Medium Access Control

Daniele Puccinelli

daniele.puccinelli@supsi.ch
http://web.dti.supsi.ch/~puccinelli
MAC = Medium Access Control

I want to talk to B...

...over a shared medium

A wants to drive to B

but there is traffic on the road: need to avoid collisions

Daniele Puccinelli
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
A wants to transmit to B...who is receiving from C
Collisions

Daniele Puccinelli
A cannot hear C...and A’s and C’s packet collide at B
Overhearing

I’m not C

Here’s a packet for C!

That’s me!

I’m not C

Daniele Puccinelli
In legacy wireless, collisions are addressed with RTS/CTS
In legacy wireless, collisions are addressed with RTS/CTS

C: You’re Clear To Send
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 magnitude) 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 = 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
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

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

![Graph showing lifetime vs check time for different sample periods]

- 1-min sample period
- 5-min sample period
- 10-min sample period
- 20-min sample period

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

Daniele Puccinelli
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
• 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 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
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!
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

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
802.15.4 Basic Topology

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

- device
- PAN coordinator

Daniele Puccinelli
802.15.4 generalized topology

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

PAN coordinator
device
coordinator

Daniele Puccinelli
802.15.4 MAC Beaconsted 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

Can I send data?
Sure!
Here's my data
Got it!

- MAC immediately acknowledges received packets

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