



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

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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)









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 code
 - 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
 - energy and a 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

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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 ion-based proto

 - + 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

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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
 - Illows 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



- 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)

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CSMA/CD requires that sender aware of collisions
 instead, CSMA/CA attempts to avoid collisions in the first place

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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
 I-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

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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

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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

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- Distributed Coordination Function (DCF) mode
 devices communicate directly with each other: ad-hoc mode
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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 sp ace (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

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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
- \bullet 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

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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

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IEEE 802.15.4

IEEE 802.15.4

- created for low-power devices in the 868 MHz, 915 MHz, and 2.45 GHz
- frequency bandssupports two transmission modes:

► UWB PHY

- OWDITHI
 - 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:
- 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

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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

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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

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Characteristics of MAC Protocols in WSNs

- Most MAC protocols are built for fairness
 - everybody should get an equal amount of resources
 - no one should receive special treatment
- In a WSN, all nodes cooperate to achieve a common purpose, therefore fairness is less of a concern
- Instead, wireless nodes are mostly concerned with energy consumption
- Sensing applications may value low latency or high reliability over fairness

Energy Efficiency

- Sensor nodes must operate using finite energy sources, therefore MAC protocols must consider energy efficiency
- Common technique: dynamic power management (DPM)

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- a resource can be moved between different operational modes such as active, idle, and asleep
- for resources such as the network, the active mode can group together multiple different modes of activity, e.g., transmitting and receiving
- Periodic traffic models are very common in WSNs
 - significant energy savings can be obtained by putting a device into a low-power sleep mode
 - fraction of time a sensor nodes spends in active mode is called the duty cycle
 - often very small due to the infrequent and brief data transmissions occurring in most sensor networks

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	RFM TR1000	RFM TR3000	MC13202	CC1000	CC2420
Data rate (kbps)	115.2	115.2	250	76.8	250
Transmit current	12mA	7.5mA	35mA	16.5mA	17.4mA
Receive current	3.8mA	3.8mA	42mA	9.6mA	18.8mA
Idle current	3.8mA	3.8mA	800µA	9.6mA	18.8mA
Standby current	0.7µA	0.7µA	102µA	96µA	426µA



Energy Efficiency

- Reasons for energy inefficiency
 - idle listening
 - inefficient protocol designs (e.g., large packet headers)
 - reliability features (collisions requiring retransmissions or other error control mechanisms)
 - control messages to address the hidden-terminal problem
 - choice of modulation scheme
 - choice of transmission rate
 - overemitting

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Scalability

- Many wireless MAC protocols have been designed for use in infrastructurebased networks
 - access points or controller nodes arbitrate access to the channel and perform some centralized coordination and management functions
- Most wireless sensor networks rely on multi-hop and peer-to-peer communications without centralized coordinators
- MAC protocols must be able to allow for efficient use of resources without incurring unacceptable overheads, particularly in very large networks
- MAC protocols based on CDMA have to cache a large number of code (may be impractical for resource-constrained sensor devices)
- WSNs are not only constrained in their energy resources, but also in their essing and m mory capaciti
- Therefore, MAC protocols should not impose excessive computational burden should not require too much memory to save state information

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Adaptability

- A key characteristic of a WSN is its ability to self-manage • adapt to changes in the network

 - including changes in topology, network size, density, and traffic characteristics
- A MAC protocol for a WSN should be able to gracefully adapt to such changes without significant overheads
- This requirement generally favors protocols that are dynamic in nature • protocols that make medium access decisions based on current demand and network state
- Protocols with fixed assignments (e.g., TDMA with fixed-size frames and slots) may incur large overheads due to adaptations of such assignments that may affect many or all nodes in the network

Low Latency and Predictability

- Many WSN applications have timeliness requirements
 - sensor data must be collected, aggregated, and delivered within certain latency constraints or deadlines
 - example: wildfire detection (sensor data must be delivered to monitoring stations in a timely fashion to ensure timely responses)
- MAC protocol design
 - choice of frame size and slot allocations in TDMA-based protocols may lead to large delays
 - in contention-based protocols, nodes may be able to access the wireless medium sooner (than TDMA), but collisions and the resulting retransmissions incur delays
 - choice of MAC protocol can affect how predictable the experienced delay is (expressed as upper latency bounds)
 - some contention-based MAC protocols allow the theoretical possibility of starvation

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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

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- 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
 - neighborhood information by carrying a set of added and deleted neighbors
 - \blacktriangleright in case no changes have occurred, these packets serve as "keep-alive" beacons
 - NP allows nodes to obtain consistent two-hop topology information

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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

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
 - ${\ensuremath{\bullet}}$ 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 slot in the unicast period
- 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)
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Y-MAC

- Medium access in Y-MAC is based on synchronous low power listening
- The contention window (at beginning of each slot) resolves contention between multiple senders
 - a node wishing to send data sets a random wait time (back-off value) within the contention window
 - after this wait time, the node wakes up and senses the medium for activity for a certain amount of time
 - if the medium is free, the node sends a preamble until the end of the contention window to suppress competing transmissions and the receiver wakes up at the end of the contention window to wait for packets in its assigned slot
 - If the medium receives no signal from any of its neighboring nodes, it turns off the radio and returns to the sleep mode

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- Every node polls the medium only during broadcast time slots and its own unicast receive time slots
 - makes this approach energy-efficient
 - however, under heavy traffic conditions, many unicast messages may have to wait in the message queue or are dropped due to the limited bandwidth reserved for the receiving node
 - as a consequence, Y-MAC uses a channel hopping mechanism to reduce packet delivery latency





Y-MAC

- After receiving a packet during its time slot on the base channel, the receiving node hops to the next channel and sends a notification • it can continue to receive packets on the second channel
- contention for the medium in the second channel is resolved as before At the end of this slot, the receiving node can decide to hop again to another channel
 - until reaching the last channel or
 - until no more data is being received
- The hopping sequence generation algorithm
 - determines the actual hopping sequence among the available channels should guarantee that there is only one receiver among one-hop neighbors on any particular channel

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Y-MAC Summary • Y-MAC uses slot assignments (such as TDMA) communication is receiver-driven to ensure low-energy consumption • i.e., a receiver briefly samples the medium during its slot and returns to the sleep mode if no packets arrive • uses multiple channels • to increase the achievable throughput ► to reduce delivery latency • main drawbacks of the Y-MAC approach: has the same flexibility and scalability issues as TDMA (i.e., fixed slot allocations) ▶ requires sensor nodes with multiple radio channels Fundamentals of Wireless Sensor Networks: Theory and Practice Waltenegus Dargie and Christian Poellabauer © 2010 John Wiley & Sons Ltd.

DESYNC-TDMA

- DESYNC is a self-organizing desynchronization algorithm
- DESYNC-TDMA is a collision-free MAC protocol based on TDMA and built using the DESYNC algorithm
- Focuses on two shortcomings of traditional TDMA:
 - it does not require a global clock
 - it automatically adjusts to the number of participating nodes to ensure the available bandwidth is always fully utilized
- Desynchronization is a useful primitive for periodic resource sharing in a variety of sensor applications
 - example: sensors sampling a common geographic region can desynchronize their sampling schedule such that the requirements of the monitoring task are equally distributed among the sensors

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DESYNC-TDMA

- Consider a network of n nodes that communicate with each other
 - each node performs a periodic task with a period T
 - each node *i* can be modeled as an oscillator with a frequency ω = 1/T and a phase φ_i(t) ∈ [0, 1]
 e.g., a phase of 0.75 indicates that the node is 75% through its cycle
 - once a node reaches phase 1, it "fires" and resets its phase to 0 podes can be imagined as has de moving along a ring with period Twh
 - nodes can be imagined as beads moving along a ring with period T where a node fires once it reaches the top
 the only information nodes can observe about the current state of the ring is the
 - firing of events and they can use this to jump forward or backward in phase
 the goal is to have nodes adjust their phase independently such that eventually
 - the network is desynchronized (i.e., nodes are equally spaced around the ring)
 specifically, a node *i* keeps track of the firings of its immediate neighbors, i.e., nodes *i* + 1(mod n) and *i* − 1(mod n)

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DESYNC-TDMA

- Assume that Δ_i represents the distance between oscillators on the ring, i.e., Δ_i(t)=Φ_i(t)-Φ_{i-1}(t)
- Then, node *i* records its neighbors' firing times $as_{\overline{\Delta}_{i+1}} and_{\overline{\Delta}_i}$,
- Node *i* can then approximate the phases of its neighbors as

 $\phi_{i+1}(t) = \phi_i(t) + \overline{\Delta}_{i+1} (\mathrm{mod} 1)$

$$\phi_{i-1}(t) = \phi_i(t) - \overline{\Delta}_i (\text{mod}1)$$

The midpoint between these neighbors can then be determined as:

$$\phi_{mid}(t) = \frac{1}{2} \Big[\phi_{i+1}(t) + \phi_{i-1}(t) \Big] (\text{mod } 1)$$
$$= \phi_i(t) + \frac{1}{2} \Big(\overline{\Delta}_{i+1} - \overline{\Delta}_i \Big) (\text{mod } 1)$$

Once the midpoint has been determined, node *i* can jump to it

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DESYNC-TDMA

- The first ring shows the global view of 5 nodes that are not desynchronized
- The second and third rings show B's local view
- When A fires, the node that fired immediately before it (node B), knows the positions of both of its neighbors (i.e., node B overheard the firing of both A and C)
- Node B can now compute its ideal position for a desynchronized network and jumps to this position
- However, C may have changed its own position in the meantime, unknown to B
- If each node can fire closer to the midpoint of its neighbors, this process will eventually bring the system to a state where all nodes are exactly at the midpoint of their neighbors
- The last ring shows the global view for the desynchronized state (distances between any two neighboring nodes are identical)



DESYNC-TDMA

- Applied to a wireless sensor network:
 - the firing corresponds to a node broadcasting a firing message
 - node *i* keeps track of the times of the firings occurring immediately before and after its own firing
 - the senders of these firing messages are then phase neighbors of node i
- Applied to TDMA:
 - node *i*'s TDMA slot is defined as beginning at the previously computed midpoint between node *i* and its previous phase neighbor and as ending at the previously computed midpoint between itself and its next phase neighbor (therefore, a node will never fire outside its own slot)
- This algorithm defines a set of non-overlapping slots that cover T and nodes can transmit data without collisions, even during desynchronization
- Once desynchronization has completed, the slots have converged to be of equal size

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DESYNC-TDMA

- DESYNC ensures the bandwidth is always fully used
 - when a node leaves the network, the desynchronization process ensures that slot boundaries are adjusted over time such that their sizes are equalized again
 - when a node joins the network, it first sends a series of short interrupt messages before sending its initial firing message
 - these interrupt messages notify the owner of the current slot that a new node wants to join
 - the slot owner should temporarily pause its transmissions to avoid message collisions

DESYNC-TDMA

Summary

- DESYNC is an adaptive TDMA-based protocol
- it does not require explicit scheduling or time synchronization
- it provides collision-free communication even during desynchronization • it further can provide high throughput while guaranteeing predictable
- message latencies and fairness • DESYNC adjusts the schedule to accommodate new nodes and to
- recapture slots given up by leaving nodes
- but: fairness is often not a key concern in wireless sensor networks and ensuring equal slot sizes can lead to inefficient bandwidth usage
 - i.e., unused slot portions are therefore wasted similarly, if a node has more data to transmit than fits into its slot, the
 - queuing latencies can be high

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Low-Energy Adaptive Clustering Hierarchy Setup phase • cluster heads are determined and communication schedules within each cluster are established • since the cluster head is responsible for coordinating cluster activity and forwarding data to the base station, its energy requirements will be significantly larger compared to other sensor nodes • therefore, LEACH rotates the cluster head responsibility among sensor nodes to evenly distribute the energy load \blacktriangleright every sensor i elects itself to be a cluster head with a certain probability $P_i(t)$ In a network with N nodes and a desired number of cluster heads of k, the probabilities can be chosen to satisfy: $\sum_{i=1}^{N} P_i(t) = k$ Fundamentals of Wireless Sensor Networks: Theory and Practice Waltenegus Dargie and Christian Poellabauer © 2010 John Wiley & Sons Ltd. 57

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Low-Energy Adaptive Clustering Hierarchy
• There are various approaches to choose
$$P_i(t)$$
, e.g.,:

$$P_i(t) = \begin{cases} \frac{k}{N-k*(r \mod N/k)}, C_i(t) = 1; \\ 0, C_i(t) = 0 \end{cases}$$
• This approach uses an indicator function $C_i(t)$ to determine whether node i has been a cluster head in the $r \mod (N/k)$ previous rounds
• Only nodes that have not been cluster heads recently are candidates for the cluster head role, in order to evenly distribute the cluster head responsibility (and energy overhead) among all nodes

Low-Energy Adaptive Clustering Hierarchy

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- This approach does not consider the actual amount of energy available to each node
- An alternative approach to determining the probability of becoming a cluster head can be used:

$$P_i(t) = \min\left\{\frac{E_i(t)}{E_{total}(t)}k, 1\right\}$$

 E_i(t) is node is actual current energy and E_{total}(t) is the sum of the energy levels of all nodes

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 a disadvantage of this approach is that every node must know (or estimate) E_{lotal}(t)

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Low-Energy Adaptive Clustering Hierarchy

- Once a sensor node has determined that it will serve as cluster head for the next round, it informs other sensor nodes of its new role by broadcasting an advertisement message (ADV) using a non-persistent CSMA protocol
- Every sensor node joins a cluster by selecting the cluster head that can be reached with the smallest amount of transmit energy, based on received signal strength of the ADV messages from the cluster heads
- Joining is achieved by transmitting a join-request (Join-REQ) message to the chosen cluster head using CSMA
- The cluster head establishes a transmission schedule for its cluster and transmits this schedule to each node in its cluster



- Steady-state phase
 - a sensor node communicates only with the cluster head
 it is allowed to transmit data only during its allocated slots (indicated by the schedule received from the cluster head)
 - the responsibility of the cluster head is to forward sensor data
 - originating at one of its sensor nodes to the base station
 in order to preserve energy:
 - each cluster member uses the minimum required transmit power to reach the cluster head
 - each cluster member turns off the wireless radio between its designated slots
 - the cluster head remains awake at all times
 - to receive sensor data from its cluster members
 - to communicate with the base station

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Low-Energy Adaptive Clustering Hierarchy

- Sensor nodes use the direct sequence spread spectrum (DSSS) technique to limit the interference among clusters, while intra-cluster communication is contention-free using TDMA-style frames and slots
- Communication occurring in one cluster can still interfere with communication in another cluster
- Each cluster uses a spreading sequence that is different from the spreading sequences used in neighboring clusters
- Another reserved sequence is used for communication between cluster heads and the base station
- Communication between cluster heads and base station is based on CSMA

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Before a cluster head transmits data, it first senses the channel to see if there is an ongoing transmission using the same spreading code

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Low-Energy Adaptive Clustering Hierarchy LEACH-C variation of LEACH protocol relies on the base station to determine the cluster heads uning setup phase, each sensor node transmits its location and energy levels to the base station abaed on this information, the base station determines the cluster heads and informs the cluster heads of their new role other sensor nodes can then join clusters using join messages as described in the original LEACH protocol

Low-Energy Adaptive Clustering Hierarchy

Summary

- LEACH relies on a variety of techniques to reduce energy consumption
 minimum transmit energy
 - avoiding idle listening of cluster members
- LEACH attempts to obtain contention-free communication
 schedule-based communication
 DSSS
 - D333
- intra-cluster communication is contention-free and interferences among clusters are avoided
- communication between the cluster heads and the base station is still based on CSMA
- assumes that all nodes are able to reach the base station (affects the scalability of this protocol; can be addressed using multi-hop routing or by implementing a hierarchical clustering approach)

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Lightweight Medium Access Control

- The LMAC protocol is based on TDMA
 - each slot is owned by exactly one node
 - nodes execute a distributed algorithm to allocate slots instead of relying on a central manager to assign slots to nodes
 - each node uses its slots to transmit a message consisting of two parts:
 control message
 - identity of the time slot controller
 - distance (in hops) of the node to the gateway (base station)
 - address of the intended receiver
 - length of the data unit
 - data unit
 - upon receiving a control message, a node determines if it is the intended receiver and decides whether to stay awake or to turn off the radio until the next slot

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Description Size (bytes) Identification of time slot controller 2 Current slot number 1 Occupied slots 4 Distance to gateway in hops 1 Collision in slot 1 Destination address 2 Data size (bytes) 1 Total 12

Lightweight Medium Access Control

- The Occupied Slots field of the control message is a bit-mask of slots
 - where an unoccupied slot is represented by 0.
 - an occupied slot is represented by 1
- A node is able to determine unoccupied slots by combining control messages from all neighbors
- The process of claiming slots starts at the gateway device, which determines its own slots
- After one frame, all direct neighbors of the gateway know the gateway's slots and choose their own slots
- This process continues throughout the network and during each frame, a new set of nodes with a higher hop distance from the gateway determine their slots
- Each node must select slots that are not in use within a two-hop neighborhood
- Slots are selected randomly, so it is possible for multiple nodes to select the same slot
 - will result in a collision of control messages during the slot
 - can be observed by the competing nodes, therefore, they will restart the slot selection process

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Mobile LMAC

- Slot allocations in LMAC are computed only once, therefore, this protocol is not suitable for mobile sensor network, where nodes frequently join and leave other nodes' radio ranges
- Mobile LMAC (MLMAC) uses a distributed slot allocation mechanism, but it is able to adapt to changes in the network topology
 - When a node X leaves the radio range of node Y, both nodes will realize that they no longer receive control messages from each other and they will remove each other from their neighbor lists
 - Assume that node X moves into the radio range of node Z and that another node in Z's range, node W, uses the same slot as X
 - Control messages from X and W will collide at Z and node Z will no longer receive any correct control messages during this slot and will therefore mark this slot as unused
 - Nodes X and W will receive Z's control message, indicating that their slot is unused and meaning that there must have been a collision.
 - As a consequence, they give up their current slot and restart the slot selection mechanism

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LMAC and MLMAC

- Both LMAC and MLMAC have the same advantages as TDMA • collision-free communication

 - energy efficiency
- Additionally, they are able to establish transmission schedules in a
- distributed fashion
- However, in both protocols
 - slot size is fixed
 - slot allocations are also fixed
 - except when a node has to restart the slot selection mechanism
 - leading to bandwidth inefficiency

Contention-Based MAC Protocols

- These protocols do not rely on transmission schedules, instead they require other mechanisms to resolve contention when it occurs
- The main advantage of contention-based techniques is their simplicity compared to most schedule-based techniques
 - schedule-based MAC protocols must save and maintain schedules or tables indicating the transmission order
 - most contention-based protocols do not require to save, maintain, or share state information
 - this also allows contention-based protocols to adapt quickly to changes in network topologies or traffic characteristics
- However, they typically result in higher collision rates and overheads due to idle listening and overhearing (overheads usually refer to additional bits in a packet or additional packets such as control packets)
- They may also suffer from fairness issues (i.e., some nodes may be able to obtain more frequent channel accesses than others)

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Power Aware Multi-Access with Signaling

Initiating a data transfer

- a PAMAS device sends an RTS message over the control channel to the receiver
- receiver responds with CTS if it does not detect activity on the data channel and has not overheard other recent RTS or CTS messages
- if the source does not receive a CTS within a specific timeout interval, it will attempt to transmit again after a back-off time (exponential back-off algorithm)
- otherwise, it begins data transmission and the receiver node issues a busy tone over the control channel (whose length is greater than twice the length of a CTS)
- the receiver device also issues a busy tone over the control channel whenever it receives an RTS message or detects noise on the control channel while it receives a frame
 - done to corrupt possible CTS message replies to the detected RTS, thereby blocking any data transmission of the receiver's neighbors

Power Aware Multi-Access with Signaling

- Every node in a PAMAS network independently decides when to power off its transceiver
- Specifically, a node decides to turn off its transceiver whenever one of two conditions holds:
 - a neighbor begins a transmission and the node has no frames to transmit
 - a neighbor transmits a frame to another neighbor, even if the node has frames to transmit
- A node can easily detect either condition by
 - ${\ensuremath{\bullet}}$ overhearing its neighbor's transmissions (condition 1) or
 - overhearing its neighbor's busy tone (condition 2)
- A node can identify how long to power down its transceiver by embedding the size or expected transmission duration into messages

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Power Aware Multi-Access with Signaling

- However, when a transmission begins while a node is still asleep, it does not know how long this transmission will last and how long it should continue to sleep
- Therefore, the node issues a probe frame (containing a certain time interval) over the control channel to all transmitting nodes in its neighborhood
 - all transmitters that will complete during this interval respond with their predicted completion time
 - if such a response is received by the awakening node without collision, it can return to the sleep mode until the completion time indicated by the transmitting node
 - if multiple transmitters respond and their responses collide, the node reissues the probe frame with a shorter time interval
 - similarly, if the node did not receive a response, it can reissue the probe with a different time interval
 - in effect, the node chooses time intervals to perform a binary search to identify when the last ongoing transmission will end

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Sensor MAC

- The goal of the S-MAC protocol is
 - to reduce unnecessary energy consumption
- while providing good scalability and collision avoidance mechanism
 S-MAC adopts a duty-cycle approach
- nodes periodically transition between a listen state and a sleep state
 - Rodes periodically full study between a noter state and a sleep state
 each node chooses its own schedule, although it is preferred when nodes synchronize their schedules such that nodes listen or sleep at the same time
 - nodes using the same schedule are considered to belong to the same virtual cluster (but no real clustering takes place)
 - + all nodes are free to communicate with nodes outside their clusters

Sensor MAC

- All nodes are free to communicate with nodes outside their clusters
- Nodes periodically exchange their schedules with their neighbors using SYNC messages (every node knows when any of its neighbors will be awake)
- If node A wants to communicate with a neighbor B that uses a different schedule, A simply waits until B is listening and then initiates the data transfer
- contention for the medium is resolved using the RTS/CTS scheme
 In order to choose a schedule, a node initially listens to the medium for a
 - In the normality in the method of the method
 - schedule as its own and this node becomes a follower
 - the node broadcasts its new schedule after a random delay t_d to minimize the possibility for collisions from multiple new followers







Sensor MAC

- A node trying to send a SYNC or RTS message randomly selects a time slot within the SYNC or RTS part of the interval, respectively
 - senses the carrier for activity from when the receiver begins listening to the selected slot
 - if no activity has been detected, it wins the medium and begins transmission
- Contention for the medium is addressed using collision avoidance based on RTS/CTS handshakes (S-MAC adopts a contention-based approach)
 - when a node hears an RTS or CTS and concludes that it cannot transmit or receive at the same time, it can go to sleep to avoid wasting energy caused by overhearing

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Sensor MAC

Summary

- S-MAC is a contention-based protocol
- utilizes the sleep mode of wireless radios to trade energy for throughput and latency
- collision avoidance is based on RTS/CTS (which is not used by
- broadcast packets, thereby increasing the collision probability)
- duty cycle parameters (sleep and listen periods) are decided beforehand and may be inefficient for the actual traffic characteristics in the network

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Timeout MAC

- If there is only little traffic, S-MAC can actually waste energy because the listening period of S-MAC is of fixed duration
- On the other hand, if traffic is heavy, the fixed duration may not be large enough
- Therefore, the T-MAC protocol is a variation of S-MAC that uses an active period that adapts to traffic density
- Nodes wake up during the beginning of a slot to listen very briefly for activity and return to the sleep mode when no communication has been observed
- When a node transmits, receives, or overhears a message, it remains awake for a brief period of time after completion of the message transfer to see if more traffic can be observed
 - this brief timeout interval allows a node to return to the sleep mode as quickly as possible
 - the end effect is that a node's awake times will increase with the heavier traffic and will be very brief if traffic is light





Timeout MAC

- Once a node hears a CTS, it knows that another node won the medium
- This node then stays awake until the end of the transmission, which can be observed by overhearing the acknowledgment (ACK) sent by node B
- This event initiates the beginning of the next contention interval and node C will have an opportunity to transmit its data if it wins the medium
- In figure, assume that messages flow from top to bottom
 - node A sends only to node B, node B sends to node C
 - every time node C wants to send a message to node D, C must contend for the medium
 - C may lose to node B (B may transmit an RTS before C does) or
 - C may lose to node A (C overhears a CTS transmitted by node B)
 - while node C stays awake after overhearing node B's CTS message, its intended receiver (node D) is not aware of C's intention to transmit data and therefore returns to the sleep mode after TA has expired

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Timeout MAC

Early sleeping problem

- possible solution: future-request-to-send technique
 - a node with pending data can inform its intended receiver by transmitting a future-request-to-send (FRTS) packet immediately after overhearing a CTS message
 - node D, upon receiving the FRTS message, knows that node C will attempt to send data to it and will therefore remain active
 - however, sending an FRTS message immediately after CTS could interfere with node B's reception of node A's data

 - therefore, Node A first sends a dummy message called Data-Send (DS) to delay the transmission of the actual data
 - DS has the same size as FRTS
 - DS can collide with FRTS at node B, which is of no consequence since it does not contain any useful information

Timeout MAC

Summarv

- T-MAC's adaptive approach allows it to adjust a node's sleep and awake intervals based on the traffic load
- nodes send messages as bursts of variable length and sleep between such bursts to conserve energy
- both S-MAC and T-MAC concentrate message exchanges to small periods of time, resulting in inefficiencies under high traffic loads
- intended receivers are kept awake using messages that indicate future transmissions, which can significantly increase the idle listening times (and energy consumption) of nodes

Pattern MAC

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- The PMAC protocol is another example of a TDMA style protocol, but it adapts its sleep schedules on the basis of its own traffic and the traffic patterns of its neighbors
- Compared to S-MAC and T-MAC, PMAC further reduces energy costs of idle listening by allowing devices to turn off their radios for long durations during periods of inactivity
- Nodes use patterns to describe their tentative sleep and awake times
 a pattern is a string of bits, each bit representing a time slot
 - a node plans to sleep: bit is 0
 - ▶ a node plans to awake: bit is 1

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Pattern MAC

- While patterns are only tentative, schedules represent the actual sequence of sleep and awake times
 - format of a pattern is always 0^m1 where m = 0, 1, . . . , N 1 and N time slots are considered to be a period (example: pattern 001 and N=6)
 - value of m (number of leading zeros) is an indicator of traffic load around the node
 - ▶ a small value indicates heavy traffic
 - a large value indicates light traffic
 - every node's pattern during the first period is 1 (m=0), i.e., every node assumes a heavy traffic load should be awake at all times

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Pattern MAC

- If a node does not have any data to send during the first slot, then it uses this as an indicator that the traffic around it is potentially light (pattern becomes 01)
- The node continues to double the sleep interval every time it has no data to send (i.e., doubling the number of zeros; allowing it to sleep longer)
- This process is continued until a predefined threshold is reached, then the number of zeros is increased linearly
- If there is no data for node i to send, the following sequence of patterns will be generated:
- 1, 01, 0²1, 0⁴1, ..., 0⁵1, 0³01, 0³0²1, 0³0³1, ..., 0^{N-1}1 ■ Whenever a node has data to send, the pattern is immediately reset to 1, allowing the node to wake up quickly and to handle the traffic load

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Pattern MAC

- While a pattern is only a tentative sleep plan, patterns are used to derive actual sleep schedules
- A node broadcasts its own pattern at the end of a period during a time interval called the Pattern Exchange Time Frame (PETF)
 - the PETF is divided into a sequence of brief slots where the number of slots is set to the maximum number of neighbors a node could have
- these slots are accessed using CSMA, i.e., collisions can occur
 If a node does not receive a pattern update from one of its neighbors, the node simply assumes the neighbor's pattern remains unchanged

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Pattern MAC

- Once a node has received the patterns from its neighbors, it determines its own schedule, where each slot can be used for one of three possible operations
 - if the neighbor has advertised a 1 for that slot, a node wakes up and transmits a message to a neighbor
 - 2. if a node has advertised a 1, but has no data to send, the slot is used to listen
 - 3. if none of these two conditions holds, the node sleeps

Pattern MAC

Summary

- PMAC provides a simple mechanism to build schedules that adapt to the amount of traffic in a neighborhood
- when traffic loads are light, a node is able to spend considerable amounts of time in the sleep mode, thereby preserving energy
- however, collisions during the PETF prevent nodes from receiving pattern updates from all neighbors, while other nodes may have received these updates
 - leads to inconsistent schedules among nodes in a neighborhood, which can cause
 - further collisions
 - wasted transmissions
 - unnecessary idle listening

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Routing-Enhanced MAC

- The RMAC protocol is another example of a protocol that exploits duty cycles to preserve energy
- Compared to S-MAC, it attempts to improve upon end-to-end latency and contention avoidance
- They key idea behind RMAC is to align the sleep/wake periods of nodes along the path of sensor data such that a packet can be forwarded to the destination within a single operational cycle
- It achieves this by sending a control frame along the route to inform nodes of the upcoming packet, allowing them to learn when to be awake to receive and forward this packet

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Routing-Enhanced MAC

- RMAC partitions an operational cycle into three components:
 SYNC period
 - hodes synchronize their clocks (to maintain sufficient precision)
 - DATA period
 used to announce and initiate the packet transmission process along the
 - packet's route to the destination
 - contention-based
 - sender waits for a randomly chosen period of time plus an additional DIFS period (and senses the medium during this time)
 - if no activity is detected, the sender transmits a Pioneer Control Frame (PION) containing the addresses of the sender, destination, and next hop, the duration of the transmission, and the number of hops travelled so far (0 at sender)
 - the next hop along the route looks up the next hop for this route and forwards the PION to the next hop after waiting for a SIFS period
 - this process continues until the PION reaches the destination
 - SLEEP period





Routing-Enhanced MAC

- Actual data transmission takes place during the SLEEP period
- Example in figure:
 - node A stays awake to receive the data packet from the sender and after successful transmission A returns an acknowledgment (ACK)
 - all data and ACK packets are separated by a SIFS period similar to the PION schedule during the DATA period
 - after receiving the ACK from node A, the sender has completed its part and it can return its radio into the sleep mode
 - node A relays the received packet to the next hop (node B) and also returns its radio to sleep mode once B has acknowledged the data packet
 - this process continues until the data packet has been received and acknowledged by the destination

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Routing-Enhanced MAC

- The sender and node A stay awake after the DATA period to immediately begin the transmission of the data packet over the first hop
- All other nodes along the route can turn off their radios after the DATA period has completed to further preserve energy
- Each node wakes up at the right time to receive the data packet from the upstream node
- This time to wake up can be computed by node *i* as:

 $T_{wakeup}(i) = (i-1) \cdot (size(DATA) + size(ACK) + 2 \cdot SIFS)$

 where size(DATA) and size(ACK) are the times required to send a single data and ACK frame

Routing-Enhanced MAC

- Summary
 - RMAC addresses the large latencies often experienced in MAC protocols based on duty cycles
 - it is able to perform end-to-end packet delivery within a single operational cycle
 - it also alleviates contention by separating medium contention and data transfer into two separate periods
 - however, collisions can still occur, even on the data packets during the SLEEP period
 - a source always commences transmission at the beginning of the SLEEP period, therefore it is possible that data packets coming from two different sources (which succeeded in the PION scheduling process during the DATA period, but cannot see each other) may still collide

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Data-Gathering MAC

- Nodes switch between sending, receiving, and sleep states During the sending state, a node sends a packet to the next hop node on
- the route and awaits an acknowledgment (ACK) At the same time, the next hop node is in the receiving state, immediately followed by a sending state to forward the packet to the next hop (unless the node is the destination of the packet)
- A node enters the sleep state between these intervals of receiving and
- sending of packets, where it can power down its radio to preserve energy ■ The sending and receiving intervals are large enough for exactly one packet
- Since there are no queuing delays, a node at depth d in the tree can then deliver a packet to the sink within d intervals
- While limiting a node's activity to brief intervals for sending and receiving reduces the contention, collisions can still occur • e.g., nodes with the same depth in the tree will have synchronized
 - schedules

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Data-Gathering MAC

- If a sender does not receive an ACK, it queues the packet until the next sending interval and after three failed retransmissions, the packet will be dropped
- To reduce collisions, nodes do not transmit immediately at the beginning of the sending slot, but instead have a back-off period (BP) plus a random time within a contention window
- When a node has multiple packets to send during a sending slot
 - it can increase its own duty cycle and
 - it requests other nodes along the route to the sink to do the same
- This is implemented through a slot-by-slot renewal mechanism using a more data flag in the MAC header
- A receiver checks for this flag and if set
 - it returns an acknowledgment that has also the more data flag set
 - it then stavs awake to receive and forward one additional packet

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Data-Gathering MAC

Summary

- DMAC's staggering technique achieves very low latency
- nodes only stay awake for brief receive and send intervals
- since many nodes in the data-gathering tree share the same schedule, collisions will occur and DMAC only employs limited collision avoidance methods
- DMAC works best for networks in which the transmission paths and rates are well known and do not change over time



- WiseMAC is a MAC protocol that is concerned with the energy consumption of downlink communication (from base station to sensor nodes) in infrastructure-based sensor networks
- To avoid energy consumption due to idle listening, WiseMAC relies on the preamble sampling technique
- Preamble sampling
 - the base station transmits a preamble preceding the actual data transmission to alert the receiving node





- Preamble sampling (contd.)
 - \bullet all sensor nodes sample the medium with a fixed period T_w but with independent and constant relative sampling schedule offsets
 - if the medium is busy, a sensor node continues to listen until the
 - medium becomes idle or a data frame is received
 the preamble's size is equal to the sampling period
 - ensures that the receiver will be awake to receive the data portion of the packet
 - this approach allows the energy-constrained sensor nodes to turn off
 - the radio when the channel is idle (without the risk of missing a packet)
 - disadvantages
 - the size of the preamble affects the achievable throughput
 a device must stay awake when a preamble is detected even if it is
 - not the intended receiver

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Preamble Sampling and WiseMAC

- WiseMAC improves upon this by adding a technique by letting a base station learn the sampling schedules of the destination, thereby allowing the base station to start the transmission of the preamble immediately before the receiver wakes up
 - allows the base station to reduce the size of the preamble
 - awake time of the receiver is also shortened since the data portion of the packet will start shortly after the receiver's radio has turned on
- A node's schedule offset is embedded into the acknowledgment (ACK)
- message allowing the base station to learn the sampling schedules
 The duration of the preamble T^p_p is then determined as the minimum of the destination's sampling period T^p_w and a multiple of the clock drift between
- the clock clock at the base station and on the receiver (grows over time) Therefore, the preamble length depends on the traffic load:
 - preamble is shorter when traffic is high (brief intervals between two consecutive communications)
 - preamble is larger under low load



Summary

- WiseMAC implements energy-efficient wake/sleep schedules for sensor nodes while ensuring that all data transmissions from a base station to the sensors will be received (i.e., the receiver will be awake)
- however, the approach is inefficient for broadcast messages since the preamble is likely to be very large (i.e., it must span over the sampling points of all receiver devices)
- WiseMAC is also affected by the hidden terminal problem (i.e., a sender's preamble can interfere with ongoing transmissions when the sender is not aware of this other transmission)

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Receiver-Initiated MAC

- The RI-MAC protocol is another contention-based solution
 - ${\ensuremath{\bullet}}$ a transmission is always initiated by the receiver of the data
 - each node wakes up periodically to check whether there is an incoming data packet
 - a node checks if the medium is idle immediately after turning on its radio
 - if so, it broadcasts a beacon message announcing that it is awake and ready to receive data

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Receiver-Initiated MAC

- A node with pending data to transmit stays awake and listens for a beacon from its intended receiver
- Once this beacon has been received the sender immediately transmits the data
 - data will be acknowledged by the receiver with another beacon
- The beacon serves two purposes:
 - it invites new data transmissions
 - it acknowledges previous transmissions
- If there is no incoming data packet for a certain amount of time after the beacon broadcast, the node goes back to sleep after waiting a certain time





Receiver-Initiated MAC

- If there are multiple contending senders, a receiver uses its beacon frames to coordinate transmissions
- A field in the beacon, called the back-off window size (BW) specifies the window over which to select a back-off value
- If the beacon does not contain a BW (the first beacon sent out after waking up does not contain a BW), senders immediately commence transmission
- Otherwise, each sender randomly selects a back-off value within BW and the receiver increases the BW value in the next beacon when it detects a collision
 - the receiver notices the collision and sends another beacon (containing a BW)

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 if multiple collisions occur and the receiver was not able to receive a packet for several beacon intervals, the node simply goes to sleep without further attempts

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Receiver-Initiated MAC

- The receiver is in control of when to receive data and it is responsible for detecting collisions and recovering lost data
- Since transmissions are triggered by beacons, the receiver will have very little overhead due to overhearing
- Senders must wait for the receiver's beacon before they can transmit (potentially leading to large overhearing costs)
- When packets collide
 - the senders will retry until the receiver gives up
 - potentially leading to more collisions in the network and to increased data delivery latencies

Hybrid MAC Protocols

- Display characteristics of both categories
 - attempt to reduce the number of collisions by relying on features present in contention-free medium access protocols
 - take advantage of the flexibility and low complexity of contention-based protocols

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Zebra MAC

 The Z-MAC protocol uses frames and slots to provide contention-free access to the wireless medium
 similar to TDMA-based protocols

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- However, Z-MAC also allows nodes to utilize slots they do not own using CSMA with prioritized back-off times
- As a consequence:
 - in low-traffic scenarios, Z-MAC emulates a CSMA-based approach
 when traffic loads are high, Z-MAC emulates a TDMA-based approach

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Zebra MAC

- When a node starts up, it enters a setup phase to allow it
 - to discover its neighbors
 - to obtain its slot in the TDMA frame
- Every node periodically broadcasts a message containing a list of its
- neighbors
- through this process, a node learns about its 1-hop and 2-hop neighbors
- this information is used as input to a distributed slot assignment protocol (provides each node with time slots)
- ensures a schedule where no two nodes within an 2-hop neighborhood will be assigned the same slot

Zebra MAC

- Z-MAC allows nodes to select the periodicity of their assigned slots where different nodes can have different periods (time frames or TF)
- The advantage of this approach is that it is not necessary to propagate a maximum slot number (MSN) to the entire network
 The protocol can adapt slot allocations locally
 - i ne protocol can adapt slot allocations loc
 - assume that node *i* is assigned slot s_i
 and F_i represents the MSN within the node's 2-hop neighborhood
 - and P_i represents the MSN within the hode's 2-hop heighborho
 then: *i*'s TF is set to be 2^a
 - a is a positive integer that satisfies $2^{a-1} \le F_i < 2^{a-1}$
 - node *i* then uses the *s*_ith slot in every 2^a time frame

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Zebra MAC

- In Z-MAC, these nodes can use frame size 4
 - increases the concurrency in the channel usage
 - reduces message delays
- The resulting schedule shows that some slots are not assigned to any node
 specifically slots 6 and 7
- In a global time frame, a frame size could have been chosen that reduces the number of empty slots

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 However, Z-MAC allows nodes to compete for these "extra" slots using CSMA

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Zebra MACAfter the schedule has been determined, every node forwards its frame size and slot number to its 1-hop and 2-hop neighbors. Even though slots are owned by nodes, Z-MAC uses CSMA to determine who may transmit. However, slot owners are given preference. by using a random back-off value chosen from the range [0, T_o]. whereas other nodes choose their back-off values from the range [T_o, T_{no}]

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Zebra MAC

- Z-MAC also uses explicit contention notification (ECN) to which it has a message
 - where each node decides to whether to send an ECN message to a neighbor based on its local estimate of the contention level (e.g., determined using the packet loss rate or channel noise level)
 - this neighbor then broadcasts the ECN to its own neighbors, which then enter a high contention level (HCL) mode
 - a node in the HCL mode only transmits data in its own slots or slots belonging to its 1-hop neighbors
 - thereby reducing the contention between 2-hop neighbors
 - it returns to a *low contention level* (LCL) mode if it has not received any ECN messages for a certain amount of time

Zebra MAC

- Summary
 - Z-MAC adopts characteristics found in both TDMA and CSMA protocols
 - allowing it to quickly adapt to changing traffic conditions
 - under light traffic loads Z-MAC behaves more like CSMA
 - under heavy traffic loads contention for slots is reduced
 - Z-MAC requires an explicit setup phase (consumes both time and energy)
 - while ECN messages be used to reduce the contention locally
 these messages add more traffic to an already busy network and take time to propagate
 - thereby causing delays in the adaptation to a more TDMA-like behavior

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Mobility Adaptive Hybrid MAC

- In many sensor networks, some or all nodes can be mobile
 can bear significant challenges for the design of a MAC protocol
- The MH-MAC protocol proposes a hybrid solution
 - uses a schedule-based approach for static nodes
 - uses a contention-based approach for mobile nodes
- While it is straightforward to determine a TDMA-style schedule for static nodes, this is not the case for mobile nodes
 - MH-MAC allows mobile nodes entering a neighborhood to use a contention-based approach to avoid the delays often needed to be inserted into the schedule

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Mobility Adaptive Hybrid MAC

- The slots of a frame belong to one of the two categories:
 - static slots
 - mobile slots
- Each node uses a mobility estimation algorithm to determine its mobility and which type of slots the node should use
 - mobility estimation is based on periodic hello messages and received signal strength
 - hello messages are always transmitted with the same transmit power
 - receiving nodes compare consecutive message signal strengths to estimate the relative position displacement between themselves and each of their neighbors
 - a mobility beacon interval is provided at the beginning of a frame to distribute mobility information to neighbors



Mobility Adaptive Hybrid MAC

- MH-MAC provides a mechanism to dynamically adjust the ratio between static and mobile slots
 - based on the observed mobility
 - ${\ensuremath{\bullet}}$ necessary since the ratio of static versus mobile nodes can vary
 - each node estimates its own mobility and sends this information in the previously mentioned beacon time slot at the beginning of a frame
 - using this mobility information, each node calculates a mobility parameter for the network, which determines the ratio of static and mobile slots

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Mobility Adaptive Hybrid MAC

Summary

- MH-MAC combines characteristics of the LMAC protocol for static
- nodes and features of contention-based protocols for mobile nodes
- mobile nodes can quickly join a network without long setup or adaptation delays
- compared to LMAC
 - MHMAC allows nodes to own more than one slot in a frame
 this increases bandwidth utilization and decreases latencies

Summary

- The choice of a medium access protocol has a substantial impact on the performance and energy-efficiency of a WSN
- MAC protocols should also be designed to accommodate changes in network topology and traffic characteristics
- Latency, throughput, and fairness among competing nodes determined or affected by the characteristics of the MAC layer
- Protocols based on transmission schedules
 - collision-free
 resource-inefficient
 - resource-inefficient
 - may require well synchronized nodes throughout the network
 - difficult to adapt to changing topologies

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Summary

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- Protocols that let nodes compete for access to the medium
- more flexible (easily accommodate changing network topologies)
- require less overhead
- not collision-free
- must possess features that allow them to recover from collisions
- network utilization may suffer when collisions occur frequently