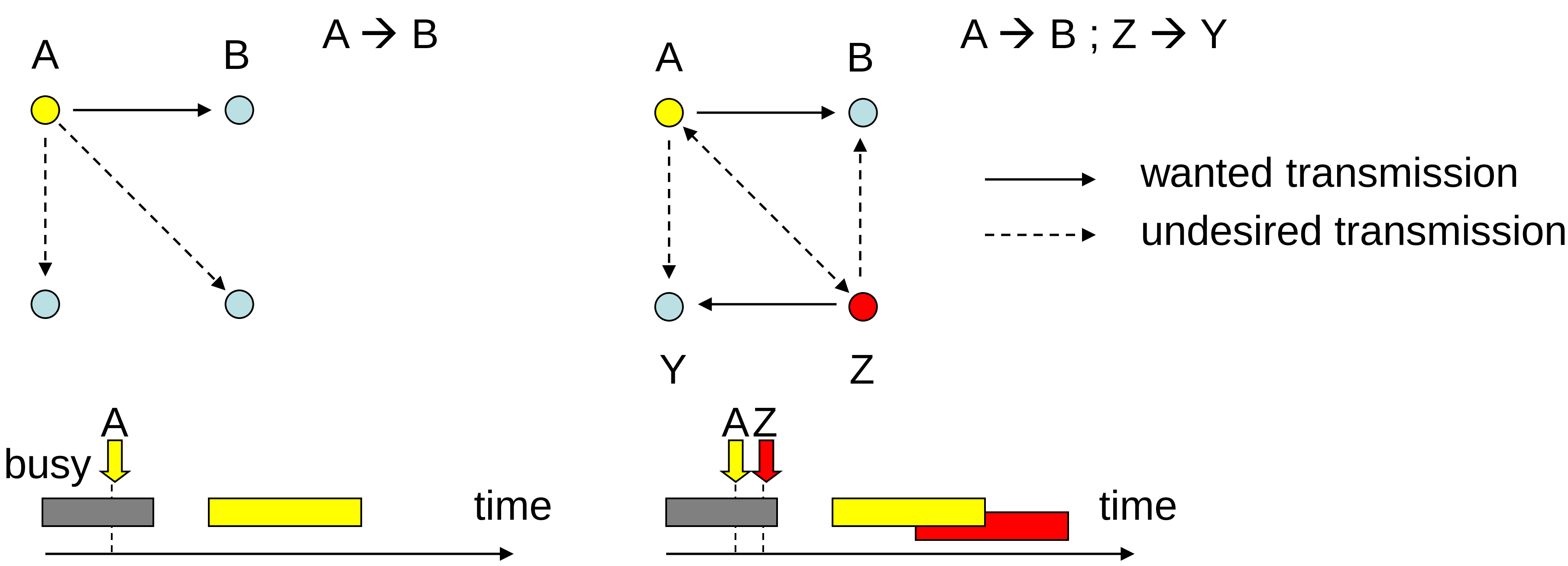
P_{collC} can not be reduced to zero unless collision resolution algorithms are used.

In an interference-limited environment, packet losses may occur, with probability $P_{lossC} < P_{collC}$.

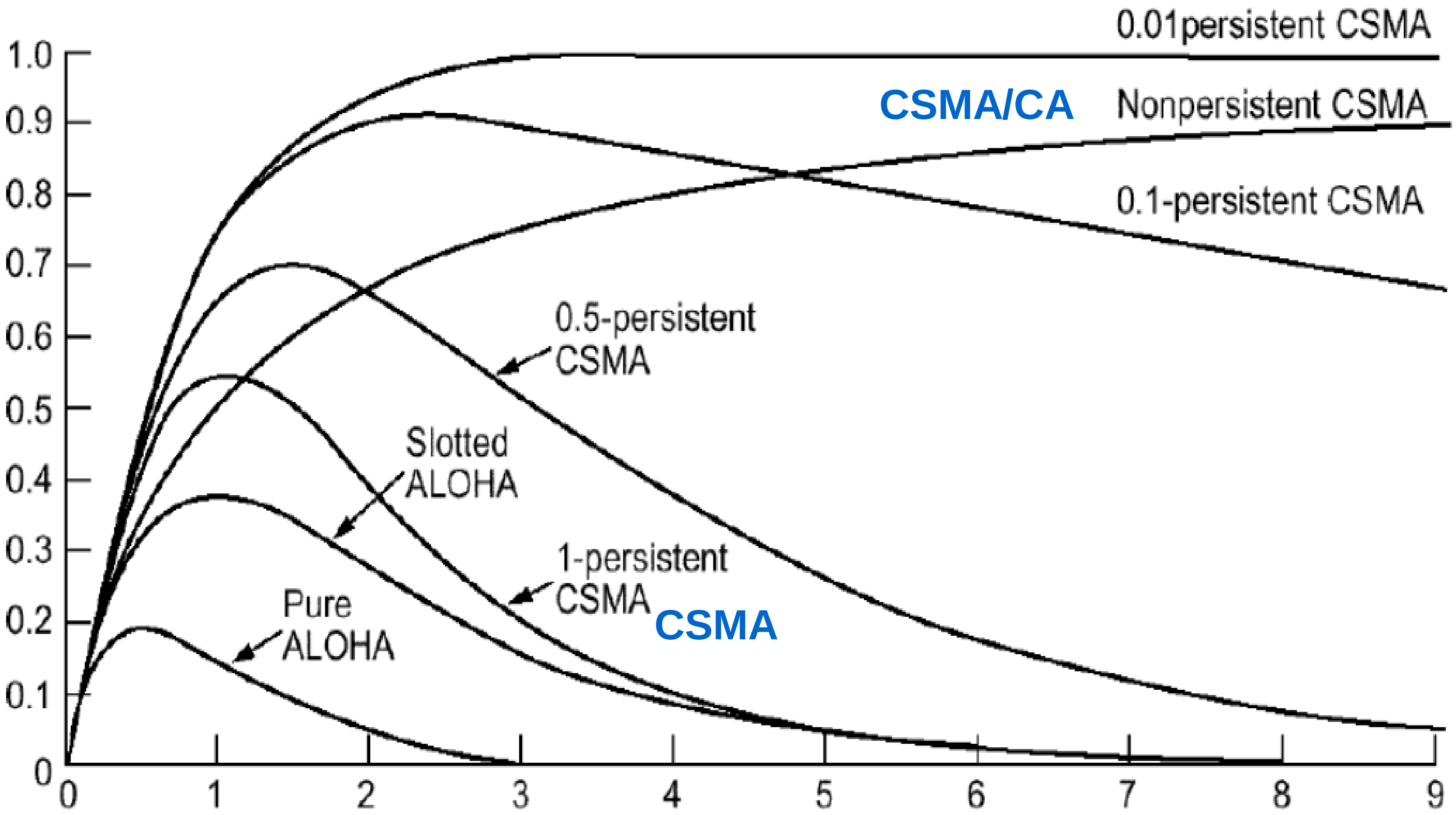


CSMA/CA (Collision Avoidance)

Whenever a node has a packet in the data link layer buffer, it starts sensing the carrier. When it detects the channel is free, a backoff phase (i.e. transmission is deferred by a random delay) is initiated; at its end, the node broadcasts the packet. Collisions may occur with probability P_{collCC}.
Large backoffs can reduce collisions deliberately (P_{collCC} can be reduced to zero).
In an interference-limited environment, packet losses may occur, with probability $P_{lossCC} < P_{collCC}$.

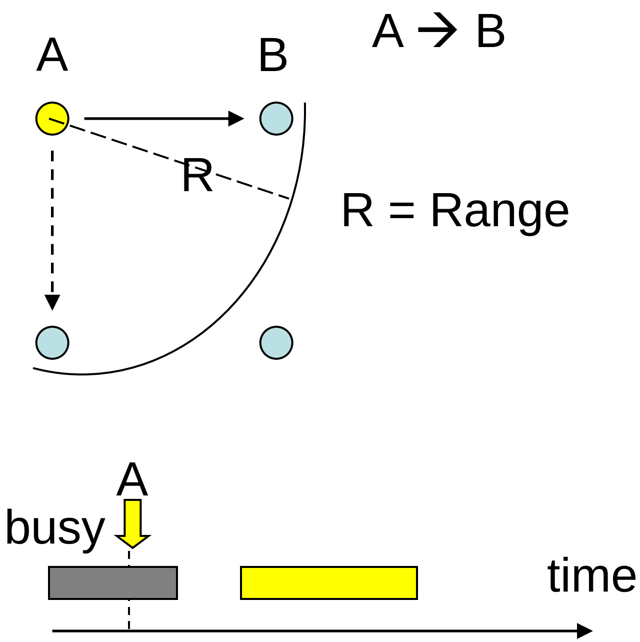


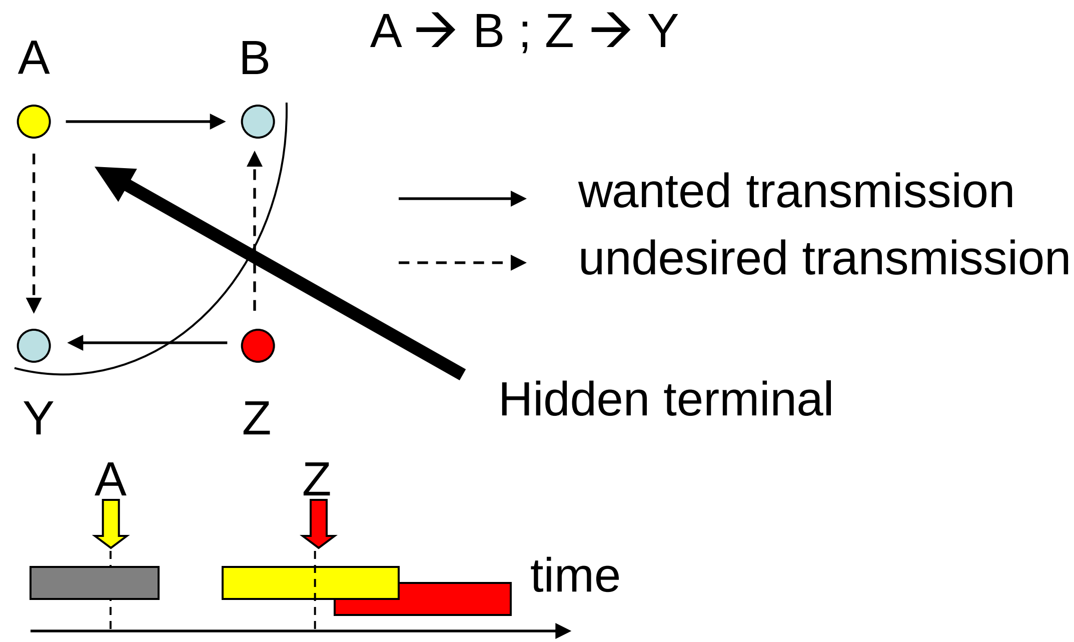
Persistent and Non Persistent CSMA



CSMA/CA – "Hidden Terminal" Problem

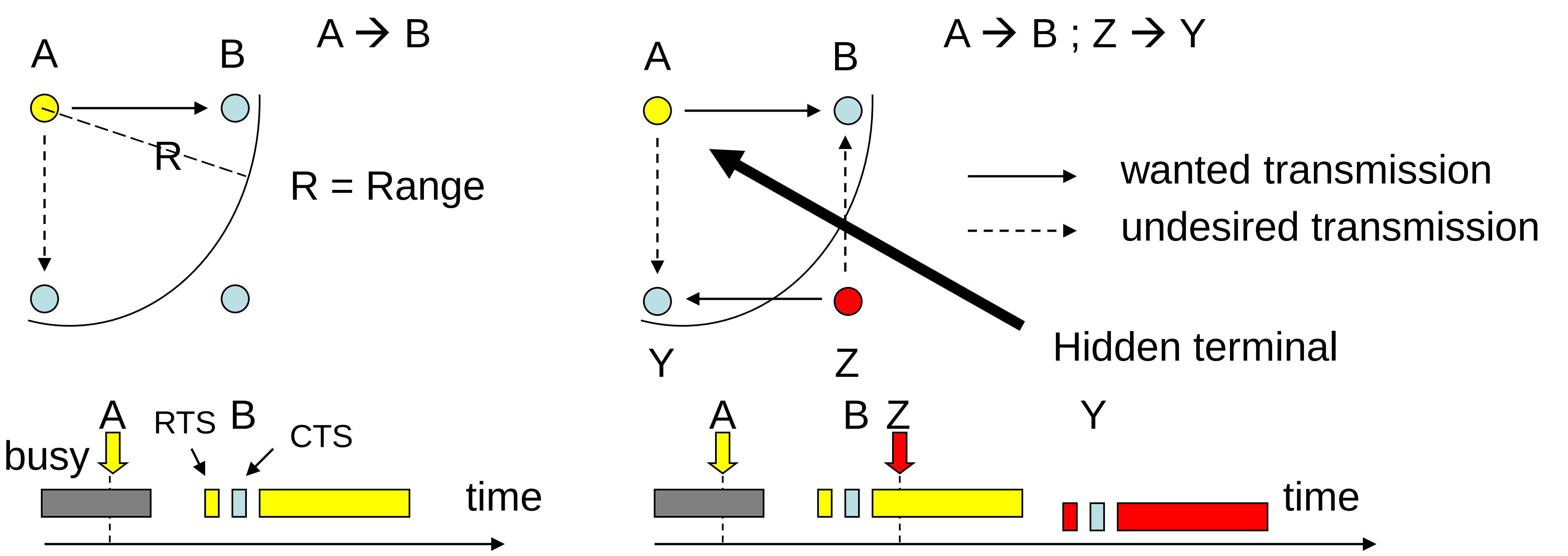
Even if backoff could solve collision problems in a perfect broadcast channel (every node is within range of all others), hidden nodes might cause collisions in an environment where transmission ranges do not cover the whole network. If a node (Z), willing to transmit to a given terminal (Y), does not sense the transmission from a given source (A) to an other node (B), but the node receiving both packets (B) is within range of both transmitting nodes (A and Z) and detects a collision, then A is said to be an hidden node for Z.





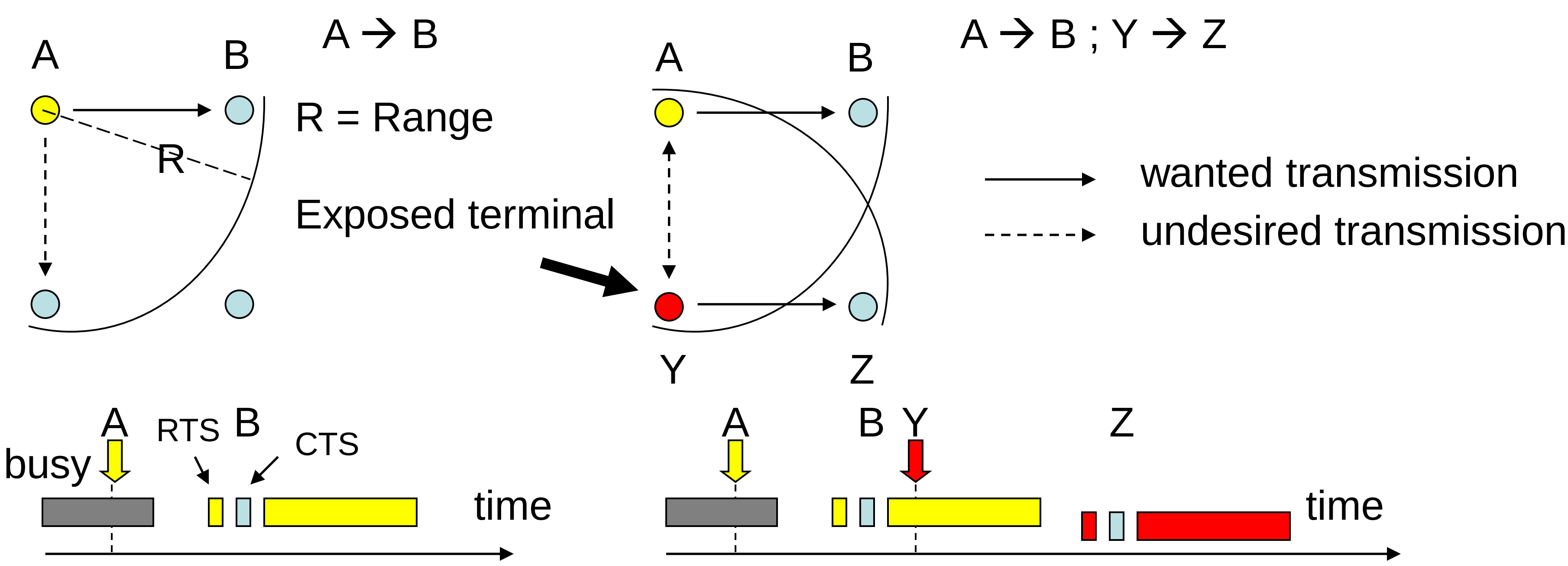
CSMA/CA with RTS/CTS (Request To Send / Clear To Send)

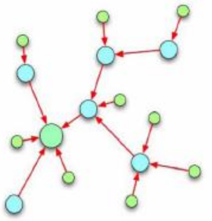
Whenever a node has a packet put in the data link layer buffer, it starts sensing the carrier. When it detects the channel is free, a backoff phase is initiated; at its end, the node sends a short RTS packet informing everyone within its range to avoid transmission for a packet time. The receiver responds with a short CTS packet allowing transmission and informing everyone within its range to avoid transmission for a packet time. Upon reception of the CTS, the source node broadcasts the packet. All nodes within range of receiver know that have to wait before transmitting a RTS.



CSMA/CA with RTS/CTS - “Exposed Terminal” Problem

If a node (A) willing to transmit a packet to a given sink (B), broadcasts the RTS, all other nodes within its range will refrain from transmitting.
On the other hand, there might be a node (Y) willing to transmit to a sink (Z) which would not detect a collision because it is not within range of the interferer (A), which refrains from transmitting though its transmission would not be a problem because its (Y’s) range does not include the other link’s sink (B).
CSMA would work better in this case. CSMA/CA with RTS/CTS reduces throughput.

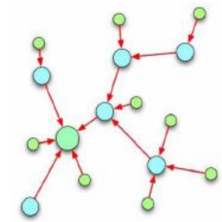




CSMA/CA with RTS/CTS

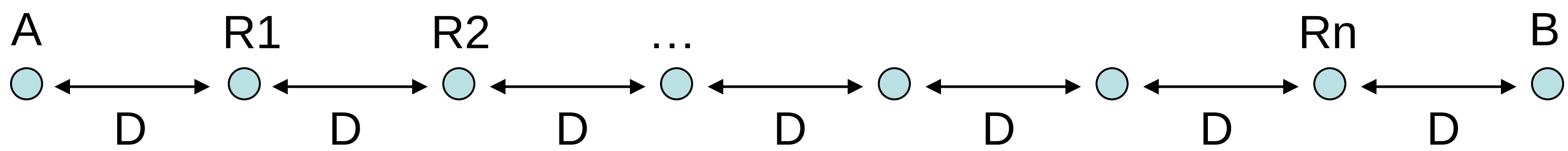
**RTS / CTS mode is a powerful tool but must be used with care, dimensioning the transmit power of such short packets so as to keep refrained from transmitting only those nodes
that would really cause packet loss.**

**Particular problems may arise in multi-hop networks.
A case study follows.**



CSMA/CA with RTS/CTS; Case Study

Homogeneous deterministic mono-dimensional multi-hop scenario: network-layer throughput evaluation for a sequence of packets from A to B through n nodes;



Assumptions:

Backoff delay equal to zero

Node A buffer always full

$C = k\,d^{-2}$ $I = k\,d_i^{-2}$ (no channel fluctuations)

Packets are captured if $C/I > z_0 = 2 \rightarrow [d/d_i]^{-2} > 2 \rightarrow [d_i/d] < 0.7$

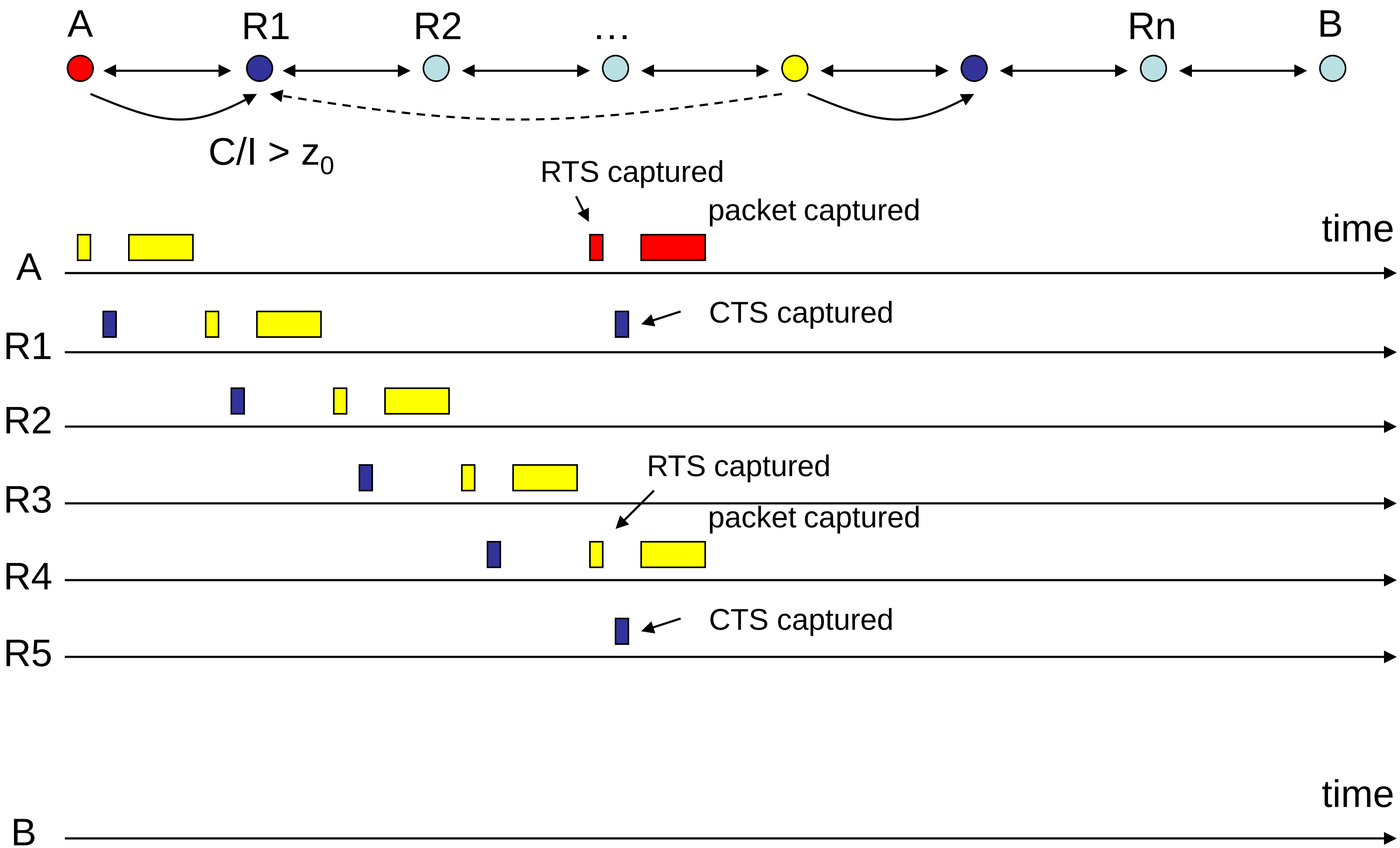
Packets are captured if $C > C_{thr} \rightarrow d < d_{thr} = 2.5\ D$

Packets are heard during sensing if $C > C_{thrs} \rightarrow d < d_{thrs} = 3.5\ D$

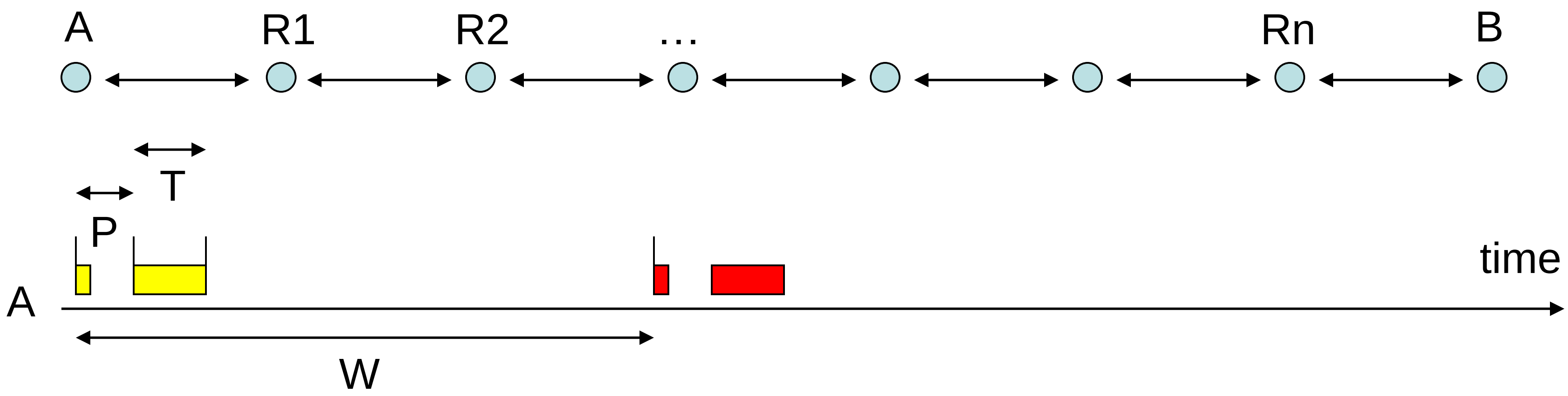
↗ transceiver sensing range

inactive transmit receive sensing

CSMA/CA with RTS/CTS; Case Study



CSMA/CA with RTS/CTS; Case Study - Throughput

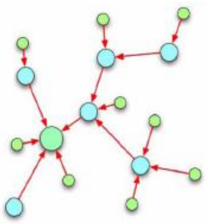


Assuming P << T, if e.m. activity can be sensed up to 3 nodes, then W = 4T.

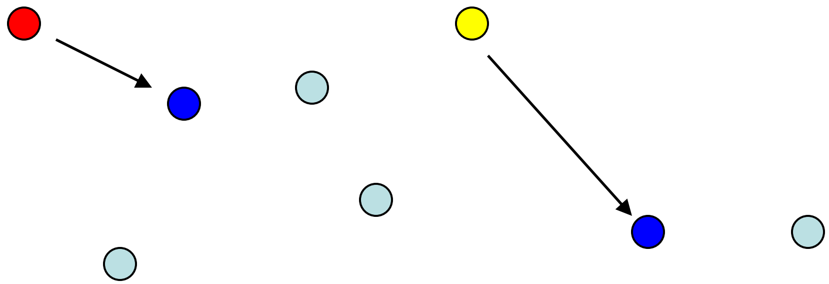
More generally, assuming P << T, if e.m. activity can be sensed up to x nodes, then W = (x+1)T.

Throughput is equal to RbT bits divided by W: $S = Rb\,T / W = Rb / (x+1)$

It is therefore relevant to make the RTS and CTS power level as low as possible, to minimise x, given packet received power is sufficient to allow packet capture.



CSMA/CA with RTS/CTS



In a more complex scenario, with nodes distributed in a bi-dimensional environment, evaluation of throughput, even under simple assumptions, is more complex.

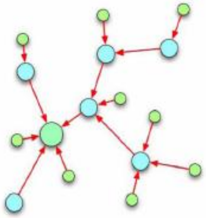
In general, power control is needed to limit the throughput decrease due to the exposed terminal problem.
The use of adaptive directional antennas (SDMA) also represents a good (more complex) alternative.

Summing-Up

CSMA Based Protocols are the most successful

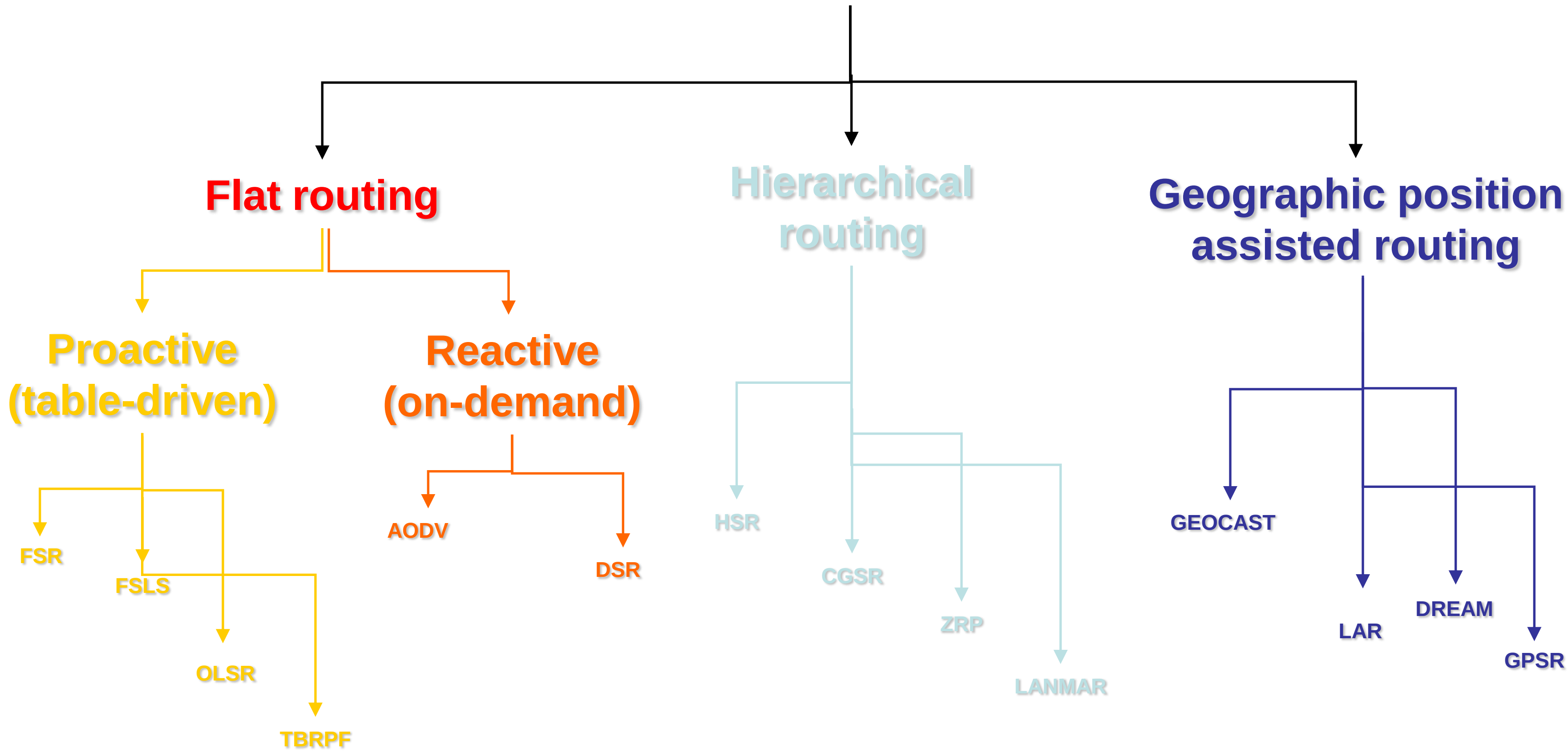
However, proper techniques have to be included to

- **Minimise Collisions**
- **Avoid Overhearing**
- **Reduce Overhead**
- **Avoid Idle Listening**



Section 3
Routing: Basics

Routing Protocols for MANETs



Routing Protocols for WSNs

Proactive protocols
require overhead to exchange routing data

Convenient if the network environment/topology is static or slowly varying

Reactive protocols
generate more latency

Convenient if the network environment/topology is highly dynamic

$T_R \ll T_{COH}$	→	Proactive
$T_R > T_{COH}$	→	Reactive