The MAC Layer in Wireless Networks

- **The wireless MAC layer roles**
  - **Access control to shared channel(s)**
    - Natural broadcast of wireless transmission
    - Collision of signal: a time/space problem
    - Who transmits when? (and where)?
      - Avoid collisions (no Collision Detection)
  - **Scarce resources utilization**
    - Channel capacity and battery power
  - **Performance and QoS**
    - System level and (or vs?) user level
  - **Frame organization, and intra-, inter-layer information management**
    - Cross layering principles for adaptive behavior?
    - Risk for “spaghetti design”? [Kumar2003]

[Kumar2003] V. Kawadia, P.R. Kumar, "A Cautionary Perspective on Cross Layer Design", Submitted for publication, 2003
(http://black1.csl.uiuc.edu/~prkumar/)

Collision of Wireless Signals

- **Collision** has destructive effect on the receiver
  - ...causes both channel and power waste
  - Collision detection is not practical in wireless systems
  - Collision avoidance/resolution + contention control on the sender
- Capture effect is possible
  - Exploited to enhance channel reuse, if possible
- Collision domain: set of nodes sharing the same channel
  - Space splitting, transitive relation
Wireless MAC protocols’ classification

Multiple access protocols

- Distributed Contention based
  - Deterministic
    - Deterministic access
    - ID mapping
  - Probabilistic
    - Contention control
    - Contention resolution
      - Random access
  - No Centralized Coordinator, static allocation of resources

- Contention free
  - Distributed dynamic
    - Implicit Reservation
    - Token based
  - Centralized static
    - Reservation based
    - Fixed TDMA, FDMA, CDMA
  - Dynamic allocation of resources
  - Centralized Coordinator, static allocation of resources

Cluster-based MAC?

Evolutionary perspective of distributed MAC

- Distributed, contention-based wireless MAC Problem:
  - The frame vulnerability (collision risk)
  - Needs resolution in distributed way (no centralized coordinator)
- Let’s analyze the time domain first
  - Aloha [Abramson1970]: no coordination
  - Slotted Aloha
  - CSMA [Kleinrock1975]: listen before to transmit
  - Slotted CSMA
  - CSMA/CD: listen before and while transmitting
    - Unpractical in wireless scenarios
    - CSMA/CA + contention resolution (reactive resolution of collisions)
    - CSMA/CA + contention control (preventive/reactive reduction of risk of collisions)

[Abramson1970]

[Kleinrock1975]
The ALOHA protocol

- An integral part of the ALOHA protocol is feedback from the receiver.
- Feedback occurs after a packet is sent.
- No coordination among sources.

Packet ready?

- yes: transmit
- no: wait for a round-trip time

Positive ack?

- yes: compute random backoff integer k
- no: delay packet transmission k times

STA i

- Frame size
- frame1
- ok1

STA j

- early1
- late2
- ok2

Collision domain

- early1
- Frame1
- collision
- late2
- ok2
- Frame1+New2 coll.
- New1+frame1 coll.

Frame vulnerability time: twice the frame size
Slotted ALOHA

Packet ready?

- yes: Wait for start of next slot, transmit
  - wait for a round-trip time quantized in slots
  - positive ack?
    - yes: delay packet transmission k times
    - no: compute random backoff integer k

- no: delay packet transmission k times

Frame vulnerability time: the frame size (slot + propagation)
CSMA Protocol

Packet ready

Channel Busy?

no

transmit

wait for a round-trip time

positive ack?

no

delay packet transmission k times

compute random backoff integer k

Packet ready

Channel Busy?

no

transmit

wait for a round-trip time

positive ack?

yes

delay packet transmission k times

compute random backoff integer k

STA i

STA j

Collision domain

Frame size

Propagation delay

Frame1 detected

Frame1+late2 vulnerability

Frame1+early2 vulnerability

Frame vulnerability time: twice the propagation delay
**Slotted CSMA Protocol**

- Frame size
- Propagation delay

Collision domain

- Frame vulnerability time: the propagation delay

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**Throughput comparison**

Analytical Results
- Pure CSMA
- Slotted CSMA
- Slotted Aloha
- Pure Aloha

Offered Load $G$
CSMA/CA: the IEEE 802.11 Wireless LAN

- **1 Medium Access Control (MAC) protocol:**
  - 2 coordination functions co-exist in a superframe structure (time division)
  - **Distributed Coordination Function (DCF)**
    - Ad-Hoc networks (peer to peer)
    - Distributed control (no base station)
    - contention based access (no QoS, no minimum delay)
    - CSMA/CA access protocol with Binary Exponential Backoff
  - **Point Coordination Function (PCF)**
    - Centralized control (Base station)
    - Polling based access (soft QoS, minimum delay)
    - minimum bandwidth guarantee

Will be analyzed later...

Evolutionary perspective of distributed MAC

- Distributed, contention-based wireless MAC Problem:
  - the frame vulnerability (collision risk)
  - Needs resolution in distributed way (no centralized coordinator)

  let’s analyze the **Space domain**

  - MACA [Karn1990]: RTS/CTS, no carrier sense (MACA-BI, RIMA...)
  - MACAW [Bharghavan et al.1994]: RTS/CTS, no carrier sense and immediate ACK (more reliable and efficient Link Layer Control)
  - FAMA [Fullmer et al.1995]: RTS/CTS, carrier sense + other stuff

- Main solution: RTS/CTS mechanism
  - Today under some criticisms

References:

Cambridge, MA, 1995
Hidden and Exposed terminals: RTS/CTS

- The space domain:
  - Hidden and exposed terminals: space vulnerability
  - RTS/CTS mechanism to contrast Hidden terminals
    - Hidden terminals: B does not sense traffic, but the receiver C cannot receive its packet due to a transmission from A to C (A hidden to B)
    - to seize the channel, according to CSMA/CA, a station transmits a short RTS (request to send) packet and waits for the CTS (Clear to Send) response.
      - A transmit RTS to C and seizing the coverage area
      - C respond with CTS to A (B receive the CTS and does not transmit even if it cannot sense A’s transmission)

RTS/CTS drawbacks

- RTS/CTS is not a “guaranteed” solution and it is additional overhead
- Power asymmetry, detection and interference range >> transmission range
Ad hoc Multi-hop: Time/Space problems

- A bi-directional chain of MAC frames
  - TCP streams (Data + Ack)
- Self-contention (MAC layer problem)
  - Inter-stream self-contention (Data vs. Ack TCP streams)
  - Intra-stream self-contention (same TCP stream)
- How to obtain coordination?
- New proposed solutions
  - Fast forward
  - Quick exchange
  - Flow numbering (pre-routing at the MAC layer???)
  - Frame transmission by forward invitation

MACA: slotted RTS/CTS, no CS

- MACA: eliminates the carrier sensing
  - ...because the contention is on the receiver!
- Introduces slotted RTS/CTS (30 bytes each) and slot time equals the RTS (and CTS) duration
- Allow exploitation of concurrent spatial transmission if the receiver is not exposed to two hidden transmitter terminals
- Variations: MACA-BI, RIMA (receiver initiated)
**MACAW: no cs + slotted RTS/CTS + ACK**

- MACAW: fairness of the backoff procedure
  - MILD + Binary Exponential Backoff
  - Cooperation-based backoff values (space-issues of contention)
- No carrier sensing before both slotted RTS/CTS
- Introduces ACK (RTS – CTS – DATA – ACK)
  - Efficient retransmission policy at Data Link layer
- Problem: both sender and receiver act as receiver during frame transmissions (no concurrent space exploitation of the channel)

**FAMA: cs + slotted RTS/CTS + ACK**

- FAMA: re-introduces carrier sensing before both slotted RTS/CTS
- Introduces lower bound for size of RTS/CTS and CTS-dominance
- Floor acquisition: principle for time and space contention
Ad hoc Multi-hop: Time/Space problems

Source to destination stream: TCP DATA

Destination to Source stream: TCP ACK

New Contention

Ad hoc Multi-hop: Time/Space problems

Fast Forward intra-stream

Quick Exchange inter-stream
Modified NAV policy

CSMA/CA: the IEEE 802.11 Wireless LAN

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    - Centralized control (Base station)
    - Polling based access (soft QoS, minimum delay)
    - Minimum bandwidth guarantee
IEEE 802.11 MAC protocol architecture

Point Coordination Function (PCF)

- point coordinated mode is a contention free, optional service
  - can co-exist with the DCF in a superframe structure.
- central coordinator, i.e. the access point
  - manages stations belonging to its access list.
  - guaranteed to access the channel in a contention-free environment.
DCF and PCF control: IFS

- Each station performs a carrier sensing activity when accessing the channel.
- Priority is determined by Interframe spaces (IFS):
  - Short IFS (SIFS) < Point IFS (PIFS) < Distributed IFS (DIFS)
  - After a SIFS only the polled station can transmit (or ack)
  - After a PIFS only the Base Station can transmit (and PCF takes control)
  - After a DIFS every station can transmit according to basic access CSMA/CA (DCF restarts)

DCF and PCF control: IFS

- SIFS
- PIFS
- DIFS
- Base station takes control
- PCF (polling based) time (scenario 2)
- Poll
- Poll trans. 1
- Poll trans. 2
- Poll trans. 3
- Poll trans. 4
- Poll trans. 5
- Base station polls stations that reserved the channel
- At the end of the PCF period the Base Station releases the channel and DCF restarts (after a DIFS)
- DCF stations wait for a DIFS...
- DIFS: restart DCF
- DCF time (scenario 1: no PCF takes control)

Point Coordination Function (PCF)

- During the PCF time the base station has priority in accessing the channel.
  - Base Station waits for a PIFS after a transmission and takes control (DCF stations must wait for DIFS>PIFS)
  - base station polls stations that reserved the channel
  - At the end of the PCF period the Base Station releases the channel and DCF restarts (after a DIFS)

DCF and PCF control: IFS

- SIFS
- PIFS
- DIFS
- Backoff period (contention)
- Poll
- Base station takes control
- PCF (polling based) time (scenario 2)
- Poll trans. 1
- Poll trans. 2
- Poll trans. 3
- Poll trans. 4
- Poll trans. 5
- Base station polls stations that reserved the channel
- At the end of the PCF period the Base Station releases the channel and DCF restarts (after a DIFS)
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- DIFS: restart DCF
- DCF time (scenario 1: no PCF takes control)
Distributed Coordination Function (DCF)

- Basic Access mode:
  - Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) access scheme (listen before transmit)
  - Carrier sensing performed to detect ongoing transmissions
  - Binary Exponential Backoff over slotted idle time
    - Each station randomly selects the transmission slot in a variable sized Contention Window
  - No Collision Detection (CD)

- CSMA/CA Access Mechanism
  - CSMA/CA is an efficient protocol for data traffic, like Ethernet
  - Listen before transmit
  - Always back-off before a transmission or retransmission
    - Designed to provide fair access to the medium
DCF Backoff procedure

• Selection of a random Backoff Time

DCF Backoff procedure

CWi=contention window size at the i-th transmission attempt. CWi is doubled after each collision experienced (to reduce the contention)

\[
\text{BackoffTime}(i) = (\text{CWi} \times \text{random}(i)) \times \text{SlotTime}
\]

<table>
<thead>
<tr>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>63</td>
<td>127</td>
<td>255</td>
<td>511</td>
<td>1023</td>
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</tbody>
</table>

• Reduction of the Backoff Time

After an idle DIFS period from the last transmission, a station decrements its Backoff Time by a Slot_time for each slot where no activity is sensed on the medium.

• Frozen

As soon as the medium is determined to be busy, the backoff procedure is suspended.

• Transmission

When the Backoff Time reaches zero, the station starts the transmission.

DCF basic access: overview

• Successful transmission

• Collision: no CD

IEEE 802.11 does not implement collision detection

collision length = \(\text{maximum}\{L_A, L_B, L_C\}\)
IEEE 802.11 Contention Control

- Effect of high contention = many collisions

FIG. 1. Channel utilization of Standard 802.11 DCF