Medium Access Control

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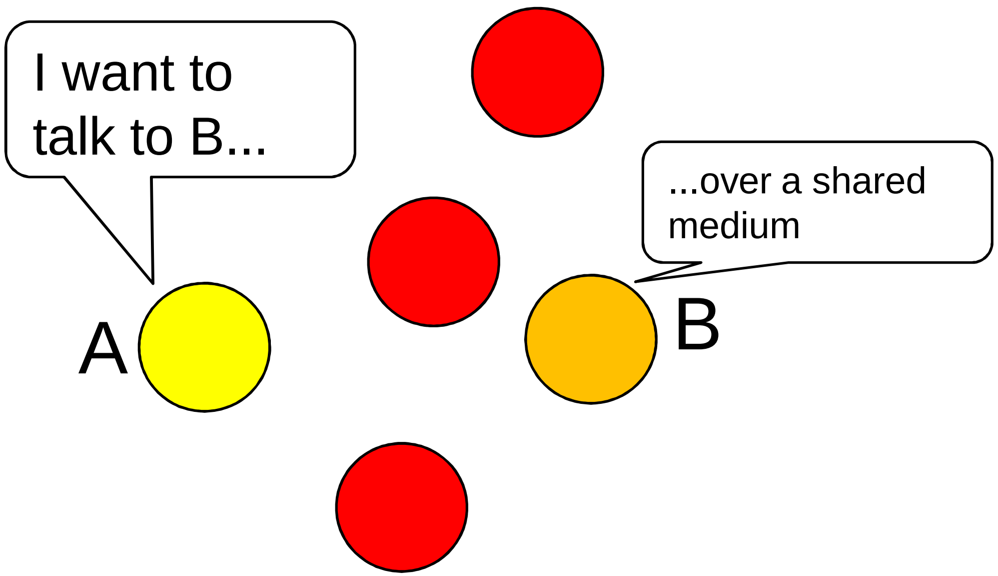
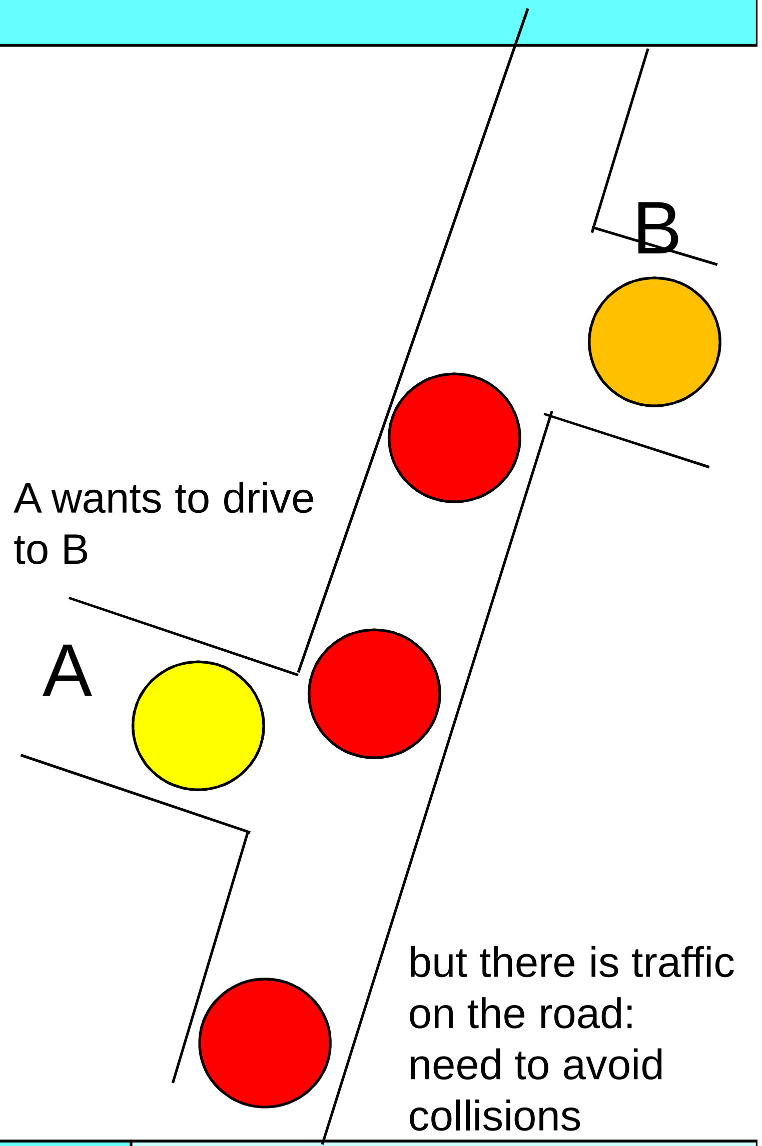
MAC protocols

MAC = Medium Access Control





There's more to WSN MACs than managing contention

- In WSNs, contention is a relatively small problem (low load)
- Overhearing and idle listening are huge problems that are closely related
- MAC-layer duty-cycling to be enforced as a baseline solution

There's no such thing as static connectivity

- Do not underestimate the temporal dynamics of wireless links
- You typically have little control over such dynamics
- The connectivity that you measure today is not (necessarily) what you will see tomorrow

Dealing with Lousy Links

Reception does not imply link existence

- Links are not Boolean
- Packets may very well arrive over ultra-poor links...but you can’t count on it
- Links must be estimated with as little overhead as possible

Asymmetric links are a very common problem

- There exists a transitional connectivity region where the PDR changes wildly
- Transitional links may be asymmetric
- Even high RSS links may be asymmetric due to interference

Link-layer retransmissions are fundamental

- They enable correct link quality estimation that benefits routing

MAC protocols for WSNs

- Low-power operation
- Channel utilization efficiency
- Flexibility (configurable by upper layers)
- Scalability (many nodes)
- Robustness (RF propagation effects)
- Simplicity (must run on resource-constrained CPU)

and, like any other MAC,

- Collision avoidance

Major sources of energy waste

- Collisions

  Retransmissions required (more latency)

- Overhearing

  Same cost as receiving

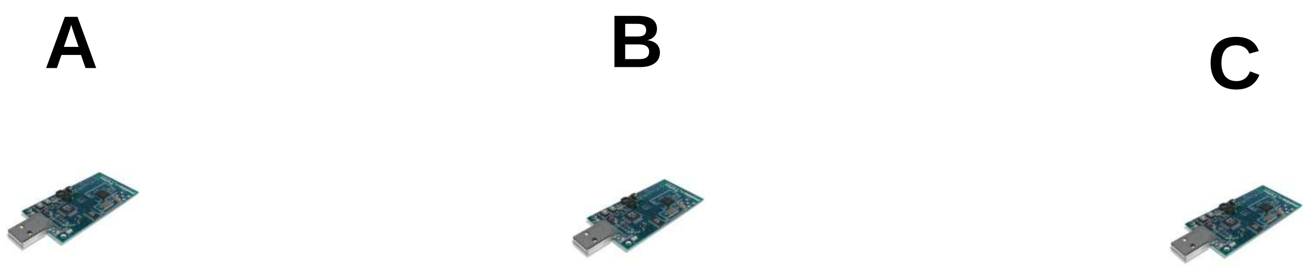
- Control overhead

  Control packets also have a cost (e.g., RTS/CTS)

- Idle listening

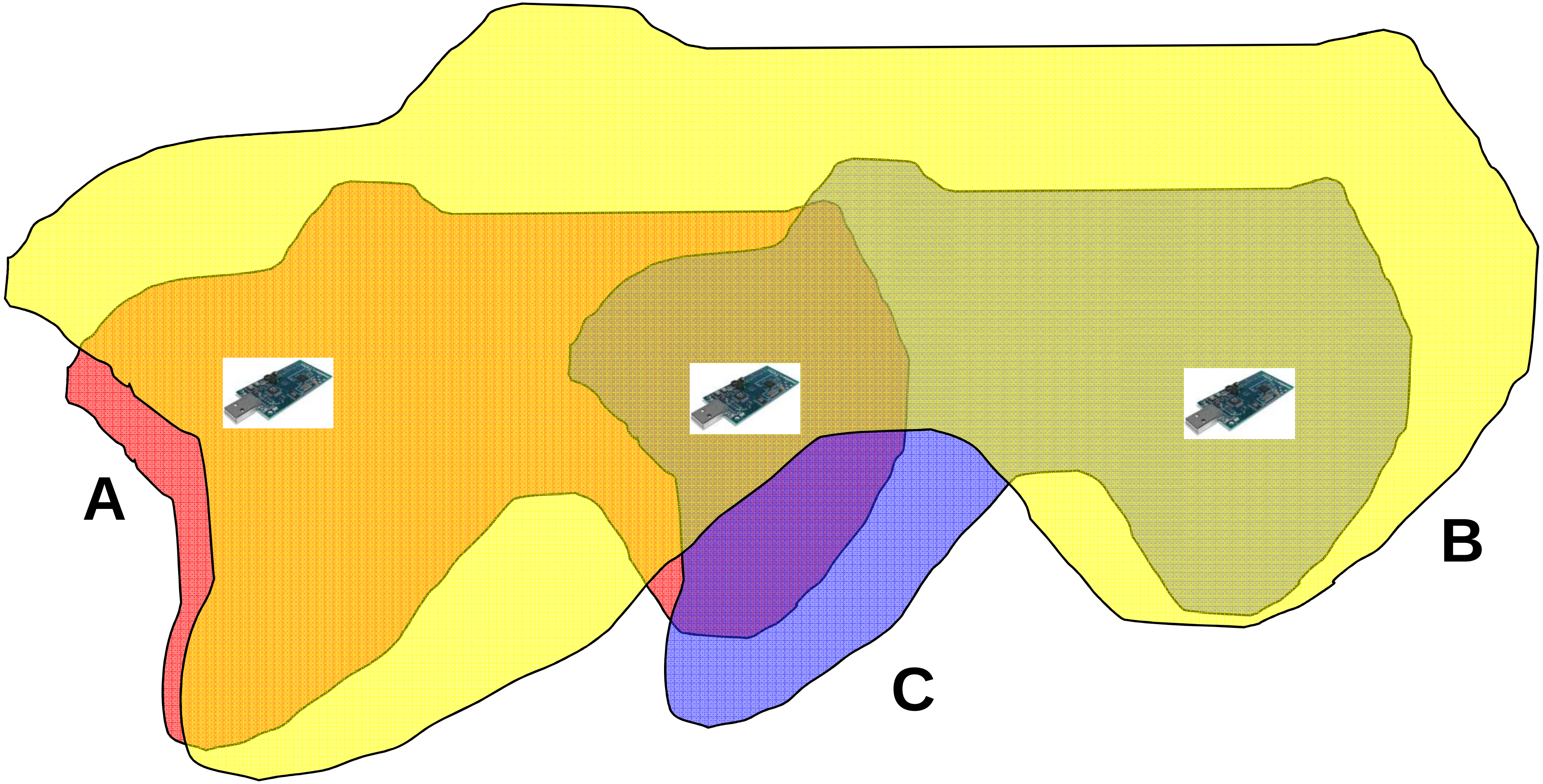
  Almost as costly as receiving

Hidden Node Problem

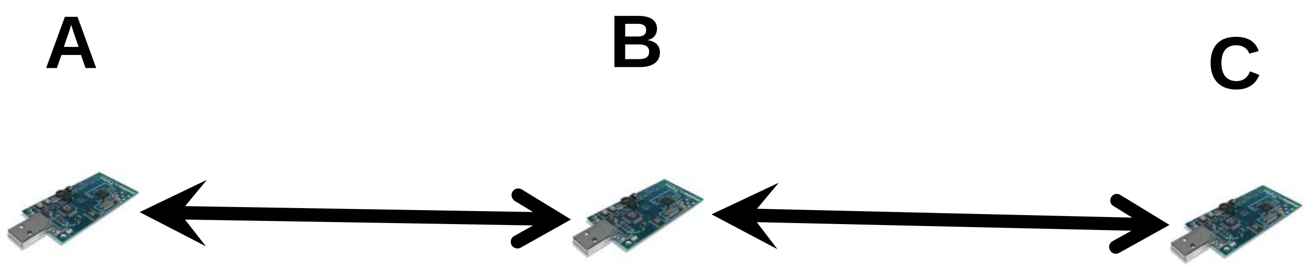


A wants to transmit to B...who is receiving from C

Collisions

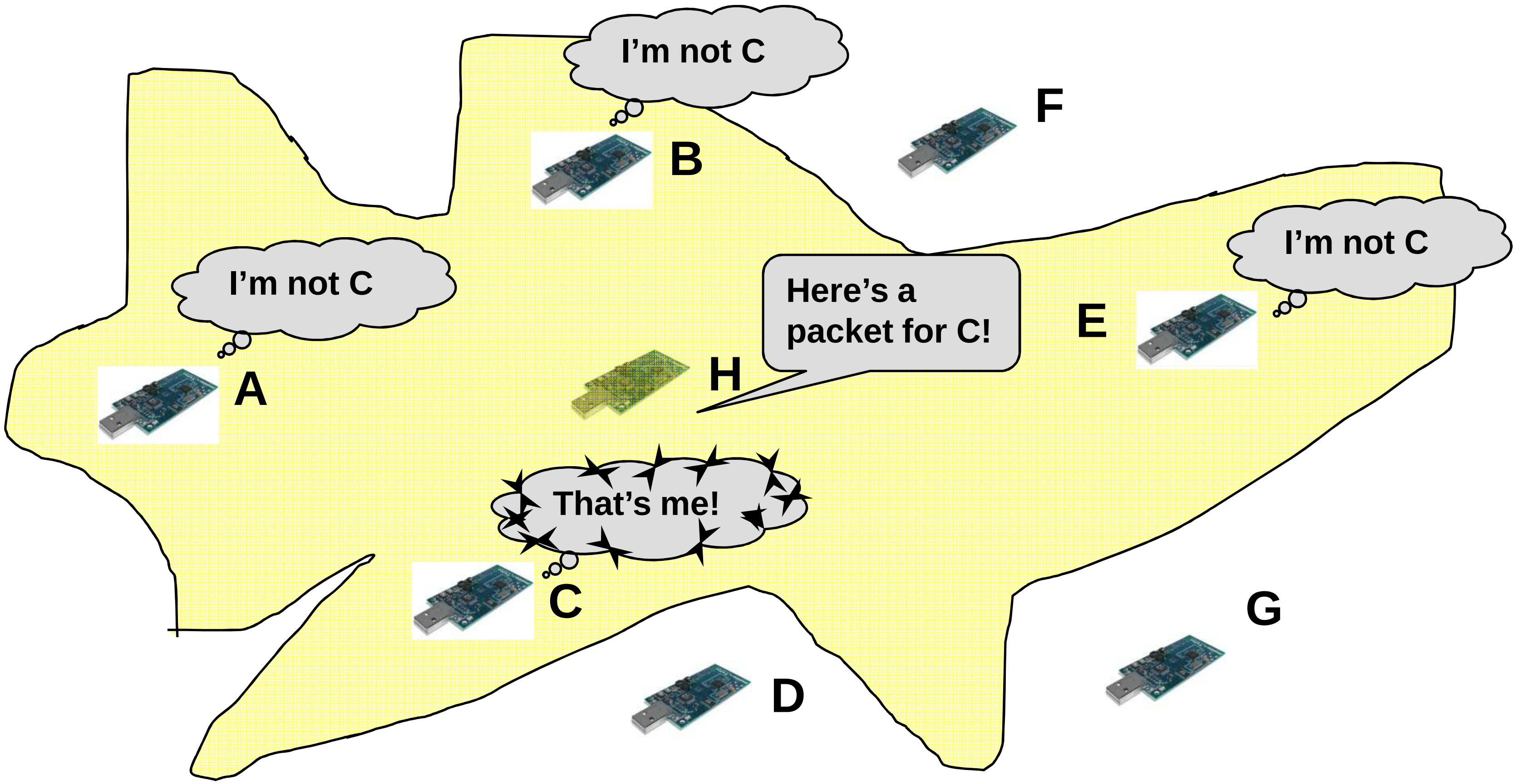


Collisions



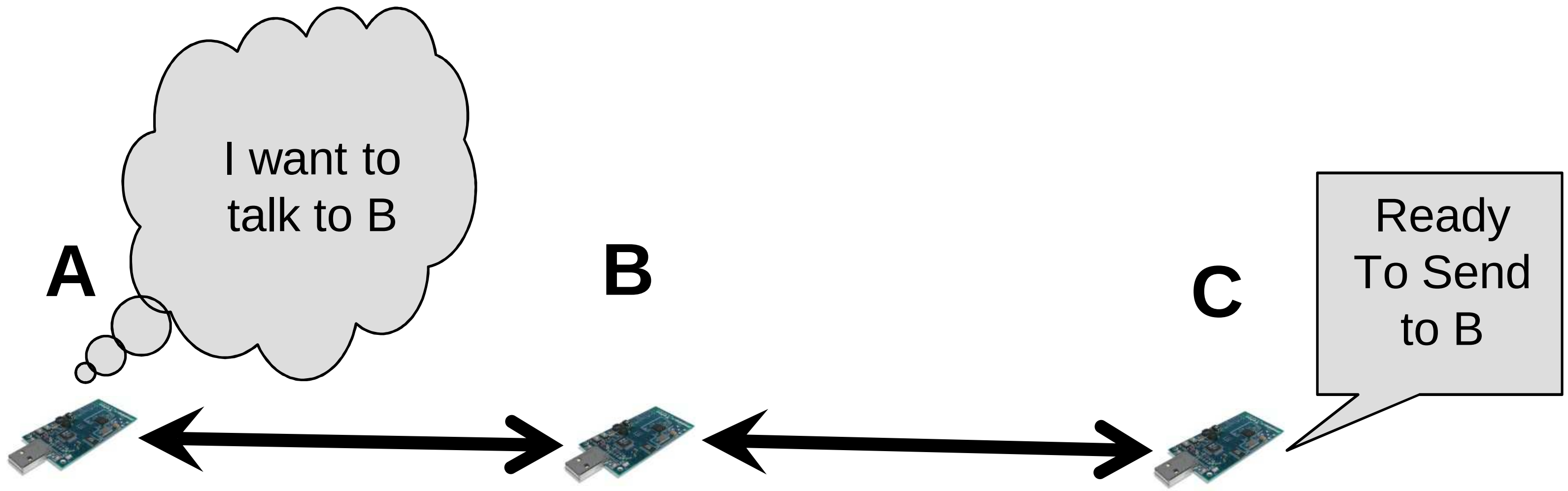
A cannot hear C...and A's and C's packet collide at B

Overhearing



Control Overhead

In legacy wireless, collisions are addressed with RTS/CTS



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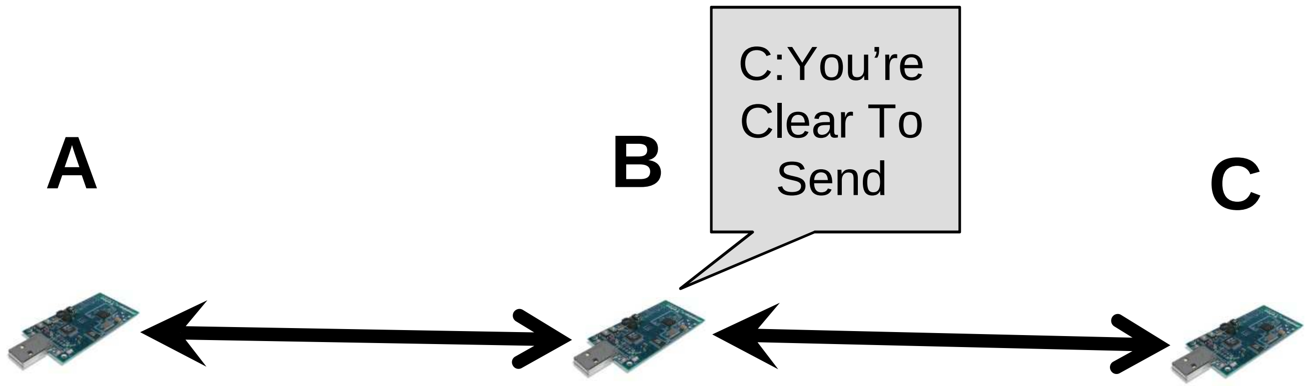
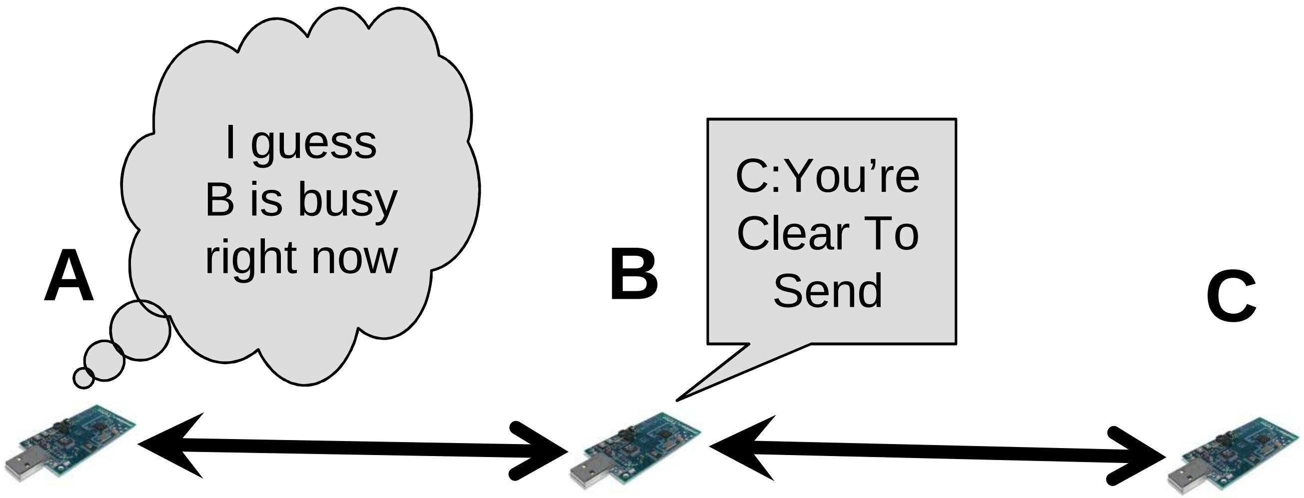


Control Overhead

RTS/CTS avoids collisions at the cost of a control overhead



The extra control packets have a significant energy cost

Idle Listening

The power consumption of short range (low-power) wireless devices is roughly the same (same order of magniture) whether the radio is transmitting, receiving, or idle

Radio must be on idle to receive anything

Most applications employ infrequent transmissions

Idle listening dominates energy consumption...

...unless duty-cycling is adopted

Two flavors of duty-cycling:
- at the MAC layer (works across different applications)
- application-informed (specific to one application)

Idle Listening

Your radio is on and ready to go
Whatever gets transmitted is received by your radio
(physically, everything is broadcast!)

Overhearing

You receive a transmission meant for another node
Your MCU discards it, but your radio receives it

Idle Listening results in **Overhearing**

The Cost of Medium Sampling

- Depends on the radio
- Constant across different protocols
- Example for the CC1000 (80µJ)

(a) (g)
Radio is asleep

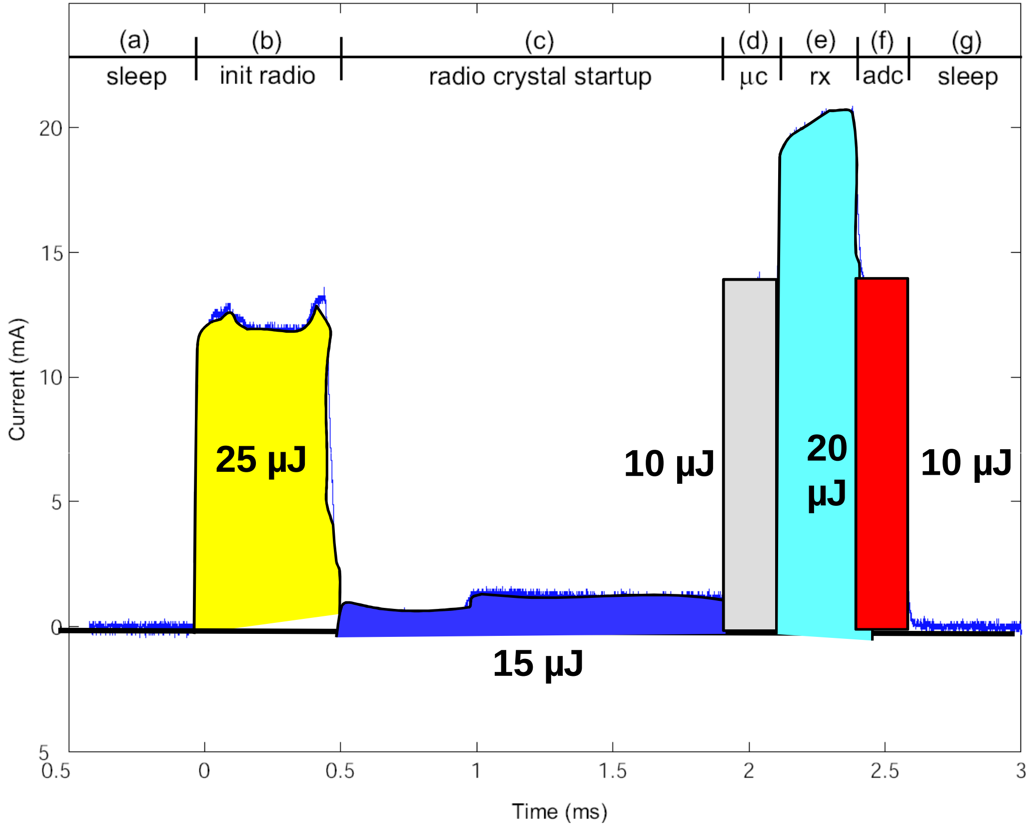
(b)
Radio wakeup and init

(c)
The oscillator stabilizes

(d)
Radio enters RX mode

(e)
The medium gets sampled

(f)
ADC conversion



Versatile Low Power Media Access for Wireless Sensor Networks
J. Polastre, J. Hill, and D. Culler, SenSys'08

Basic WSN MAC Techniques

Coordinated synchronized slotted scheduling

- Arrange a schedule of communication opportunities
- Maintain coordinated clocks and schedule
- Listen during specific slots
- Examples: S-MAC, T-MAC

Sampled Listening

- Listen for very short intervals to detect transmissions
- On detection, listen actively to receive
- Examples: LPL, BMAC, XMAC
- Maintain **always on illusion**

TDMA basic scheme

TDMA = Time Division Media Access

- Each node has a schedule of awake times
- Typically used in star around coordinator
  - Bluetooth, ZigBee
  - Coordinator hands out slots
- Far more difficult with multi-hop networks
- Further complicated by network dynamics

CSMA basic scheme

CSMA = Carrier Sense Multiple Access

- Sense the medium
- If busy, back off
- If free, talk right away (1-persistent CSMA)...
- ...or pick a future time slot when you get to talk (non-persistent CSMA)

Non-persistent CSMA is the standard solution

MACs for WSN

- WSN MAC is one of the key research areas
- A smart MAC can save tons of energy

- S-MAC: seminal work
- BMAC: most influential design
- Optimizations: WISEMAC, X-MAC
- Building blocks: LPL, SIFT
- Special solutions: Wake-Up Radio (STEM)

- Check out the *MAC Alphabet Soup* at: http://www.st.ewi.tudelft.nl/~koen/MACsoup/index.php

S-MAC

- A MAC scheme targeted at WSNs

- Use RTS/CTS while duty-cycling the nodes

- Fairness is not so important in WSNs

o In regular wireless networks, each user deserves an equal share of medium access

o In WSNs, typically:

  - all nodes cooperate toward the same goal
  - a node may have a lot more data to send than everyone else

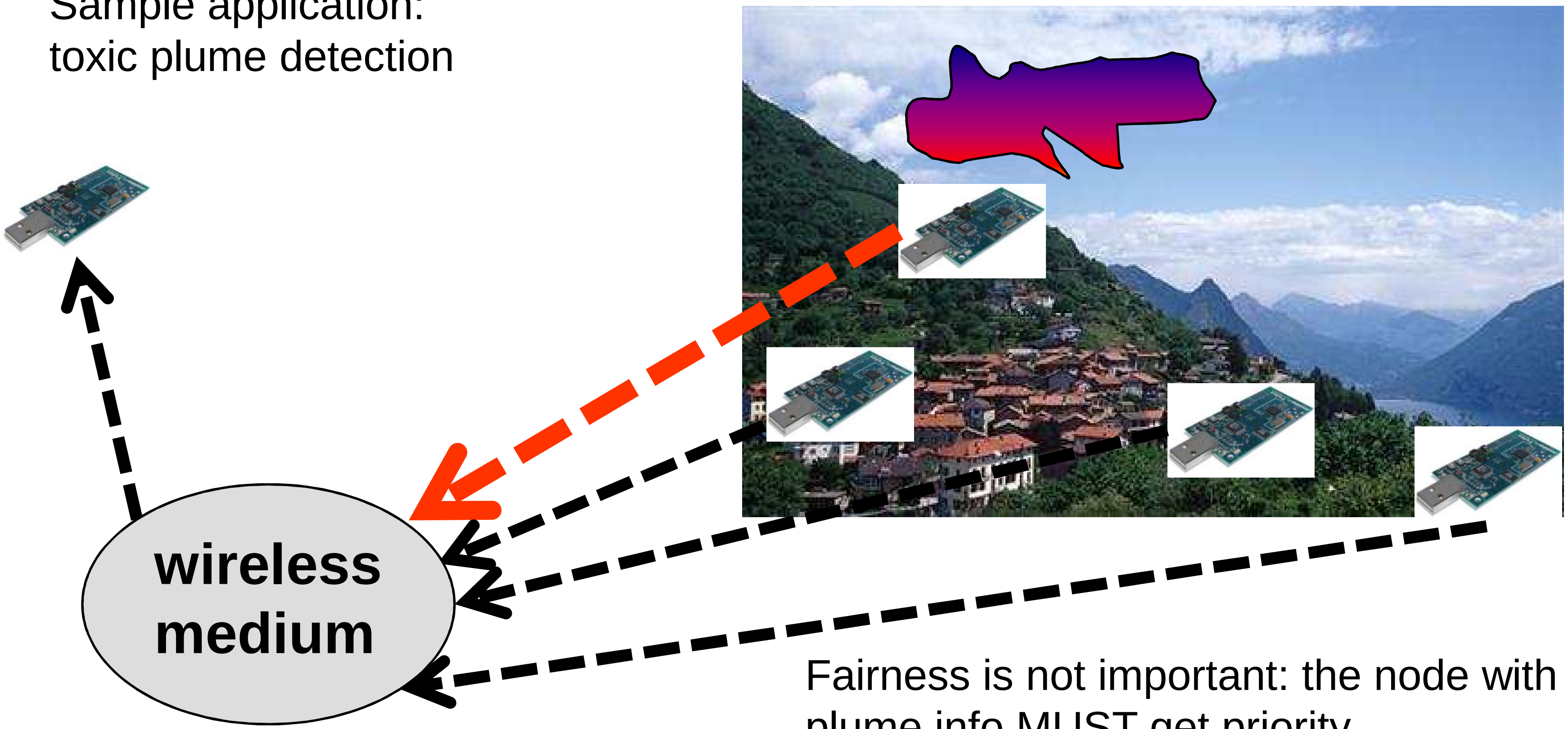
S-MAC solution: if you have more data, you get a bigger share

- Latency is not so important in many applications

S-MAC solution: nodes put their radios to sleep for part for the time

An Energy-Efficient MAC Protocol for Wireless Sensor Networks
W. Ye, J. Heidemann, and D. Estrin, INFOCOM'02

Sample application:
toxic plume detection



Fairness is not important: the node with the plume info MUST get priority

More on S-MAC

- Nodes set up schedules (sleep/activity)
- Schedules are exchanged
- Medium contention (RTS/CTS) only within activity periods
- RTS/CTS reserves medium for a whole message (unfair)
- Overhearing avoidance: extra-sleep if you get RTS or CTS

- Nodes need to be synchronized
- Control overhead is significant: sync and RTS/CTS
- Poor scalability properties (schedules require memory space)

Addressing all sources of inefficiency

S-MAC tries to reduce energy waste from all four sources of energy inefficiency

- Collision – with RTS and CTS
- Overhearing – by duty-cycling the radio
- Control overhead – with message passing
- (messages get broken down into small packets and sent as a burst)
- Idle listening – with periodic listen and sleep

Duty-Cycling

- WSN Problem: Idle listening uses up tons of energy
- S-MAC Solution: Periodic listen and sleep

- Benefit: much lower energy consumption
- Drawbacks:

  more latency

  less fairness

Latency and Fairness are a small price to pay

MAC-level Duty Cycling is now a standard technique

Collision Avoidance

WSN Problem: Multiple senders want to talk together

Options: Contention vs. TDMA

S-MAC Solution:

Similar to IEEE 802.11 ad hoc mode (DCF)

- Physical and virtual carrier sense
- Randomized back-off time
- RTS/CTS for hidden terminal problem
- RTS/CTS/DATA/ACK sequence

Overhearing Avoidance

WSN Problem: You receive packets destined to others
S-MAC Solution: Sleep when neighbors talk

Who should sleep?

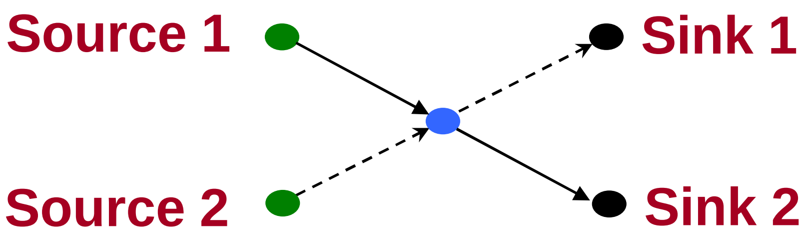
- All immediate neighbors of sender and receiver

How long to sleep?

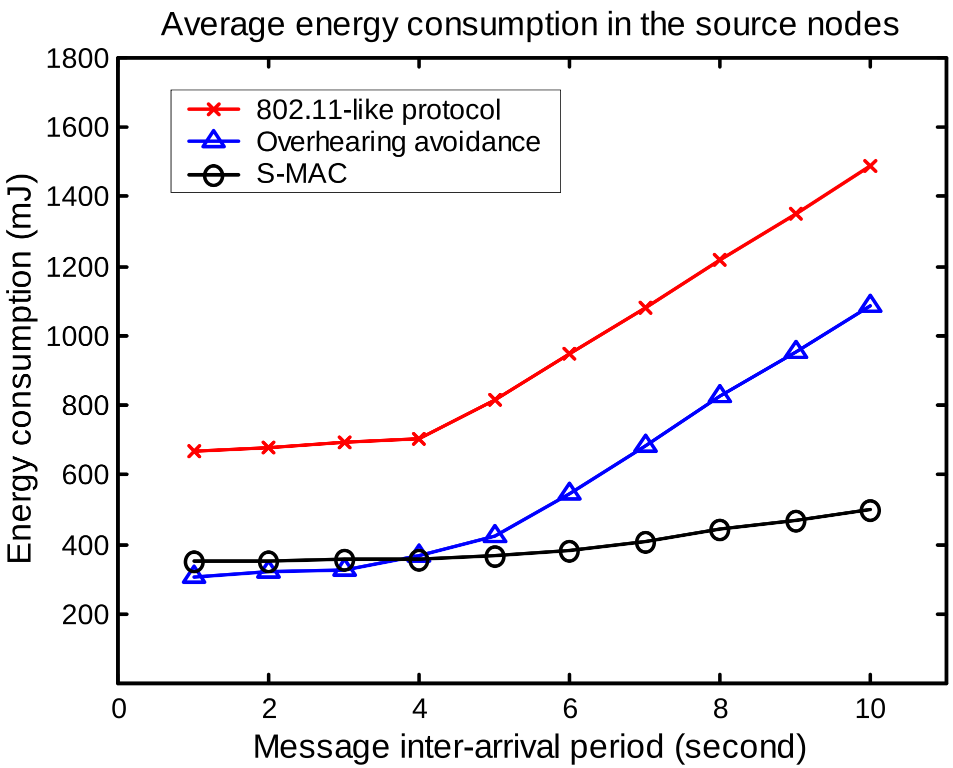
- The *duration* field in each packet informs other nodes the sleep interval

Synchronization is needed, but not as tight as TDMA

Performance Evaluation



- Each source node sends 10 messages
- Each message has 400B in 10 fragments
- Measure total energy over time to send all messages



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B-MAC

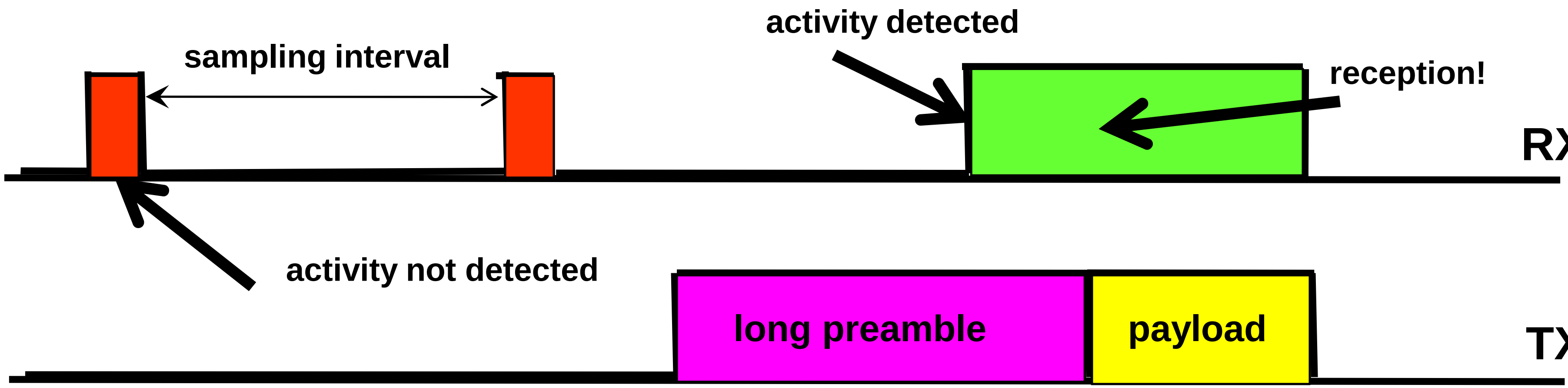
- Uses CSMA/CA
- Radio duty-cycling: Low Power Listening
- Packets can be individually acknowledged

- No schedule exchange (less control overhead)
- Channel is sampled periodically for activity
  - Preamble matched to sampling interval to ensure activity detection
  - Rx cost is reduced, but Tx cost is increased
  - False positives mess up the duty-cycling

- Puts simplicity first to ensure a small footprint
- Modular and tunable

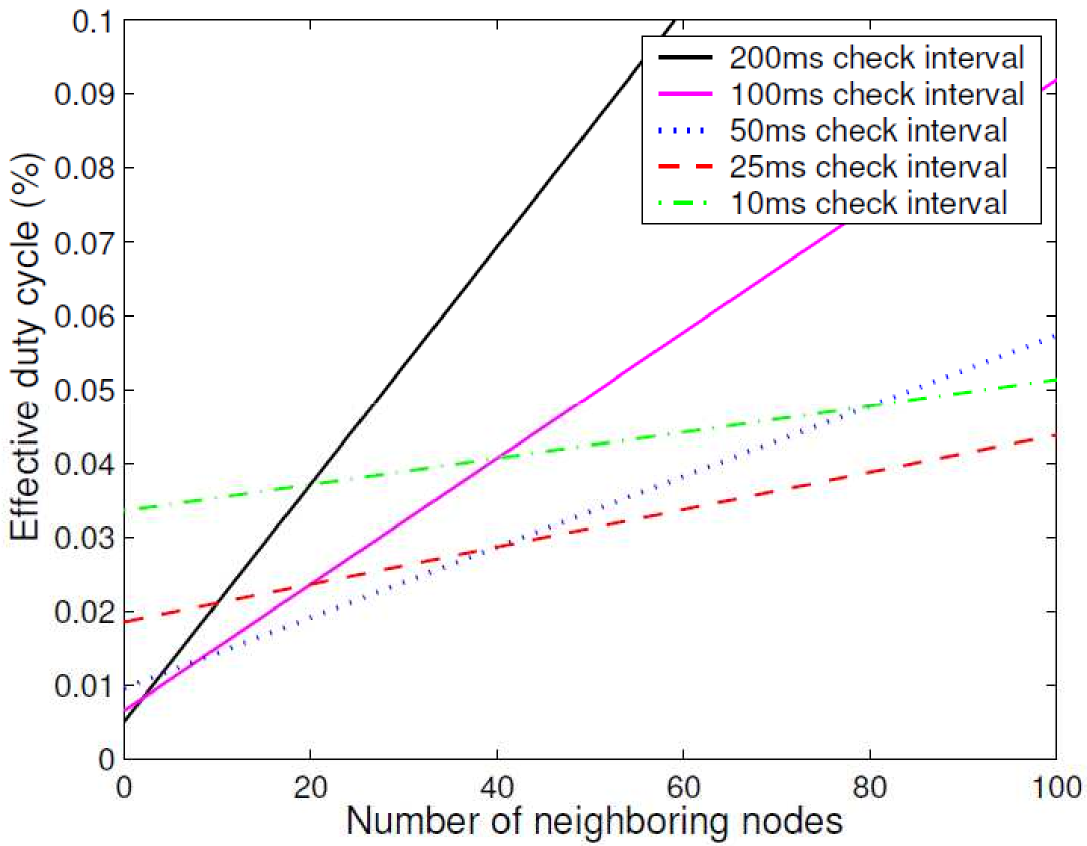
B-MAC's long preamble concept

Low Power Listening (LPL) is the centerpiece of B-MAC



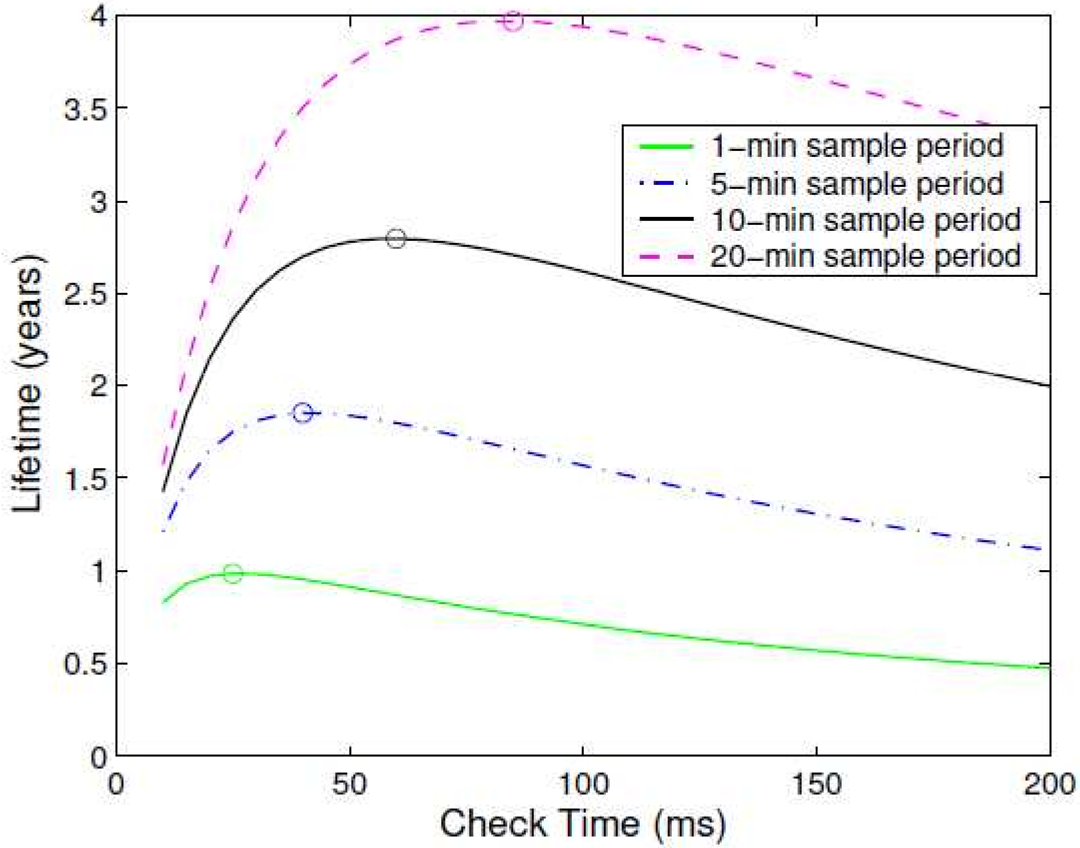
- B-MAC shifts the energy burden from the RX to the TX

Duty-Cycle vs. Neighborhood Size



Versatile Low Power Media Access for Wireless Sensor Networks
J. Polastre, J. Hill, and D. Culler, SenSys'04

BMAC Sleep Time Settings



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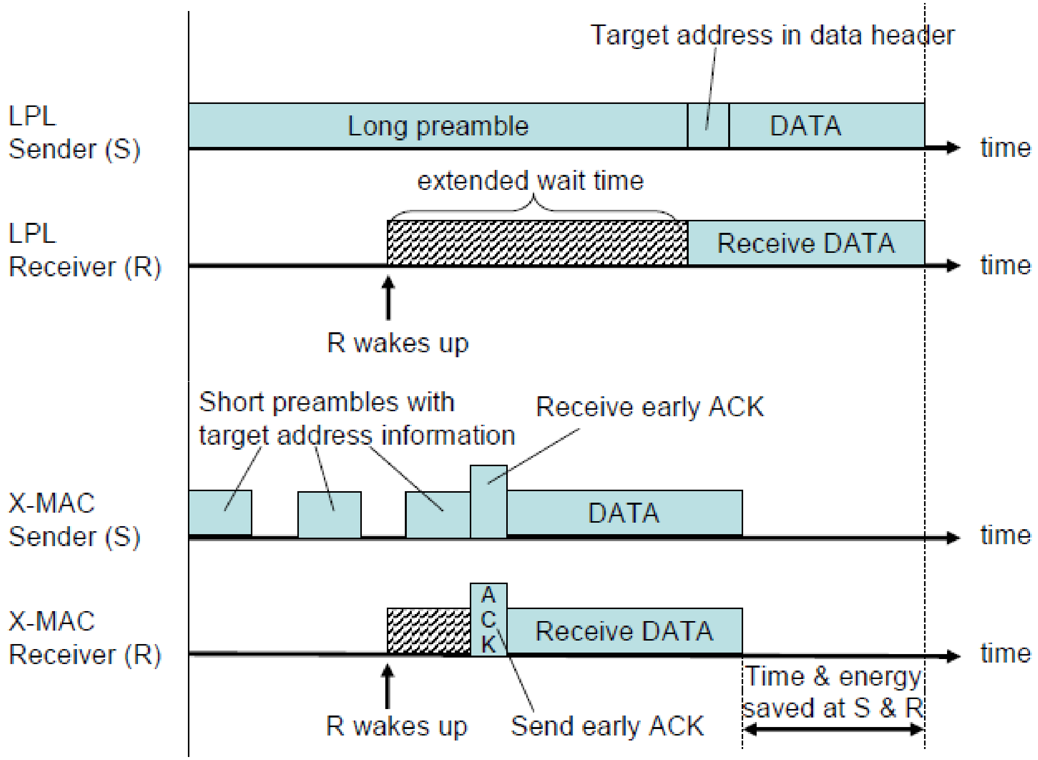
J. Polastre, J. Hill, and D. Culler, SenSys'04

X-MAC



- A long preamble means too much latency
- A strobed preamble allows the receiver to cut the preamble short

X-MAC: a short preamble MAC protocol for duty-cycled wireless sensor networks

M. Buettner et al., SenSys'06

WISEMAC

- Keep track of your neighbors

Achieve a coarse synchronization to them

- Avoid a long preamble for frequent traffic exchanges

Preamble Length is proportional to Inter-Packet Interval
Longer preambles for infrequent traffic

- Timing information gets piggy-backed on packets

Preambles start out long and get shorter as more packets are exchanged

- A shorter preamble saves energy at the tx as well as at the overhearing nodes

- Only works for unicast (broadcast must reach everyone)

Collisions

Collisions are natural with random access
When a collision occurs, node back off

Standard Approach: Binary Exponential Backoff

- When a collision first occurs, pick a slot in your Contention Window (CW) uniformly at random
  - o CW = bunch of slots
  - o Slot = opportunity for a node to start transmitting
- In your slot, sense the medium and back off if it's busy
- Each time a collision reoccurs, double the CW

- You win if you catch the earliest slot

CSMA and Event-Driven WSNs

In event-driven sensor networks:

- Collisions are spatially correlated
- Traffic is bursty
- The number of competing senders changes rapidly

With a uniformly random slot choice, scalability is poor

With more than 15 contending senders and 32 slots, the probability of success drops dramatically

Increasing the CW is a waste of time!

SIFT

A building block for the MAC layer of event-driven WSNs

• With a uniform distribution for slot choice, any node can pick any slot in the CW with the same probability
• Use a skewed distribution that makes it more likely for nodes to choose later slots

Benefit: only a few nodes will pick the early slots

Up to a 7-fold latency reduction compared to standard CSMA

Sift: A MAC Protocol for Event-Driven Wireless Sensor Networks, K. Jamieson, H. Balakrishnan, and Y. Tay, EWSN'06

The Wake Up Radio Concept

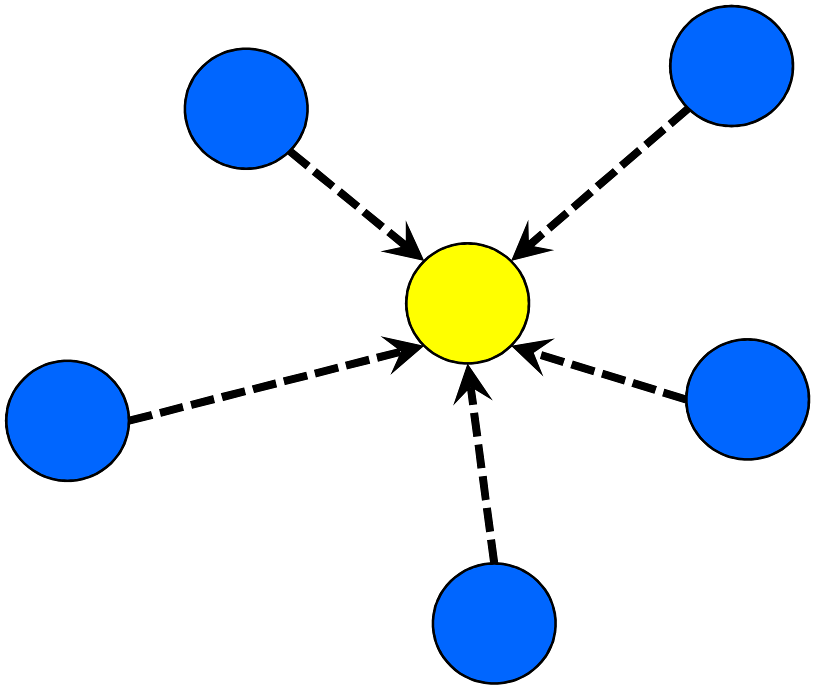
Use an ultra-cheap radio to wake up your low-power radio

Pioneered by the PicoRadio Project
- Susceptible to noise (false alarms)
- The ultra-cheap wake-up radio can't reach as far as the transfer radio

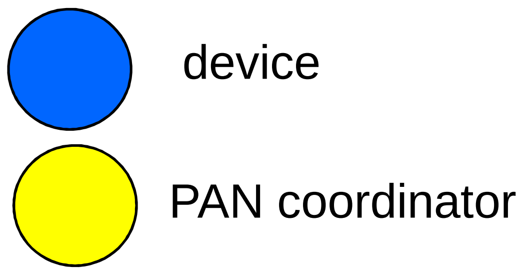
STEM (Sparse Topology and Energy Management), Schurgers et al., 2002
- Your wake-up radio needs not be ultra-cheap...just run it wisely
- Decouple wake-up from transfer:
  - one radio turns on the link (on-demand continuous polling)
  - another radio uses the link
  - rationale: continuous polling hurts ongoing data transfers
- Same radio at different frequencies?
  - no concurrent transfer and wake-up

802.15.4 MAC

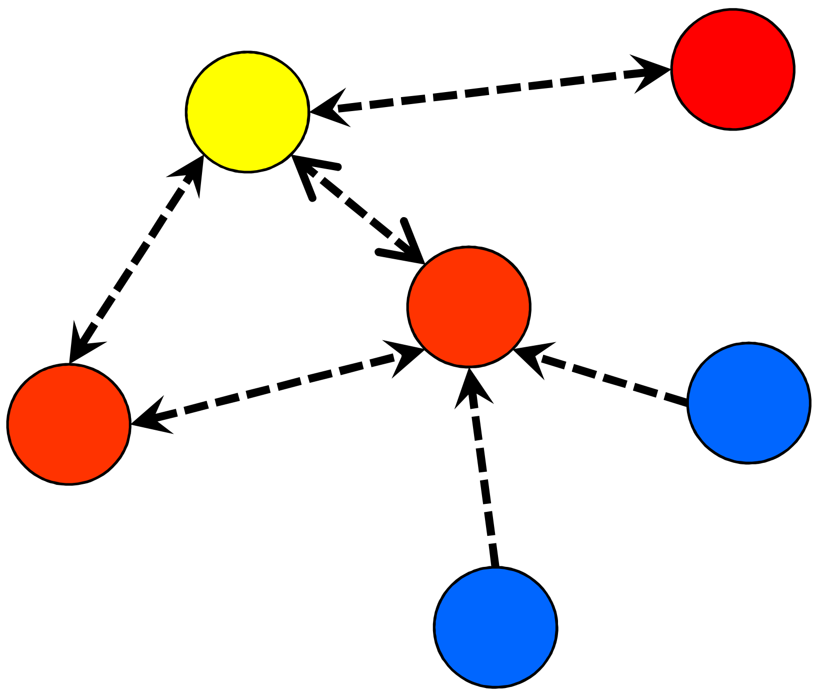
- Contention-based (with optional priority)
- Hierarchical
- Nodes can be coordinators or devices
- One coordinator is elected as PAN coordinator
- Coordinators are in charge, devices comply
- FFDs (Full Function Devices) can be either
- RFDs (Reduced Function Devices) are devices
- Two possible communication patterns: star and peer-to-peer
- Two modes: beaconed and non-beaconed



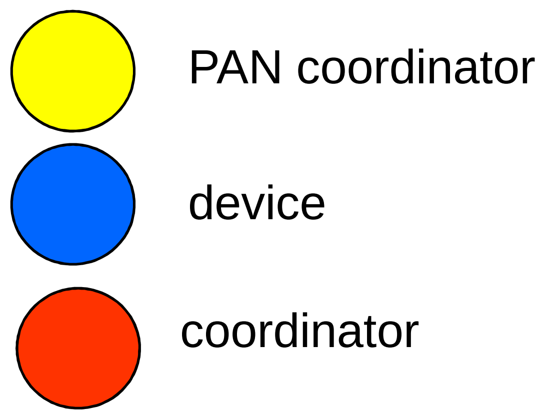
- Devices can only obey
- They cannot talk to each other
- They comply with the instructions of a coordinator



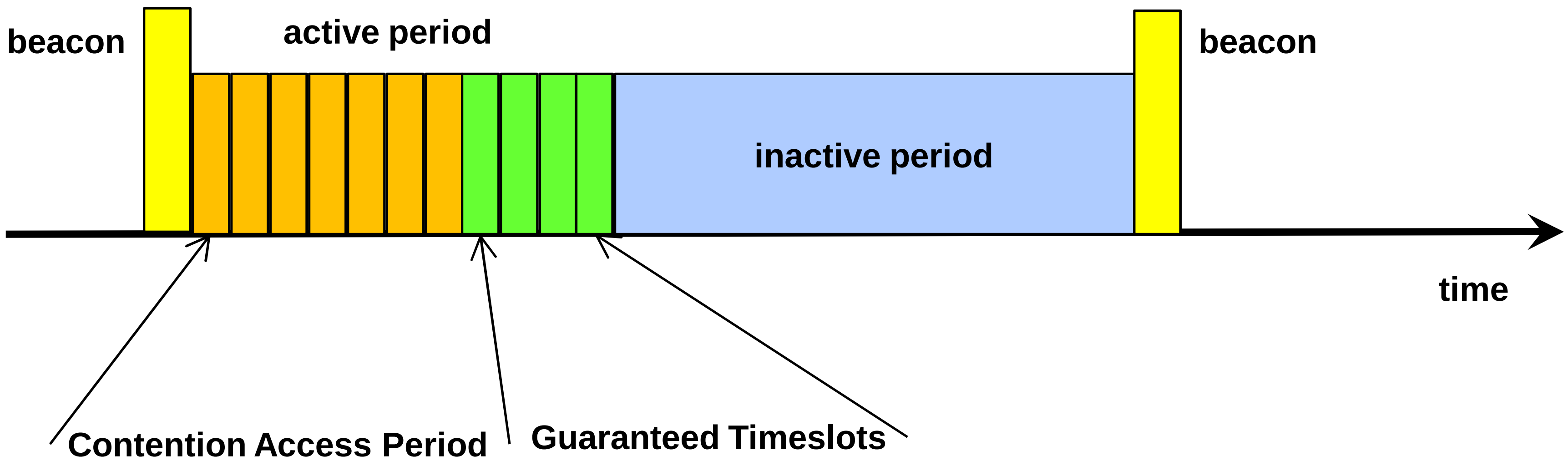
802.15.4 generalized topology



• Coordinators can talk to each other (peer-to-peer)



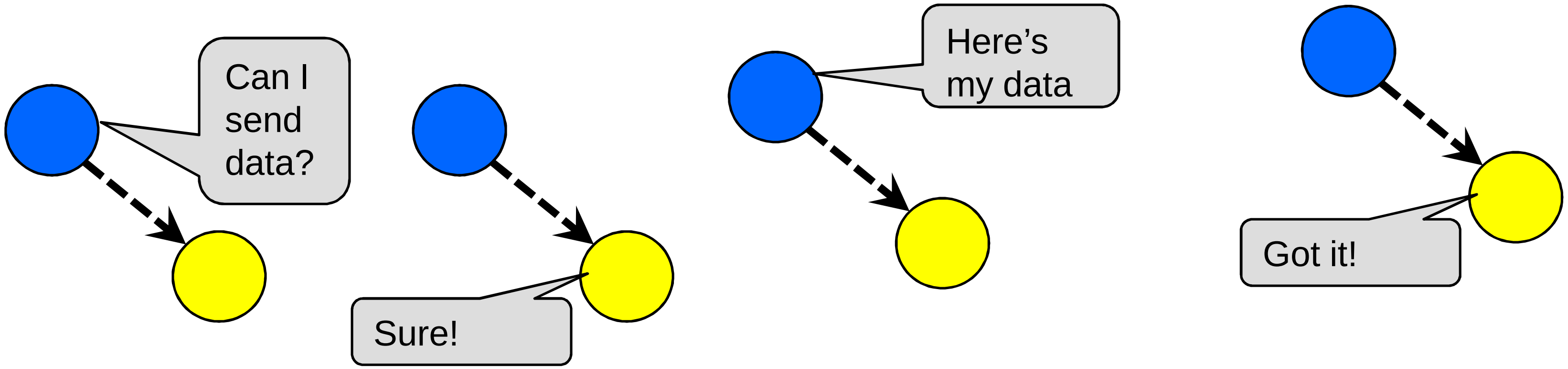
802.15.4 MAC Beaconed Mode



- Active/inactive for duty-cycling of coordinators
- Contention Access Period: slotted CSMA/CA, backoff in [0, (2^*B*)-1]*t*
  B=Backoff Exponent: starts out at 1, incremented at each failed access
- Guaranteed Timeslots: TDMA medium access
- Beacons for management (sync, association, timeslot assignment)

802.15.4 Non-Beaconed Mode

- Coordinators always on (no duty-cycling for the boss)
- Unslotted CSMA for devices
- Data/ack handshake



- MAC immediately acknowledges received packets

Reading List

1. W. Ye, J. Heidemann, and D. Estrin", An Energy-Efficient MAC protocol for Wireless Sensor Networks, INFOCOM’02 (S-MAC paper)

2. J. Polastre, D. Culler, "Versatile Low Power Media Access for Wireless Sensor Networks", SenSys'04 (B-MAC paper)