An overview of soft real-time wireless communication for Sensor Networks

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Outline

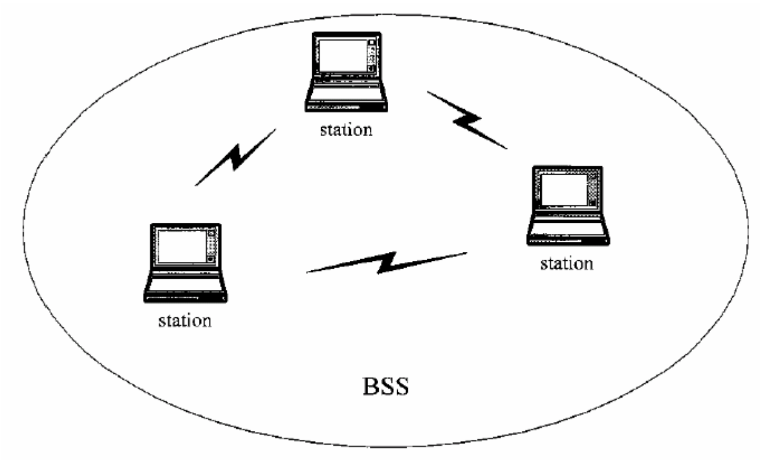
- Wireless LANs background
- Enforce priorities with CSMA/CA access
- Speed routing protocol
- Real-time chains

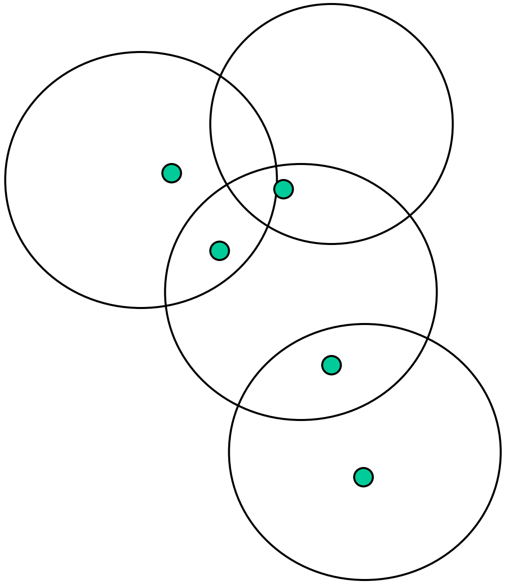
Motivations

- New generations of wireless technologies should support universal wide-bandwidth access to a variety of services
  - Multimedia conference, remote audio, data access….
- QoS requirements are needed
  - Widely varying QoS requirements
    - Delay QoS, bandwidth QoS …
  - Specifically for real time traffic
- IEEE 802.11 is wireless LAN standard widely used
  - No priorities in DCF
  - No mechanisms to guarantee access delay bound
- This paper proposed a prioritized scheme modifying IEEE 802.11 protocol's CSMA/CA (DCF) access method to support station priority.

Wireless LAN preliminaries

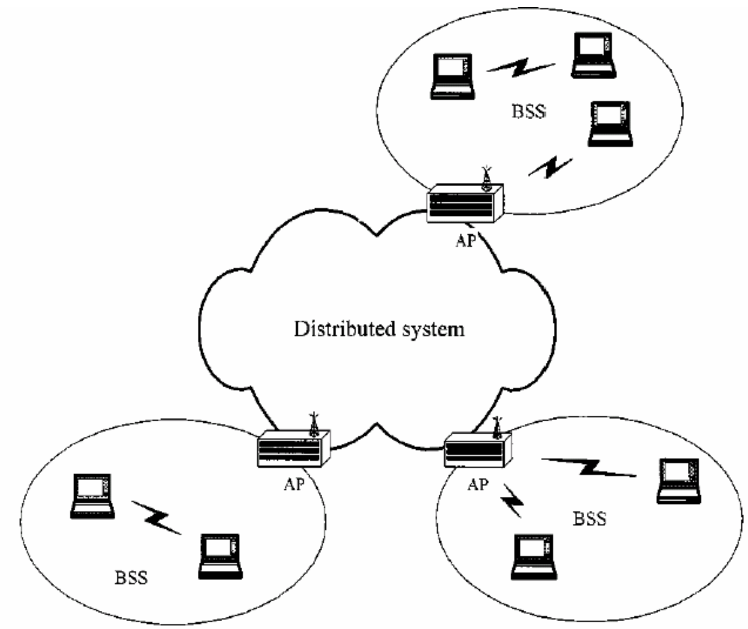
- Two kind of wireless network topologies
  - Both supported by IEEE 802.11 MAC protocols
  - Ad hoc network
    - Mobile terminals communicate with each other in an independent basic service set (BSS)
      - BSS: single hop ad hoc network
    - A packet may need to traverse multiple links to reach a destination





Two kind of network topologies

– Infrastructure network
  - Mobile terminals communicate with the backbone network through an access point (AP)
  - APs can be bridged supporting range extension between multiple BSSs, forming an extended service set (ESS)

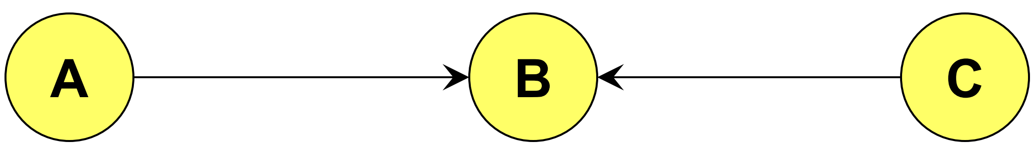


MAC

- Media Access Control protocol: coordination and scheduling of transmissions among competing neighbors
- Goals for a real-time MAC: low latency; good channel utilization; best effort + real time support

(1) Hidden Terminal Problem [Tobagi75]

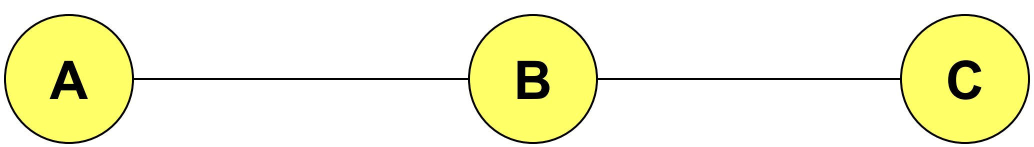
- Node B can communicate with A and C both
- A and C can not hear each other
- When A transmits to B, C cannot detect the transmission using the *carrier sense* mechanism
- If C transmits, collision will occur at node B



The wireless LAN background is based on Nitin Vaidya's wireless MAC tutorial

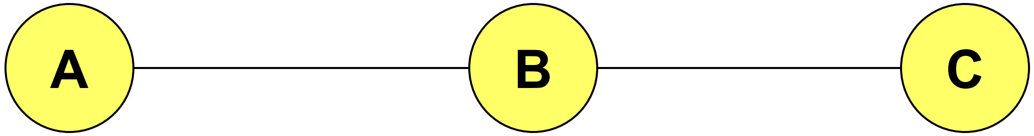
A solution for Hidden Terminal Problem
[MACA , Karn90]

- When node A wants to send a packet to node B, node A first sends a *Request-to-Send (RTS)* to B
- On receiving RTS, node B responds by sending *Clear-to-Send (CTS)*, provided node B is able to receive the packet
- When a node (such as C) overhears a CTS, it keeps quiet for the duration of the transfer
  - Transfer duration is included in both RTS and CTS



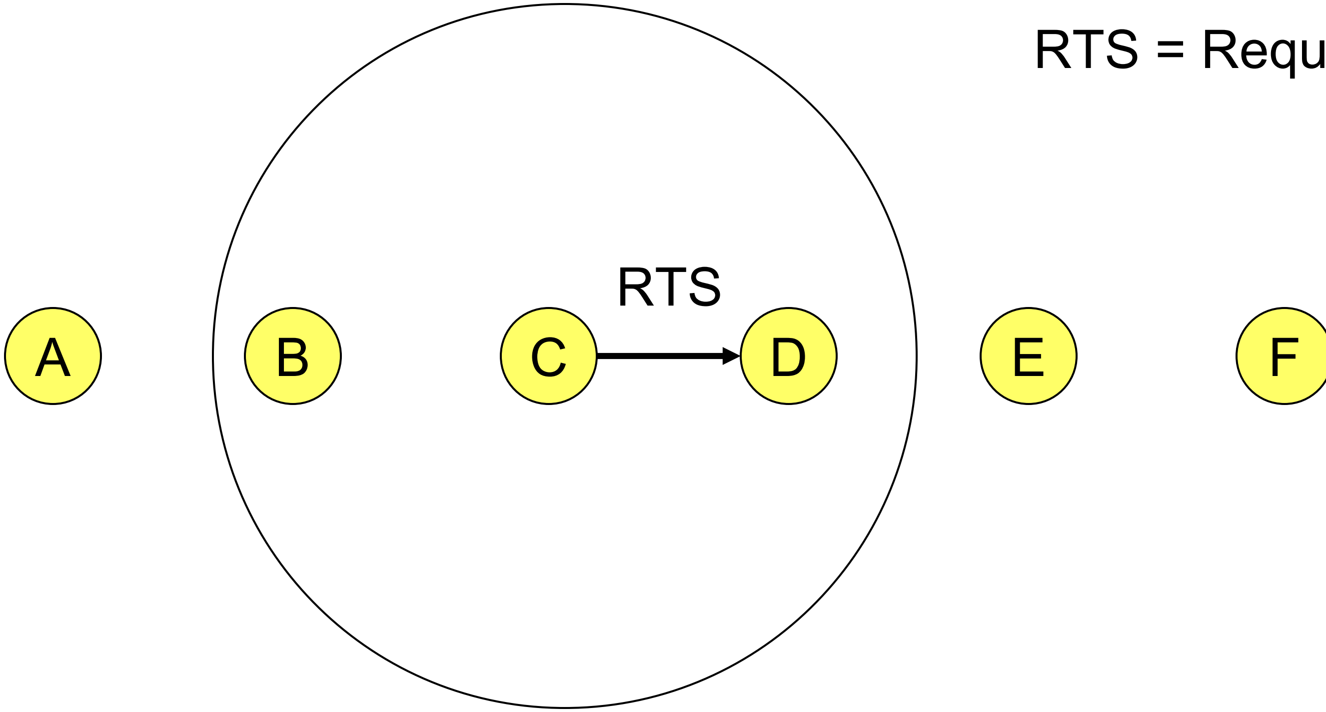
A simple solution to improve reliability

- Wireless links are prone to errors.
  - Much higher Bit Error Rate (BER) than wired networks due to noise, channel fading etc
- When node B receives a data packet from node A, node B sends an Acknowledgement (Ack). This approach adopted in many protocols such as IEEE 802.11
- If node A fails to receive an Ack, it will retransmit the packet



IEEE 802.11

RTS = Request-to-Send



IEEE 802.11

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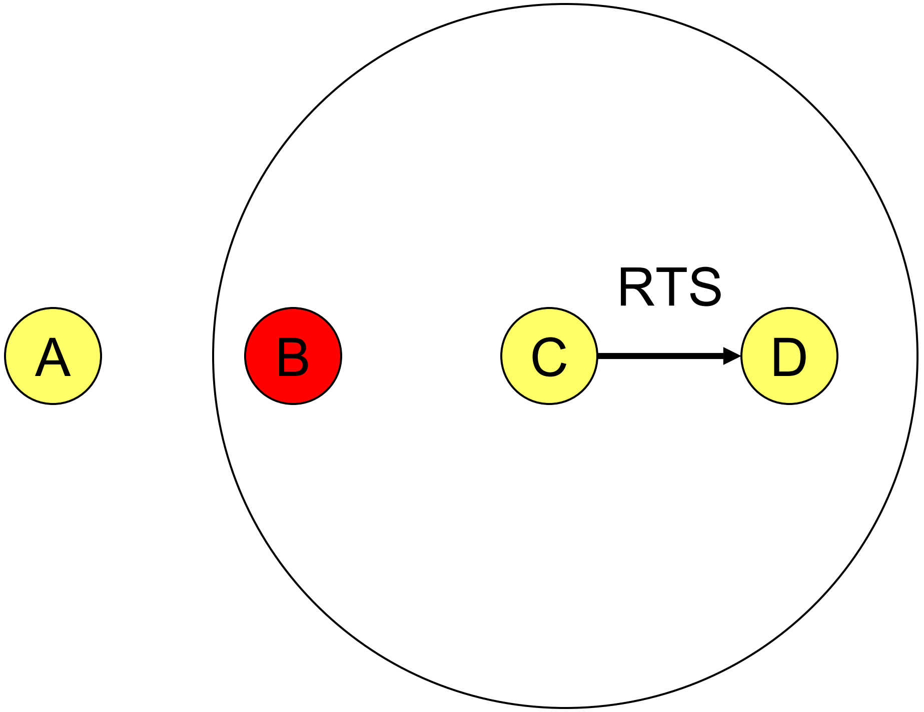
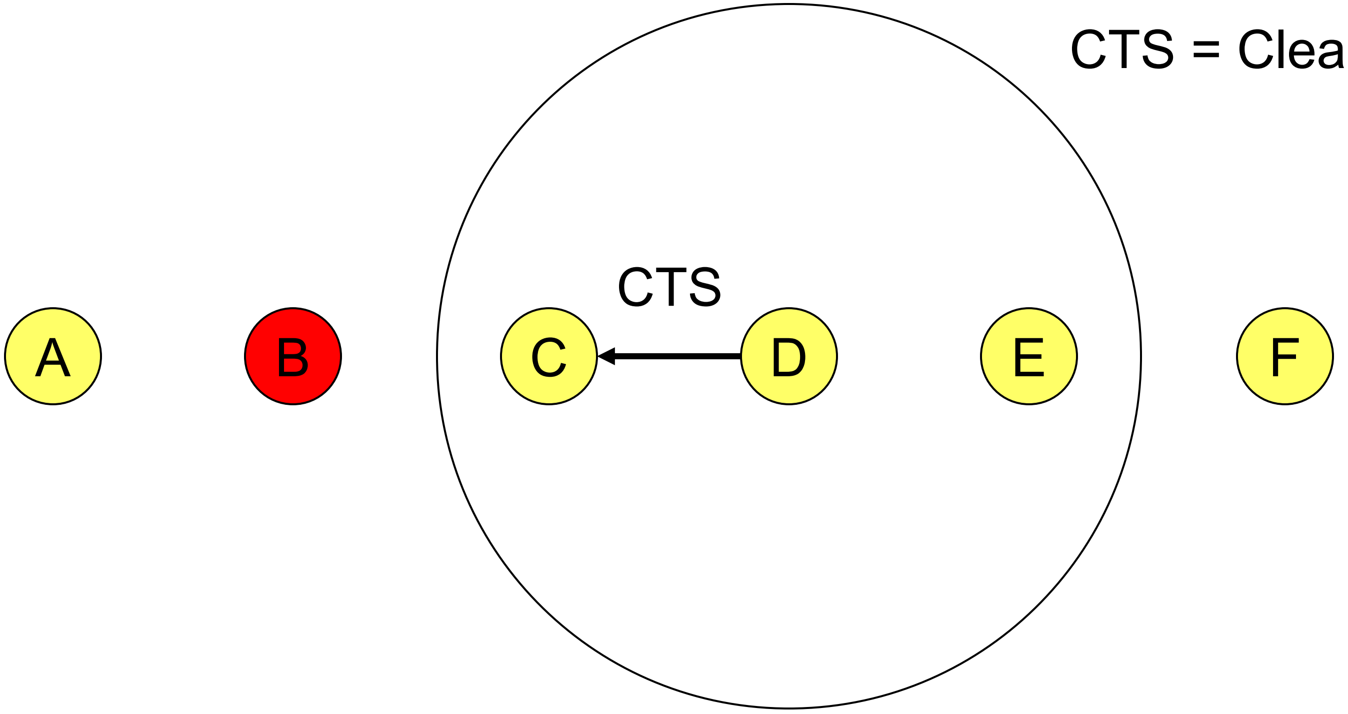


IEEE 802.11

CTS = Clear-to-Send



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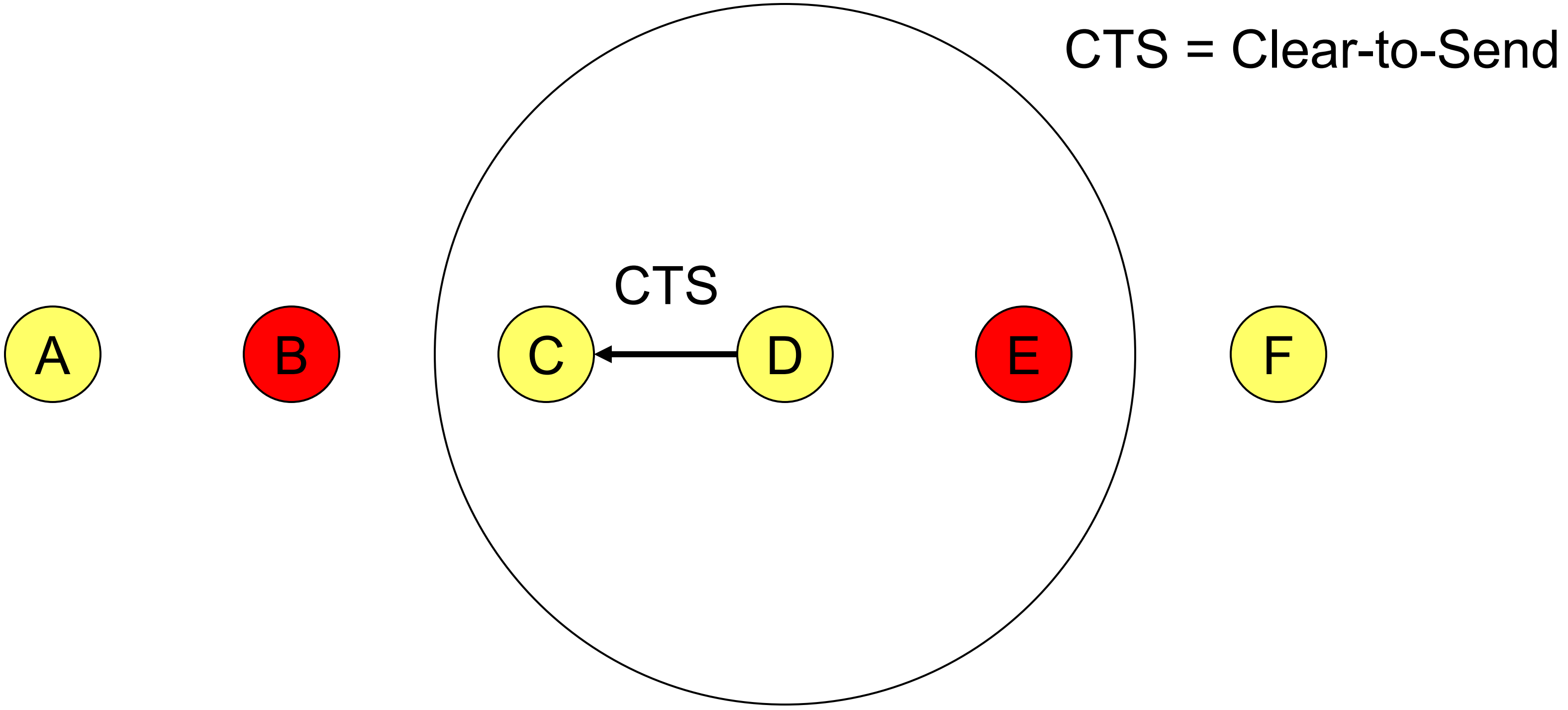

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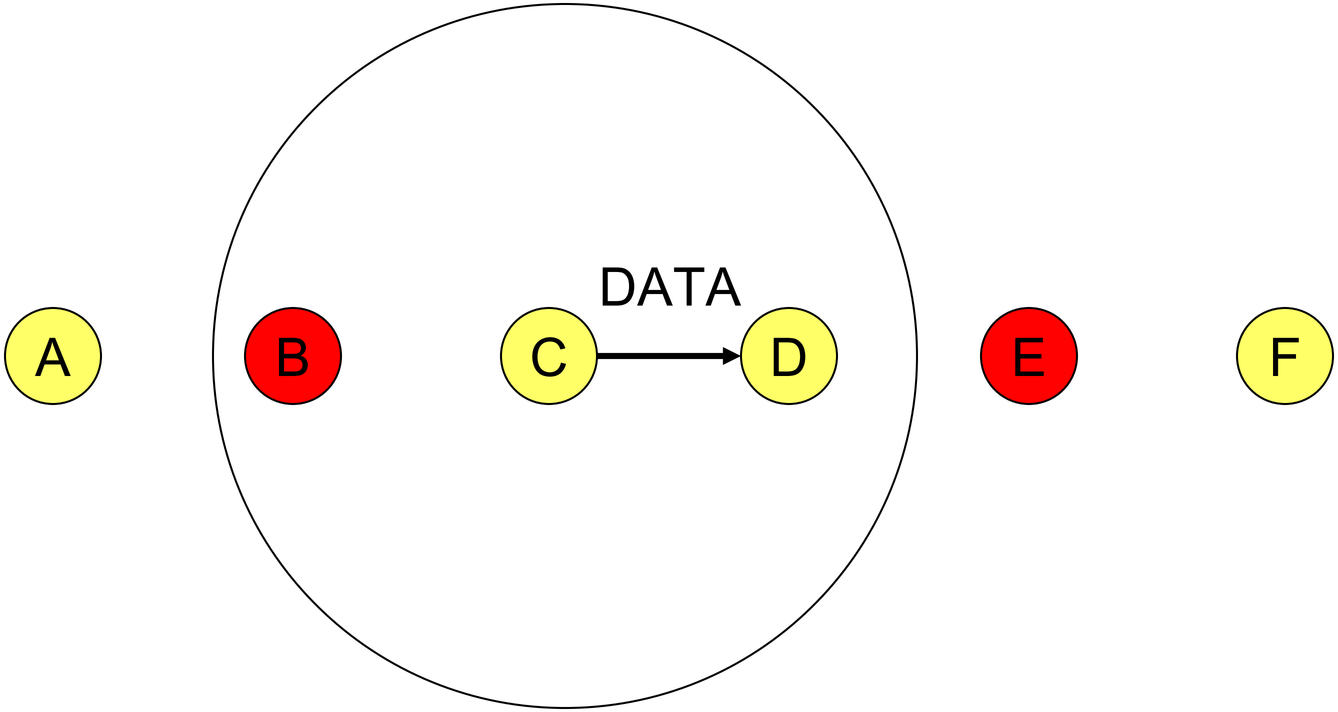
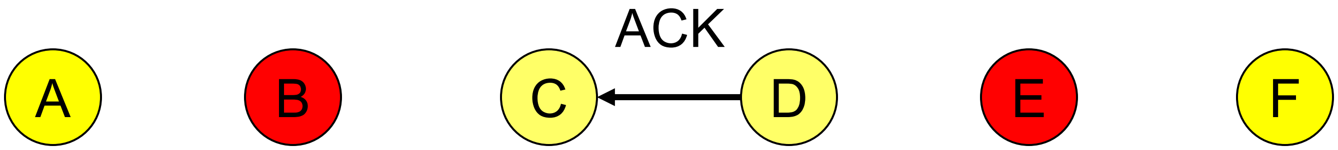


IEEE 802.11



MACs to transmit time-sensitive data

- Reservation based schemes
  - Allow time-bounded traffic to reserve a periodic slot on the channel that they can access alone
  - Need a central agent to decide slot schedule.
  - Waste unused but reserved resource
  - E.g. IEEE 802.11 PCF (Point Coordination Function)

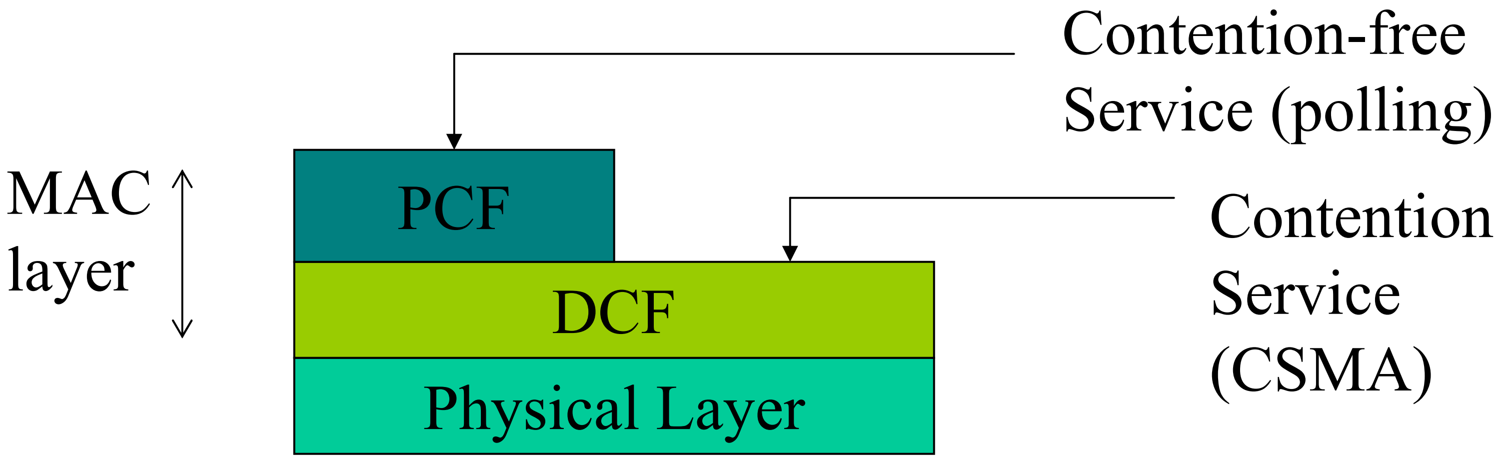
- Priority based schemes
  - Enforce priorities to let some stations to have precedence over others when accessing the wireless channel.

IEEE 802.11 wireless MAC

- MAC options:
  - Distributed and centralized MAC components
  - DCF (Distributed Coordination Function):
    - DCF is suitable for multi-hop ad hoc networking
    - DCF is a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol
    - short IFS -> high priority (ACKs, CTS)

  - PCF (Point Coordination Function):
    - Uses polling to grant stations their turn to transmit.
    - Polling performed by Access Point (AP)
    - PCF and DCF intervals are combined building a periodic frame

IEEE 802.11 MAC Architecture



– Why not CSMA/CD as in Ethernet?
  - Hard for transmitter to distinguish its own transmission from incoming weak signals
  - So, wireless LAN can not use collision detection, should use collision avoidance.

CSMA/CA in details

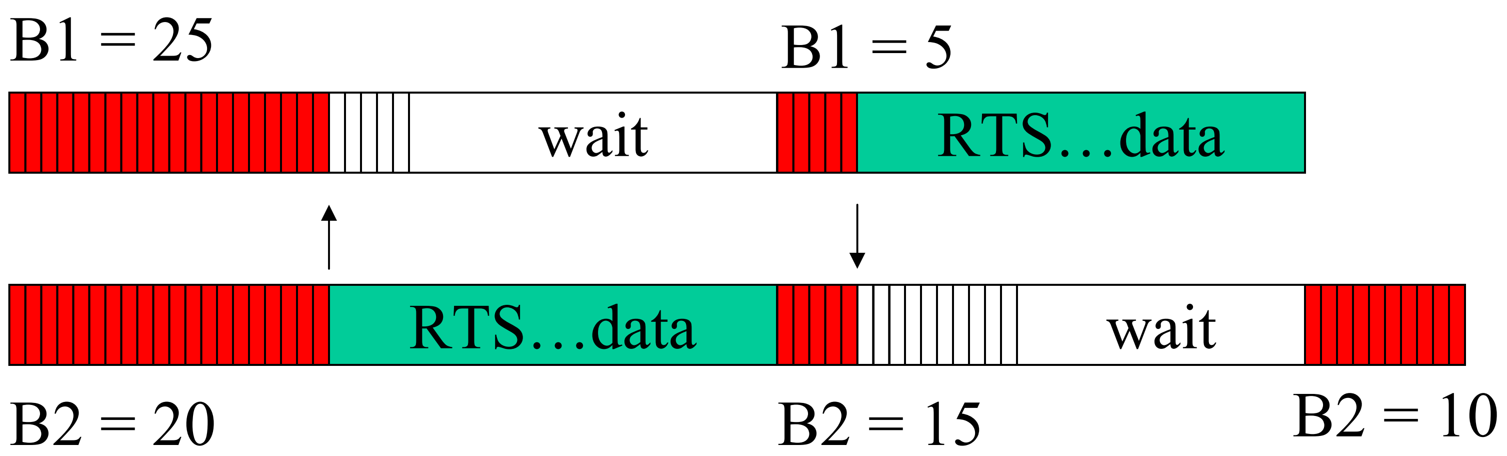
- Carrier sense in IEEE 802.11
  - Physical carrier sense
  - Virtual carrier sense using Network Allocation Vector (NAV)
  - NAV is updated based on overheard RTS/CTS/DATA/ACK packets, each of which specified duration of a pending transmission
- Collision avoidance
  - Nodes stay silent when channel is sensed busy (physical/virtual)
  - Backoff intervals used to reduce collision probability

Backoff interval (Collision Avoidance)

- When transmitting a packet, choose a random backoff value in the range [0,cw-1]
  - cw is called contention window
  - cw begins with 8
- Count down the backoff interval when medium is idle

  ➔ Count-down is suspended (frozen) if medium becomes busy
- When backoff interval reaches 0, transmit RTS

DCF backoff example (Collision Avoidance)



cw = 31

B1 and B2 are backoff intervals at nodes 1 and 2

Binary exponential backoff in DCF

- When a packet transmission fails, the transmitter increases the contention window
  - *cw* is doubled (up to an upper bound, *CWmax*)

$$\lfloor ranf() \cdot 2^{2+i} \rfloor \cdot \text{Slot\_Time}$$

    - Random backoff value into $(0 \sim 2^{2+i} - 1)$* Slot_Time
    - Random backoff use number of slots
    - i is the number of consecutive attempts to send a frame
    - ranf() is a uniform random number generator
- If a node transmits successfully, it restores *cw* to *CWmin*
- *cw* follows a saw-tooth curve

Priority scheduling in IEEE 802.11

- Priority scheduling problem: packets from different stations might belong to different priority classes

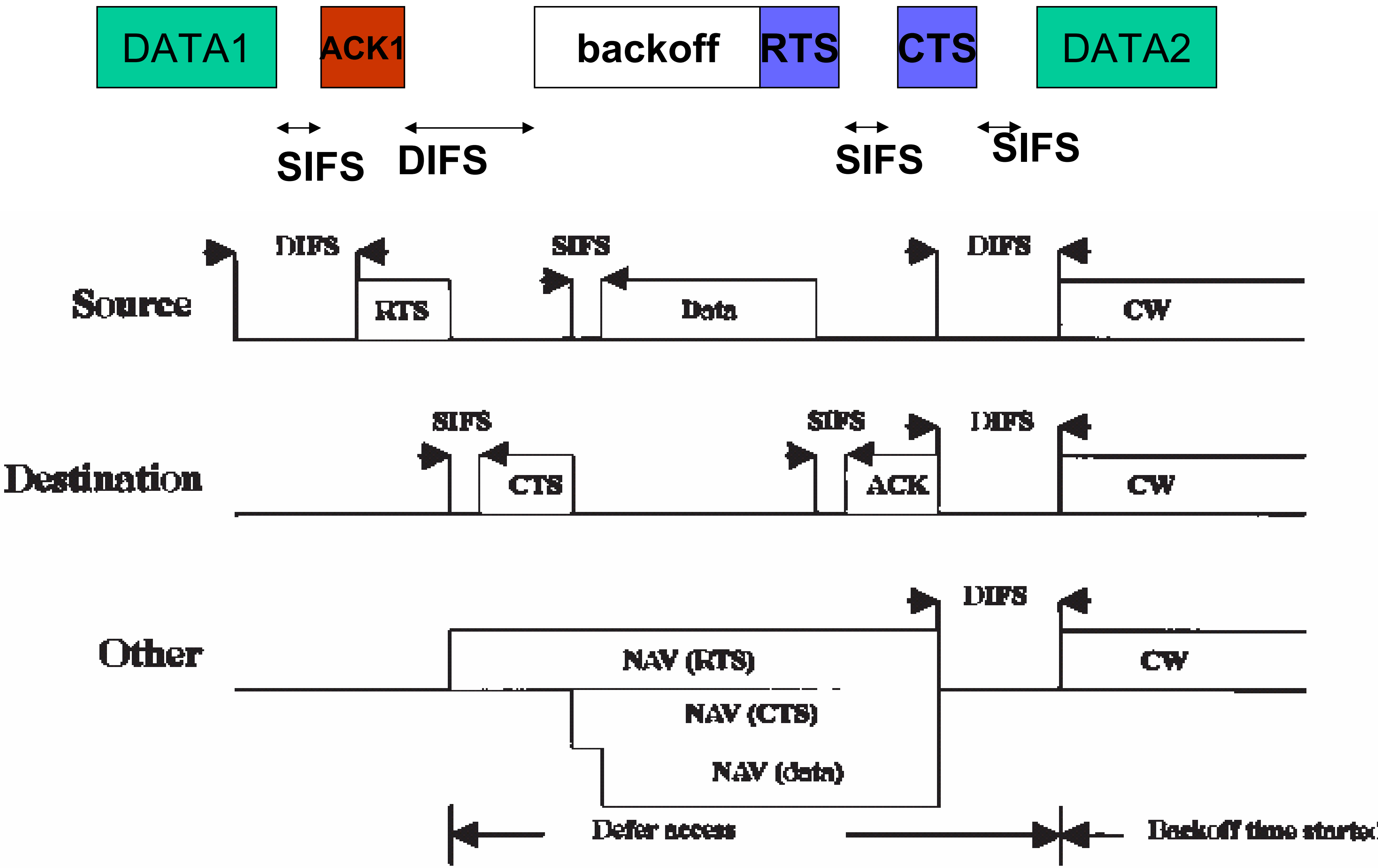
➔ packets with higher priority should be transmitted first

- Since the packets may be at different nodes sharing the wireless channel, how to coordinate access?

Enforcing priorities with IEEE 802.11

- Inter frame space (IFS)
  - Short IFS (SIFS), DCF IFS (DIFS), PCF IFS (PIFS)
  - SIFS<PIFS<DIFS
  - The shorter IFS a station uses, the higher priority it will get
- CTS and ACK have priority over RTS
  - If a node wants to send CTS/ACK, it waits SIFS duration after channel goes idle
- If a node wants to send RTS, it waits for DIFS > SIFS

Transmitting data using SIFS and DIFS in DCF



Enforce priorities for DCF access

- Two parts
  - Shorter IFS for higher priority stations
  - Shorter random backoff time for higher priority stations
  - Totally, 4 classes of priorities (see table)

Shorter Random Backoff Time

- To support priority
  - Set backoff time window to $\lfloor ranf() \bullet 2^{2+i} / 2 \rfloor$ for high priority stations
    - Random backoff into $0 \sim 2^{1+i} - 1$
  - Set backoff time window to $\lfloor ranf() \bullet 2^{2+i} \rfloor + 2^{2+i} / 2$ for low priority stations.
    - Random backoff into $2^{1+i} \sim 2^{2+i} - 1$
- Dividing the backoff time in more detail can support more levels of priorities

  ➔ collisions in the same priority level may increase

Combination of shorter IFS and shorter random backoff

Backoff algorithm \ Priority \ IFS	PIFS	DIFS
$\left\lfloor ranf() \cdot \frac{2^{2+i}}{2} \right\rfloor$	3	1
$\frac{2^{2+i}}{2} + \left\lfloor ranf() \cdot \frac{2^{2+i}}{2} \right\rfloor$	2	0

back

➔ 3 is the highest priority

SPEED: A Stateless Protocol for Real-Time Communication in Sensor Networks

Tian He, John A. Stankovic, Chenyang Lu, and Tarek Abdelzaher

ICDCS 2003

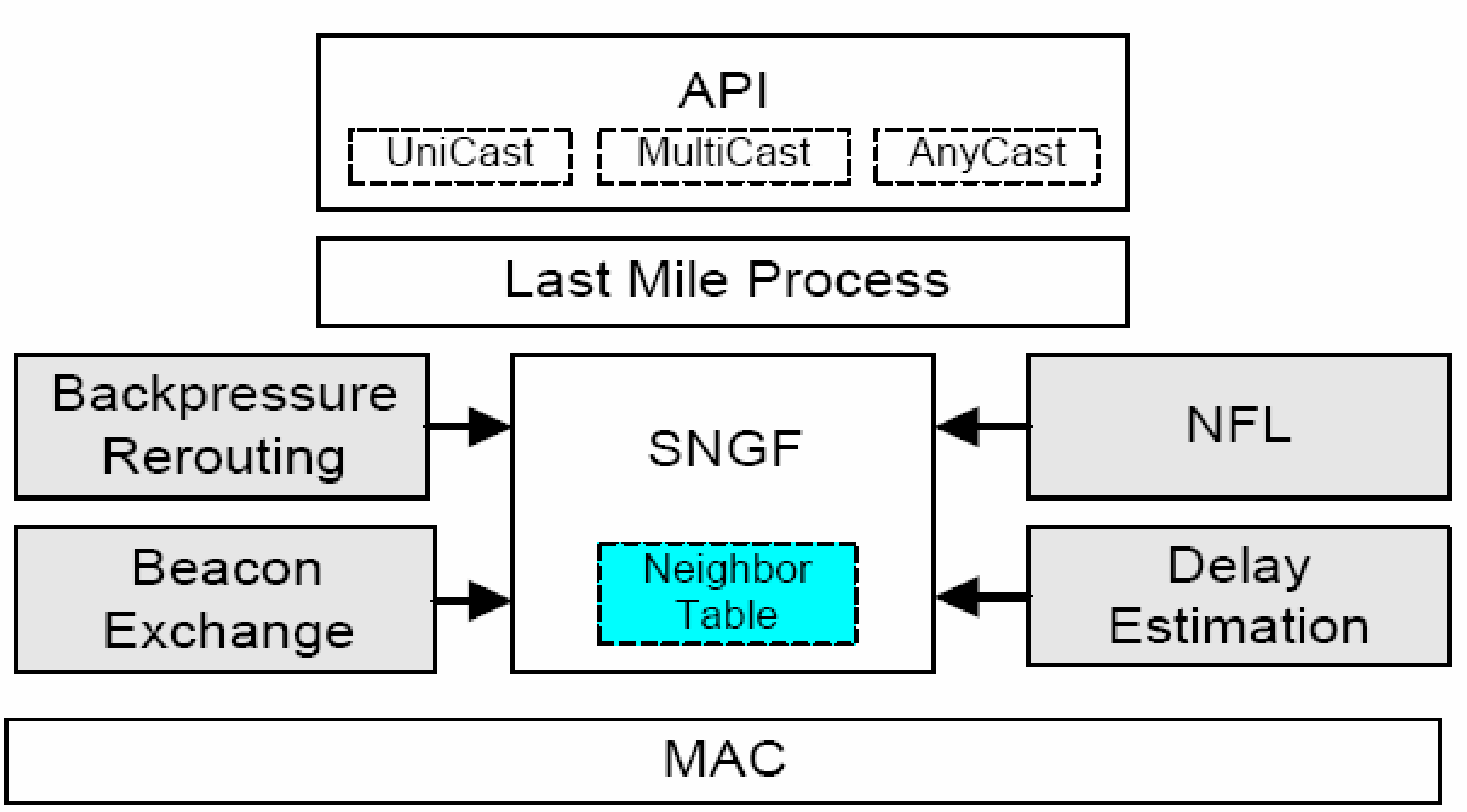
What is Speed Protocol?

- Provide soft real-time routing service
- Maintain a desired delivery speed across the sensor network
- Speed = distance/delay
  - i.e. end-to-end delay is proportional to the distance between source and destination

Main Approaches in Speed

- Non-deterministic geographic routing
  - Geographic routing + back-pressure rerouting
- Relay ratio feedback control

Structure of Speed Protocol



API

- AreaMulticastSend (position, radius, packet)
  - BS asks sensors in a region to report
- AreaAnyCastSend (position, radius, packet)
  - BS asks any one sensor in a region to report
- UnicastSend(Global_ID, packet)
  - Sensors report to a remote base station (BS)
- SpeedReceive()
  - Set a targeted speed

Neighbor Beacon Exchange

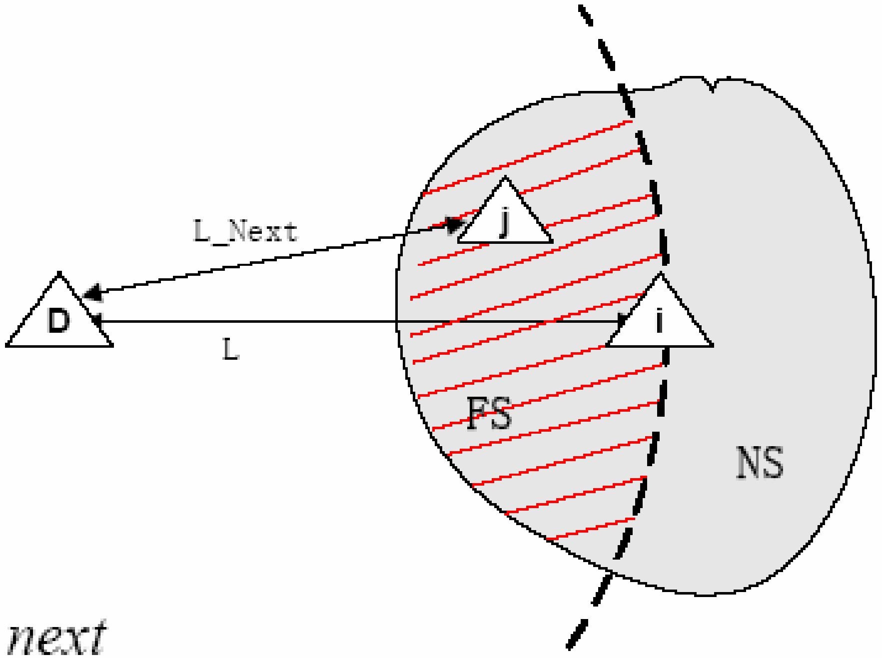
- Periodic beaconing
  - Every node periodically send a beacon to its neighbors
  - The sending rate can be low in the case of low mobility of sensors
  - Piggyback method can reduce the beacon overhead
- Delay estimation beacon
- Backpressure beacon
- Neighbor table
  - Entry: (NeighborID, Position, SendToDelay, ExpireTime).

Delay Estimation

- Use single hop delay as the metric of traffic load
- Delay is the period from the time entering the output queue to reception of ACK
  - Including queueing delay, backoff time, retransmission, propagation delay etc.
  - Excluding ACK processing time in the receiver
  - Use exponential weighted moving average to calculate the average delay
  - Only use data packets but not broadcast packets as estimation of delay

Stateless Non-deterministic Geographic Forwarding (SNGF)

- Neighbor set NS_i
- Forwarding candidate set $FS_i(D)$
  - Neighbors closer to D than I
- Relay **Speed**



$$Speed_i^j(Destination) = \frac{L - L\_next}{HopDelay_i^j}$$

Forwarding Rules in SNGF

- Only forward pkt to a node in FS_i
  - If such a node does not exist, drop the pkt and send a backpressure beacon
- Divide the FS_i into two groups based on if their speed $\geq S_{setpoint}$ (a predefined value)
- If the nodes in the first group ($\geq$) are available, pick one with highest speed
- If not, a relay ratio is calculated based on the Neighborhood Feedback Loop(NFL) and a random number is picked in [0,1]; compare two numbers to determine whether to relay or drop it

Properties of SNGF

- Achieve e2e delay bound = L_{e2e}/ $S_{setpoint}$ if a node in the first group is always avail.
- Load balancing
  - Avoid congestions
  - Disperse energy consumption

Neighborhood Feedback Loop (NFL)

- Purpose
  - To control the relay ratio used in SNGF
  - To maintain a single hop relay speed above $S_{setpoint}$
- Definition of a miss:
  - If a pkt's relay speed < $S_{setpoint}$
  - If there is a loss due to collision
- Objective fn of controller: miss ratio ≈ 0
- A simple multiple inputs and single output (MISO) proportional controller

$$u = 1 - K\frac{\sum e_i}{N} \quad if\ \forall e_i > 0$$

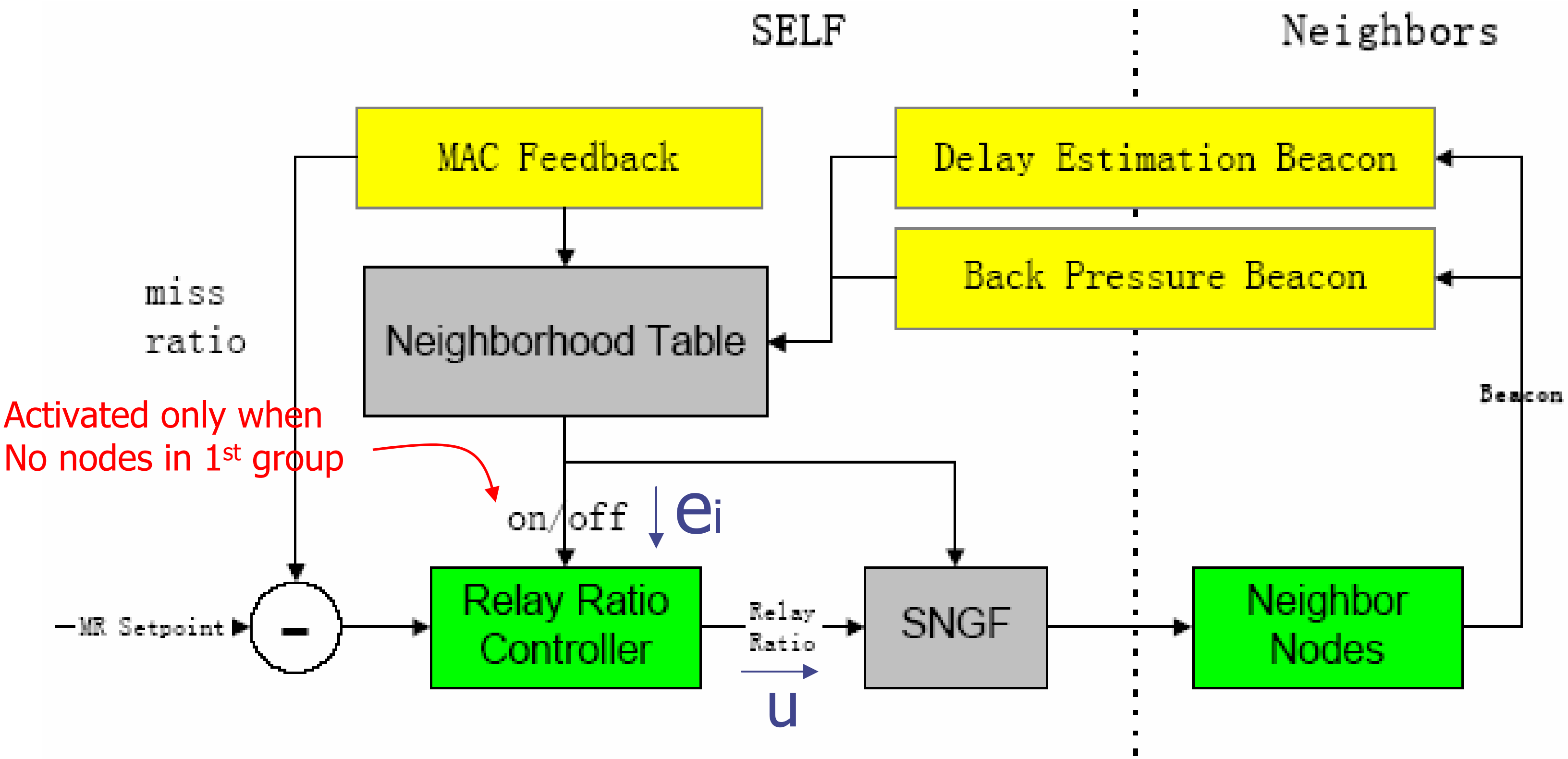
$$u = 1 \quad if\ \exists e_i = 0$$

e_i is the miss ratio of the neighbor i

N is size of the FS set

u is the output (relay ratio)

NFL controller



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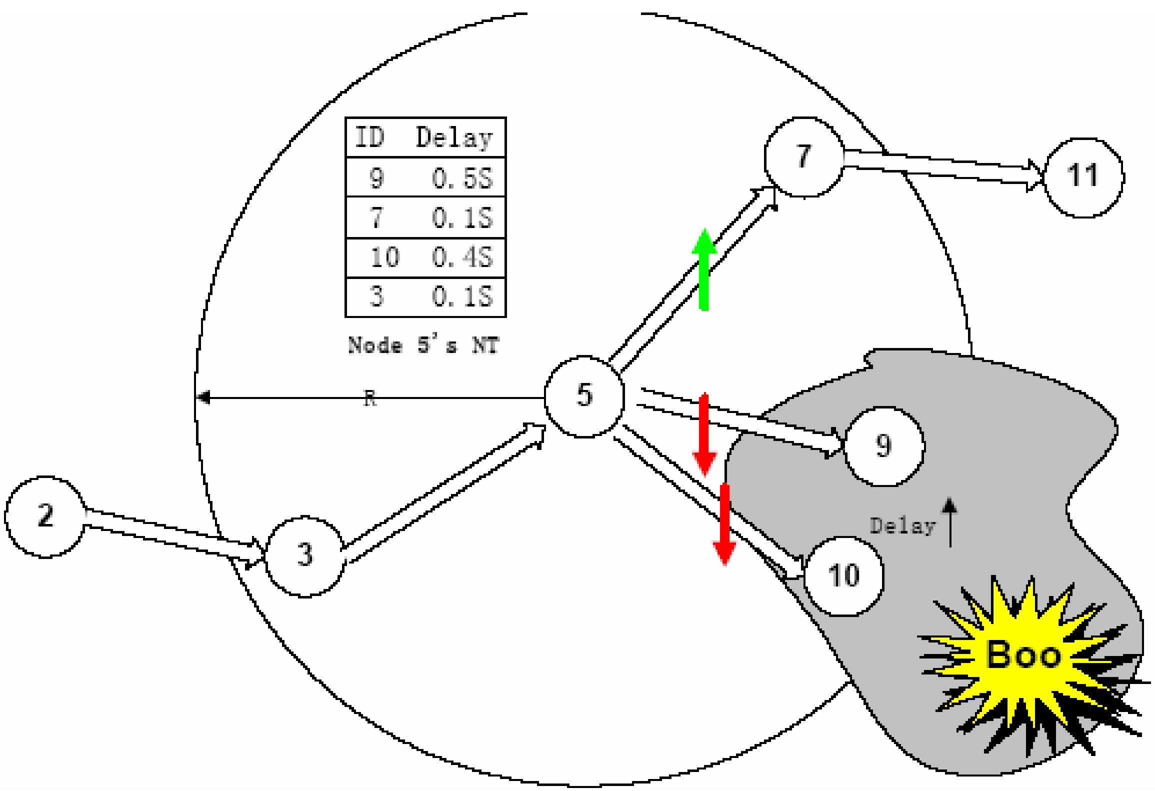
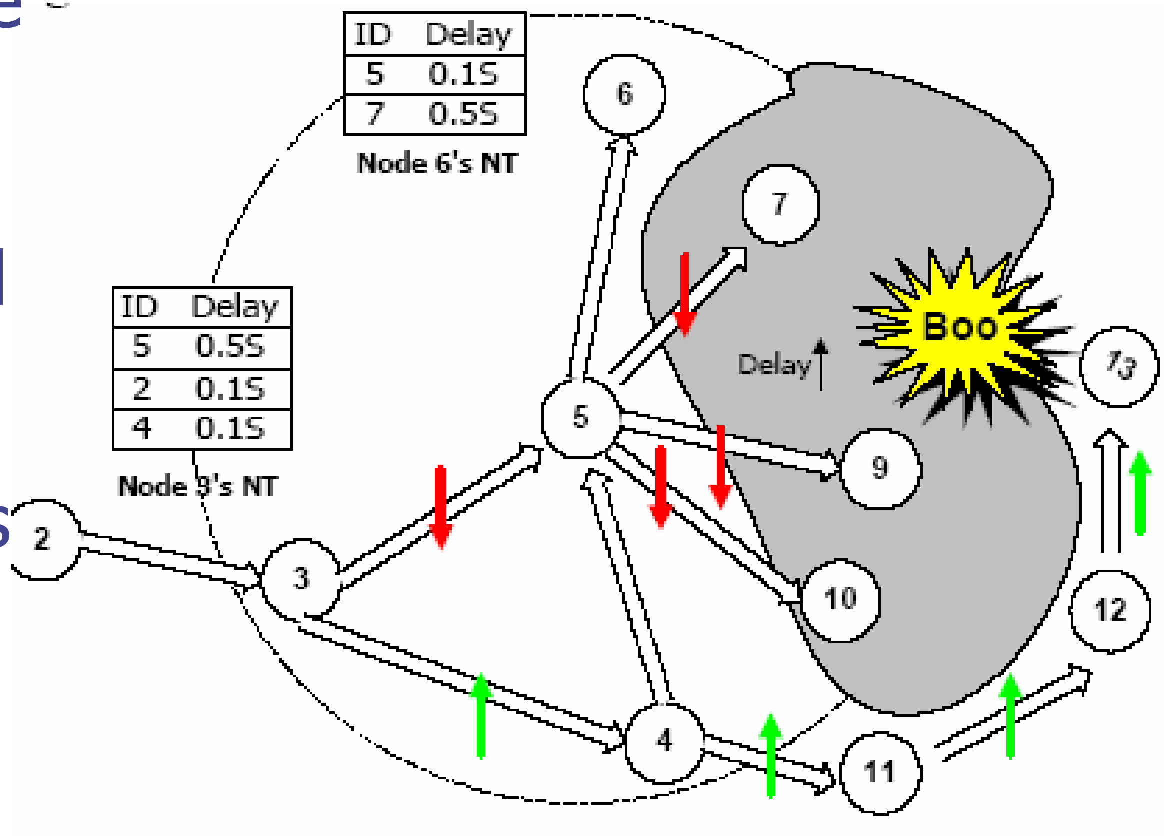
Back-Pressure Rerouting – Case I

- N5 knows N9, N10 congest
- N5 reroute to N7
- Reduce traffic in N9, N10 effectively



Back-Pressure Rerouting – Case II

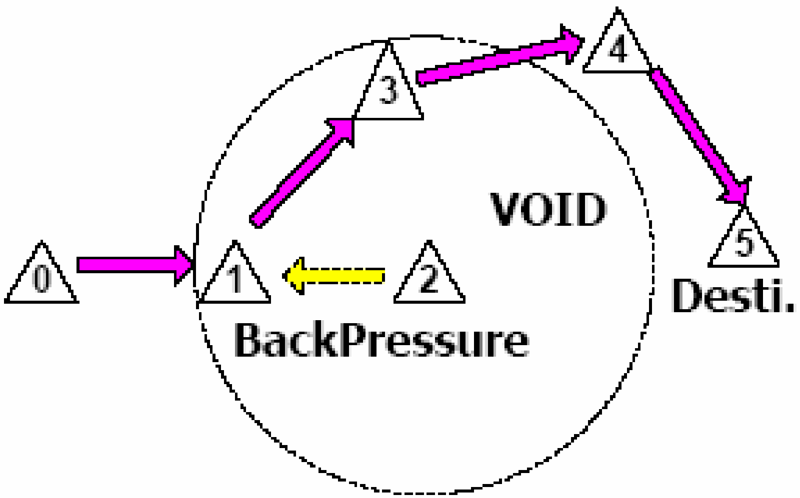
- All nbrs of N5 are congested
- NFL is activated
- Pkts are dropped and a back-pressure beacon (ID,Dest,avg_send_delay) is broadcast
- N3 will choose another route



Void Avoidance

- A problem for all geographic routing
  - Greedy algorithm does not work for void
- When encountering a void, a node sends a back-pressure beacon

$$(ID, dest, \infty)$$



Last Mile Process

- Is activated only when pkts arrive at the dest Region
- For anycast pkt, a node within the dest region, forward it to transport layer
- For multicast pkt,
  - the first node in the dest region receive it
    - Broadcast it with TTL
  - Other nodes within dest region rebroadcast pkts and ignore duplicated pkts

Simulation Comparison

- SPEED: full-fledge SPEED
- SPEED-S: choose the next hop with the max relay speed
- SPEED-T: with the shortest relay delay
- GF: geographic forwarding
- DSR
- AODV

Results

- Less routing overhead in GF routing
- Effective pkt dropping + rerouting help in heavy traffic condition