Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Extending IEEE802.15.4 to Support Low-power, IP-based Mesh Networking
Date Submitted: 15 July, 2008
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Re: Preliminary Proposal for 802.15.4e

Abstract: This talk outlines the proposed extensions to 802.15.4 to support low-power, IP-based mesh networking.

Purpose: Preliminary Proposal for 802.15.4e

Extending IEEE802.15.4 to Support Low-power, IP-based Mesh Networking

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Key Extensions To 802.15.4

- Low-power(LP) FFD-FFD communication
- LP FFD – LP RFD communication
- Secure ACK with integrity
- Multi-channel communication
- Responsive, low-power operation

Guiding Principles

- Permit migration path from current hardware
- MUST be possible to operate in low power in entire network lifecycle
  - associate, discovery, join, recovery, etc.
- Facilitate efficient upper-layer protocols
  - including IP and other industrial protocols
  - Routing and local connectivity
- Able to operate without central control
- Simple baseline implementations

Outline

- Review of low-power techniques
- Sampled Listening
- Coordinated Sampled Listening (CSL)
- Multi-channel operation
- Proposal Summary
- Evaluation
- Conclusion

Key To Low-power Mesh

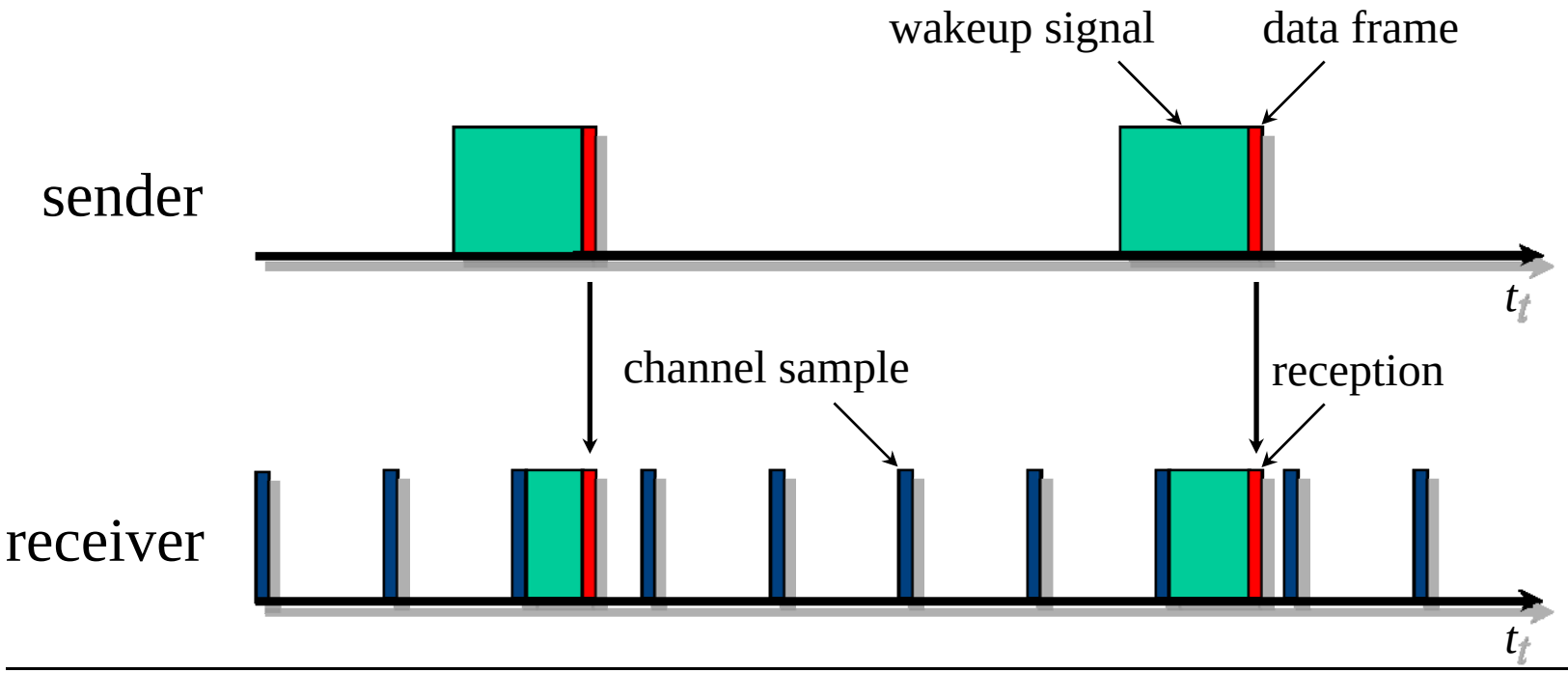
- Low power: < 1% duty cycle, multi-year battery life
- Minimize idle listening

$$P_{total} = P_{listen} + P_{rx} + P_{tx}$$

- Low-power RFD
  - turn off radio when not transmitting
- Low-power FFD
  - How to duty-cycle the radio while forwarding traffic from other FFDs and RFDs?

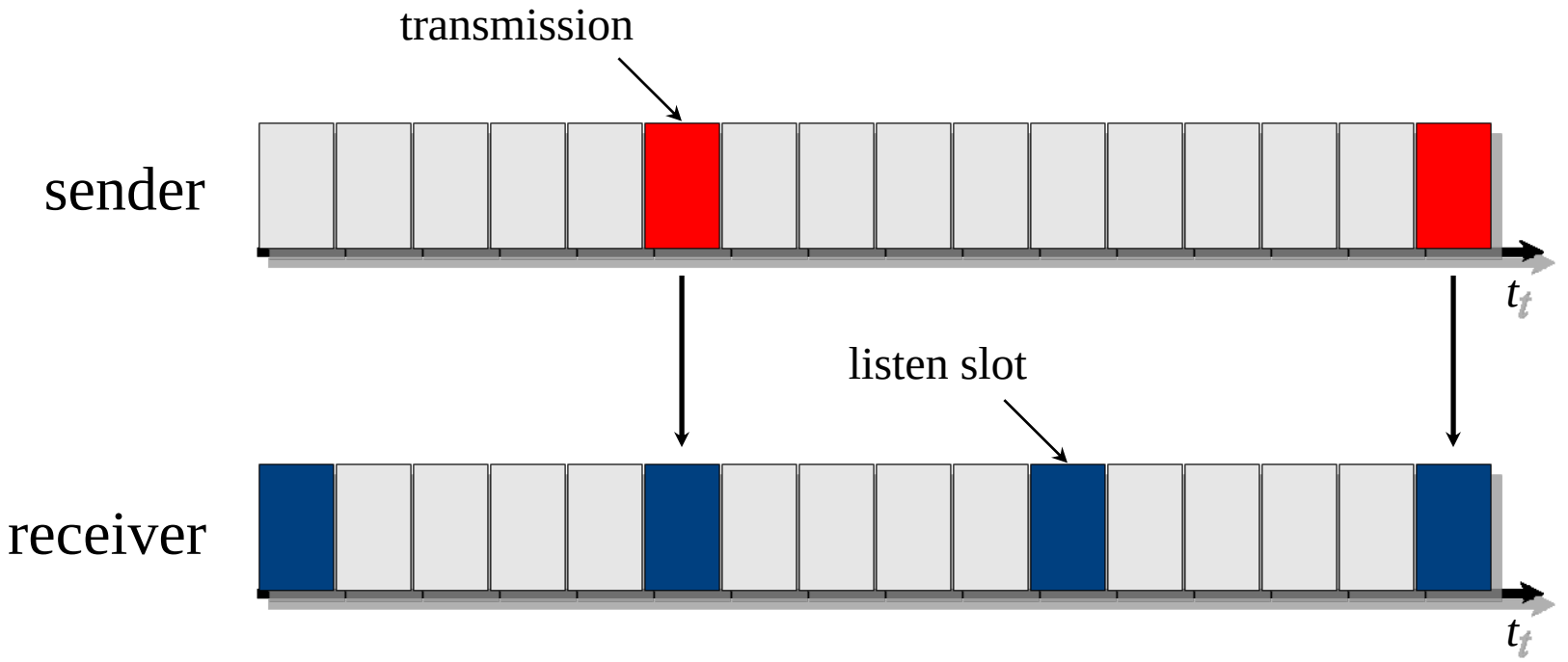
Review Of Low-power Techniques

- Sampled Listening
  - DARPA Packet Radio 1987
  - Aloha-PS, B-MAC, X-MAC, etc.



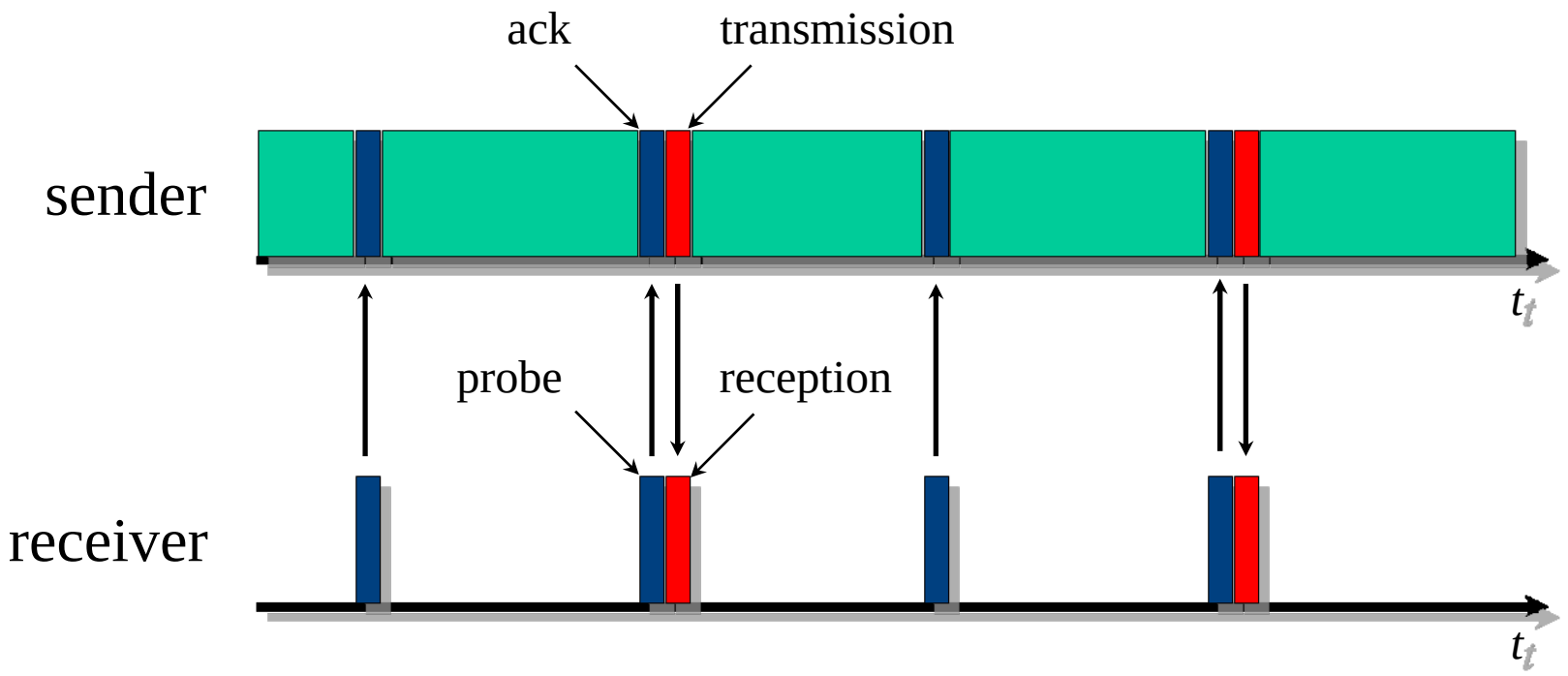
Review Of Low-power Techniques (cont)

- Scheduling
  - e.g. S-MAC, T-MAC, TSMP, etc



Review Of Low-power Techniques (cont)

- Listen After Send
  - e.g. 802.11, 802.15.4 (for RFD)

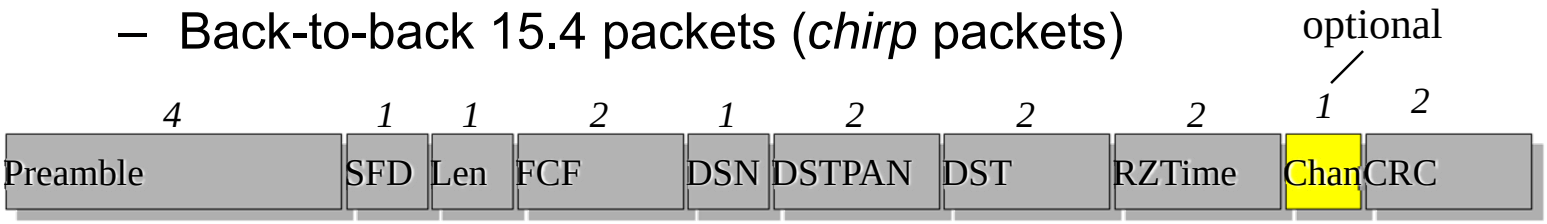


Advantages of Sampled Listening

- Always-on illusion
  - Good for IP
  - Good for manageability
  - Good for asynchronous, event-driven communication
  - Good for mobility and discovery
- Shifting overhead to transmissions
  - Good tradeoff for infrequent communication
- Stateless
  - No prior synchronization of time and state required
- Other low-power techniques can be layered on top

Coordinated Sampled Listening (CSL) Over 802.15.4

- Wakeup signal
  - Back-to-back 15.4 packets (*chirp* packets)



  - Introduce a new frame type in 15.4e
  - Can be a data frame for backward compatibility
- Channel sampling
  - Staged-wakeup of receiver based on RSSI threshold and SFD detection
  - Receive chirp packet
    - Abort if DST is for someone else, otherwise
    - Turn off receiver until rendezvous time (RZTime) then receive data frame

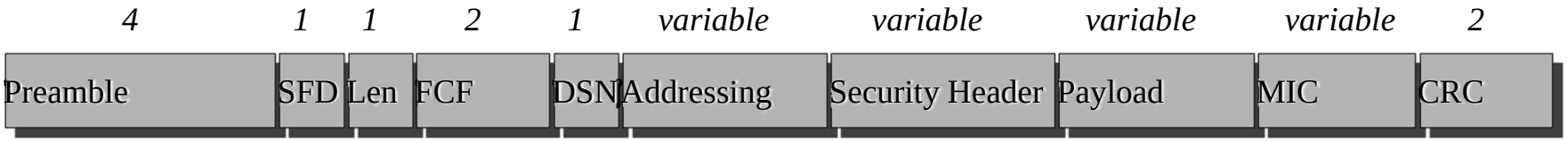
Key Properties of Basic CSL

- Overhearing cost ≤ cost of receiving 1 chirp
- Receive cost ≤ cost of receiving 1 chirp + 1 data
- RFD does not need to chirp to send to a non-duty cycled FFD

- Stay tuned for optimizations to reduce sender cost

Secure and Robust Acknowledgement

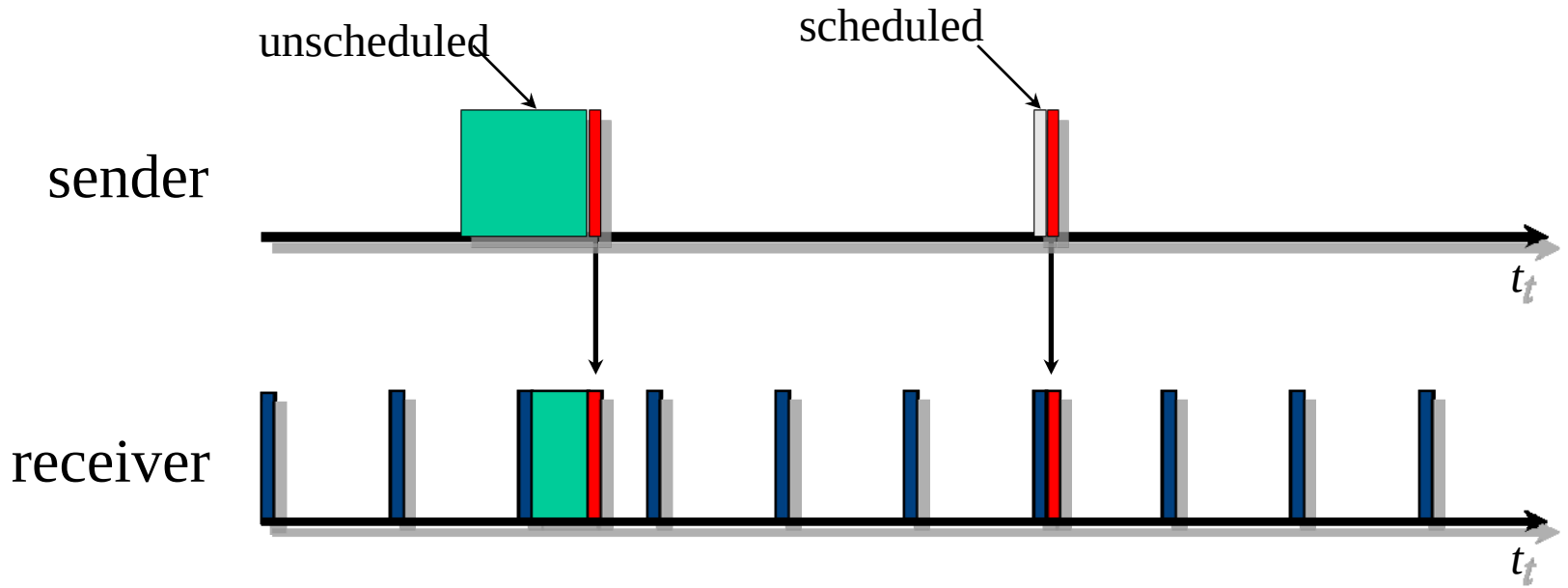
- Problems in current 15.4 ACK frame
  - Lack of addressing information → false positives
  - Lack of security → vulnerability to link-layer attacks
  - Lack of payload → difficulty to piggyback neighbor info
- New ACK frame



  - Same as data frame except frame type is ACK
  - Addressing + DSN to eliminate ambiguity
  - Same security modes as data frame
  - Payload for piggybacking schedule information

Local Scheduling

- Include channel sampling phase and period in ACK payload
- Sender wait to transmit right before receiver's next channel sampling time

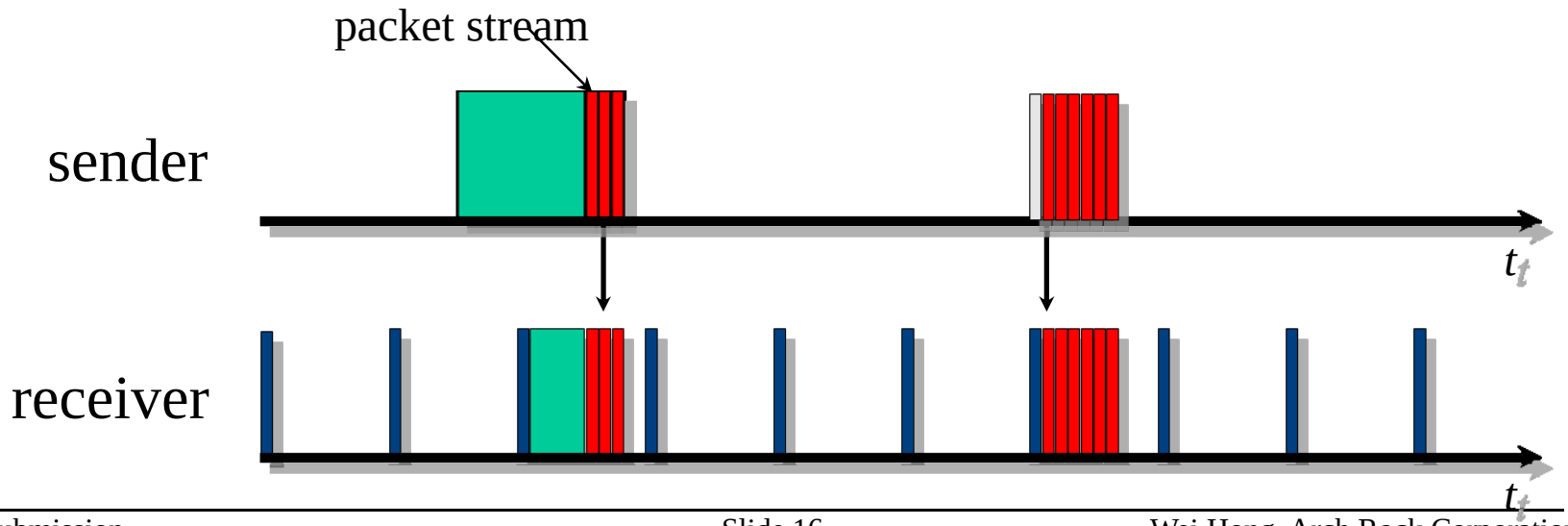


Local Scheduling (cont)

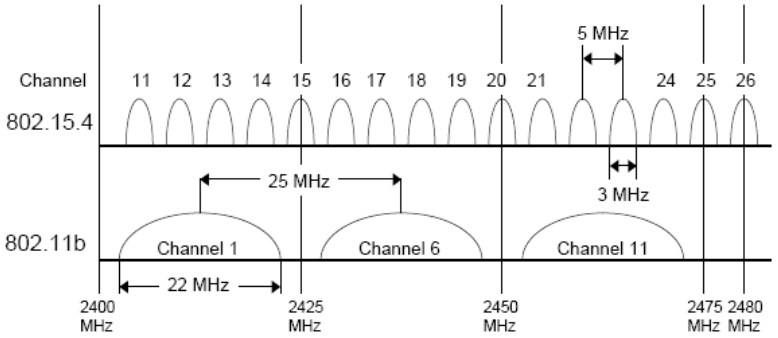
- Short chirps before transmission to guard against synchronization error
- Worst case bounded by channel sample interval
- Schedule information as a hint, not required
- Each node determines its own schedule
- Each node decides which neighbors' schedules to track
- Global synchronization manager not required although can be incorporated

Streaming over Sampled Listening

- Set Frame Pending bit in 15.4 header when communicating multiple frames back-to-back to the same destinations
- Receiver keeps listening when Frame Pending bit is set
- Sender only chirps at the beginning of stream
- Better throughput and efficiency



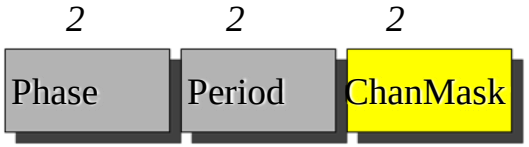
Why Channel Agility?



- Coexist better with WiFi, etc.
  - Best channels may change over lifetime
  - Interference is a fact of life in RF
- Additional source of diversity,
  - Modulation & coding diversity (OQPSK)
  - Temporal diversity (retransmission)
  - Spatial diversity (multiple nodes)
  - Routing diversity (multiple paths)
- Overcome narrow-band fading proble
  - Multiple nodes in proximity, but no single channel that connects them all
  - Fundamental requires multiple transmissions
    - Just hopping does not help

Multi-channel Operation

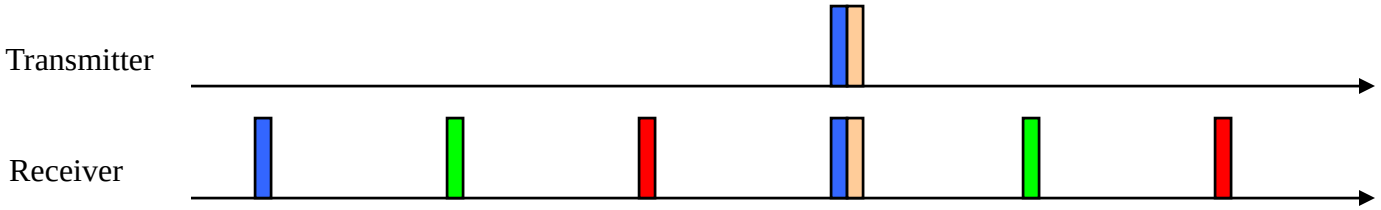
- Generalize single-channel operation
  - Chirp frame optionally contains channel for data frame
  - ACK optionally contains channel information with schedule



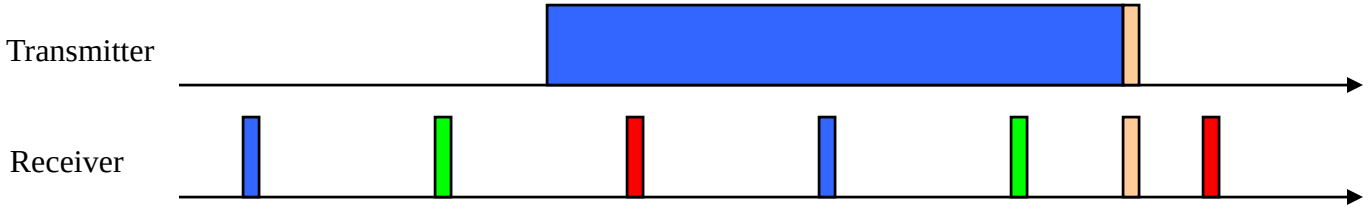
- Simple extension, but maintains all design principles
  - Purely local interactions
  - No added overhead in the common case
  - Allow communication when no information is known
    - Robust, low-latency
    - Low-power join and discovery

Multi-channel Operation (cont)

- Spread channel samples across *c* channels
- No increase in cost when receiver schedule is known



- Increase transmit cost by *c* times when nothing is known

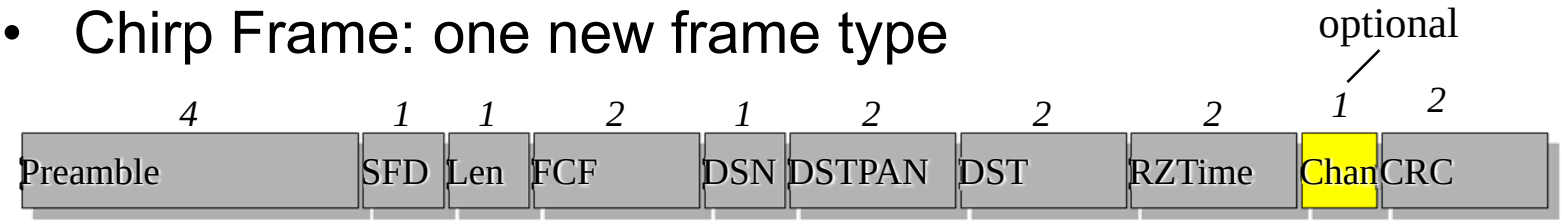


Multi-channel Operation (cont)

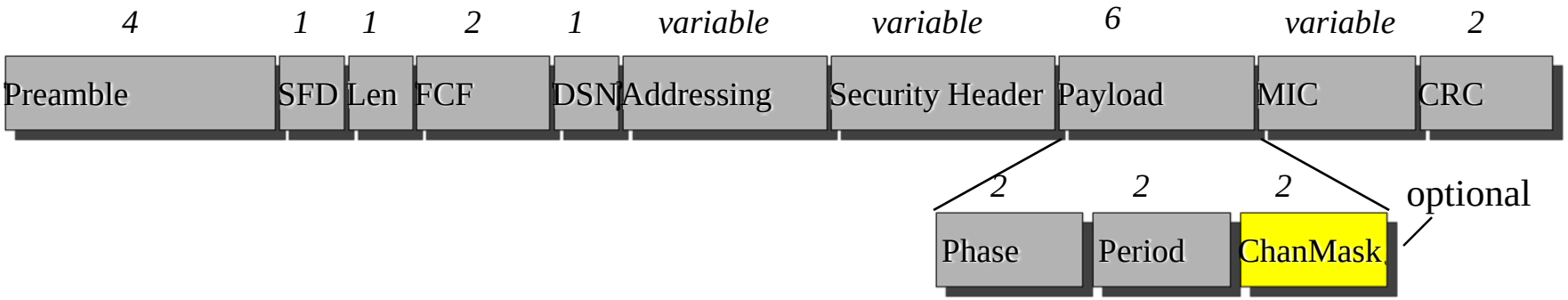
- Overhead analysis:
  - Listen cost: no change
  - Receive cost: no change
  - Transmit cost:
    - When receiver schedule known: no change
    - When receiver schedule is unknown: *c* times per channel
      - *For node discovery only*
      - *Relatively rare*

Proposal Summary

- Chirp Frame: one new frame type



- Secure ACK Frame: extend existing ACK frame

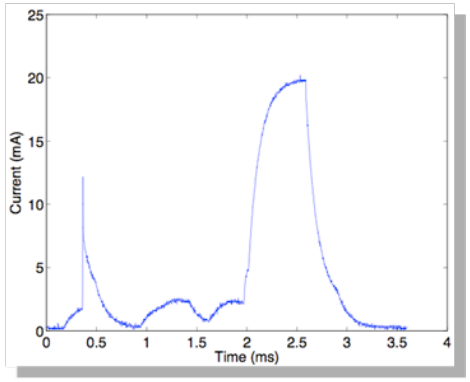


- Add Coordinated Sampled Listening (CSL) to 15.4e MAC

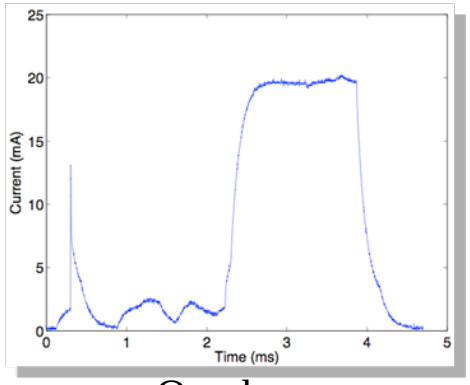
New Interfaces For Upper Layers

- Set/get sampled listening period, phase and channel list
- Set/reset frame pending bit
- Query neighbor table entries
  - Hopcount, link quality estimate, last heard, etc

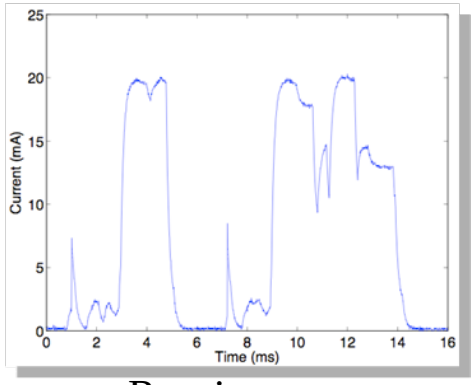
Evaluation: Link Layer Primitive Profiles



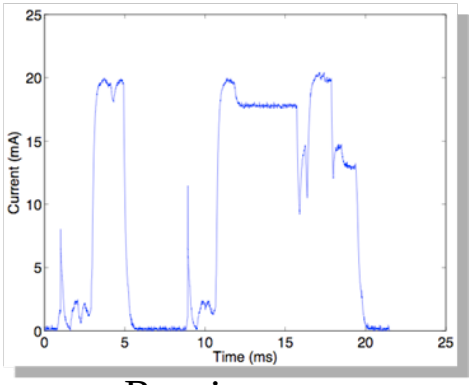
Channel Sample



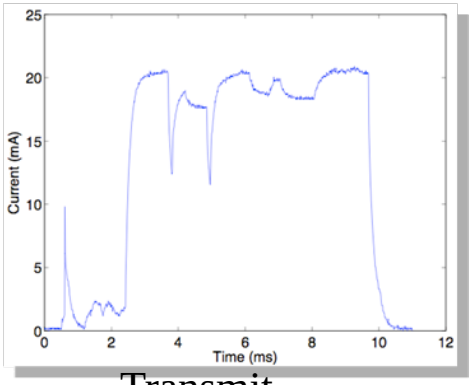
Overhear



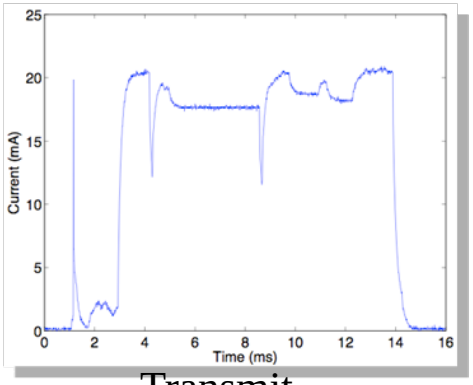
Receive (26 bytes)



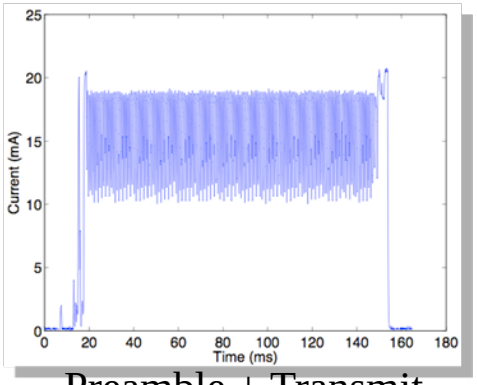
Receive (127 bytes)



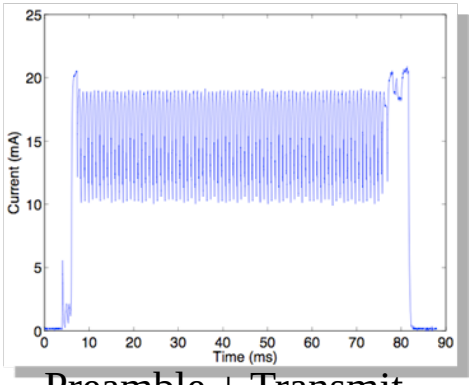
Transmit (26 bytes)



Transmit (127 bytes)



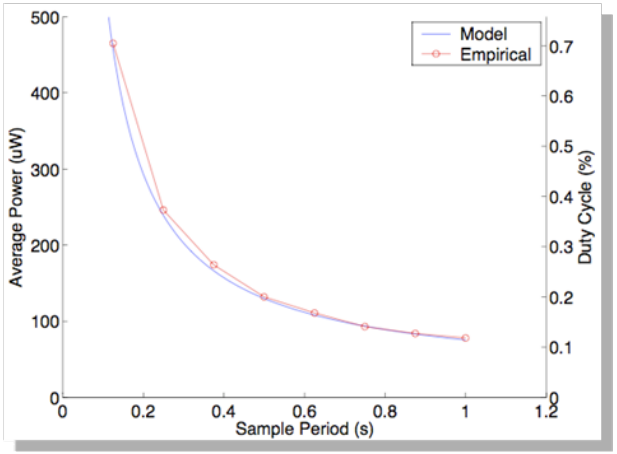
Preamble + Transmit (64 ms)

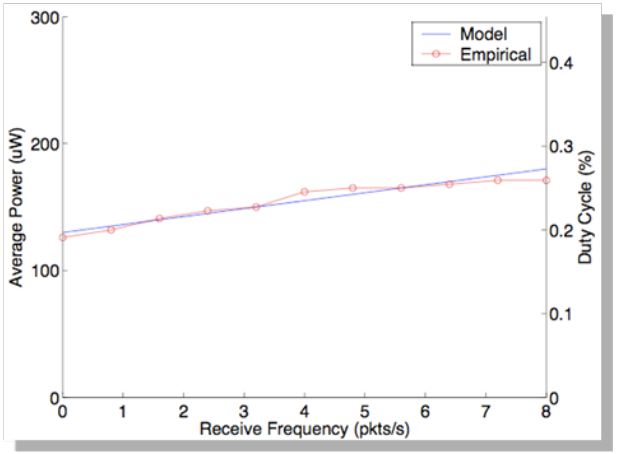


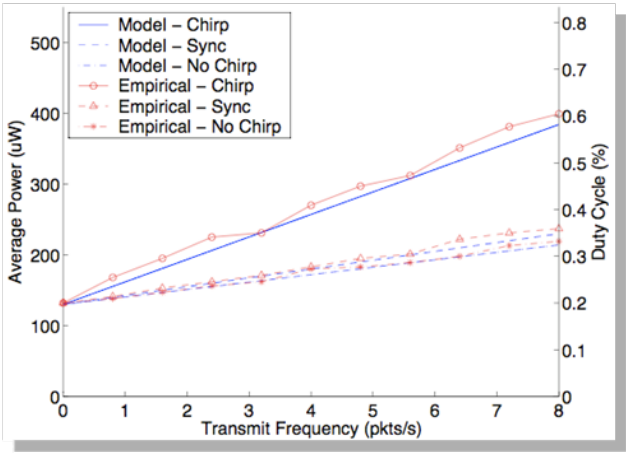
Preamble + Transmit (128 ms)

Evaluation: Link Power Model

$$P_{total} = P_{listen} + P_{rx} + P_{tx}$$







$$P_{listen} = P_{sleep} + f_{sample} E_{sample}$$

$$P_{rx} = f_{rx} E_{rx}$$

$$P_{txb} = f_{txb}\left(E_{tx} + E_{cb} + E_{cd}\frac{1}{f_{sample}}\right)$$

$$P_{txu} = f_{txu}\left(E_{tx} + E_{cb} + E_{cd}\left(2 + \frac{f_{\Delta}}{f_{txu}}\right)\right)$$

Conclusion

- Proposal to 15.4e
  - New *chirp* frame
  - Secure ACK frame
  - Add Coordinated Sampled Listening (CSL) to MAC
- Advantages
  - Low-power operation for entire network lifecycle for both FFD and RFD
  - Always-on illusion, IP-friendly
  - Responsive to asynchronous, unscheduled events
  - Simple to implement
  - Independent of central control
  - Safety net for further optimizations

Thanks You

- Questions?