Medium Access Control

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Roadmap

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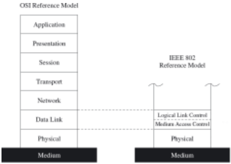
Medium Access Control

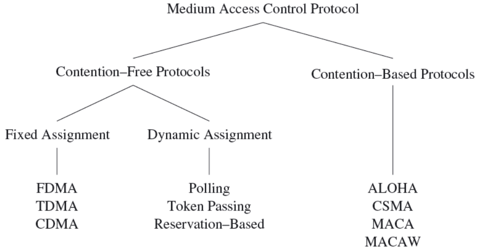
- In most networks, multiple nodes share a communication medium for transmitting their data packets
- The medium access control (MAC) protocol is primarily responsible for regulating access to the shared medium
- The choice of MAC protocol has a direct bearing on the reliability and efficiency of network transmissions
  - due to errors and interferences in wireless communications and to other challenges
- Energy efficiency also affects the design of the MAC protocol
  - trade energy efficiency for increased latency or a reduction in throughput or fairness

Overview

- Responsibilities of MAC layer include:
  - decide when a node accesses a shared medium
  - resolve any potential conflicts between competing nodes
  - correct communication errors occurring at the physical layer
  - perform other activities such as framing, addressing, and flow control
- Second layer of the OSI reference model (data link layer) or the IEEE 802 reference model (which divides data link layer into logical link control and medium access control layer)



MAC Protocol Categorization



Contention-Free Medium Access

- Collisions can be avoided by ensuring that each node can use its allocated resources exclusively
- Examples of fixed assignment strategies:
  - FDMA: Frequency Division Multiple Access
    - the frequency band is divided into several smaller frequency bands
    - the data transfer between a pair of nodes uses one frequency band
    - all other nodes use a different frequency band
  - TDMA: Time Division Multiple Access
    - multiple devices to use the same frequency band
    - relies on periodic time windows (frames)
      - frames consist of a fixed number of transmission slots to separate the medium accesses of different devices
      - a time schedule indicates which node may transmit data during a certain slot

Contention-Free Medium Access

- Examples of fixed assignment strategies (contd.):
  - CDMA: Code Division Multiple Access
    - simultaneous accesses of the wireless medium are supported using different codes
    - if these codes are orthogonal, it is possible for multiple communications to share the same frequency band
    - forward error correction (FEC) at the receiver is used to recover from interferences among these simultaneous communications
- Fixed assignment strategies are inefficient
  - it is impossible to reallocate slots belonging to one device to other devices if not needed in every frame
    - generating schedules for an entire network can be a taunting task
    - these schedules may require modifications every time the network topology or traffic characteristics in the network change

Contention-Free Medium Access

- Dynamic assignment strategies: allow nodes to access the medium on demand
  - polling-based protocols
    - a controller device issues small polling frames in a round-robin fashion, asking each station if it has data to send
    - if no data to be sent, the controller polls the next station
  - token passing
    - stations pass a polling request to each other (round-robin fashion) using a special frame called a token
    - a station is allowed to transmit data only when it holds the token
  - reservation-based protocols
    - static time slots used to reserve future access to the medium
    - e.g., a node can indicate its desire to transmit data by toggling a reservation bit in a fixed location
    - these often very complex protocols then ensure that other potentially conflicting nodes take note of such a reservation to avoid collisions

Contention-Based Medium Access

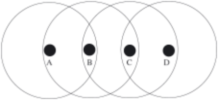
- Nodes may initiate transmissions at the same time
  - requires mechanisms to reduce the number of collisions and to recover from collisions
- Example 1: ALOHA protocol
  - uses acknowledgments to confirm the success of a broadcast data transmission
    - allows nodes to access the medium immediately
    - addresses collisions with approaches such as exponential back-off to increase the likelihood of successful transmissions
- Example 2: slotted-ALOHA protocol
  - requires that a station may commence transmission only at predefined points in time (the beginning of a time slot)
  - increases the efficiency of ALOHA
  - introduces the need for synchronization among nodes

Contention-Based Medium Access

- Carrier Sense Multiple Access (CSMA)
  - CSMA with Collision Detection (CSMA/CD)
    - sender first senses the medium to determine whether it is idle or busy
      - if it is found busy, the sender refrains from transmitting packets
      - if the medium is idle, the sender can initiate data transmission
  - CSMA with Collision Avoidance (CSMA/CA)
    - CSMA/CD requires that sender aware of collisions
    - instead, CSMA/CA attempts to avoid collisions in the first place

Hidden and Exposed Terminal Problems

- Hidden-terminal problem
  - senders A and C are able to reach B, but cannot overhear each other's signals
  - it is possible for A and C to transmit data to B at the same time, causing a collision at B, without being able to directly detect this collision
- Exposed-terminal problem
  - C wants to transmit data D, but decides to wait because it overhears an ongoing transmission from B to A
  - B's transmission could not interfere with data reception at C



Carrier Sense Multiple Access

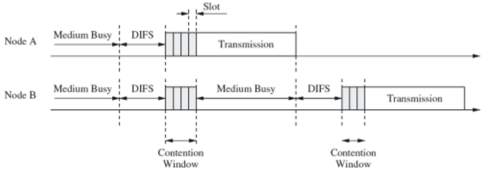
- Nodes first sense the medium before they begin a transmission (reduces number of collisions)
- Non-persistent CSMA
  - node is allowed to immediately transmit data once medium is idle
  - if the medium is busy, the node performs a back-off operation
    - wait for a certain amount of time before attempting to transmit again
- 1-persistent CSMA
  - node wishing to transmit data continuously senses the medium for activity
  - once the medium is found idle, the node transmits data immediately
  - if a collision occurs, the node waits for a random period of time before attempting to transmit again

Carrier Sense Multiple Access

- p-persistent CSMA
  - node continuously senses the medium
  - node transmits data with a probability *p* once the medium becomes idle
  - delays transmission with a probability $1 - p$
  - random back-off values are either continuous values in the case of un-slotted CSMA or multiples of a fixed slot size in slotted CSMA
- CSMA/CA (CSMA with Collision Avoidance)
  - nodes sense the medium, but do not immediately access the channel when it is found idle
  - instead, a node waits for a time period called DCF interframe space (DIFS) plus a multiple of a slot size
  - in case there are multiple nodes attempting to access the medium, the one with the shorter back-off period will win

Carrier Sense Multiple Access

- Example:
  - node A waits for DIFS + 4 ∗ *s* (where *s* represents the slot size), while node B's back-off is DIFS + 7 ∗ *s*
  - once node A begins with its transmission, node B freezes its own back-off timer and resumes the timer after node A completes its transmission plus another period of DIFS
  - once node B's back-off timer expires, it can also begin its transmission



MACA and MACAW

- Multiple Access with Collision Avoidance (MACA)
  - dynamic reservation mechanism
  - sender indicates desire to send with ready-to-send (RTS) packet
  - intended receiver responds with clear-to-send (CTS) packet
  - if sender does not receive CTS, it will retry at later point in time
  - nodes overhearing RTS or CTS know that reservation has taken place and must wait (e.g., based on the size of data transmission)
  - address hidden terminal problem and reduces number of collisions
- MACA for Wireless LANs (MACAW)
  - receiver responds with acknowledgment (ACK) after data reception
    - other nodes in receiver's range learn that channel is available
  - nodes hearing RTS, but not CTS do not know if transmission will occur
    - MACAW uses data sending (DS) packet, sent by sender after receiving CTS to inform such nodes of successful handshake

MACA By Invitation

- In MACA-BI, destination device initiates data transfers by sending a Ready To Receive (RTR) packet to the source
  - source then responds with the data message
- Compared to MACA, MACA-BI reduces overhead
  - increases the theoretical maximum throughput
  - depends on the destination knowing when to receive data
- Source nodes can use an optional field within the data message to indicate the number of queued messages
  - providing the destination with an indication that more RTS packets will be required

IEEE 802.11

- Published in 1999 by the Institute of Electrical and Electronics Engineers (IEEE)
  - specifies the physical and data link layers of the OSI model for wireless connections
- Often referred to as Wireless Fidelity (Wi-Fi)
  - certification given by Wi-Fi Alliance, a group that ensures compatibility between hardware devices that use the 802.11 standard
- Wi-Fi combines concepts found in CSMA/CA and MACAW, but also offers features to preserve energy
- Two modes of operation
  - Point Coordination Function (PCF) mode
    - communication among devices goes through a central entity called an access point (AP) or base station (BS): managed mode
  - Distributed Coordination Function (DCF) mode
    - devices communicate directly with each other: ad-hoc mode

IEEE 802.11

- IEEE 802.11 is based on CSMA/CA
  - before a node transmits, it first senses the medium for activity
  - the node is allowed to transmit, if the medium is idle for at least a time period called the DCF interframe space (DIFS)
  - otherwise the device executes a back-off algorithm to defer transmission to a later time
  - this algorithm randomly selects a number of time slots to wait and stores this value in a back-off counter
  - for every time slot that passes without activity on the network, the counter is decremented and the device can attempt transmission when this counter reaches zero
  - if activity is detected before the counter reaches zero, the device waits until the channel has been idle for a period of DIFS before it continues to decrement the counter value

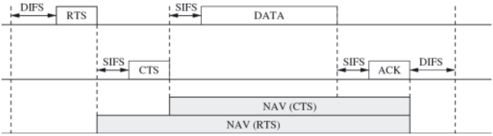
IEEE 802.11

- After a successful transmission
  - receiver device responds with an acknowledgment after waiting for a time period called the short interframe space (SIFS)
  - the value of SIFS is smaller than the value of DIFS to ensure that no other device accesses the channel before the receiver can transmit its acknowledgment
- Once a node A makes a reservation using RTS and CTS control messages
  - another neighboring node B, overhearing the RTS message, must refrain from accessing the medium until node A's transmission has been completed and acknowledged
  - however, this would mean that node B has to continuously sense the medium to detect when it becomes idle again

IEEE 802.11

- Instead, A's RTS message carries the size of the data it will transmit
  - allowing node B to estimate how long the transmission will take and to decide whether to enter a low-power sleep mode
  - some neighboring nodes may only overhear CTS (but not RTS), therefore, the data size is also carried in the CTS message
  - using the data size information, neighboring nodes set a network allocation vector (NAV) that indicates how long the medium will be unavailable
    - reduces the need for continuously sensing the medium, allowing a node to save power

IEEE 802.11



IEEE 802.11

- PCF mode
  - access point (AP) coordinates channel access to ensure collision-free communication
    - periodically broadcasts a beacon to its client devices (includes list of devices with data pending at AP)
  - during contention-free period, AP transmits these packets to its client devices
  - AP can also poll client devices to allow them to initiate data transfers
  - AP uses a wait period called the PCF interframe space (PIFS)
    - PIFS is shorter than DIFS, but longer than SIFS
    - ensures that PCF traffic has priority over traffic generated by devices operating in the DCF mode, without interfering with control messages in the DCF mode such as CTS and ACK

IEEE 802.11

- Focus of IEEE 802.11 is on providing fair access to the medium with support for high throughput and mobility
  - since devices spend a large amount of time listening to the medium and collisions occur frequently, this standard incurs large overheads, including significant energy costs
- Energy consumption problem
  - IEEE 802.11 offers a power saving mode (PSM) for devices operating in the PCF mode
  - devices can inform the AP that they wish to enter a low-power sleep mode using special control messages
  - these devices wake up periodically to receive beacon messages from the AP to determine if they should stay awake to receive incoming messages
  - saves energy, but only works in the infrastructure mode and it is not specified when or how long devices should sleep

IEEE 802.15.4

- IEEE802.15.4
  - created for low-power devices in the 868 MHz, 915 MHz, and 2.45 GHz frequency bands
  - supports two transmission modes:
    - UWB PHY
      - bit rates: 110 kbps, 851 kbps (nominal), 6.81 kbps, and 27.24 Mbps
    - CSS PHY
      - bit rates: 1 Mbps (nominal) and 250 kbps

ZigBee

- Before 802.15.4, ZigBee Alliance worked on low-cost communication technology for low data rates and low power consumption
- IEEE and ZigBee Alliance joined forces and ZigBee has become the commercial name for the IEEE 802.15.4 technology
- Star mode:
  - communication via the Personal Area Network (PAN) coordinator
  - synchronized mode (beacon-enabled)
    - PAN coordinator periodically broadcasts beacons for synchronization and management
    - slotted channel access: device performs random backoff before channel is sensed
      - if no activity, node waits until next slot and senses channel again until no activity has been detected for two consecutive slots
      - if activity, backoff procedure is repeated
  - unsynchronized mode: device access channel immediately when no activity is detected during the first initial backoff time

ZigBee

- Peer-to-peer mode:
  - devices are free to communicate directly with each other
  - but they still must associate with the PAN coordinator before they can participate in peer-to-peer communication
- Data transfer between the device and its PAN coordinator is always initiated by the device
  - allows a device to determine when data is transferred and to maximize its energy savings
    - when a device wants to send data to the PAN coordinator, it can use the previously described channel access method
    - the PAN coordinator transmits data intended for a device only after the device explicitly requested such a transmission
  - in both cases, optional acknowledgments can be used to let the PAN coordinator or device know that the transmission was successful

IEEE 802.15.4 and ZigBee

- Challenges:
  - standard does not clearly define the operation of the peer-to-peer approach
  - in large WSNs, it is unlikely that all devices will be able to use the same PAN coordinator
  - standard does allow communication among PAN coordinators, but this again is not well defined

Contention-Free MAC Protocols

- Concept:
  - allow only one sensor node to access the channel at any given time
  - thereby avoiding collisions and message retransmissions
  - assuming a perfect medium and environment
    - i.e., no other competing networks or misbehaving devices exist that could otherwise cause collisions or even jam a channel
- Contention-free protocols allocate resources to individual nodes to ensure exclusive resource access by only one node at any given time
- Exposes a number of desirable characteristics
  - node knows exactly when it has to turn on its radio
  - during all other times, radio can be turned off to preserve energy
  - fixed slot allocations impose upper bounds on delay
  - difficult to design schedules for large networks
  - difficult to handle changes in topology, density, traffic load

Traffic-Adaptive Medium Access

- TRAMA is an example of a contention-free MAC protocol with the goal to increase network throughput and energy efficiency (compared to TDMA)
- It uses a distributed election scheme to determine when nodes are allowed to transmit
  - based on information about the traffic at each node
  - avoids assigning slots to nodes with no traffic to send (increased throughput)
  - allows nodes to determine when they can become idle and do not have to listen to the channel (increased energy efficiency)

Traffic-Adaptive Medium Access

- TRAMA assumes a time-slotted channel, where time is dived into:
  - periodic random-access intervals (signaling slots)
  - scheduled-access intervals (transmission slots)
- Random-access intervals
  - Neighbor Protocol (NP) is used to propagate one-hop neighbor information among neighboring nodes
    - nodes join a network by transmitting during a randomly selected slot
    - packets transmitted during these slots are used to gather neighborhood information by carrying a set of added and deleted neighbors
    - in case no changes have occurred, these packets serve as "keep-alive" beacons
  - NP allows nodes to obtain consistent two-hop topology information

Traffic-Adaptive Medium Access

- Random-access intervals (contd.)
  - Schedule Exchange Protocol (SEP) establishes and broadcasts actual schedules (i.e., allocations of slots to a node)
    - each node computes a duration SCHEDULE_INTERVAL
      - represents the number of slots for which the node can announce its schedule to its neighbors
      - this duration depends on the rate at which the node's applications can produce packets
    - at time *t*, the node then computes the number of slots within [t, t+ SCHEDULE_INTERVAL] for which it has the highest priority among its two-hop neighbors
    - the node announces the selected slots and the intended receivers using a schedule packet
    - the last slot in this schedule is used to announce the next schedule for the next interval

Traffic-Adaptive Medium Access

- Random-access intervals (contd.)
  - Schedule Exchange Protocol (SEP) (contd.)
    - example:
      - a node's SCHEDULE_INTERVAL is 100 slots
      - the current time (slot number) is 1000
      - a possible slot selection for interval [1000, 1100] for this node could be 1011, 1021, 1049, 1050, and 1093
      - during slot 1093, the node broadcasts its new schedule for interval [1093, 1193]
    - list of intended receivers in the schedule packet is implemented as a bitmap
      - length of a bitmap is equal to the number of one-hop neighbors
        - » each bit in the bitmap corresponds to one particular receiver ordered by its identities
        - » every node can determine the receiver address based on the bitmap and its list of neighbors

Traffic-Adaptive Medium Access

- Random-access intervals (contd.)
  - Schedule Exchange Protocol (SEP) (contd.)
    - slot selection is based on the node's priority at time *t*
      - uses a pseudo-random hash of the concatenation of the node's identity *i* and *t*:

$$prio(i,t) = hash(i \oplus t)$$

      - node can indicate which slots it gives up, allowing other nodes to claim these unused slots
    - a node can determine its state for any given time slot *t* based on its two-hop neighborhood information and the announced schedules
      - node *i* is in the transmit (TX) state if it has the highest priority and if it has data to send
      - node *i* is in the receive (RX) state if it is the intended receiver of the transmitter during slot *t*
      - otherwise, the node can be switched into the sleep (SL) state

Traffic-Adaptive Medium Access

- Summary
  - compared to CSMA-based protocols
    - reduces the probability of collisions
    - increases the sleep time and energy savings
  - unlike standard TDMA approaches
    - TRAMA divides time into random-access and scheduled-access intervals
    - during the random-access intervals
      - nodes are awake to either transmit or receive topology information
      - the length of the random-access interval affects the overall duty cycle and achievable energy savings of a node

Y-MAC

- Y-MAC uses TDMA-based medium access but for multiple channels
- Divides time into frames and slots
  - each frame contains a broadcast period and a unicast period
  - every node must wake up at the beginning of a broadcast period
  - nodes contend for access to the medium during this period
    - if there are no incoming broadcast messages, each node turns off its radio awaiting its first assigned slot in the unicast period
    - each slot in the unicast period is assigned to only one node for receiving data
- Y-MAC uses a receiver-driven model
  - can be more energy-efficient under light traffic conditions, because each node samples the medium only in its own receive time slots
  - particularly important for radio transceivers, where the energy costs for receiving are greater than for transmitting (e.g., due to sophisticated despreading and error correction techniques)