Wireless Sensor Networks
5. Routing

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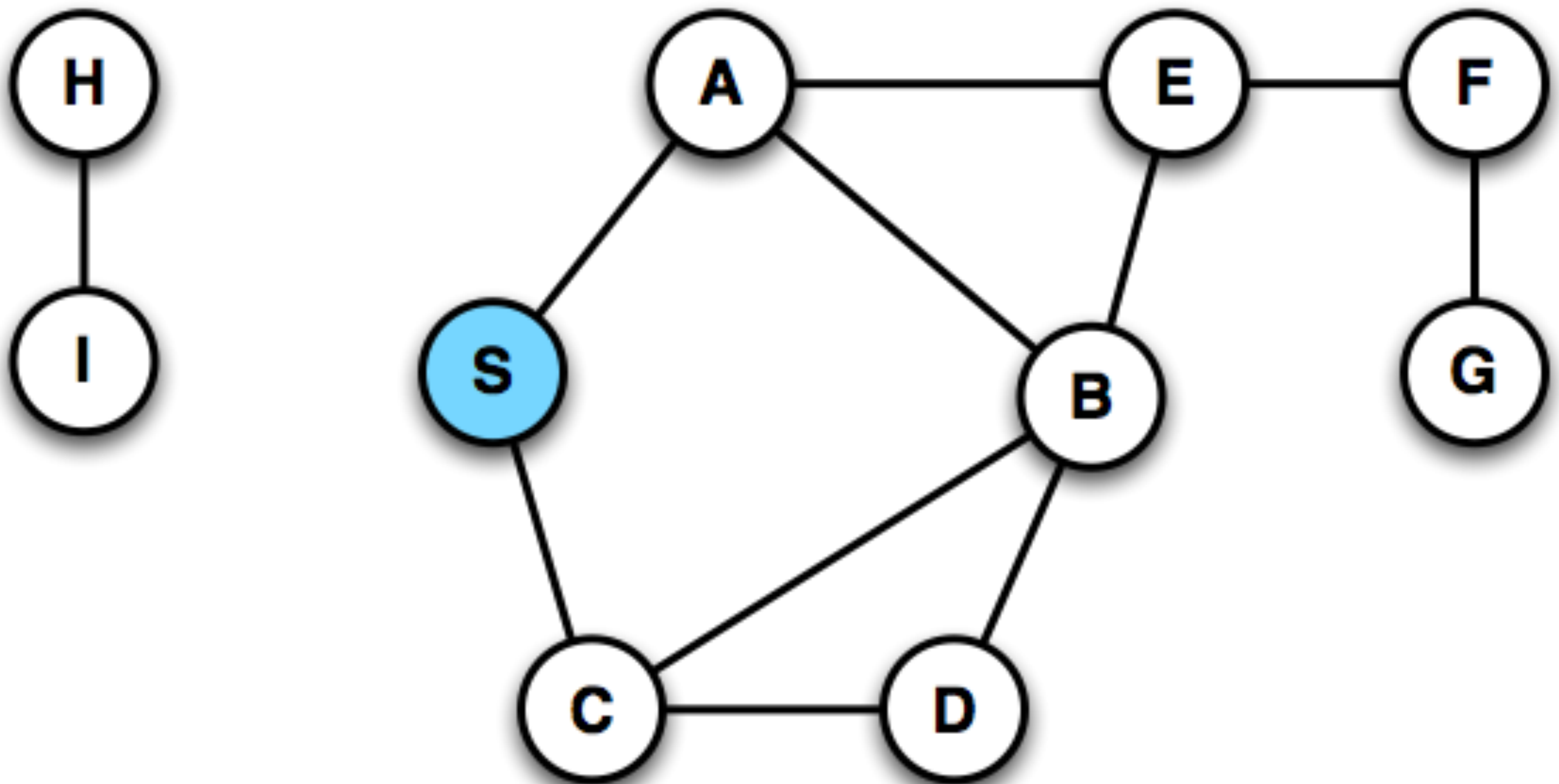
Version 30.05.2016

AODV

- Perkins, Royer
  - Ad hoc On-Demand Distance Vector Routing, IEEE Workshop on Mobile Computing Systems and Applications,1999
- Reaktives Routing-Protokoll
- Reactive routing protocol
  - Improvement of DSR
  - no source routing
  - Distance Vector Tables
    - but only for nodes with demand
  - Sequence number to help identify outdated cache info
  - Nodes know the origin of a packet and update the routing table

AODV

- Algorithm
  - Route Request (RREQ) like in DSR
  - Intermediate nodes set a reverse pointer towards thesender
  - If the target is reached, a Route Reply (RREP) is sent
  - Route Reply follow the pointers
- Assumption: symmetric connections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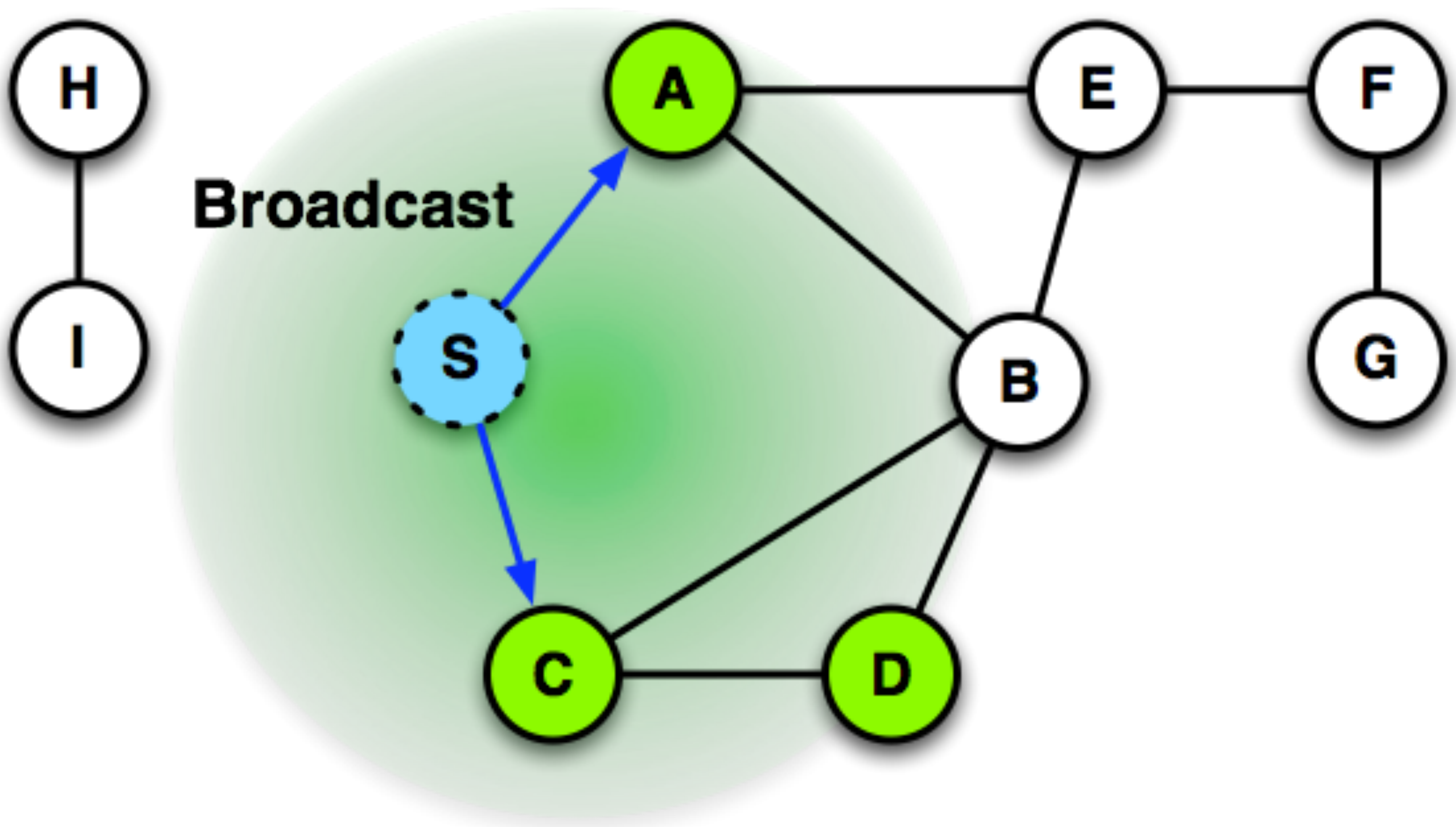
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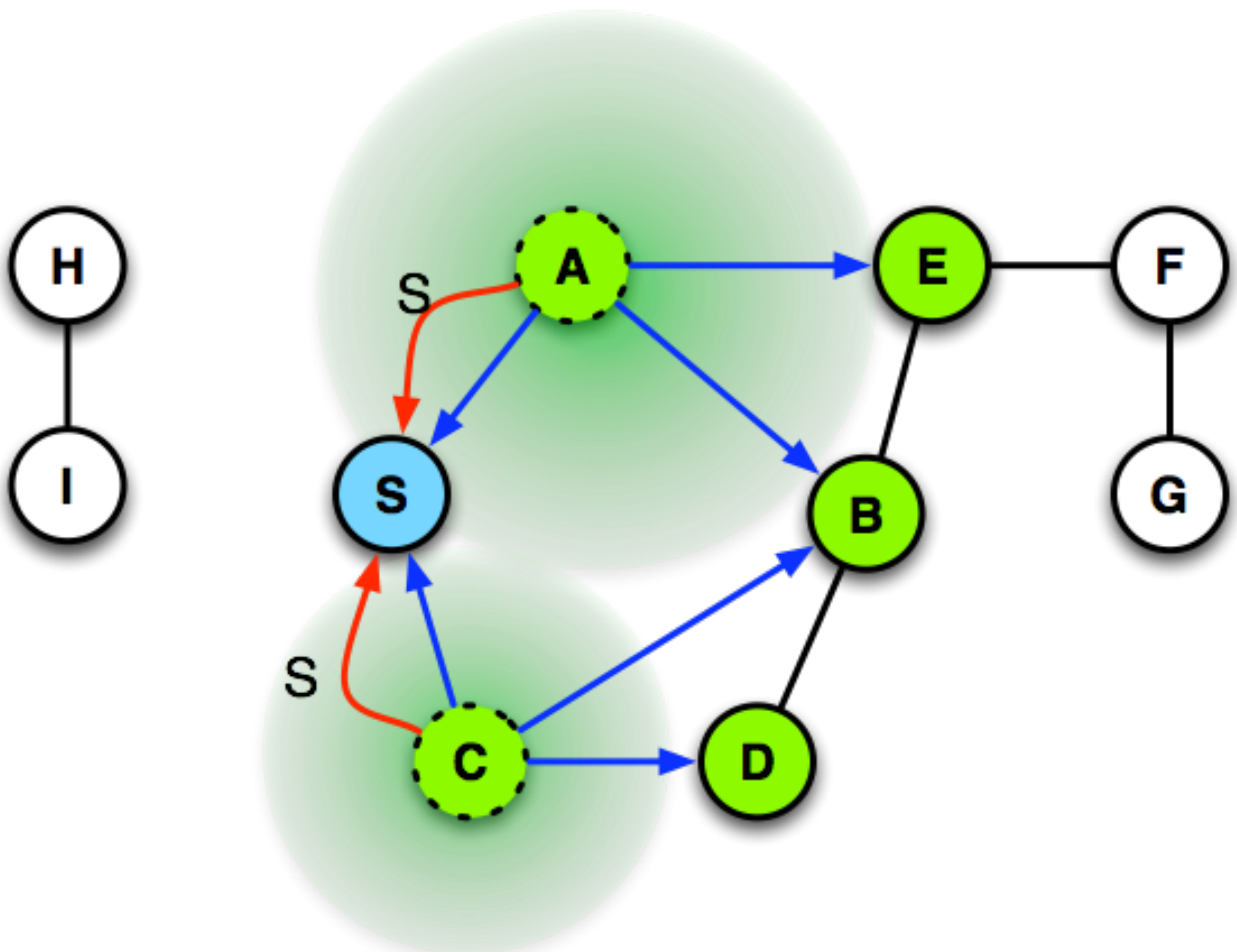
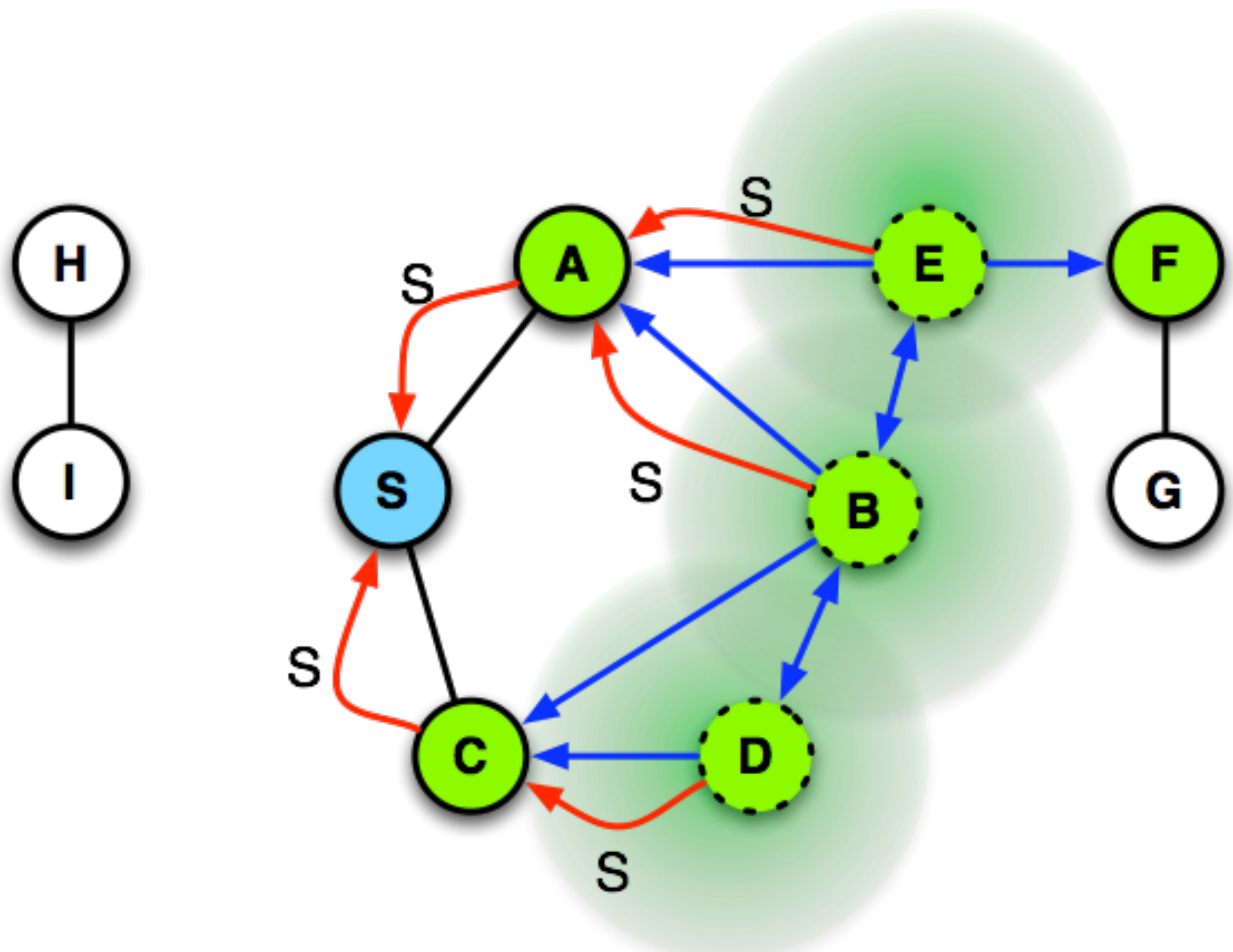
~~RRO~~ RREQ

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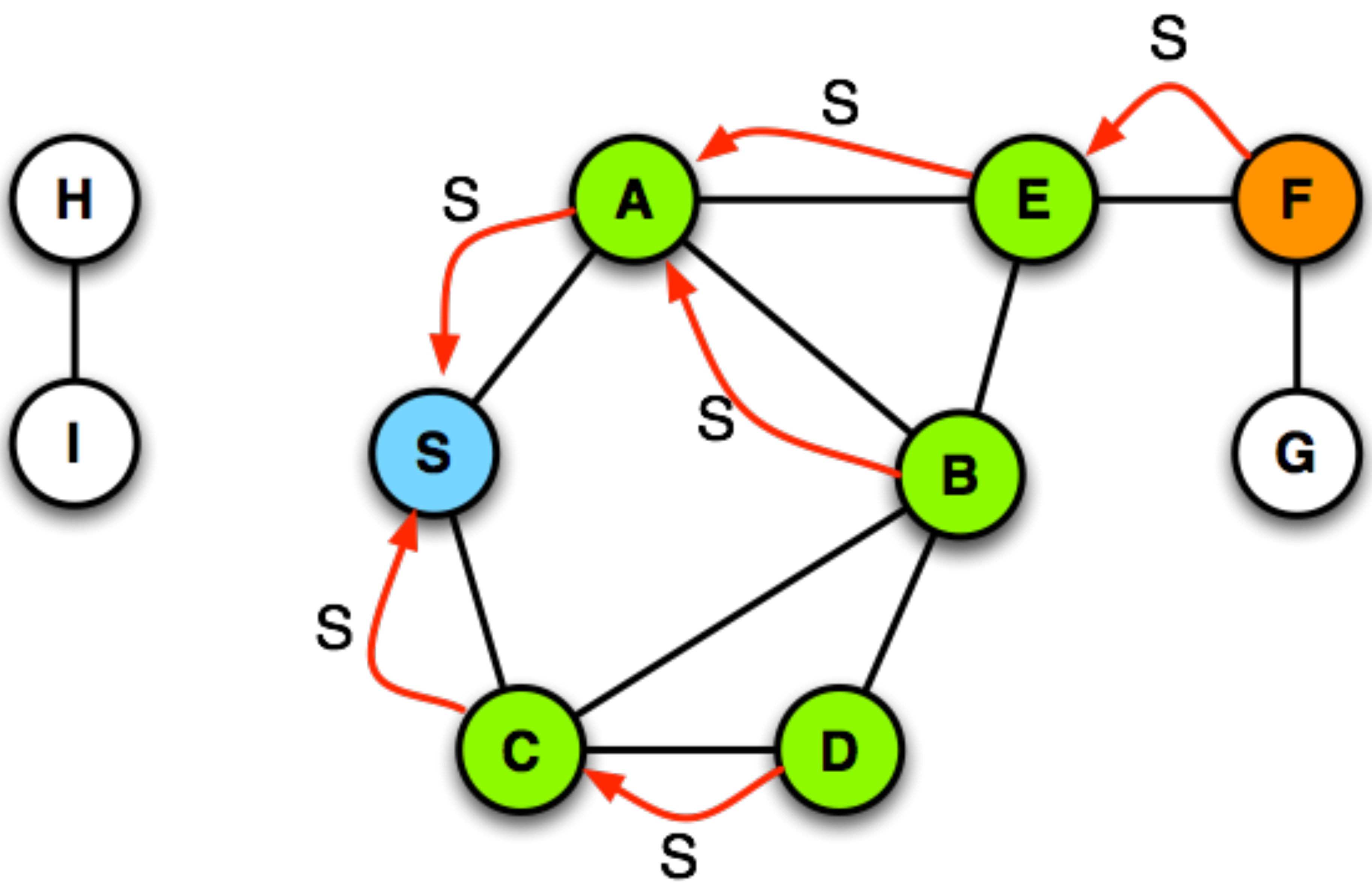
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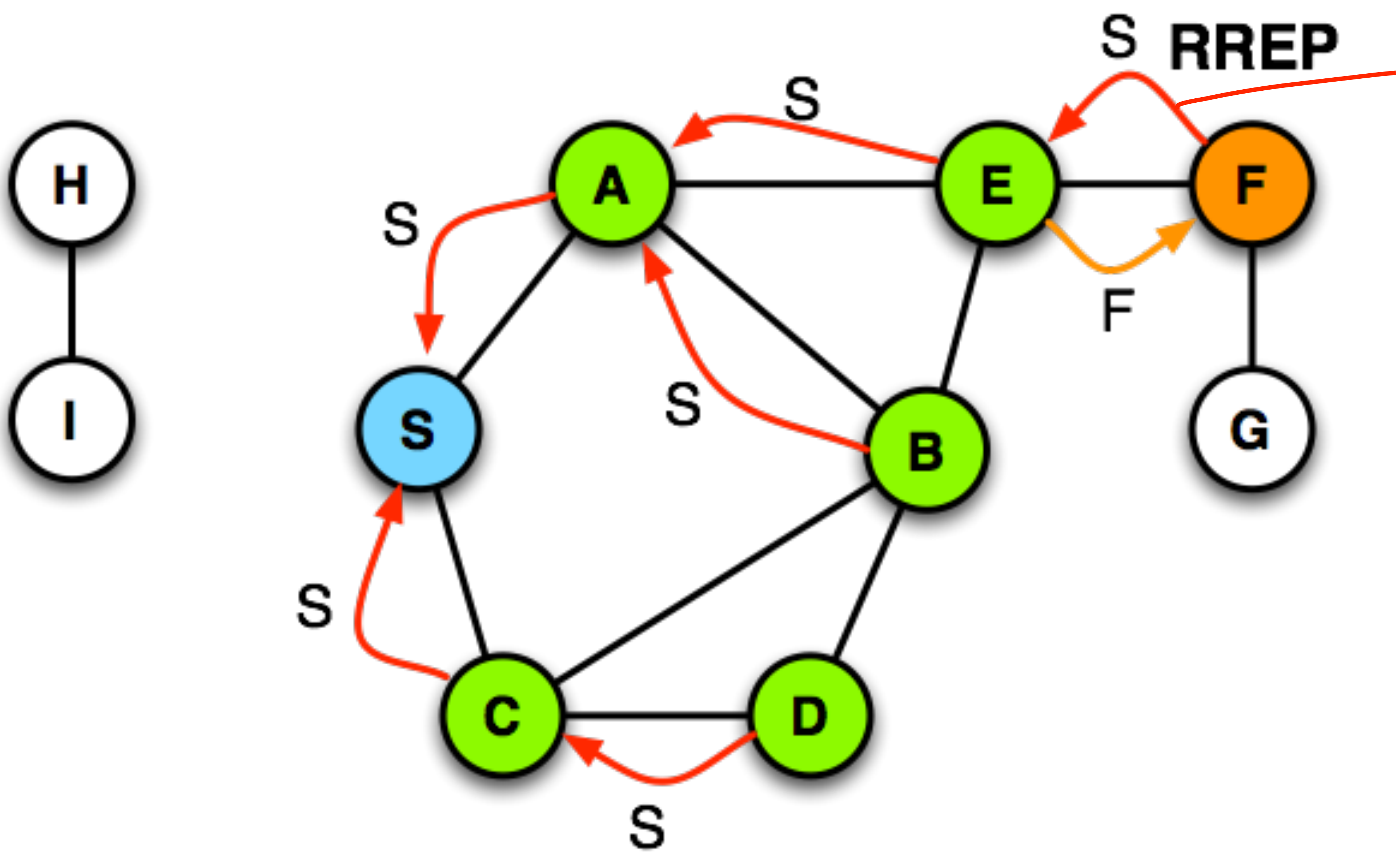
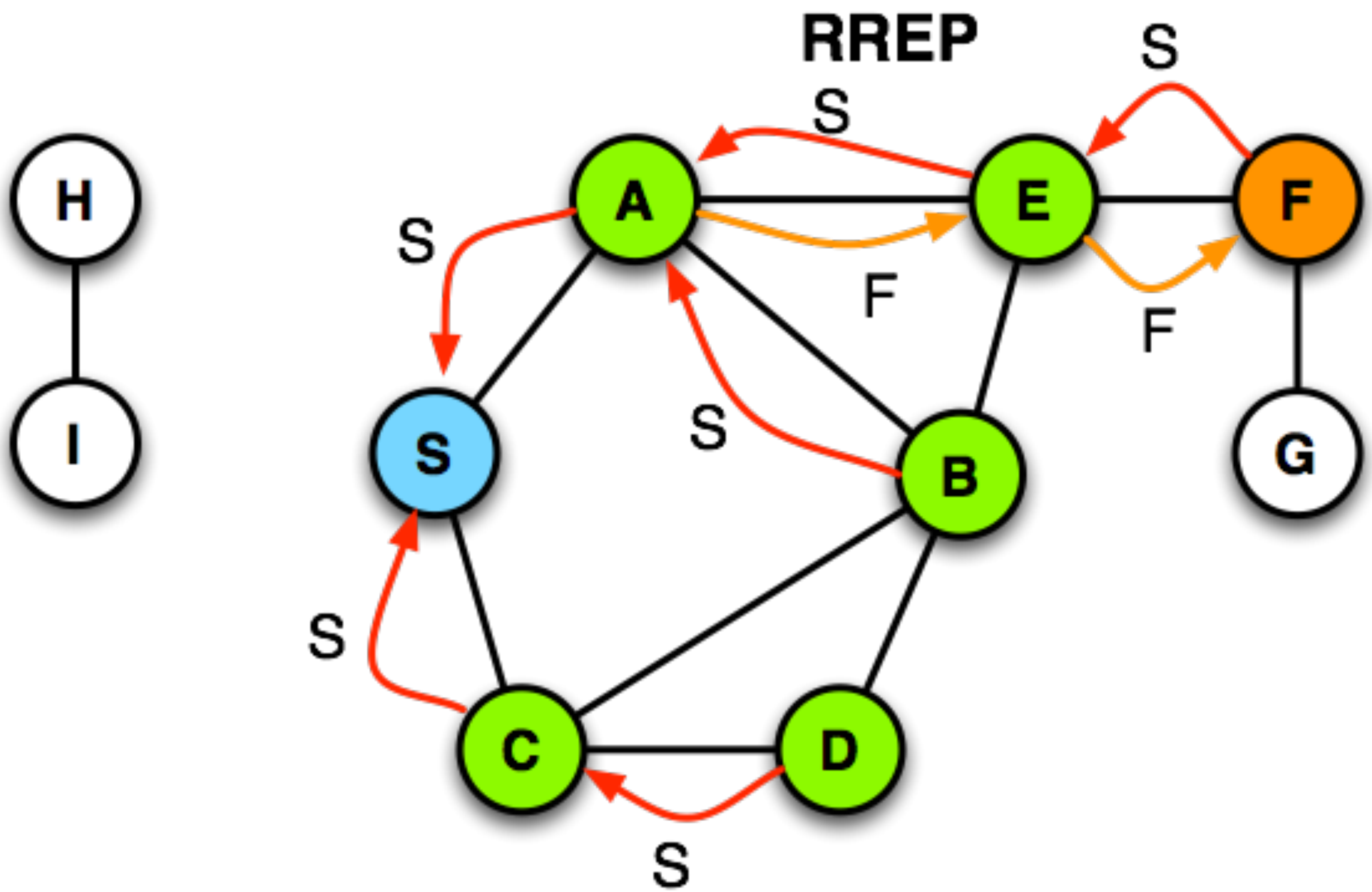
Route Reply

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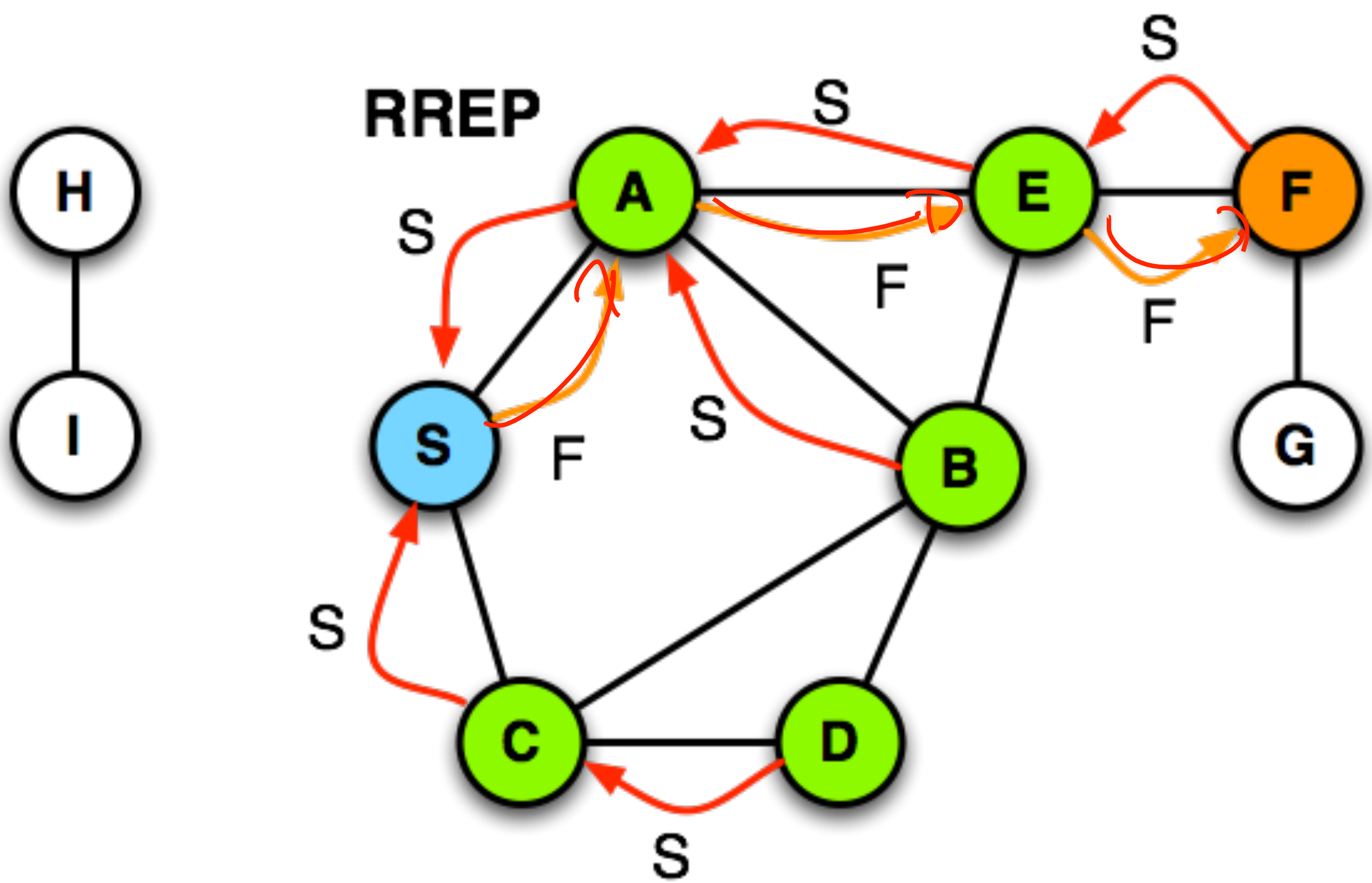
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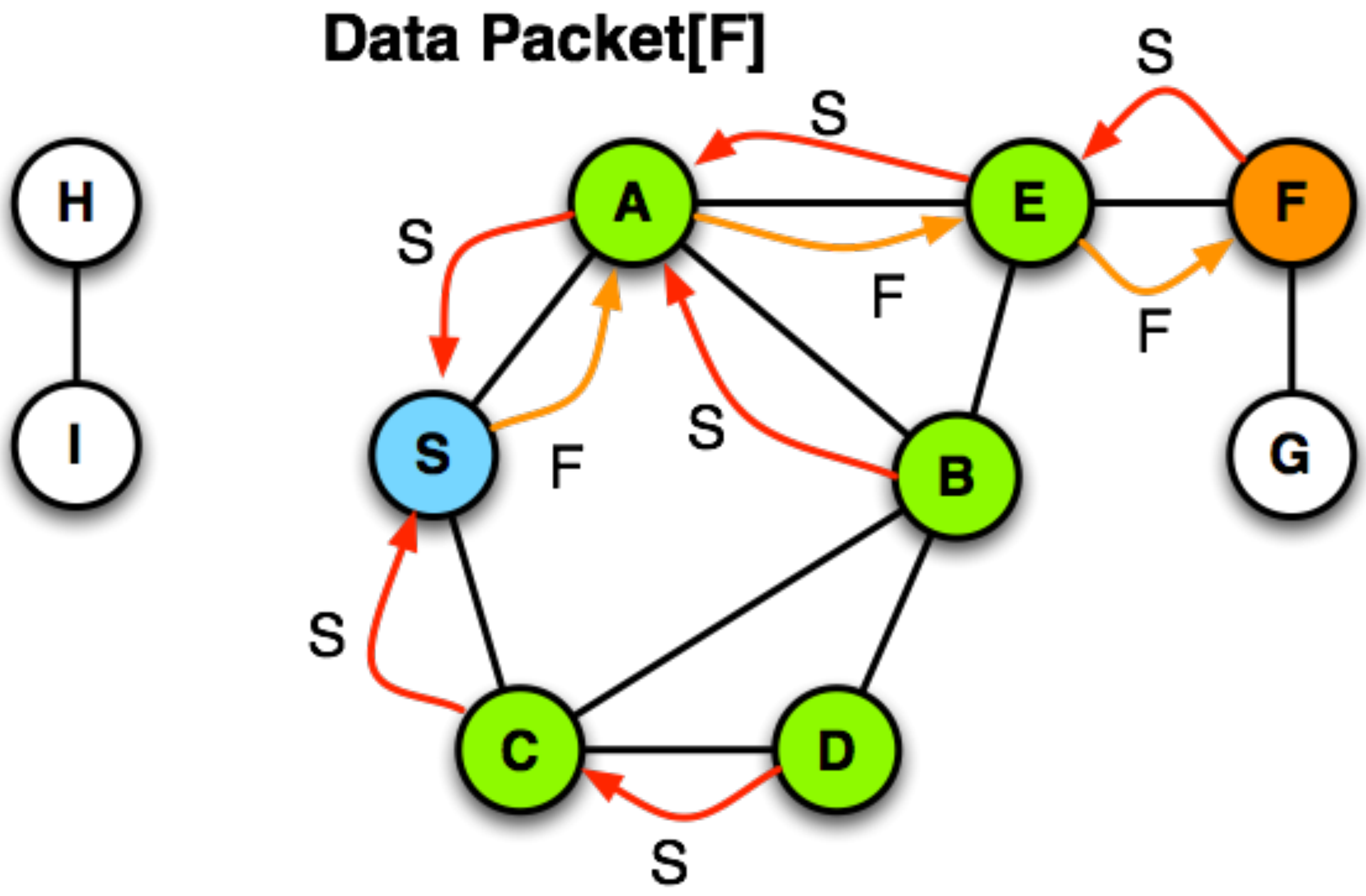
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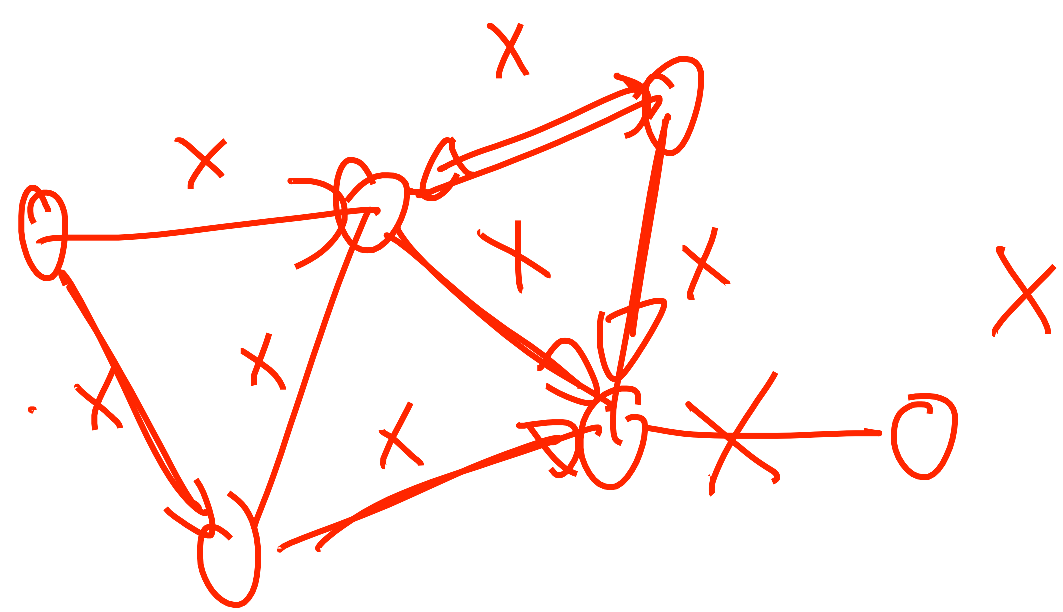
Route Reply in AODV

- Intermediate nodes
  - may send route-reply packets, if their cache information is up-to-date
- Destination Sequence Numbers
  - measure the up-to-dateness of the route information
  - AODV uses cached information less frequently than DSR
  - A new route request generates a greater destination sequence number
  - Intermediate nodes with a smaller sequence number may not generate a route reply (RREP) packets

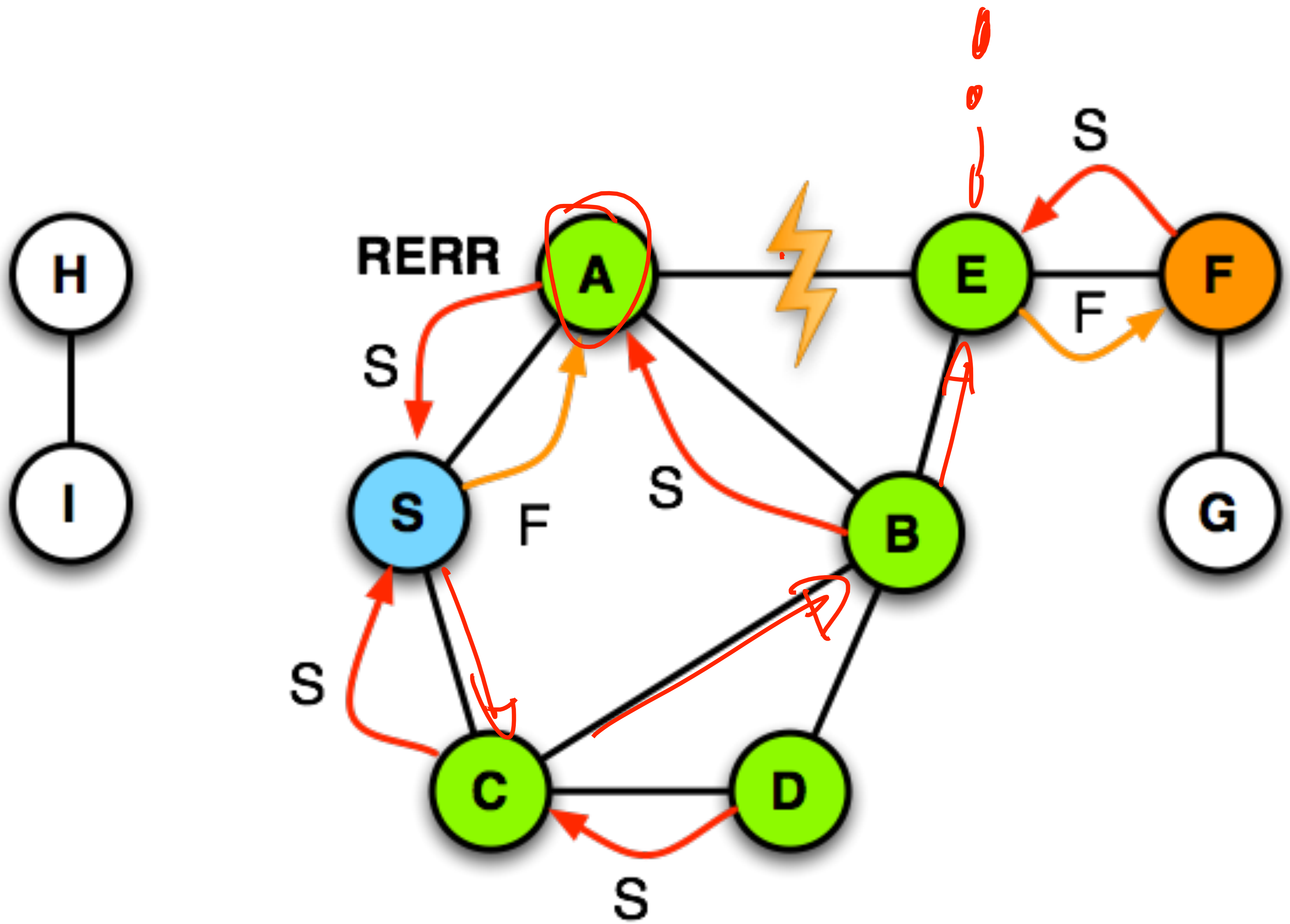
Timeouts

- Reverse pointers are deleted after a certain time
  - RREP timeout allows the transmitter to go back
- Routing table information to be deleted
  - if they have not been used for some time
  - Then a new RREQ is triggered



Link Failure Reporting

- Neighbors of a node X are active,
  - if the routing table cache are not deleted
- If a link of the routing table is interrupted,
  - then all active neighbors are informed
- Link failures are distributed by Route Error (RERR) packets to the sender
  - also update the Destination Sequence Numbers
  - This creates new route request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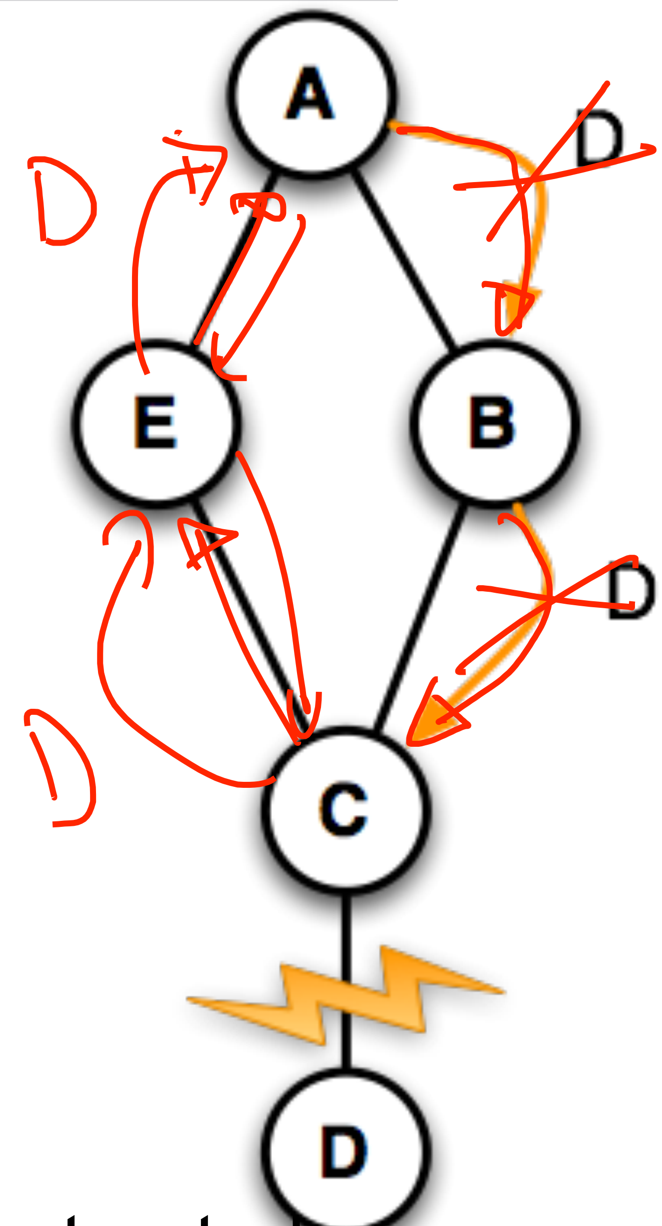
Detection of Link Failure

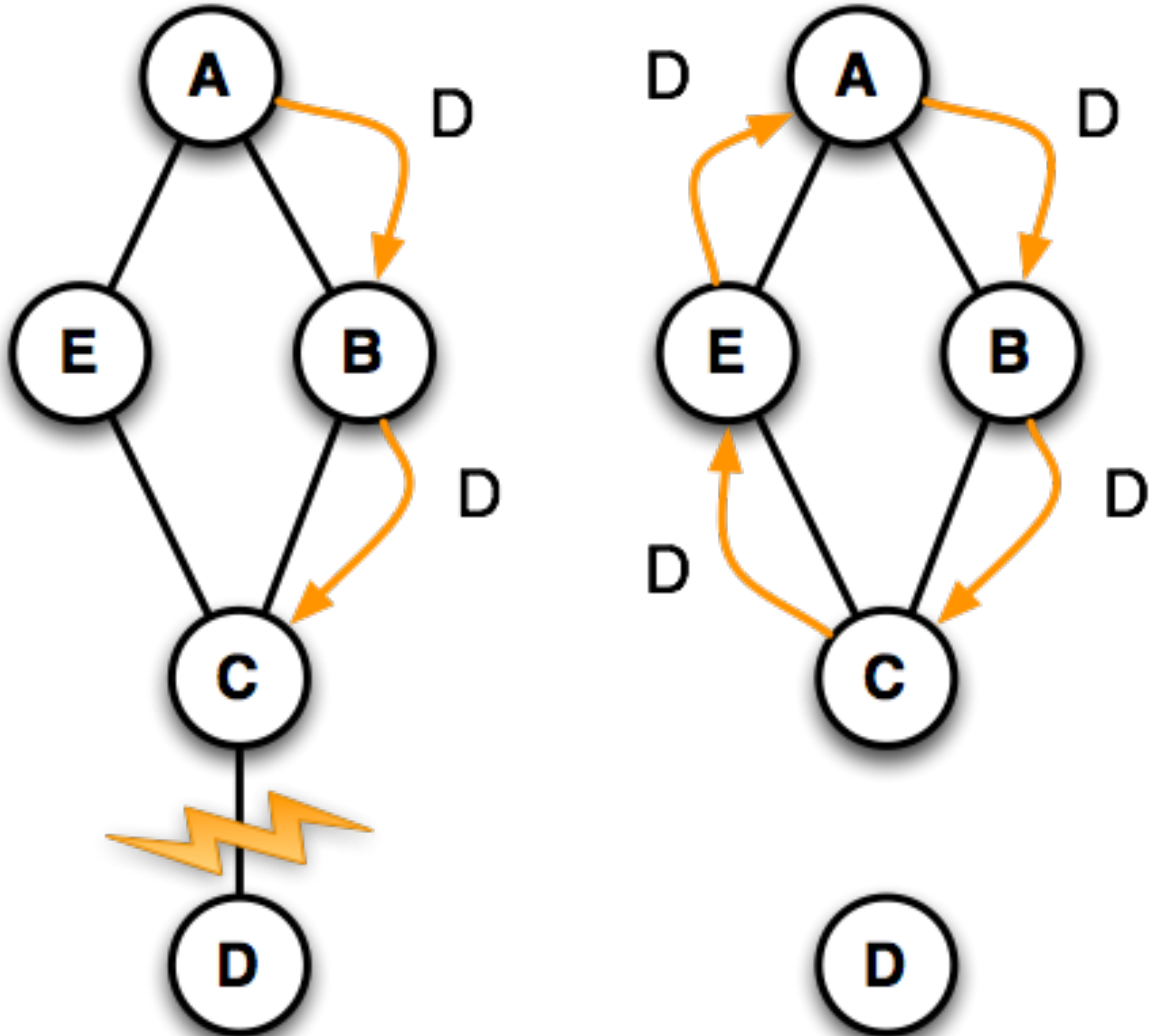
- Hello messages
  - neighboring nodes periodically exchange hello packets from
  - Absence of this message indicates link failure
- Alternative
  - use information from MAC protocol

Sequence Numbers

- When a node receives a message with destination sequence number N
  - then this node sets its number to N
  - if it was smaller before
- In order to prevent loops
  - If A has not noticed the loss of link (C, D)
    - (for example, RERR is lost)
  - If C sends a RREQ
    - on path C-E-A
  - Without sequence numbers, a loop will be constructed
    - since A "knows" a path to D, this results in a loop (for instance, CEABC)



Sequence Numbers



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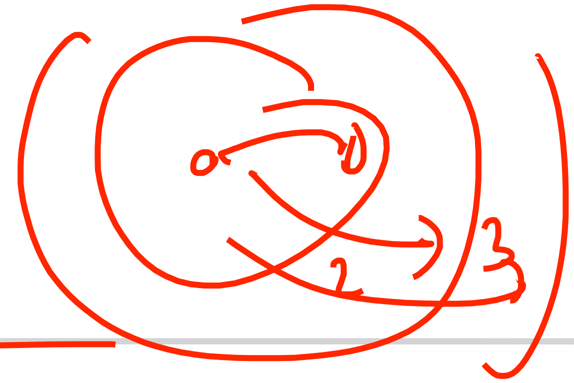
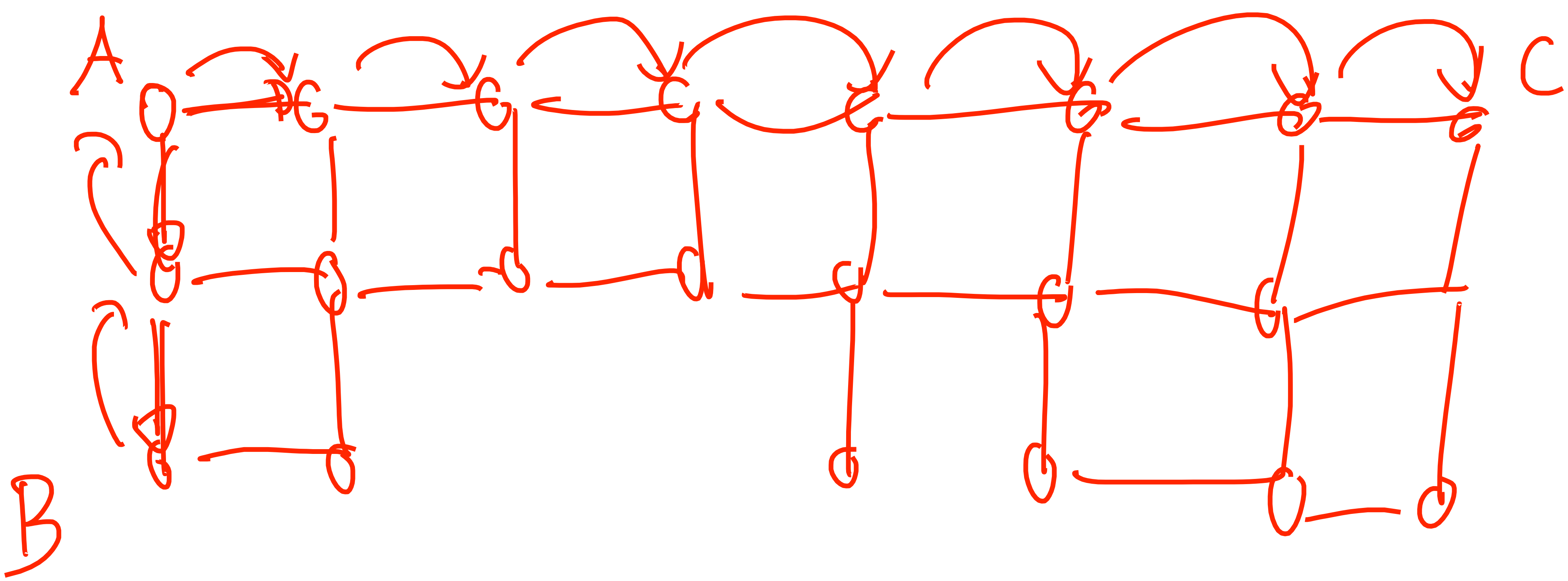
Optimization
Expanding Ring Search



- Route Requests
  - *start with small time-to-live value (TTL)* ↔ IPv4
  - if no Route Reply (RREP) is received, the value is increased by a constant factor and resent
- This optimization is also applicable for DSR

hop count

TTL	∞		
1	1	1	1
2	2	2	4
3	3	3	9
⋮		4	16



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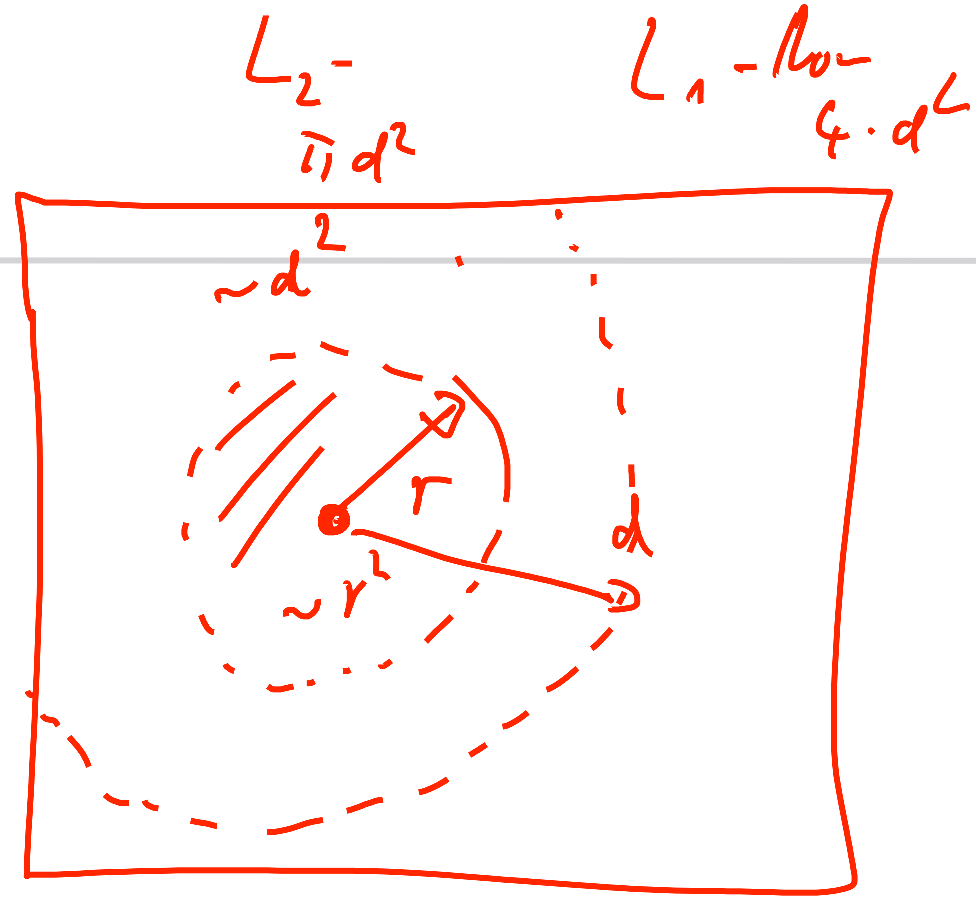
	best
∘ Traffic	$\Theta(d^2)$
∘ Time	$2d$



1, 2, 3, 4 ...

Traffic: $1^2 + 2^2 + 3^2 + \ldots + d^2 = \Theta(d^3)$

Time: $2(1 + 2 + 3 + \ldots + d) = \frac{d(d+1)}{2} = \Theta(d^2)$

$1, 2^2, 3^2, 4^2$

4

Time: $1 + (2^2) + (3^2) + (4^2) \ldots + d^2 =$ ~~$\Theta(d^{2.5})$~~ $\Theta(d^{1.5})$

Traffic: $\Theta(d^{2.5})$

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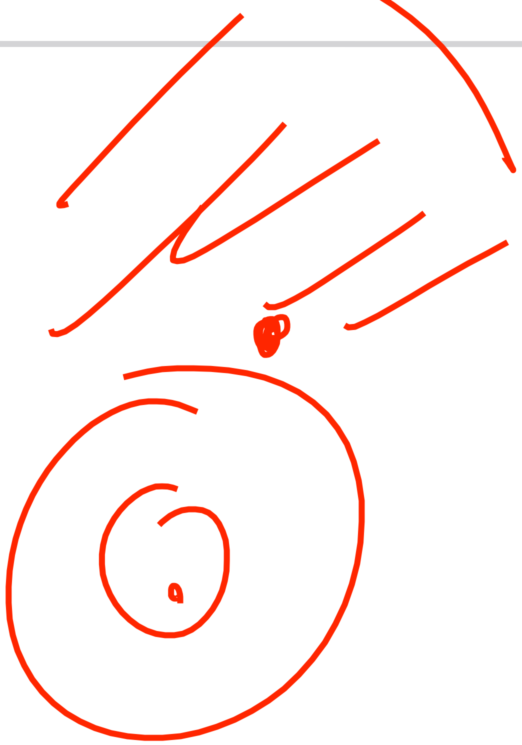
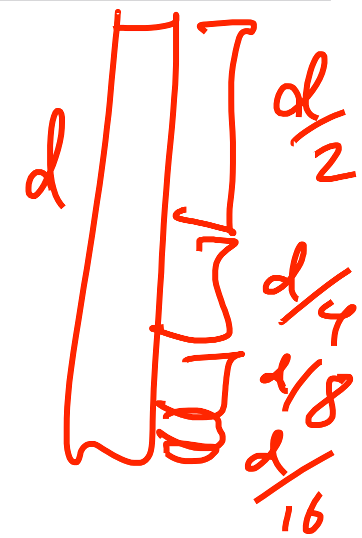
exponential expanding ring search



$1, 2, 4, 8, 16, \ldots, d$

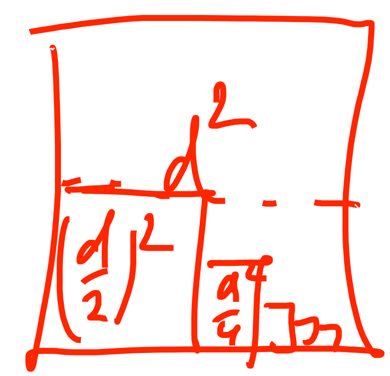


Time: $2 \cdot (1 + 2 + 4 + 8 \ldots + d)$

$\le 2d = 4d$

Traffic: $1 + 2^2 + 4^2 + 8^2 + \ldots + d^2$

$\le d^2 \cdot \frac{3}{2}$



$1, \; 2, \; 2^2, \; 2^{2^2}, \; 2^{2^{2^2}} \;\; | \;\; 2^n, \; 3^n$

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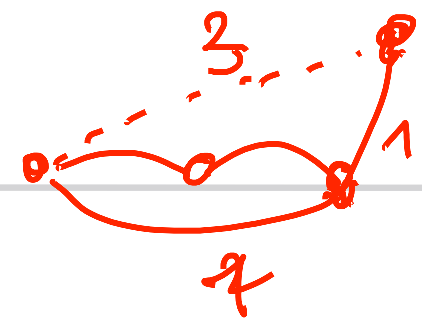
DYMO - Dynamic MANET On-demand (AODVv2) Routing



- Literature
  - I. Chakeres and C. Perkins, “Dynamic MANET On-demand (DYMO) Routing,” IETF MANET, Internet-Draft, 5 December 2008, draft-ietf-manet-dymo-16.
- Improvement of AODV
  - RREQ, RREP to construct shortest length paths
  - Path accumulation
    - a single route-request creates routes to all the nodes along the path to the destination
  - Unreliable links can be assigned a cost higher than one
  - Sequence numbers to guarantee the freshness routing table entries

Routing in MANETs

- Routing
  - Determination of message paths
  - Transport of data
- Protocol types
  - proactive
    - Routing tables with updates
  - reactive
    - repair of message paths only when necessary
  - hybrid
    - combination of proactive and reactive

Routing Protocols for MANETs

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- **Proactive**
  - Routes are **demand independent**
  - Standard Link-State und Distance-Vector Protocols
    - Destination Sequenced Distance Vector (**DSDV**)
    - Optimized Link State Routing (**OLSR**)
- **Reactive**
  - Route are determined when needed
    - Dynamic Source Routing (**DSR**)
    - Ad hoc On-demand Distance Vector (**AODV**)
    - Dynamic MANET On-demand Routing Protocol
    - Temporally Ordered Routing Algorithm (**TORA**)
- **Hybrid**
  - combination of reactive und proactive
    - Zone Routing Protocol (**ZRP**)
    - Greedy Perimeter Stateless Routing (**GPSR**)

Optimized Link State Routing

- Literature
  - RFC3626: Clausen, Jacquet, *Optimized Link State Routing Protocol, 2003*
  - First published 1999
- Most proaktive protocols are are based on
  - Link-state routing
  - Distance-Vector routing

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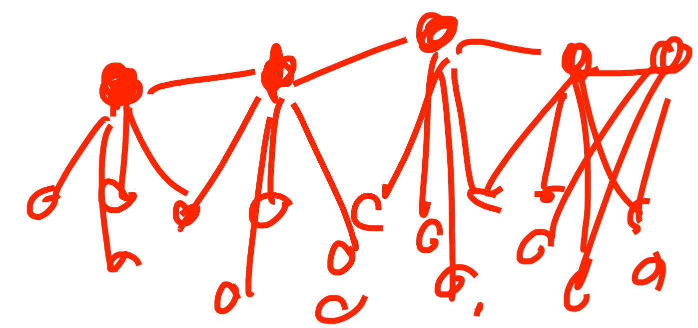
Link State Routing

- Connections are periodically published throughout the network
- Nodes propagate information to their neighbors
  - i.e. flooding
- All network information is stored
  - with time stamp
- Each node computes shortest paths
  - possibly also other route optimizations

Optimized Link State Routing (OLSR)

- Each nodes broadcasts its neighborhood list
  - Each node can determinate its 2-hop neighborhood
- Reducing the number of messages
  - fewer nodes participate in flooding

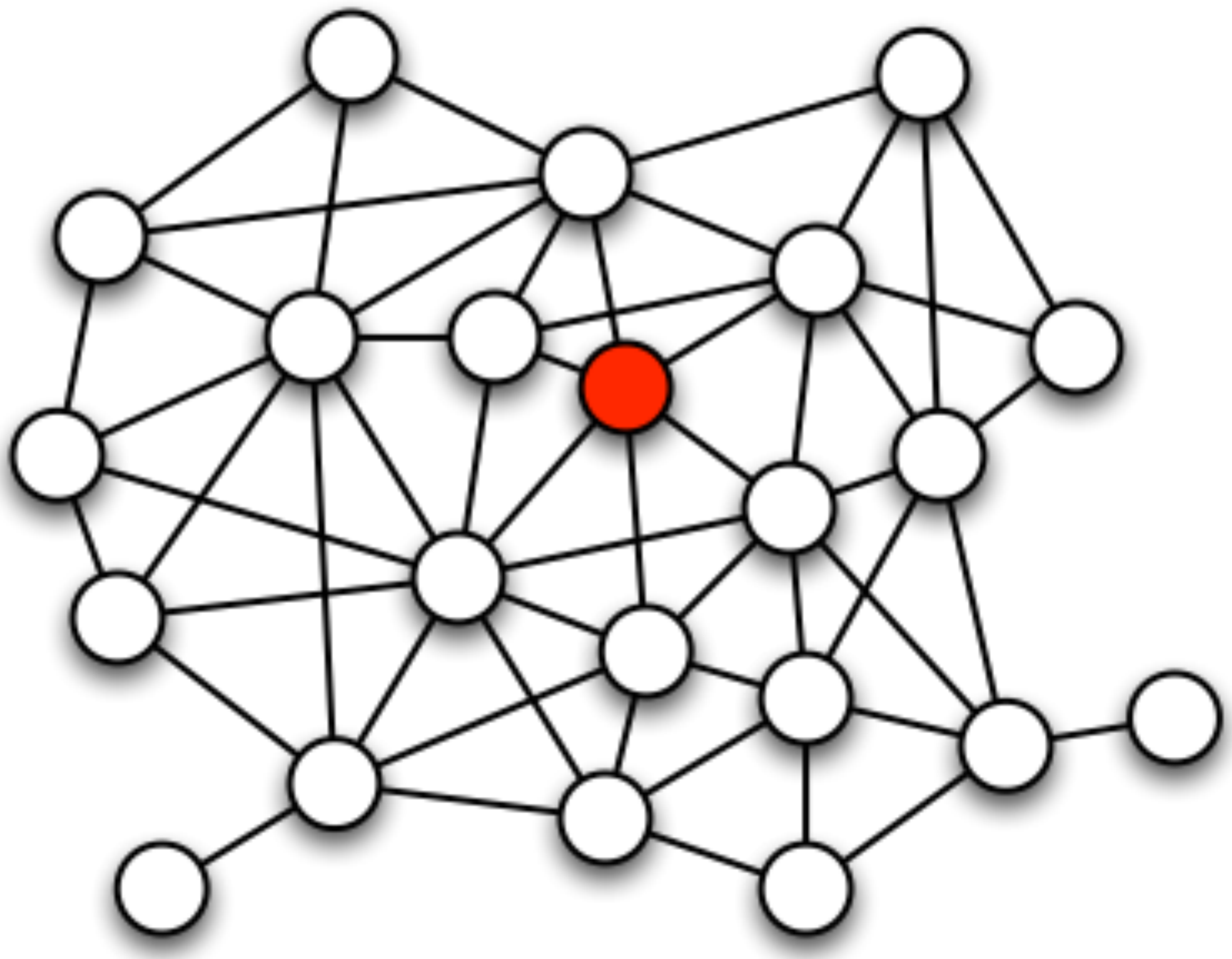


- Multipoint relay node (MPRs)
  - are chosen such that each node has at least one multipoint relay node as in its 2-hop neighborhood
  - Only multipoint relay nodes propagate link information
- Node sends their neighborhood lists
  - such that multipoint relay nodes in the 2-hop neighborhood can be chosen

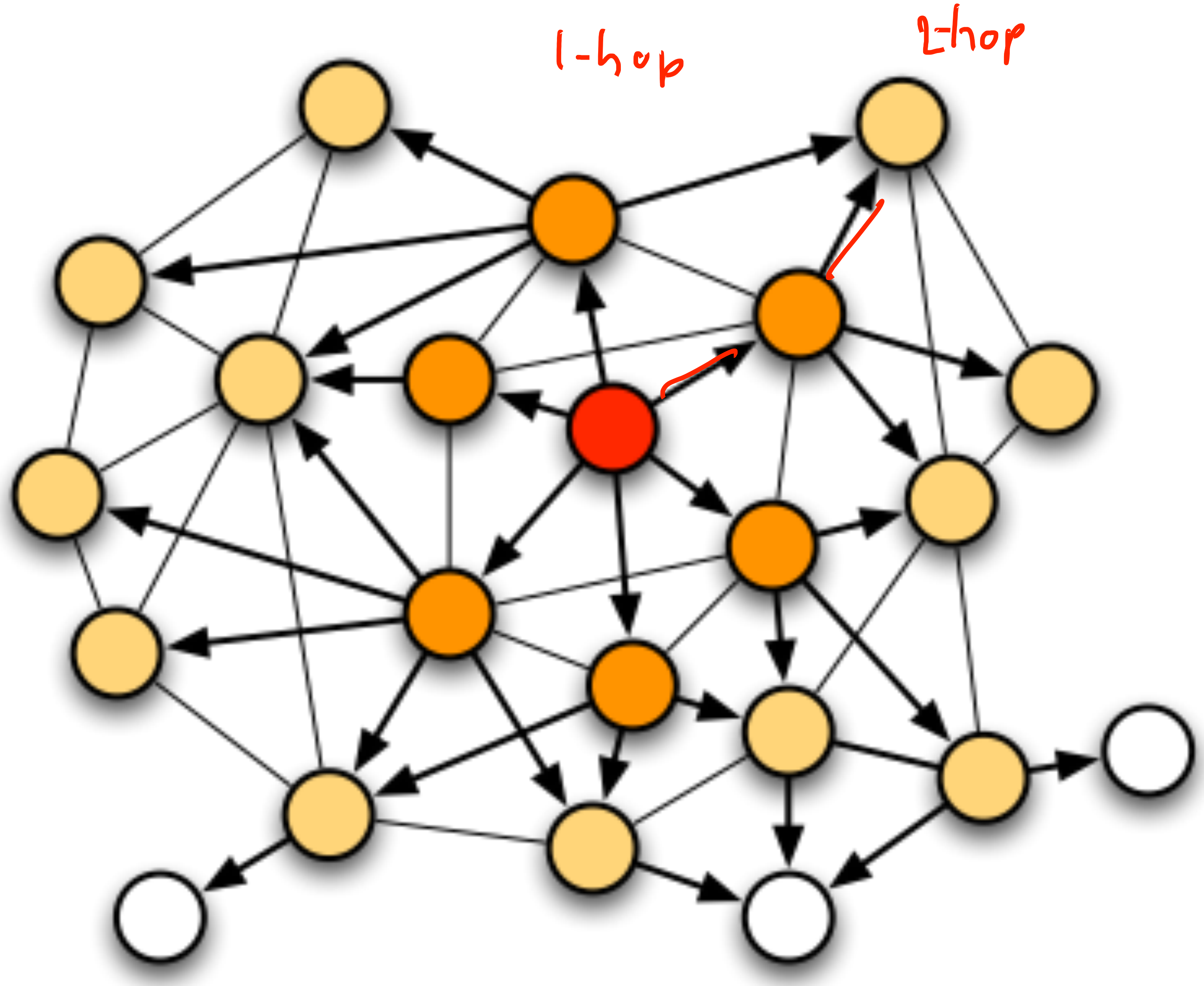
Optimized Link State Routing (OLSR)

- Combines Link-State protocol and topology control
- Topology control
  - Each node chooses a minimal dominating set of the 2 hope neighborhood
    - ***multipoint relays (MPR)***
    - Only these nodes propagate link information
    - More efficient flooding
- Link State component
  - Standard link state algorithm on a reduced network

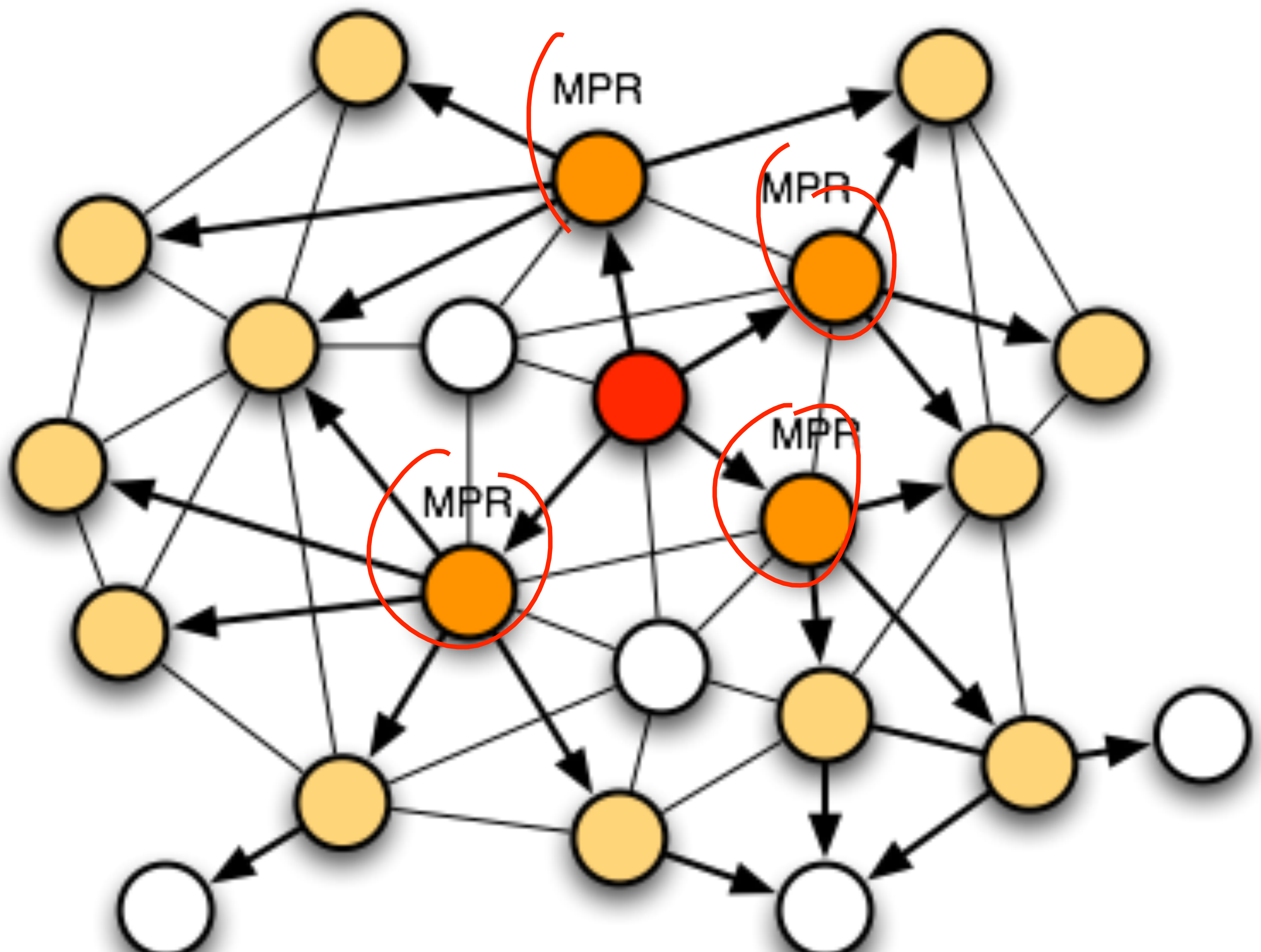
Optimized Link State Routing (OLSR)



Optimized Link State Routing (OLSR)



Optimized Link State Routing (OLSR)

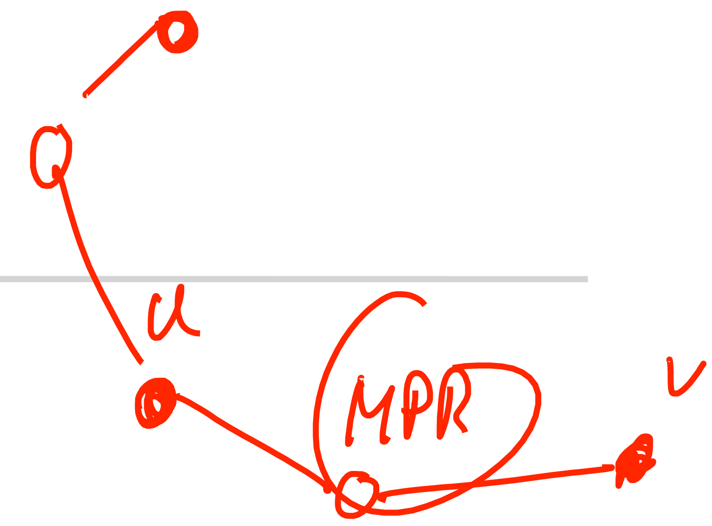


Selection of MPRs

- Multipoint Relaying for Flooding Broadcast Messages in Mobile Wireless Networks, Amir Qayyum, Laurent Viennot, Anis Laouiti, HICCS 2002
- Problem is NP-complete
- Heuristics
  - recommended for OLSR
- Notations
  - N(x): 1 hop neighborhood of x
  - $N^2(x)$: 2 hop neighborhood of x
  - Alle connections are symmetrical

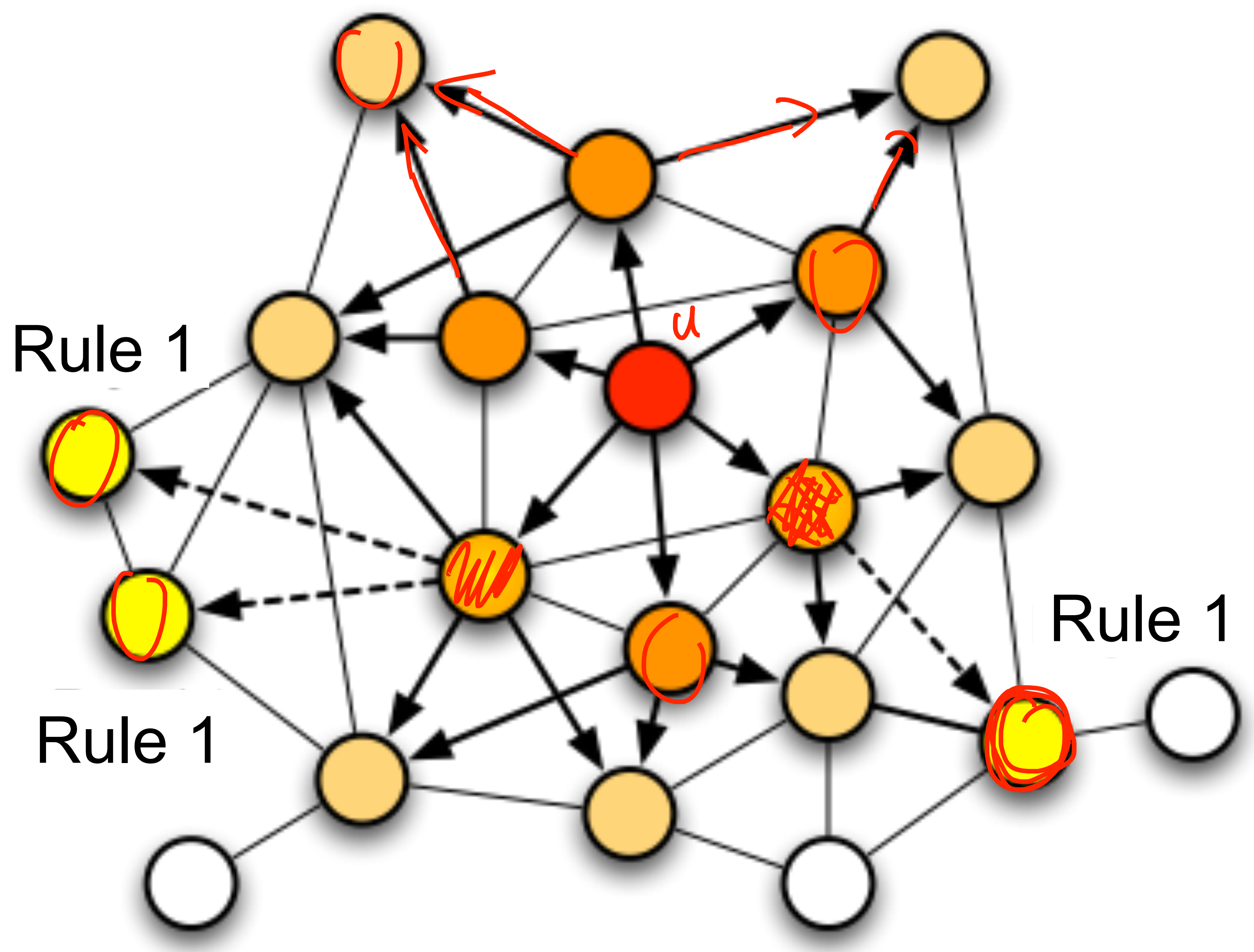
$N^2(x) = N(N(x))$

Selection of MPRs

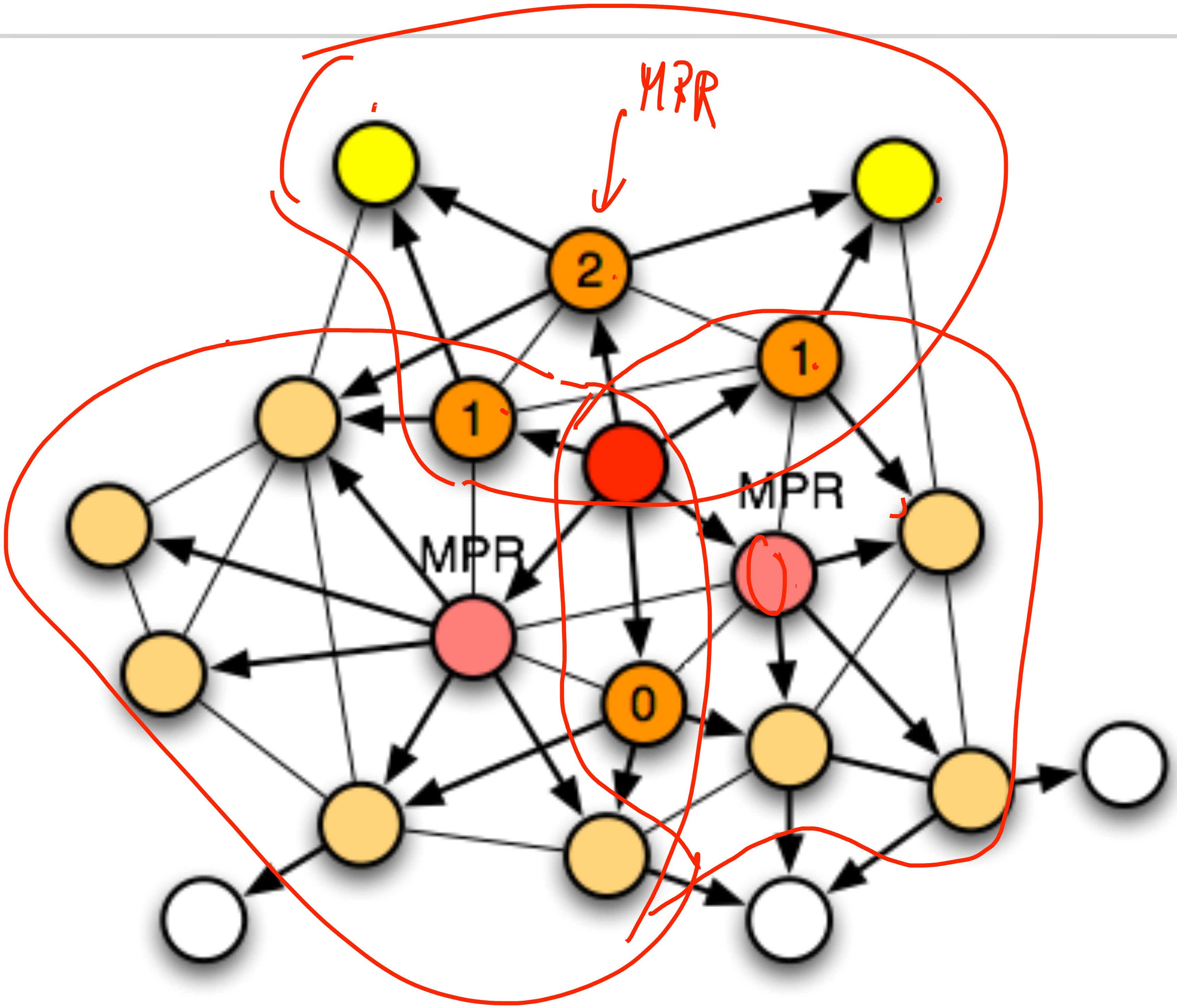


- At the beginning there is no MPR
  - Each node chooses its MPRs
- Rule 1: A node of x is selected as MPR, if
  - it in N(x) and
  - it is the only neighborhood node in the node $N^2(x)$
- Rule 2: If nodes in N^2 (x) are not covered:
  - Compute for each node in N(x) the number of uncovered nodes in $N^2(x)$
  - Select as MPR the node that maximizes the value

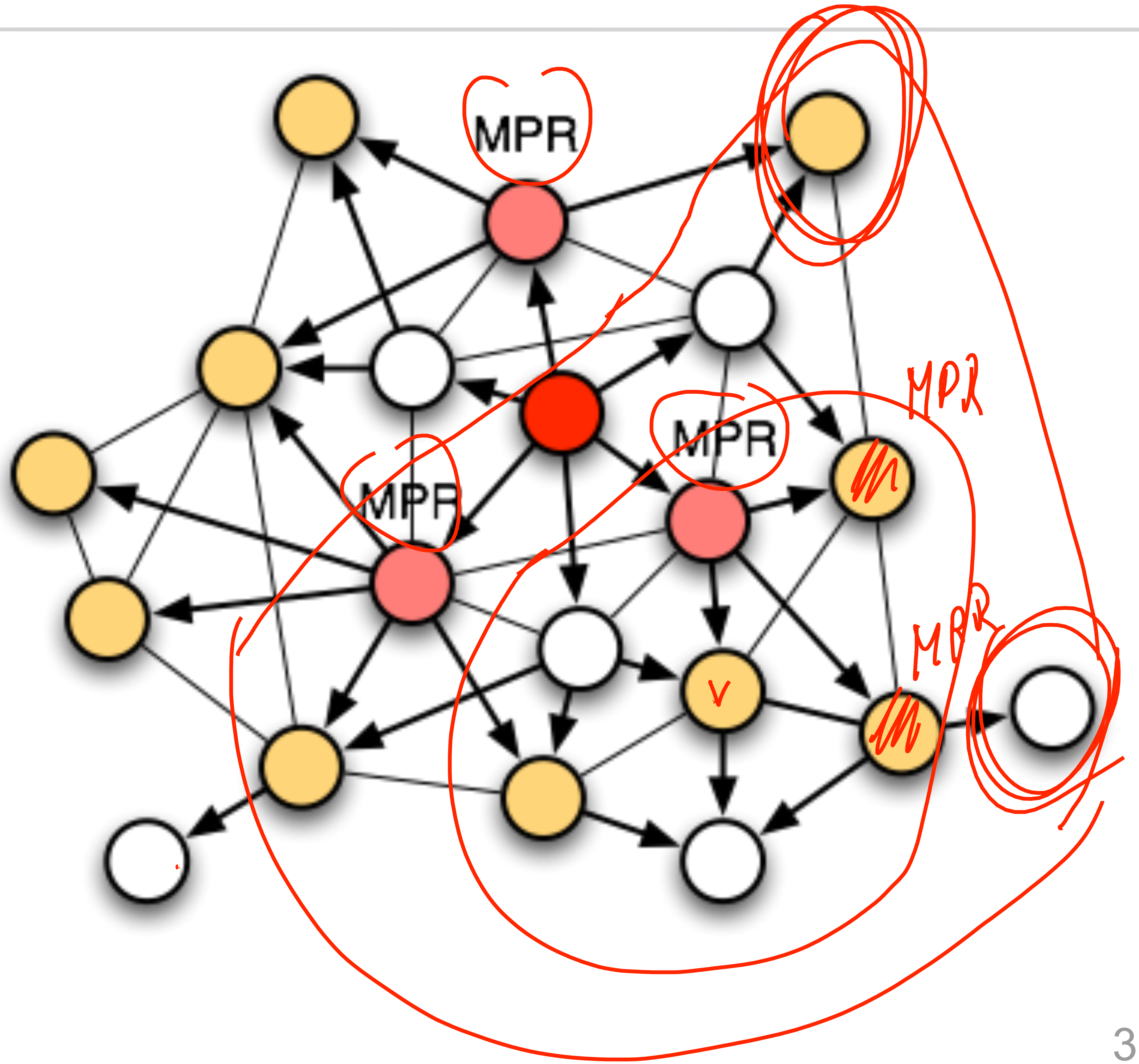
Rule 1

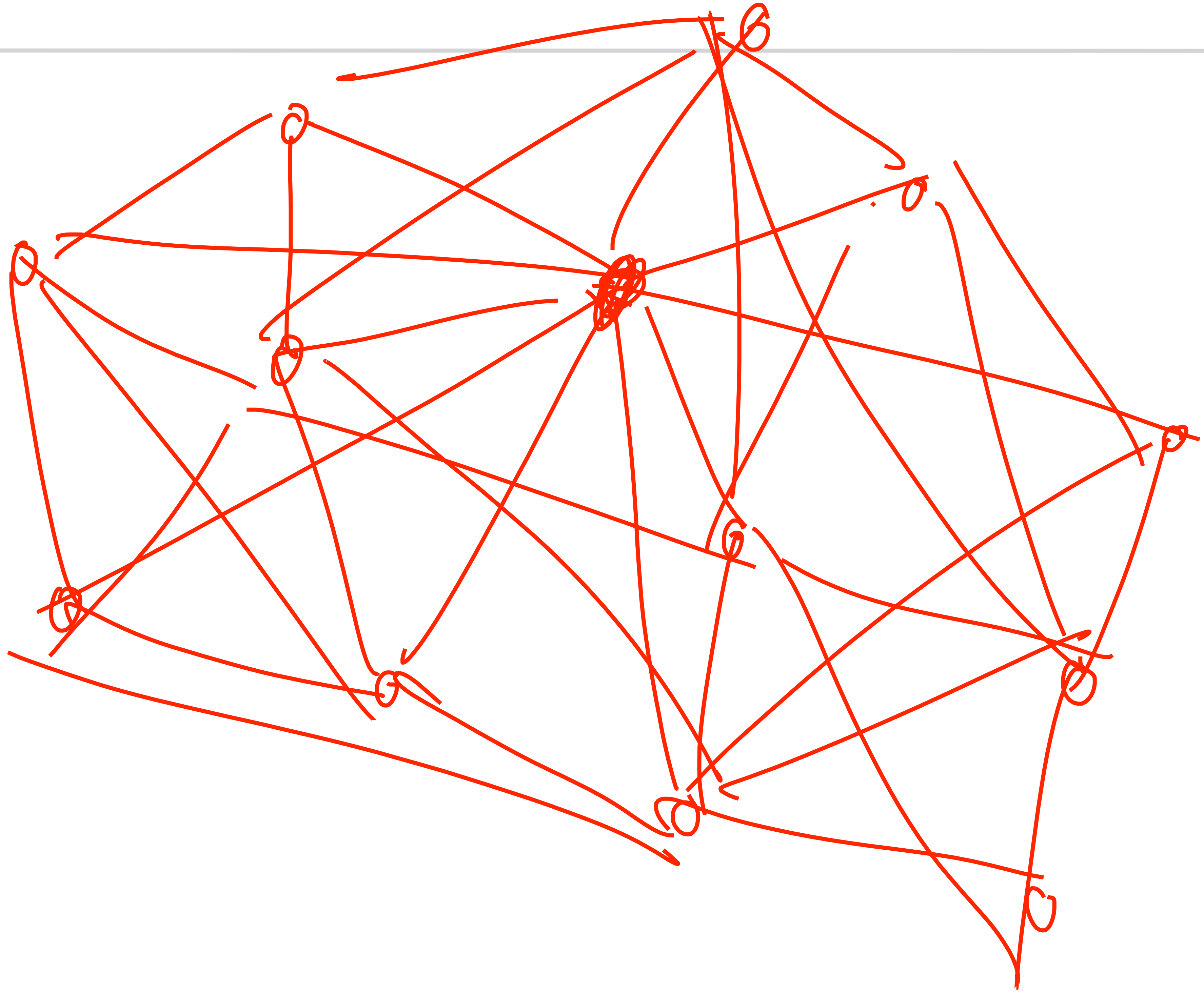


Rule 2

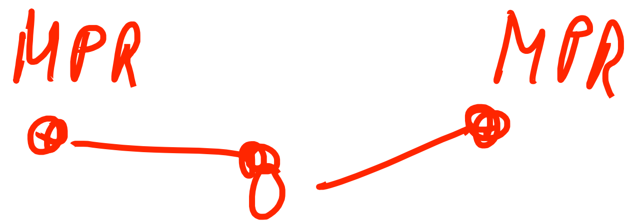


MPRs





OLSR



- OLSR is flooding link information using MPRs
  - Multipoint-Relays
- Receivers choose their own MPRs for propagating
  - Each node chooses its own MPRs
- Routes use only MPRs as intermediate nodes

Zone Routing Protocol (ZRP)

- Haas 1997
  - *A new routing protocol for the reconfigurable wireless networks*, Proc. of IEEE 6th International Conference on Universal Personal Communications, 562–566
- Zone Routing Protocol combine
  - Proactive protocol
    - for local routing
  - reactive protocol
    - for global routing

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ZRP

- Routing zone of a node x
  - Nodes in a given maximum hop-distance d
- Peripheral nodes
  - all nodes have exactly the hop-distance d
  - within the routing zone x

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ZRP

- Intra zone routing
  - proactive update the connection information in the routing zone of node
    - e.g. with link state or distance vector protocols
- Inter zone routing
  - Reactive route discovery is used for distant / unknown nodes
  - Procedure similar to DSR
  - Only peripheral nodes reach further information

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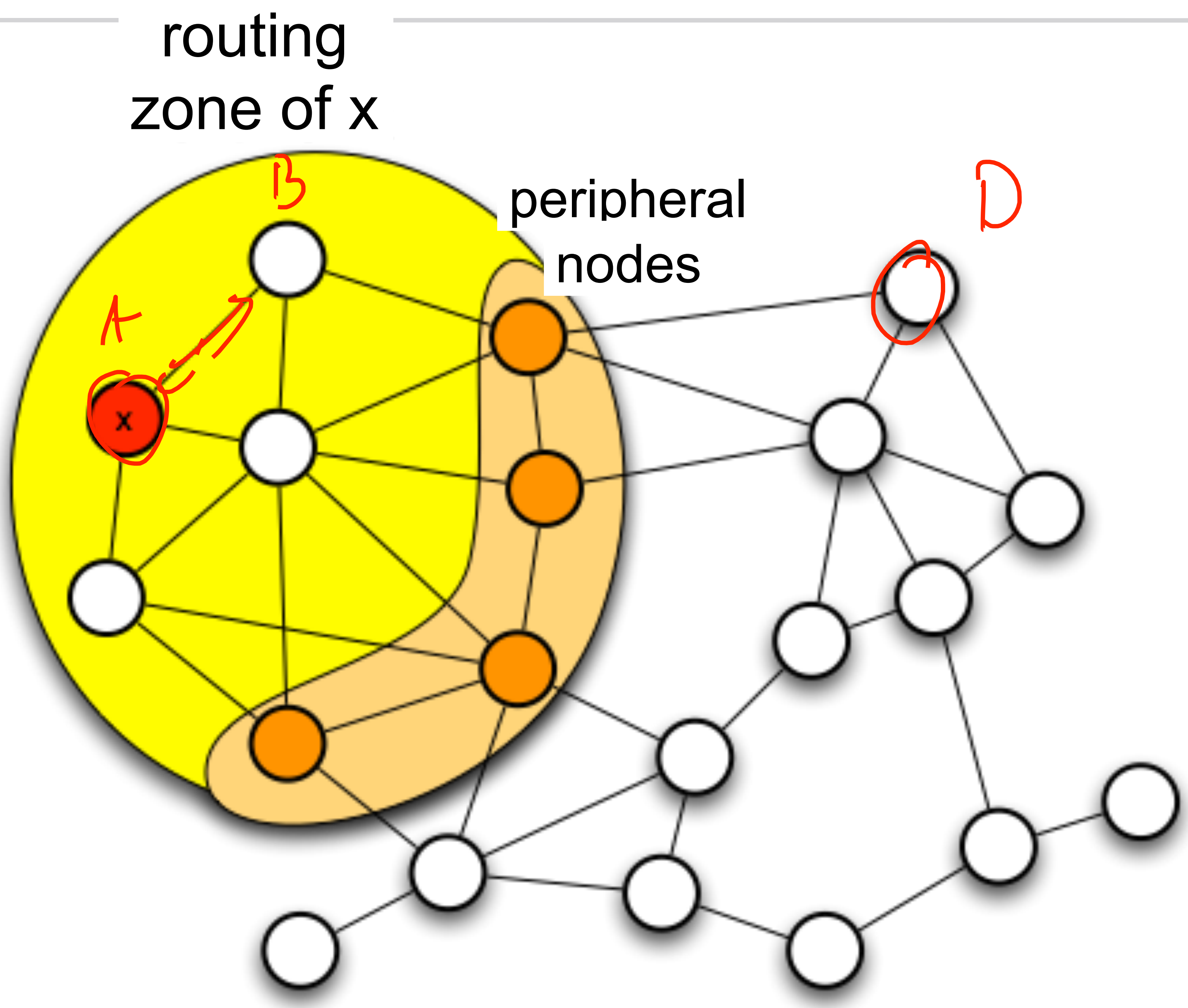
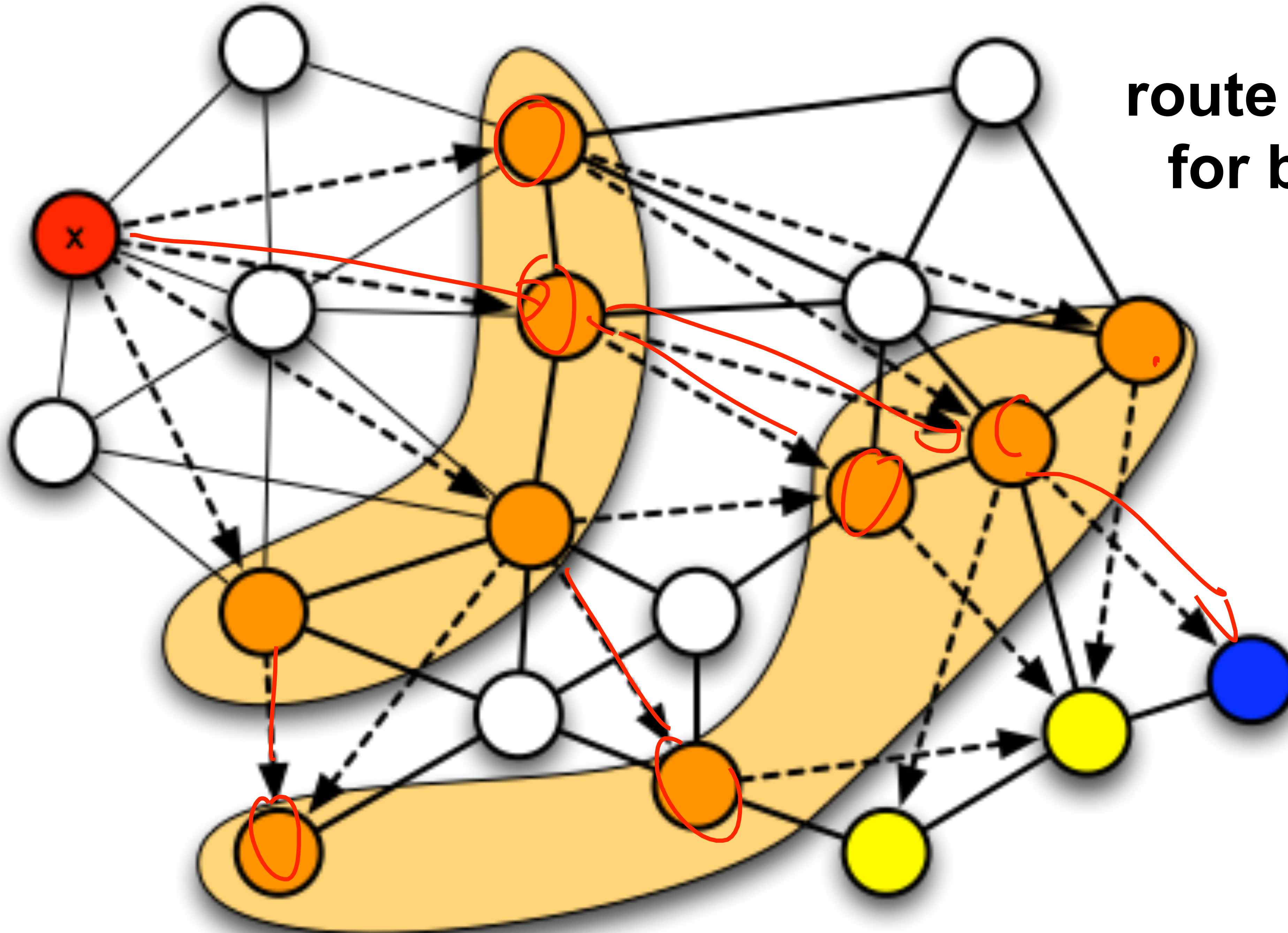
ZRP: Example with radius d=2

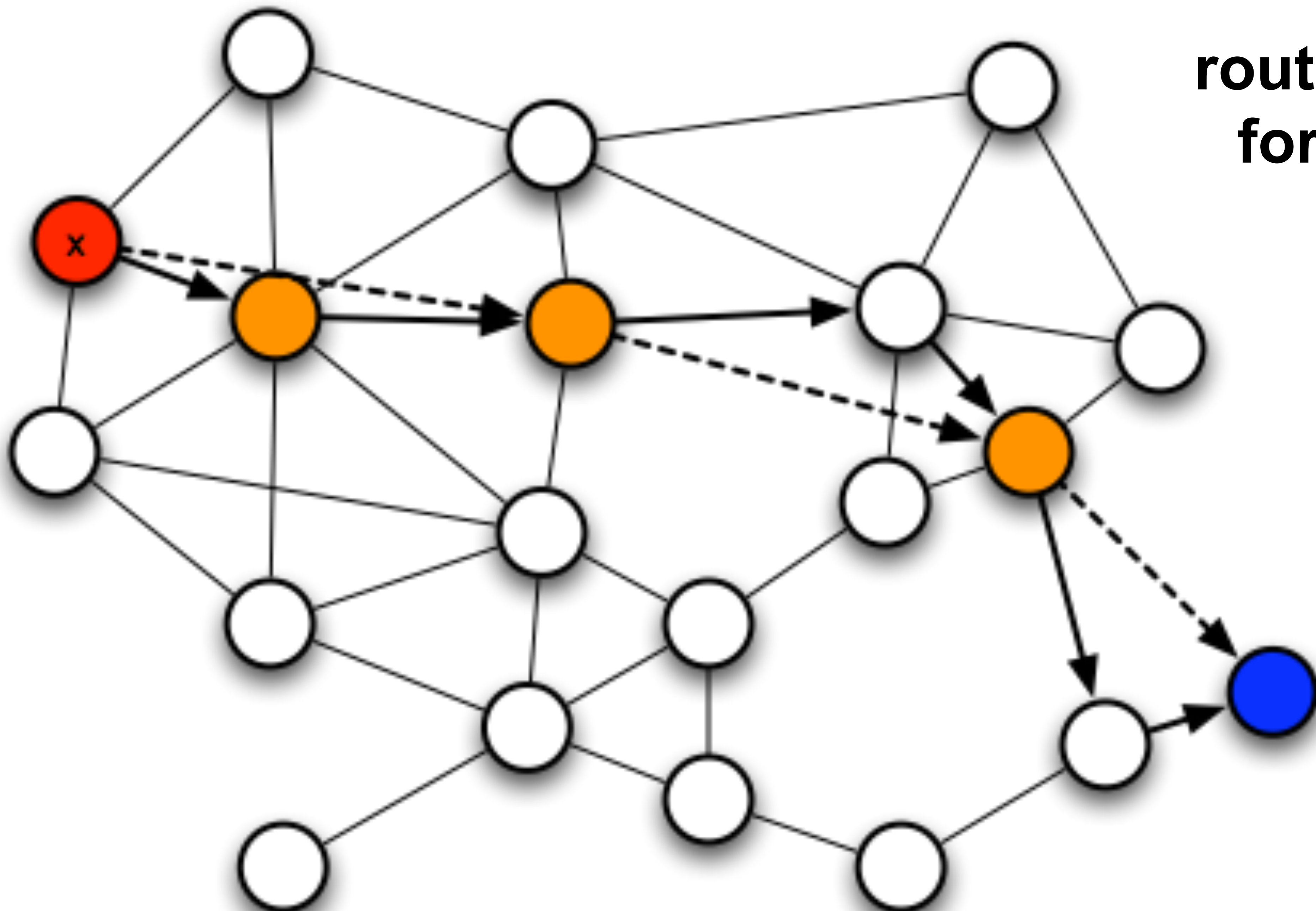


ZRP: Example with radius d=2



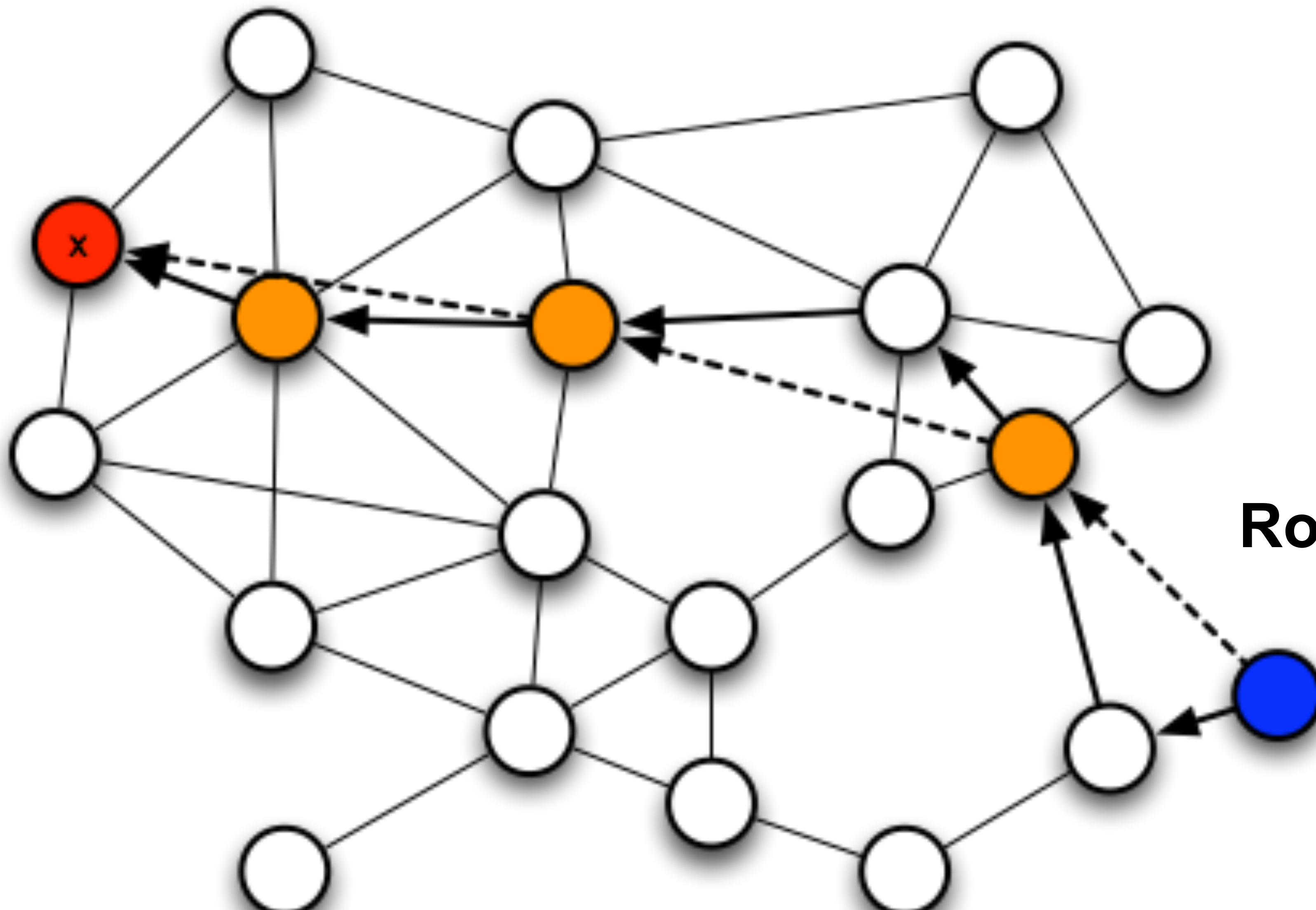
route discovery for blue node

ZRP: Example with radius d=2



route discovery for blue node

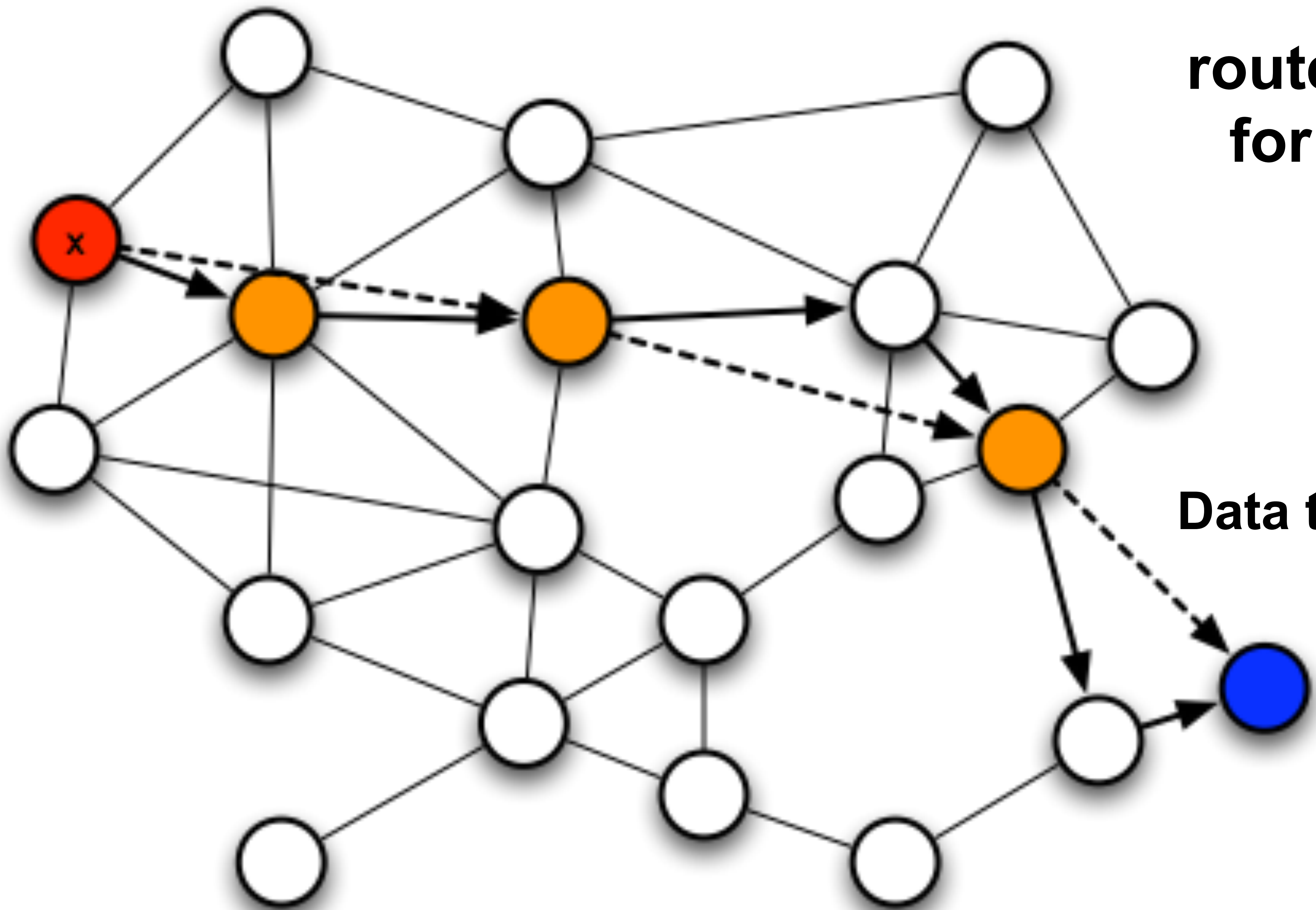
ZRP: Example with radius d=2



route discovery for blue node

Route Reply

ZRP: Example with radius d=2

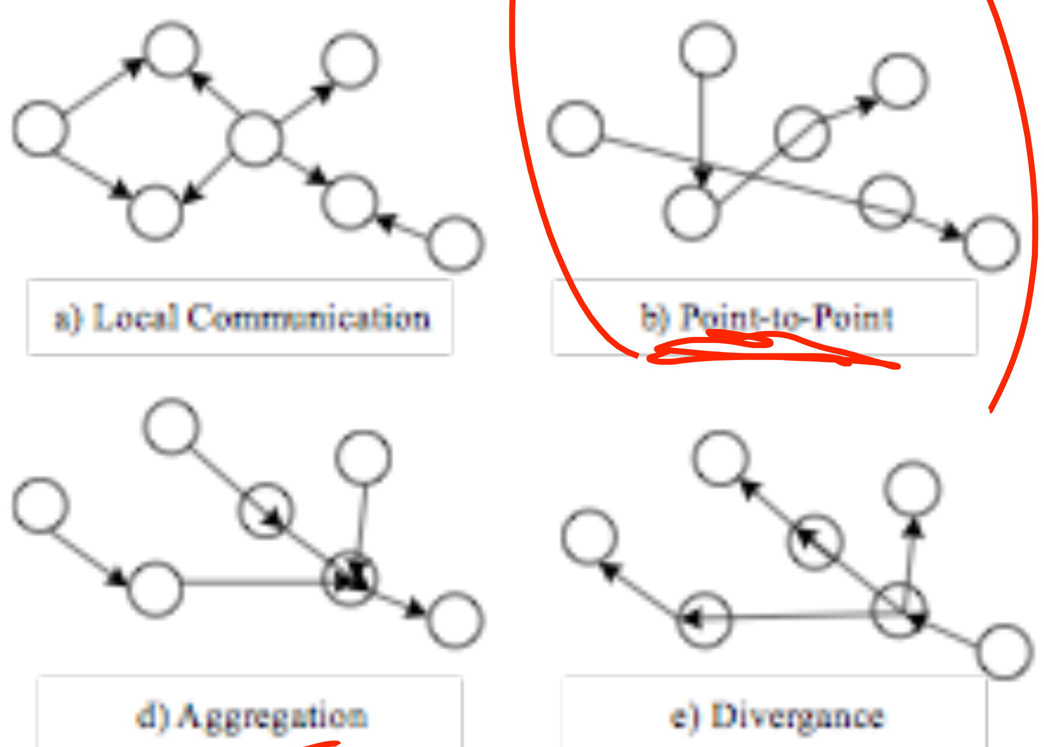


Routing Protocols for WSNs

- Literature
  - From MANET To IETF ROLL Standardization: A Paradigm Shift in WSN Routing Protocols, Watteyne et al, IEEE Communication Survey & Tutorials, Vol. 13, No. 4, 4th Quarter, 2011
  - Routing Protocols in Wireless Sensor Networks: A Survey, Goyal, Tripathy, 2012 Second International Conference on Advanced Computing & Communication Technologies
  - Energy-Efficient Routing Protocols in Wireless Sensor Networks: A Survey, Pantazis et al., IEEE Communication Survey & Tutorials, Vol. 15, No. 2, 2nd Quarter, 2013

Types of Communication

- Single Hop
  - Two participants, sender/receiver, e.g. outdoor temperature sensor
  - Base stations: master/slave, e.g. Bluetooth
  - Many participants, i.e. data mule
- Multihop
  - Local Communication
  - Point-to-Point/Unicast
  - Convergence
  - Aggregation
  - Divergance

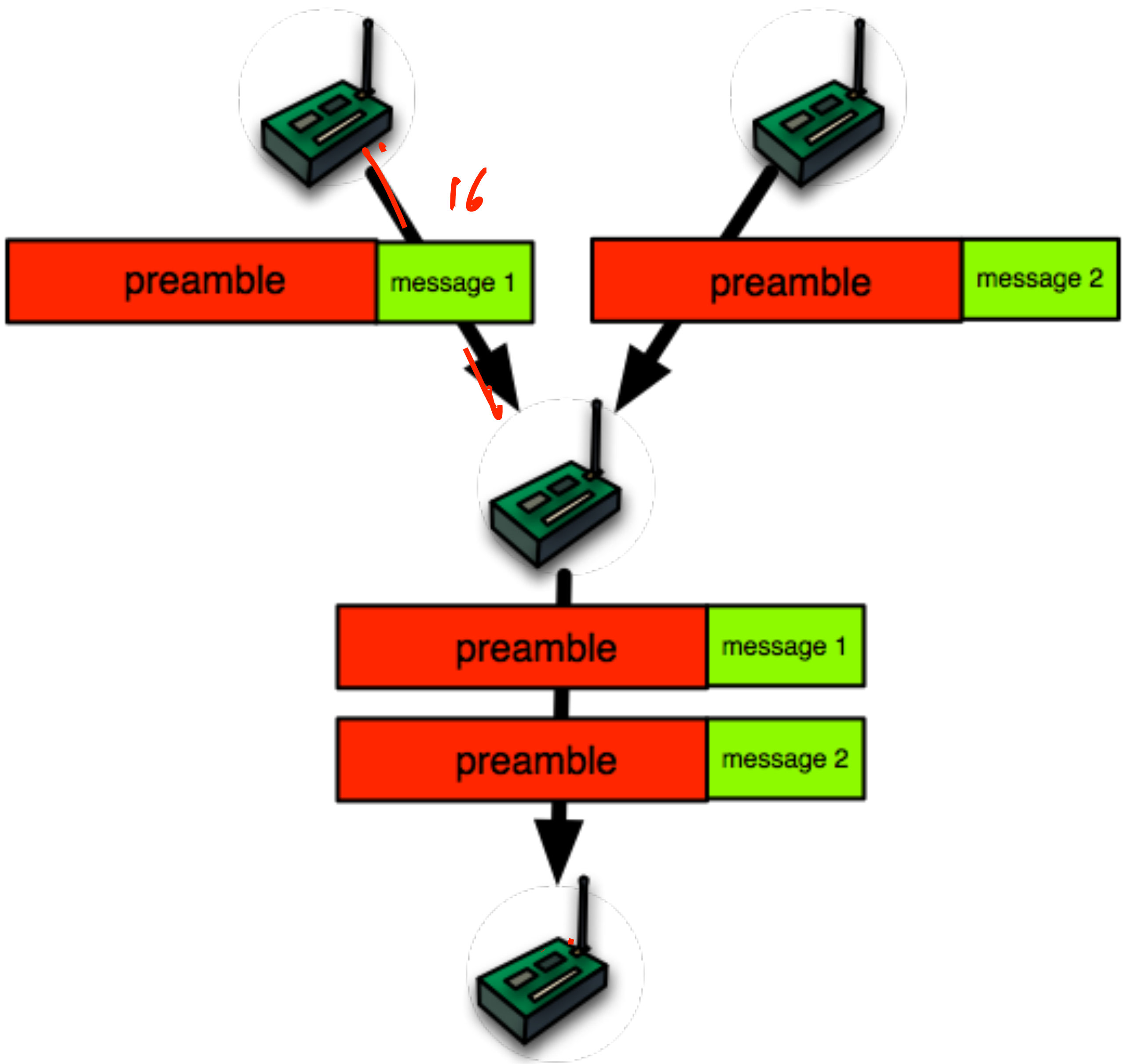


Energy-Efficient Routing Protocols in Wireless Sensor Networks: A Survey, Pantazis et al., IEEE Communication Survey & Tutorials, Vol. 15, No. 2, 2nd Quarter, 2013

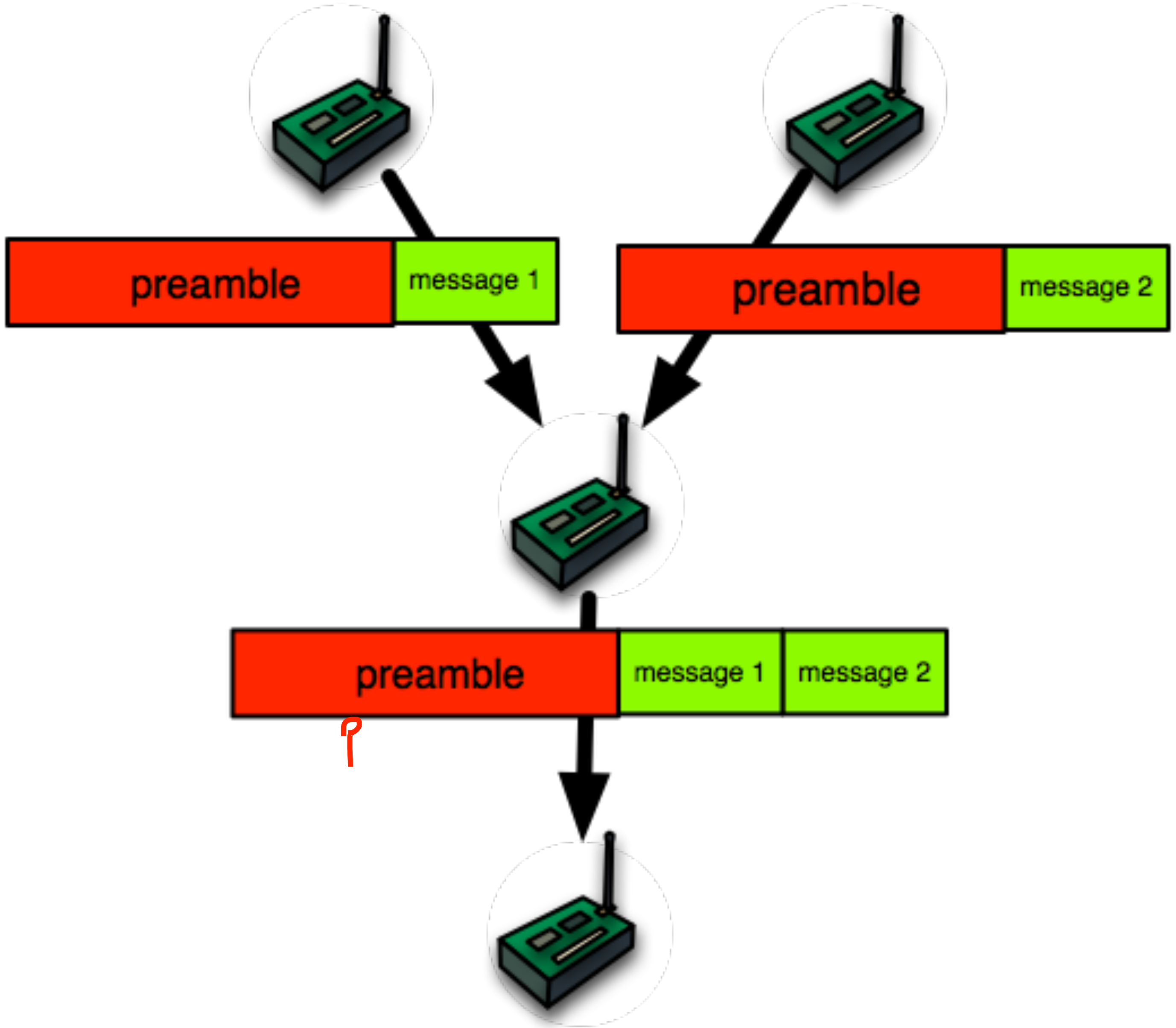
Data Aggregation

- In multi-hop networks combining mesage can improve networking
- Concatenation of messages
  - overall number of headers is reduced
    - especially for Preamble Sampling
  - smaller costs for collision avoidance
- Recalculation of contents
  - e.g. If the minimum temperature is required, then it satisfies to forward the smallest value
  - For this purpose, collect the input over some time

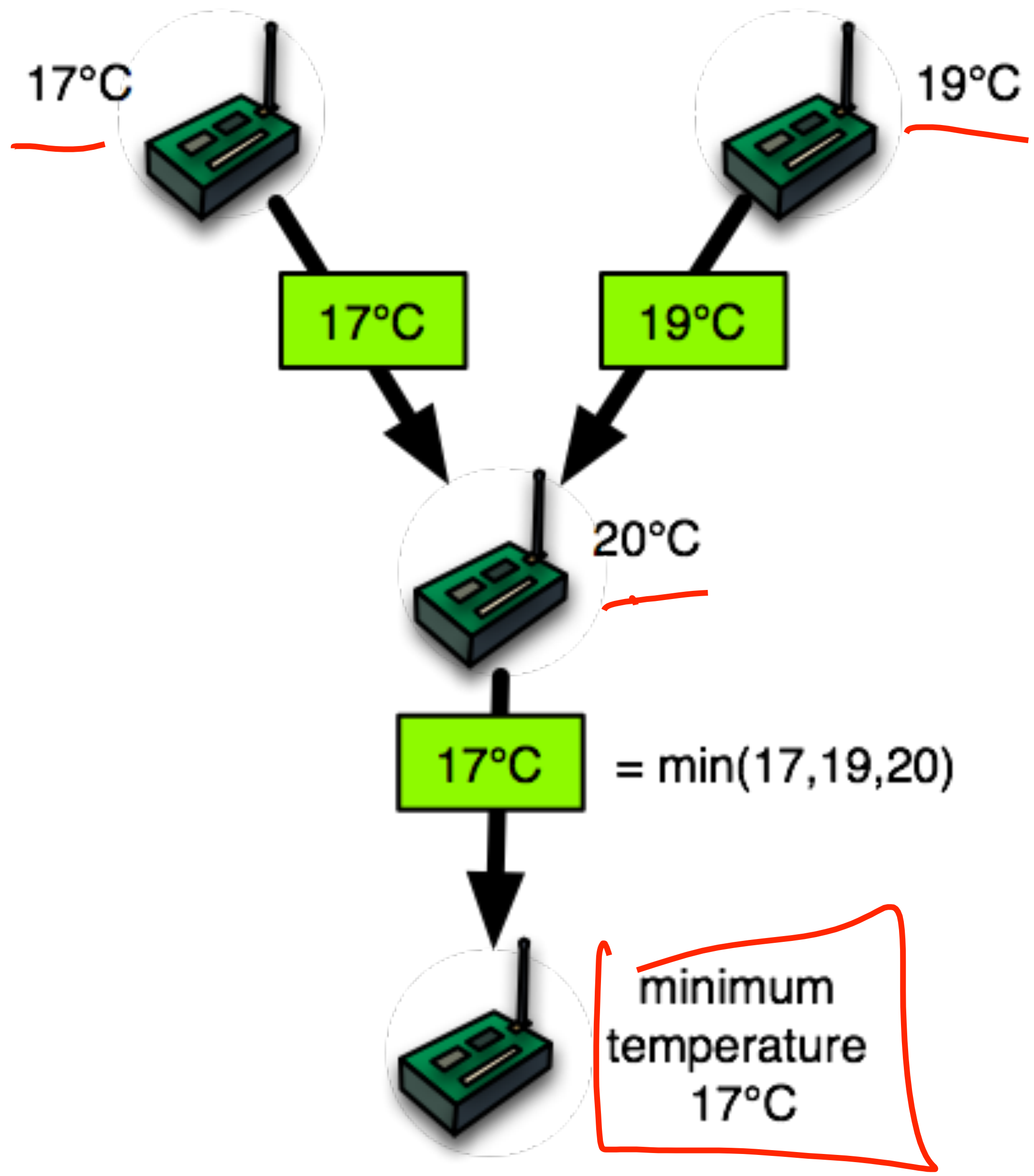
Convergence



Data Aggregation by Concatenation

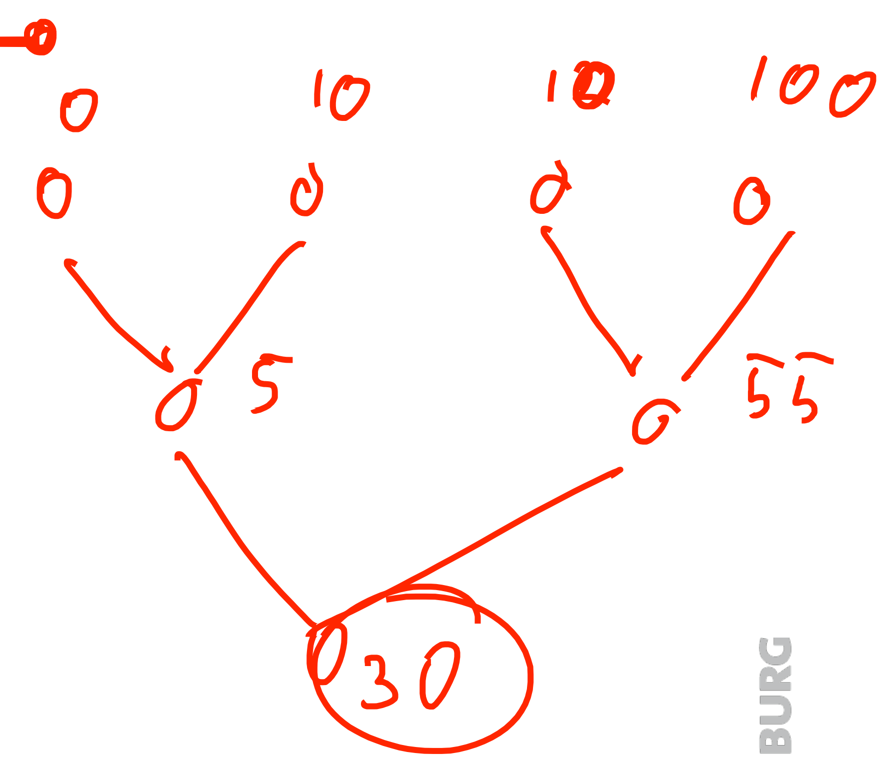


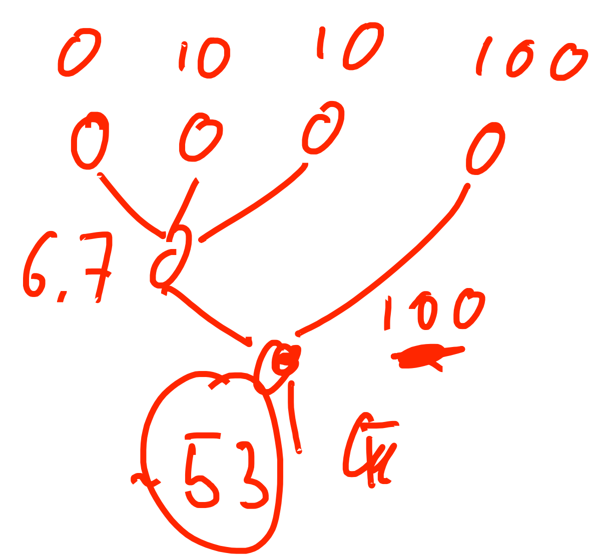
Real Data Aggregation by Recalculation



Simple Functions for Data Aggregation

- Minimum
  - inner node computes the minimum of input values
- Maximum
  - like Minimum
- Number of sources
  - inner node adds input values
- Sum
  - addition at inner nodes





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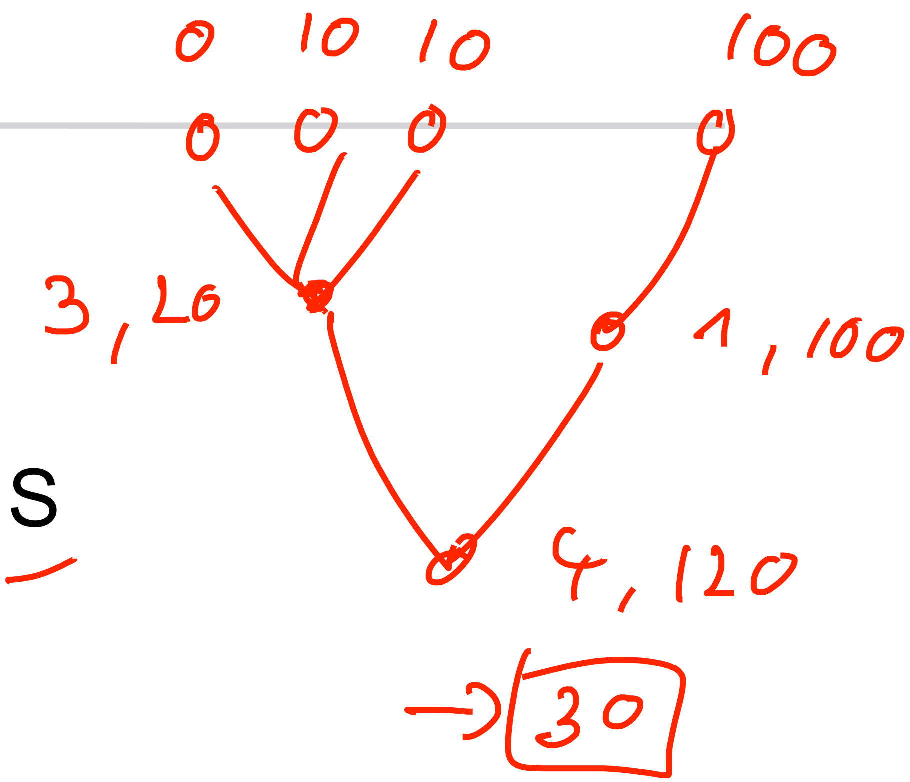
Aggregable Functions



- Mean
  - compute the number of sensors: n
  - compute the sum of sensor values: S
  - mean = S/n
- Variance
  - Compute average and the average of squares of values
  - $V(X) = E(X^2)-E(X)^2$

- Median | median(10, 0, 0, 15, 24) = 10

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Hard Aggregable Functions

- The following functions cannot be aggregated easily
  - median
  - p-quantile
    - if p is not very small or large
  - number of different values
    - only for large data sets an approximation is possible
- Approximate solution
  - was presented in „Medians and Beyond: New Aggregation Techniques for Sensor Networks, Shrivastava et al. Sensys 04
  - using k words in each message an approximation ratio of log n/k can be achieved

50%

25%

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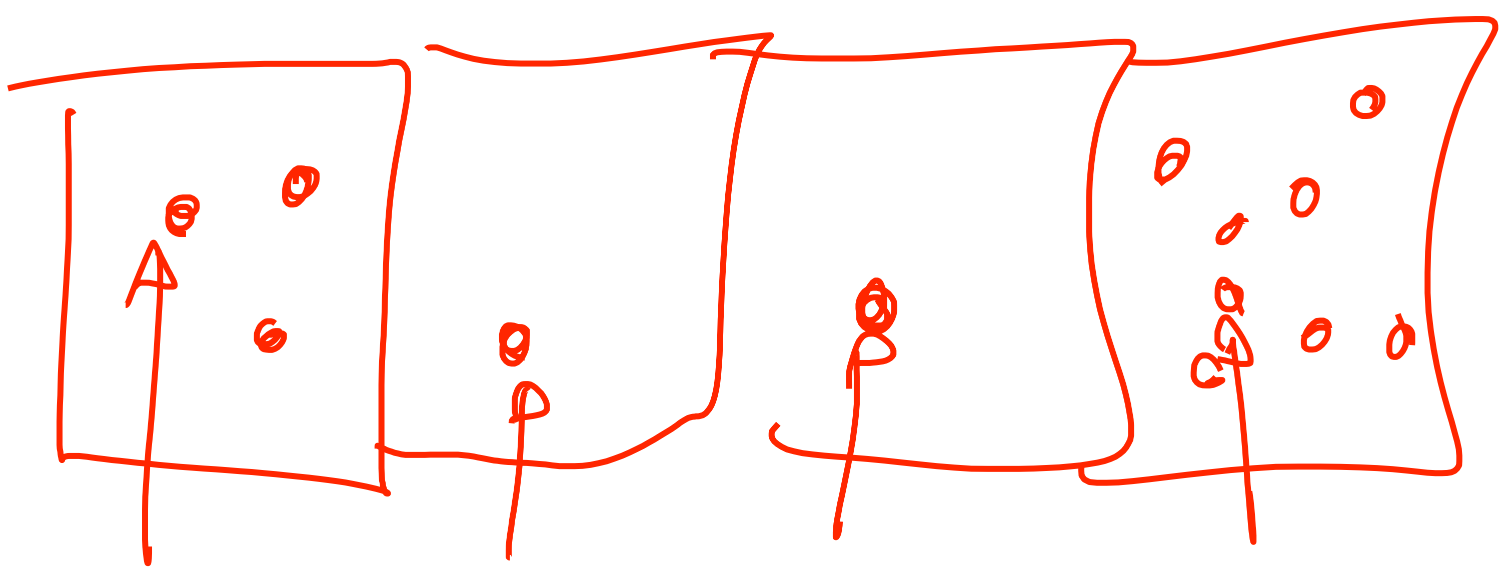
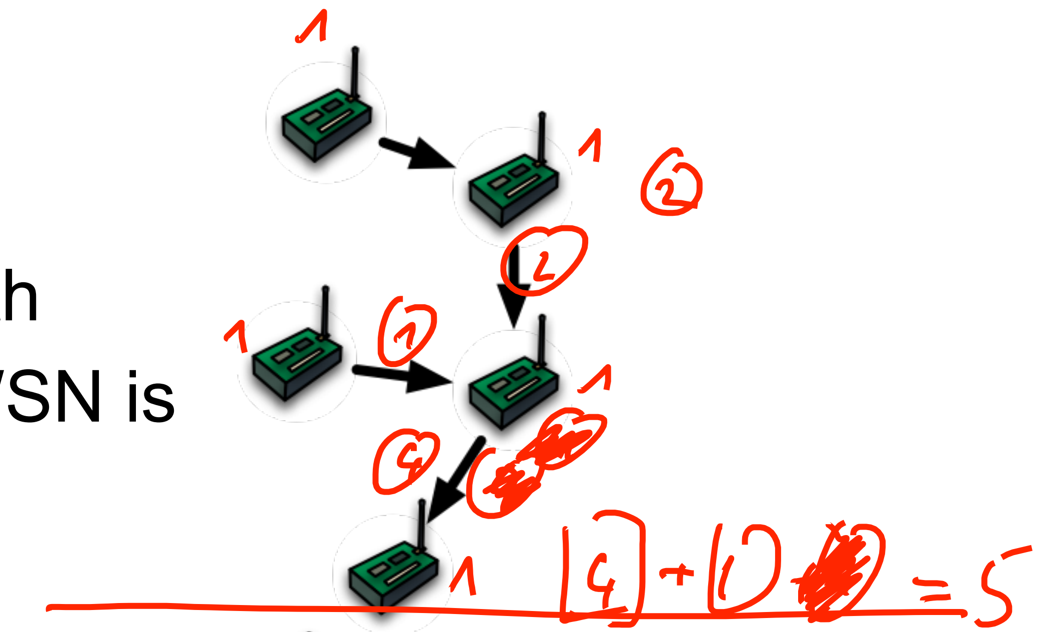
Routing Models for Data Aggregation

- Address Centric Protocol
  - each sensor sends independently towards the sink
  - not suitable for (real) aggregation
- Data Centric Protocol
  - Forwarding nodes can read and change messages

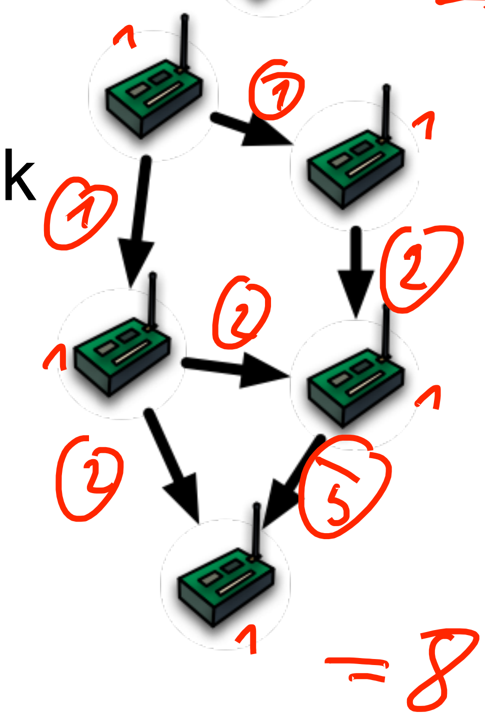


Communication Graphs for Aggregation

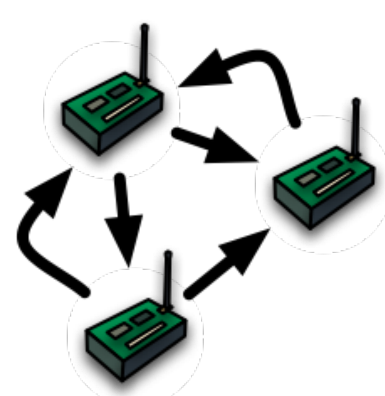
- Tree Structure
  - If there is only a single sink
  - and every source uses only a single path
  - then every communication graph in a WSN is a tree

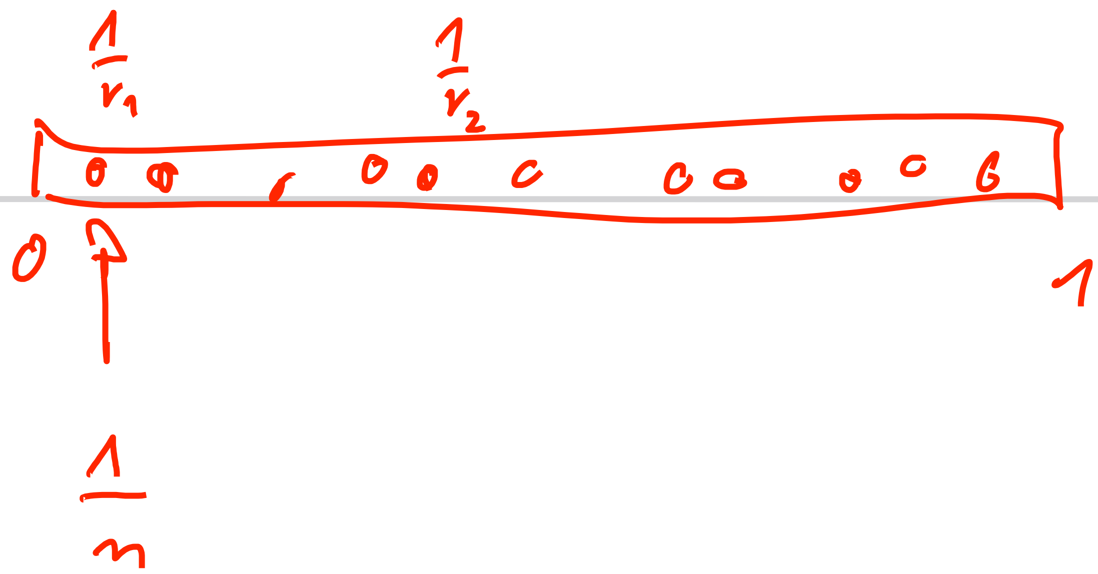


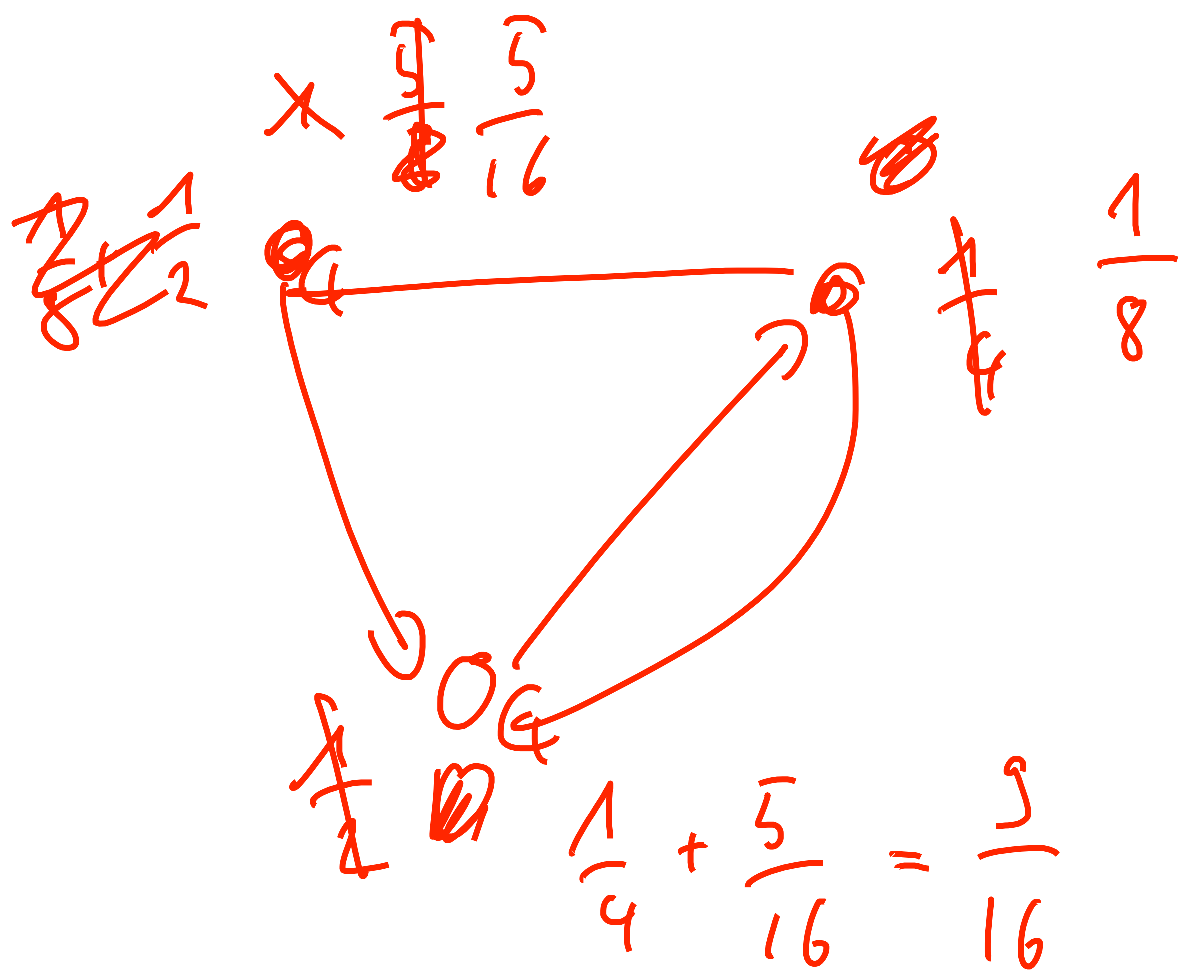
- DAG (directed acyclic graph)
  - general case
  - caused by changing routing paths to the sink
  - may complicate data aggregation
    - e.g. sum

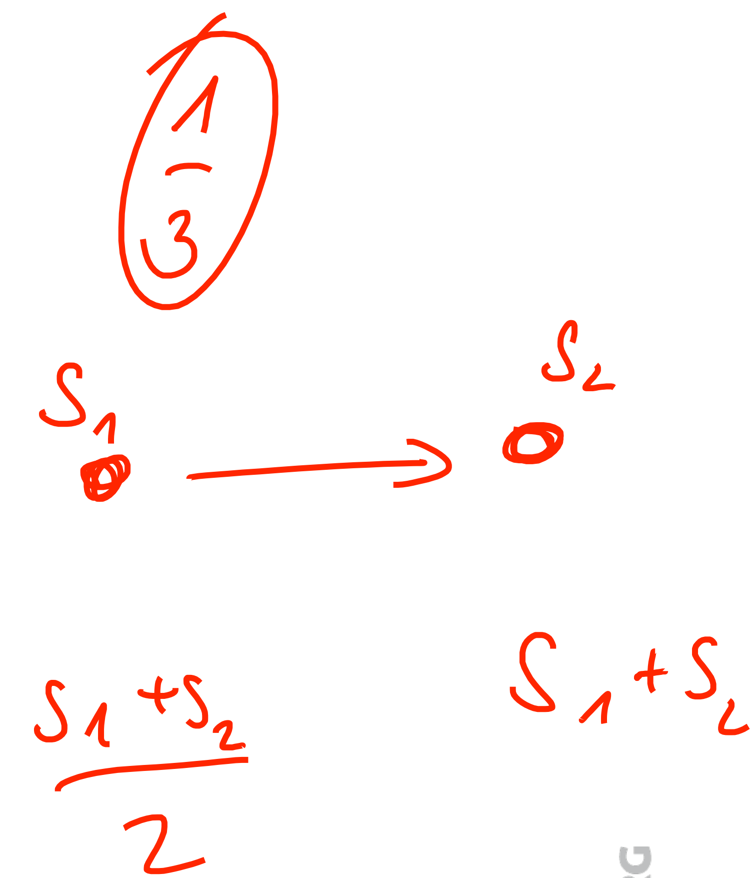


- General graph
  - Population protocols
  - are not used in WSNs

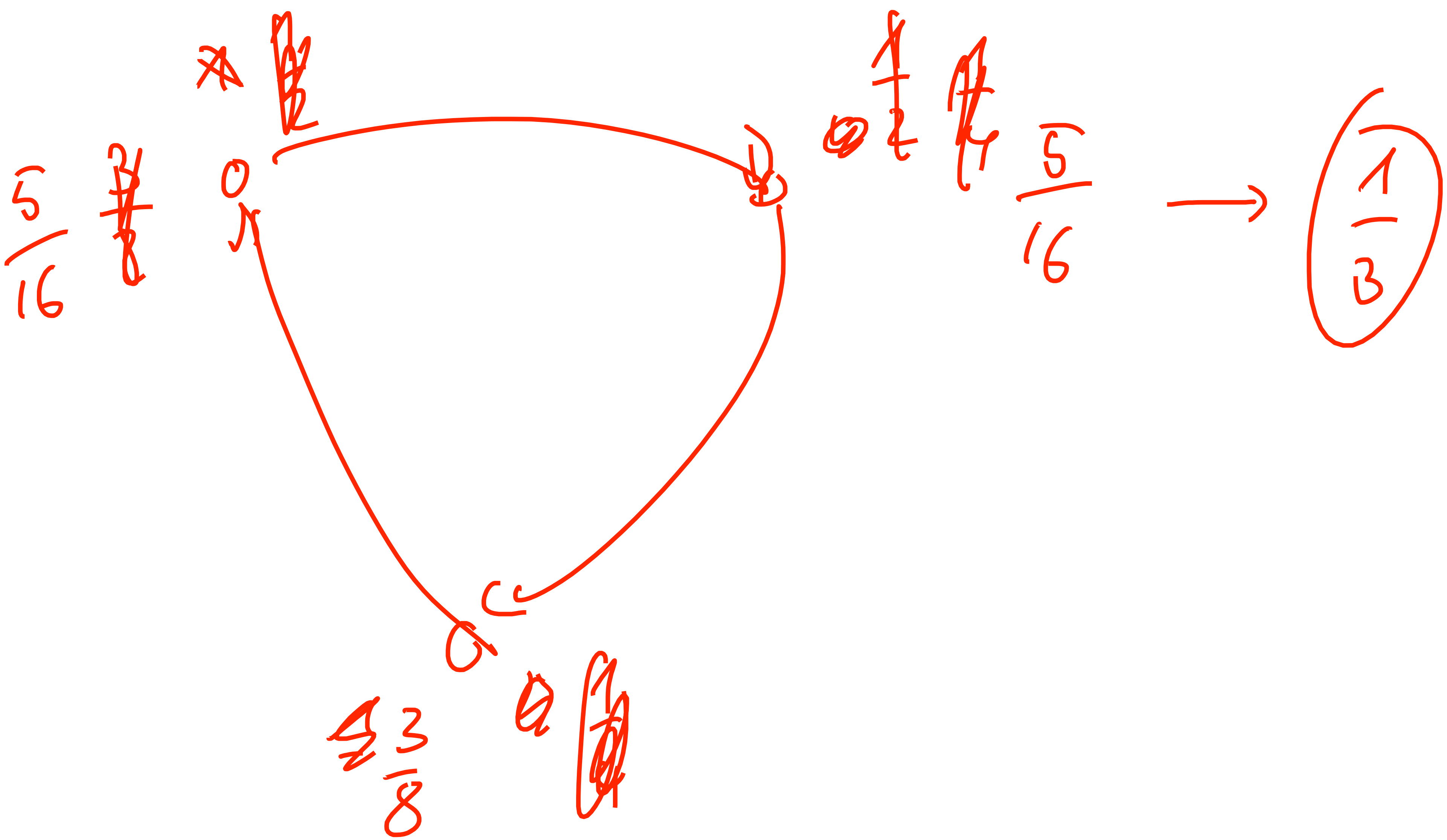



1/r1
1/r2
0
1
1/n


5/16
1/8
1/4 + 5/16 = 9/16


1/3
S1
S2
(S1+S2)/2
S1+S2

$$\frac{\frac{3}{8} + \frac{2}{8}}{2}$$



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Probabilistic Counting for Data Aggregation

- Hard problems for Data Aggregation
  - Counting of different elements in a multiset
  - Computation of Median
- Exact computation needs complete knowledge
  - therefore we compute approximations
- Main Technique
  - probabilistic counting
    - „Counting by Coin Tossings“, Philippe Flajolet, ASIAN 2004
  - probabilistic sampling
    - „A note on efficient aggregate queries in sensor networks“, Boaz Patt-Shamir, Theoretical Computer Science 370 (2007) 254–264

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Types of WSN Routing

Energy-Efficient Routing Protocols in Wireless Sensor Networks: A Survey, Pantazis et al., IEEE Communication Survey & Tutorials, Vol. 15, No. 2, 2nd Quarter, 2013

- MANET Routing
  - Flooding Based Routing (MANET)
    - Flooding, DSR, AODV, DYMO
  - Cluster-Based Hierarchical Routing
    - Low-Energy Adaptive Clustering Hierarchy (LEACH)
- Geographic Routing
  - Greedy Routing
  - Face Routing
- Self-Organizing Coordinate Systems
  - Inferring Location from Anchor Nodes, Virtual Coordinates
  - Gradient Routing
    - Gradient-Based Routing (GBR)
    - Routing Protocol for Low Power and Lossy Networks (RPL)

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Algorithms for Radio Networks

Routing

University of Freiburg
Technical Faculty
Computer Networks and Telematics
Christian Schindelhauer

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