Wireless Protocols for IoT Part II: IEEE 802.15.4 Wireless Personal Area Networks

Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

These slides and audio/video recordings of this class lecture are at:
http://www.cse.wustl.edu/~jain/cse574-18/

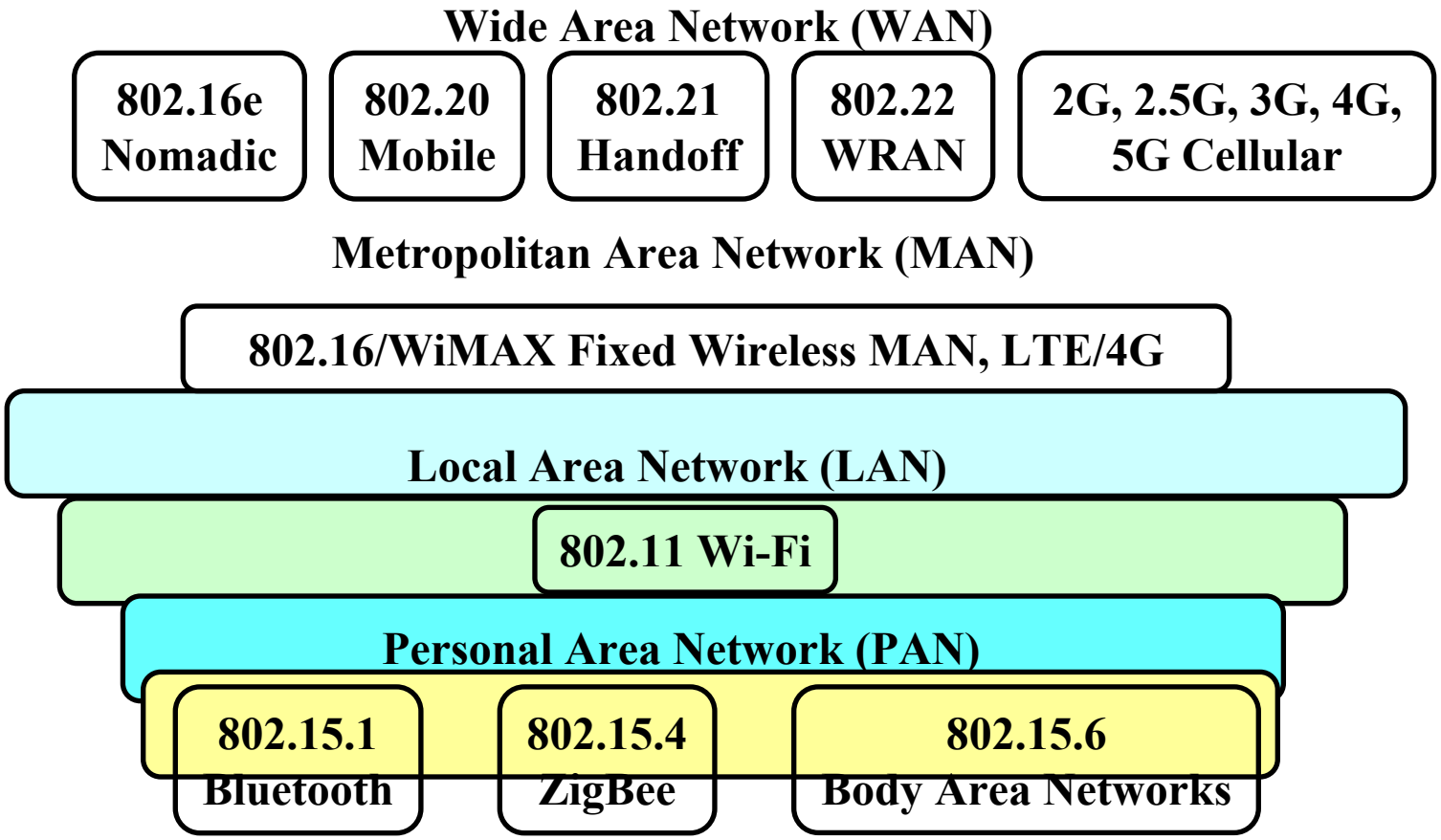
Overview

1. Internet of Things and Wireless Protocols for IoT
2. IEEE 802.15.4: Topologies, MAC, PHY
3. New PHY concepts: Offset-QPSK, Parallel Sequence Spread Spectrum, Chirp Spread Spectrum, Ultra-Wideband
4. IEEE 802.15.4e Enhancements

Note: This is the 3rd lecture in series of class lectures on IoT. Bluetooth and Bluetooth Smart are also used in IoT and were covered in the previous lectures. Future lectures will cover ZigBee and other protocols.

Wireless Personal Area Networks (WPANs)

- 10m or less



WPAN: Design Challenges

- **Battery powered**: Maximize battery life.
  A few hours to a few years on a coin cell.
- **Dynamic topologies**: Short duration connections and then device is turned off or goes to sleep
- **No infrastructure**
- **Avoid Interference** due to larger powered LAN devices
- **Simple and Extreme Interoperability**: Billions of devices. More variety than LAN or MAN
- **Low-cost**: A few dollars

IEEE 802.15 Projects

- **IEEE 802.15.1-2005**: **Bluetooth** 1.2
- IEEE 802.15.2-2003: Coexistence Recommended Practice
- IEEE 802.15.3-2016: High Rate (55 Mbps) Multimedia WPAN, includes 3c-2009 mm wave phy, 3b-2005 High rate WPAN
- IEEE 802.15.3d-2017: 100 Gbps point-to-point Phy
- IEEE 802.15.3e-2017: High-Rate close proximity point-to-point MAC and PHY
- IEEE 802.15.3f-2017: High-rate wireless multi-media networks using mm waves
- IEEE 802.15.4a-2007: Precision Ranging
- IEEE 802.15.4c-2009: Chinese 314-316, 430-434, 779-787 MHz
- IEEE 802.15.4d-2009: Japanese 950 MHz
- IEEE 802.15.4e-2012: MAC Enhancements
- IEEE 802.15.4f-2012: PHY for **Active RFID**

IEEE 802.15 Projects (Cont)

- IEEE 802.15.4g-2012: PHY for Smart Utility Networks
- IEEE 802.15.4j-2013: Medical **Body Area Network** 2.36-2.4 GHz
- IEEE 802.15.4k-2013: Low Energy Critical Infrastructure Monitoring PHY
- IEEE 802.15.4m-2014: TV **White Spaces** PHY – between 56 MHz and 862 MHz
- IEEE 802.15.4n-2016: China Medical Band PHY
- IEEE 802.15.4p-2014: Rail (Train) Communications & Control PHY
- **IEEE 802.15.4-2015**: Low Rate (250kbps) WPAN – **ZigBee**
- IEEE 802.15.4md: Maintenance of IEEE 802.15.4-2015
- IEEE 802.15.4q-2016: Ultra Low Power PHY
- IEEE 802.15.4s-2018: System resource management capability
- IEEE 802.15.4t-2017: High rate (2 Mbps) PHY

IEEE 802.15 Projects (Cont)

- IEEE 802.15.4u-2016: 865-867 MHz band in India
- IEEE 802.15.4v-2017: Enabling use of regional sub-GHz bands (4n ,4q, 4t, 4u)
- IEEE P802.15.4w: Low-Rate Low-Power Wide Area Network (**LPWAN**) extension to 802.15.4 PHY to cover 10-15 km
- IEEE P802.15.4x: Field Area Network extensions for devices with no battery or very limited battery consumption (Smart Utility Network)
- IEEE P802.15.4y: Security next generation using AES-256
- IEEE P802.15.4z: Enhanced impulse radio **Ultra-Wide Band** (UWB)
- IEEE 802.15.5-2009: Mesh Networking. Full/partial meshes. Range Extension
- IEEE 802.15.6-2012: Body Area Networking. Medical and entertainment. Low power
- IEEE 802.15.7-2011: Short Range **Optical Wireless**

IEEE 802.15 Projects (Cont)

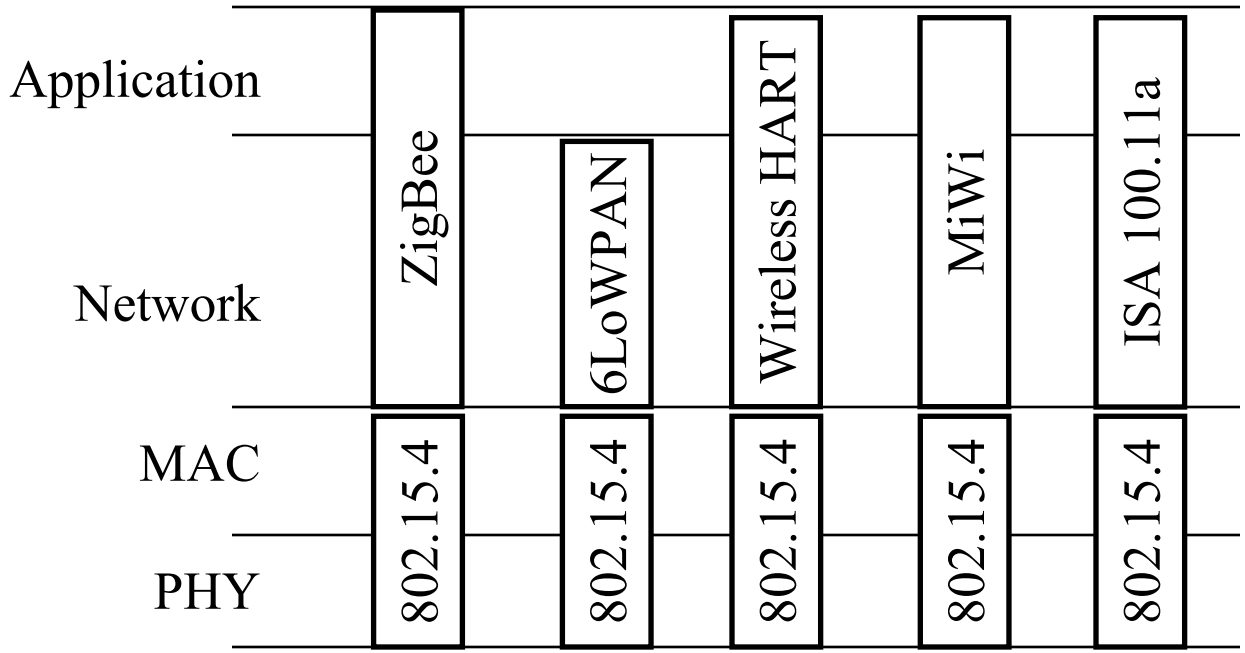
- IEEE P802.15.7r1: Optical wireless (infrared, ultraviolet, visible light)
- IEEE P802.15.7m: Maintenance of 802.15.7-2011
- IEEE 802.15.8-2017: Peer Aware Communications
- IEEE 802.15.9-2016: Key Management Support
- IEEE 802.15.10-2017: Routing packets in dynamically changing wireless networks
- IEEE P802.15.10a: Routing mode additions. Automated discovery of nodes and route configuration
- IEEE P802.15.12: Upper Layer Interface (ULI) to harmonize fragmentation, configuration etc for all 802.15.4 (Upper L2 and interface to L3)
- IEEE P802.15.13: **Multi-Gigabit/s Optical Wireless** with ranges up to 200m
- IEEE 802.15 IG6T: Consolidate Link Layer Control interest group
- IEEE 802.15 IGdep: Enhanced Dependability interest group
- IEEE 802.15 IGvat: **Vehicular** Assistive Technology

IEEE 802.15 Projects (Cont)

- IEEE 802.15 IGguide: Guide for 15.4 use interest group
- IEEE 802.15 IGhrrc: High Rate Rail Communications interest group
- IEEE 802.15 ITTHz: **Terahertz** interest group
- IEEE 802.15 SCwng: Wireless Next-Generation standing committee
- IEEE 802.15 SCmaint: Maintenance standing committee
- IEEE 802.15 SCietf: IETF Liaison

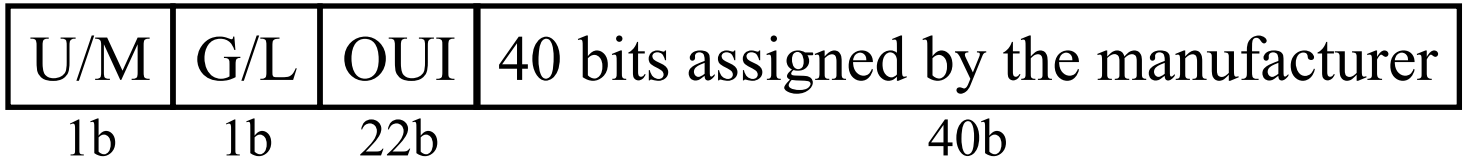
IEEE 802.15.4

- Used by several "Internet of Things" protocols: ZigBee, 6LowPAN, Wireless HART, MiWi, and ISA 100.11a



IEEE 802.15.4 Overview

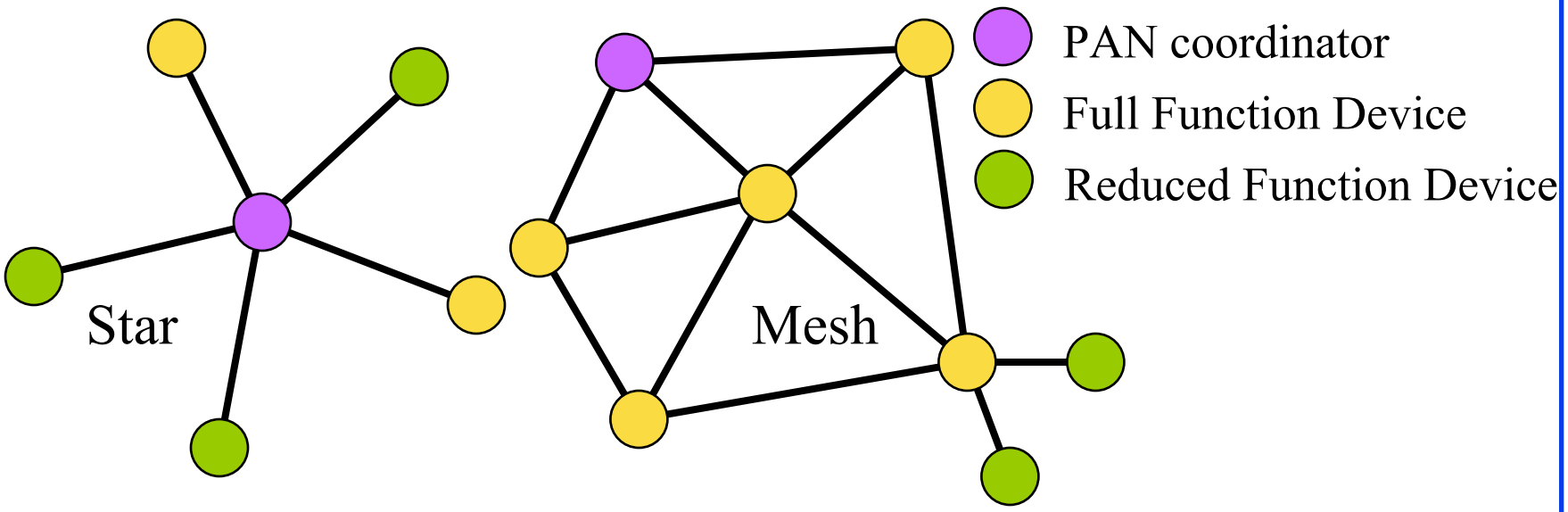
- Low Rate Wireless Personal Area Network (LR-WPAN)
- 2.4 GHz (most common). 16 5-MHz channels
- 250 kbps PHY ⇒ 50 kbps application data rate
- Peak current depends upon symbol rate ⇒ multilevel 4b/symbol)
- Similar to 802.11: Direct Sequence Spread Spectrum, CSMA/CA, Backoff, Beacon, Coordinator (similar to Access point)
- Lower rate, short distance ⇒ Lower power ⇒ Low energy
- Each node has a 64-bit Extended Unique ID (EUI-64):



- No segmentation/reassembly. Max MAC frame size is 127 bytes with a payload of 77+ bytes.

IEEE 802.15.4 Topologies

- Star and peer-to-peer
- Two types of devices: Full Function device (FFD), Reduced Function device (RFD)



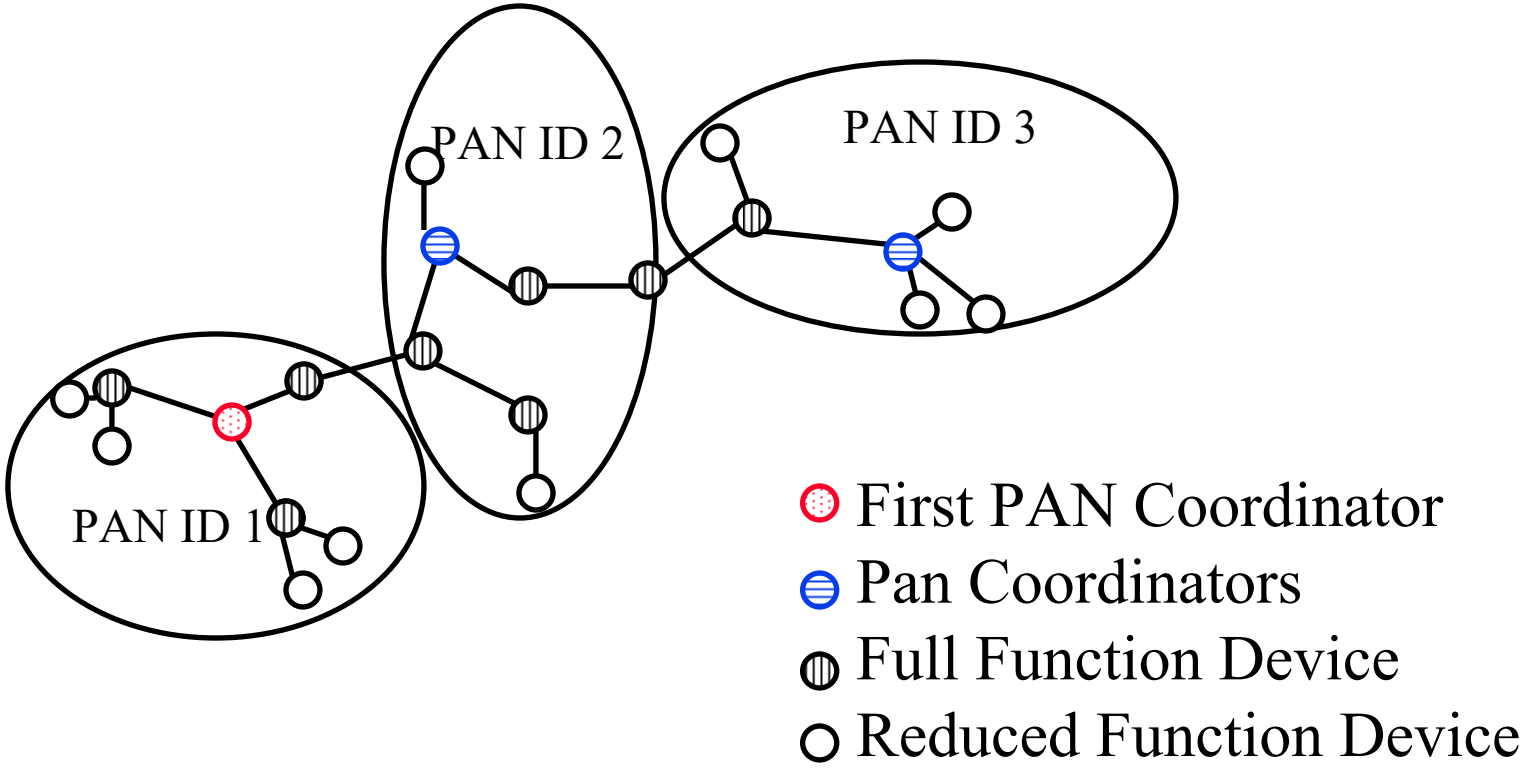
Ref: IEEE 802.15.4-2011

Coordinator

- FFDs can become coordinator and can also route messages to other nodes
- RFDs cannot become coordinator and can only be a leaf
- FFD that starts a PAN becomes the coordinator
- In star topology, all communication is to/from the coordinator
- In P2P topology, FFDs can communicate directly also.
- Each piconet has a PAN ID and is called a **cluster**.
- Nodes join a cluster by sending association request to the coordinator. Coordinator assigns a 16-bit short address to the device. Devices can use either the short address or EUI-64 address.

Cluster Tree Network

- A coordinator can ask another FFD to become a coordinator for a subset of nodes. Tree ⇒ No loops

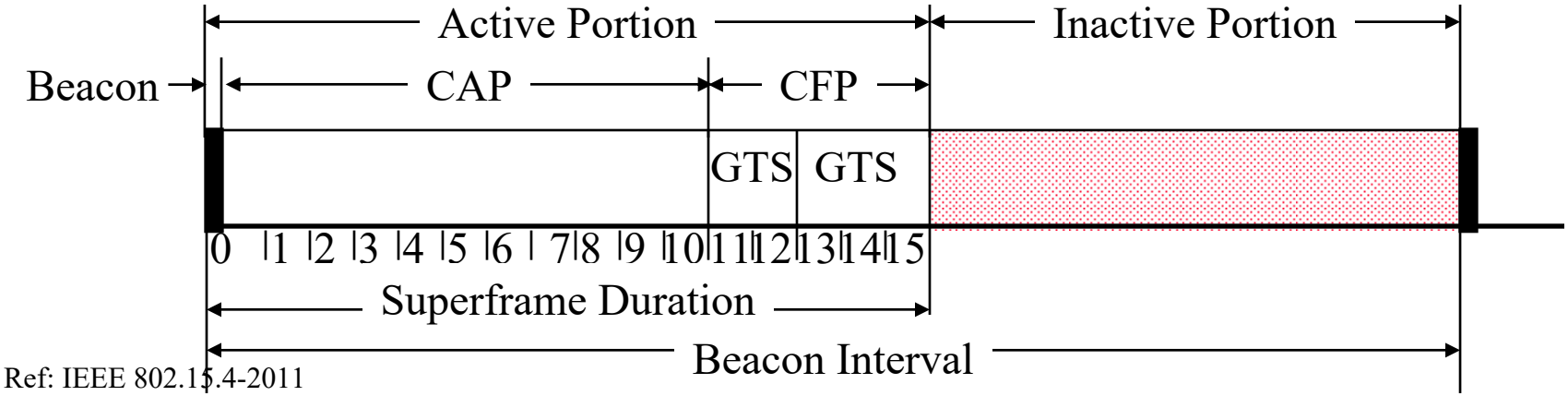


Ref: IEEE 802.15.4-2011

IEEE 802.15.4 MAC

Beacon-Enabled CSMA/CA

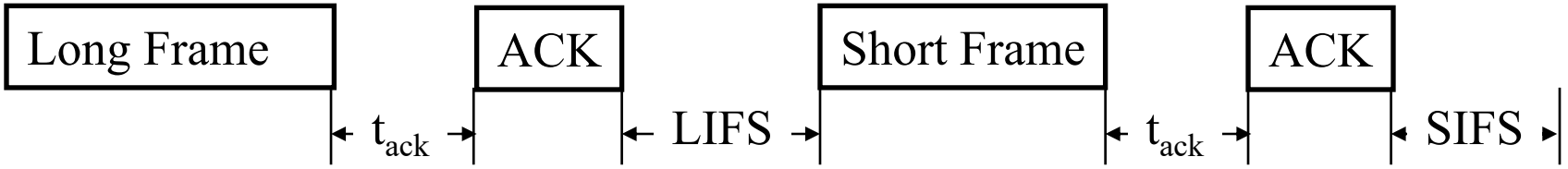
- Coordinator sends out beacons periodically
- Part of the beacon interval is inactive ⇒ Everyone sleeps
- Active interval consists of 16 slots
- Guaranteed Timed Slots (GTS): For real-time services. Periodic reserved slots.
- Contention Access Period (CAP). Slotted CSMA.



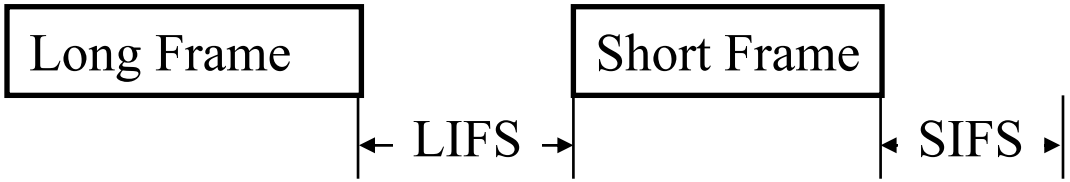
IEEE 802.15.4 MAC (Cont)

- **Beaconless Operation**: Unslotted CSMA
  - If coordinator does not send beacons, there are no slots
- Acknowledgements if requested by the sender.
- Short inter-frame spacing (SIFS) if previous transmission is shorter than a specified duration. Otherwise, Long inter-frame spacing (LIFS)

Acknowledged Transmissions



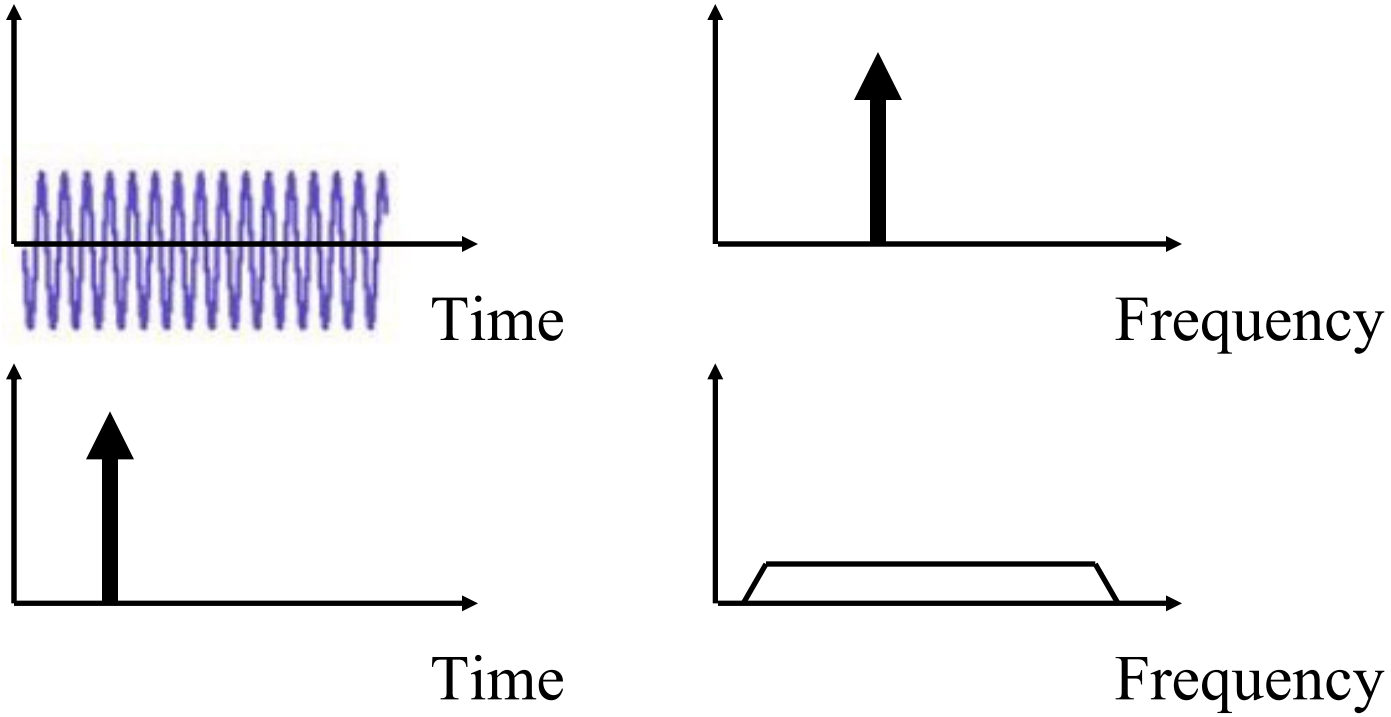
Unacknowledged Transmissions



802.15.4 CSMA/CA

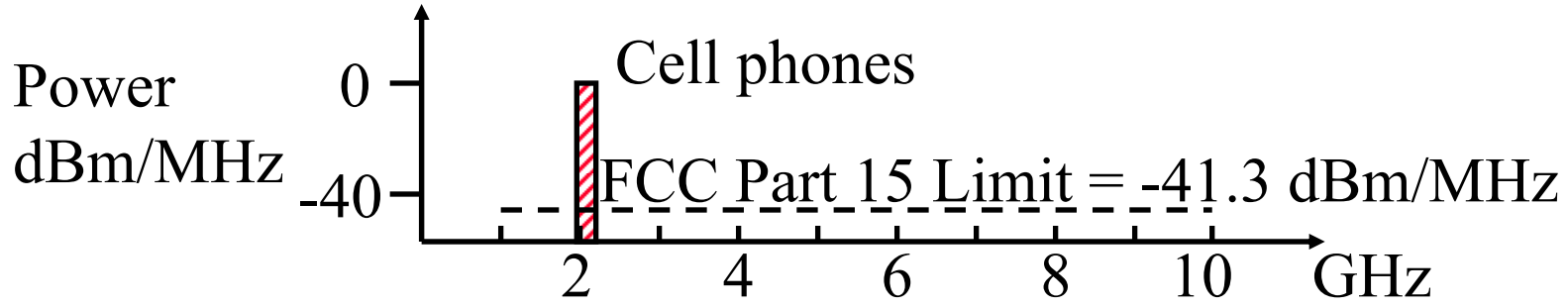
- Wait until the channel is free.
- Wait a random back-off period
  If the channel is still free, transmit.
- If the channel is busy, backoff again.
  Backoff exponent limited to 0-2 in battery life-extension mode.
- Acknowledgement and Beacons are sent without CSMA-CA.

Ultra-Wideband



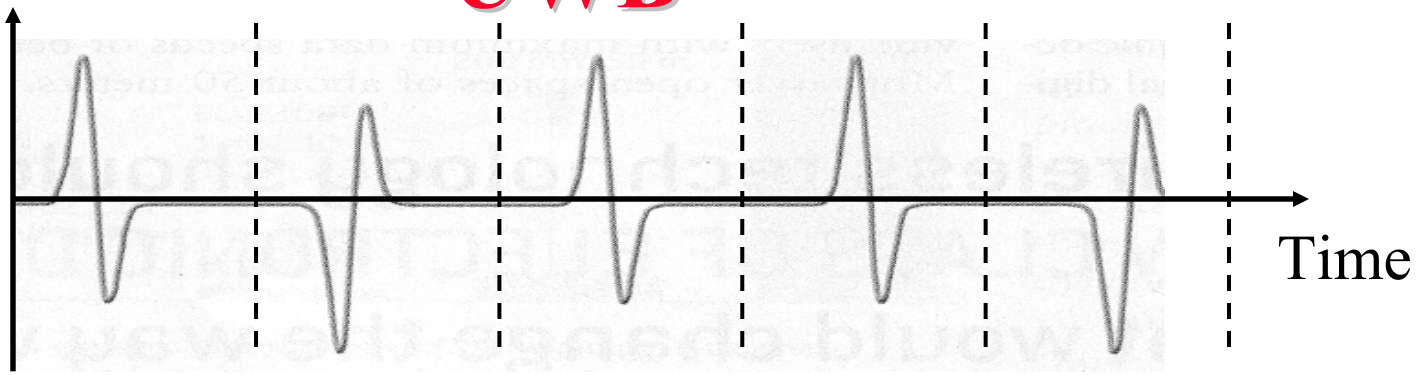
- An impulse in time domain results in a ultra wide spectrum in frequency domain and essentially looks like a white noise to other devices

Ultra-Wideband (UWB)



- FCC rules restrict the maximum noise generated by a wireless equipment (0 dBm = 1mW, -40 dBm = 0.1 μW)
- It is possible to generate very short (sub-nano sec) pulses that have spectrum below the allowed noise level
  ⇒ Possible to get Gbps using 10 GHz spectrum
- FCC approved UWB operation in 2002
- UWB can be used for high-speed over short distances
- UWB can see through trees and underground (radar)
  ⇒ collision avoidance sensors, through-wall motion detection
- Position tracking: cm accuracies. Track high-value assets

UWB



- Sub-nanosecond impulses are sent many million times per second
- Became feasible with high-speed switching semiconductor devices
- Pulse width = 25 to 400 ps
- Impulses may be position, amplitude, or polarity modulated
- 0.25 ns Impulse ⇒ 4 B pulses/sec ⇒ 100's Mbps
- 802.15.4 uses pulse position and binary phase shift keying modulation

Advantages of UWB

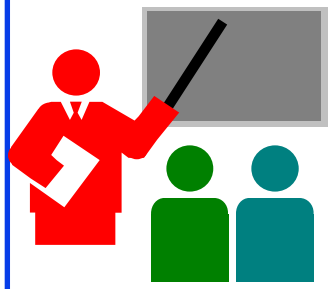
- Very low energy consumption: Good Watts/Mbps
- Line of sight not required. Passes through walls.
- Sub-centimeter resolution allows precise motion detection
- Pulse width much smaller than path delay
  $\Rightarrow$ Easy to resolve multipath
  $\Rightarrow$ Can use multipath to advantage
- Difficult to intercept (interfere)
- All digital logic $\Rightarrow$ Low cost chips
- Small size: 4.5 mm^2 in 90 nm process for high data rate designs

Direct sequence (DS-UWB)

- Championed by Motorola/XtremeSpectrum
- Uses CDMA with multiple chips per bit
- Chips are encoded using pulse
- This is the scheme used in 802.15.4
- Low power density ⇒ Good for body area network

IEEE 802.15.4e Enhancements

- Low latency deterministic operation: pre-assigned slots
- Channel adaptation: Different channels used by different nodes for contention free period
- Time slotted channel hopping: Higher layers coordinate the slot allocation along with its frequency. Good for harsh industrial environments.
- Each device can select its listening channel
- Transmitter and receiver coordinate their cycles (very low duty cycle)
- Transmit only when requested by receiver



Summary

1. IoT fueled initially by smart grid is resulting in several competing protocols: Bluetooth Smart, ZigBee Smart, ...
2. IEEE 802.15.4 is a low-data rate wireless personal area network and is the PHY and MAC layer used by many IoT protocols, such as ZigBee, and WirelessHART.
3. 802.15.4 uses full function and reduced function devices. FFDs can act as coordinator. Allows a star, mesh, or a cluster tree topology.
4. Uses Slotted/Unslotted CSMA/CA. Supports Guaranteed timed slots for low-latency application.
5. UWB allows transmission with very low average power spread over a large band.

Reading List

- A. Elahi and A. Gschwender, "ZigBee Wireless Sensor and Control Network," Prentice Hall, 2009, 288 pp., ISBN:0137134851, (Chapters 3 and 4) Safari Book.
- O. Hersent, et al., "The Internet of Things: Key Applications and Protocols," Wiley, 2012, 344 pp., ISBN:9781119994350, Safari book.

Wikipedia Pages

- http://en.wikipedia.org/wiki/Machine_to_machine
- http://en.wikipedia.org/wiki/Internet_of_Things
- http://en.wikipedia.org/wiki/IEEE_802.15.4
- http://en.wikipedia.org/wiki/IEEE_802.15.4a
- http://en.wikipedia.org/wiki/IEEE_802.15
- http://en.wikipedia.org/wiki/Chirp_spread_spectrum
- http://en.wikipedia.org/wiki/Carrier_sense_multiple_access_with_collision_avoidance
- http://en.wikipedia.org/wiki/Phase-shift_keying
- http://en.wikipedia.org/wiki/Chirp_spread_spectrum
- http://en.wikipedia.org/wiki/Ultra-wideband
- http://en.wikipedia.org/wiki/Personal_area_network
- http://en.wikipedia.org/wiki/Piconet
- http://en.wikipedia.org/wiki/Scatternet

References

- J. T. Adams, "An introduction to IEEE STD 802.15.4" IEEEAC paper #1055, Dec 30, 2005, 8 pp., https://web.sonoma.edu/users/f/farahman/sonoma/courses/cet543/resources/802_intro_01655947.pdf
- E. Karapistoli, et al., "An overview of the IEEE 802.15.4a Standard," IEEE Communications Magazine, January 2010, pp. 47-53, http://www.ee.oulu.fi/~kk/dtsp/tutoriaalit/Karapistoli.pdf
- D. Gratton, "The Handbook of Personal Area Networking Technologies and Protocols," Cambridge University Press, August 2013, 424 pp. ISBN: 978-0-521-19726-7, Safari Book
- I. Guvenc, et al., "Reliable Communications for Short-Range Wireless Systems," Cambridge University Press, March 2011, 426 pp., ISBN: 978-0-521-76317-2, Safari Book
- D. Raychaudhuri and M. Gerla, "Emerging Wireless Technologies and the Future Mobile Internet," Cambridge University Press, March 2011, 330 pp., ISBN: 978-0-521-11646-6, Safari Book
- N. Hunn, "Essentials of Short-Range Wireless," Cambridge University Press, July 2010, 344 pp., ISBN: 978-0-521-76069-0, Safari Book

References (Cont)

- H. Zhou, "The Internet of Things in the Cloud: A Middleware Perspective," CRC Press, 2013, 365 pp., ISBN: 9781439892992, Safari Book
- H. Schwetlick, "PSSS-Parallel Sequence Spread Spectrum – A Potential Physical Layer for OBAN?," http://oban.tubit.tu-berlin.de/5-PSSS-Schwetlick.pdf
- Z. Ianelli, "Introduction to Chirp Spread Spectrum (CSS) Technology," IEEE 802 Tutorial, http://www.ieee802.org/802_tutorials/03-November/15-03-0460-00-0040-IEEE-802-CSS-Tutorial-part1.ppt

Acronyms

- 6LowPAN IPv6 over Low Power Personal Area Network
- ACK Acknowledgement
- AES Advanced Encryption Standard
- AMCA Asynchronous Multi-Channel Adaptation
- ANSI American National Standards Institute
- ANT Name of a company
- BPM Burst Position Modulation
- CDMA Code Division Multiple Access
- CFP Contention Free Period
- COSEM Company Specification for Energy Metering
- CPS Cyber-Physical Systems
- CRC Cyclic Redundancy Check
- CSMA Carrier Sense Multiple Access
- CSMA/CA Carrier Sense Multiple Access with Collision Avoidance
- CSS Chirp Spread Spectrum
- dBm deci-Bell milli-Watt

Acronyms (Cont)

- DLMS Device Language Message Specification
- DQPSK Differential Quadrature Phase-shift keying
- ETSI European Telecommunications Standards Institute
- EUI-64 Extended Unique Identifier
- FCC Federal Communications Commission
- FFD Full Function device
- GFSK Gaussian Frequency-Shift Keying
- GHz Giga Hertz
- GTS Guaranteed Timed Slots
- HART Highway Addressable Remote Transducer Protocol
- ID Identifier
- IEEE Institution of Electrical and Electronics Engineer
- IETF Internet Engineering Task Force
- IoT Internet of Things
- ISA International Society of Automation
- ITTHz Interest Group for TeraHertz

Acronyms (Cont)

- LAN Local Area Network
- LECIM Low energy critical infrastructure monitoring
- LIFS Long Inter-frame Spacing
- LPWAN Low-Power Wide Area Network
- LR-WPAN Low-Rate Wireless Personal Area Networks
- LTE Long-Term Evolution
- MAC Media Access Control
- MAN Metropolitan Area Network
- MHz Mega Hertz
- MiWi Microchip Wireless
- OUI Organizatinally Unique Identifier
- PAN Personal Area Network
- PCA Priority Channel Access
- PHY Physical Layer
- PLC Powerline Communications
- PPDU Physical Layer Protocol Data Unit

Acronyms (Cont)

- PSSS Parallel Sequence Spread Spectrum
- QPSK Quadrature Phase Shift Keying
- RFD Reduced Function device
- RFID Radio Frequency Identifier
- SCADA Supervisory control and data acquisition
- SCietf Standing Committee for IETF Liason
- SCwng Wireless Next Generation Standing Commttee
- SIFS Short inter-frame spacing
- ULI Upper Layer Interface
- UWB Ultra Wide Band
- WirelessHART Wireless Highway Addressable Remote Transducer Protocol
- WPAN Wireless Personal Area Network
- WRAN Wireless Regional Area Network

Scan This to Download These Slides

Raj Jain
http://rajjain.com

Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Recent Advances in Networking (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw