Wireless and Sensor Networks - MAC

2nd Class

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Contents

- MAC in Wireless Networks
- MAC Attributes
- Scheduling Based MAC
- Contention Based MAC
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- Summary

Introduction to MAC

- The role of medium access control (MAC)
  - Controls when and how each node can transmit in the wireless channel
- Why do we need MAC?
  - Wireless channel is a shared medium
  - Radios transmitting in the same frequency band interfere with each other – collisions
  - Other shared medium examples: Ethernet

Where Is the MAC?

- Network model from Internet

Application layer	
Transport layer	→ End-to-end reliability, congestion control
Network layer	→ Routing
Link/MAC layer	→ Per-hop reliability, flow control, multiple access
Physical layer	→ Packet transmission and reception

- A sublayer of the Link layer
  - Directly controls the radio
  - The MAC on each node only cares about its neighborhood

MAC Attributes

- Collision avoidance/minimization
- Energy efficiency
  - MAC layer controls radio. Radio often consume most energy
- Scalability and adaptivity
  - Nodes join, exit, rejoin, die, move to different location
  - Good MAC should accommodate such changes
- Channel utilization
  - Very important in cellular or wireless LAN
  - Often secondary in WSNs (Why?)
- Latency
- Throughput
- Fairness
  - Important in traditional cellular/wireless LAN, less important in WSNs (Why?)

MAC Attributes

- For WSNs, most important attributes of a good MAC are
  - Effective collision avoidance
  - Energy Efficiency
  - Scalability and adaptivity
- Other attributes are normally secondary
  - Fairness
  - Latency
  - Channel utilization

MAC Caution

- The idle listen problem is often associated with Media Access Control (MAC) protocols,
  - TDMA, CSMA, …
- but MACs provide arbitration among multiple transmitters attempting to utilize a shared medium simultaneously.
  - Reduce Contention and associated loss.
  - May involve scheduling (TDMA) or transmission detection (CSMA)
- The problem here is the opposite.
  - Most of the time, nothing is transmitting.
  - Avoid listening when there is nothing to hear.
  - Scheduling and detection are involved, but to determine when to turn on receiver, rather than when to turn off transmission.

Medium Access Control (MAC): 2 Approaches

- One Approach (Be nice – share)
  - Avoid interference by scheduling nodes on sub-channels
    - TDMA (Time-Division Multiple Access)
    - FDMA (Frequency-Division Multiple Access)
    - CDMA (Code-Division Multiple Access)
- Another Approach (Compete/*contend*)
  - Don't pre-allocate transmission, compete => probabilistic coordination
  - ALOHA (Transmit. Collision? Yes, discard packet, retransmit later)
  - Carrier Sense (IEEE 802.11)

Energy Efficiency in MAC Protocols

- Motivation – Energy efficiency is very important in WSNs.
- Question – what causes energy waste from a MAC perspective?
  - Collision
    - Collided packets are discarded, retransmission require energy
    - Not a big issue in scheduled (TDMA, CDMA, FDMA) MAC protocols, but an issue in contention MAC protocols.
  - Idle listening
    - Long distance (500 m or more) Tx energy consumption dominates, but in short-range communication Rx energy consumption can be close to Tx energy consumption
    - Can be a dominant factor in WSN energy consumption

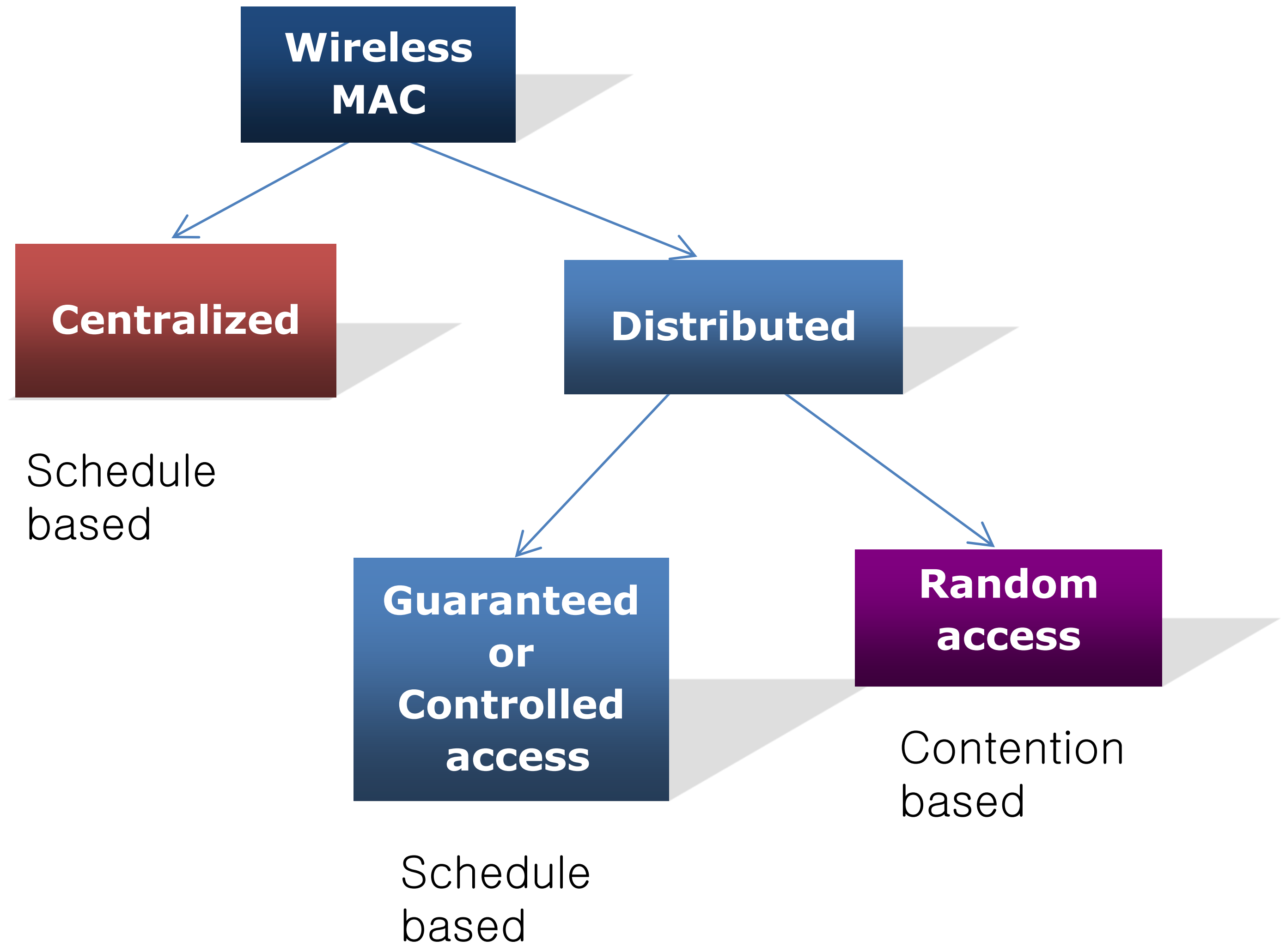
Energy Efficiency in Mac Protocols

- Overhearing
  - When a node receives packets that are destined for another node
- Control packet overhead
  - Sending, receiving, listening, all consumes energy
- Adaptation
  - Reconfiguring when nodes join leave

Classification of MAC Protocols

- Schedule-based protocols
  - Schedule nodes onto different sub-channels
  - Examples: TDMA, FDMA, CDMA
- Contention-based protocols
  - Nodes compete in probabilistic coordination
  - Examples: ALOHA (pure & slotted), CSMA

MAC : A Simple Classification



Schedule Based MAC

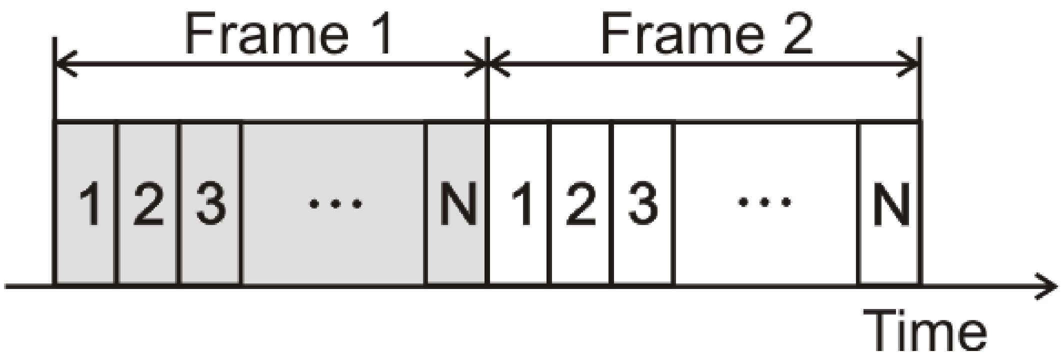
- TDMA
- Polling
- Bluetooth
- LEACH

Energy Conservation in Scheduled MAC Protocols

- Collision free
- No need for idle listening
- TDMA naturally support low-duty cycle operation

Scheduled Protocols:TDMA

Channel is divided into N slots (a frame)



- Each node gets a time slot (No collision)
- It only transmits in its time slot
- It only need listen during its time slot (energy efficient)
- Frame may be static – fix number of slots
- Need to be synchronized
- Difficult to accommodate network change
- Typically, nodes communicate with base station (sensor network)

Scheduled Protocols: Polling

- Master-slave configuration
  - The master node decides which slave can send by polling the corresponding slave
  - Only direct communication between the master and a slave
  - A special TDMA without pre-assigned slots
  - Examples
    - IEEE 802.11 infrastructure mode
    - Bluetooth *piconets*

Scheduled Protocols: Bluetooth

- Wireless personal area network (WPAN)
  - Short range, moderate bandwidth, low latency
  - IEEE 802.15.1 (MAC + PHY) is based on Bluetooth
  - Not attractive for sensor network
- Nodes are clustered into *piconet*
  - Each piconet has a master and up to 7 active slaves – scalability problem
  - The master polls each slave for transmission
  - CDMA among piconets
  - Multiple connected piconets form a *scatternet*
    - Difficult to handle inter-cluster communications

Scheduled Protocols:LEACH

- Low-Energy Adaptive Clustering Hierarchy (LEACH)
  - Organize nodes into cluster hierarchies
  - TDMA within each cluster
  - Nodes only talk to node head
  - Position of head is rotated among nodes depending on remaining energy
  - Node then uses long-range/high-power communication to base
  - Nodes don’t need to know global topology
  - Nodes don’t need control information from base station

Contention based MAC: Protocols

- Aloha
- Carrier Sense
- CSMA
- MACA
- 802.11 MAC

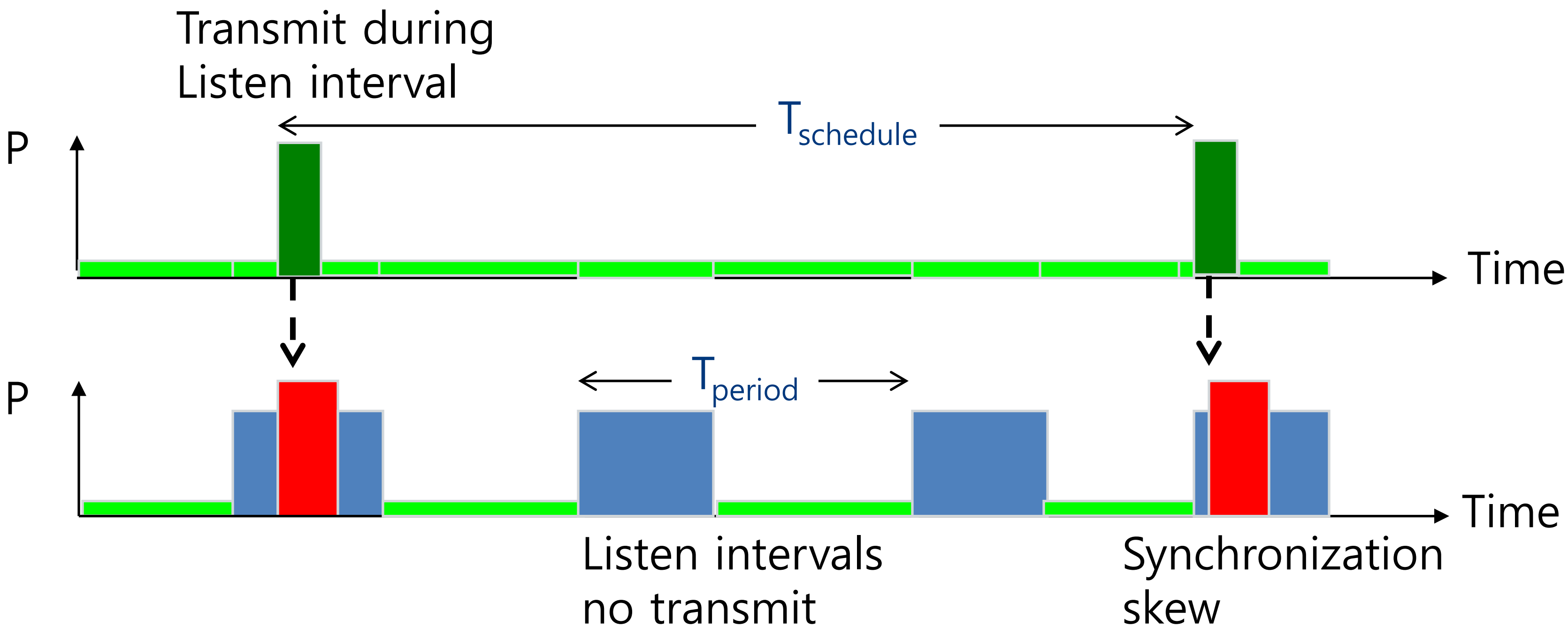
Contention-Based MAC Protocols

- Channel are not divided, but shared
  - channel allocated on-demand
- Advantages
  - Scale easily across node density and load
  - More flexible (no need to make clusters, hierarchies) peer-to-peer directly supported
  - Don’t require fine-grained synchronization as in TDMA
- Major disadvantage
  - Inefficient use of energy

Review: Energy Efficiency in MAC Protocols

- Question – what causes energy waste from a MAC perspective?
  - Collision
  - Idle listening
  - Overhearing
    - When a node receives packets that are destined for another node
  - Control packet overhead
    - Sending, receiving, listening, all consumes energy
  - Adaptation
    - Reconfiguring when nodes join leave

Scheduled Listen



- $P_{ave} \cong P_{sleep} + P_{listen} \bullet T_{listen} / T_{schedule} + P_{xmit} \bullet T_{xmit} / T_{xmit\text{-}interval} + P_{clock\text{-}sync\text{-}ave} + P_{discover\text{-}ave}$
- Full power listen to discover and join schedule.

Schedule Mechanisms

- Compute schedule off-line and distribute it to the nodes
  - Requires some unscheduled communication mechanism to perform survey of who-communicates-with-whom and who-interferes-with-whom, collect results, and distributed schedule.
  - Changing conditions, additions and deletions are problematic
- Define set of slots, advertise, resolve
  - Typically, coordinator schedules for one-hop neighbors and coordinators (cluster heads) stay powered.

Contention Protocols: Classics

- ALOHA
  - Pure ALOHA: send when there is data
  - Slotted ALOHA: send on next available slot
  - Both rely on retransmission when there's collision
- CSMA — Carrier Sense Multiple Access
  - Listening (carrier sense) before transmitting
  - Send immediately if channel is idle
  - Backoff if channel is busy

Carrier Sense Multiple Access (CSMA) in Wireless Networks

- A host may transmit only if the channel is idle
- How to determine whether a channel is idle?
- One possibility is a threshold-based energy detection mechanism ….

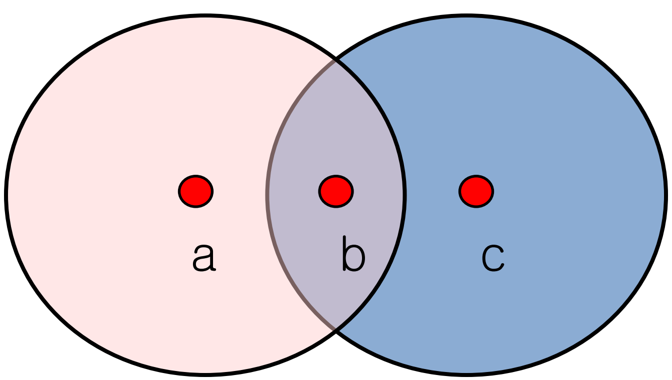
Carrier Sense Multiple Access (CSMA)

Implementation using Carrier Sense (CS) threshold

- if received power < CS threshold → Channel idle
- Else channel busy

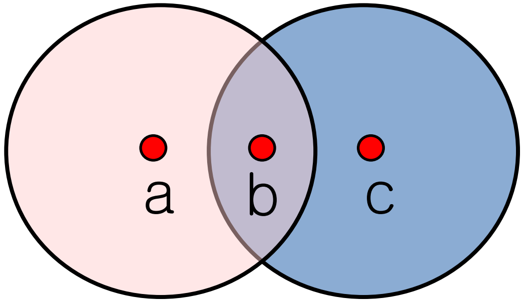
Hidden Terminal Problem in CSMA

- Node a, b, and c can only hear their immediate neighbors
- When node a send to b, c is unaware of a, its carrier sense indicates carrier free
- Node c starts transmitting
- Packets from a and c collide at b
- CSMA is not enough for multi-hop networks (collision at receiver)



CSMA/CA

- Establish a brief handshake between sender and receiver before sending data
  - Sender sends Request-to-Send (RTS) packet to intended receiver
  - Receiver replies with Clear-to-Send (CTS) packet
  - Only then does transmitter send data



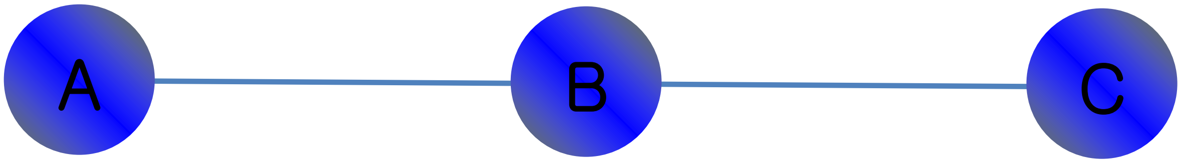
  - RTS-CTS packets announce to neighbors
  - Node c hears CTS packets from b to a, and does not transmit
  - Does not eliminate collisions, but collisions are now mostly (brief) RST

MACA and MACAW

- MACA — Multiple Access w/ Collision Avoidance
  - Based on CSMA/CA
  - Add duration field in RTS/CTS informing other node about their backoff time
- MACAW
  - Improved over MACA
  - RTS/CTS/DATA/ACK
  - Fast error recovery at link layer
- IEEE 802.11
  - CSMA/CA, MACA, and MACAW => Distributed coordination function (DCF) + enhancements

MACA Solution for hidden Terminal Problem

- 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 A is able to send 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 RTS and CTS both



Contention Protocols: IEEE 802.11

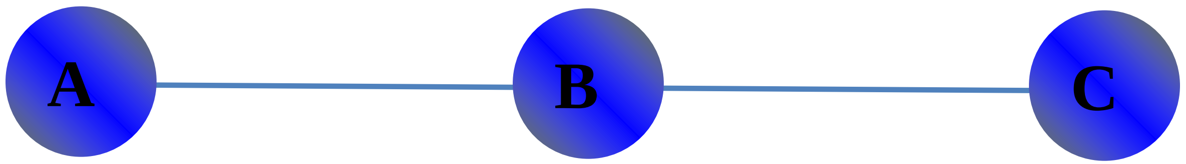
- IEEE 802.11 ad hoc mode (DCF)
  - Virtual and physical carrier sense (CS)
    - Network allocation vector (NAV), duration field
  - Binary exponential backoff
  - RTS/CTS/DATA/ACK for unicast packets
  - Broadcast packets are directly sent after CS

Contention Protocols: IEEE 802.11 (cont.)

- Power save (PS) mode in IEEE 802.11 DCF
  - Assumption: all nodes are synchronized and can hear each other (single hop)
  - Nodes in PS mode periodically listen for beacons & ATIMs (ad hoc traffic indication messages)
  - Beacon: timing and physical layer parameters
    - All nodes participate in periodic beacon generation
  - ATIM: tell nodes in PS mode to stay awake for Rx
    - ATIM follows a beacon sent/received
    - Unicast ATIM needs acknowledgement
    - Broadcast ATIM wakes up all nodes — no ACK

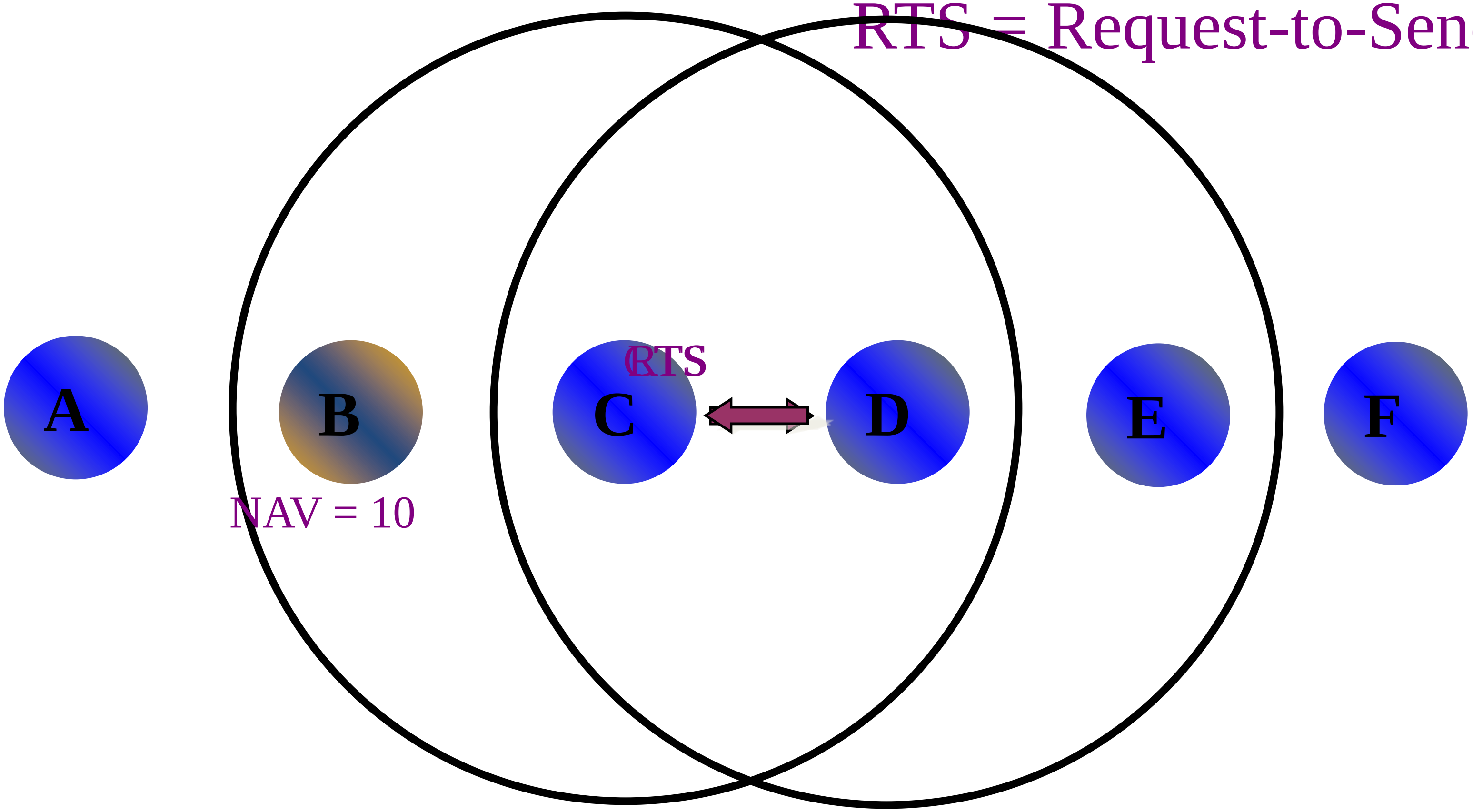
IEEE 802.11 DCF

- Uses RTS-CTS exchange to avoid hidden terminal problem
  - Any node overhearing a CTS cannot transmit for the duration of the transfer
- Uses ACK to achieve reliability
- Any node receiving the RTS cannot transmit for the duration of the transfer
  - To prevent collision with ACK when it arrives at the sender
  - When B is sending data to C, node A will keep quite



IEEE 802.11-(1)

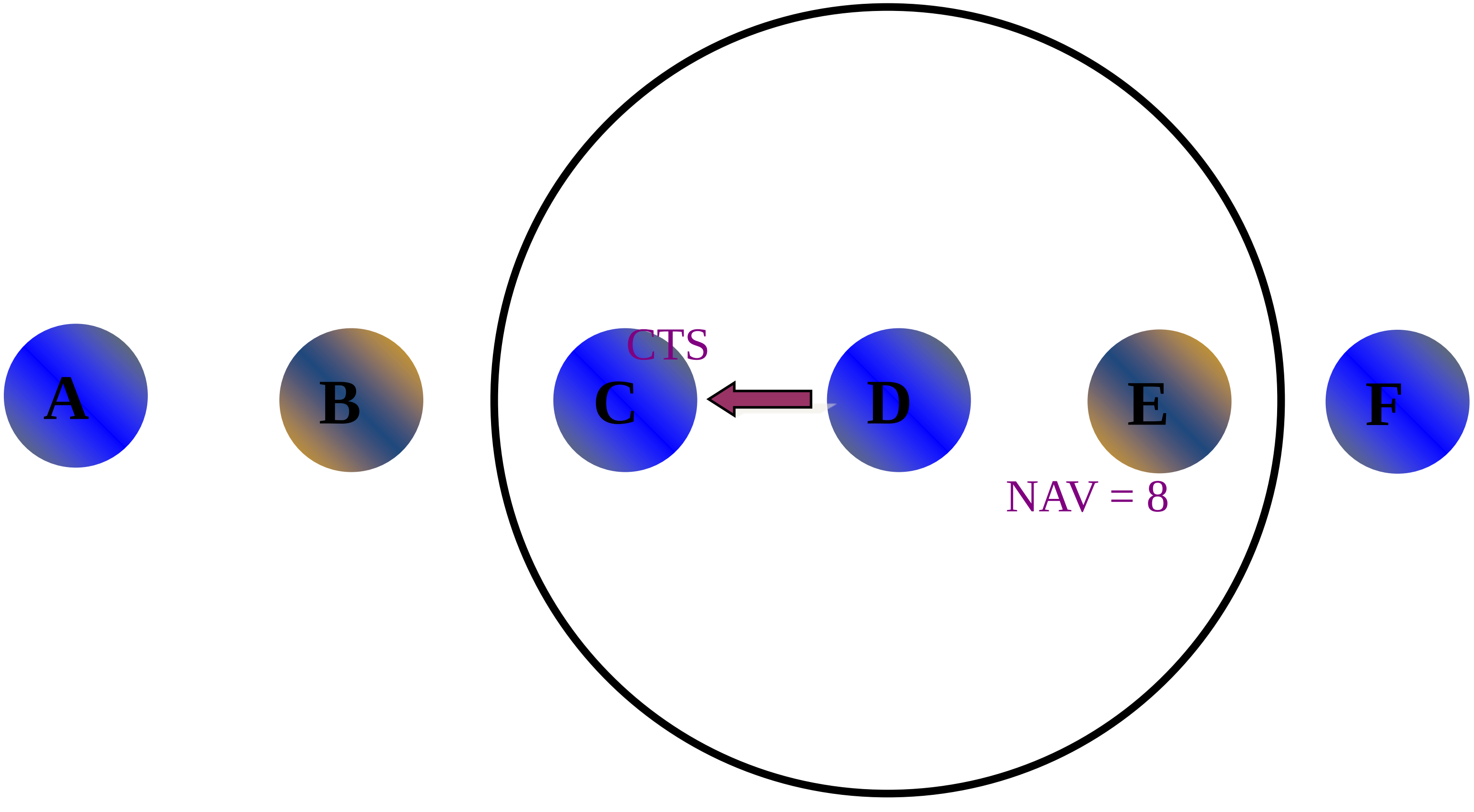
CTS = Clear-to-Send
RTS = Request-to-Send



NAV = remaining duration to keep quiet

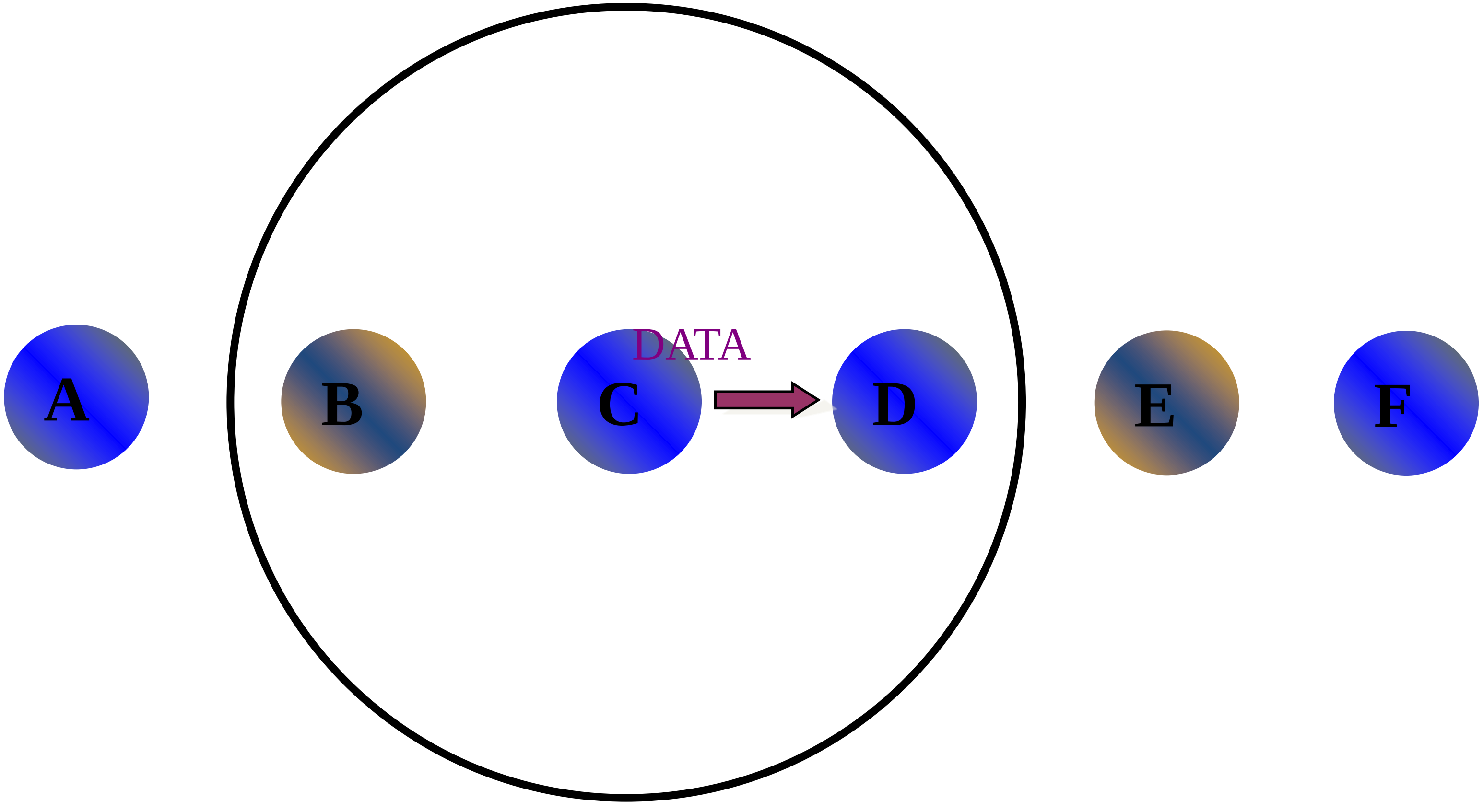
IEEE 802.11-(2)

CTS = Clear-to-Send

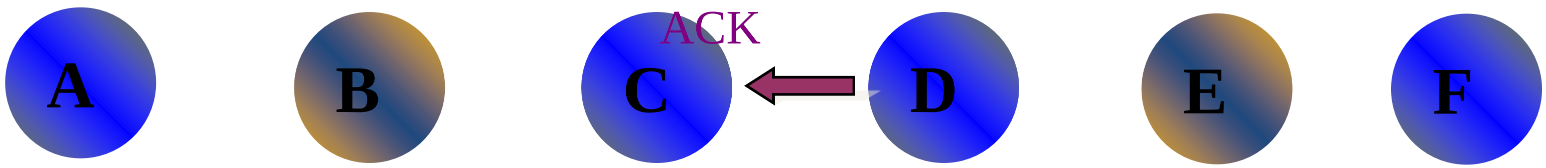


IEEE 802.11-(3)

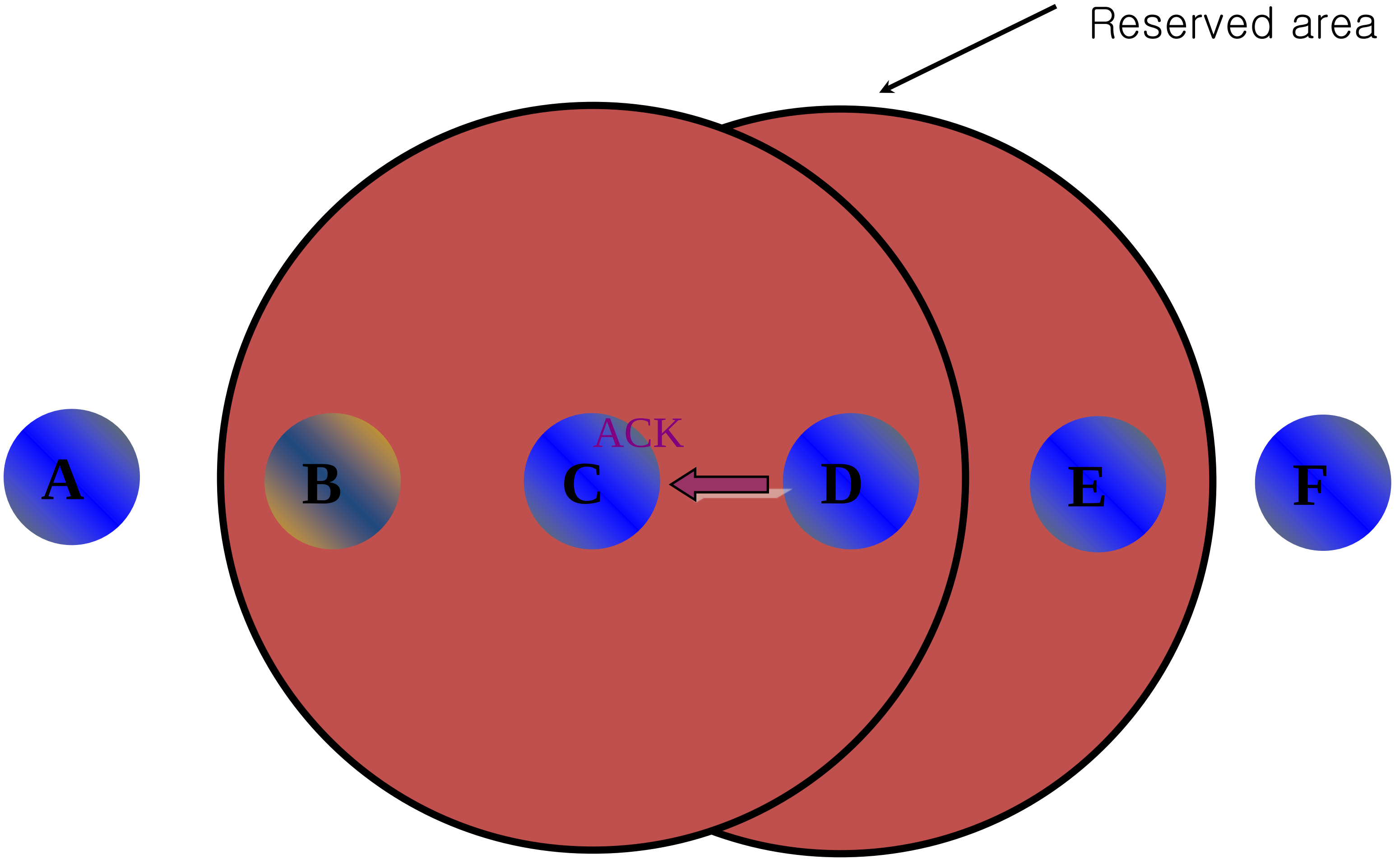
- DATA packet follows CTS. Successful data reception acknowledged using ACK.



IEEE 802.11-(4)



IEEE 802.11-(5)

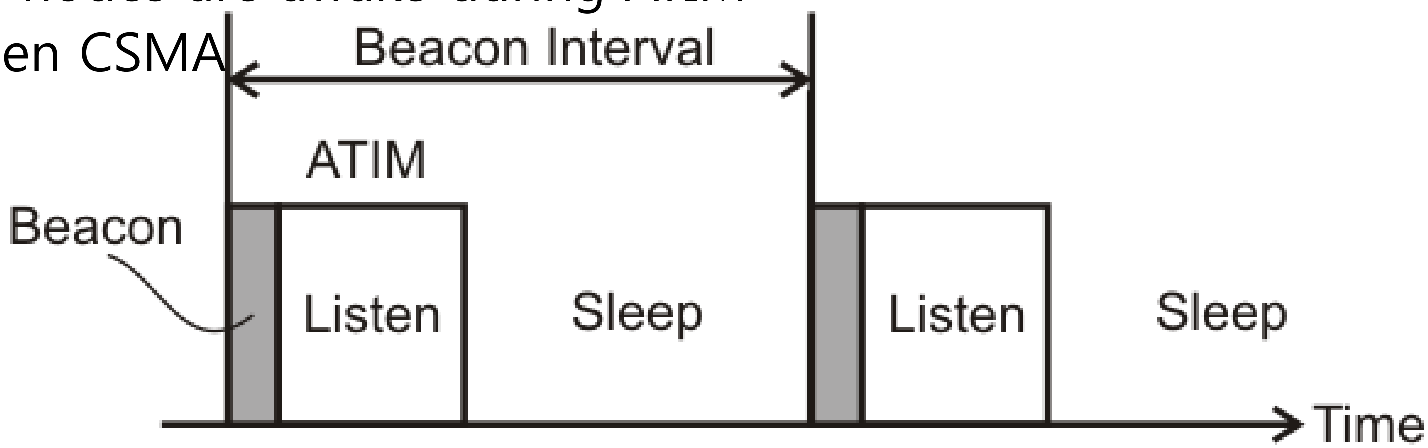


CSMA/CA

- Physical carrier sense, and
- 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
- Nodes stay silent when carrier sensed (physical/virtual)
- Backoff intervals used to reduce collision probability

Beacons (IEEE 802.11 & Piconet)

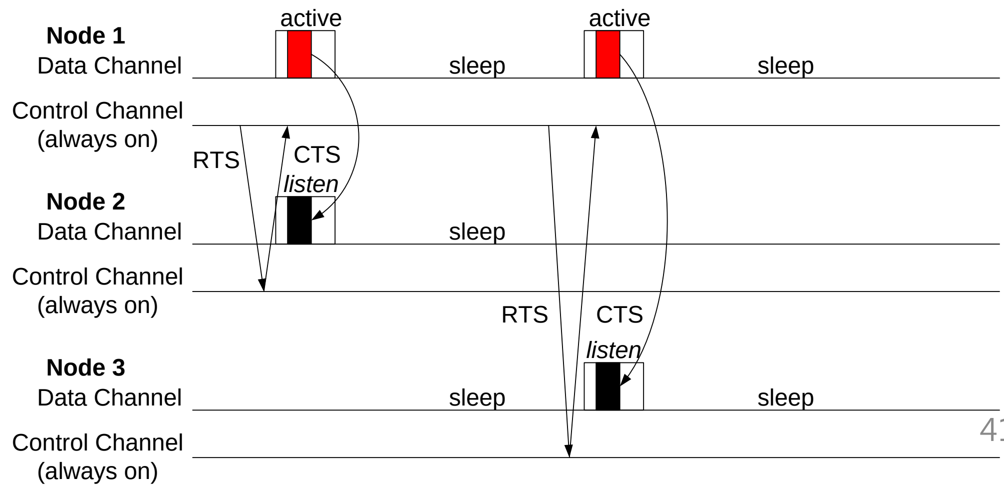
- One node periodically broadcast beacon (all participate)
- Beacon synchronizes all nodes
- After each beacon, ad hoc traffic indication message (ATIM).
- All nodes are awake during ATIM
- Then CSMA



- Assumption: all nodes can hear each other. Generalizing to multi-hop is not easy

Dual-channel MAC: PAMAS [SR98]

- Power Aware Multi-Access with Signaling
- Synchronization of PAMAS:
  - Each node sends and receives RTS/CTS messages over control channel, which is always turned on.
- Power Saving of PAMAS:
  - Data channel is turned on when activity is expected.
- Pros: Easy to implement.
- Cons: Requires dual-channel, control channel still consumes power

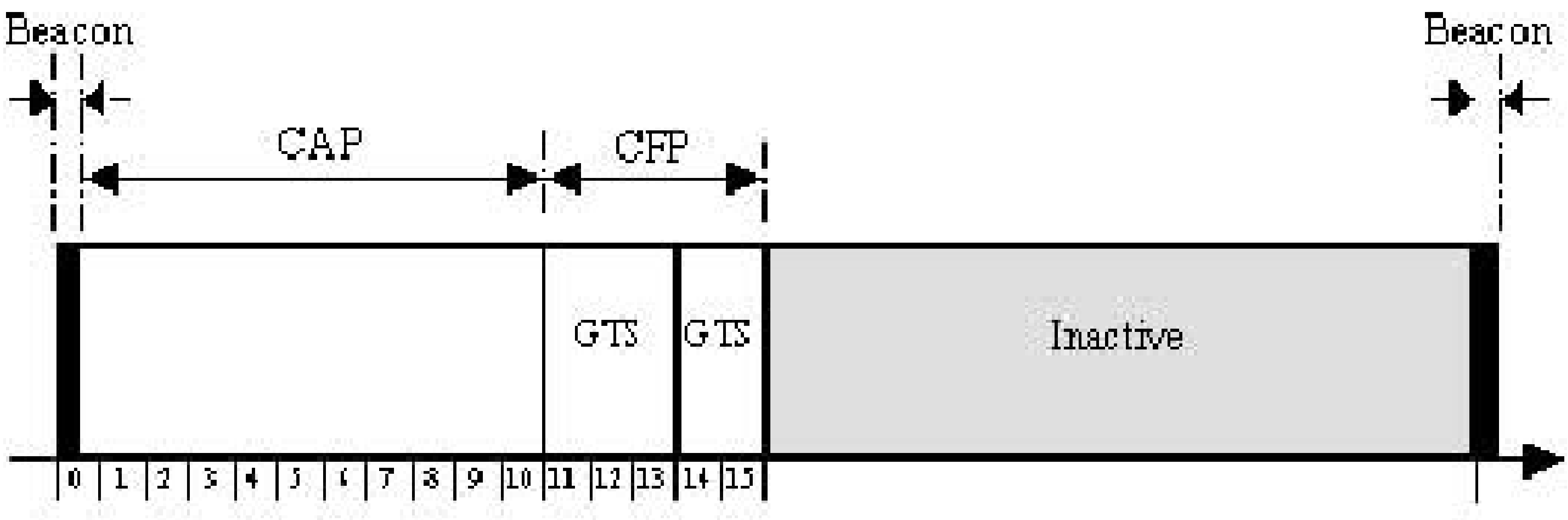


Contention Protocols: ZigBee

- Based on IEEE 802.15.4 MAC and PHY
  - Three types devices
    - Network Coordinator
    - Full Function Device (FFD)
      - Can talk to any device, more computing power
    - Reduced Function Device (RFD)
      - Can only talk to a FFD, simple for energy conservation
  - CSMA/CA with optional ACKs on data packets
  - Optional beacons with superframes
  - Optional guaranteed time slots (GTS), which supports contention-free access

Contention Protocols: ZigBee (cont.)

- Low power, low rate (250kbps) radio
- MAC layer supports low duty cycle operation (Content Access Period, Free)



Next…

- Introduction to MAC
- MAC attributes
- Scheduled-based MAC protocols
- Contention-based MAC protocols
- Case studies
- Summary

Case Studies

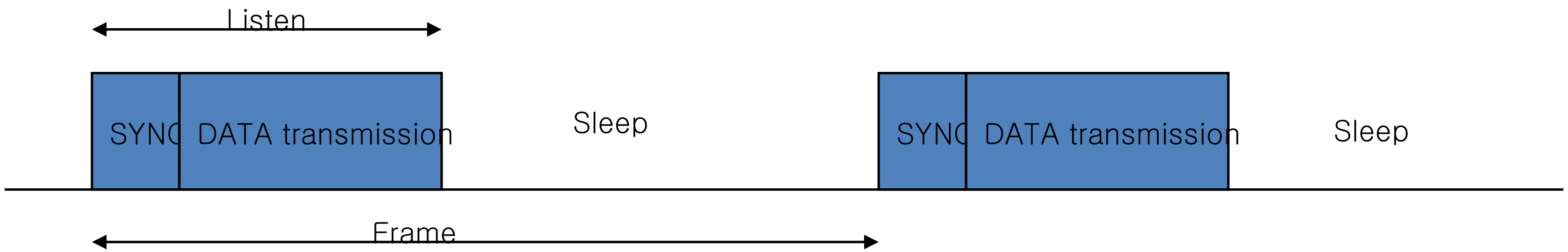
- Energy-aware medium access schemes for WSNs (modifications of existing protocols for WAHNs)
- Four recently proposed schemes for WSNs
  1. Sensor MAC (SMAC)
  2. Self-organizing MAC for sensor networks (SMACS)
  3. Traffic adaptive medium access protocol (TRAMA)
  4. Power-efficient and delay-aware medium access protocol for sensor networks (PEDAMACS)

SMAC-Introduction

- Objective is to conserve energy in WSNs. Fairness and latency are less critical issues compared to energy savings.
- Establishes a low duty cycle operation in nodes. It is the default operation of all nodes.
- Nodes only become more active by changing the duty cycle when:
  - Heavy traffic is present in the network
  - An event occurs in case of event-driven WSN
- Reduces idle listening by periodically putting nodes into sleep.

SMAC- Operation

- Following assumptions have been considered
  - Short-range multihop communications will take place among a large number of nodes.
  - Most communications will be between nodes as peers, rather than to a single base station.
  - Applications will have long idle periods and can tolerate some latency.
  - Network lifetime is critical for the application.
- All nodes follow a sleep-and-listen cycle called a frame.
- The duration of the listen period is fixed.
- The sleep interval may be changed according to application requirements, changing the duty cycle.



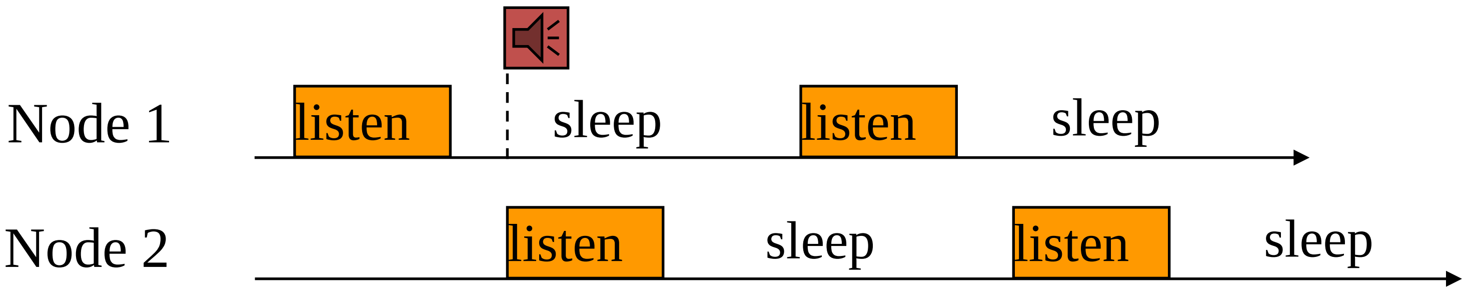
Periodic listen-and-sleep schedule in SMAC

SMAC- Coordinated Sleeping

- A node can freely choose its own active/sleep schedules and synchronize schedules of neighboring nodes together.
- Nodes periodically broadcast a SYNC packet to their immediate neighbors at the beginning of each listen interval, forming a virtual cluster.
- Neighboring nodes are allowed to have different schedules but they are free to talk to each other.
- A considerable portion of the nodes will belong to more than one virtual cluster → intercluster communication.
- This scheme is claimed to be adaptive to topology changes.

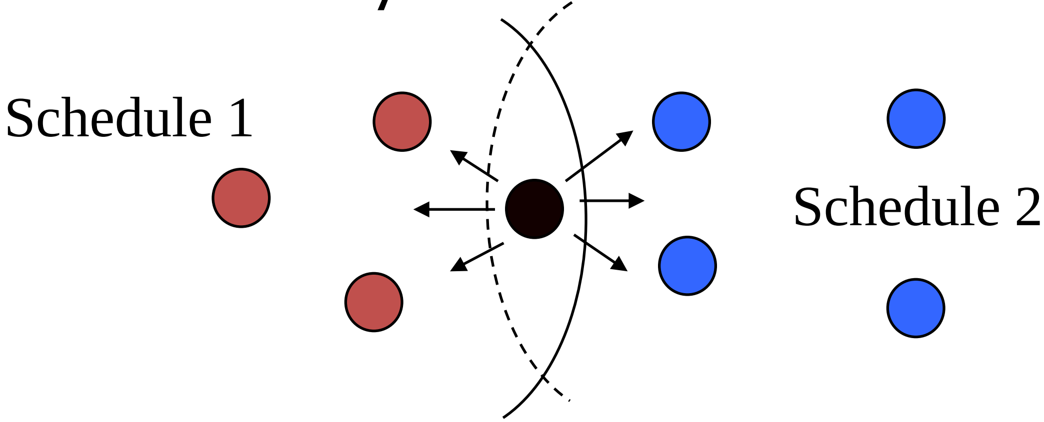
Coordinated Sleeping

- Schedules can differ



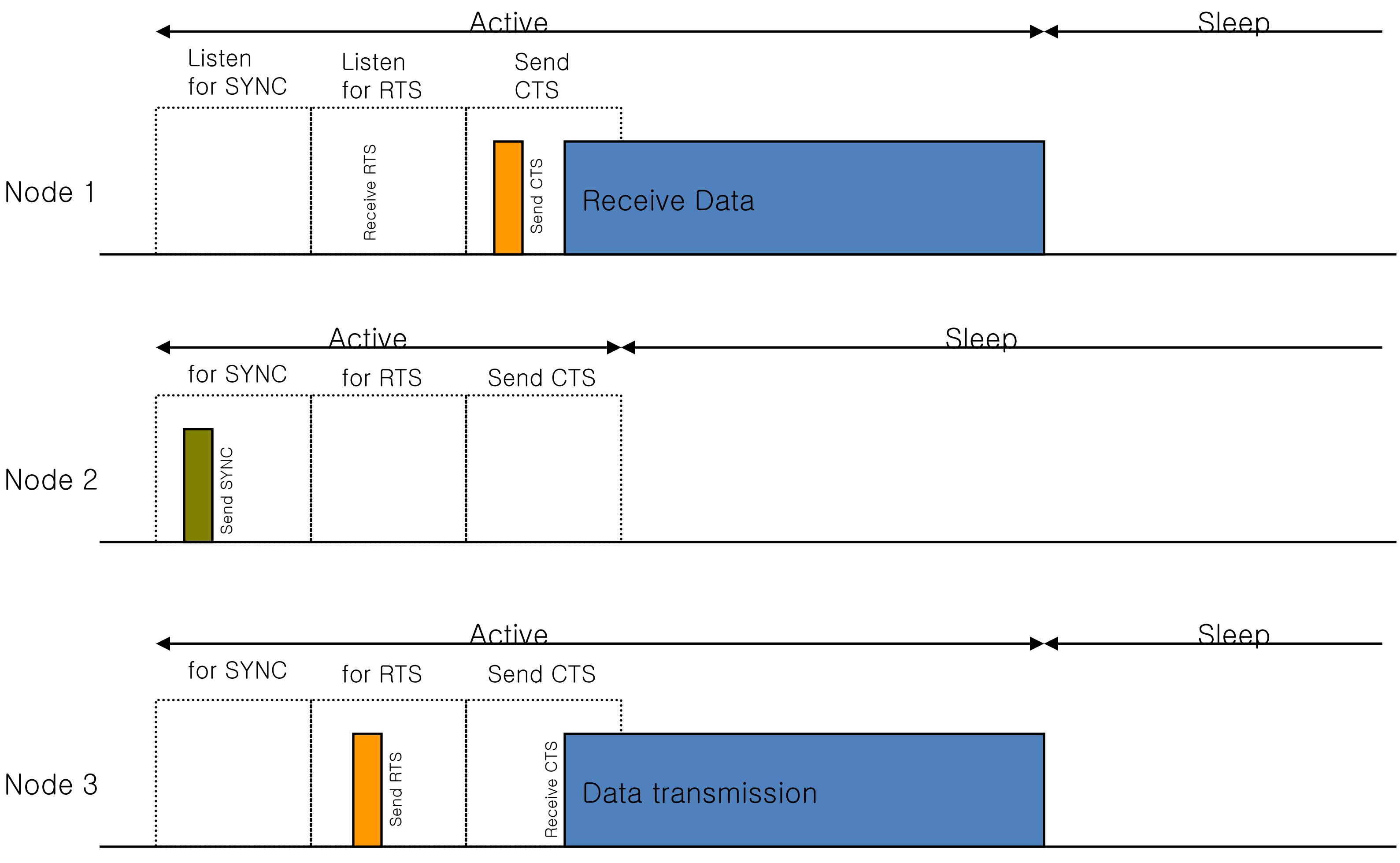
- *Prefer* neighboring nodes have same schedule

  — easy broadcast & low control overhead



Border nodes:
two schedules or
broadcast twice

1.3. Coordinated Sleeping (cont)



Timing schedules among different nodes in SMAC

Overhearing Avoidance

- Problem: Receive packets destined to others
- Solution: Sleep when neighbors talk
  - Basic idea from PAMAS (Singh, Raghavendra 1998)
  - But with in-channel signaling
- Who should sleep?
  - All immediate neighbors of sender and receiver
- How long to sleep?
  - The *duration* field in each packet informs other nodes the sleep interval

SMAC- Neighbor Discovery

- It is possible that a new node fails to discover an existing neighbor because of collision or delays in sending SYNC packets by neighbor due to busy medium.
- Requiring each node to listen periodically to the channel for the whole synchronization period.
- The frequency can be varied depending on the network conditions.

2. SMACS

2.1. Introduction

2.2. Operation

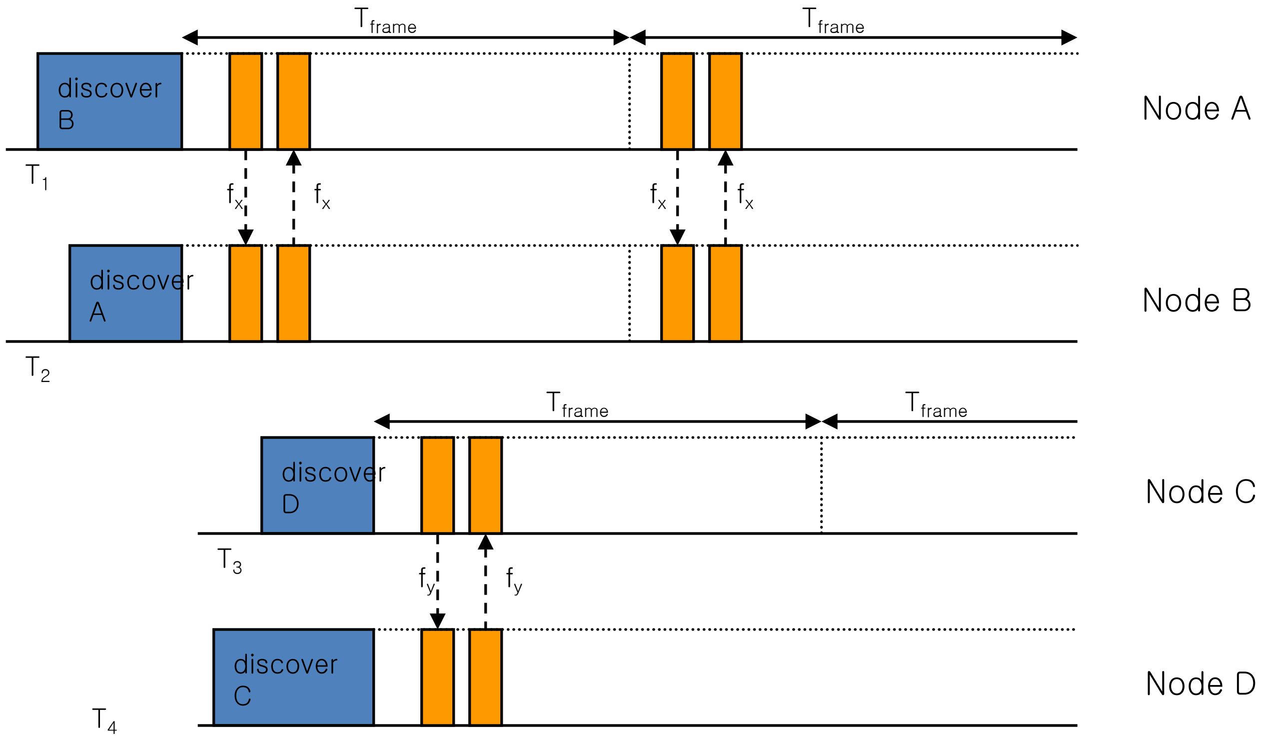
2.1. Introduction

- Each node maintains a TDMA frame in which the node schedules different time slots to communicate with its known neighbors.
- During each time slot, it only talks to one neighbor.
- Using different frequency channels (FDMA) or spread spectrum codes (CDMA) → avoid interference between adjacent links.
- It does not prevent 2 interfering nodes from accessing the medium at the same time.
- The actual multiple access is accomplished by FDMA or CDMA.

2.2. Operation

- Following assumptions have been considered
  - Nodes are able to tune the carrier frequency to different bands and the number of available bands is relatively large.
  - Nodes are randomly deployed. After deployment, each node wakes up at some random time according to a certain distribution.
  - The network is assumed to consist primarily of stationary nodes, with few mobile nodes.
- Each node assigns links to its neighbors immediately after they are discovered.
- When all nodes hear all their neighbors, they have formed a connected, multihop network.
- Each node is only partially aware of the radio connectivity in its vicinity → collisions can occur if a simple TDMA scheme is used alone.
- To avoid collision problems, frequency bands chosen at random from a large pool are assigned for each slot.

2.2. Operation (cont)



Nonsynchronous scheduled communication in SMACS

3. TRAMA

3.1. Introduction

3.2. Operation

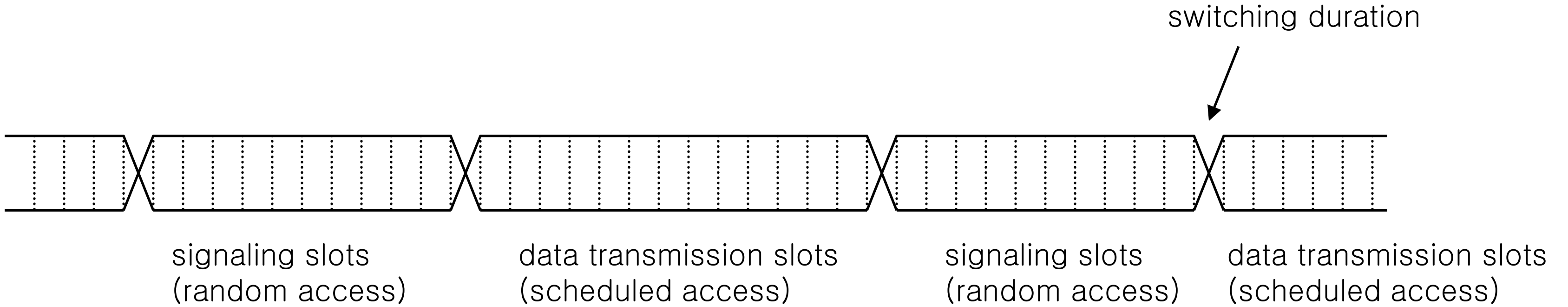
3.1. Introduction

- A MAC protocol for energy-efficient and collision-free channel access in WSNs.
- Using traffic-based information to decide on schedules for individual nodes → adaptive to network traffic.
- Providing support for unicast, broadcast, and multicast traffic.

3.2. Operation

- Assumes a single, time-slotted channel for data and signaling transmissions.
- The time schedule of each node is organized in two major sections.
  - A collection of signaling slots using random access.
  - Data transmission slots using schedules access.
- The duty cycle of switching between these states could be adjusted according to the application requirements and the different network types.
- Communication in TRAMA consists of 3 major components:
  - The neighbor protocol (NP)
  - The adaptive election algorithm (AEA)
  - The schedule exchange protocol (SEP)

3.2. Operation (cont)



Time slot organization in TRAMA

4. PEDAMACS

4.1. Introduction

4.2. Operation

4.1. Introduction

- For continuous data gathering applications.
- Assumptions:
  - A single access point (AP) exists in the network and all nodes communicate with this AP.
  - AP has no energy constraints and is capable of transmitting at higher power levels when needed so that it can reach any node in the network in a single hop.
  - The sensor nodes have limited transmission power and will reach the AP using multiple hops.

4.2. Operation

- 3 major phases
  - Topology learning phase
  - Topology collection phase
  - Scheduling phase

Header	Current time	Next packet transmission time	CRC

(a) Topology learning and topology collection packet from AP

Header	Number of hops	Parent transmission node ID	CRC

(b) Tree construction packet from AP

Header	Node ID	Node level	Parent ID	No.of neighbors	Neighbor IDs	No.of interferers	Interferer IDs	CRC

(c) Topology packet from nodes

Header	Slot seq. No.	No. of nodes scheduled for current slot	Scheduled node IDs…	CRC

(d) Schedule coordination packet from AP

Packet formats in PEDAMACS

Comparison of MAC Schemes for WSNs

	SMAC	SMACS/EAR	TRAMA	PEDAMACS
Features	-TDMA scheduling -Coordinated sleeping schedules among neighbors -Adaptive listening -Virtual clustering	-Hybrid TDMA/FDMA scheduling --Mobile node attachment	-Random access (CSMA) for neighbor discovery -Scheduled access (TDMA) for data transmission	-Access point (AP) with high-power transmitter -Centralized TDMA scheduling by AP node -Hierarchical organization
Applications	-WSNs with more stationary nodes	-Low traffic WSN with strict latency requirements	-Event-driven WSNs	-Centralized data gathering WSNs
Merits	-Reduced latency for multihop messages -Simple hardware for TDMA	-Low latency -Ability to create links on the fly -No clustering requirements -No synchronization requirements	-TDMA slot reuse -No collisions due to hidden nodes -Traffic adaptable	-Higher energy savings in centralized WSNs
Drawbacks	-Synchronization required -Virtual clusters may not coincide with physical clusters	-Complex hardware for FDMA or CDMA -Waste of time slots -Low bandwidth utilization -Frequent switching can cause heavy energy losses	-Synchronization required -Low bandwidth utilization in periodic data gathering WSNs	-Centralized control necessary -AP node requires high power -High overhead for scheduling

Summary

- MAC classification
- MAC attributes
- Schedule based MAC
- Contention based MAC
- Case Studies