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

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
    - No Centralized Coordinator, static allocation of resources
  - Probabilistic
    - Contention control
      - Random access
    - No Centralized Coordinator, dynamic allocation of resources

- Contention free
  - Distributed dynamic
    - Implicit Reservation
      - Token based
    - No Centralized Coordinator, dynamic allocation of resources
  - Centralized static
    - Reservation based
      - Fixed TDMA, FDMA, CDMA
    - 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)

The ALOHA protocol

Packet ready?  

- yes: transmit
- wait for a round-trip time

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

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

The ALOHA protocol

STA i

Frame size

STA j

early1 
late2 
no2 

Collision domain

early1 
Frame1 
late2 
no2

collision

- Frame vulnerability time: twice the frame size

© Luciano Bononi 2007
Sistemi e Reti Wireless
Slotted ALOHA

Packet ready?

no

Wait for start of next slot
delay packet transmission k times

transmit

yes

positive ack?

no

compute random backoff integer k

yes

wait for a round-trip time quantized in slots

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

STA i

Framesize

STA j

time slot

Collision domain

Frame1 + frame2 collision

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

STA $i$

- Frame size
- frame1

STA $j$

- Propagation delay
- early2
- late2 detected
- late2

Collision domain

- collision
- early2
- late2

- Frame1+late2 vulnerability
- Frame1+early2 vulnerability

Frame vulnerability time: twice the propagation delay
Slotted CSMA Protocol

- Frame vulnerability time: the propagation delay

Throughput comparison

© Luciano Bononi 2007
Sistemi e Reti Wireless
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...

---

**Homework challenge**

- Come mettere in ordine (in fila) un numero arbitrario \( M \) (sconosciuto a tutti) di persone sulla base di un parametro locale (es. l’età) con un algoritmo di complessità \( O(1) \) (non funzione di \( M \))new

- **Vincoli del mondo:**
  - Tutti vedono lo stesso mondo (diciamo anche solo un singolo muro dello stesso mondo)
  - Tutti hanno lo stesso algoritmo implementato locale
  - Nessuno può comunicare o vedere gli altri
  - Esiste nozione comune di tempo (anche non allineata)
Homework challenge

- Soluzione approssimata
  - Genera $P_{\text{stop}}(\eta)$
  - Ciclo
    - Fermaì = $(\text{Rnd()} <= P_{\text{stop}})$
    - Fai un passo allontanandoti dal muro
  - Finché (Fermaì == True)

- Soluzione esatta (metrica spaziale comune)
  - Genera Distanza($\eta$) [cfr $P_{\text{stop}}$]
  - Percorri Distanza allontanandoti dal muro

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:

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 seize 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

Fast Forward intra-stream

Quick Exchange inter-stream

© Luciano Bononi 2007  Sistemi e Reti Wireless
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
IEEE 802.11 MAC protocol architecture

- **Contention free services**
- **Contention based services**

**MAC sublayer**

- **Point Coordination Function (PCF)**
- **Distributed Coordination Function (DCF)**
- **Physical Layer (PHY)**

**Fundamental Access Method**

**Point coordinated mode (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 (Beacon).
  - 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)

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)
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**
  
  CW\textsubscript{i} = contention window size at the i-th transmission attempt. CW\textsubscript{i} is doubled after each collision experienced (to reduce the contention)
  
  \[
  \text{BackoffTime}(i) = (\text{CW}_i \times \text{random()} \times \text{SlotTime})
  \]

<table>
<thead>
<tr>
<th>(i)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{CW}_i)</td>
<td>15</td>
<td>31</td>
<td>63</td>
<td>127</td>
<td>255</td>
<td>511</td>
<td>1023</td>
</tr>
</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**
  
  IEEE 802.11 does not implement collision detection.

- **Collision: no CD**
  
  \[\{L_A, L_B, L_C\} = \text{lengths of colliding packets}\]

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

- Effect of high contention = many collisions

![Graph showing channel utilization for Standard 802.11 DCF with congestion control off and on.](#)

**FIG. 1.** Channel utilization for Standard 802.11 DCF

---

IEEE 802.11 Contention Control

- Information known due to carrier sense

![Diagram showing channel state observed by each station.](#)

**FIG. 2.** A sample of the channel state observed by each station.

Slot Utilization = \( \frac{\text{Num Busy Slots}}{\text{Initial Backoff}} \)

Slot Utilization in [0..1]

---
IEEE 802.11 Contention Control

- Adoption of Slot Utilization in Distributed contention control (DCC)
- Probability of Transmission = $P_T$
- $P_T = (1 - S_U)^{\text{Num\_Att}}$

IEEE 802.11 Contention Control

- Probabilistic Distributed Contention Control

Extends 802.11 MAC

Stable (avoids collapse)
IEEE 802.11 Contention Control

- DCC => better performance (no overheads)

**FIG. 6.** Mean number of collisions for each successful transmission.

**FIG. 7.** Mean Access Delay

**FIG. 10.** Channel Utilization

IEEE 802.11 Contention Control

- DCC => better performance (no overheads)
IEEE 802.11 Contention Control

- DCC distributed priority mechanism

\[ P_T = (1 - S_U) \]

AOB = optimum performance
- No need to estimate number of stations