CS 498wn: Wireless IoT Lab

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
  - Remain awake when there is active communication
  - Otherwise, suspend
  - Adapt the sleep duration to reflect the communication patterns of the application
- 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 $\Rightarrow$ buffer packet
    - Confused sender $\Rightarrow$ dropped packet, extra energy consumption
  - How can a suspended node know there is communication for it?
    - Wake up too soon $\Rightarrow$ waste energy
    - Wake up too late $\Rightarrow$ delay/miss packets

Communication Device Suspension

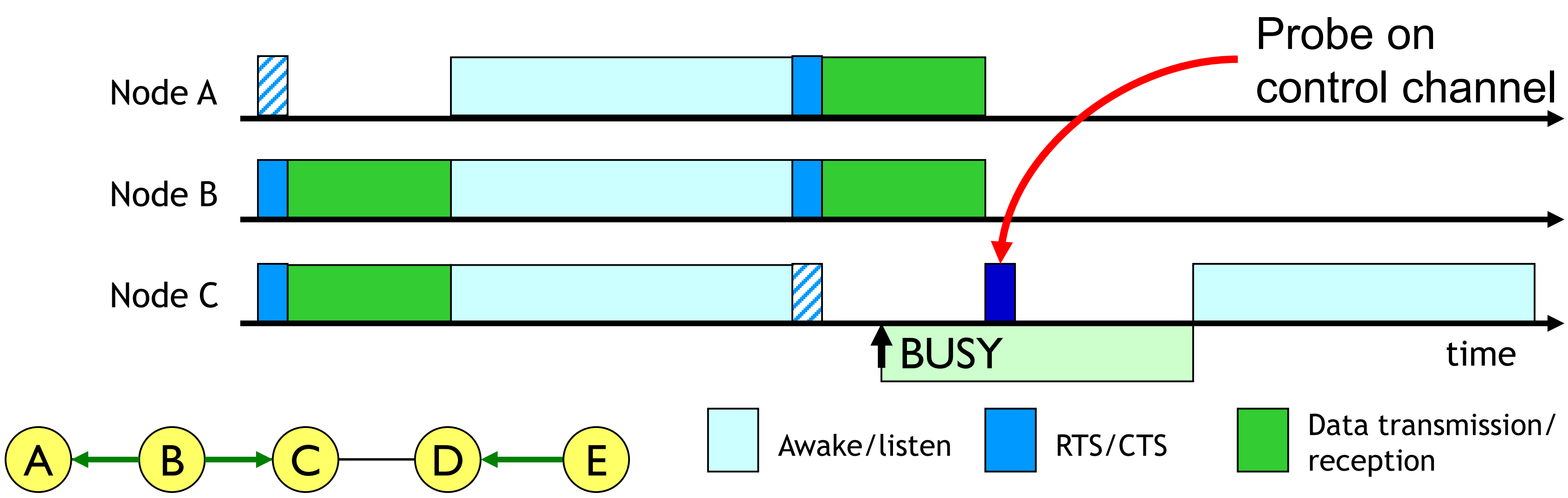
- Approach
  - Ensure overlap between sender's and receiver's awake times
- Protocols
  - Triggered Resume
  - Periodic Resume
    - Synchronous
    - Asynchronous

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: BLE, ZigBee, RFID, 915Mhz

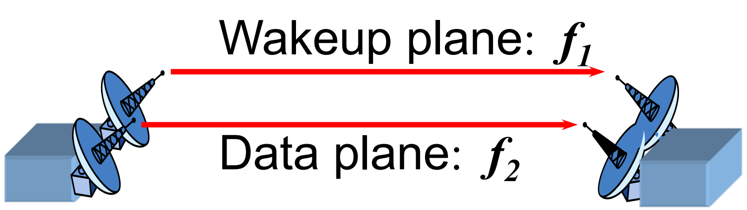
Triggered Resume

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



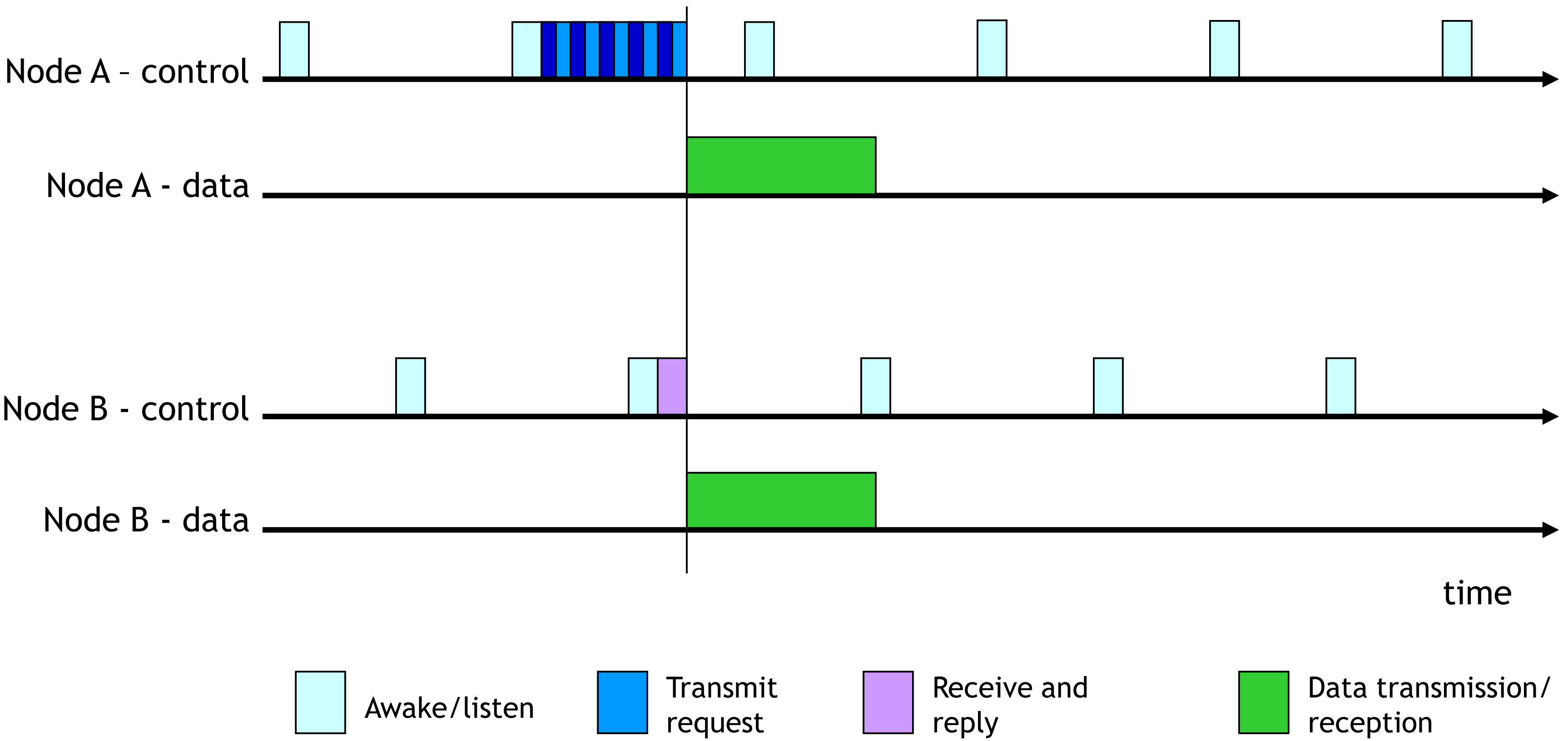
Triggered Resume

- 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



Triggered Resume

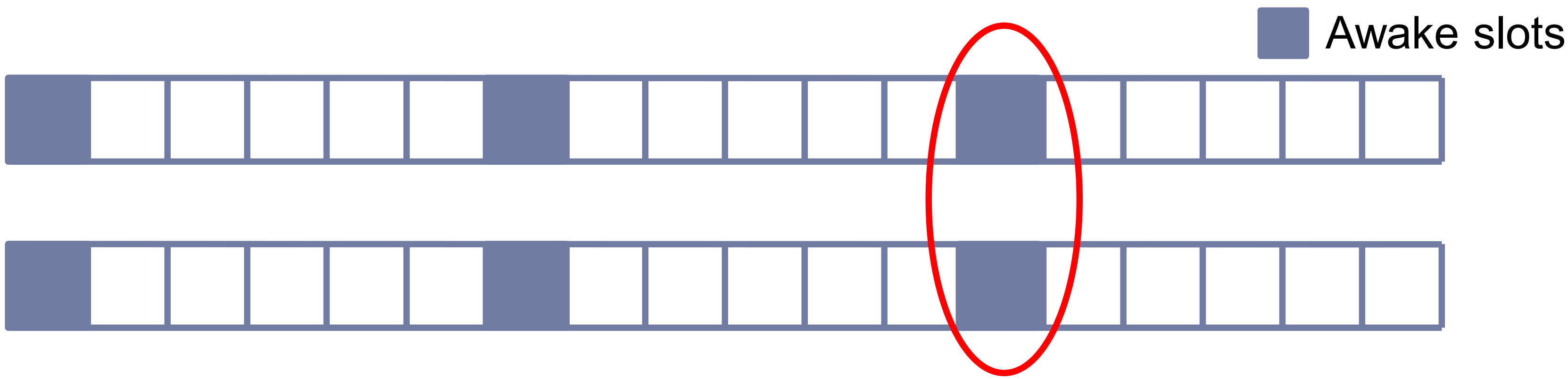
- Challenges
  - Two radios are more complex than one
  - Channel characteristics may not be the same for both radios
    - A successful RTS on the control channel does not guarantee a the reverse channel works
    - A failed RTS on the control channel does not indicate that the reverse channel does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

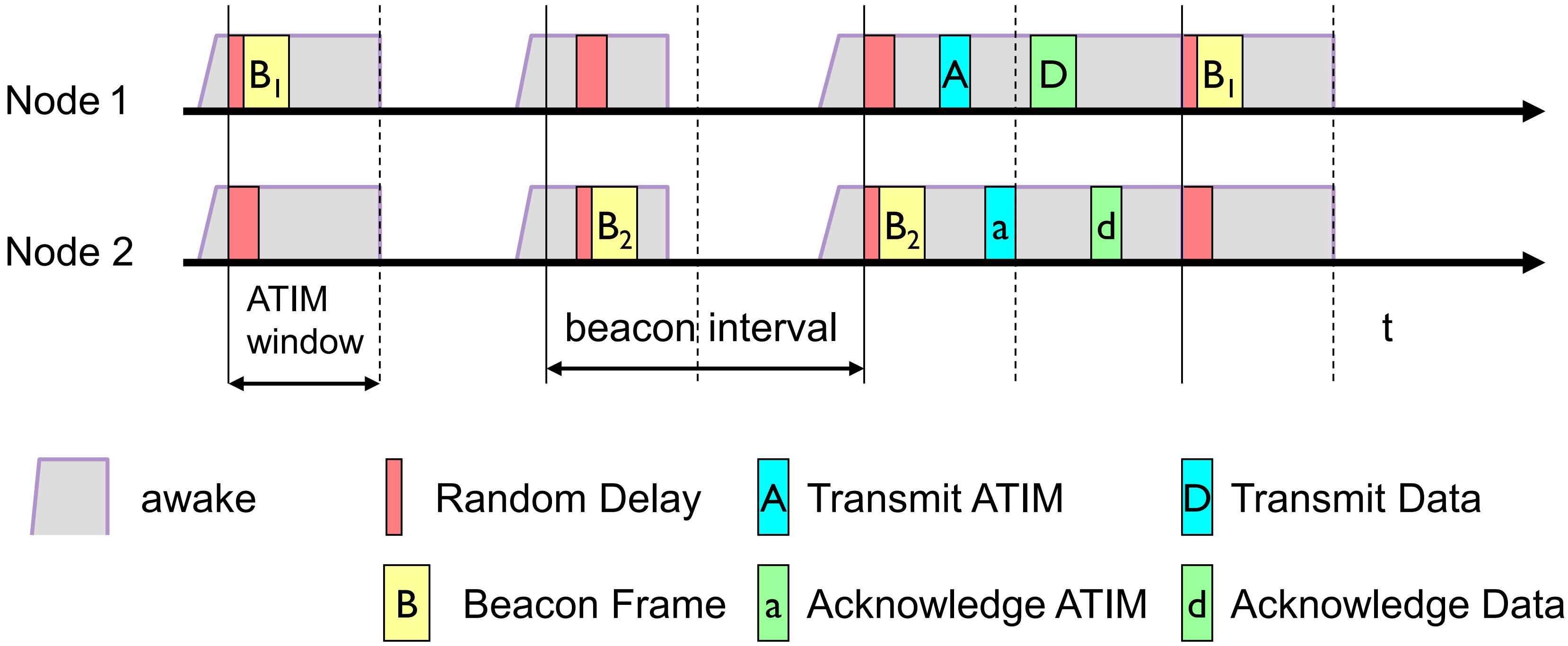


Synchronous Periodic Resume

- 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

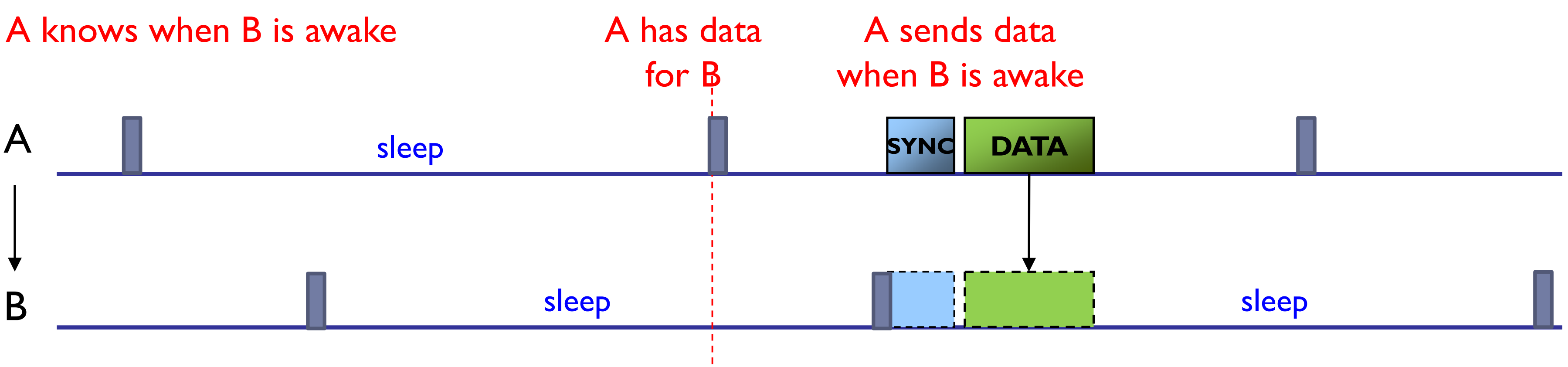


Synchronous Periodic Resume

- 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

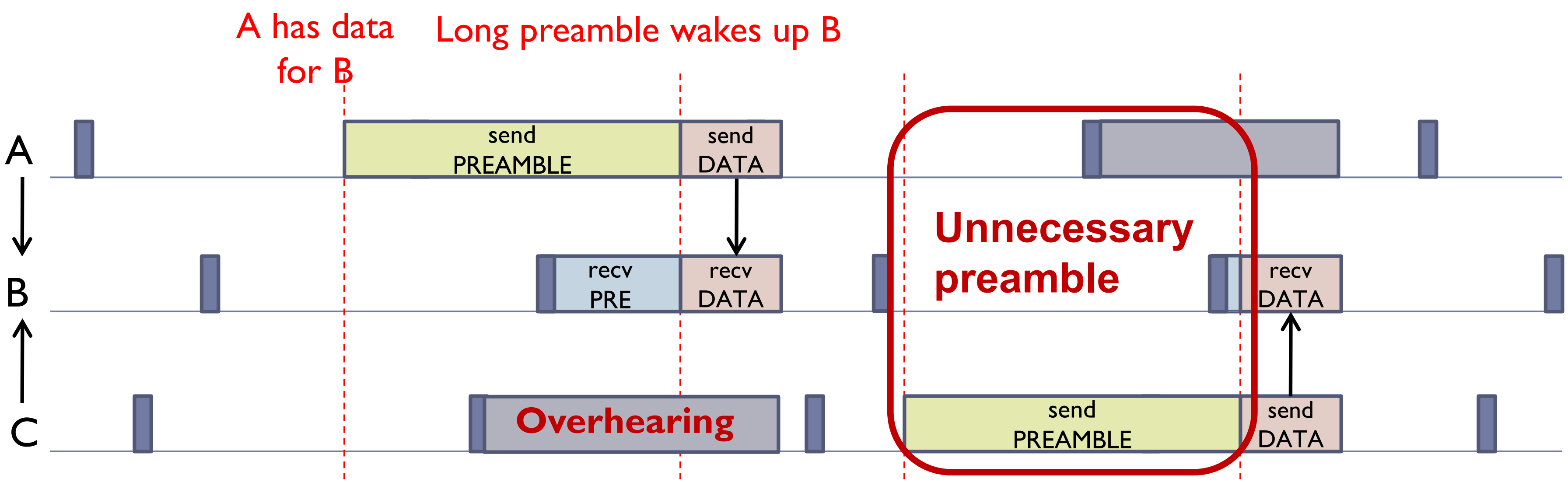
Distributed Synchronous Periodic Resume

- Persistent loose synchronization
  - Constant, high synchronization overhead



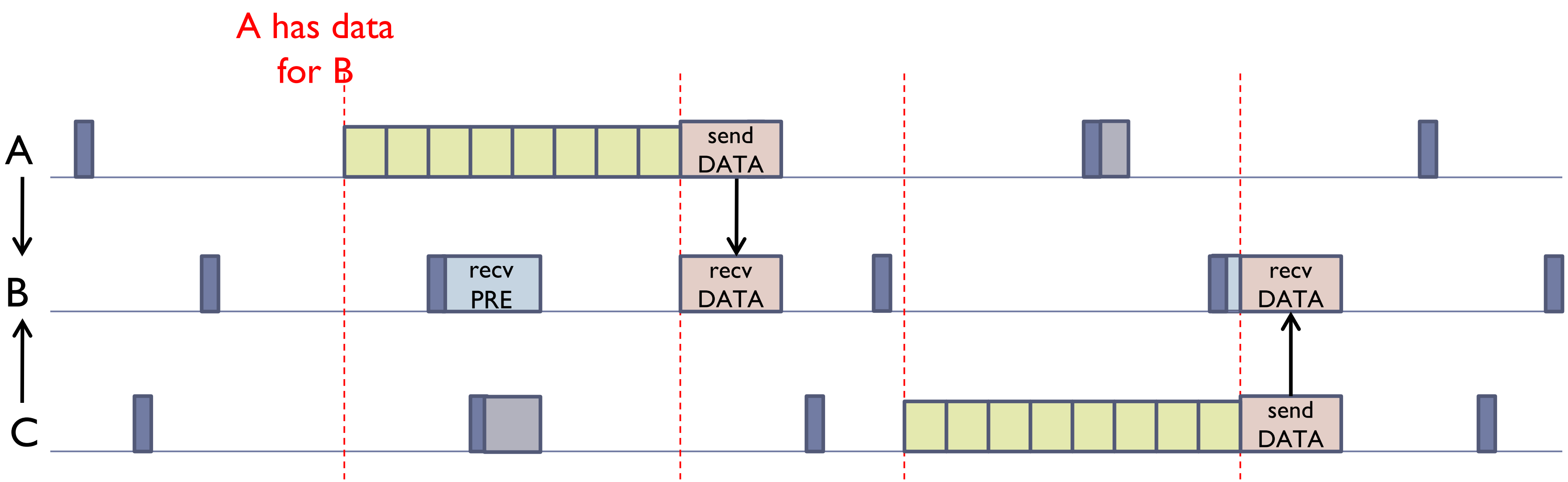
Distributed Synchronous Periodic Resume

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



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



Distributed Synchronous Periodic Resume

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

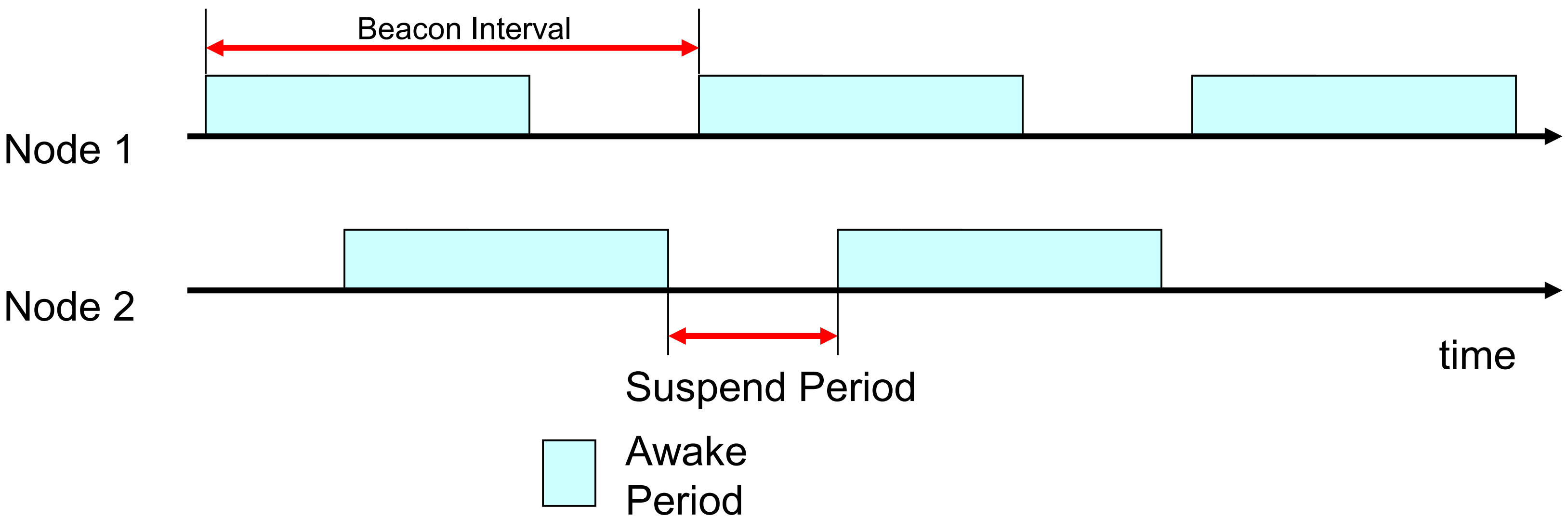
- Problem with all approaches
  - Communication costs are mostly paid by the sender
  - The amount of time the sender spends transmitting may be much longer than the actual data length

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

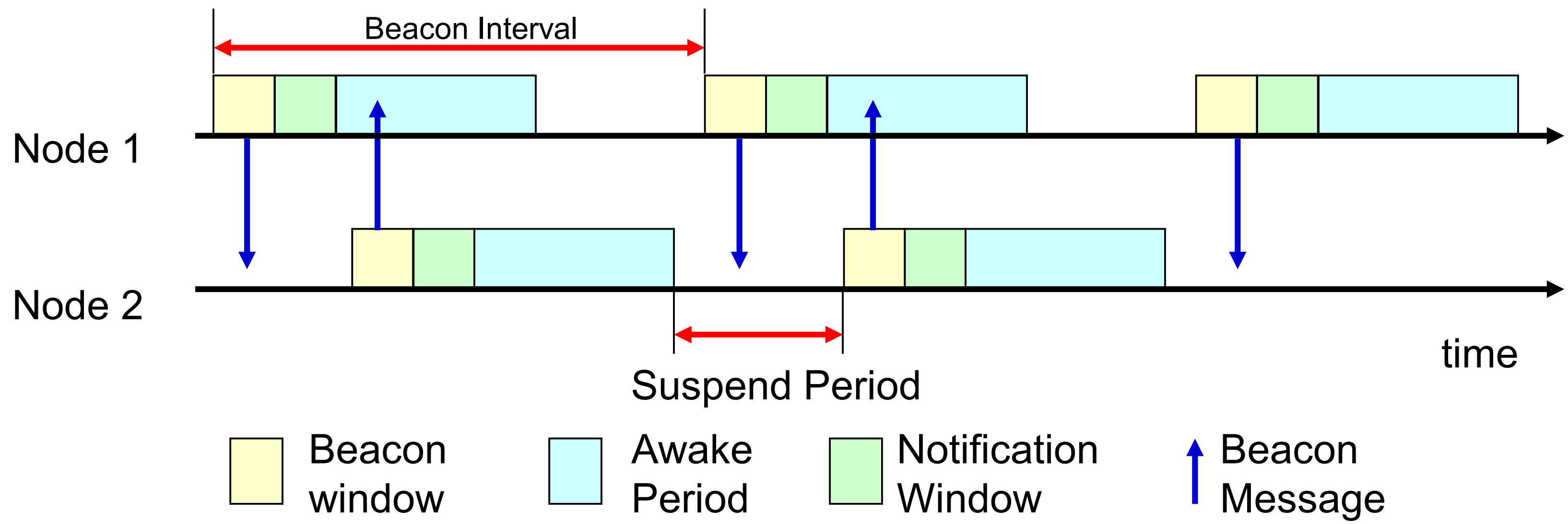
Asynchronous Periodic Resume

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



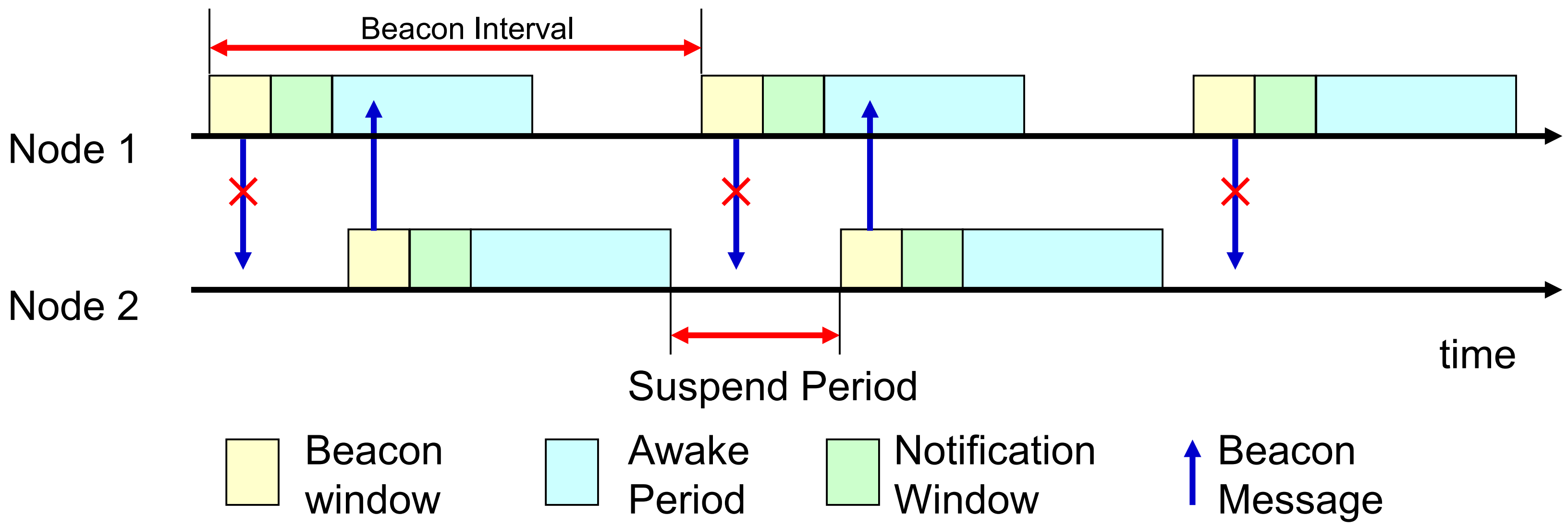
Asynchronous Periodic Resume

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



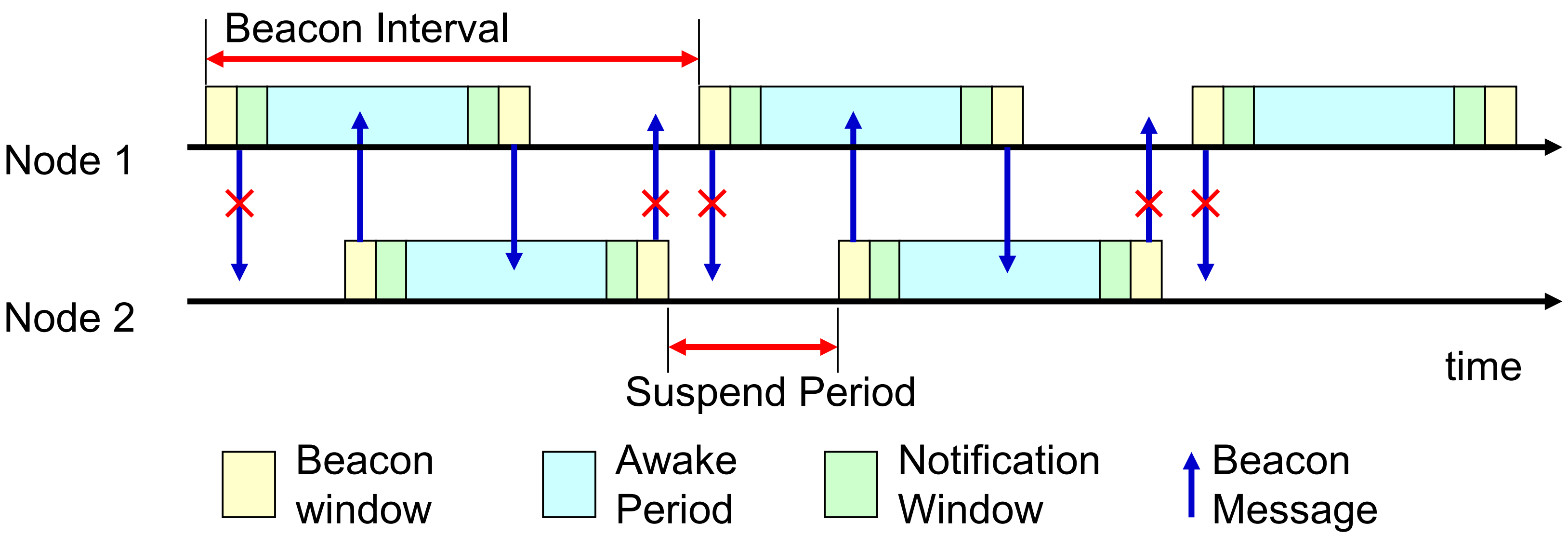
Asynchronous Periodic Resume

- Problem
  - No guarantee that all nodes will hear each other's beacon or notification messages



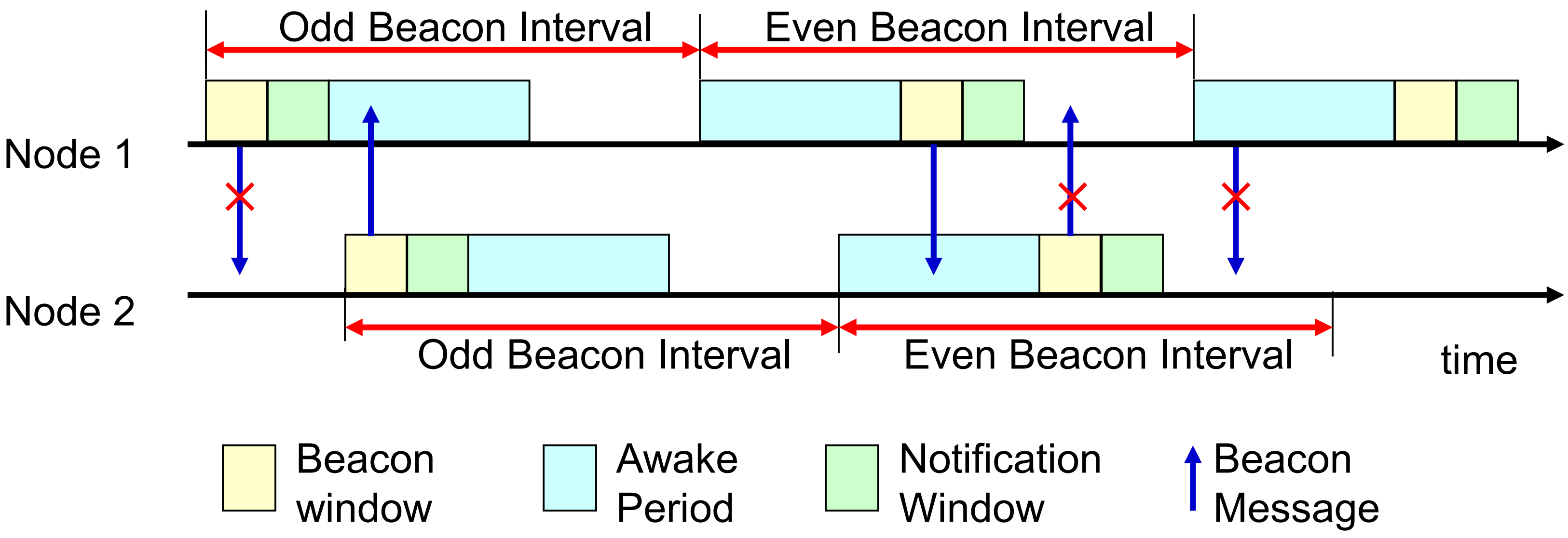
Asynchronous Periodic Resume

- Solution
  - Have a beacon at the beginning and end of the beacon interval



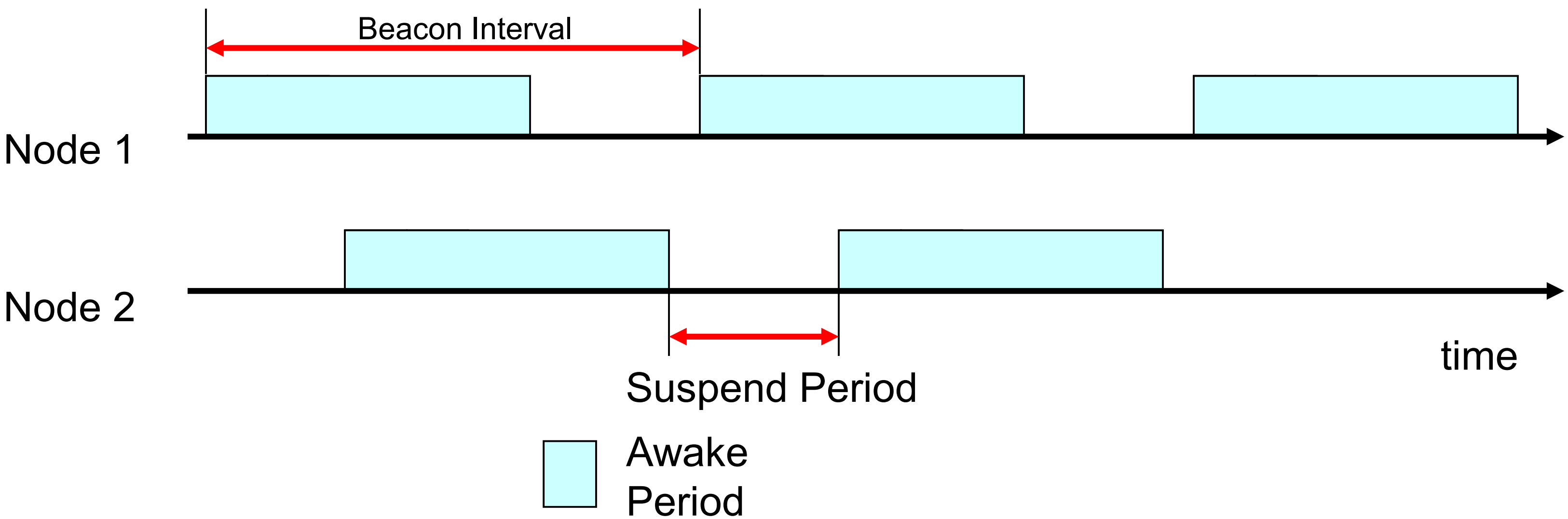
Asynchronous Periodic Resume

- Alternate solution
  - Beacon at the beginning of odd periods
  - Beacon at the end of even periods



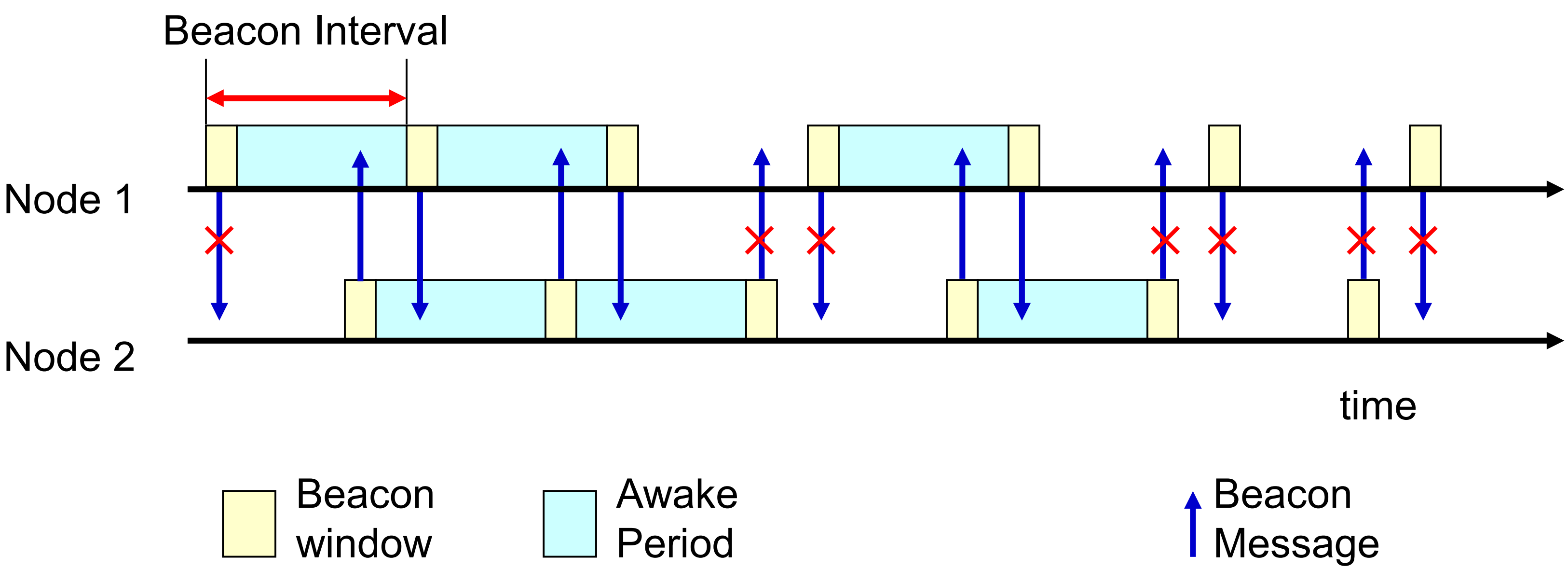
Asynchronous Periodic Resume

- Problem
  - Nodes stay awake more than half the time
  - Wastes too much energy!



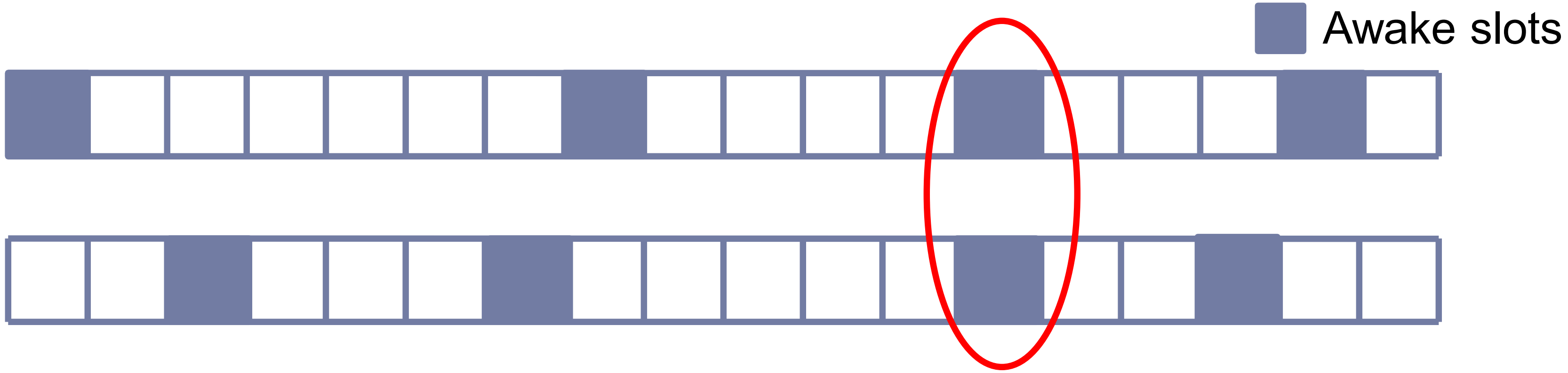
Asynchronous Periodic Resume

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



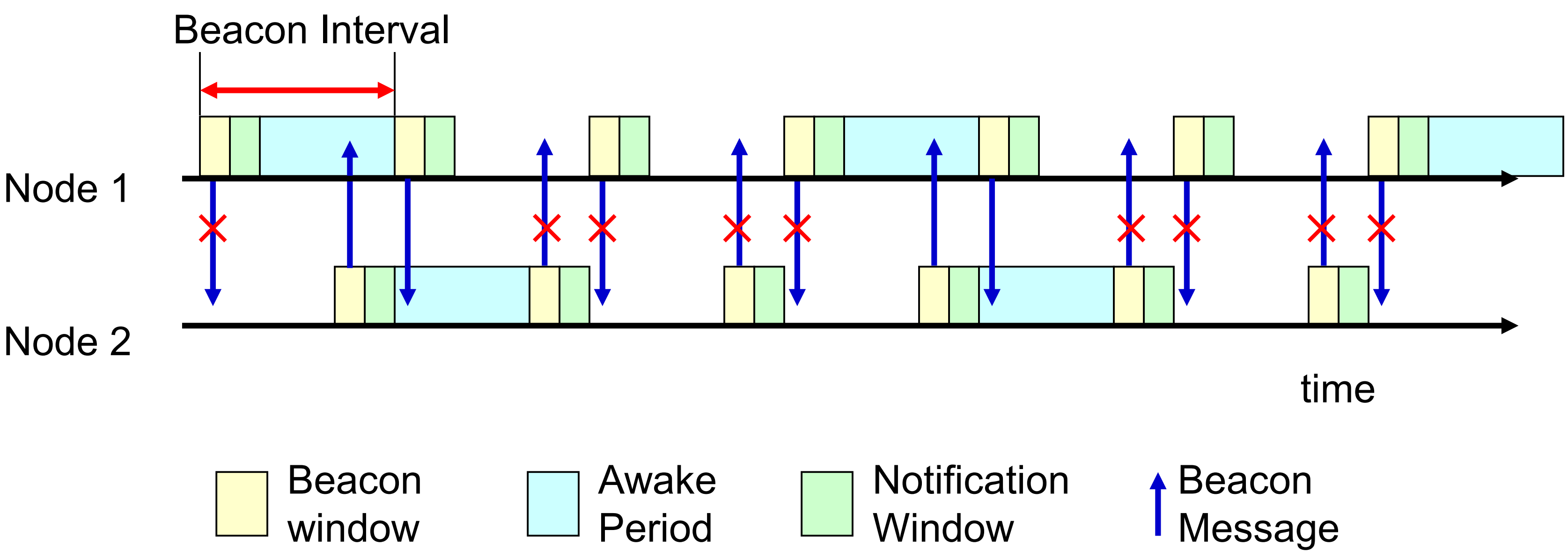
Asynchronous Periodic Resume

- 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



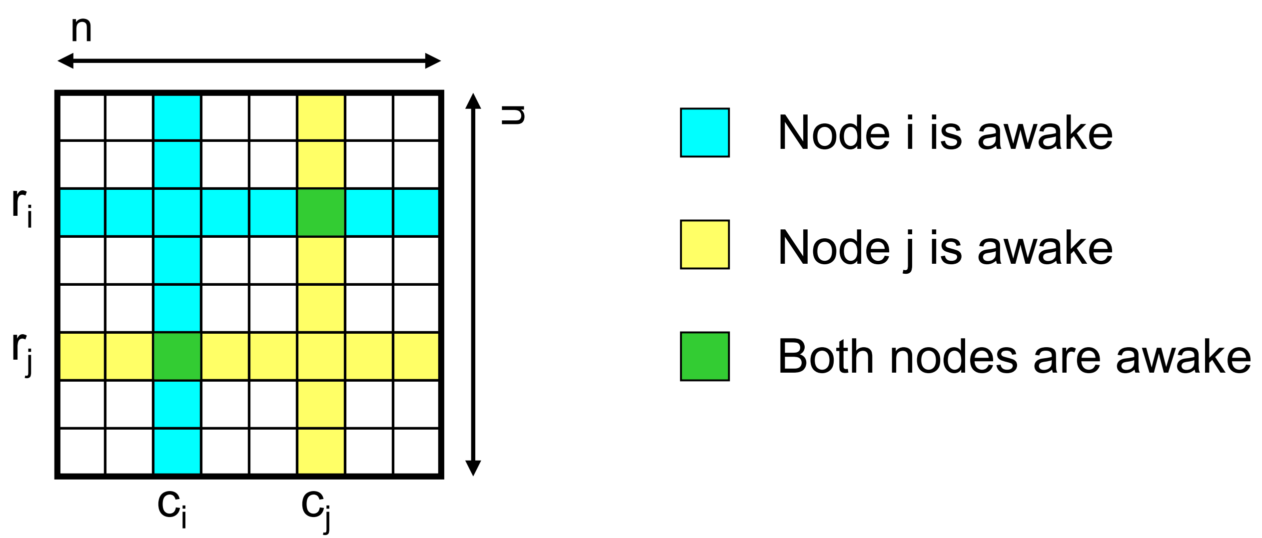
Asynchronous Periodic Resume

- Extended sleep
  - Wake up once every T intervals
  - Adds delay up to T× length of beacon interval



Asynchronous Periodic Resume

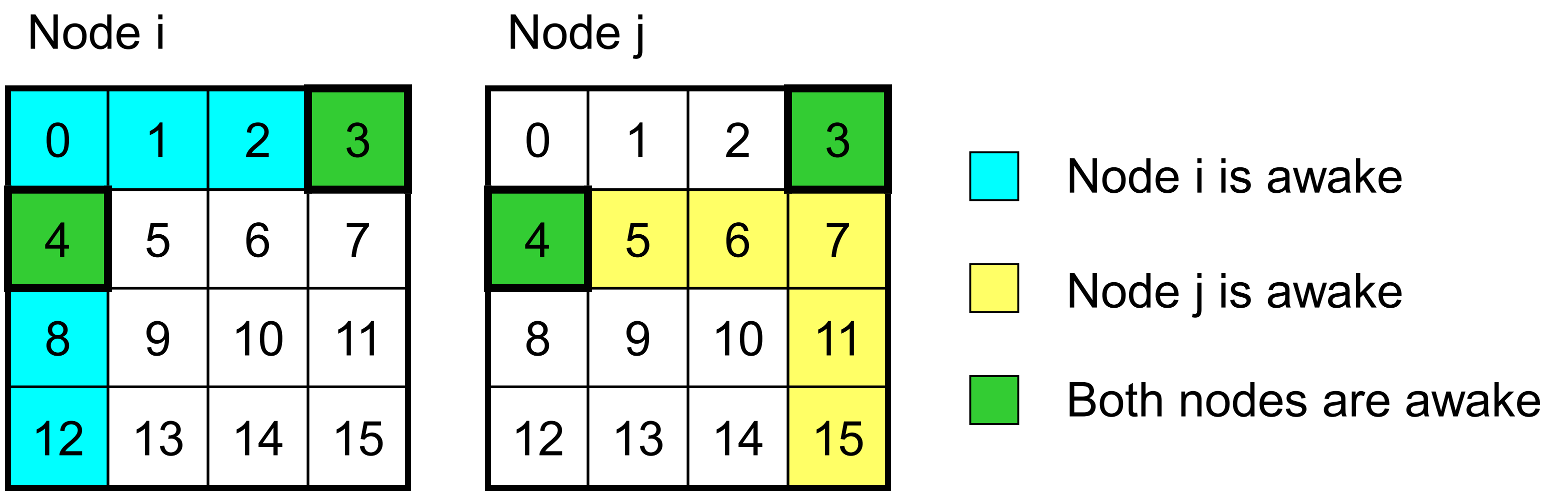
- Quorum
  - Increase number of beacon intervals in cycle (n)
  - Increase number of awake periods (2n – 1 of n^2)



Delay is determined by where the overlap is (worst case n^2)

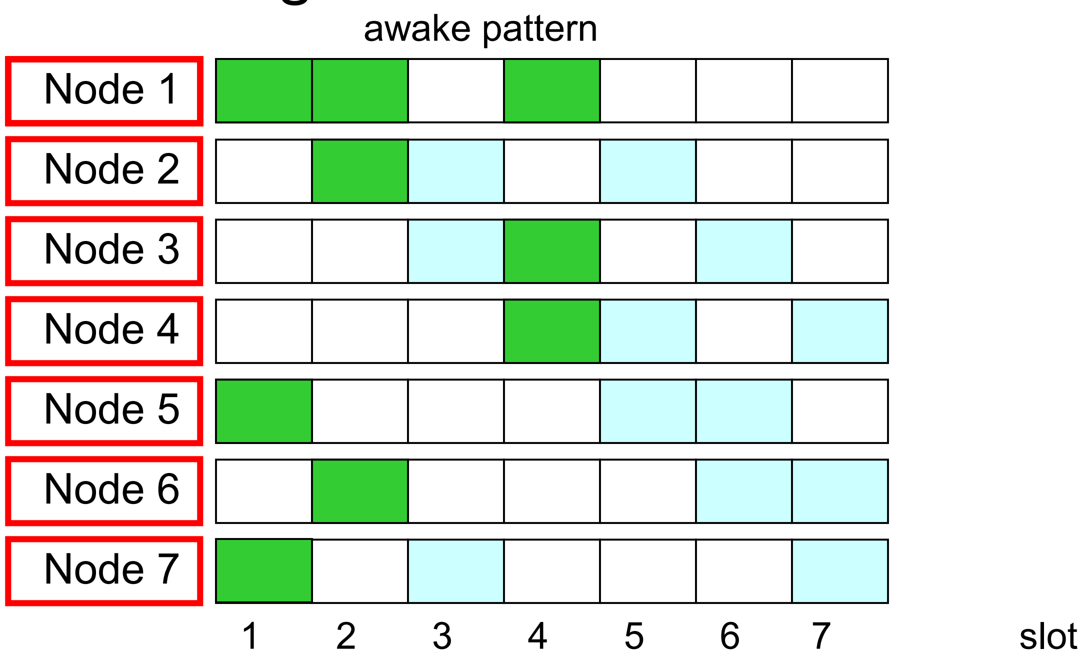
Asynchronous Periodic Resume

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



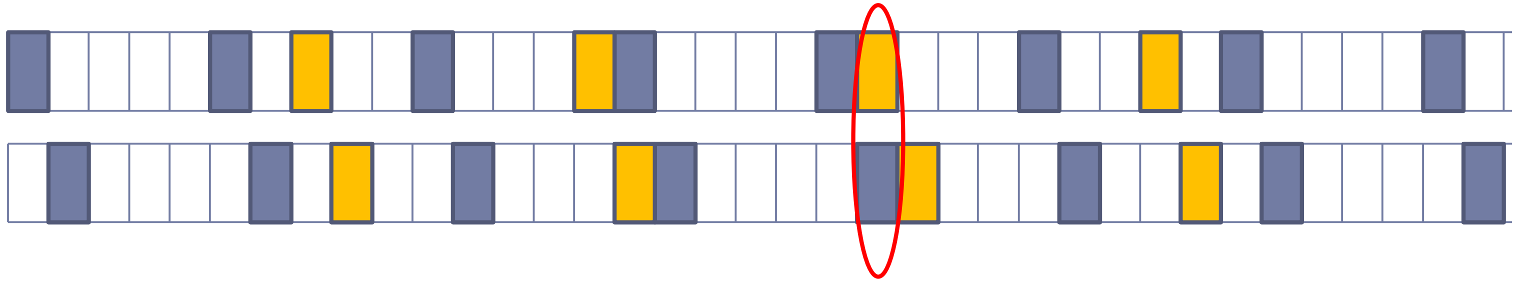
Asynchronous Periodic Resume

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



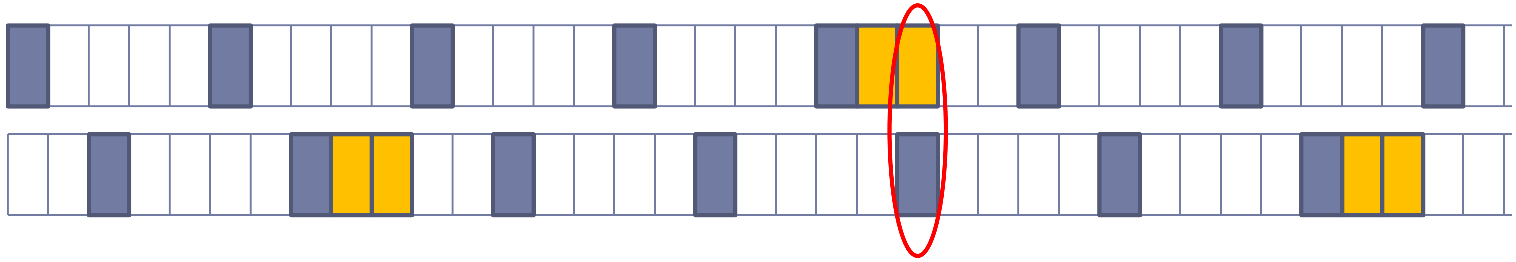
Asynchronous Periodic Resume

- Deterministic: Prime-based
  - Disco
    - Pick two primes p1 and p2
    - Wake up every p1 and p2 slot
    - Guarantees discovery in p1 x p2 slots



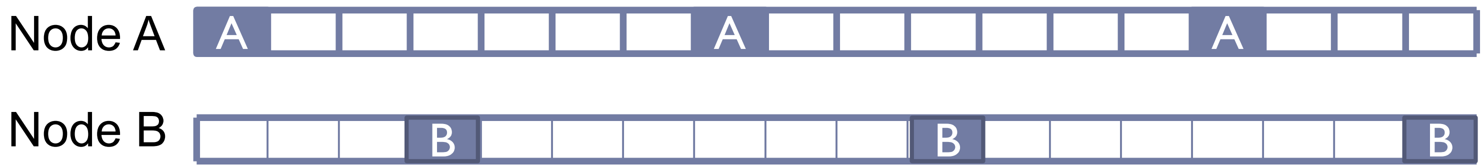
Asynchronous Periodic Resume

- Deterministic: Prime-based
  - U-Connect
    - Select 1 prime p
    - Wake up every pth slot and (p-1)/2 slots every p*p slots
    - Overlap is guaranteed within p2 slots



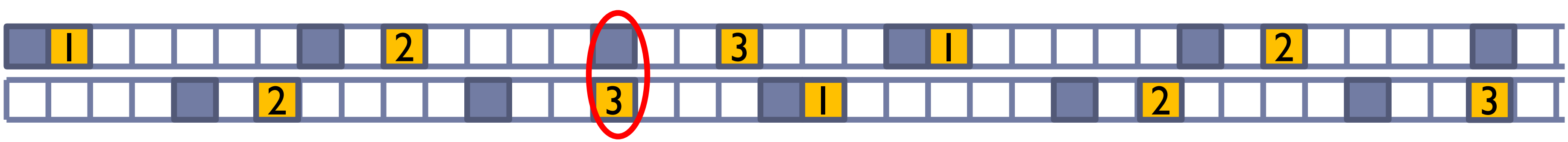
Asynchronous Periodic Resume

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



Asynchronous Periodic Resume

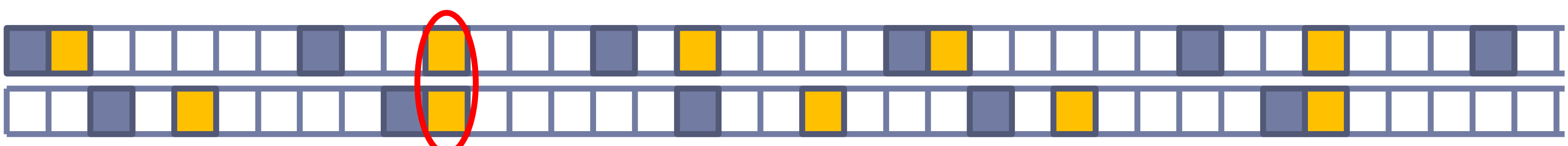
- Searchlight
  - Two slots per t slots (period)
    - Anchor slot: Keep one slot fixed at slot 0
    - Probe slot: Move around the other slot sequentially
  - Guaranteed overlap in t*t/2 slots
    - Based on the time needed to ensure a probe-anchor overlap
  - Probe-probe overlap can also lead to discovery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