Low-Power System Design

227-0781-00L

Fall Semester 2019

Jan Beutel

ETH zürich

Plan for Today

- Background: Introduce basics of wireless packet data networking (on embedded devices)
- Classification of MAC protocols
- Tradeoff and protocol scheme variants

- Advanced MAC Layer Schemes

- Slides contain material from P. Dutta, F. Oesterlind and F. Ferrari

Highly Resource Constrained

Distributed State

Wireless Networked Embedded Systems

Unreliable Communication

Interaction and Tight Embedding in Environment

Low-Power System Design

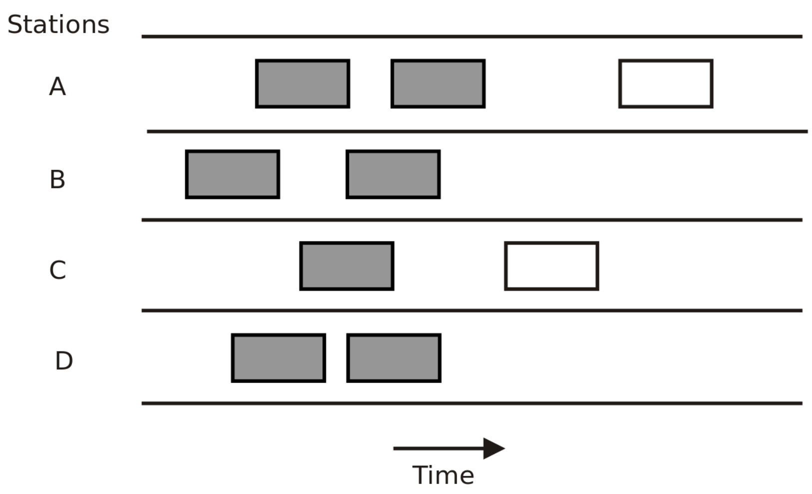
PHYSICAL AND MEDIUM ACCESS LAYER NETWORKING BACKGROUND

Wireless Packet Data Networking

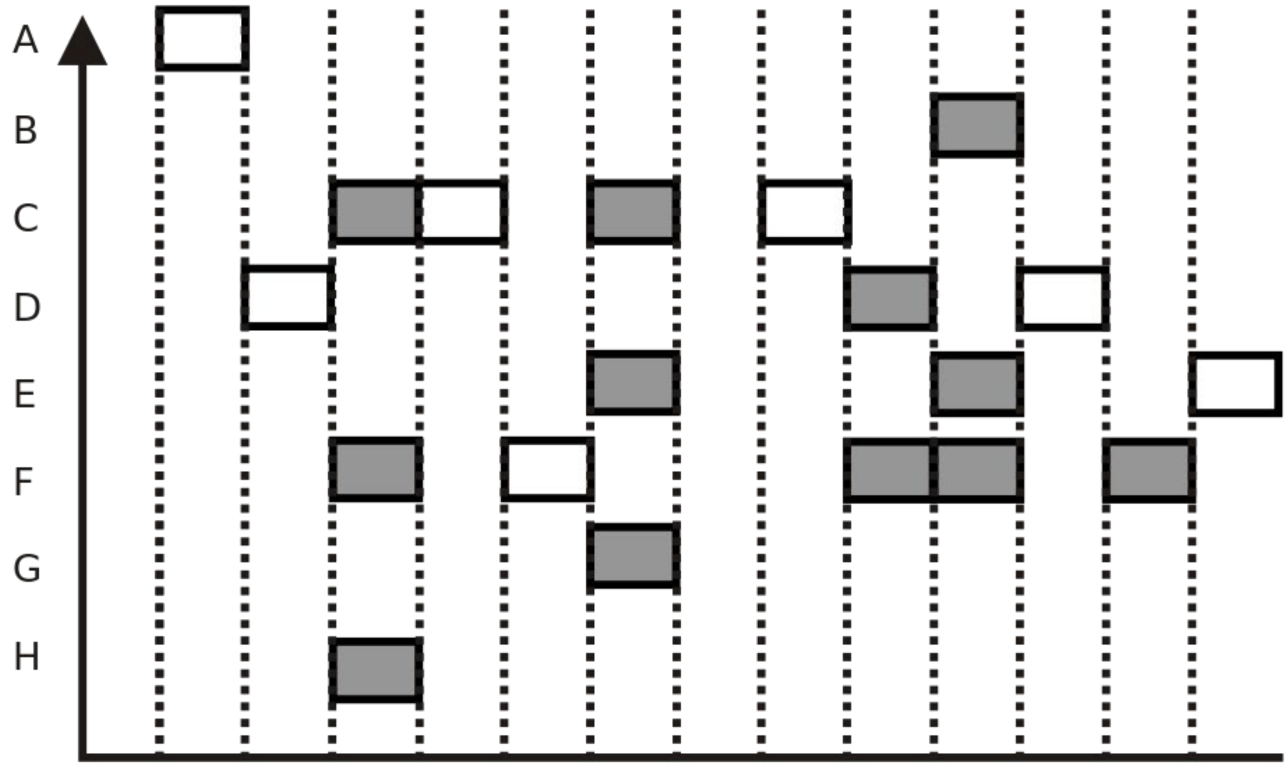
- **ALOHAnet**, also known as the **ALOHA System** [University of Hawaii, 1971]

[N. Abramson (1970). "The ALOHA System - Another Alternative for Computer Communications" (PDF). Proc. 1970 Fall Joint Computer Conference. AFIPS Press.]

  - If you have data to send, send the data.
  - If, while you are transmitting data, you receive any data from another station, there has been a message collision. All transmitting stations will need to try resending "later".



Simple Improvement – Slotted ALOHA



Slotted ALOHA protocol (shaded slots indicate collision)

Typical Design Tradeoff Questions

- The quantity and type of physical channels used
- The degree of organization between nodes
- The way in which a node is notified of an incoming message
- Coupling of radio and protocol processor

Sources of (Energy) Overhead

- Idle listening
  - Since a node does not know when it will be the receiver of a message from one of its neighbors, it must keep its radio in receive mode all the time.
- Collision
  - Energy used during transmission and reception is wasted.
  - RTS/CTS
- Overhearing
  - A node may receive packets that are not destined for it.
  - Turn off the radio.
- Protocol overhead
  - MAC headers and control packets do not contain application data.
  - The data is short.
- Traffic fluctuations
  - A sudden peak in activity raises the probability of collision.
  - Much time and energy are spent on waiting in the random back off.
  - The performance collapse when the load approaches the channel capacity.

[abridged from K. Langendoen, Delft]

Wireless Media Access Control

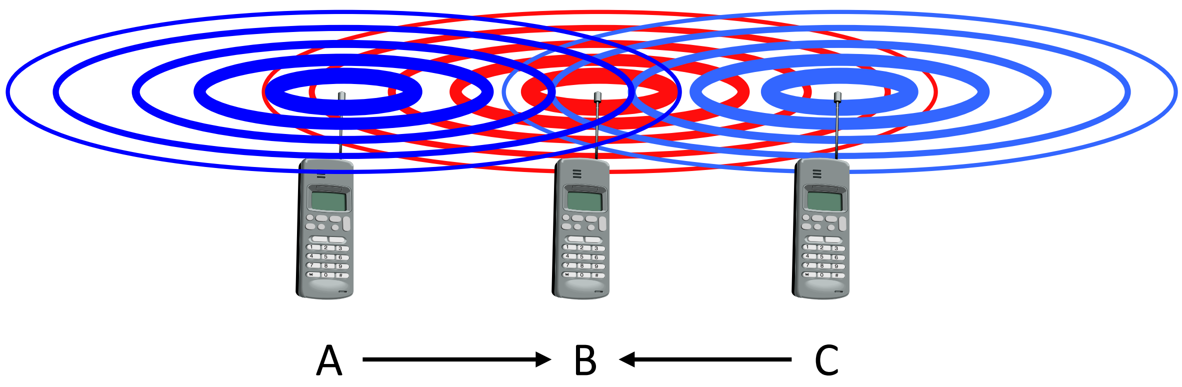
Naïve question:

Can we apply media access methods from fixed networks?

- Example CSMA/CD
  - **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection
  - Send as soon as the medium is free, listen into the medium if a collision occurs (original method in IEEE 802.3)
- Problems specific to wireless networks
  - **Physical Channel**: Signal strength decreases quickly with distance
  - **Arbitration**: Senders apply CS and CD, but the collisions happen at the receivers
  - **Energy efficiency**: Radio turned on costs almost as much energy as transmit or receive -> turn off the radio

Wireless – Hidden Terminal Problem

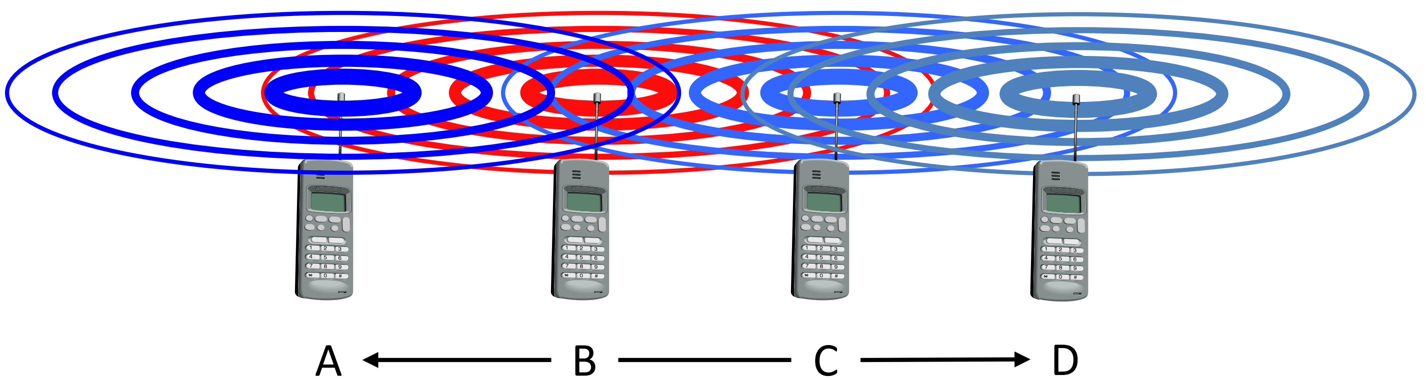
- A sends to B, C cannot receive A
- C wants to send to B, C senses a “free” medium (CS fails)
- Collision happens at B, A cannot receive the collision (CD fails)
- A is “hidden” for C



[abridged from R. Wattenhofer]

Wireless – Exposed Terminal Problem

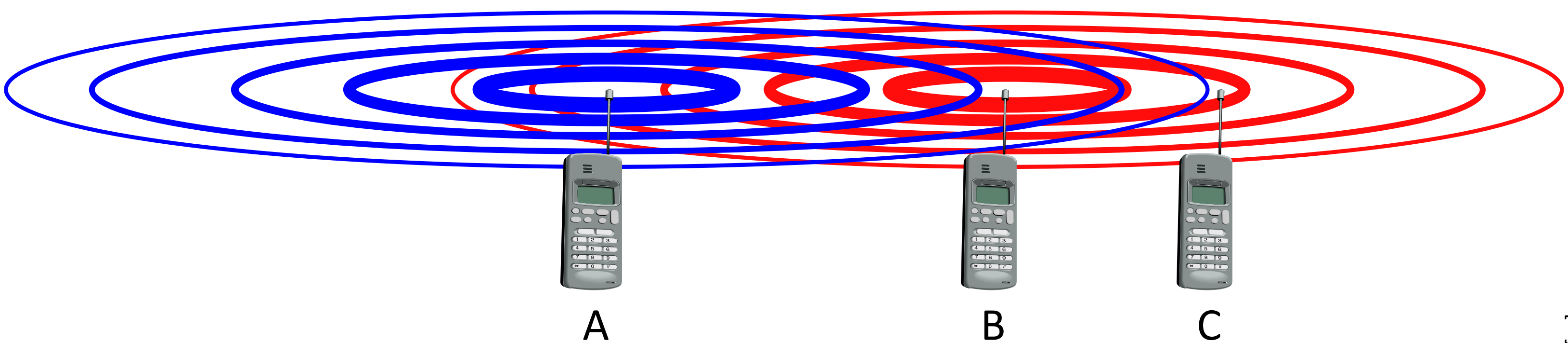
- B sends to A, C wants to send to D
- C has to wait, CS signals a medium in use
- Since A is outside the radio range of C waiting is not necessary
- C is “exposed” to B



[abridged from R. Wattenhofer]

Wireless - Near and Far Terminals

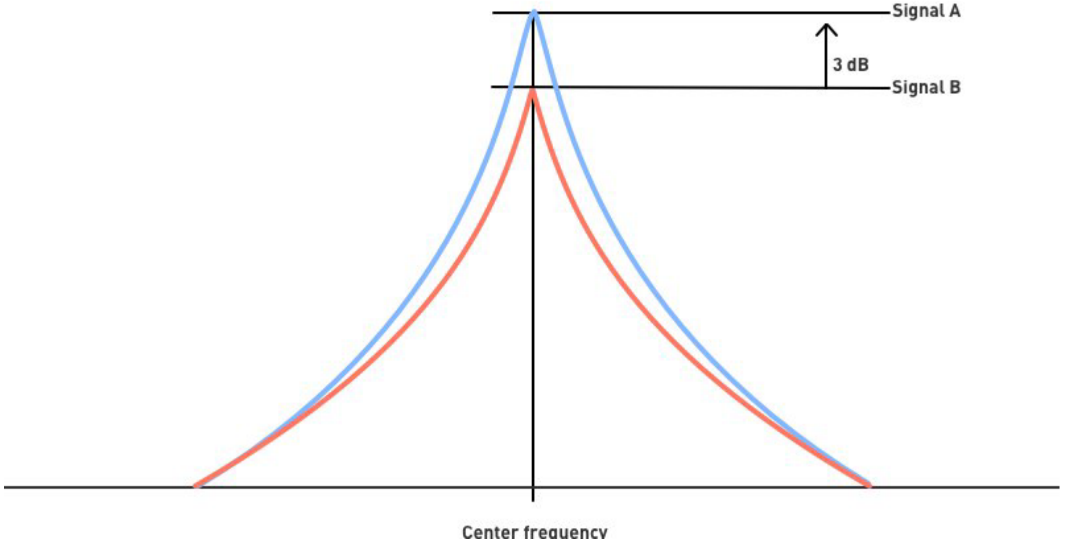
- Terminals A and B send, C receives
- The signal of terminal B hides A's signal
- C cannot receive A



[abridged from R. Wattenhofer]

Wireless – Capture Effect

- A phenomenon, associated with FM reception, in which **only the stronger of two signals** at or near the same frequency **will be demo**



In Reality Collisions are Signal Reception

Q: Is there a way to make sense of the signal (mess) received?

- **Power capture**: One response has a sufficiently higher power than the sum of the others…

  and it arrives first
- **Delay capture**: One response frame arrives some time before the remaining ones…

  and its power is higher than the sum of the others
- **Message-in-Message capture**: Like power capture, but the highest power frame arrives in the middle of another frame transmission and radio detects elevated energy…

  and the radio does continuous preamble detection

Wireless Medium Access Methods

- **SDMA** (Space Division Multiple Access)
  - Segment space into sectors, use directed antennas
  - Use cells to reuse frequencies
- **FDMA** (Frequency Division Multiple Access)
  - Assign a certain frequency to a transmission channel
  - Permanent (radio broadcast), slow hopping (GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- **TDMA** (Time Division Multiple Access)
  - Assign a fixed sending frequency for a certain amount of time
- **CDMA** (Code Division Multiple Access)
  - Use coding to discern individual signals (802.11 DSSS)
- And combinations!

[abridged from R. Wattenhofer]

Comparison SDMA/TDMA/FDMA/CDMA

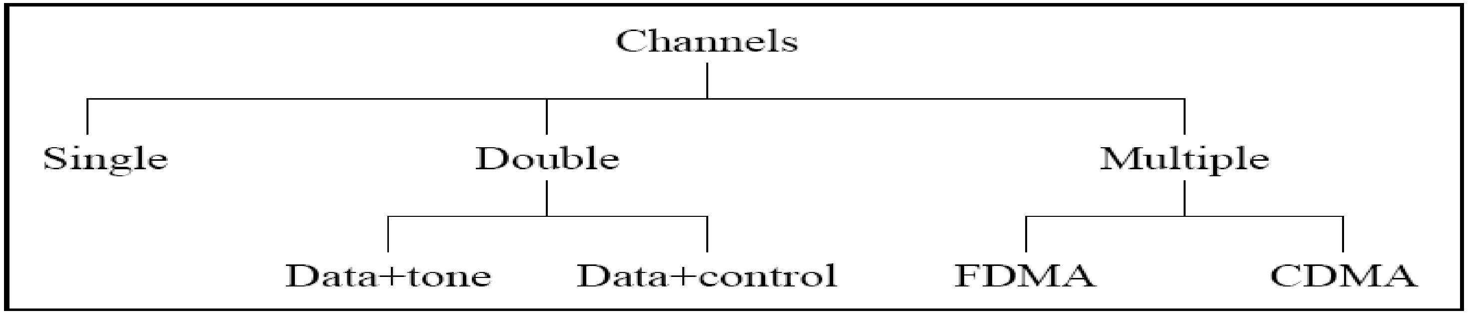
Approach	SDMA	TDMA	FDMA	CDMA
Idea	segment space into cells/sectors	segment sending time into disjoint time-slots, demand driven or fixed patterns	segment the frequency band into disjoint sub-bands	spread the spectrum using orthogonal codes
Terminals	only one terminal can be active in one cell/one sector	all terminals are active for short periods of time on the same frequency	every terminal has its own frequency, uninterrupted	all terminals can be active at the same place at the same moment, uninterrupted
Signal separation	cell structure, directed antennas	synchronization in the time domain	filtering in the frequency domain	code plus special receivers
Advantages	very simple, increases capacity per km²	established, fully digital, flexible	simple, established, robust	flexible, less frequency planning needed, soft handover
Dis-advantages	inflexible, antennas typically fixed	guard space needed (multipath propagation), synchronization difficult	inflexible, frequencies are a scarce resource	complex receivers, needs more complicated power control for senders
Comment	only in combination with TDMA, FDMA or CDMA useful	standard in fixed networks, together with FDMA/SDMA used in many mobile networks	typically combined with TDMA (frequency hopping patterns) and SDMA (frequency reuse)	still faces some problems, higher complexity, lowered expectations; will be integrated with TDMA/FDMA

[abridged from J.Schiller]

Low-Power System Design

MEDIUM ACCESS LAYER CLASSIFICATION & EXAMPLES

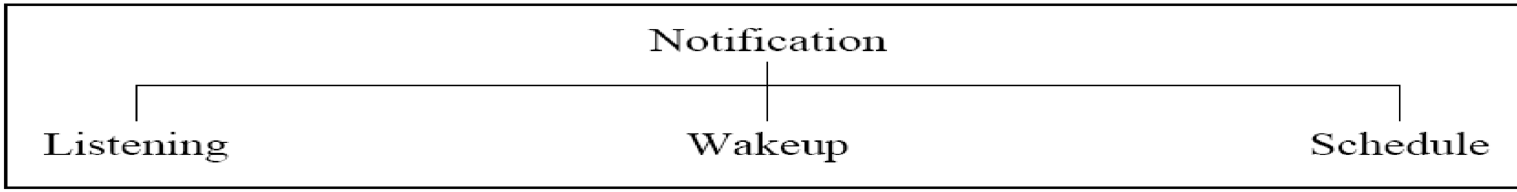
Is it good to use multiple channels?



- Single channels
- Multiple channels
  - FDMA or CDMA
    - It requires a rather complicated radio consuming considerable energy
  - Tone or control signal
    - Use a second, extremely low power radio that can be used for signaling an intended receiver to wake up

[abridged from K. Langendoen, Delft]

How do remote receivers get notified?

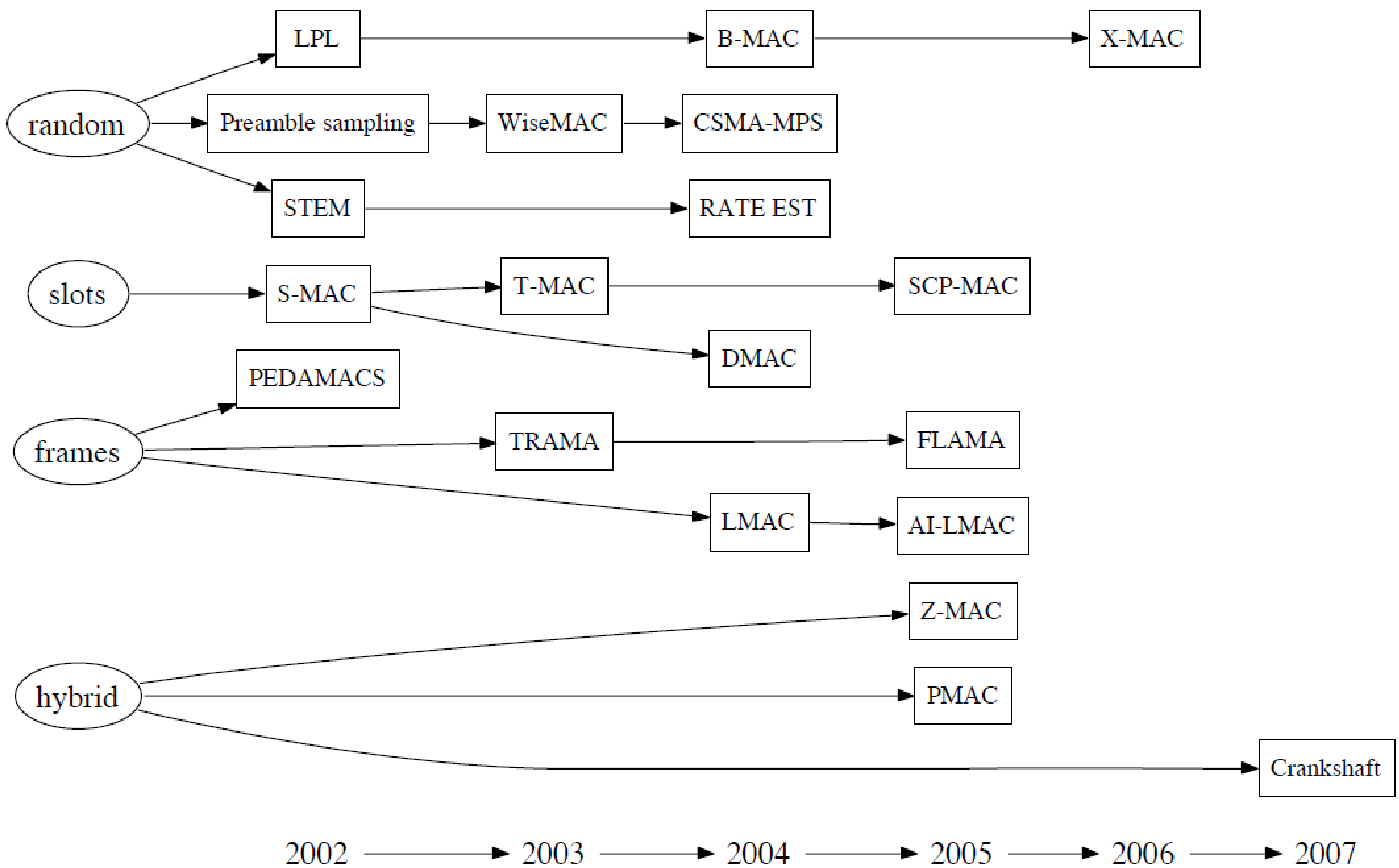


- Schedule-based protocols
  - Data transfers are scheduled ahead of time, so receiving nodes know exactly when to turn on the radio

- Contention-based protocols
  - Based on stochastic rendezvous techniques
  - Idle-listening
    - Use duty cycle
      - Individually (e.g. Low power listening)
      - Collectively per slot (e.g. S-MAC)
    - Use a cellular topology with access points (e.g. Sift)
  - Wakeup
    - Send a wake up tone over a second, very low-power radio

[abridged from K. Langendoen, Delft]

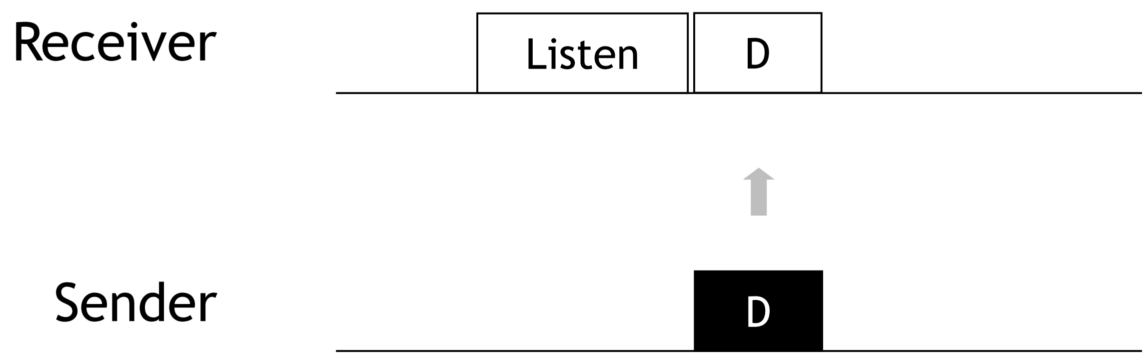
Contention vs. Time-based Schemes



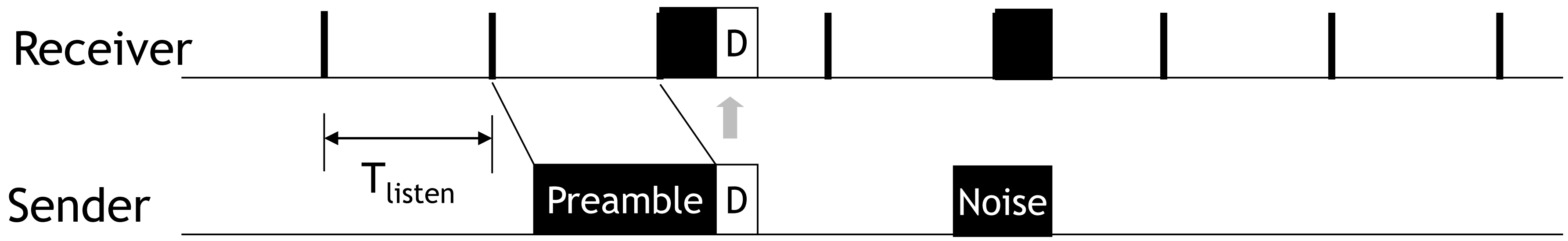
[K. Langendoen, Delft]

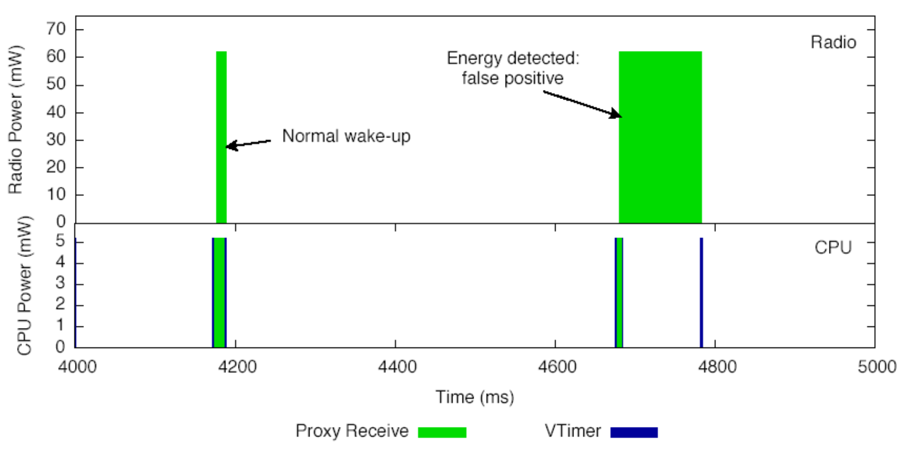
Simple Sender-Initiated MAC

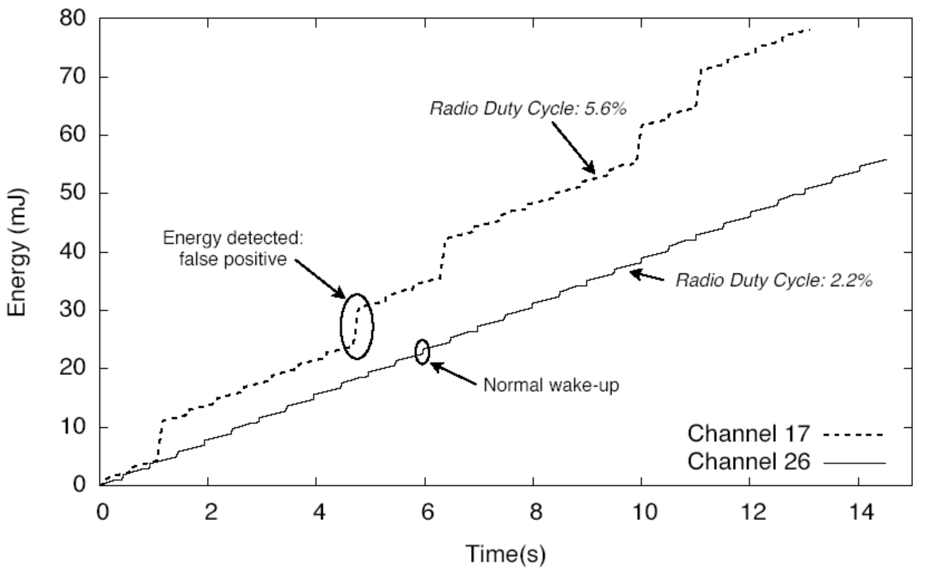
- Sender triggers communications by transmitting data
- Receiver is listening



Low-Power Listening (LPL) with a Sender-Initiated MAC



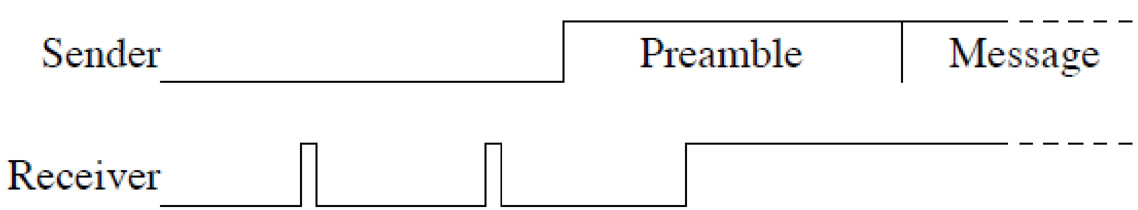




Overhearing/noise adds significant unpredictability to node lifetime

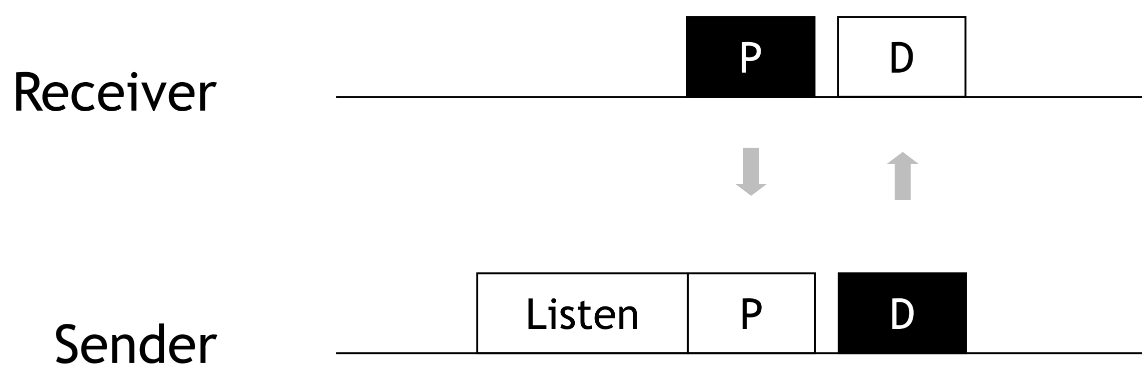
Contention-based: Low-Power Listening

- Messages are prefixed with wakeup preamble
- Periodical sensing of channel
  - Nodes sensing a “busy tone” keep radios on (until end of the message)
  - Requirement: Preamble longer than sleep interval to guaranteed wake up
- Benefit
  - Shift load from the receiver (reduced idle listening) to the sender (long preamble)
  - Saves energy for low-traffic and # receivers >> # sender scenarios
  - Very robust, no synchronization required, instant recovery after channel disruption
- Drawback
  - No collision avoidance, slight increase in latency
  - All nodes in range wake up
  - Preamble length can be much longer than the actual data length.

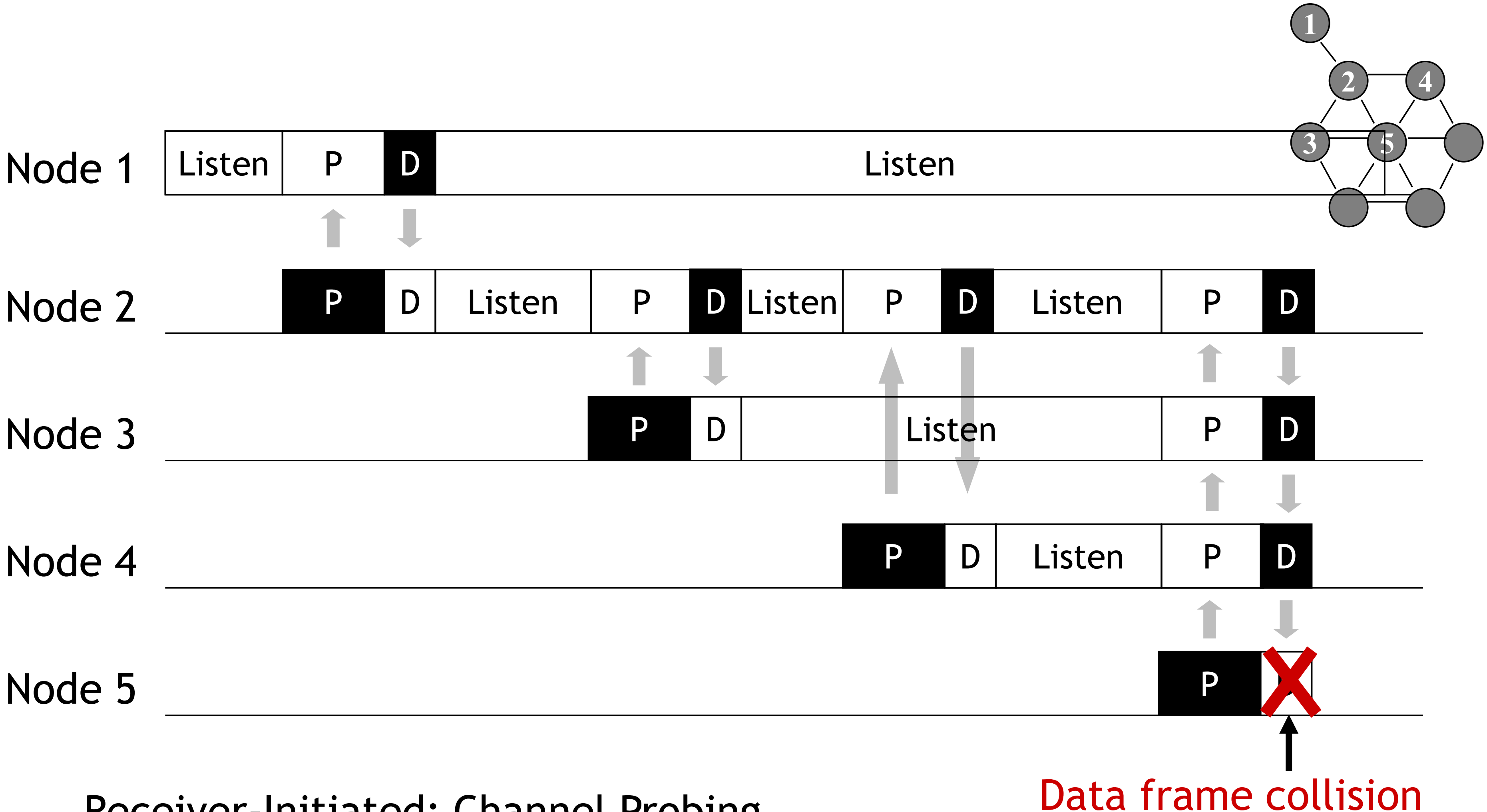


Simple Receiver-Initiated MAC

- Receiver triggers exchange by transmitting a probe
- Sender receives probe and sends data



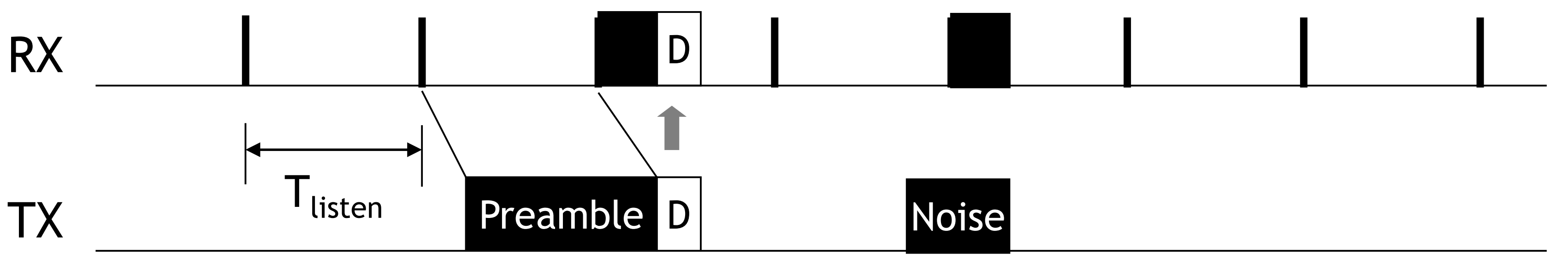
Example: Asynchronous Network Wakeup



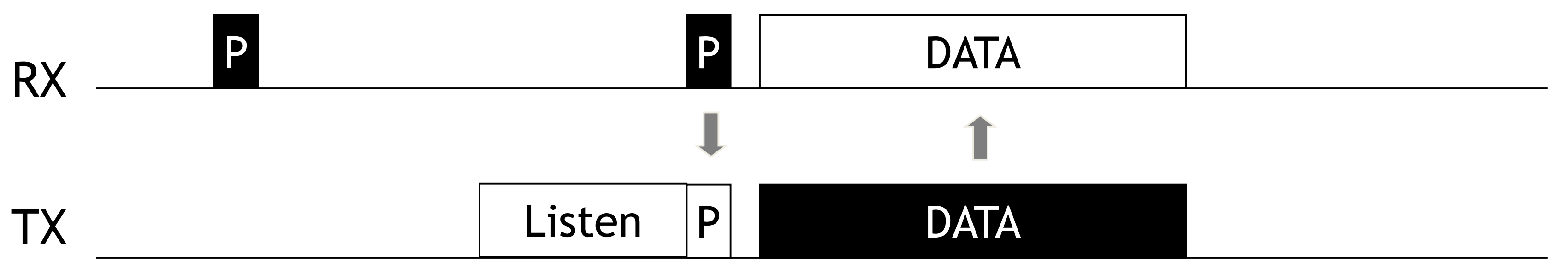
Receiver-Initiated: Channel Probing

MAC Layer Decision: Stay awake or go to sleep?

Sender-Initiated: Channel Sampling

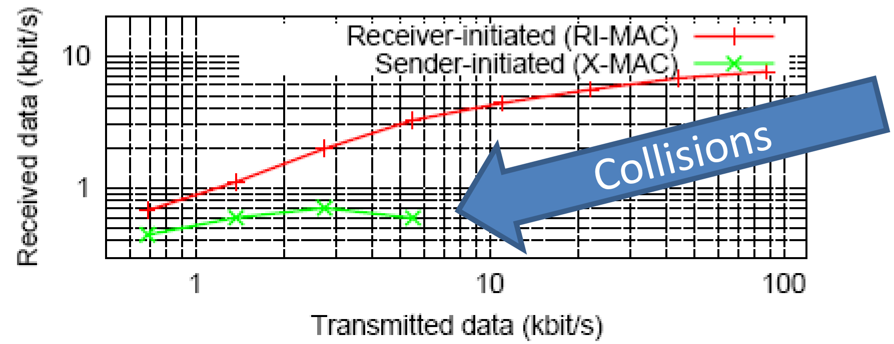


Receiver-Initiated: Channel Probing



Receiver vs. Sender-initiated Tradeoff

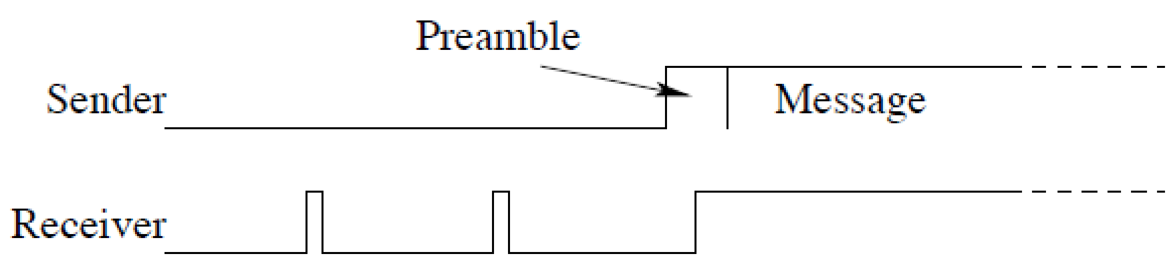
- Receiver-initiated Pro's
  - Handle hidden terminals better than sender-initiated ones
  - Support asynchronous communication w/o long-preambles
  - Support extremely low duty cycles or high data rates



- Receiver-initiated Con's
  - Probe (LPP) is more expensive than channel sample (LPL)
    - Baseline power is higher
  - Frequent probe transmissions
    - Could congest channel & increase latency
    - Could disrupt ongoing communications
    - Channel usage scales with node density rather than traffic

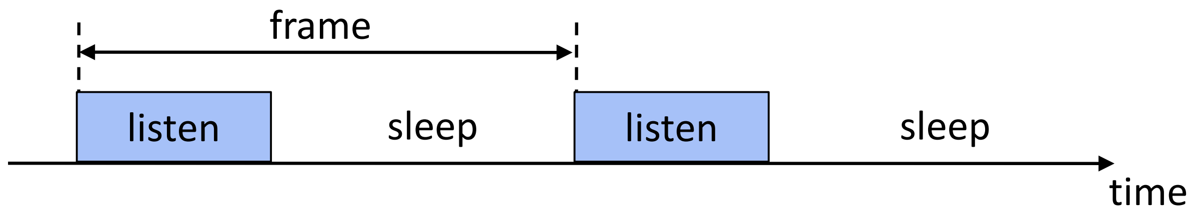
Optimizing LPL: Shorter Preamble Sampling

- Bookkeeping to avoid sending out long preambles
  - Maintaining the phase offset (clock) to selected neighbors
  - Start transmitting a message just before receiver wakes
  - Synchronized transmit/receive
  - Piggybacking of local phase offset on ACKs of the underlying CSMA protocol
- Benefits
  - WiseMAC is able to squeeze out up to 80% (20 out of 25 ms) of TX cost and up to 67% (10 out of 15ms) of RX costs
  - Shortening the preambles also reduces overhearing by nodes other than the sender/receiver pair

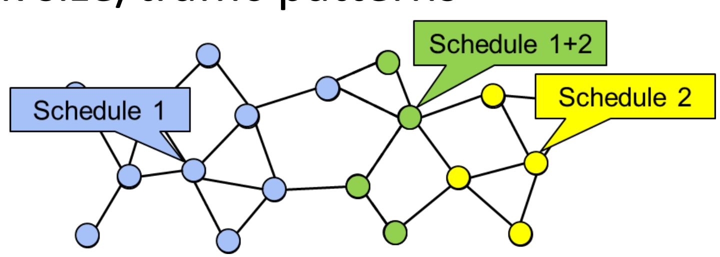


Time-based Protocol Schemes

- S-MAC: Coarse-grained TDMA-like sleep/awake cycles



- All nodes choose and announce schedules
  - Synchronization to schedules of neighboring nodes
- Use RTS/CTS to resolve contention during listen intervals
  - Allowing interfering nodes to go to sleep during data exchange
- Static schedule parameterization
  - A-priori knowledge of network size/traffic patterns
  - Partitioning problems
  - Inflexible



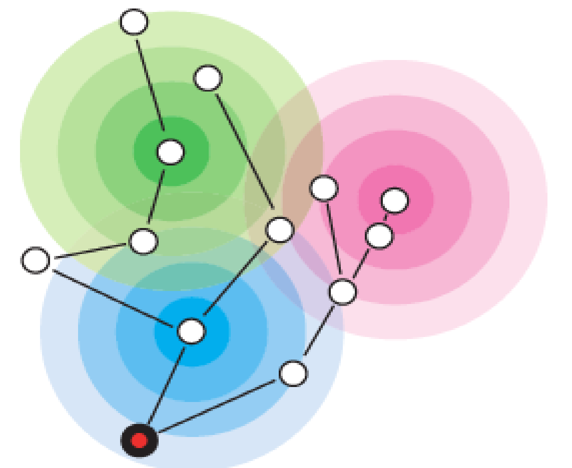
[abridged from R. Wattenhofer]

Networked Embedded Systems

ADVANCED MAC LAYER SCHEMES

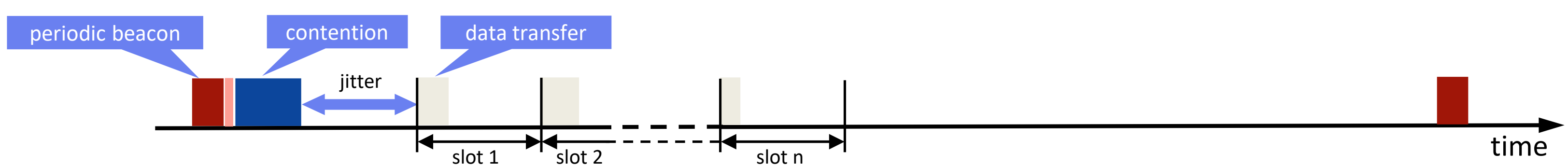
Hybrid Protocol Schemes

- Dozer ultra low-power data gathering system
  - Beacon based, 1-hop synchronized TDMA
  - Tree-based routing towards a sink
  - Optimized for ultra-low duty cycles
  - **0.167%** duty-cycle, **0.032mA** (@ 30sec beacons)



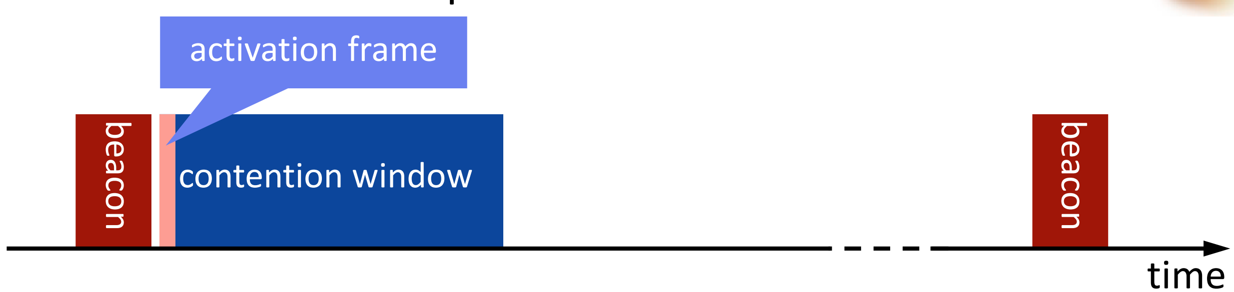
[Burri, N., von Rickenbach, P., & Wattenhofer, R. (2007). Dozer: Ultra-Low Power Data Gathering in Sensor Networks. 2007 6th International Symposium on Information Processing in Sensor Networks, 450–459.]

- Application is integrated with the protocol
  - Dynamic adaptation
  - Back-off randomization for diversity
  - Jitter adaptation over multiple hops
  - Adaptive duty-cycle accounts for long-term loss of connectivity



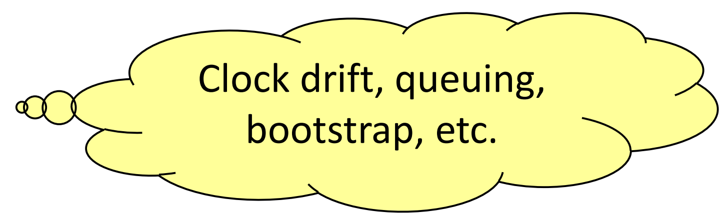
Dozer System

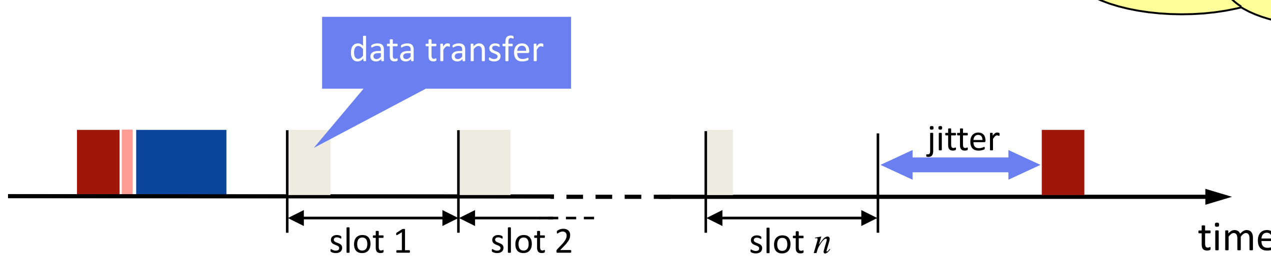
- Tree based routing towards data sink
  - No energy wastage due to multiple paths
  - Current strategy: SPT
- TDMA based link scheduling
  - Each node has two independent schedules
  - No global time synchronization
- The parent initiates each TDMA round with a beacon
  - Enables integration of disconnected nodes
  - Children tune in to their parent's schedule



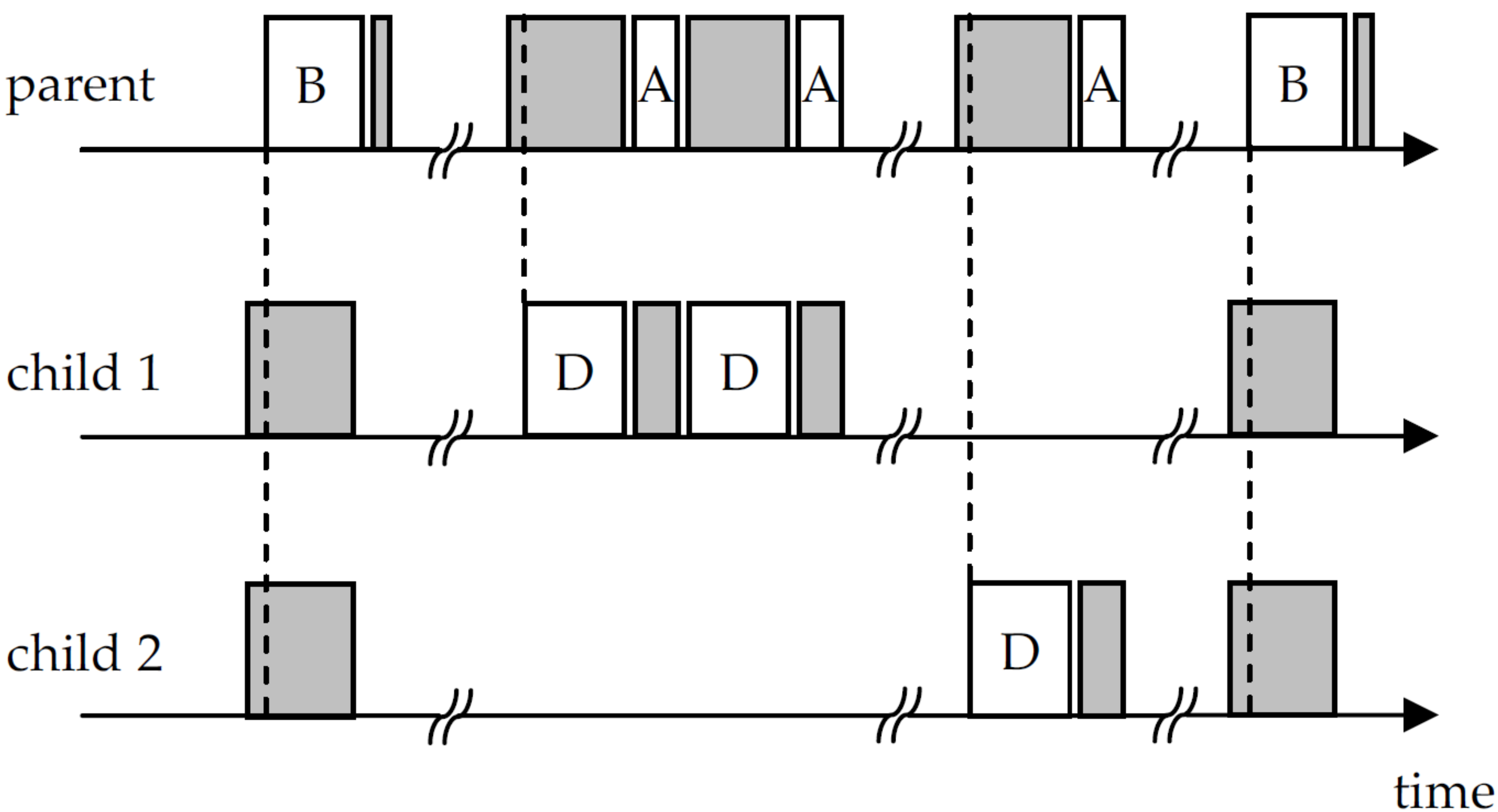
Dozer System

- Parent decides on its children data upload times
  - Each interval is divided into upload slots of equal length
  - Upon connecting each child gets its own slot
  - Data transmissions are always ack'ed
- No traditional MAC layer
  - Transmissions happen at exactly predetermined point in time
  - Collisions are explicitly accepted
  - Random jitter resolves schedule collisions



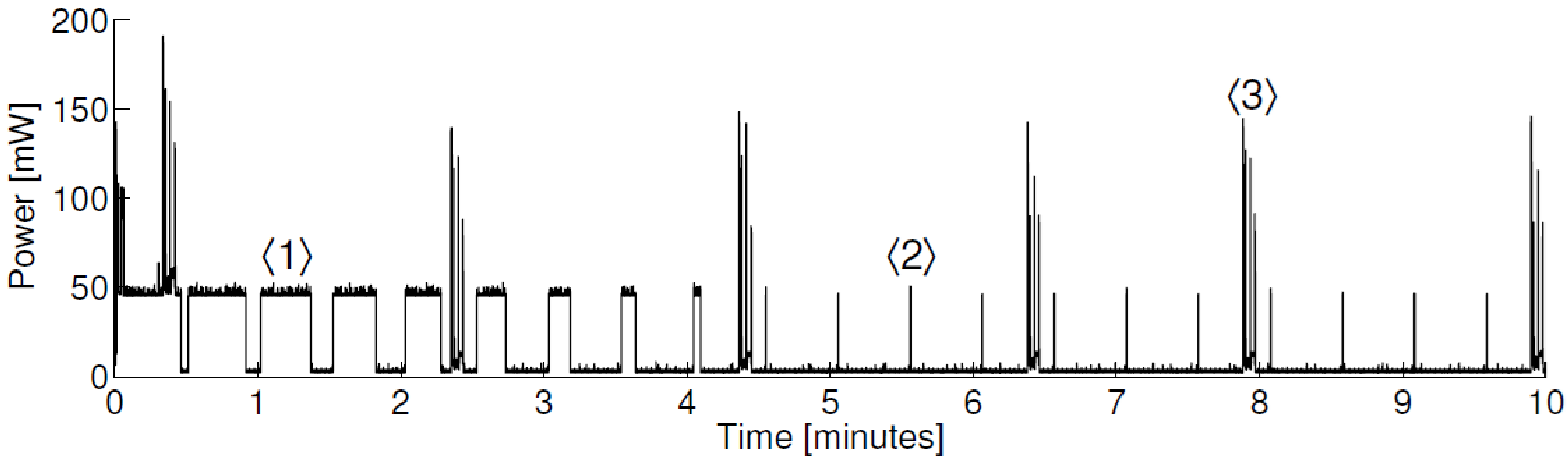


Dozer Scheduled Data Transfers



Graceful Degradation & Effective Retries

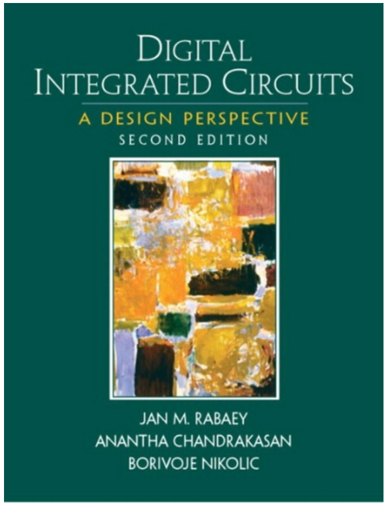
- Configurable beacon synchronization timeouts
  - Typically 3-5 retries
- Adaptive scanning activity
  - Reduction on intermittent loss of connectivity
  - Energy savings on bootstrapping and longer network failures



Today's Hot Researcher & Paper

- Jan M. Rabaey
  - Faculty at UC Berkeley
  - Co-Founder Berkeley Wireless Research Center

- Digital Integrated Circuits, Prentice Hall, 2006.



JM Rabaey, MJ Ammer, JL da Silva Jr, D Patel, S Roundy: *PicoRadio supports ad hoc ultra-low power wireless networking*. Computer 33 (7), 42-48

Recap of Today

- Wireless medium access /arbitration is challenging

- Many protocol solutions exist:
  - Two families: Contention and schedule-based
  - Initiating and handshaking can be done both ways
  - No one-size-fits-all (Swiss Army Knife)

- Networked Embedded Systems focus on cross-layer solutions
  - No strict division across interfaces (like OSI model)