# MAC Protocols for Sensor Networks

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# Outline

- Introduction
- Motivation
- Types of MAC protocols for sensor networks
  - Contention Based (Week 1)
  - Reservation Based (Week 2)
  - Other tailored solutions (Week 2)
- MAC design for Sensor Networks

# Introduction

- Sensor Network
  - Consists of a large number of low-cost, low-power sensor nodes
  - Random deployment in hostile environments e.g. inaccessible terrains
  - Nodes contain sensing, data processing & communicating components
  - Self-organizing – may collect data, process it & send it to the Base Station by cooperating with each other (Multi-hop communication)

# Introduction (Contd.)

- Challenges
  - Wireless Communication Medium
  - Limited power
  - Failure prone
  - Topology changes are frequent
  - Large number of sensor nodes

# MAC layer for sensor networks

- Goals:
  - Creation of the network infrastructure
    - Establish communication links for data transfer
  - Fairly & efficiently share resources (e.g. communication medium & energy) between sensor nodes
- Existing MAC protocols in wireless networks
  - Cellular systems
  - Mobile ad-hoc networks & Bluetooth

# Existing MAC protocols

- Cellular system
  - Base stations form a wired backbone
  - Mobile node is single hop away from the Base Station
  - QoS & bandwidth efficiency are core issues
  - Power conservation is of secondary importance
  - Dedicated resource assignment is used
  - Network wide synchronization is difficult to do in sensor networks without a central controlling agent

# Existing MAC protocols (Contd.)

- Bluetooth
  - Short range wireless system (tens of meters)
  - Star network with master node having up to seven slave nodes to form a piconet
  - Each piconet uses a centrally assigned time-division multiple access (TDMA) schedule & frequency hopping pattern

# Existing MAC protocols (Contd.)

- Mobile ad-hoc networks (MANET)
  - Primary goal: High QoS under mobile conditions
  - Power consumption is secondary as even though the nodes are battery powered, they can be replaced and/or recharged

# Motivation

- Sensor networks Vs. Wireless Networks
  - May have a much larger number of nodes
  - Transmission power is much less than Bluetooth or MANET
  - Topology changes are much more frequent
    - Mobility (typically lower than MANET)
    - Node failure
  - Primary concern is power conservation

# MAC protocols for sensor networks

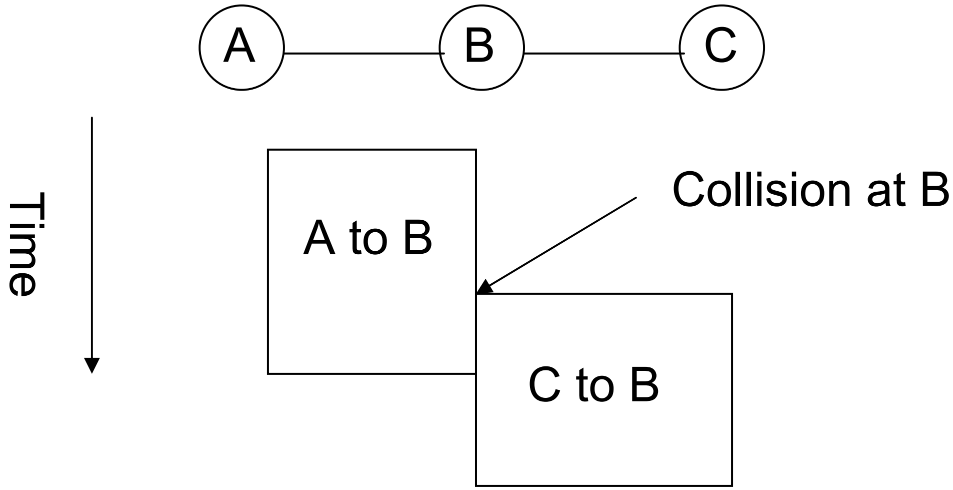
- Contention-based
  - Nodes contend for the wireless channel
  - E.g. CSMA based schemes
- Fixed allocation
  - Reservation & scheduling
  - E.g. TDMA, FDMA etc.
- Hybrid
  - Combination of the two
  - E.g. Sensor-MAC (S-MAC)

# Contention based schemes

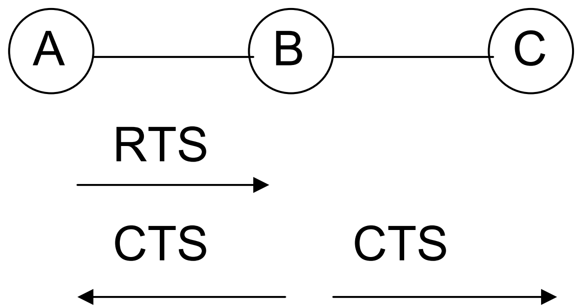
- IEEE 802.11 Distributed Coordination Function (DCF)
  - A form of CSMA/CA
    - Sense the medium before transmitting
  - Uses RTS/CTS/DAT/ACK
  - Binary exponential backoff
  - Based on Multiple Access with Collision Avoidance (MACA), [3]

# Motivation for RTS/CTS in MACA

- Hidden Terminal Problem
  - A & C cannot hear each other



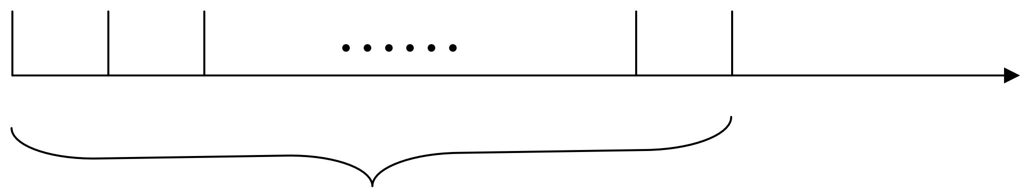
# Use of RTS/CTS




- C receives CTS from B & thus can hold off transmission until B receives A's packet
  - Length of the packet is contained in RTS/CTS

# Binary Exponential Backoff

Packet collision occurs



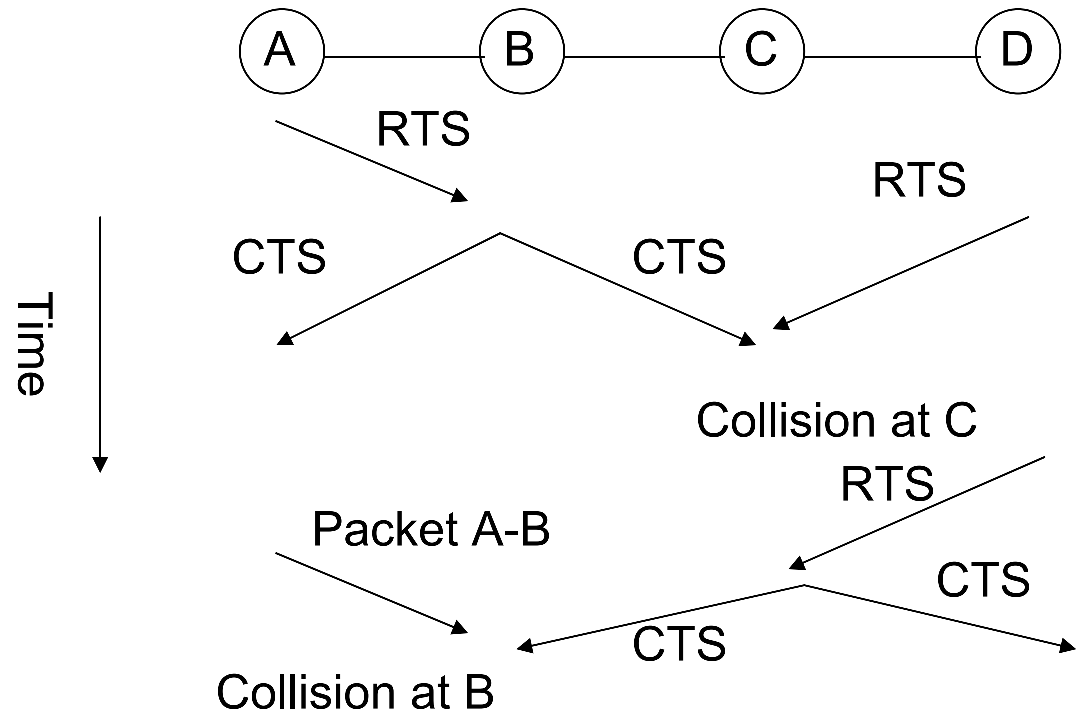

Next attempt: Transmit at a random slot over the contention window

- The contention window size is adjusted dynamically.
  - Binary Exponential Backoff is used.

# Binary Exponential Backoff (Conrd.)

- When a terminal fails to receive CTS in response to its RTS, it increases the contention window
  - *cw* is doubled (up to an upper bound, $CW_{max}$)
- When a node successfully completes a data transfer, it restores *cw* to $CW_{min}$

# A Problem with RTS/CTS




- C hears a collision (for CTS) & hence transmits CTS (to D) which collides with packet at node B

# Solution to the problem

- Add link layer ACKs (in MACAW, [4])
  - E.g. B won't send an ACK & hence A will begin the retransmission process
- Other protocols (FAMA, [5]) have made the length of the CTS longer than the RTS
  - Receiving part of the CTS (in RTS-CTS collision) will cause a node to ignore all transmissions for the time taken to transmit a maximum length packet

# Power Conserving MAC Protocols

- For Ad-hoc Networks: PAMAS, [1]
  - Power Aware Multi-Access protocol with Signaling
- PAMAS
  - Uses the original MACA protocol & a separate signaling channel
  - RTS-CTS exchange on signaling channel (to be used to power radios off)
  - Delay or throughput shouldn't be changed by the power conserving behavior

# PAMAS Operation

- A node may be in any one of the six states
  - Idle, AwaitCTS, BEB (Binary Exponential Backoff), Await Packet, Receive Packet & Transmit Packet
- Idle
  - Not transmitting or receiving a packet
  - Doesn't have packets to transmit
  - Does have packets to transmit but cannot transmit (because a neighbor is receiving a transmission)

# PAMAS Operation (Contd.)

- A node has packet to transmit
  - It transmits RTS & goes into AwaitCTS state
  - If CTS doesn't arrive, it goes into BEB
  - Else, it begins transmitting packet (Transmit Packet state)
- Receiving a RTS ⇨ Responds with CTS if
  - No neighbor is in Transmit Packet state (by sensing channel)
  - No neighbor is in AwaitCTS state

# PAMAS Operation (Contd.)

- Neighbor in AwaitCTS state?
  - If a node heard noise over the control channel within $\zeta$ of the arrival of RTS, it doesn't respond with a CTS (The transmission of the RTS by the neighbor may have collided)
  - $\zeta$ = One roundtrip time + Transmission time for RTS/CTS
  - However if a node doesn't hear packet transmission within next $\zeta$ , it assumes none of its neighbors are in AwaitCTS state anymore

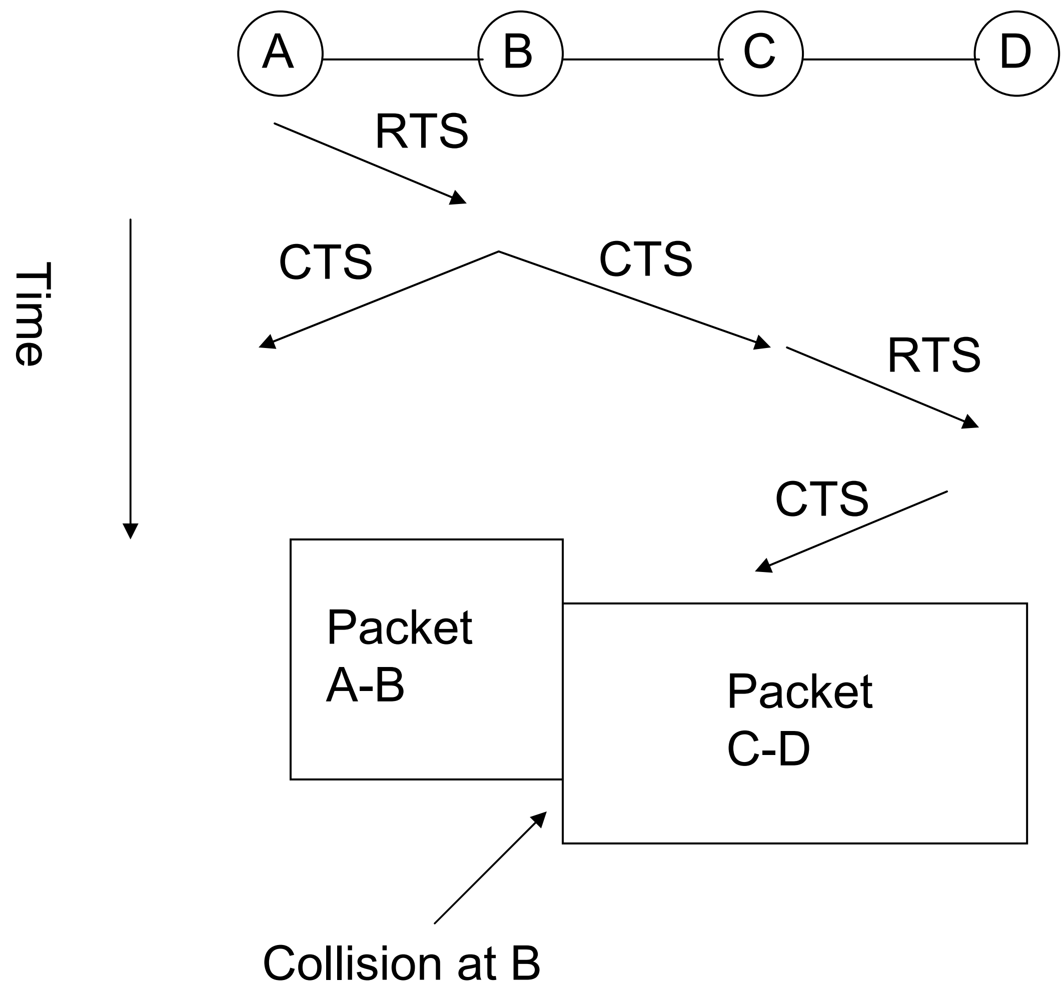
# PAMAS Operation (Contd.)

- Neighbor that is receiving packet responds to RTS
  - Busy tone (twice as long as RTS/CTS) that will collide with reception of CTS
- When a node begins receiving packet
  - Enters Receive Packet state
  - Transmits busy tone (length > 2*lengthof(CTS) )
- This mechanism solves hidden terminal problem

# Hidden Terminal Problem Solution

- The case described before wont happen as a control packet (CTS) cannot collide with a packet transmission
- What about packet to packet collisions due to hidden terminal problem?

# Hidden Terminal Problem (Contd.)




C doesn't hear B's CTS since it was transmitting its own RTS to D

# PAMAS Solution

- When node B receives a packet from A
  - It transmits busy tone to C which overlaps with CTS transmission from Node D to C
  - Thus C enters BEB & transmits RTS which may be met with busy tone unless B has finished receiving packet
  - This continues until B finishes receiving or D sends RTS to C (C may begin receiving packet from D)

# Power Conservation

- Packet transmission is overheard by all neighbors wasting energy in reception
- To conserve energy, nodes shut themselves off under two conditions
  - If a node has no packets to transmit, it powers off if a neighbor begins transmitting
  - If at least one neighbor is transmitting & another is receiving, the node powers off (even if transmit queue is non-empty as it can neither transmit or receive)

# Power Conservation (Contd.)

- Every node takes decision to power off independently
- What happens if a neighbor wishes to communicate to a node that is powered off?
  - Does this increase delays?
  - No because the amount of time a node is powered off is when it can neither receive nor transmit packets
- How long does a node keep itself powered off?

# Duration of sleeping

- If a node has an empty transmit queue & a packet transmission begins (of duration *l*), then the node can sleep for *l* seconds
- How to estimate length of transmissions that start when a node is powered off?
  - Since control channel is also powered off, length of those transmissions is not known
  - Uses transmitter probe packet & does a binary search on the interval in which a packet transmission can end

# Duration of sleeping (Contd.)

- For example, it probes [*l*/2,*l*]
  - Transmitters with transmissions ending in that interval reply with the time their transmissions will end
- Collision in replies
  - Probes other interval
  - Or if a node hears a collision when probing for inetrval [$t_1$,$t_2$], it powers itself off for the period $t_1$ (to minimize packet delay although a transmission may be ongoing when it switches on)

# Duration of sleeping (Contd.)

- When a node has a non-empty transmit queue & wakes up
  - Transmits RTS rather than probing
  - Node that is receiving a transmission in the neighborhood replies with a busy tone
  - If the busy tone collides, the node probes both receivers (Result *r*) & transmitters (Result *t*) & powers itself off for *min*(*r*,*t*).

# Duration of sleeping (Contd.)

- If $t<r$, it can switch on after $t$ so that some other node can transmit to this node
- If $t>r$, it must switch on at $r$, so that it can begin transmitting packets from its queue

- The probe protocol can be simplified considerably if the signaling interface is left powered on even when its data interface is powered off
  - It will be able to know the length of all ongoing transmissions

# PAMAS Results

- No effect on delay or throughput
  - Err on side of caution & never power off a node more than what is necessary
- Simulations performed over ad-hoc networks (10-20 nodes) show power savings of between 10-70%
- Issues: Is a separate signaling channel needed?

# Other CSMA Schemes

- A. Woo and D. Culler, "A transmission control scheme for media access in sensor networks", *ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom) 2001*,2001.

# CSMA for sensor networks

- Different variants of CSMA analyzed & simulated
- Goals:
  - Communication efficiency in terms of energy consumed per unit of successful communication
  - Fairness: Fair allocation of bandwidth to the Base Station from each node over multiple hops
- Apply rate control
  - Both originating & route-thru traffic

# Other aspects considered

- Power scheduling as in PAMAS not considered
  - Energy efficiency in basic media access control schemes is dealt with
- Talks about design issues for MAC in sensor networks

# MAC Design

- Listening mechanism
  - CSMA involves listening to the channel which wastes energy
  - Shorten length of carrier sensing e.g. during backoff
  - Synchronized nature of traffic in sensor networks call for randomness in CSMA
    - An event may be detected by multiple nodes & all sensing channel to be free may start sending resulting in collisions

# MAC Design (Contd.)

- Backoff Mechanism
  - Typical function: Restrain a node from sending for a period of time
  - The backoff should be used as a phase shift to the periodicity of the application so that synchronization among periodic streams of data can be broken
- Contention based mechanism
  - RTS-CTS-DAT-ACK handshake can be a large overhead for small packet sizes (sensor networks)

# MAC Design (Contd.)

- Contention based mechanism (Contd.)
  - In a bidirectional multihop network, ACKs are free!
    - When a node routes a node's packet (even if aggregation has been done), the node can hear it & determine success of transmission
  - RTS-CTS
    - Effective in eliminating hidden node problem
    - Should only be used when the amount of traffic is high
    - A simple CSMA scheme is usually adequate for low traffic when the probability of collision is low

# MAC Design (Contd.)

- Rate Control Mechanism
  - Goals:
    - Control rate of originating data to allow route-thru traffic to access the channel & reach the Base Station
    - Capability to decrease route-thru traffic should exist to open up channel for nodes close to the Base Station
  - Basic mechanism
    - Periodically a node originates data
    - If the packet is injected successfully, it signals that the transmission rate can be increased
    - Unsuccessful: Decreases rate of originating data

# MAC Design (Contd.)

- Rate Control Mechanism (Contd.)
  - If the application transmission rate is *S*, the actual rate of originating data is $S*p$ where $p \in [0,1]$ is the probability of transmission
  - Linear increase: Multiply *p* by α
  - Multiplicative decrease: Multiply *p* by β ,0< β<1 (When failure of transmission occurs)
  - Preference given to route-thru traffic: So $\beta_{route}=1.5* \beta_{originate}$

# MAC Design (Contd.)

- Rate Control Mechanism (Contd.)
  - A node should give a fair proportion of its bandwidth to each node routing through it
    - If a node has route-thru traffic from *n* children, then bandwidth for original data should be 1/(*n*+1)
    - Thus $\alpha_{originate} = \alpha_{route}/(n+1)$
- Multihop Hidden Node Problem
  - Without explicit control packets
    - Tuning transmission rate
    - Performing phase changes

# MAC Design (Contd.)

- Multihop Hidden Node Problem (Contd.)
  - Child node can avoid hidden node problem with its grandparent
    - Let packets are routed after processing time *x*
    - If a child node hears end of parent's transmission at time *t*, it should not transmit from *t* to *t*+*x*+PACKETTIME
    - In fact, if a child node detects above situation it should backoff to change its phase
    - Issues:
      - Estimates of *x*?

# Various CSMA Schemes

- Design parameters
  - Carrier sense (or listening) mechanism (Random or Constant)
  - Backoff mechanism (Fixed Window, Exponential Decrease or Exponential Increase)
  - Random delay prior to listening (to unsynchronize) (Optional)

# Simulation Results

- Delivered Bandwidth
  - All CSMA schemes achieve greater bandwidth than 802.11 with its explicit ACKs
  - Constant listen period & no random delay achieve highest bandwidth
    - But their aggregate bandwidth is not very robust, due to failure to eliminate repeated collisions
  - Random delay or random listening intervals achieve less bandwidth but are more robust
    - Randomness introduced by backoff avoids repeated collisions

# Simulation Results (Contd.)

- Delivered Bandwidth (Contd.)
  - Constant listening window & no random delay achieve zero bandwidth in worst case
  - 802.11 doesn't have zero bandwidth as ACKs provide collision detection & trigger backoff, desynchronizing the nodes
- Energy Usage
  - Energy consumed in listening is separated from energy in transmitting or receiving

# Simulation Results (Contd.)

- Energy Usage (Contd.)
  - 802.11 has the worst energy efficiency due to listening to the channel throughout backoff
  - CSMA schemes with constant listen period are the most energy efficient
  - Random listen time schemes are less efficient (due to an increase in average listen time as average number of backoffs are approx. constant)
- Thus schemes with constant listen period & random delay are the most energy efficient
  - These three schemes are analyzed further

# Simulation Results (Contd.)

- Fairness
  - Three CSMA schemes are very similar, so difference in backoff is insignificant in terms of fairness
  - 802.11 gives unfair allocation of bandwidth among the nodes
    - Nodes with an earlier transmission time end up capturing the channel

# Analysis of Multihop Scenario

- Challenges
  - If nodes near the Base Station originate too much traffic, less bandwidth is available for more distant nodes
  - If distant nodes collectively originate more traffic than is available as the flows reach the Base Station, packets are dropped
  - Transmission Control Protocol
    - RTS/CTS contention control scheme
    - Adaptive Rate Control (ARC): Adjusts rate based on observed packet loss

# Analysis of Multihop Scenario (Contd.)

- Results
  - CSMA Schemes don't perform well
  - RTS/CTS perform better than CSMA Schemes
    - However, bandwidth allocation is unfair: Nodes close to the Base Station dominate the channel
  - ARC Scheme provides the most fair delivered bandwidth but cannot eliminate hidden node problems

# Conclusions

- Random delay should be introduced prior to any transmission
  - Backoff acts as phase shift for periodicity
- Given that energy efficiency & delay are main metrics
  - Random delay & constant listen period should be used with radio off during backoff period
- Adaptive rate control scheme with new CSMA mechanism provides effective media access control
  - Efficient in energy for low traffic situation

# References

1) S. Singh and C. Raghavendra, “PAMAS - power aware multi-access protocol with signalling for ad hoc networks”, *ACM Computer Communication Review*,1998.
2) A. Woo and D. Culler, “A transmission control scheme for media access in sensor networks”, *ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom) 2001*,2001.
3) P. Karn, “MACA – A New Channel Access Method for Packet Radio”, in *ARRL/CRRL Amateur Radio 9th Computer Networking Conference,* pp. 134-140, 1990

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4) V. Bhargavan, A. Demers, S. Shenkar & L. Zhang, "MACAW: A Media Access Protocol for Wireless LANs", *Proceedings ACM SIGCOMM '94,* pp. 212-225, 1994

5) Chane L. Fullmer & J.J. Garcia-Luna-Aceves, "Solutions to Hidden Terminal Problems in Wireless Networks", Proceedings *ACM SIGCOMM'97,* Cannes, France