CS/ECE 439: Wireless Networking

MAC Layer – Power!
Energy Conservation Techniques

- Wi-Fi devices consume significant amounts of energy when idle
  - Idle ≈ 1W

- Conservation Approach: Device suspension (sleep)
  - Reduced energy consumption
    - Sleep ≈ 0.05W
  - Suspended communication capabilities
    - Buffer overflow
    - Wasted bandwidth
    - Lost messages
    - If all nodes are asleep, no one can communicate!
Communication Device Suspension

- **Goal**
  - Adapt the sleep duration to reflect the communication patterns of the application
  - Remain awake when there is active communication
  - Otherwise, suspend

- **Ideal**
  - Sleep whenever there is no data to receive from the base station
  - Wake up for any incoming receptions
Communication Device Suspension

- **Problems**
  - How can a sender differentiate between a suspended node and a node that has gone away?
    - Suspended receiver ⇒ buffer packet
    - Confused sender ⇒ dropped packet, extra energy consumption
  - How can a suspended node know there is communication for it?
    - Wake up too soon ⇒ waste energy
    - Wake up too late ⇒ delay/miss packets
Communication Device Suspension

- **Approach**
  - Ensure overlap between sender’s and receiver’s awake times

- **Protocols**
  - Triggered Resume
  - Periodic Resume
    - Synchronous
    - Asynchronous
Triggered Resume

Approach

- Use a second control channel (second radio)
  - Sender transmits RTS or beacon messages in control channel
  - Receiver replies in control channel and turns on main channel

- Main channel is only used for data

- Second channel
  - Must consume less energy than the main channel
  - Must not interfere with the main channel
  - Ex: RFID, 915Mhz
Triggered Resume

- **Protocols**
  - **Power Aware Multi-Access Protocol (PAMAS)**
    - Shut off device when channel is busy
  - **Wake-on-Wireless**
    - Control channel is always active
  - **STEM**
    - Control channel is managed similar to IEEE 802.11 PSM
Triggered Resume

- **Approach – PAMAS**
  - **Data channel**
    - Power off radio when data is destined to a different node
  - **Control channel**
    - Probe neighbors to find longest remaining transfer

![Diagram showing the PAMAS approach with nodes A, B, C, D, and E.]

- Node A
- Node B
- Node C

Legend:
- **Awake/listen**
- **RTS/CTS**
- **Data transmission/reception**
Triggered Resume

- **Dual radio**
  - Low duty cycle paging channel to wake up a neighboring node
  - Use separate radio for the paging channel to avoid interference with regular data forwarding
  - Trades off energy savings for setup latency
Triggered Resume

- Dual radio

- Node A - control

- Node A - data

- Node B - control

- Node B - data

- Time

- Awake/listen
- Transmit request
- Receive and reply
- Data transmission/reception
Triggered Resume

Challenges

- Two radios are more complex than one
- Channel characteristics may not be the same for both radios
  - A successful RTS on the control channel does not guarantee a the reverse channel works
  - A failed RTS on the control channel does not indicate that the reverse channel does not work
Periodic Resume

- **Approach**
  - Suspend most of the time
  - Periodically resume to check for pending communication

- **Communication indications**
  - Out-of-band channel
  - In-band signaling

- **Protocols**
  - Synchronous
  - Asynchronous
Synchronous Periodic Resume

- **Basic Idea**
  - Time is slotted
  - Nodes selectively remain awake for full slot duration
  - Discovery occurs when two active slots overlap
  - If all nodes are synchronized, all nodes are guaranteed to have overlapping awake periods
Synchronous Periodic Resume

- **Protocol: IEEE 802.11 Power Save Mode (PSM)**
  - Nodes are synchronized and wakeup periodically (Beacon Period)
  - Each beacon period is broken up into two segments
    - **Ad-hoc Traffic Indication Map (ATIM) Window**
      - Announcement in the ATIM indicates data
      - Target node responds with an ATIM ACK
      - If a node receives no announcements, it goes back to sleep
    - **Transmission period**
      - Sender can transmit packet until the end of the beacon period
Synchronous Periodic Resume

IEEE 802.11 PSM

Node 1

- $B_1$ Beacon Frame
- Random Delay
- Transmit ATIM
- $B_2$ ATIM window
- Transmit Data
- $B_1$ Beacon Interval

Node 2

- $B_2$ Beacon Frame
- Random Delay
- Transmit ATIM
- $B_2$ ATIM window
- Acknowledge ATIM
- $d$ Acknowledge Data
- $a$ Acknowledge Data

Time ($t$)
Synchronous Periodic Resume

- **Centralized solution**
  - Synchronization driven by base station
  - In beacon message

- **Distributed solution**
  - No base station
  - Synchronization protocols can be used to loosely synchronize nodes
    - Nodes wake up for a short period and check for channel activity
    - Return to sleep if no activity detected
Distributed Synchronous Periodic Resume

- Persistent loose synchronization
  - Constant, high synchronization overhead
Distributed Synchronous Periodic Resume

- **Signaling**
  - No synchronization overhead
  - High signaling overhead
    - Long preambles, all nodes wake up

A has data for B
Long preamble wakes up B

Unnecessary preamble

Overhearing
**Distributed Synchronous Periodic Resume**

- **Signaling: Wake-up packets**
  - Send wake-up packets instead of preamble
  - Wake-up packets tell when data is starting so that receiver can go back to sleep as soon as it receives one wake-up packet

A has data for B
Distributed Synchronous Periodic Resume

- **Signaling: Multiple send**
  - Send data several times
  - Receiver can listen at any time and get all data

- **Problem with all approaches**
  - Communication costs are mostly paid by the sender
  - The amount of time the sender spends transmitting may be much longer than the actual data length
Synchronous Periodic Resume

- Problems
  - Maintaining synchronization may be difficult
  - Throughput is limited by the size of the notification window
    - If the notification window is too small, packets get buffered
    - Buffers may eventually overflow
Asynchronous Periodic Resume

**Approach**
- Stay awake longer to guarantee overlap of awake periods
- Overlap is guaranteed if the awake periods are more than half the beacon period
Asynchronous Periodic Resume

- Basic protocol
  - Use beacon messages at the start of awake periods
  - Some protocols use notification messages (similar to ATIM)
Asynchronous Periodic Resume

Problem

- No guarantee that all nodes will hear each other’s beacon or notification messages
Solution

- Have a beacon at the beginning and end of the beacon interval
Asynchronous Periodic Resume

- **Alternate solution**
  - Beacon at the beginning of odd periods
  - Beacon at the end of even periods
Asynchronous Periodic Resume

Problem

- Nodes stay awake more than half the time
- Wastes too much energy!
Asynchronous Periodic Resume

- **Reduce awake time**
  - Do not wake up every beacon interval
  - Delay depends on number of overlapping intervals

![Diagram](image)

- Beacon Interval
- Node 1
- Node 2
- Beacon window
- Awake Period
- Beacon Message
- time
Asynchronous Periodic Resume

- **Randomized Approach**
  - **Birthday protocol**
    - Randomly select a slot to wake up in with a given probability
  - Advantage
    - Good average case performance
  - Disadvantage
    - No bounds on worst-case discovery latency

![Awake slots](image.png)
Asynchronous Periodic Resume

- **Extended sleep**
  - Wake up once every $T$ intervals
  - Adds delay up to $T \times$ length of beacon interval

![Diagram](image)
Asynchronous Periodic Resume

- **Quorum**
  - Increase number of beacon intervals in cycle \((n)\)
  - Increase number of awake periods \((2n - 1)\) of \(n^2\)

Delay is determined by where the overlap is (worst case \(n^2\))
Asynchronous Periodic Resume

- **Quorum**
  - Example: $n = 4$, $n^2 = 16$, $2n-1 = 7$
  - Two overlapping intervals: delay $= n^2 - 2$

![Node i and Node j diagrams with awake states indicated]

- Node i is awake
- Node j is awake
- Both nodes are awake
Asynchronous Periodic Resume

- **Deterministic**
  - Find a feasible overlapping pattern
  - Guarantee at least one overlapping interval
  - Requires knowledge of number of nodes

![Awake Pattern Diagram]

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Asynchronous Periodic Resume

- Deterministic: Prime-based

  - Disco
    - Pick two primes $p_1$ and $p_2$
    - Wake up every $p_1$ and $p_2$ slot
    - Guarantees discovery in $p_1 \times p_2$ slots
Asynchronous Periodic Resume

- Deterministic: Prime-based
  - U-Connect
    - Select 1 prime $p$
    - Wake up every $p$th slot and $(p-1)/2$ slots every $p^2$ slots
    - Overlap is guaranteed within $p^2$ slots
Asynchronous Periodic Resume

- **Searchlight**
  - Have a **deterministic** discovery schedule that has a **pseudo-random** component

Node A: 

Node B:
Asynchronous Periodic Resume

- **Searchlight**
  - Two slots per t slots (period)
    - Anchor slot: Keep one slot fixed at slot 0
    - Probe slot: Move around the other slot sequentially
  - Guaranteed overlap in \( t \times t/2 \) slots
    - Based on the time needed to ensure a probe-anchor overlap
  - Probe-probe overlap can also lead to discovery
    - Sequential scanning means less chance of a probe-probe overlap

Discovery through anchor-probe overlap
Asynchronous Periodic Resume

- **Searchlight**
  - Extension: randomized probing
    - Move the probe slot randomly
  - Each node randomly chooses a schedule for its probe slot that repeats every \((t*t/2)\) slots
    - Schedules of two nodes appear random to each other
- **Advantage**
  - Retains the same worst-case bound
  - Improves average case performance

**Discovery through probe-probe overlap**
Asynchronous Periodic Resume

- **Challenges**
  - Reducing time spent awake
  - Reducing delay
  - No support for broadcast
    - None of the current approaches provide an interval where all nodes are awake