Wireless Ad Hoc & Sensor Networks

Medium Access Control

- Application
- Transport Protocol
- Network Protocol
- **Media Access Protocol**
- Physical Channel (Radio)

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Outline

- Multiple Access Technique
- Designing Issues of MAC protocols
- Classification of MAC protocols
- Protocols examples
- Link layer protocols
- The lower layers in detail
- Summary

Multiple Access Technique

- Reservation-based (Recall: mobile communication 1)
  - FDMA : Frequency Division Multiple Access
  - TDMA : Time Division Multiple Access
  - CDMA : Code Division Multiple Access
  - SDMA : Space Division Multiple Access
- Random
  - ALOHA : University of Hawaii Protocol
  - CSMA : Carrier Sense Multiple Access
  - MACA : Multiple Access with Collision Avoidance
- Random with reservation
  - DAMA : Demand Assigned Multiple Access
  - PRMA : Packet Reservation Multiple Access

Reservation-based

- FDMA (Frequency Division Multiple Access)
  - assign a certain frequency to a transmission channel
  - permanent (radio broadcast), slow hopping (GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- TDMA (Time Division Multiple Access)
  - assign a fixed sending frequency for a certain amount of time
- CDMA (Code Division Multiple Access)
- SDMA (Space Division Multiple Access)
  - segment space into sectors, use directed antennas
  - Use cells to reuse frequencies
- Combinations

FDD and TDD

- In case of two communicating parties sharing the medium:
  - Simplex : one way communication from sender to receiver
  - Duplex : two way communication between two parties
  - Frequency division duplex (FDD)
    - Combination of two simplex channels with different carrier frequencies
  - Time division duplex (TDD)
    - Time sharing of a single channel achieves quasi-simultaneous duplex transmission

Random Access

- However, wireless communication is often much more ad-hoc
  - New terminals have to register with the network
  - Terminals request access to the medium spontaneously
  - In many cases there is no central control

⇨ Other access methods such as distributed and non-arbitrated = random access

Multiple Access

Characteristics:

- Shared medium : radio channel is shared by a priori unknown number of stations
- Broadcast medium: all stations within transmission range of a sender receive the signal

Challenge:

- Wireless communication channel is prone to errors and problems, e.g., hidden/exposed node problems & signal attenuation

Wired vs. Wireless

- Ethernet uses 1-persistent CSMA/CD
  - carrier sense multiple access with collision detection
    - Sense if the medium is free and start sending as soon as it becomes free
    - While sending listen to the medium to detect other senders
    - In case of a collision immediately stop sending and wait for the random amount of time
- Problems in wireless networks
  - signal strength decreases quickly with distance
  - senders apply CS and CD, but the collisions happen at receivers
  - Energy efficiency: having the radio turned on costs almost as much energy as transmitting, so to seriously save energy one needs to turn the radio off!

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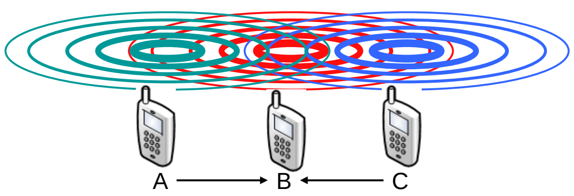
Need for MAC Protocols ?

- Popular CSMA/CD (Carrier Sense Multiple Access/Collision Detection) scheme is not applicable to wireless networks
- CSMA suffers hidden terminal & exposed terminal problems
- Collision Detection is impossible in wireless communication

→ Specific MAC protocols for the access to the physical layer

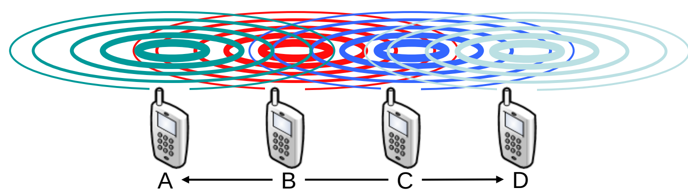
Hidden Terminal Problem

- A sends to B, C cannot receive A
- C wants to send to B, C senses a “free” medium (CS fails)
- collision at B, A cannot receive the collision (CD fails)
- A is “hidden” for C



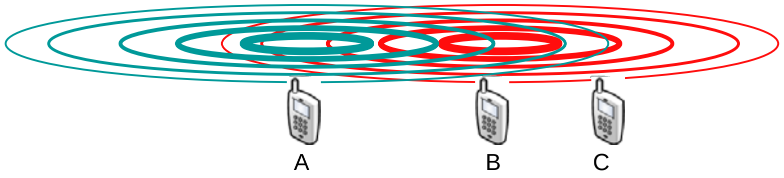
Exposed Terminal Problem

- B sends to A, C wants to send to D
- C has to wait, CS signals a medium in use
- since A is outside the radio range of C waiting is not necessary
- C is “exposed” to B



Near and Far Terminals

- Terminals A and B send, C receives
  - the signal of terminal B hides A's signal
  - C cannot receive A



  - precise power control required

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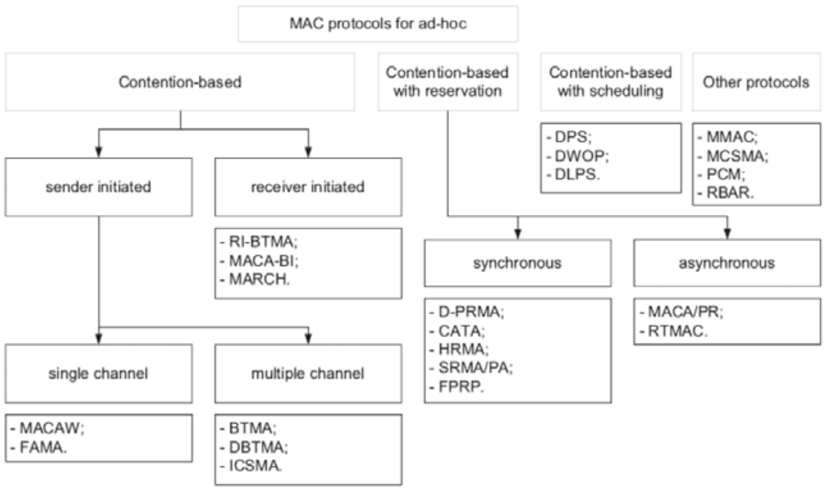
Classification of MAC protocols



In general (1/2)

- Contention-based protocols:
  - A node does not make any resource reservation a priori.
  - Whenever a node receives a packet to be transmitted, it contends with its neighbour nodes for access
  - Can not provide QoS (Quality of Service) guarantees to session since nodes are not guaranteed to haveregular access to the channel
- Contention-based with reservation
  - Wireless networks may need to support real-time traffic
  - Reservation mechanisms for reserving bandwidth a priori
  - Such protocols can provide QoS support to time-sensitive traffic sessions

In general (2/2)

- Contention-based with scheduling
  - These protocols focus on packet scheduling at nodes, and also scheduling nodes for access to the channel
  - Used for enforcing priorities among flows whose packets are queued at nodes
  - Some of them take into consideration battery characteristics (remaining battery power)
- Other protocols

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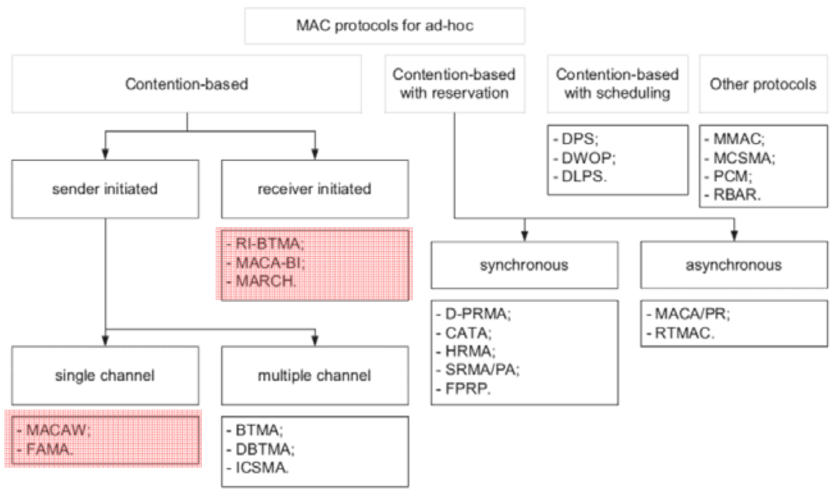
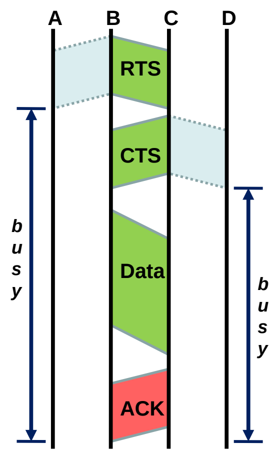


Multiple Access with Collision Avoidance (MACA)

- MACA uses a two step signaling procedure to address the hidden and exposed terminal problems
- Use short signaling packets for collision avoidance
  - Request (or ready) to send RTS: a sender requests the right to send from a receiver with a short RTS packet before it sends a data packet
  - Clear to send CTS: the receiver grants the right to send as soon as it is ready to receive

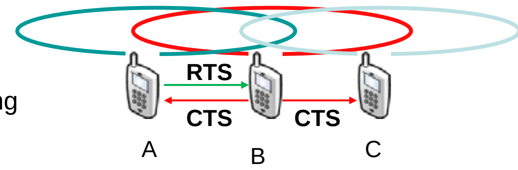


MACA (cont.)

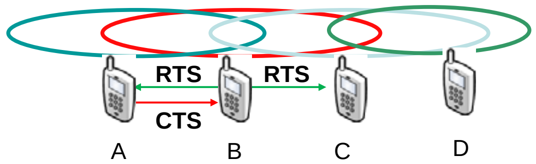
- Signaling packets contain
  - sender address
  - receiver address
  - packet size
    - Network allocation vector (NAV)
    - Duration during which other sender have to keep quiet to avoid a collision
- If control (RTS-CTS) messages collide with each other or with data packets, a backoff procedure is activated (backoff is binary exponential)
- Example: Wireless LAN (IEEE 802.11)

MACA examples

- MACA avoids the problem of hidden terminals
  - A and C want to send to B
  - A sends RTS first
  - C waits after receiving CTS from B



- MACA avoids the problem of exposed terminals
  - B wants to send to A, and C to D
  - now C does not have to wait as C cannot receive CTS from A



MACA extensions (1/2)

- MACAW extends MACA : RTS-CTS-**DS**-DATA-**ACK**
  - DLL (Data Link Layer) acknowledgements
  - An improved backoff mechanism
  - DS (Data Sending) message:
    - Say that a neighbour of the sender overhears an RTS but not a CTS (from the receiver)
    - In this case it can not tell if RTS-CTS was successful or not
    - When it overhears the DS, it realizes that the RTS-CTS was successful, and it defers its own transmission

MACA extensions (2/2)

- MACA –by invitation (MACA-BI) : **RTR**-DATA
  - Is a receiver-initiated MAC protocol, the receiver node initiate data transmission
  - It reduces the number of control packets used in the MACA protocol
  - MACA-BI eliminate the need for the RTS packet, it uses RTR (ready to receive) control packet to the sender.
  - RTR packets carries information about the time interval during which the DATA packet would be transmitted
  - The efficiency of the MAC-BI scheme is mainly dependent on the ability of the receiver node to predict accurately the arrival rates of the traffic at the sender nodes.

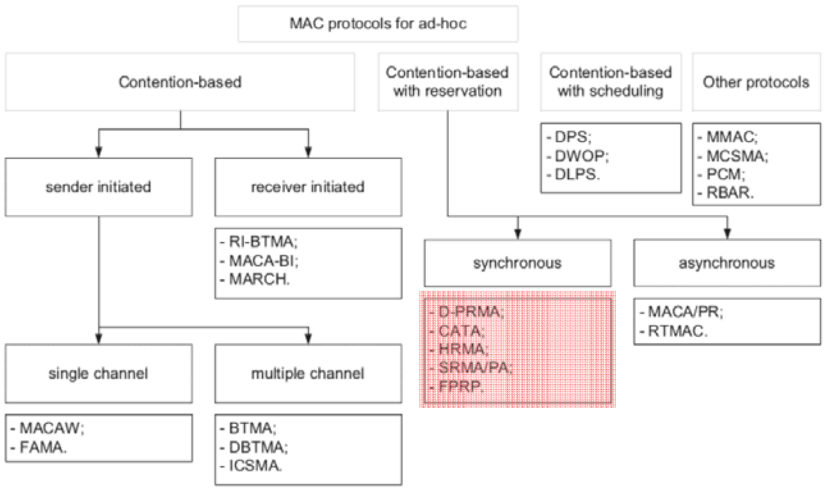
Media Access with Reduced Handshake (MARCH)

- MARCH is receiver-initiated protocol
- Unlike MACA-BI does not require any traffic prediction mechanism
- In MARCH the RTS packet is used only for the first packet of the stream. From the second packet onward, only the CTS packet is used
- The protocol exploits the broadcast nature of the traffic to reduce the number of the handshakes involved in data transmission

Reservation-based MAC protocol - DAMA

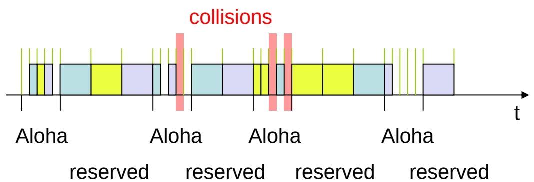
- Demand Assigned Multiple Access (DAMA)
- Practical systems therefore use reservation whenever possible.
  - But: Every scalable system needs an Aloha style component.
- DAMA allows a sender to reserve timeslots. Two phase approach
- Reservation phase:
  - a sender *reserves* a future time-slot
  - sending within this reserved time-slot is possible without collision
  - reservation also causes higher delays
- Termination phase: collision-free transmission using reserved timeslots

Classification of MAC protocols



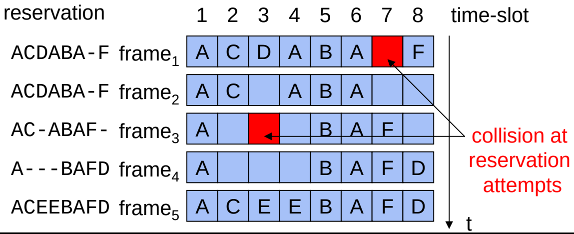
DAMA: Explicit Reservation

- *Aloha mode* for reservation: competition for small reservation slots, collisions possible.
- *Reserved mode* for data transmission within successful reserved slots (no collisions possible).
- It is important for all stations to keep the reservation list consistent at any point in time and, therefore, all stations have to synchronize from time to time.



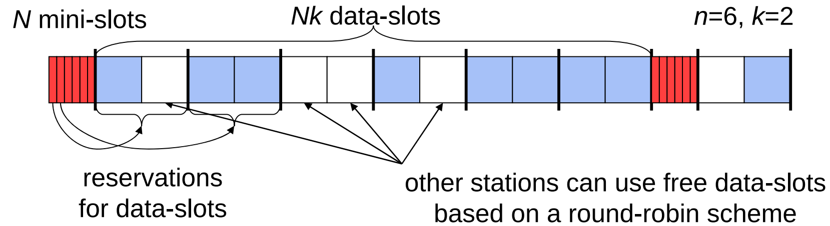
PRMA: Implicit Reservation

- Packet Reservation Multiple Access
- A certain number of slots form a frame, frames are repeated.
- Stations compete for empty slots according to the slotted aloha principle.
- Once a station reserves a slot successfully, this slot is automatically assigned to this station in all following frames.
- Competition for this slots starts again as soon as the slot was empty in the last frame .

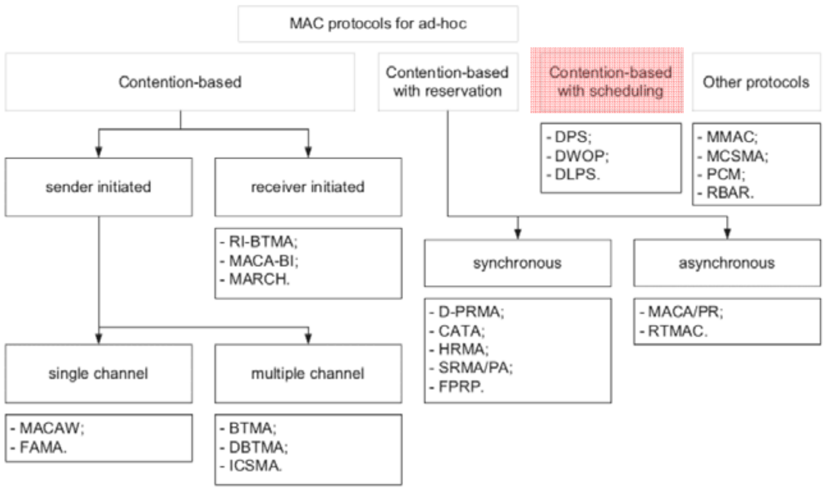


Distributed PRMA

- Every frame consists of n mini-slots and x data-slots
- Every station has its own mini-slot and can reserve up to k data-slots using this mini-slot (i.e. $x = nk$).
- Other stations can send data in unused data-slots according to a round-robin sending scheme (best-effort traffic)



Classification of MAC protocols



Schedule-based MAC protocols – SMACS

- Given
  - Many radio channels
  - super-frames of known length ➔ Time synchronisation required
- Goal: set up directional links between neighbouring nodes
  - Link: radio channel + time slot at both sender and receiver
  - Free of collisions at receiver
  - Channel is picked randomly, slot is searched greedily until a collision free slot is found
- Receivers sleep and only wake up in their assigned time slots, once per super-frame

Schedule-based MAC protocols – SMACS II

- Link Setup
  - Case 1: Node A and B are both not connected
    - Node A sends invitation message
    - Node B answers that it is not connected to any other node
    - Node A tells B to pick slot/frequency for the link
    - Node B returns the link specification
  - Case 2: Node A has neighbours and node B does not
    - Node A creates the link specification and instructs Node B to use it
  - Case 3: Node A has no neighbours, but node B has some
    - Node B creates the link specification and instructs node A to use it
  - Case 4: Both nodes have links to neighbours
    - Nodes exchange their schedules and pick free slots/frequencies in mutual agreement

Schedule-based MAC protocols – TRAMA

- TRAMA: Traffic-adaptive medium access protocol
- Nodes are synchronised
- Time is divided into cycles that consists of
  - Random access periods
  - Scheduled access periods
- Nodes exchange neighbourhood information
  - Learning about their two-hop neighbourhood by using the ‘neighbourhood exchange protocol’
    - In random access period send small incremental neighbourhood update information in randomly selected time slots
- Nodes exchange schedules
  - Using the ‘schedule exchange protocol’
    - Similar to neighbourhood information exchange

Schedule-based MAC protocols – TRAMA II

- As a result: Each node knows its two-hop neighbourhood and the schedule
- Problem
  - How to decide which slot (in scheduled access period) to use?
- Solution: ‘Adaptive Election’
  - Use node identifier x and globally known hash function h
  - For time slot t, compute priority p as follows: $p = h(x \oplus t)$
  - Compute this priority for next k time slots for the node itself and all two-hop neighbours
  - Node can use those time slots for which it has the highest priority

***Example*: Priorities of node A and its two-hop neighbours B and C**

	t=0	t=1	t=2	t=3	t=4
A	23	9	56	3	26
B	64	8	12	44	6
C	18	6	33	57	2

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Link Layer Protocols

- Link Layer protocols cover the following topics
  - Error Control
    - Make sure that the sent bits arrive and no other
      ➔ forward and backward error control
  - Framing
    - Group bit sequence into packets/frames
      ➔ format, size
  - Flow Control
    - Ensure that a fast sender does not overrun a slower receiver
  - Link Management
    - Discovery and management of links to neighbouring nodes

➔Goal: Create a reliable communication link

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Error control

- Error control has to ensure that data transport is
  - Error-free ➔ deliver exactly the sent bits/packets
  - In-Sequence ➔ deliver them in the original order
  - Duplicate-free ➔ and at most once
  - Loss-free ➔ and at least once
- Causes: fading, interferences, loss of bit synchronisation
  - Results in bit errors, packet losses
    - Mostly occurring in bursts
  - In wireless networks high average bit error rates: 10^{-2} .. 10^{-4}
- Approaches
  - Backward error control: ARQ (Automatic Repeat Request)
  - Forward error control: FEC (Forward Error Correction)

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Error control – ARQ

- Idea of ARQ
  - Transmitting node's link layer accepts a data packet, creates a link-layer packet by adding a header and a checksum and transmits this packet to the receiver
  - Receiver checks packet's integrity with the help of the checksum and provides feedback; on negative feedback ➔ retransmission
- Standard ARQ Protocols
  - **Alternating bit**
    - Transmitter buffers one packet; single bit sequence number
  - **Go-back N**
    - Buffer up to N packets; packets that were not ack. are retransmitted
  - **Selective Repeat/ Selective Reject**
    - Sender and Receiver can buffer up to N packets; timer exceeds missing packets are re-requested

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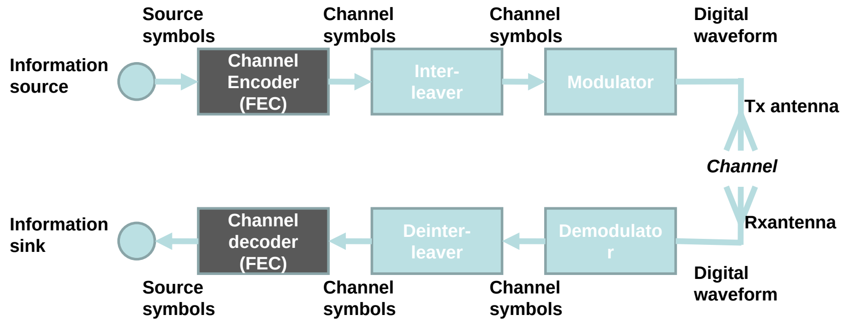
Error control – FEC

- Idea of FEC
  - Transmitter accepts a stream or a block of user data or source bits add suitable redundancy and transmit the result to the sender
  - Depending on the amount and structure of dependency receiver can correct some bit errors



Error control – FEC

- Block-coded FEC
  - Block or a word of a number k of p-ary source symbols will be used to produce a block consisting of n of q-ary channel symbols
  - Examples:
    - Reed-Solomon codes (RS)
    - Bose-Chaudhuri-Hocquenghem codes (BCH)
- Convolutional codes
  - K bits of user data are mapped to n channel symbols; however, coding of two successive k-bit blocks is not independent
- Also hybrid schemes, i.e. combination of ARQ and FEC exist

Framing

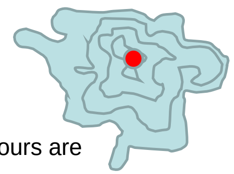
- Packet size
  - Small packets: Low packet error rate; high overhead
  - Large packets: High packet error rate; low overhead
- Optimal packet size depends on
  - Overhead
  - payload size
  - and bit error rate (BER)
- For known BER optimal frame length is easy to determine
- Problem: How to estimate BER? (➔ adaptive schemes)
  - Collect channel state information at the receiver (RSSI, FEC, …)
- Second problem: How long are observations valid? (aging)
  - Only recent past is credible

Link management

- Goal
  - Decide to which neighbours a link should be established
- Problem: Link quality
  - is not binary (good vs. bad), i.e. link quality has several characteristics
  - is time variable due to mobility, interferences, etc.
  - has to be estimated, actively by sending probe packets and evaluating Reponses or passively by overhearing
- Establish a ‘neighbourhood table’ to store neighbouring nodes and their associated link qualities
  - Can be automatically constructed as part of MAC protocols

Link management – Link Quality Characteristics

- Experiments show that the simple circular shape for the region of communication is not realistic
  - Instead
    - Irregular shape of the region of communication
    - Correlation between distance and loss rate is weak
    - Asymmetric links are rather frequent
    - Packet loss rate is time variable even when neighbours are stationary ➔ Significant short-term variations



- Regions of communication
  - Effective region: consistently >= 90% of packets arrive
  - Poor region: packet loss rates beyond 90%
  - Transitional region: anything in between

Link quality should be understood in a statistical and time-varying sense

Link quality estimation

- How to estimate the quality of a link in the field?
- Conflicting requirements
  - Precision
    - Collect enough results and give statistically meaningful results
  - Agility
    - Detect significantly changing link conditions quickly
  - Stability
    - Estimation should be immune to short/transient fluctuations in the link quality ➔ averaging over multiple samples/events
  - Efficiency
    - Reduce unnecessary link quality estimation effort to save energy
- Passive vs. active estimators
  - Active: node sends out special packets and collects responses
  - Passive: node observers transmissions in its neighbourhood

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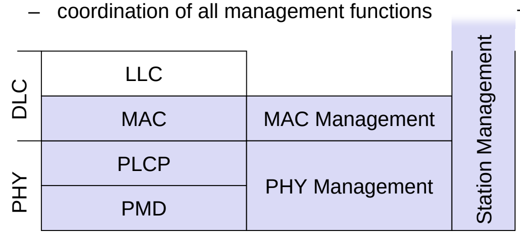
802.11 – The lower layers in detail

- PMD (Physical Medium Dependent)
  - modulation, coding
- PLCP (Physical Layer Convergence Protocol)
  - clear channel assessment signal (carrier sense)
- PHY Management
  - channel selection, PHY-MIB
- Station Management
  - coordination of all management functions
- MAC
  - access mechanisms
  - fragmentation
  - encryption
- MAC Management
  - Synchronization
  - roaming
  - power management
  - MIB (management information base)



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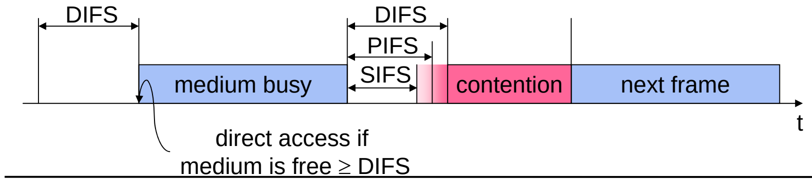
MAC layer: DFWMAC (Distributed Foundation Wireless MAC)

- Traffic services
  - Asynchronous Data Service (mandatory)
    - exchange of data packets based on “best-effort”
    - support of broadcast and multicast
  - Time-Bounded Service (optional)
    - implemented using PCF (Point Coordination Function)
- Access methods
  - DFWMAC-DCF CSMA/CA (mandatory)
    - collision avoidance via binary exponential back-off mechanism
    - minimum distance between consecutive packets
    - ACK packet for acknowledgements (not used for broadcasts)
  - DFWMAC-DCF w/ RTS/CTS (optional)
    - avoids hidden terminal problem
  - DFWMAC-PCF (optional)
    - access point polls terminals according to a list

MAC layer

- defined through different inter frame spaces
- no guaranteed, hard priorities
- SIFS (Short Inter Frame Spacing)
  - highest priority, for ACK, CTS, polling response
- PIFS (PCF IFS)
  - medium priority, for time-bounded service using PCF
- DIFS (DCF, Distributed Coordination Function IFS)
  - lowest priority, for asynchronous data service



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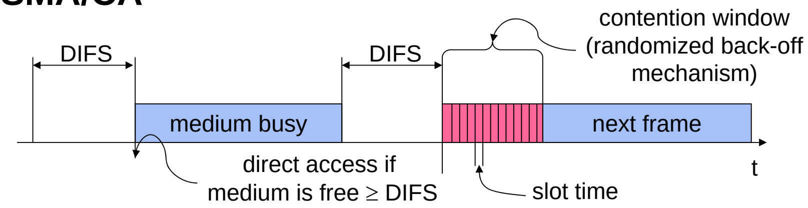
CSMA/CA



- station ready to send starts sensing the medium (Carrier Sense based on CCA, Clear Channel Assessment)
- if the medium is free for the duration of an Inter-Frame Space (IFS), the station can start sending (IFS depends on service type)
- if the medium is busy, the station has to wait for a free IFS, then the station must additionally wait a random back-off time (collision avoidance, multiple of slot-time)
- if another station occupies the medium during the back-off time of the station, the back-off timer stops (fairness)

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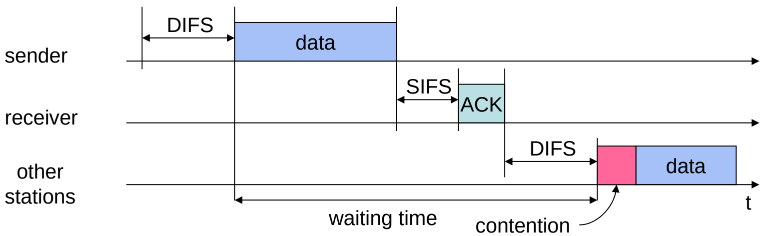
CSMA/CA 2

- Sending unicast packets
  - station has to wait for DIFS before sending data
  - receivers acknowledge at once (after waiting for SIFS) if the packet was received correctly (CRC)
  - automatic retransmission of data packets in case of transmission errors



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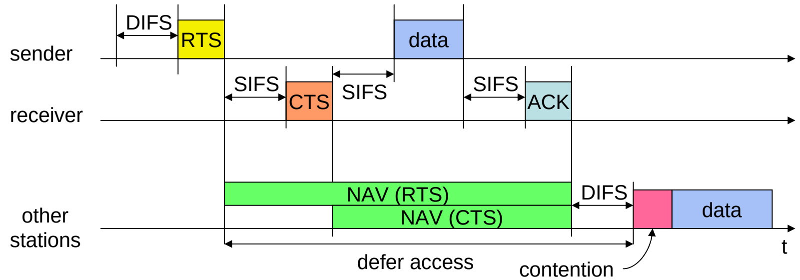
DFWMAC

- station can send RTS with reservation parameter after waiting for DIFS (reservation determines amount of time the data packet needs the medium)
- acknowledgement via CTS after SIFS by receiver (if ready to receive)
- sender can now send data at once, acknowledgement via ACK
- other stations store medium reservations distributed via RTS and CTS



Frame format

2	2	6	6	6	2	6	0-2312	4 bytes
Frame Control	Duration ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Data	CRC

Byte 1: version, type, subtype
Byte 2: two DS-bits, fragm., retry, power man., more data, WEP, order

- Type
  - control frame, management frame, data frame
- Sequence control
  - important against duplicated frames due to lost ACKs
- Addresses
  - receiver, transmitter (physical), BSS identifier, sender (logical)
- Miscellaneous
  - sending time, checksum, frame control, data

MAC address format

scenario	to DS	from DS	address 1	address 2	address 3	address 4
ad-hoc network	0	0	DA	SA	BSSID	-
infrastructure network, from AP	0	1	DA	BSSID	SA	-
infrastructure network, to AP	1	0	BSSID	SA	DA	-
infrastructure network, within DS	1	1	RA	TA	DA	SA

DS: Distribution System
AP: Access Point
DA: Destination Address
SA: Source Address
BSSID: Basic Service Set Identifier
RA: Receiver Address
TA: Transmitter Address

Special Frames: ACK, RTS, CTS

- Acknowledgement

ACK

bytes	2	2	6	4
	Frame Control	Duration	Receiver Address	CRC

- Request To Send

RTS

bytes	2	2	6	6	4
	Frame Control	Duration	Receiver Address	Transmitter Address	CRC

- Clear To Send

CTS

bytes	2	2	6	4
	Frame Control	Duration	Receiver Address	CRC

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Summary

- The most important design goal of a MAC protocol is to enable shared access to the common wireless medium
- The issues associated with the design of the MAC protocol of wireless ad hoc networks are:
  - Bandwidth efficiency
  - QoS support
  - Time-synchronization
  - Node mobility
  - Error-prone shared broadcast channel
  - Hidden and exposed problems
  - Distributed nature / lack of central coordination

Summary

- The Ad Hoc wireless networks MAC protocols have been classified into different categories
- Some protocols were discussed as examples
- In the MAC layer of the sensor networks lectures other MAC protocols design issues will be discussed

- Outlook: Next lecture will talk about routing protocols for ad hoc networks

Summary – Next Session