Self-Organization in Autonomous Sensor/Actuator Networks [SelfOrg]

Dr.-Ing. Falko Dressler

Computer Networks and Communication Systems
Department of Computer Sciences
University of Erlangen-Nürnberg

http://www7.informatik.uni-erlangen.de/~dressler/
dressler@informatik.uni-erlangen.de

Overview

- **Self-Organization**
  Introduction; system management and control; principles and characteristics; natural self-organization; methods and techniques

- **Networking Aspects: Ad Hoc and Sensor Networks**
  Ad hoc and sensor networks; self-organization in sensor networks; evaluation criteria; medium access control; ad hoc routing; data-centric networking; clustering

- **Coordination and Control: Sensor and Actor Networks**
  Sensor and actor networks; coordination and synchronization; in-network operation and control; task and resource allocation

- **Bio-inspired Networking**
  Swarm intelligence; artificial immune system; cellular signaling pathways

MAC Protocols for Ad Hoc and Sensor Networks

- Principles and Classification
- MACA / MACAW
- S-MAC
- Power Control MAC

Principal Options and Difficulties

- Medium access in wireless networks is difficult mainly because of
  - Impossible (or very difficult) to send and to receive at the same time
  - Interference situation at receiver is what counts for transmission success, but can be very different to what sender can observe
  - High error rates (for signaling packets) compound the issues

- Requirements
  - As usual: high throughput, low overhead, low error rates, …
  - Additionally: energy-efficient, handle switched off devices!

Requirements for Energy-efficient MAC Protocols

- Recall
  - Transmissions are costly
  - Receiving about as expensive as transmitting
  - Idling can be cheaper but is still expensive

- Energy problems
  - ***Collisions*** – wasted effort when two packets collide
  - ***Overhearing*** – waste effort in receiving a packet destined for another node
  - ***Idle listening*** – sitting idly and trying to receive when nobody is sending
  - ***Protocol overhead***

- Always nice: Low complexity solution

Design Issues

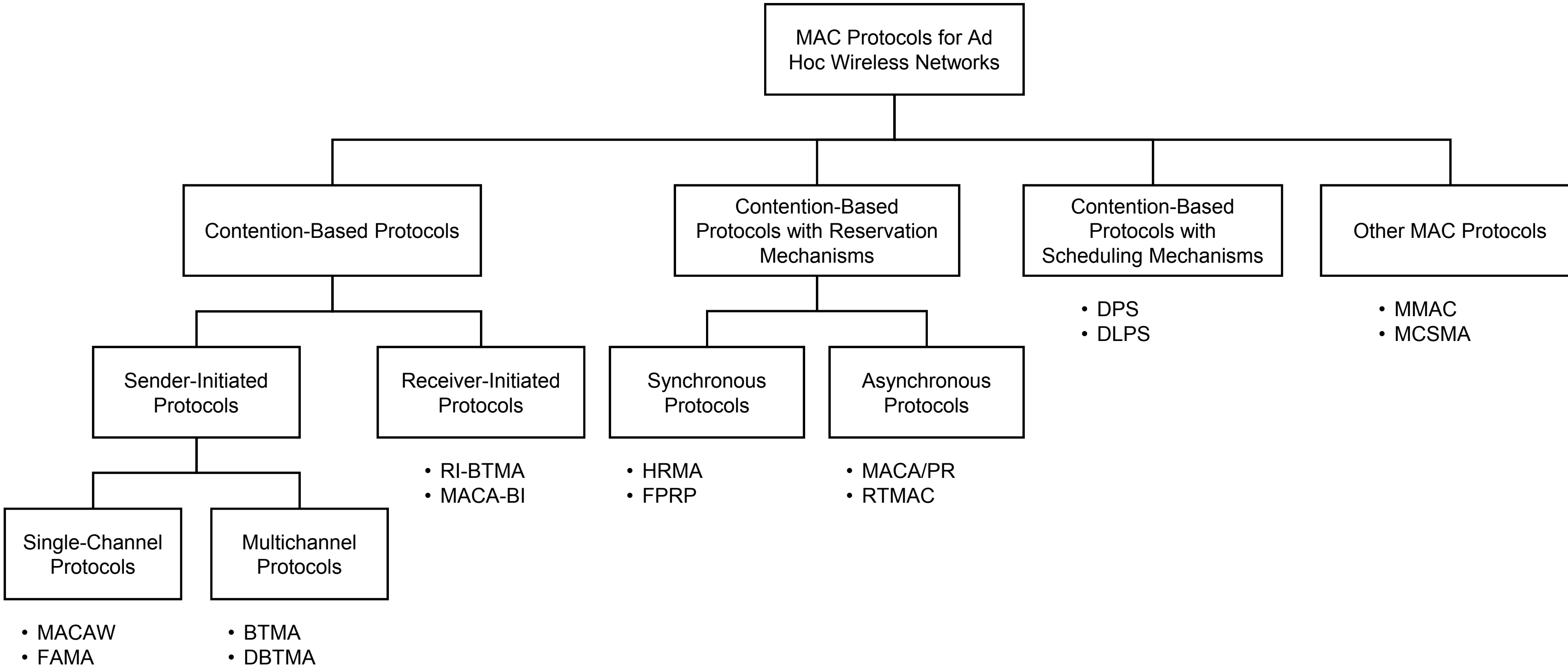
- Distributed nature/lack of central coordination
  - Nodes must be scheduled in a distributed fashion
  - Exchange of control information

    → control packets must not consume too much of network bandwidth

- Mobility of nodes
  - Very important factor affecting the performance (throughput) of the protocol
  - Bandwidth reservations or control information exchanged may end up being of no use if the node mobility is very high
  - Protocol design must take this mobility factor into consideration

    → system performance should not significantly affected due to node mobility

Classification of MAC Protocols



Classification of MAC Protocols

- ***Contention-based protocols***
  - No *a priori* resource reservation
  - Whenever a packet should be transmitted, the node contends with its neighbors for access to the shared channel
  - Cannot provide QoS guarantees

  - *Sender-initiated protocols* – packet transmissions are initiated by the sender node
    - Single-channel sender-initiated protocols – the total bandwidth is used as it is, without being divided
    - Multi-channel sender-initiated protocols – available bandwidth is divided into multiple channels; this enabled several nodes to simultaneously transmit data

  - *Receiver-initiated protocols* – the receiver node initiates the contention resolution protocol

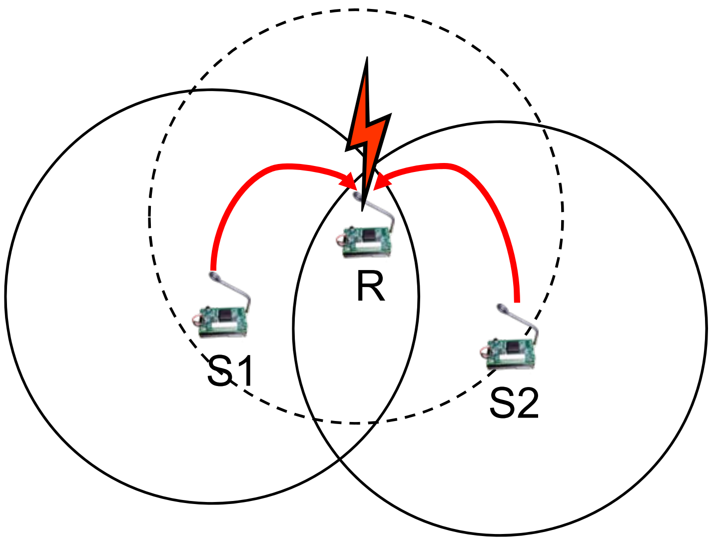
Classification of MAC Protocols

- ***Contention-based protocols with reservation mechanisms***
  - Support for real-time traffic using QoS guarantees
  - Using mechanisms for reserving bandwidth *a priori*
  - Synchronous protocols – require time synchronization among all nodes in the network → global time synchronization is generally difficult to achieve
  - Asynchronous protocols – do not require any global time synchronization, usually rely on relative time information for effecting reservations
- ***Contention-based protocols with scheduling mechanisms***
  - Focus on packet scheduling at nodes and also scheduling nodes for access to the channel

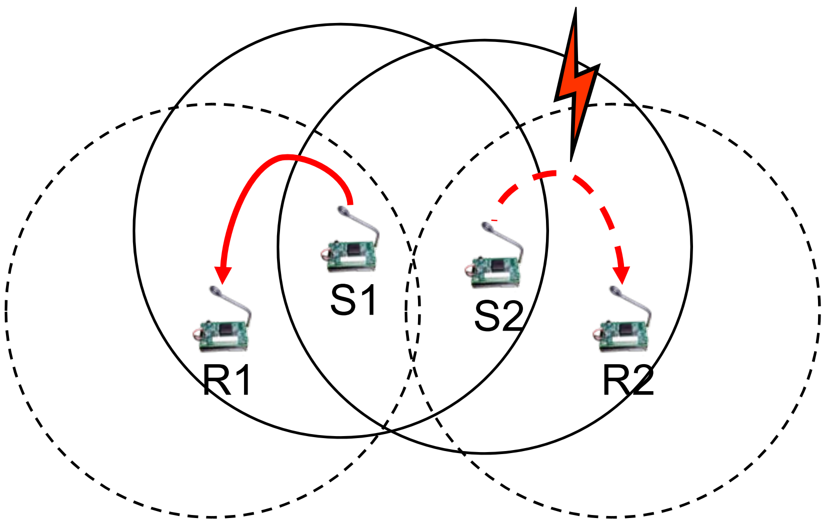
    → requirement for fair treatment and no starvation
  - Used to enforce priorities among flows
  - Sometimes battery characteristics, such as remaining battery power, are considered while scheduling nodes for access to the channel

Contention-based Protocols: Main Problems

- Hidden and exposed terminals - unique problem in wireless networks
  - ***Hidden terminal problem*** – collision of packets due to the simultaneous transmission of those nodes that are not within the direct transmission range of the sender but are within the transmission range of the receiver
  - ***Exposed terminal problem*** – inability of a node, which is blocked due to transmission by a nearby transmitting node, to transmit to another node



Hidden terminal



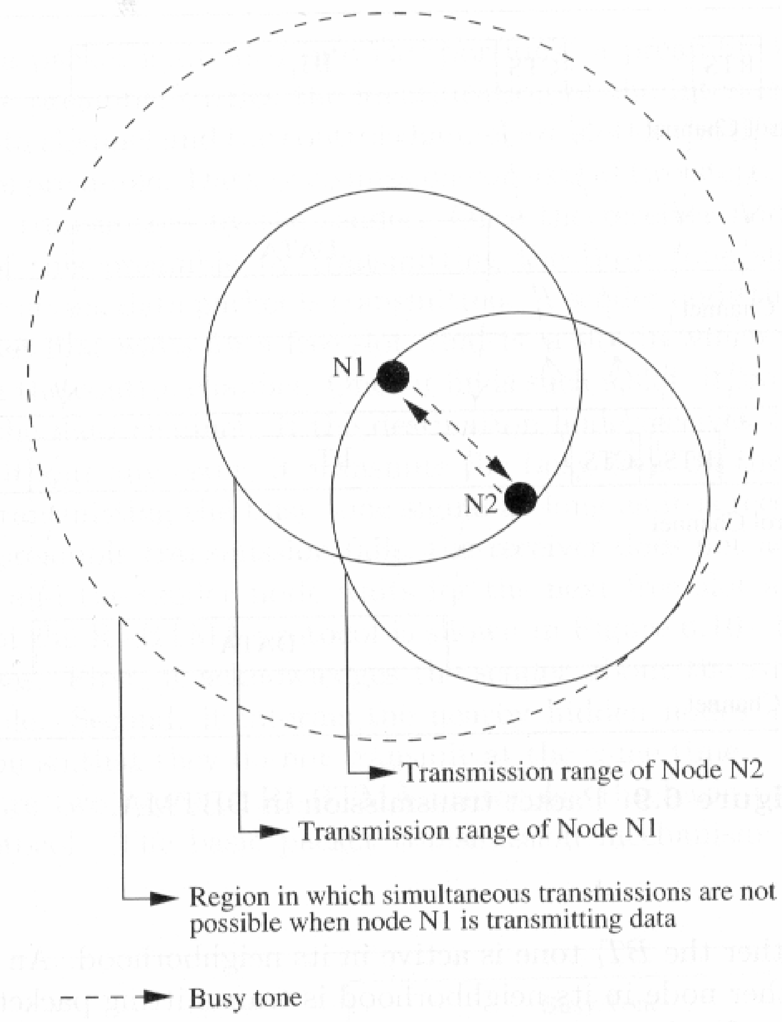
Exposed terminal

Main Options to Shut Up Senders

- Receiver informs potential interferers ***while*** a reception is on-going
  - By sending out a signal indicating just that
  - Problem: Cannot use same channel on which actual reception takes place
  - → Use separate channel for signaling
  - ***Busy tone*** protocol
- Receiver informs potential interferers ***before*** a reception is on-going
  - Can use same channel
  - Receiver itself needs to be informed, by sender, about impending transmission
  - Potential interferers need to be aware of such information
  - ***MACA*** protocol

BTMA – Busy Tone Multiple Access

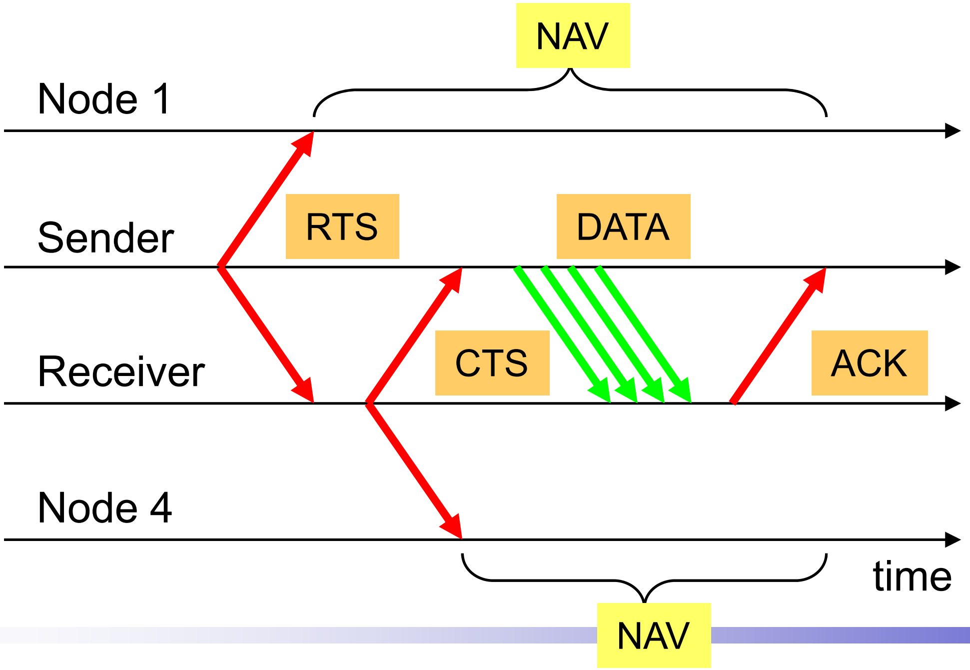
- The transmission channel is split into data and control channel
- General behavior
  - When a node wants to transmit a packet, it senses the channel to check whether the busy tone is active
  - If not, it turns on the busy tone signal and starts transmission
- Problem: very poor bandwidth utilization



MACA – Multiple Access Collision Avoidance

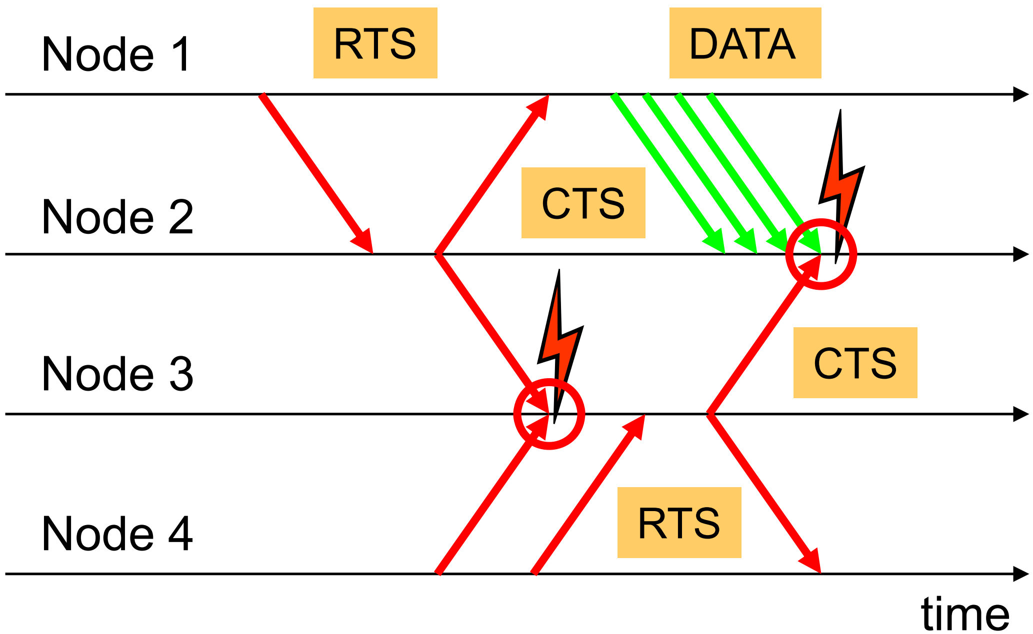
- Use of additional signaling packets
  - Sender asks receiver whether it is able to receive a transmission - ***Request to Send (RTS)***
  - Receiver agrees, sends out a ***Clear to Send*** **(*CTS*)**
  - Sender sends, receiver acks

- Potential interferers overhear RTS/CTS
  - RTS/CTS packets carry the expected duration of the data transmission
  - Store this information in a ***Network Allocation Vector (NAV)***



MACA – Problems

- RTS/CTS ameliorate, but do not solve hidden/exposed terminal problems



MACA – continued

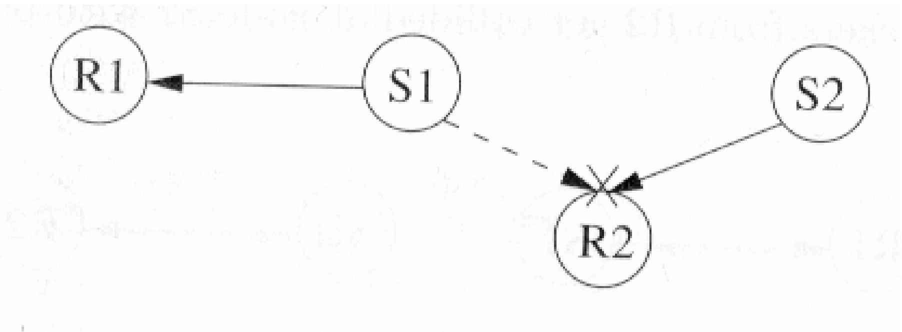
- Collision handling
  - If a packet is lost (collision), the node uses the binary exponential back-off (BEB) algorithm to back off for a random time interval before retrying
  - Each time a collision is detected, the node doubles its maximum back-off window

- Idle listening: need to sense carrier for RTS or CTS packets
  - In some form shared by many CSMA variants; but e.g. not by busy tones
  - Simple sleeping will break the protocol

→ ***MACA protocol*** (used e.g. in ***IEEE 802.11***)

MACAW Protocol

- The binary back-off mechanism can lead to starvation of flows
- Example
  - S1 and S2 are generating a high volume of traffic
  - If one node (S1) starts sending, the packets transmitted by S2 get collided
    → S2 backs off and increases its back-off window
    → the probability of node S2 acquiring the channel keeps decreasing



- Solution
  - Each packet carries the current back-off window of the sender
  - A node receiving this packet copies this value into its back-off counter

MACAW Protocol

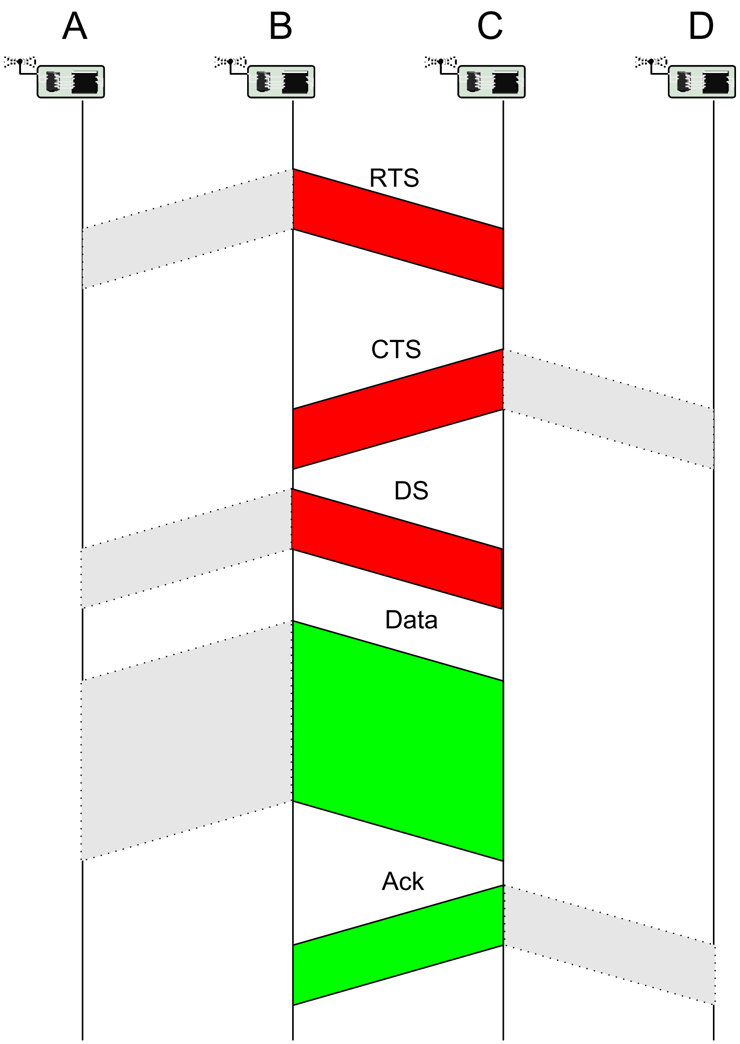
- Large variations in the back-off values
  - the back-off window increases very rapidly and is reset after each successful transmission
- Solution
  - multiplicative increase and linear decrease (MILD) back-off mechanism (increase by factor 1.5)

- Fairness
  - MACA: per node fairness
  - MACAW: per flow fairness (one back-off value per flow)

- Error detection
  - Originally moved to the transport layer
  - Slow and introducing much overhead
- Solution
  - New control packet type: data-sending (DS)

MACAW Protocol

- Exposed terminal problem
  - RTS/CTS mechanism does not solves the exposed terminal problem
- Solution
  - New control packet type: data-sending (DS), a small packet (30 Byte) containing information such as the duration of the forthcoming data transmission



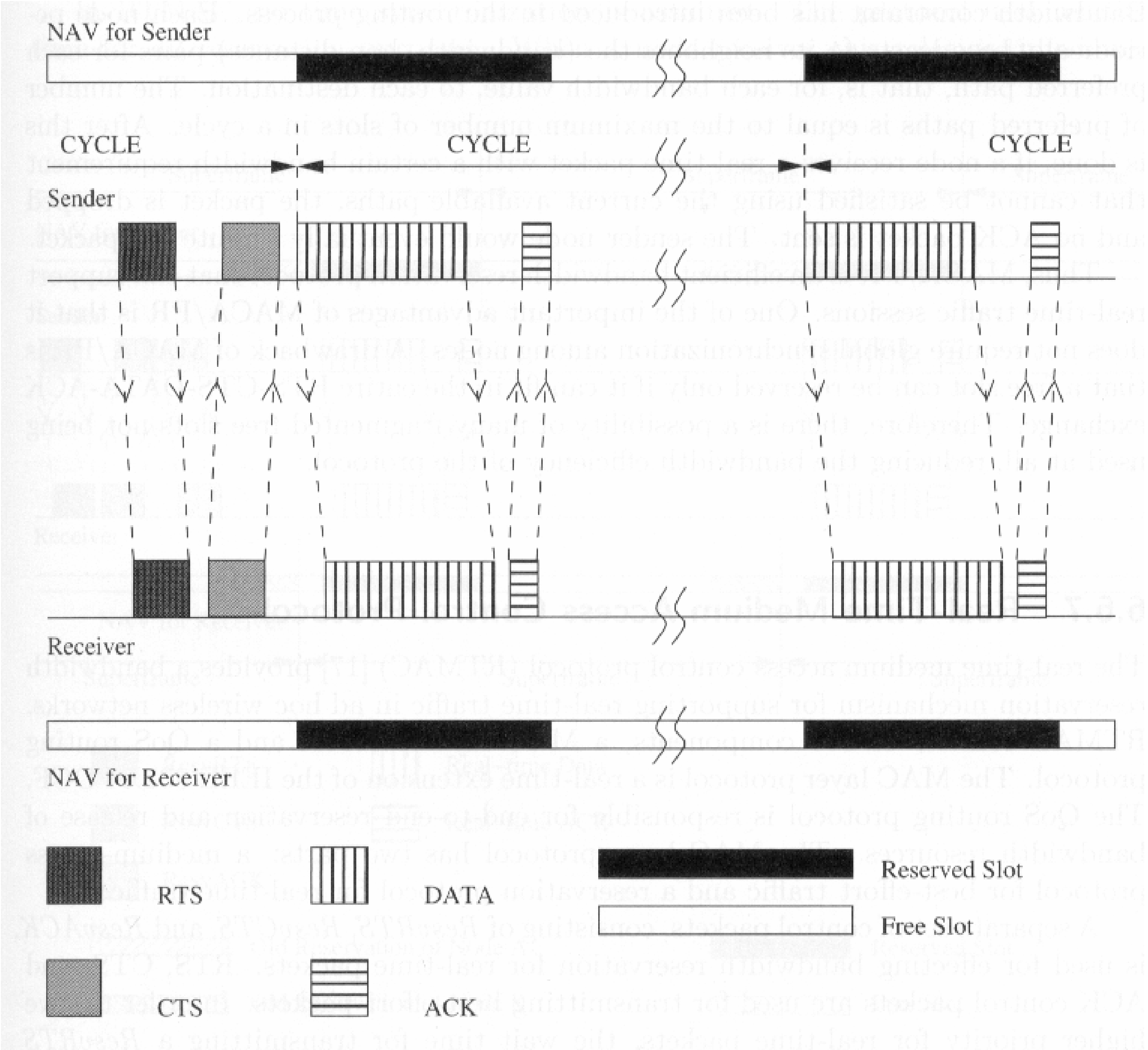
Contention-Based Protocols with Reservation

- MACA/PR – MACA with Piggy-Backed Reservation
- Multi-hop routing protocol based on MACAW
- Main components
  - MAC protocol
  - Reservation protocol
  - QoS routing protocol
- Differentiation of real-time and best-effort packets
- General behavior
  - ***Slotted mechanisms***
  - Maintenance of a reservation table (RT) at each node that records all the reserved transmit and receive slots / windows of all nodes within its transmission range
  - Network allocation vectors (NAV) for cycles
  - Destination sequenced distance vector (DSDV) used for routing

→ TDM-like system for real-time traffic

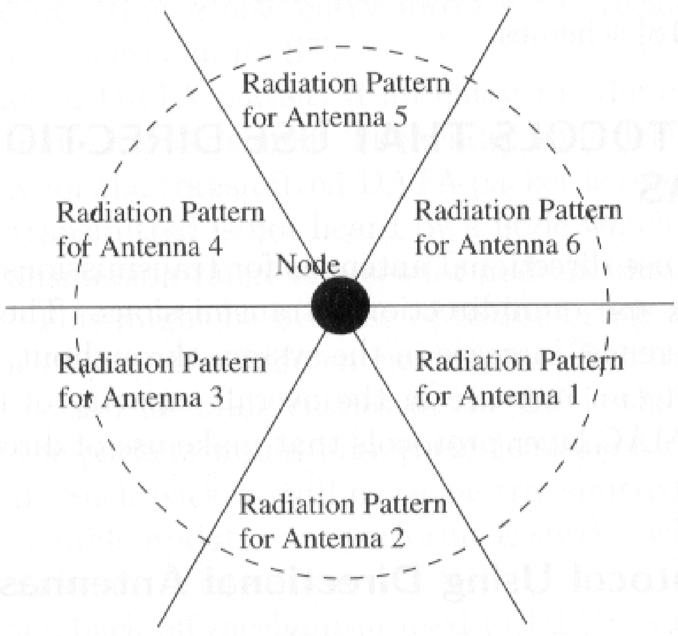
→ Best-effort traffic using MACAW in free slots

MACA/PR Protocol



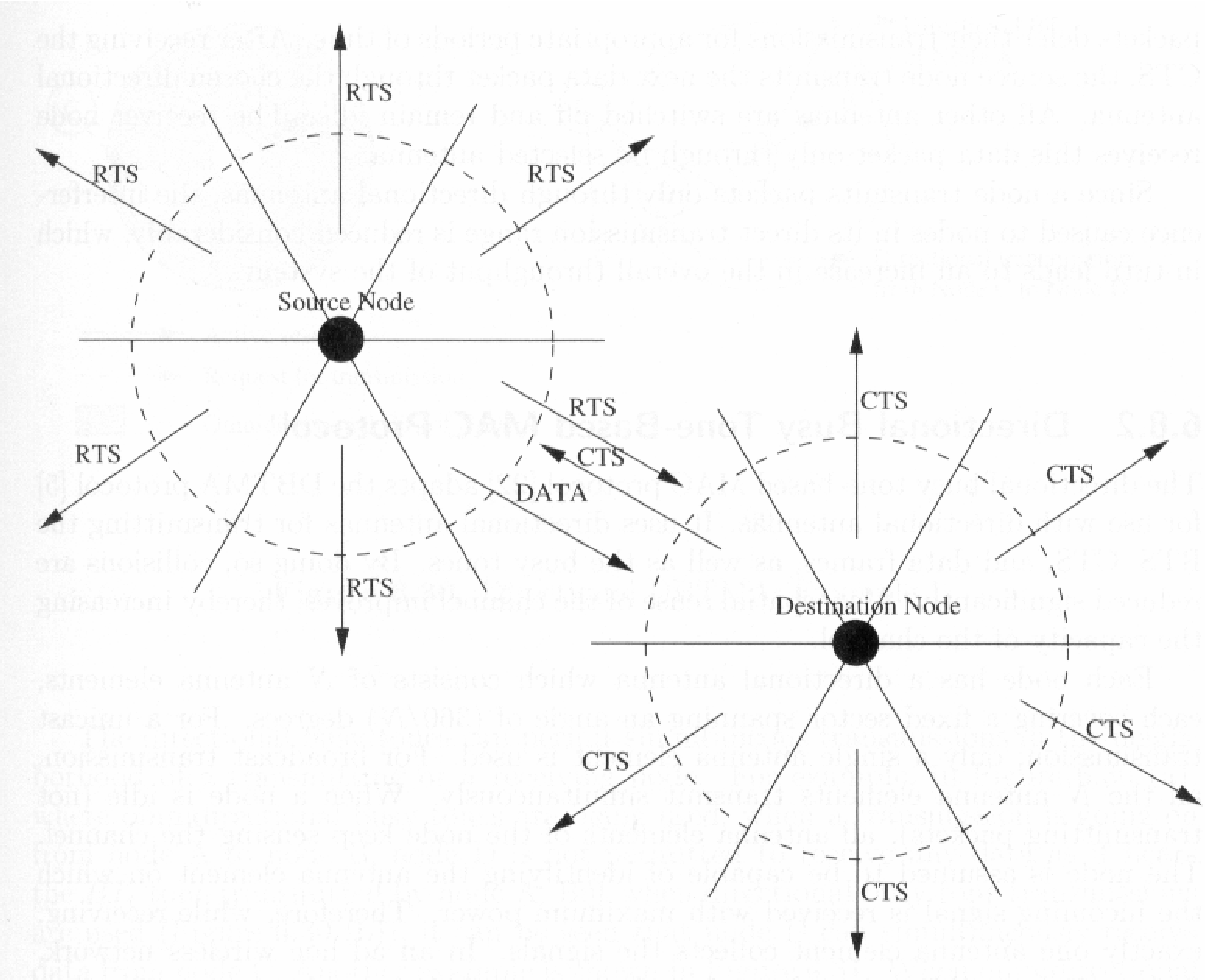
MAC Protocol Using Directed Antennas

- Properties
  - One receiver per node, which can transmit and receive only one packet at any given time
  - Each transceiver is equipped with M directional antennas
  - Each antenna has a conical radiation pattern spanning an angle of $2\pi/M$ radians
  - Basic RTS/CTS scheme (as used in MACA)



Node with 6 antennas (M=6)

MAC Protocol Using Directed Antennas



Power-Control MAC Protocol (PCM)

- Properties
  - RTS/CTS are transmitted with maximum power p_{max}
  - RTS-CTS handshake to determine the required transmission power $p_{desired}$
  - RTS is received at the receiver with a signal level p_r

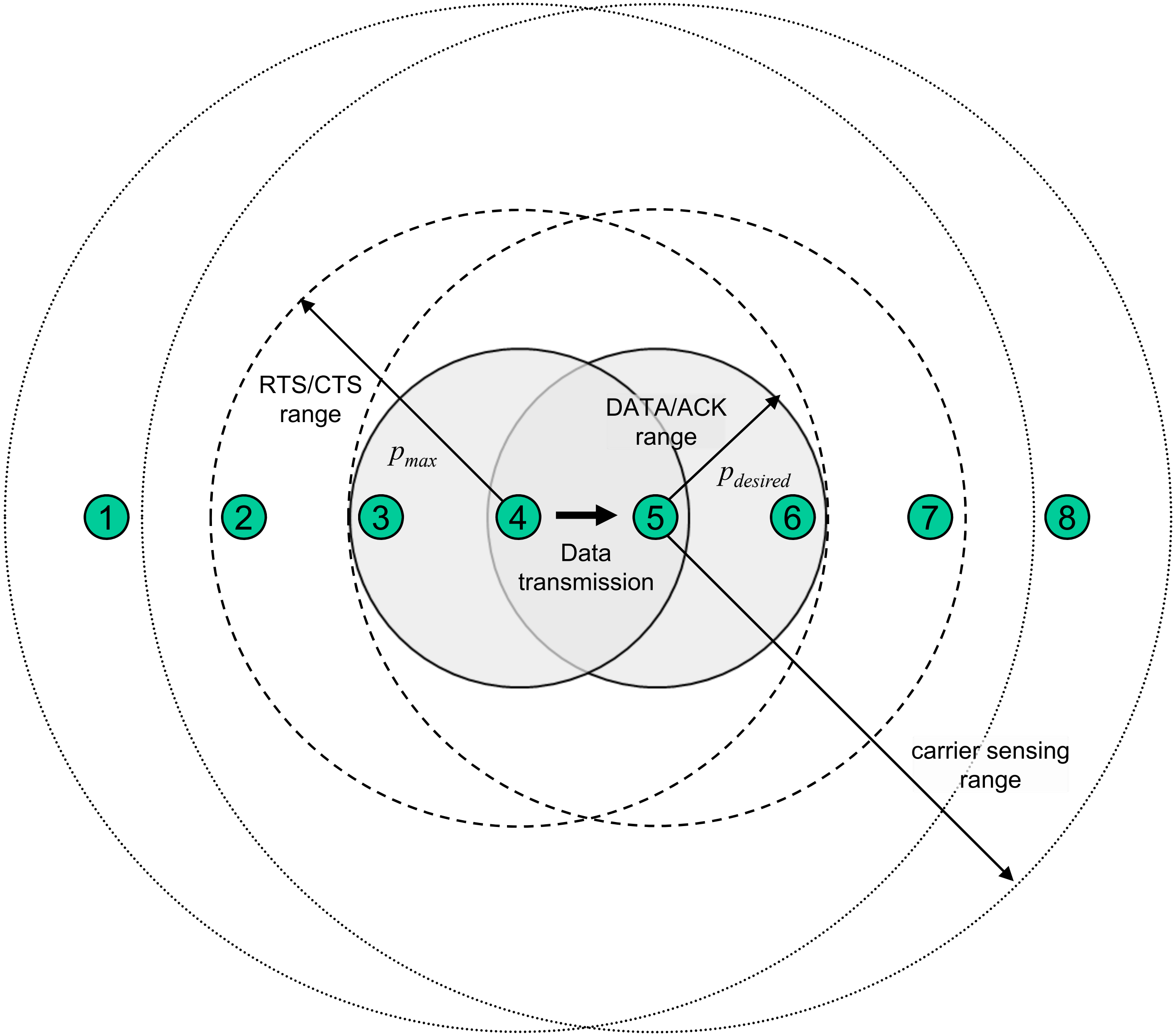
- Calculation of $p_{desired}$
  - Rx_{thresh} is the minimum necessary received signal strength
  - c … constant

known in advance

$$p_{desired} = \frac{p_{max}}{p_r} Rx_{thresh} * c$$

measured

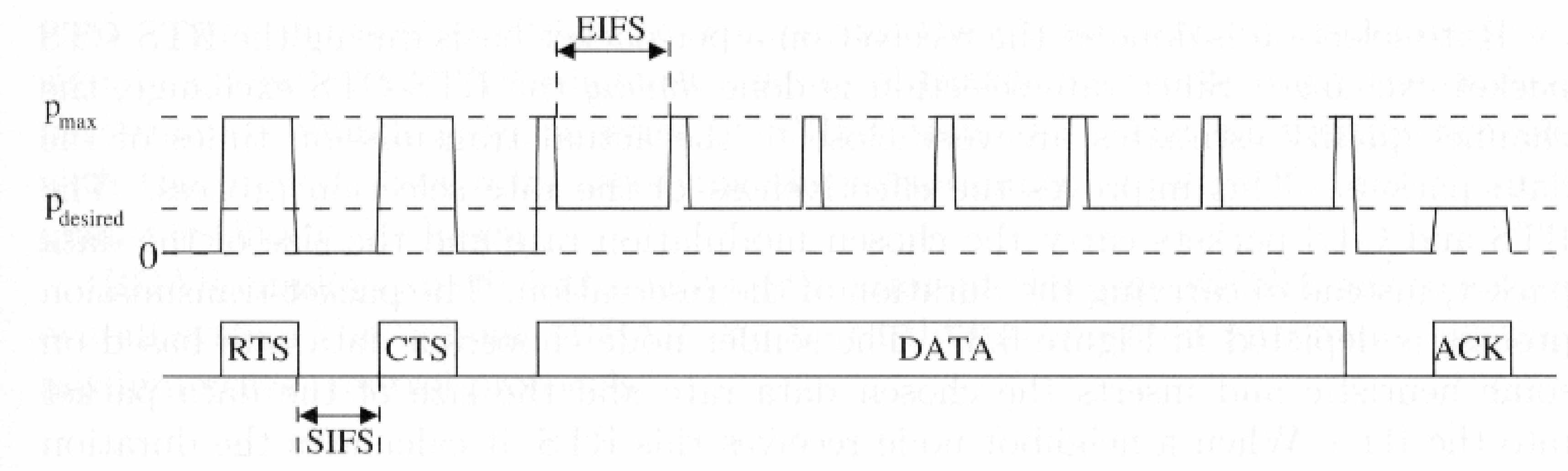
Power-Control MAC Protocol



Power-Control MAC Protocol

- Properties
  - Adaptation to changing conditions, e.g. caused by mobility
  - Instantaneous check and re-calculation of the necessary transmission power $p_{desired}$

- Collision avoidance
  - Periodic bursts (after each EIFS) using p_{max} to notify neighbors about ongoing transmissions

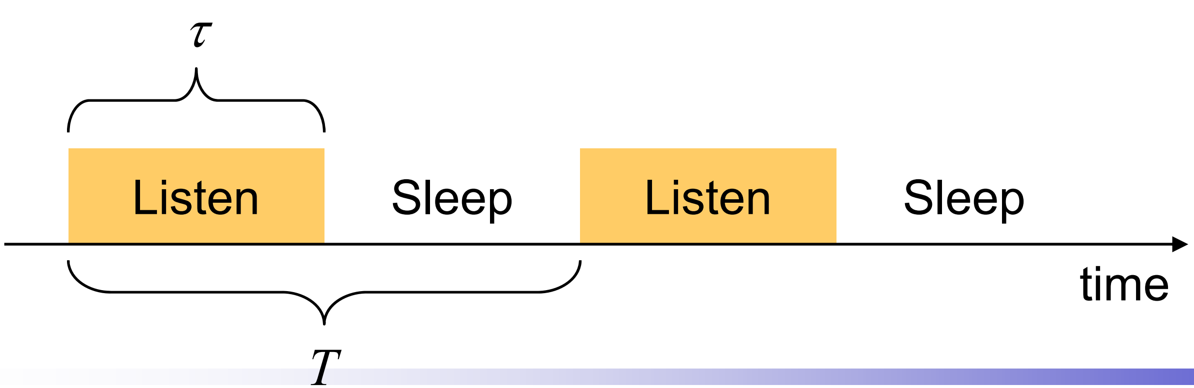


Sensor-MAC (S-MAC)

- Primary goal
  - To retain ***flexibility*** of contention-based protocols while ***improving energy efficiency*** in multi-hop networks

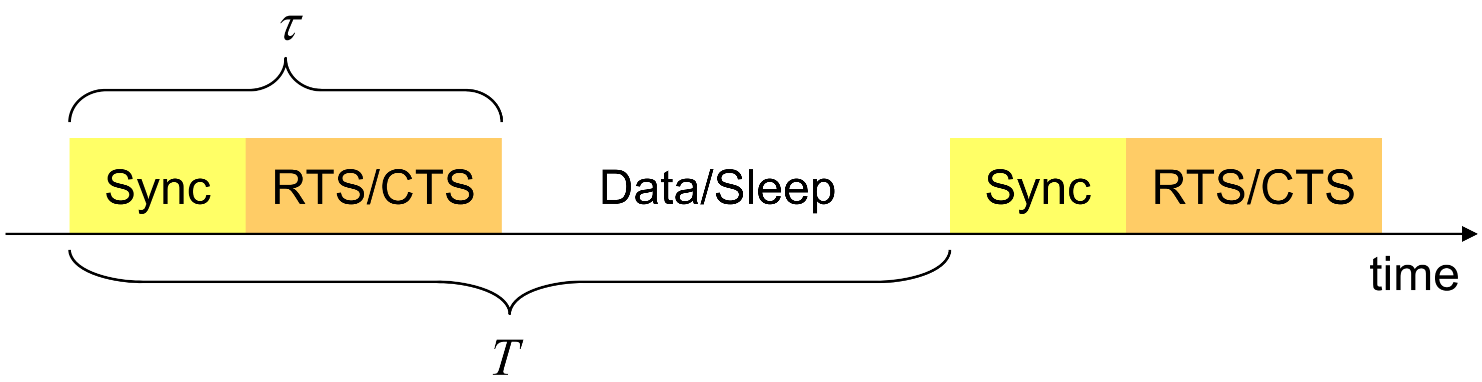
    (MACA's idle listening is particularly unsuitable if average data rate is low - most of the time, nothing happens)

- Idea: Switch nodes off, ensure that neighboring nodes turn on simultaneously to allow packet exchange (rendez-vous)
  - Only in these ***active periods***, packet exchanges happen
  - Need to also exchange wakeup schedule between neighbors
  - When awake, essentially perform RTS/CTS
  - Coarse-grained sleep/wakeup cycle with duty cycle $D = \tau / T$



S-MAC – Scheduling

- Use SYNC, RTS, CTS phases



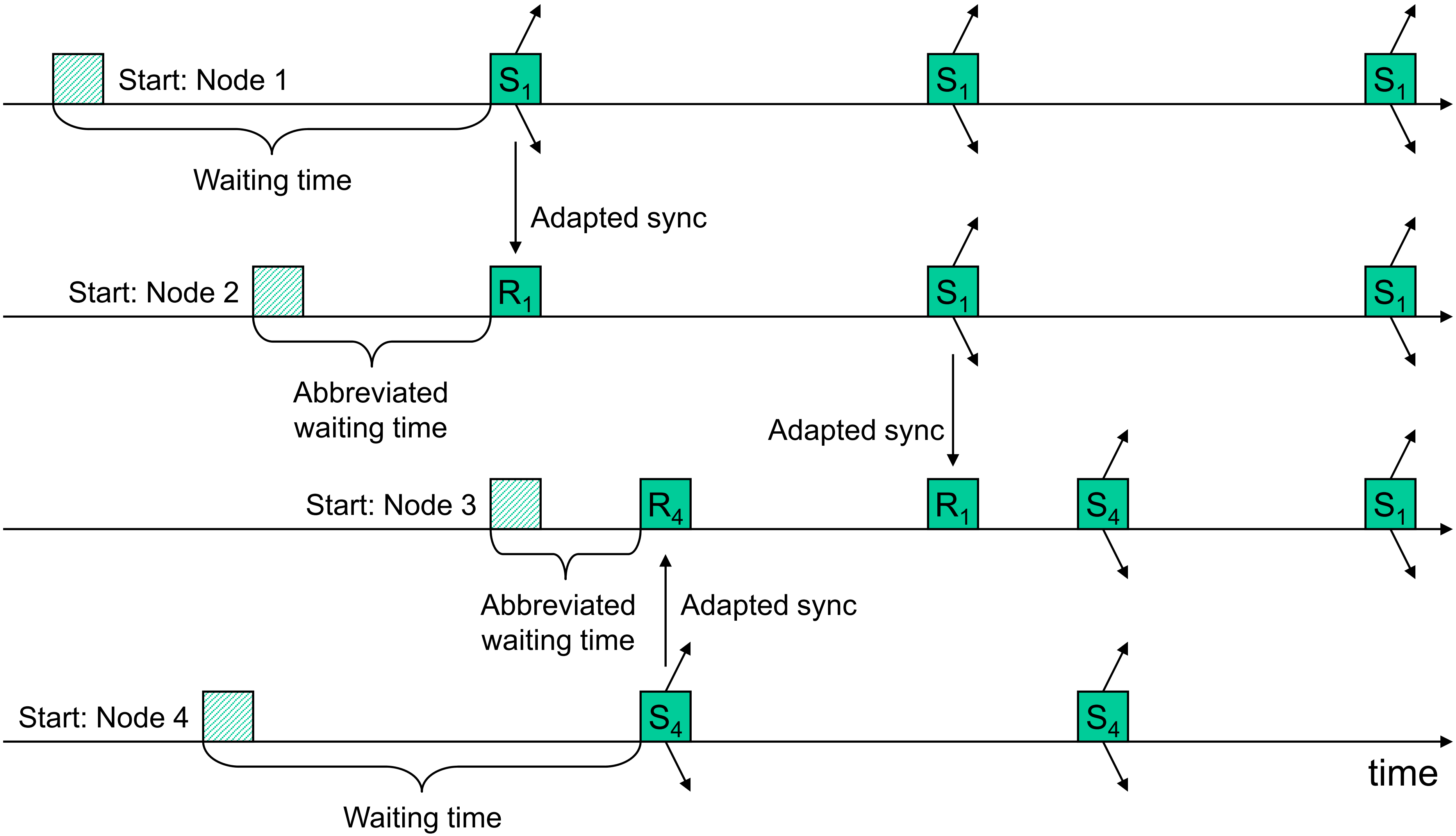
- Scheduling
  - Low-duty-cycle operation (1-10%)
  - All nodes choose their own listen/sleep schedules
  - These schedules are shared with their neighbors to make communication possible between all nodes
  - Each node periodically broadcasts its schedule in a SYNC packet, which provides simple time synchronization
  - To reduce overhead, S-MAC encourages neighboring nodes to adopt identical schedules

S-MAC – Synchronization

- Nodes try to pick up schedule synchronization from neighboring nodes
- If no neighbor found, nodes pick some schedule to start with
- If additional nodes join, some node might learn about two different schedules from different nodes
  - “Synchronized islands”
- To bridge this gap, it has to follow both schemes

- Complete algorithm
  1. Listen for “waiting time” (at least one complete busy/sleep cycle) for SYNC messages – if nothing happens, the node chooses its own schedule
  2. If a node receives a SYNC ***before*** setting up its own schedule, it takes over the received schedule
  3. If a node receives a SYNC ***after*** setting up its own schedule, its adopts both schedules to bridge two islands

S-MAC – Synchronization

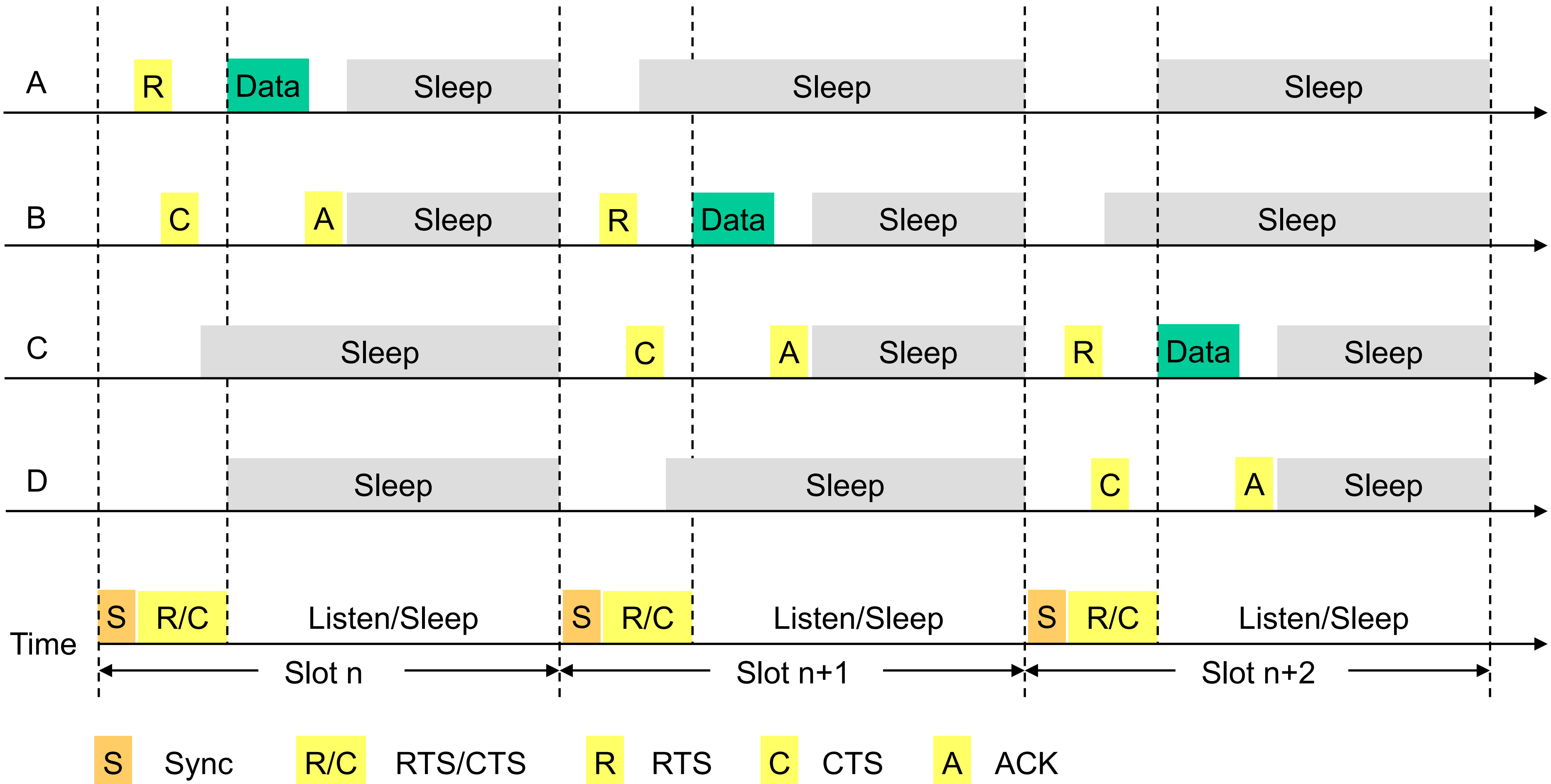


S-MAC – Performance Aspects

- Standard S-MAC
  - Energy saving through periodic sleep
  - Depending on the duty cycle, the end-to-end performance is increasing as
    - Per busy period, exactly ***one*** packet can be transmitted within a common radio range
    - If rather short packets need to be transmitted either long sleep intervals must be prevented (energy wastage) or the per-hop delay is further increased
- Improved S-MAC
  - ***Adaptive listening*** allows additional energy savings (nodes wake up immediately after the exchange completes for immediate contention for the channel)

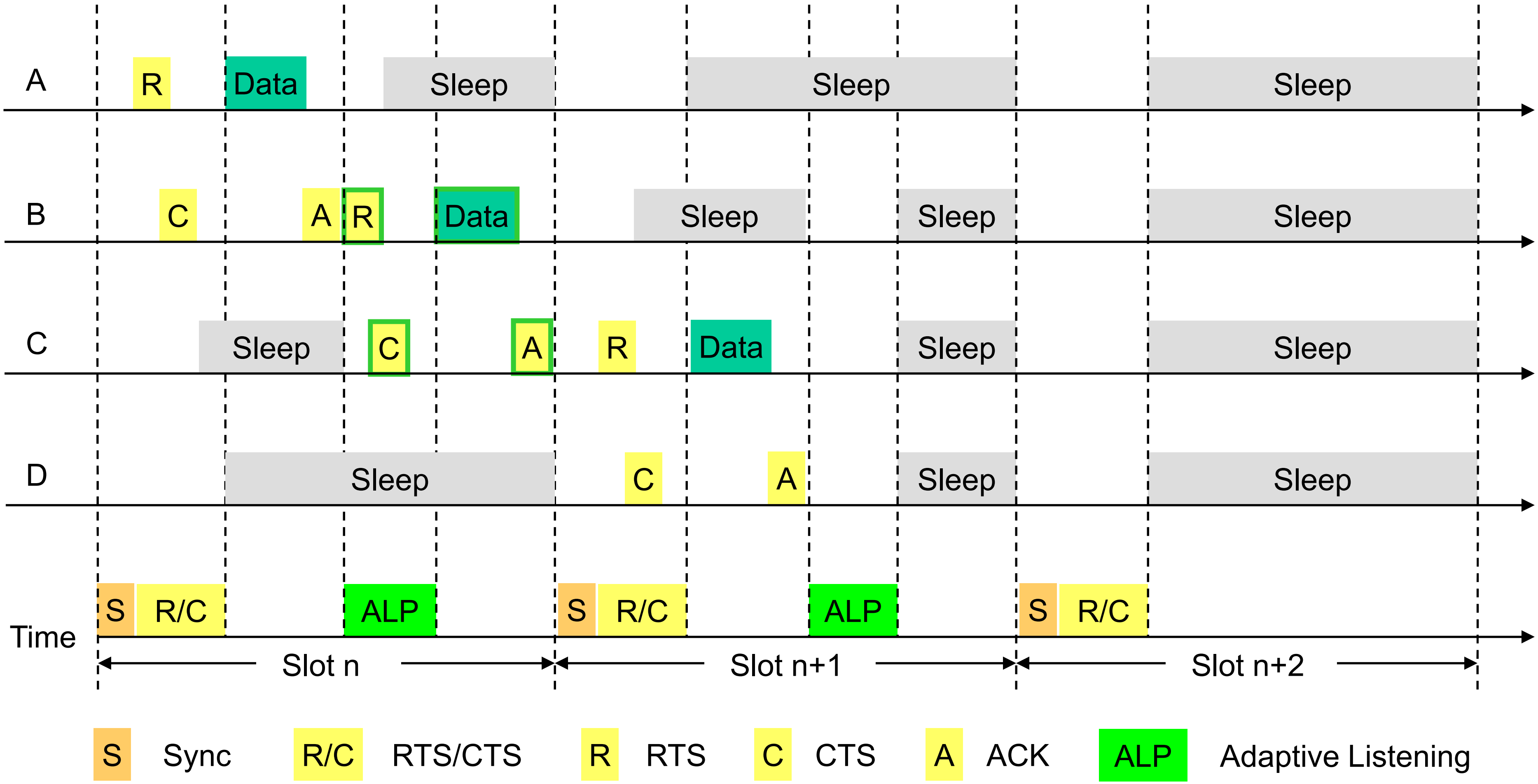
S-MAC – Performance Aspects

- Standard S-MAC w/o adaptive listening



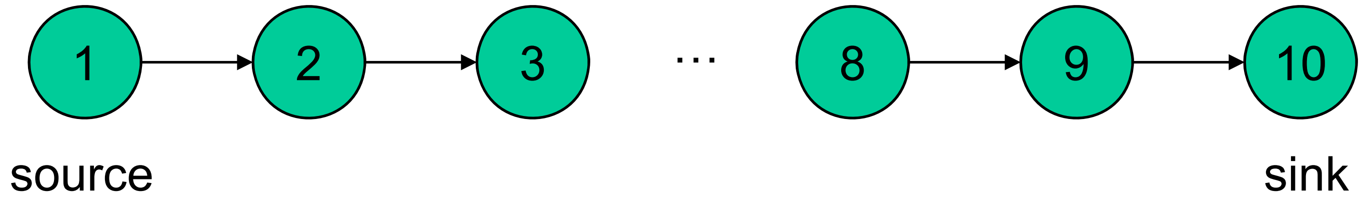
S-MAC – Performance Aspects

- Improved S-MAC w/ adaptive listening



S-MAC – Performance Evaluation

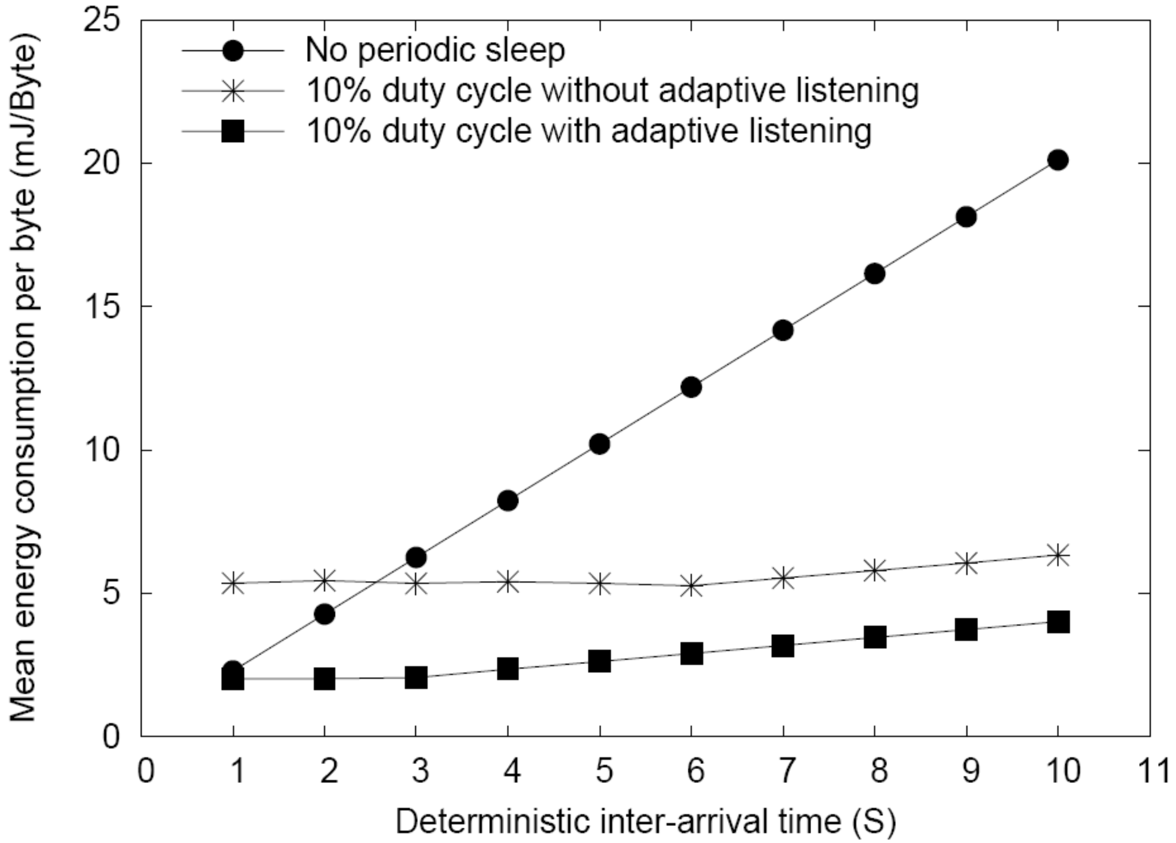
- Experimental setup
  - Ten nodes in a line



- Analyzed S-MAC modes
  - Mode1: no periodic sleep (= MACA)
  - Mode2: 10% duty cycle, w/o adaptive listening (= standard S-MAC)
  - Mode3: 10% duty cycle, w/ adaptive listening (= improved S-MAC)

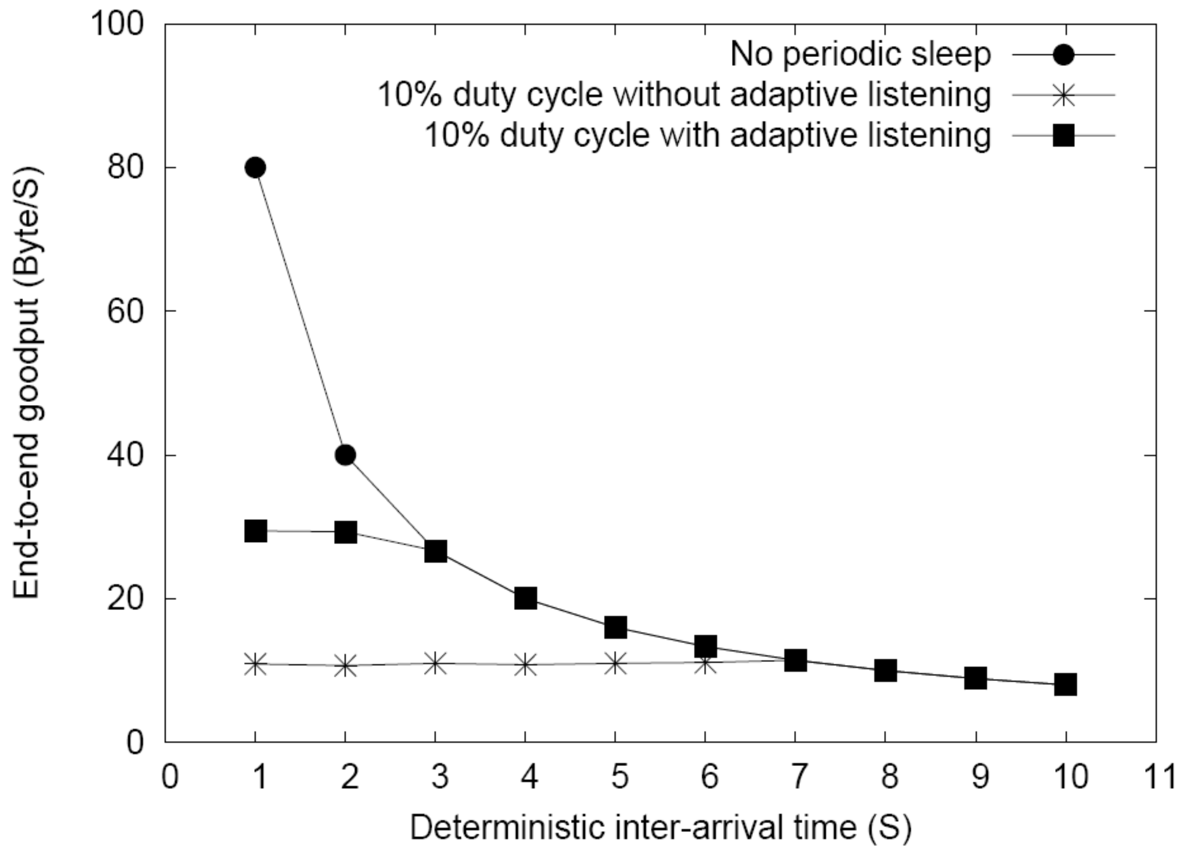
S-MAC – Performance Evaluation

- *Mean energy consumption per byte* – the total energy consumed by all nodes divided by the total number of bytes received by the sink



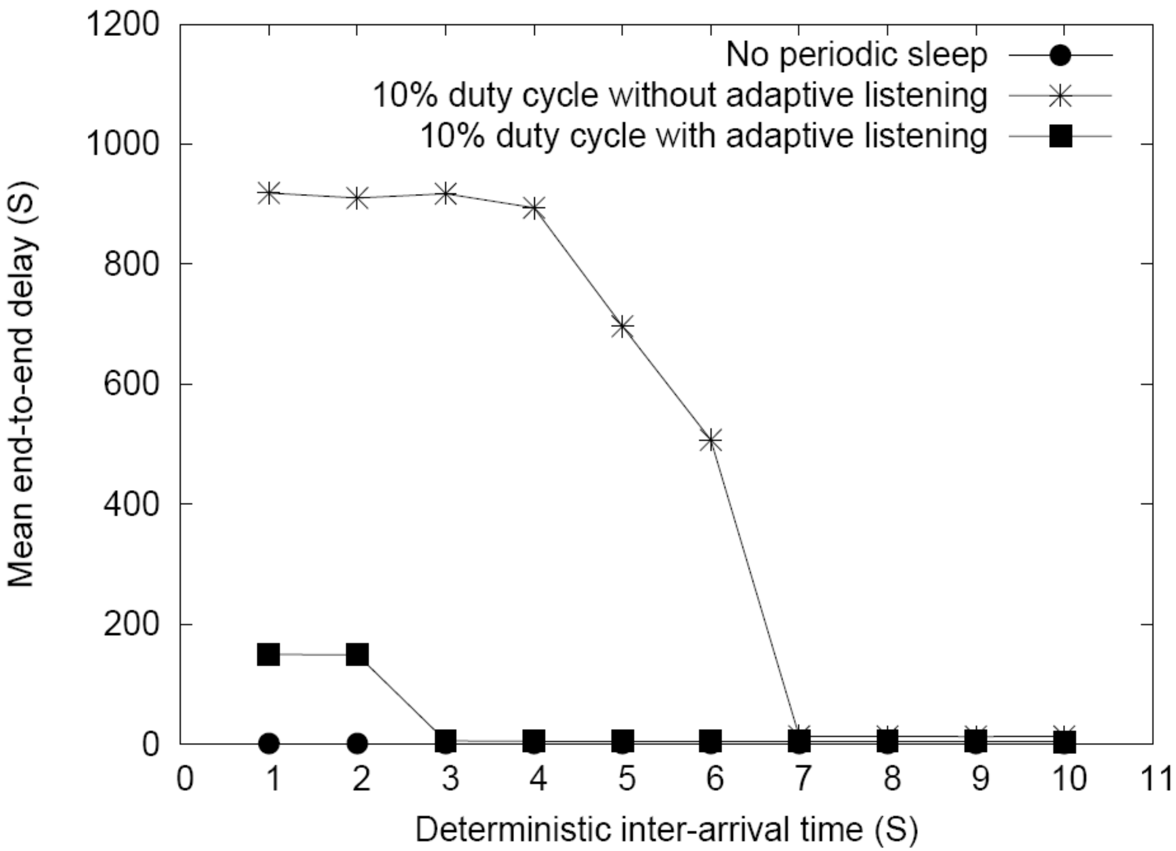
S-MAC – Performance Evaluation

- *End-to-end goodput* – the total number of bytes received by the sink divided by the time from the first packet generated at the source until the last packet was received by the sink



S-MAC – Performance Evaluation

- *Mean end-to-end delay* – the sum of all end-to-end delays divided by the total number of packets



Summary (what do I need to know)

- Well-established MAC protocols in the ad hoc domain
  - MACA / MACAW / 802.11
  - Similar solutions for hidden/exposed terminal problem

- Applicability for wireless sensor networks
  - ***Scalability*** – MACA/802.11 needs a global sync; adaptive solutions are demanded
  - ***Energy efficiency*** - limited sleeping time in MACA/802.11; low duty cycles and/or adjustments of the transmission power are needed

- Specific developments
  - ***PCM*** – well-controlled transmission power, can be combined with any RTS/CTS based MAC protocol
  - ***S-MAC*** – supports multiple schedules and long sleep cycles with adaptive listening

References

- V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A Media Access Protocol for Wireless LAN's," Proceedings of ACM SIGCOMM'94, London, UK, September 1994, pp. 212-225.
- P. Karn, "MACA: a new channel access method for packet radio," Proceedings of ARRL/CRRL Amateur Radio 9th Computer Networking Conference, London, Ontario, Canada, 1990, pp. 134-140.
- IEEE, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification," IEEE Std. 802.11-1999 edition, 1999.
- E.-S. Jung and N. Vaidya, "A Power Control MAC Protocol for Ad Hoc Networks," Proceedings of ACM/IEEE MobiCom, September 2002.
- W. Ye, J. Heidemann, and D. Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Networks," Proceedings of 21st International Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM), vol. 3, New York, NY, USA, June 2002, pp. 1567-1576.
- W. Ye, J. Heidemann, and D. Estrin, "Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks," *IEEE/ACM Transactions on Networking (TON)*, vol. 12 (3), pp. 493-506, June 2004.
- F. Chen, F. Dressler, and A. Heindl, "End-to-End Performance Characteristics in Energy-Aware Wireless Sensor Networks," Proceedings of Third ACM International Workshop on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (ACM PE-WASUN'06), Torremolinos, Malaga, Spain, October 2006, pp. 41-47.