Lecture 7 Overview

- Last Lecture
  - Introduction to wireless sensor networks (WSNs)
- This Lecture
  - Routing & MAC protocol design in WSNs
  - Source: lecture note
- Next Lecture
  - Data Center Networking
  - Source: lecture note

Roadmap

- Routing protocols for WSNs
  - Design challenges
  - Energy-aware routing
  - Hierarchical routing
  - Geographic routing
  - Graph routing
- Routing protocol design in Contiki
  - Communication architecture in Contiki
  - Rime communication stack
- MAC protocols for WSNs
  - Design challenges
  - Existing MAC protocols

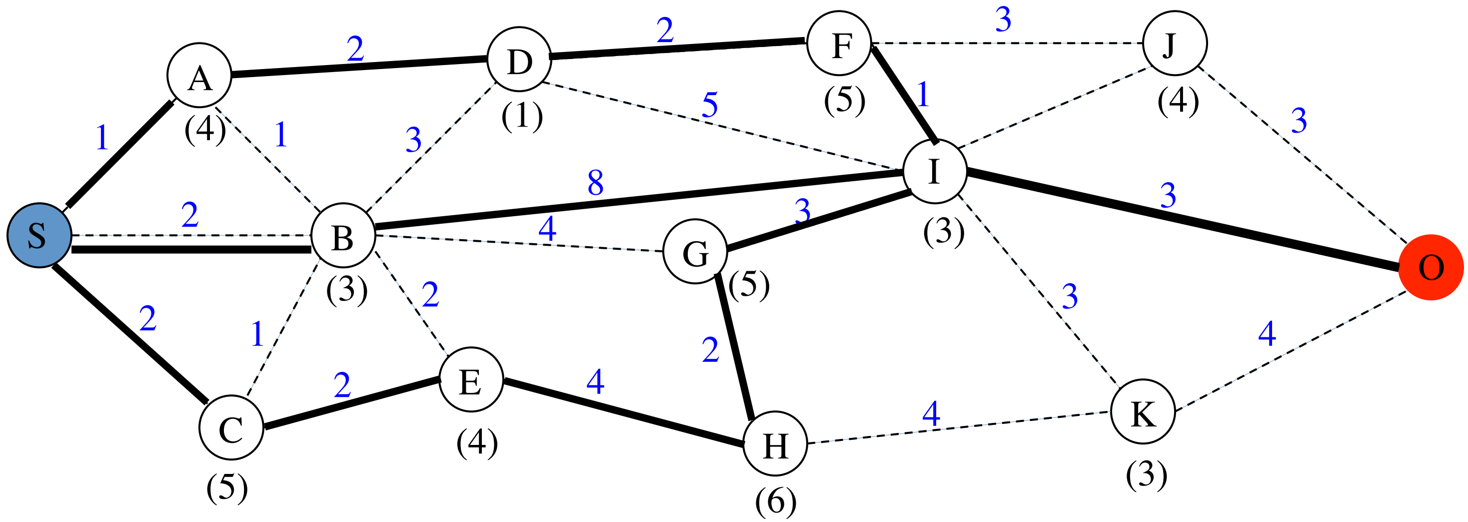
Routing in WSNs

- What is routing? Why do we need routing?
- Internet (TCP/IP)
  - Routing tables (often large)
  - Automatic update
- WSNs
  - Large number of nodes (scalability)
  - Modest storage (memory efficiency)
  - Limited computation capability (simple routing)
  - Powered by battery (energy-efficient routing)
  - High data redundancy (data aggregation)

Routing Metrics

- Hop-count
- Energy
  - Minimum energy consumption per packet
  - Minimize variance in node power levels
  - Maximum time to network partition
- Quality of Service
  - Latency
  - Throughput
  - Reliability (packet loss)
    - ETX metric
- Location-based
  - Progress
  - Advance

Energy-efficient routing



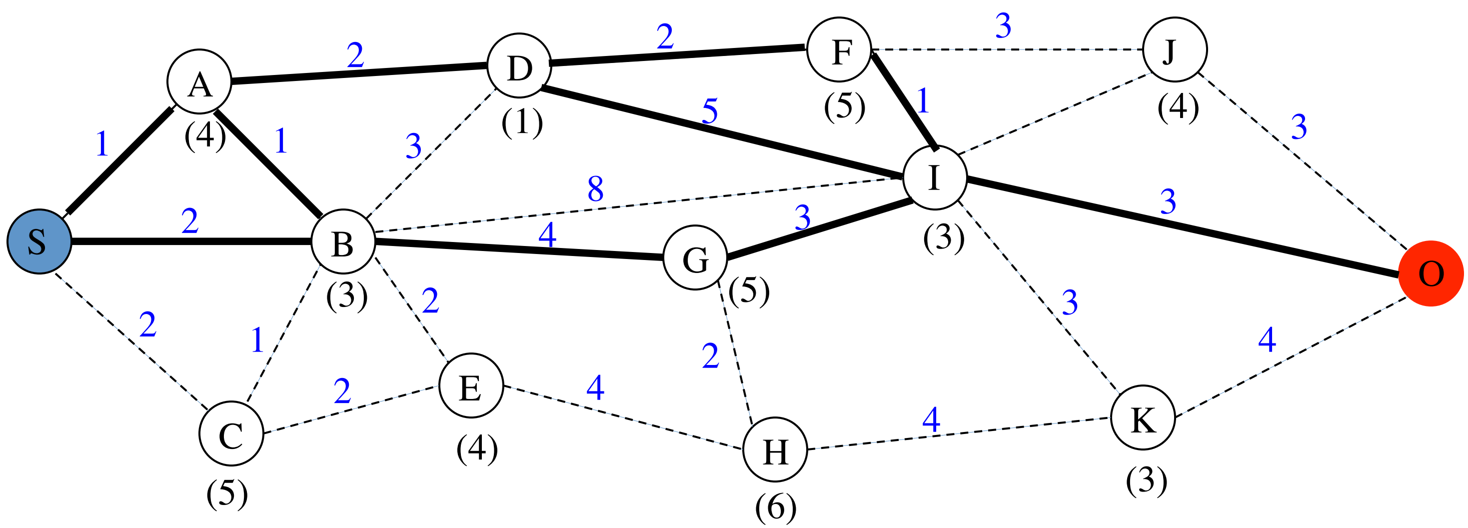
- Number along links: energy for transmission over link
- Number in parentheses: remaining energy capacity

- Minimum hop: S-B-I-O (13)
- Minimum energy: S-A-D-F-I-O (9)
- Maximum minimum residual energy: S-C-E-H-G-I-O (16)

Energy-efficient routing (cont.)

- Max-min zPmin (ACM Sigmobile 2001)
- Two extremes
  - Compute a path with minimal energy consumption Pmin
  - Computer a path that maximizes the minimal residual power
- Tradeoff in Max-min zPmin
  - Consume at most zPmin ($z \geq 1$)
  - Maximize the minimal residual power

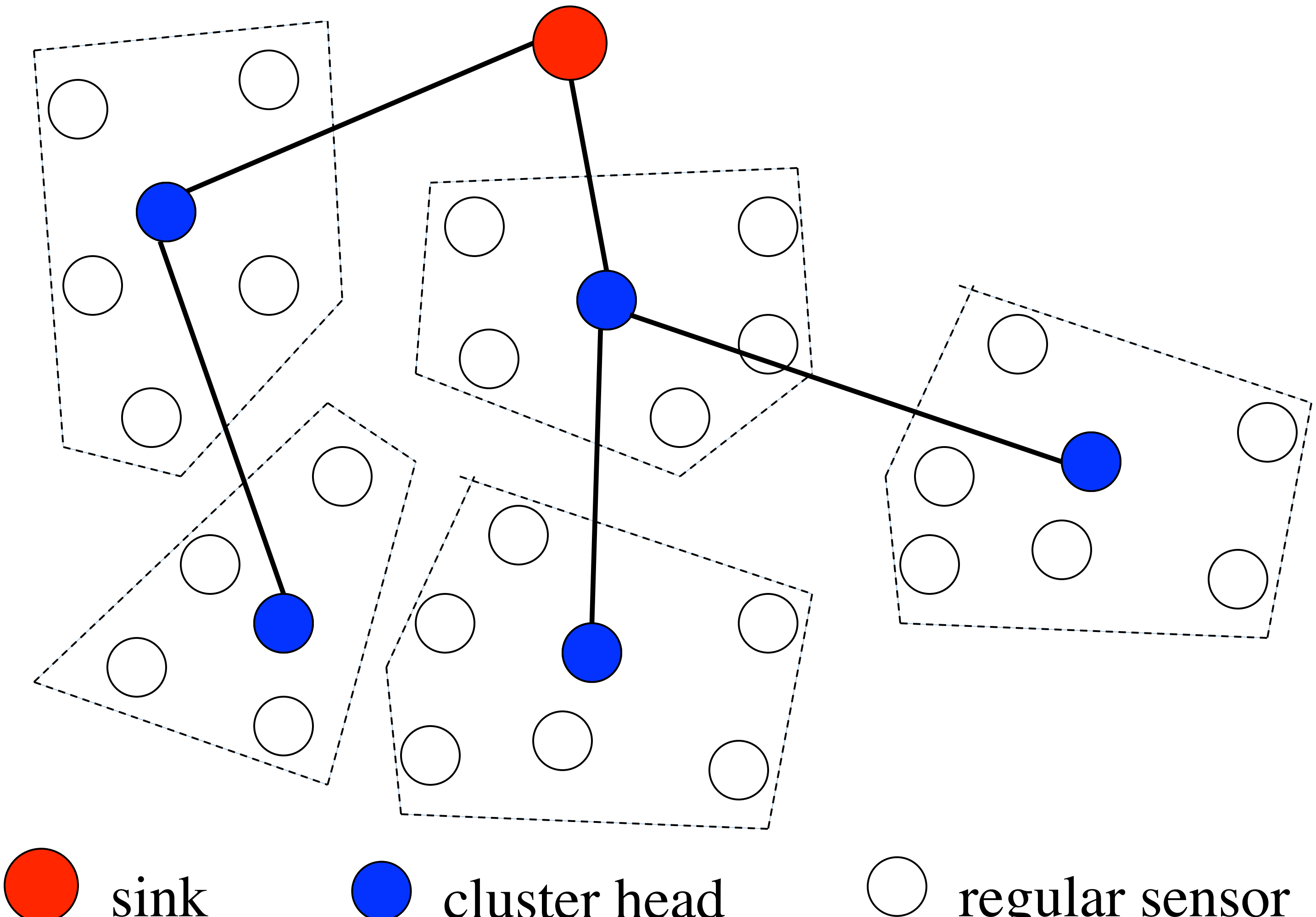
Energy-efficient routing (cont.)



- $z = 4/3$ zPmin =12
- Path with energy cost less than zPmin

Path	minimum residual energy
S-A-D-F-I-O (9)	1
S-B-G-I-O (12)	3
S-A-D-I-O (11)	1
S-A-B-G-I-O (12)	3

Hierarchical Routing



Hierarchical Routing (cont.)

- Sensor communicate directly only with a cluster head
- Cluster head
  - responsible for propagating sensor data to sink
  - sometimes more powerful than “regular” nodes
  - experiences more traffic than “regular” nodes
- Challenges in cluster formation:
  - selection (election) of cluster heads
  - selection of cluster to join
  - adaptation of clusters in response to topology changes, failures, etc.
- Advantages
  - potentially fewer collisions (compared to flat routing)
  - easier duty cycling (energy efficiency)
  - easier routing process (though routes may be longer)
  - easier in-network data aggregation

Hierarchical Routing (cont.)

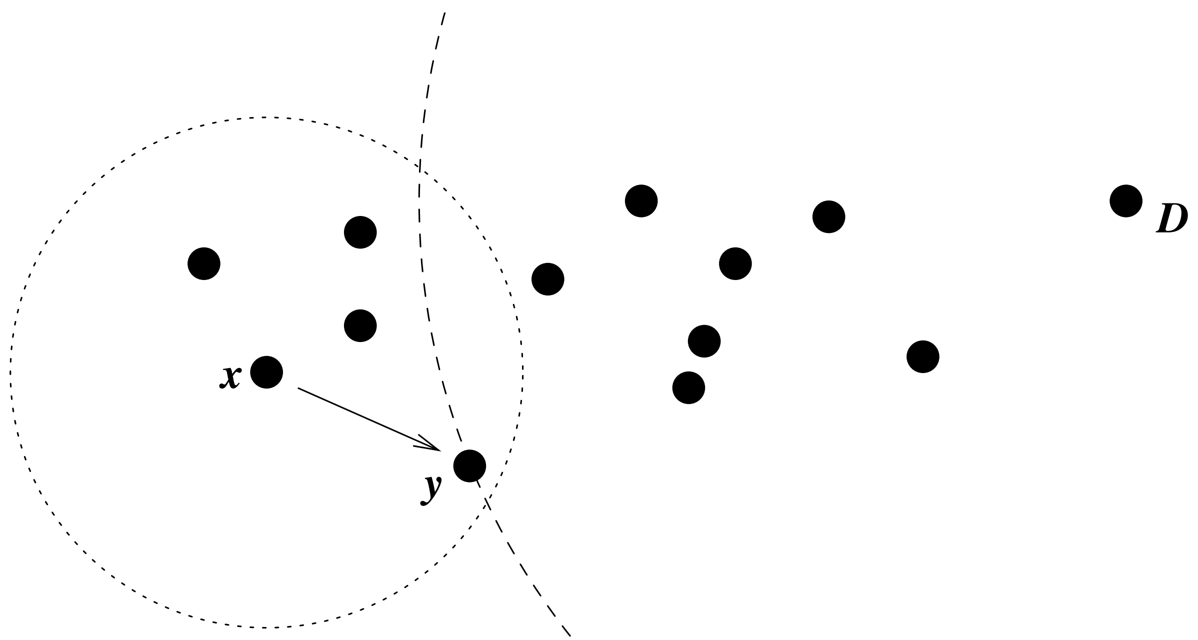
- LEACH (Low-Energy Adaptive Clustering Hierarchy)
  - Wendi Rabiner Heinzelman et al HICSS 2000
  - Adaptive clustering
    - Periodic independent self-election
    - Nodes select advertisement with strongest signal strength
  - Randomized rotation
    - Recent cluster heads disqualified
    - Optimal number not guaranteed
    - Residual energy not considered
  - Heads perform compression/aggregation
- HEED: Hybrid Energy Efficient Distributed Clustering
  - Residual energy considered for heads selection
- Energy-Efficient Unequal Clustering (EEUC)
  - Clusters close to the sink have smaller size

Geographic Routing

- Key Idea
  - Make use of node location information in routing
- Assumptions
  - Nodes know their own geographical location (e.g. GPS)
  - Nodes know their 1-hop neighbors
  - Routing destinations are specified geographically (a location, or a geographical region)
  - Greedy localized routing

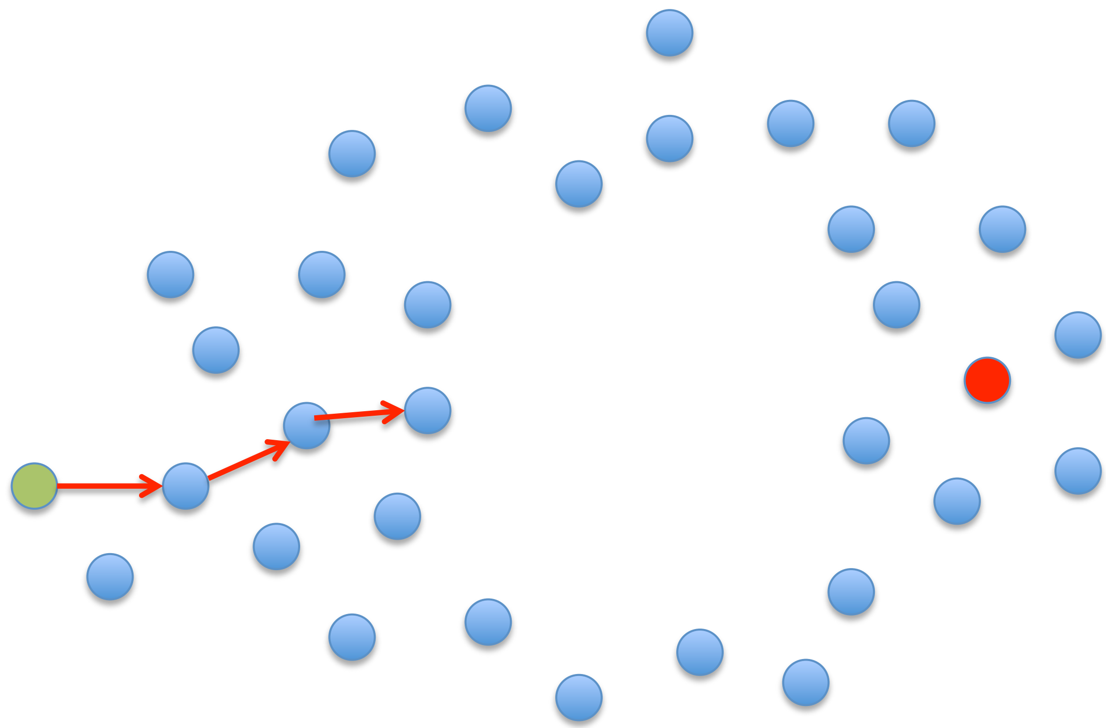
Geographic Routing (cont.)

- GPSR: Greedy Perimeter Stateless Routing
  - Brad Karp and H. T. Kung (MobiCom 2000)
- Greedy forwarding



Geographic Routing (cont.)

- Drawback: holes (local minimums)

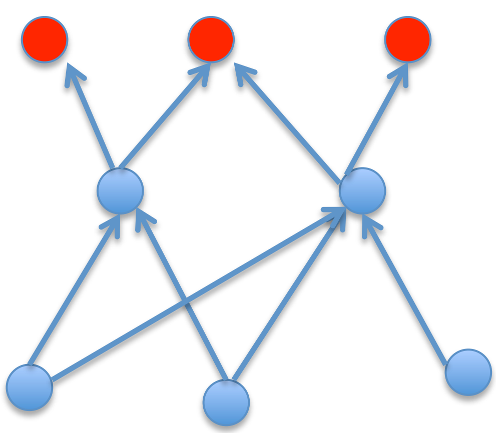


Graph Routing

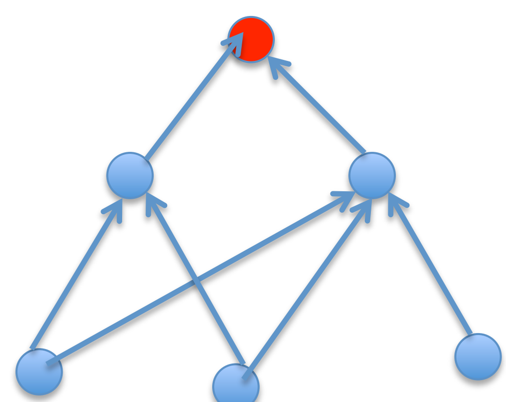
- LLNs: Low power and Lossy Networks
  - Devices have constraints in processing power, memory and energy (battery power)
  - Interconnection links have high loss rate, low data rate and instability
- RPL: IPv6 Routing Protocol for LLNs
  - IETF draft
  - ROLL group - (Routing Over Low power and Lossy networks) group

Graph Routing (cont.)

- Terminology
  - **Directed Acyclic Graph (DAG)**: A directed graph in which all edges are oriented in such a way that no cycles exist.
  - **Destination Oriented DAG (DODAG)**: A DAG rooted at a single destination, i.e. at a single DAG root (the DODAG root) with no outgoing edges.



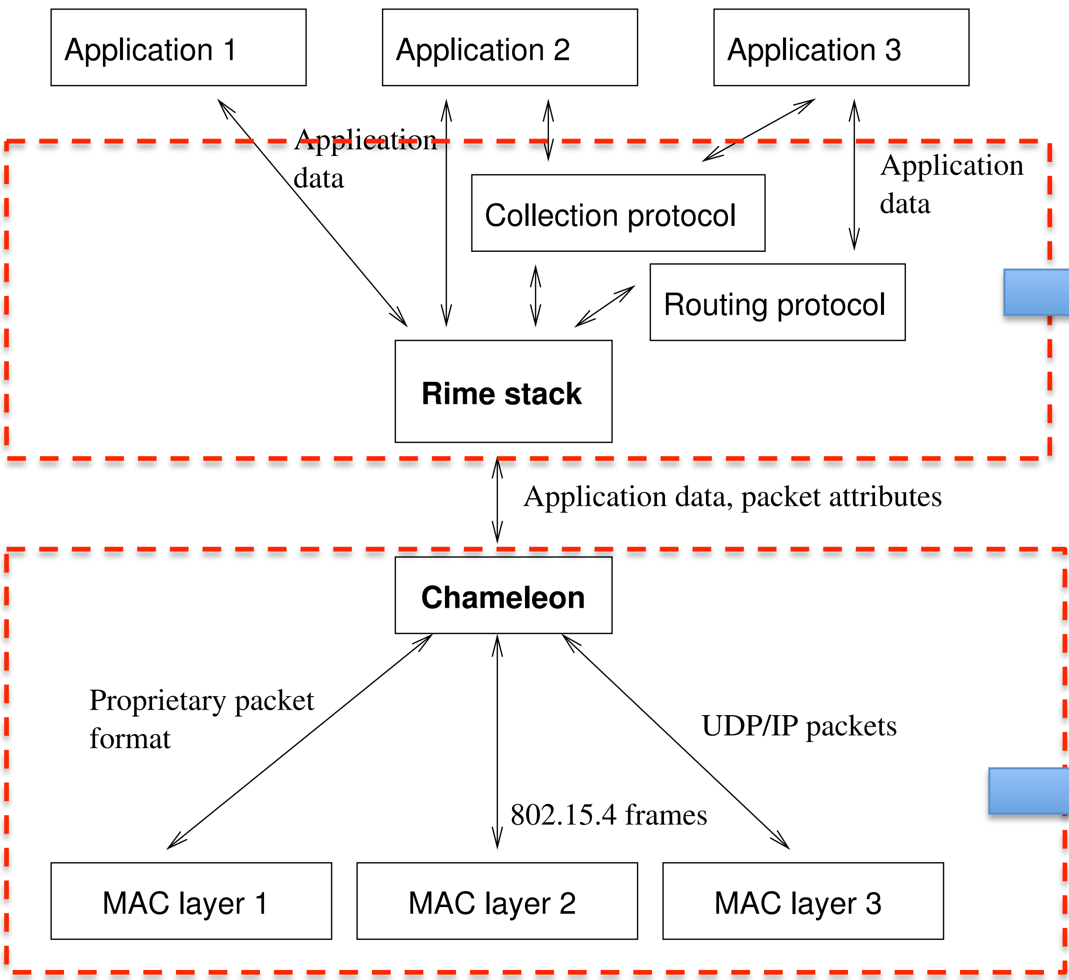
DAG



DODAG

Architecture

- The communication architecture in Contiki



- A set of communication primitives
- A set of network protocols

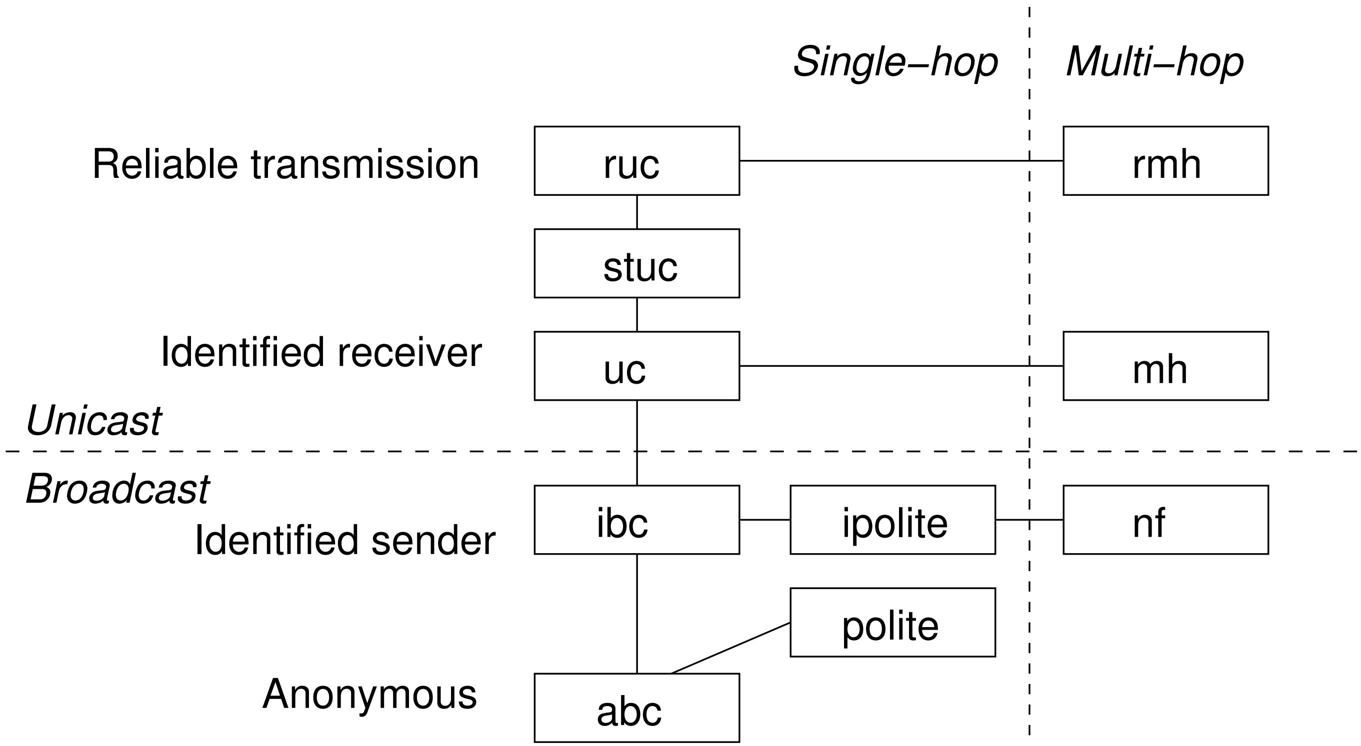
- Tightly bit-packet packet headers
- Headers that conform to specific MAC or link layer protocols.

Architecture (cont.)

- Design objectives
  - Simplify the implementation of sensor networks communication protocols (via Rime protocol stack)
  - Allow sensor network protocols to use the features of underlying MAC and link layer protocols (via packet attributes instead of packet headers)
  - Allow packet headers to be formed independently of the protocols or applications (via separate packet transformation modules)

Rime

- The rime communication stack provides a set of communication primitives

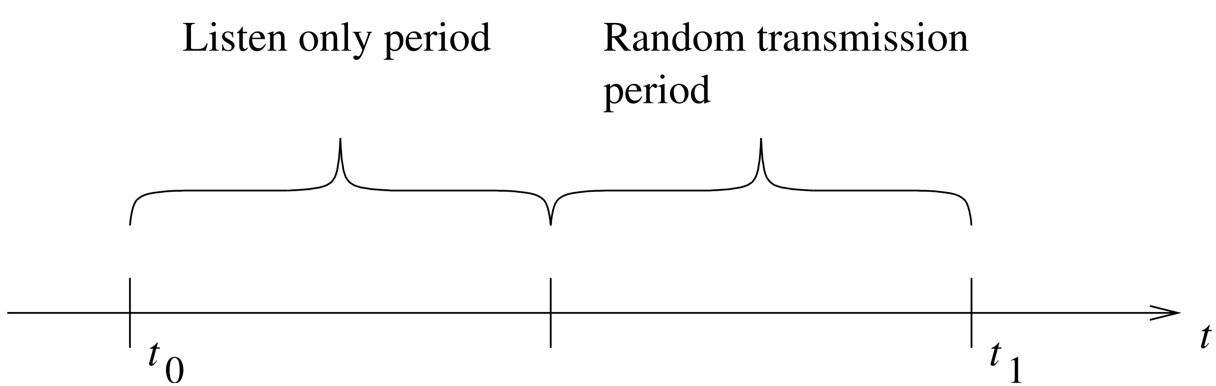


Rime (cont.)

- Anonymous Best-effort Single-hop Broadcast (abc)
  - Send a data packet to all local neighbours that listen to the channel on which the packet is sent.
  - No information about who sent the packet is included in the transmission.
  - The most basic communication primitive. All other primitives are based on the abc primitive
- Identified Best-effort Single-hop Broadcast (ibc)
  - Same as abc but adds the single-hop sender address as a packet attribute to the outgoing packets.

Rime (cont.)

- Polite Single-hop Broadcast (polite)
  - Sends a packet to all neighbours
  - Avoid that multiple copies of a specific set of packet attributes is sent on a specified logical channel in the local neighbourhood during a time interval.



Rime (cont.)

- Identified Polite Single-hop Broadcast (ipolite)
  - Works in the same way as polite but adds the identity of the sender as a packet attribute
- Best-effort Multi-hop Unicast (mh)
  - Sends a packet to an identified node using multi-hop forwarding
  - Application protocol that uses the mh primitive supplies a routing function for selecting the next-hop neighbor
  - When the next-hop neighbour is found, the mh primitive uses the best-effort unicast primitive to send the packet.

Rime (cont.)

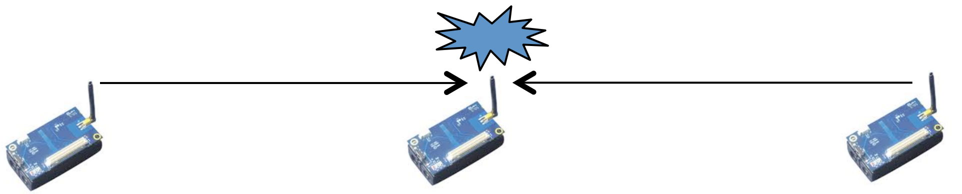
- Best-effort Single-hop Unicast (uc)
  - Sends a packet to an identified single-hop neighbour.
  - Uses the ibc primitive and adds the single-hop receiver address attribute to the outgoing packet.s
- Stubborn Single-hop Unicast (suc)
  - Repeatedly sends a packet to a single-hop neighbour using the uc primitive until an upper layer primitive or protocol cancels the transmission.
- Reliable Single-hop Unicast (ruc)
  - Reliably sends a packet to a single-hop neighbour
  - Uses ack and retransmission to ensure successful packet delivery.
  - Can specify the maximum number of transmissions for a packet

Rime (cont.)

- Hop-by-hop Reliable Multi-hop Unicast (rmh)
  - Works in the same way as mh except that it uses the ruc primitive for the communication between two single-hop neighbours.
- Best-effort Network Flooding
  - Sends a packet to all nodes in the networks.
  - Uses polite broadcast at every hop to reduce the number of redundant transmissions.

MAC Design Goals

- Medium Access Control (MAC)
  - Avoid interference between transmissions
  - Mitigate effects of collisions (retransmit)
  - Optimize channel access



- Design Goals
  - Minimize energy consumption
    - Overhearing: unnecessarily receive a packet destined to another node
    - Idle listening: staying active to receive even if there is no sender
  - Minimize the active time
  - Eliminate packet collisions
  - Minimize control packet overhead
  - Prevent buffer overflow
  - …

Energy Consumption in a Sensor Mote

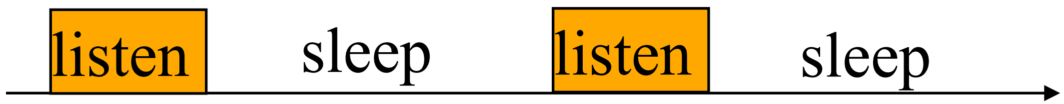
UCLA Medusa node (ATMEL CPU)

MCU Mode	Sensor	Radio(mW)	Data rate	Power(mW)
Active	On	Tx(0.74,OOK)	2.4Kbps	24.58
		Tx(0.74,OOK)	19.2Kbps	25.37
		Tx(0.10,OOK)	2.4Kbps	19.24
		Tx(0.74,OOK)	19.2Kbps	20.05
		Tx(0.74,ASK)	19.2Kbps	27.46
		Tx(0.10,ASK)	2.4Kbps	21.26
Active	On	Rx	-	22.20
Active	On	Idle	-	22.06
Active	On	Off	-	9.72
Idle	On	Off	-	5.92
Sleep	Off	Off	-	0.02

- Observations
  - Radio activities dominate the energy consumption
  - Idle listening consumes much energy
  - Turning radio off saves much energy
  - Keeping MCU in sleep state further reduces energy consumption

Periodic Listen and Sleep

- **Problem:** Idle listening consumes significant energy
- **Solution:** Periodic listen and sleep



  - Turn off radio when sleeping
  - Reduce duty cycle

- **Tradeoffs**

Latency ⟷ Energy

S-MAC

- S-MAC: An Energy-Efficient MAC Protocol for Wireless Sensor Networks
  - Wei Ye, John Heidemann and Deborah Estrin, INFOCOM 2002

- Key ideas:
  - Idle listening --- Periodic listen and sleep
  - Collision --- Using RTS and CTS
  - Overhearing --- Interfering nodes go to sleep during transmission
  - Control overhead --- Message passing

S-MAC (cont.)

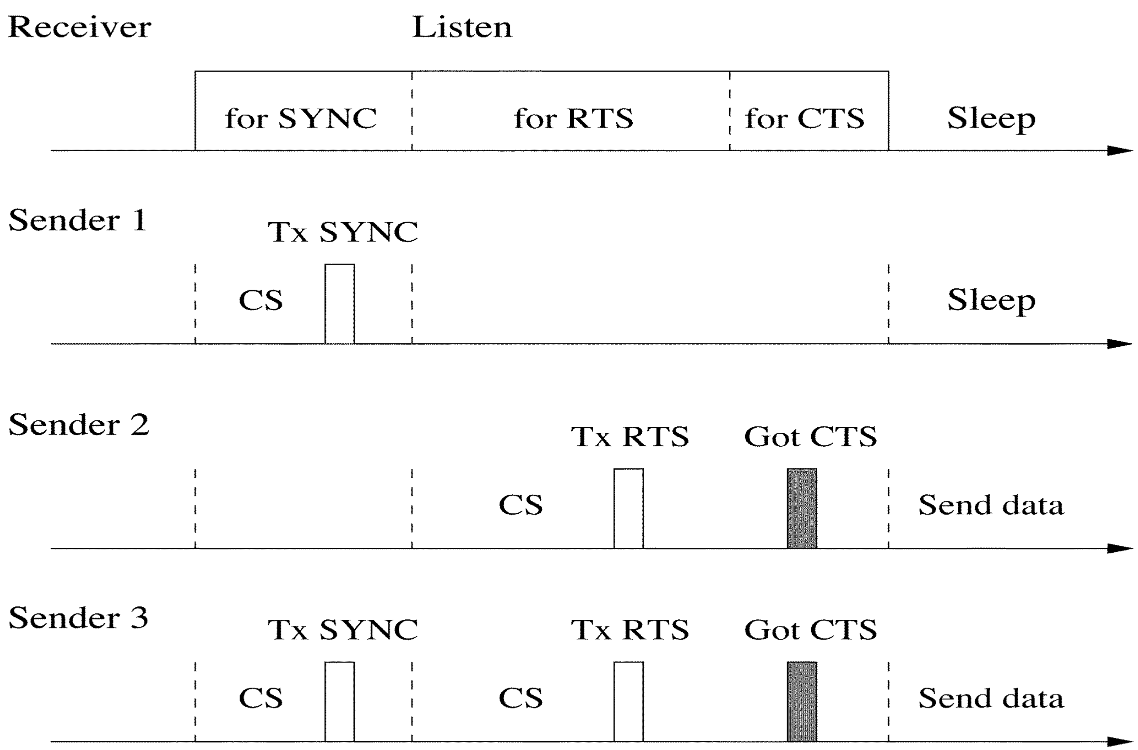
- Periodic listen and sleep
  - Each node sleeps for some time, and then wakes up and listens to see if any other node wants to talk to it
  - All nodes are free to choose their own listen/sleep schedule, but needs to synchronize with neighbors, that is, nodes and their neighbors listen at the same time and go sleep at the same time.
  - Synchronization is achieved by periodically broadcasting SYNC packets.

S-MAC (cont.)

- Collision avoidance
  - RTS/CTS exchange for the hidden terminal problem
- Choosing and maintaining schedules
  - Each node maintains a schedule table that stores the schedules of all its known neighbors.
  - To communicate with a neighbor, the node chooses its neighbor’s schedule

S-MAC (cont.)

- Adaptive listening
  - Periodic listen and sleep can increase communication delay
  - Let the node who overhears its neighbor’s transmission wake up for a short period of time at the end of the transmission.



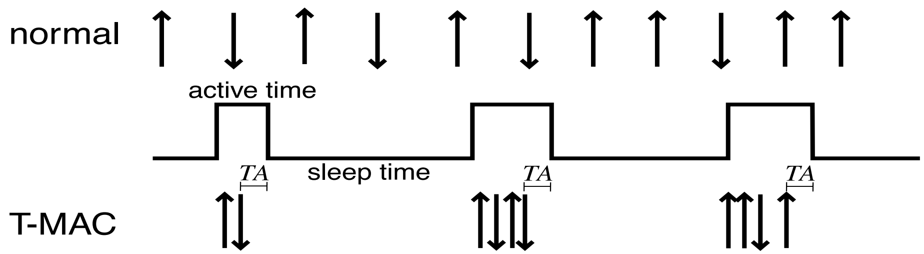
T-MAC

- T-MAC: An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks
  - Tijs van Dam and Koen Langendoen, *SenSys 2003*

- Key ideas:
  - Reduce idle listening by transmitting all messages in bursts of variable length, and sleeping between bursts.
  - Dynamically determine the optimal length of active time based on the traffic load.

T-MAC (cont.)

- Overview



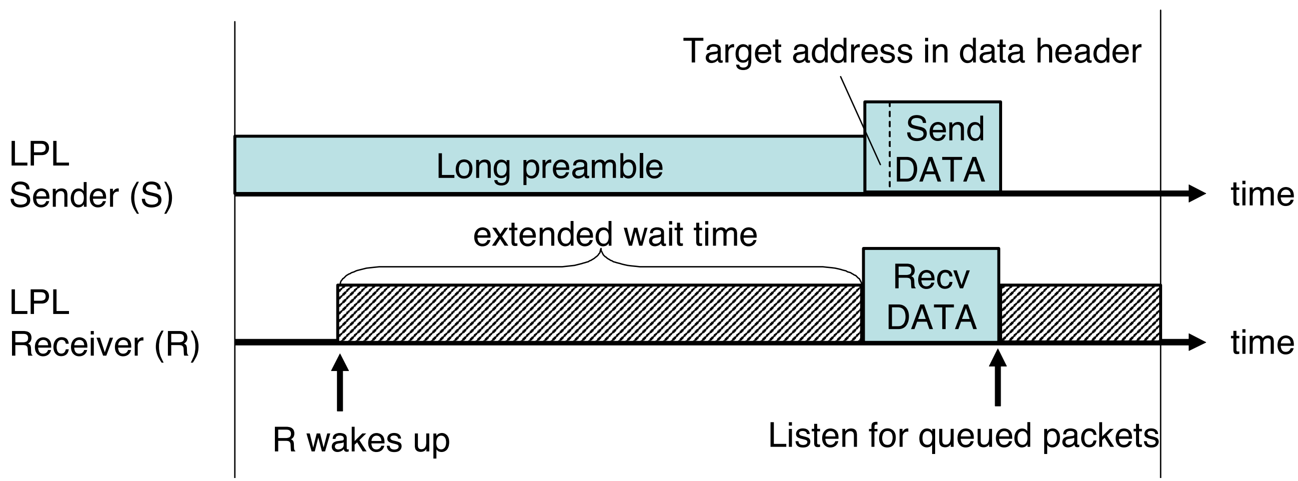
  - RTS/CTS/ACK
  - An active period ends when none of the following events has occurred during a period of TA
    - The firing of a periodic frame timer
    - Receiving data packets
    - Sense radio activity
    - The end-of-transmission of a node's own packet or acknowledgement
    - The knowledge that a data exchange of a neighbor has ended.

B-MAC

- B-MAC: Berkeley Media Access Control for low power wireless sensor networks
  - "Versatile Low Power Media Access for Wireless Sensor Networks", Joseph Polastre, Jason Hill, and David Culler, *SenSys 2004*
- Key ideas:
  - Low power listening (LPL) for low power communication.
  - Clear channel assessment (CCA) and packet backoff for channel arbitration
  - Link layer acknowledge for reliability

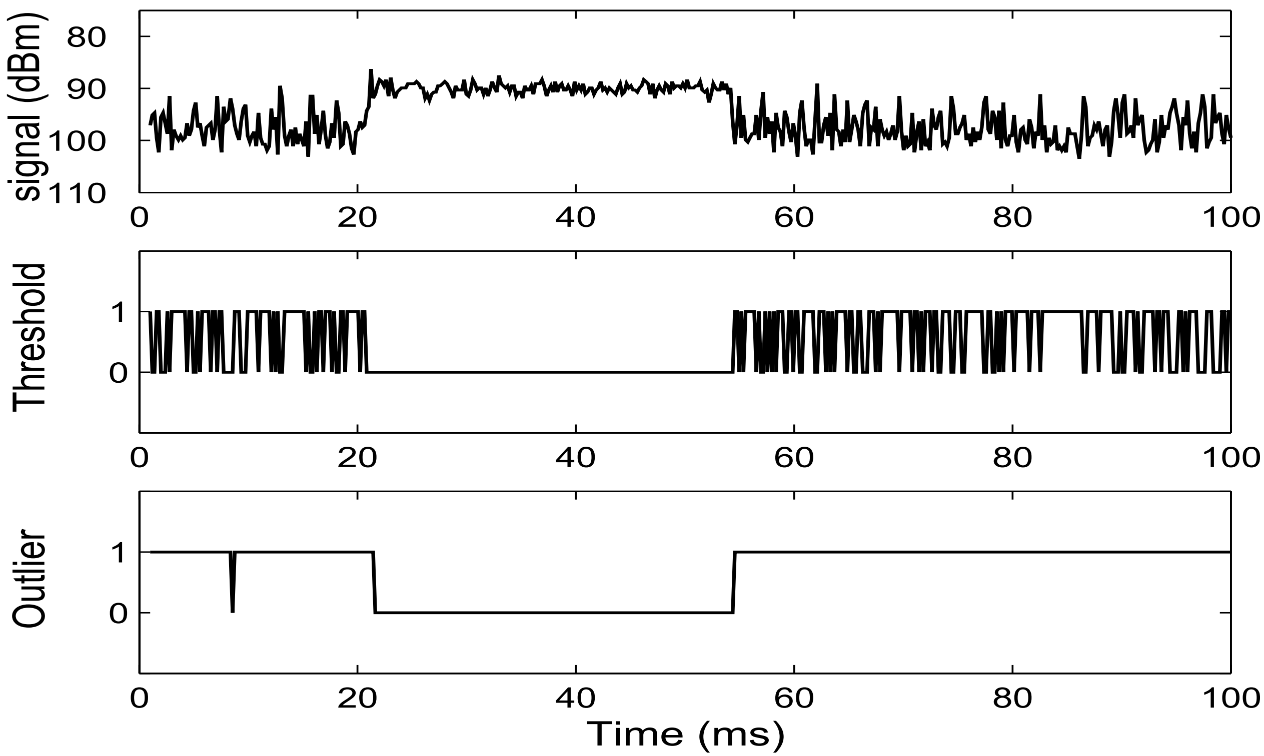
B-MAC (cont.)

- Low power listening (LPL)
  - Extended preamble and preamble sampling
  - Each time a node wakes up, it turns on its radio to check for activity. If a preamble signal is detected, it will stay awake for the time required to receive the incoming packet.
  - The preamble length is matched to the interval that the channel is check, e.g., the preamble must be at least 100ms if the channel is check every 100ms.



B-MAC (cont.)

- Clear Channel Assessment (CCA)
  - filtering to remove noise
  - thresholding to estimate channel status

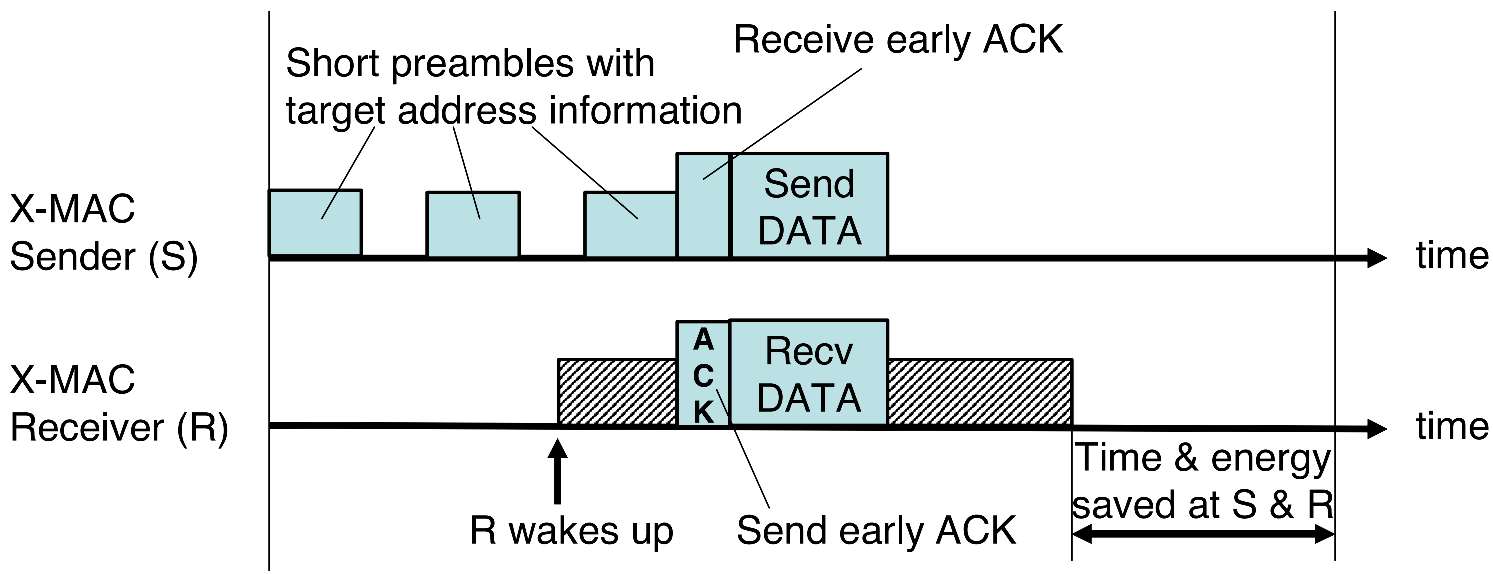


X-MAC

- X-MAC: A Short Preamble MAC Protocol for Duty-Cycled Wireless Sensor Networks
  - Michael Buettner, Gary V. Yee, Eric Anderson and Richard Han, *SenSys 2006*
- Key ideas:
  - employs a *short preamble* to further reduce energy consumption and to reduce latency.
  - embed address information of the target in the preamble so that non-target receivers can quickly go back to sleep
  - use a *strobed preamble* to allow the target receiver to interrupt the long preamble as soon as it wakes up and determines that it is the target receiver.

X-MAC (cont.)

- Embedding the target ID in the preamble
  - Divide the one long preamble into a series of short preamble packets.
  - Each packet contains the ID of the target node.



X-MAC (cont.)

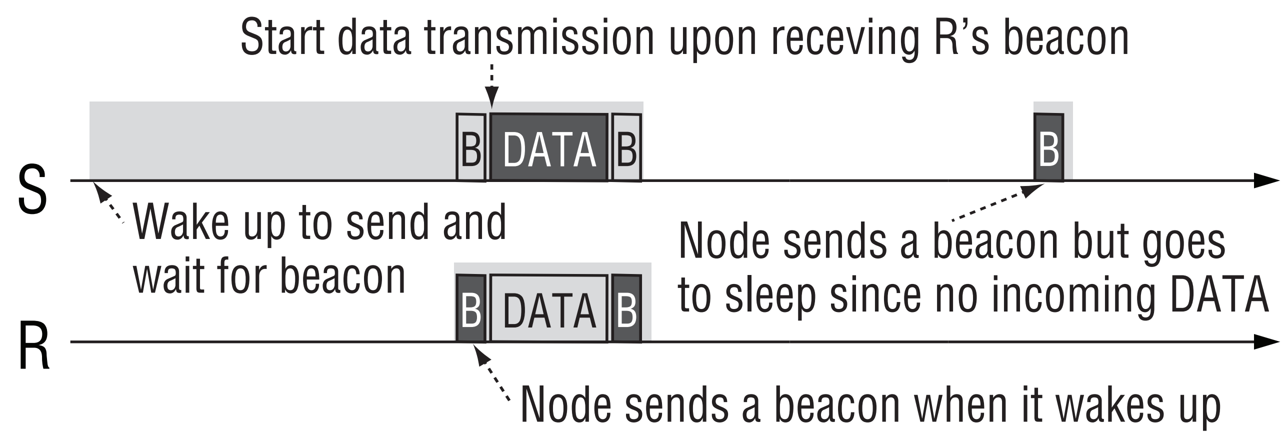
- Reducing excessive preamble using strobing
  - Insert small gaps between the series of short preamble packets.
  - These gaps enable the receiver to send an early acknowledgement during the short pause between preamble packets.
  - When a sender receives an acknowledgement for the intended receiver, it stops sending the preamble and starts sending the data packet

RI-MAC

- RI-MAC: A Receiver-Initiated Asynchronous Duty Cycle MAC Protocol for Dynamic Traffic Loads in Wireless Sensor Networks
  - Yanjun Sun, Omer Gurewitz, and David B. Johnson, SenSys 2008
- Key Idea
  - Receiver-Initiated, which uses receiver-initiated data transmission in order to efficiently and effectively operate over a wide range of traffic loads.

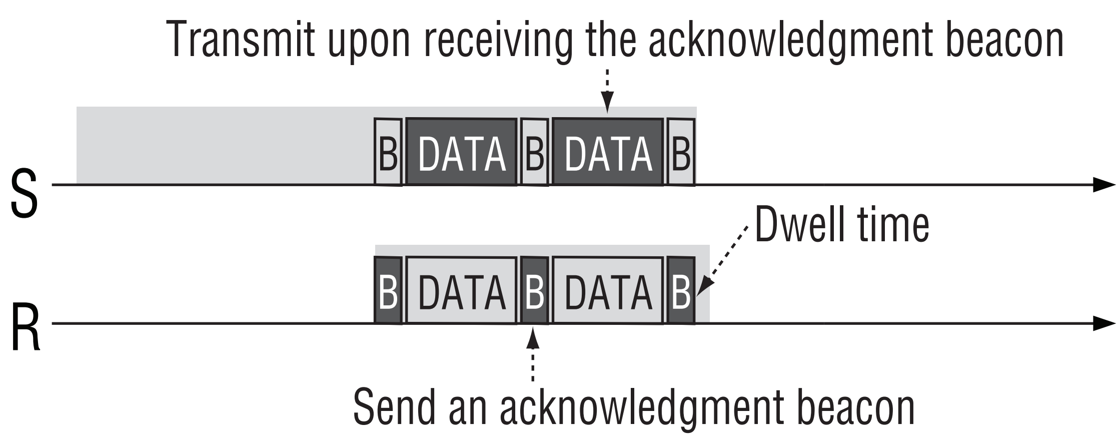
RI-MAC (cont.)

- Overview
  - Each node periodically wakes up based on its won schedule to check if there are any incoming data intended for this this node
  - A node with pending data to send stays active silently while waiting for the beacon from the intended receiver
  - Upon receiving a beacon from the intended receiver, the node start sending data packet
  - Received packet will be acknowledged with another beacon



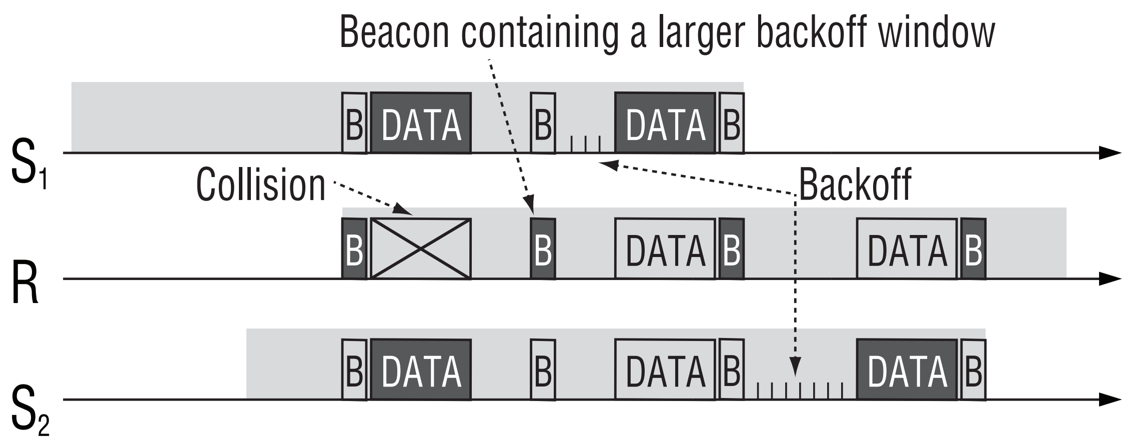
RI-MAC (cont.)

- Dwell time for queued packets
  - After receiving a packet, a node remains active for some extra time to allow the sending of queued packets
  - The extra time is called the dwell time, which can be adapted based on the number of contending senders.



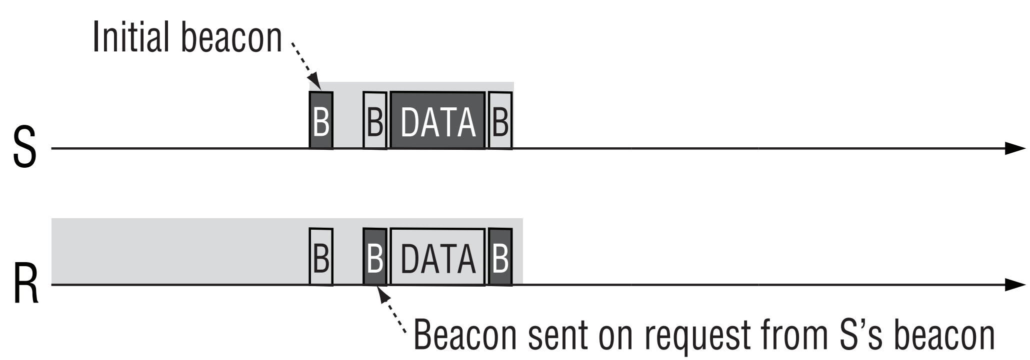
RI-MAC (cont.)

- Data transmissions from contending senders
  - Employs beacon frames to coordinate data packet transmission from contending senders.
  - The beacon contains the size of the backoff window that the senders should use when they contend for the medium.



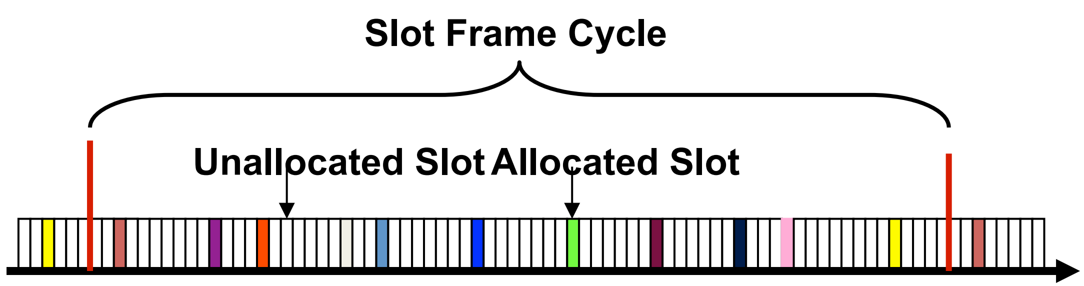
RI-MAC (cont.)

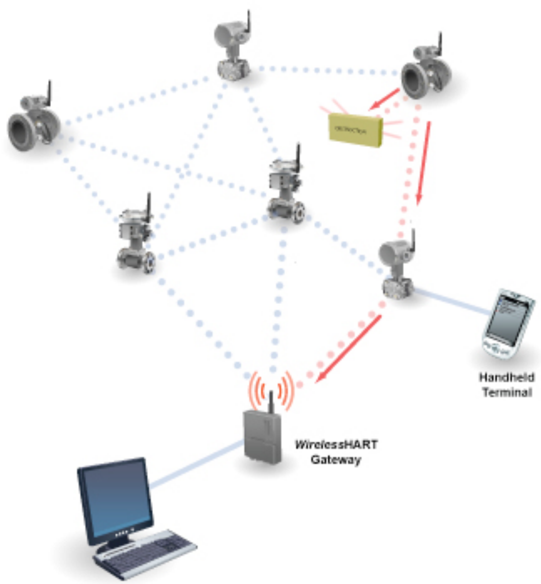
- Beacon-on-request
  - The intended receiver for some sender is already active when the sender wakes up to transmit a data packet to it.
  - After waking up for data transmission, the sender will broadcast a beacon after a CCA check.
  - If the receiver happens to be active, it generates a beacon in response after some random delay larger than the backoff window.



TDMA MAC

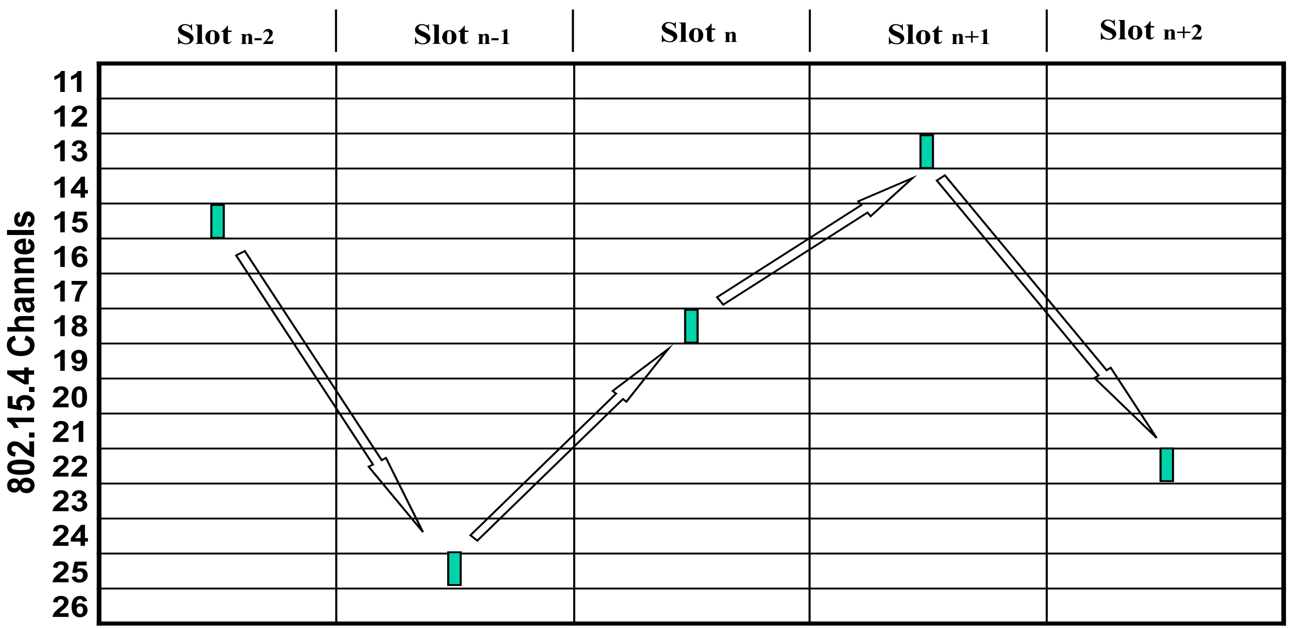
- Applications
  - Industrial networks with stringent requirement of communication delay and reliability
  - WirelessHART, ISA 100.11a, IEEE802.15.4e





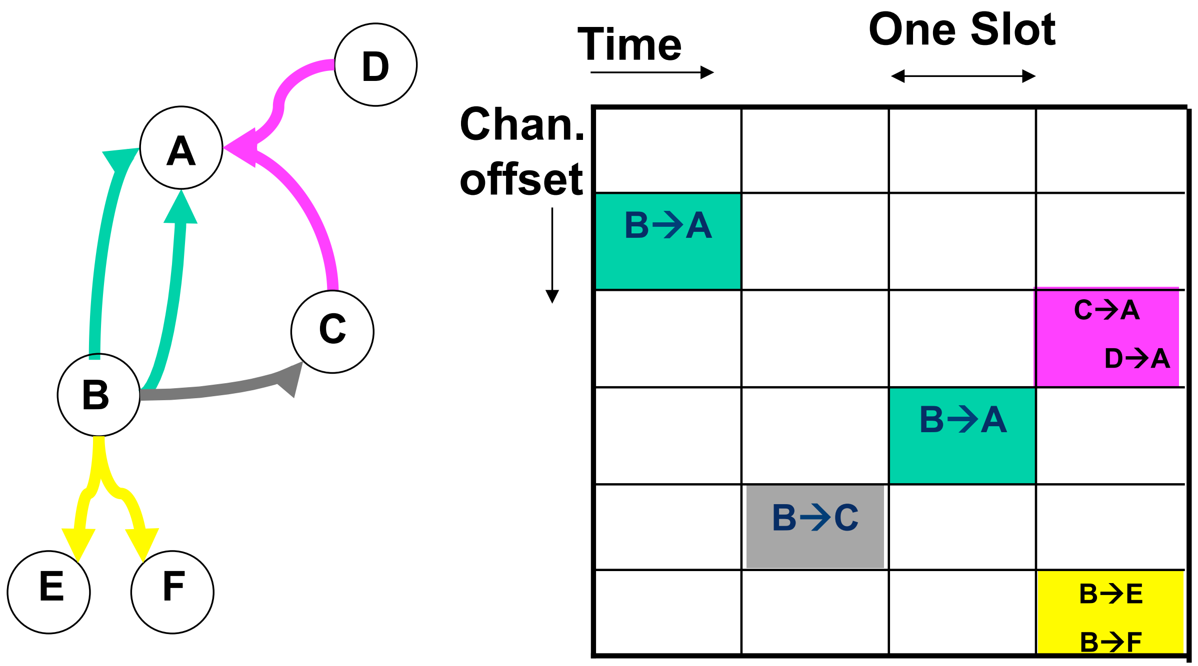
TDMA MAC (cont.)

- Channel hopping
  - Mitigate Channel Impairments: adds frequency diversity to mitigate the effects of interference and multipath fading
  - Increase Network Capacity: one timeslot can be used by multiple links at the same time



TDMA MAC (cont.)

- Link Scheduling
  - Dedicated slots
  - Shared slots



Conclusions

- Routing protocols for WSNs
  - Design challenges
  - Energy-aware routing
  - Hierarchical routing
  - Geographic routing
  - Graph routing
  - Routing protocol design in Contiki
- MAC protocols for WSNs
  - Design challenges
  - S-MAC, T-MAC, B-MAC, X-MAC, RI-MAC, TDMA MAC