

# 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/cse574-16/>

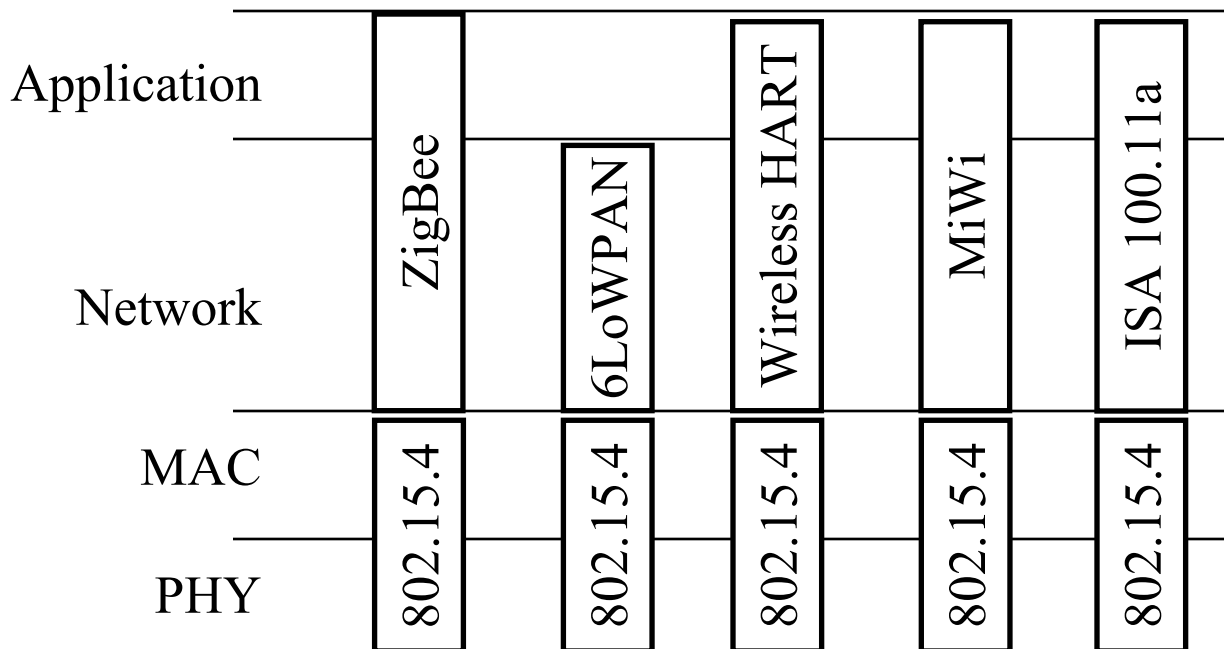


1. Internet of Things and Wireless Protocols for IoT
2. IEEE 802.15.4: Topologies, MAC, PHY
3. New PHY concepts: Offset-QPSK, Parallel Sequence Spread Spectrum, Chirp Spread Spectrum, Ultra-Wideband
4. IEEE 802.15.4e Enhancements

Note: This is the 3<sup>rd</sup> 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.

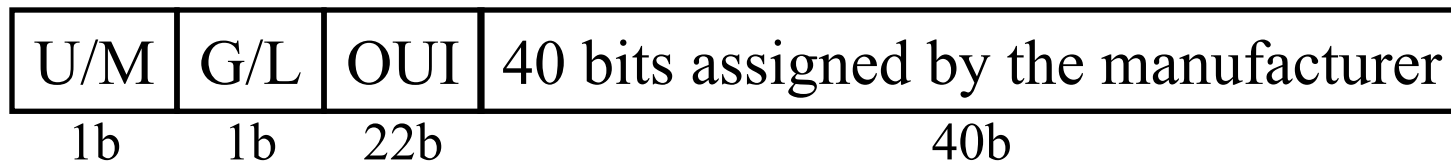
# IEEE 802.15.4

- Used by several “Internet of Things” protocols:  
ZigBee, 6LoWPAN, Wireless HART, MiWi, and ISA 100.11a



# IEEE 802.15.4 Overview

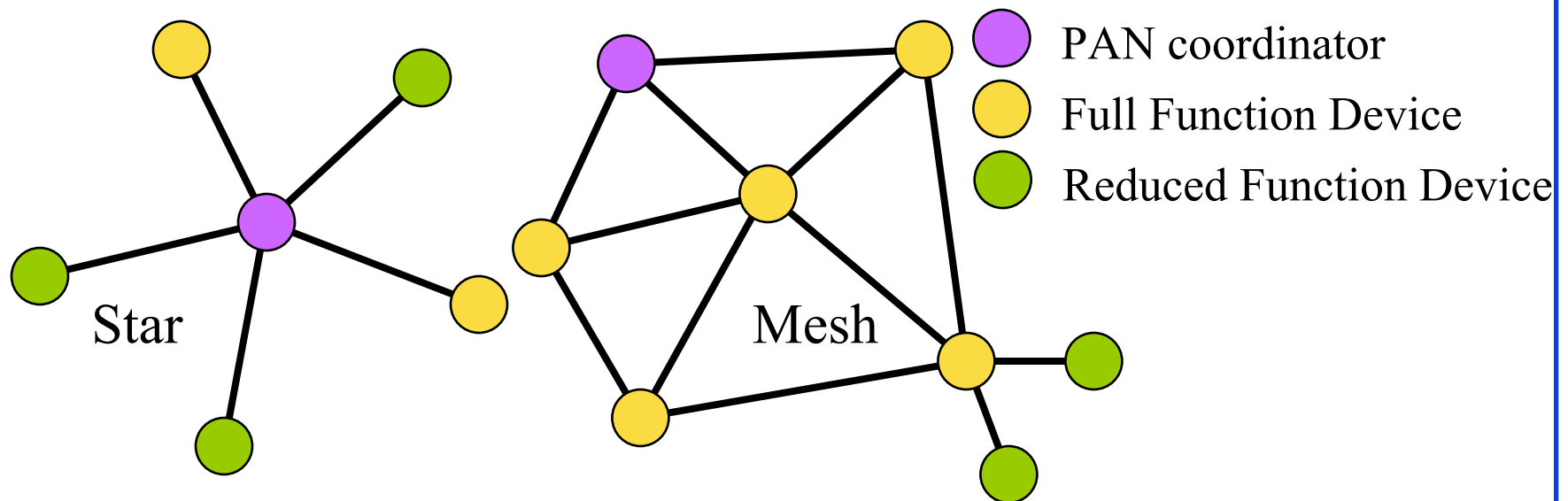
- ❑ Low Rate Wireless Personal Area Network (LR-WPAN)
- ❑ 2.4 GHz (most common). 16 5-MHz channels
- ❑ 250 kbps PHY  $\Rightarrow$  50 kbps application data rate
- ❑ Peak current depends upon symbol rate  $\Rightarrow$  multilevel (4b/symbol)
- ❑ Similar to 802.11: Direct Sequence Spread Spectrum, CSMA/CA, Backoff, Beacon, Coordinator (similar to Access point)
- ❑ Lower rate, short distance  $\Rightarrow$  Lower power  $\Rightarrow$  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

Washington University in St. Louis

<http://www.cse.wustl.edu/~jain/cse574-16/>

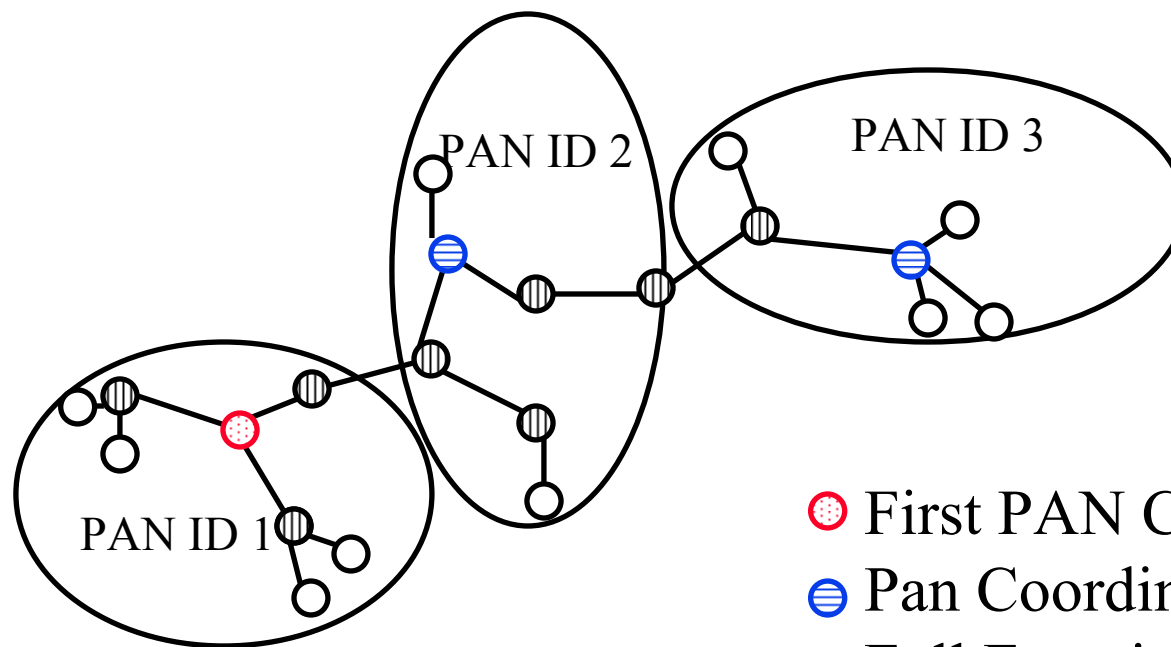
©2016 Raj Jain

# 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  $\Rightarrow$  No loops

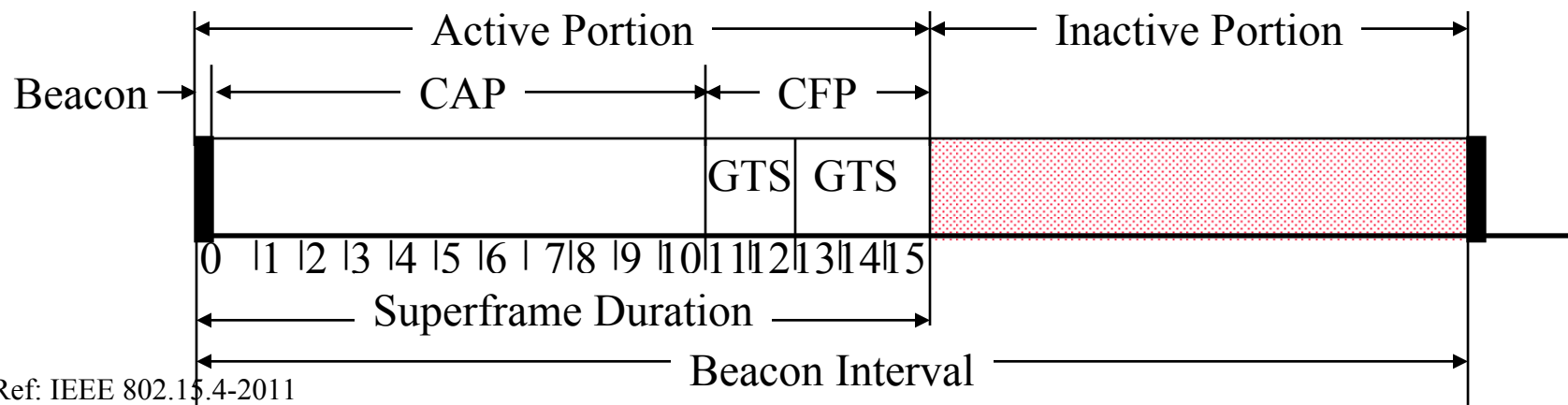


- First PAN Coordinator
- Pan Coordinators
- Full Function Device
- Reduced Function Device

# IEEE 802.15.4 MAC

## Beacon-Enabled CSMA/CA

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



Ref: IEEE 802.15.4-2011

Washington University in St. Louis

<http://www.cse.wustl.edu/~jain/cse574-16/>

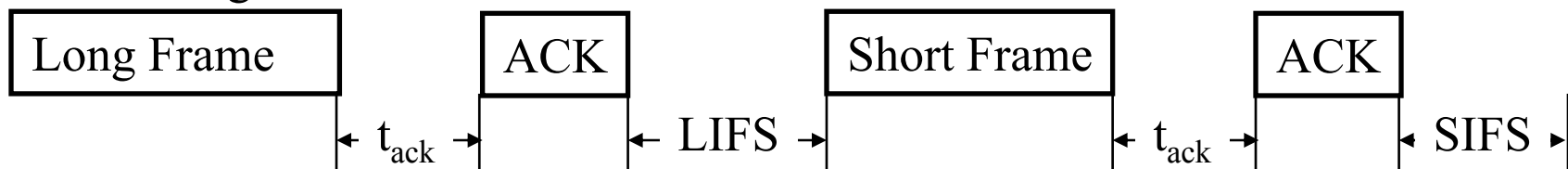
©2016 Raj Jain



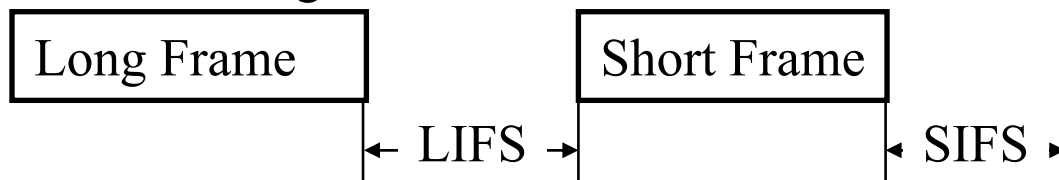
# IEEE 802.15.4 MAC (Cont)

- ❑ **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



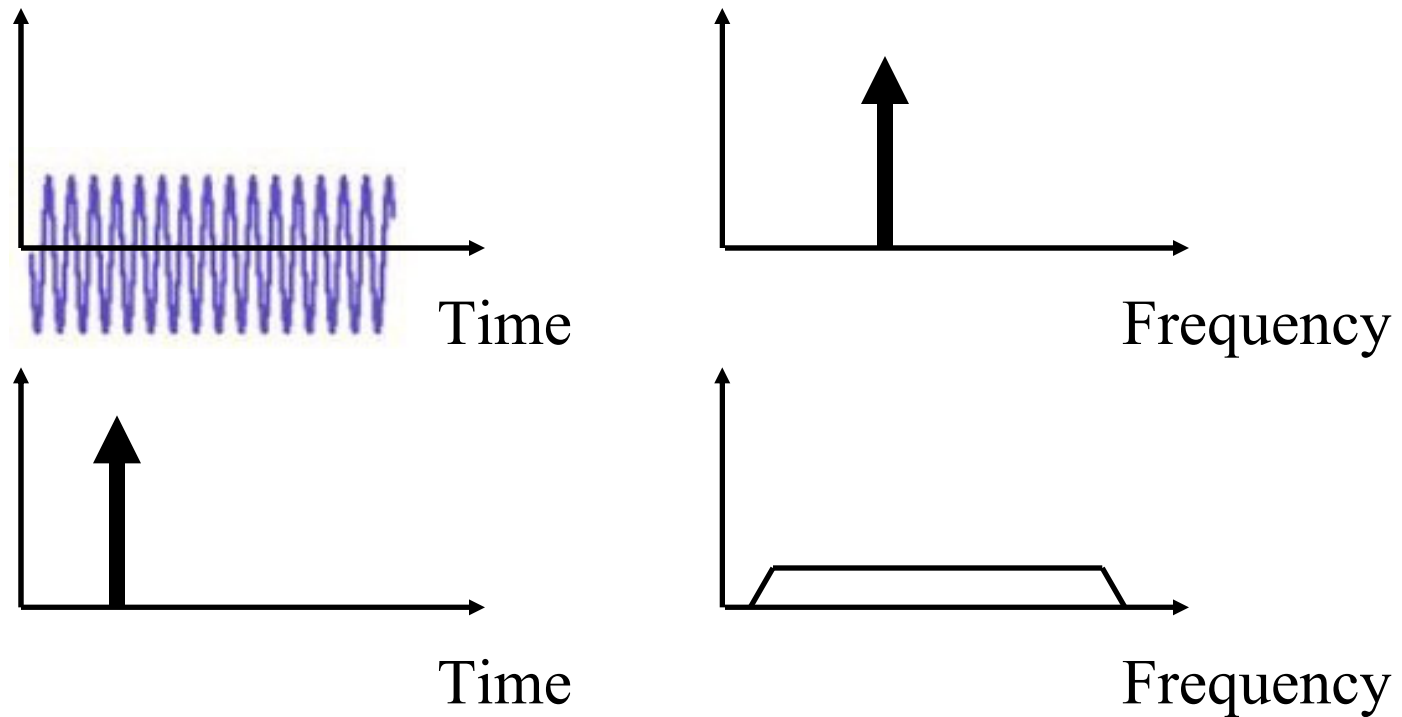
## Unacknowledged Transmissions



## 802.15.4 CSMA/CA

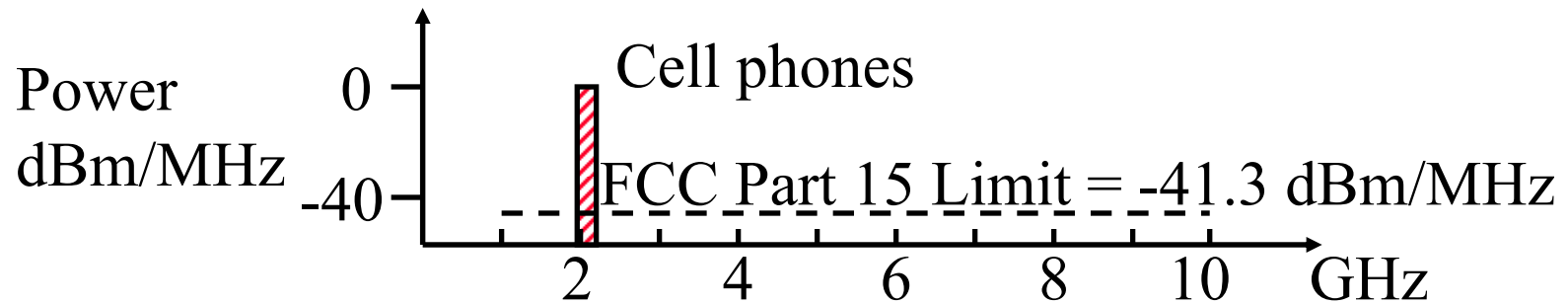
- ❑ Wait until the channel is free.
- ❑ Wait a random back-off period  
If the channel is still free, transmit.
- ❑ If the channel is busy, backoff again.  
Backoff exponent limited to 0-2 in battery life-extension mode.
- ❑ Acknowledgement and Beacons are sent without CSMA-CA.

# Ultra-Wideband

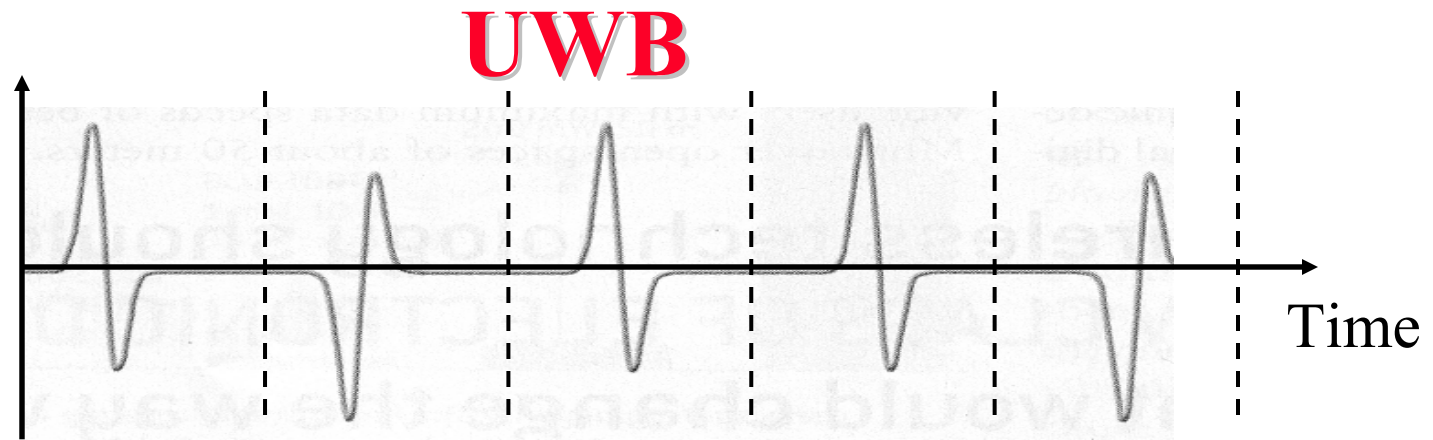


- An impulse in time domain results in a ultra wide spectrum in frequency domain and essentially looks like a white noise to other devices

# Ultra-Wideband (UWB)



- ❑ FCC rules restrict the maximum noise generated by a wireless equipment ( $0 \text{ dBm} = 1 \text{ mW}$ ,  $-40 \text{ dBm} = 0.1 \text{ } \mu\text{W}$ )
- ❑ It is possible to generate very short (sub-nano sec) pulses that have spectrum below the allowed noise level  
 $\Rightarrow$  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)  
 $\Rightarrow$  collision avoidance sensors, through-wall motion detection
- ❑ Position tracking: cm accuracies. Track high-value assets



- ❑ 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  $\Rightarrow$  4 B pulses/sec  $\Rightarrow$  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
  - ⇒ Easy to resolve multipath
  - ⇒ Can use multipath to advantage
- ❑ Difficult to intercept (interfere)
- ❑ All digital logic ⇒ Low cost chips
- ❑ Small size: 4.5 mm<sup>2</sup> 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  $\Rightarrow$  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 transmission services 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/Machine_to_machine)
- ❑ [http://en.wikipedia.org/wiki/Internet\\_of\\_Things](http://en.wikipedia.org/wiki/Internet_of_Things)
- ❑ [http://en.wikipedia.org/wiki/IEEE\\_802.15.4](http://en.wikipedia.org/wiki/IEEE_802.15.4)
- ❑ [http://en.wikipedia.org/wiki/IEEE\\_802.15.4a](http://en.wikipedia.org/wiki/IEEE_802.15.4a)
- ❑ [http://en.wikipedia.org/wiki/IEEE\\_802.15](http://en.wikipedia.org/wiki/IEEE_802.15)
- ❑ [http://en.wikipedia.org/wiki/Chirp\\_spread\\_spectrum](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/Carrier_sense_multiple_access_with_collision_avoidance)
- ❑ [http://en.wikipedia.org/wiki/Phase-shift\\_keying](http://en.wikipedia.org/wiki/Phase-shift_keying)
- ❑ [http://en.wikipedia.org/wiki/Chirp\\_spread\\_spectrum](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/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.,  
[http://sonoma.edu/users/f/.../802\\_intro\\_01655947.pdf](http://sonoma.edu/users/f/.../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
- ❑ H. Zhou, “The Internet of Things in the Cloud: A Middleware Perspective,” CRC Press, 2013, 365 pp., ISBN: 9781439892992, Safari Book

## References (Cont)

- H. Schwetlick, “PSSS-Parallel Sequence Spread Spectrum – A Potential Physical Layer for OBAN?,”  
<http://oban.tubit.tu-berlin.de/5-PSSS-Schwetlick.pdf>
- Z. Ianneli, “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](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
- ❑ AMCA Asynchronous Multi-Channel Adaptation
- ❑ ANSI American National Standards Institute
- ❑ ANT Name of a company
- ❑ ASK Amplitude Shift Keying
- ❑ BPM Burst Position Modulation
- ❑ BPSK Binary Phase Shift Keying
- ❑ CDMA Code Division Multiple Access
- ❑ COSEM Company Specification for Energy Metering
- ❑ CPS Cyber-Physical Systems
- ❑ CRC Cyclic Redundancy Check
- ❑ CSL Coordinated Sampled Listening
- ❑ 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
- ❑ DSME Deterministic and Synchronous Multi-Channel Extension
- ❑ DSSS Direct Sequence Spread Spectrum
- ❑ ETSI European Telecommunications Standards Institute
- ❑ EUI-64 Extended Unique Identifier
- ❑ FCC Federal Communications Commission
- ❑ FFD Full Function device
- ❑ FSK Frequency Shift Keying
- ❑ GFSK Gaussian Frequency-Shift Keying
- ❑ GHz Giga Hertz
- ❑ GTS Guaranteed Transmission Services
- ❑ HART Highway Addressable Remote Transducer Protocol
- ❑ ID Identifier
- ❑ IEEE Institution of Electrical and Electronics Engineer
- ❑ IoT Internet of Things

## Acronyms (Cont)

- ❑ ISA International Society of Automation
- ❑ LECIM Low energy critical infrastructure monitoring
- ❑ LIFS Long Inter-frame Spacing
- ❑ LLDN Low-Latency Deterministic Network
- ❑ LR-WPAN Low-Rate Wireless Personal Area Networks
- ❑ MAC Media Access Control
- ❑ MHz Mega Hertz
- ❑ MPSK m-ary Phase-Shift Keying
- ❑ OFDM Orthogonal Frequency Division Multiplexing
- ❑ OUI Organizatinally Unique Identifier
- ❑ PAN Personal Area Network
- ❑ PCA Priority Channel Access
- ❑ PHY Physical Layer
- ❑ PLC Powerline Communications
- ❑ PPDU Physical Layer Protocol Data Unit
- ❑ PSSS Parallel Sequence Spread Spectrum



## Acronyms (Cont)

- ❑ QPSK            Quadrature Phase Shift Keying
- ❑ RFD            Reduced Function device
- ❑ RFID           Radio Frequency Identifier
- ❑ RIT            Receiver Initiated Transmission
- ❑ RPL            Routing Protocol for Low Power and Lossy Networks
- ❑ RX             Receiver
- ❑ SCADA        Supervisory control and data acquisition
- ❑ SIFS           Short inter-frame spacing
- ❑ SUN            Smart metering utility network
- ❑ TSCH          Time Slotted Channel Hopping
- ❑ UWB            Ultra Wide Band
- ❑ WirelessHART Wireless Highway Addressable Remote Transducer Protocol
- ❑ WPAN          Wireless Personal Area Network

# Scan This to Get These Slides



## Related Modules



Internet of Things,

[http://www.cse.wustl.edu/~jain/cse574-16/j\\_10iot.htm](http://www.cse.wustl.edu/~jain/cse574-16/j_10iot.htm)

Wireless Protocols for IoT Part I: Bluetooth and Bluetooth Smart,

[http://www.cse.wustl.edu/~jain/cse574-16/j\\_11ble.htm](http://www.cse.wustl.edu/~jain/cse574-16/j_11ble.htm)



Wireless Protocols for IoT Part III: ZigBee,

[http://www.cse.wustl.edu/~jain/cse574-16/j\\_13zgb.htm](http://www.cse.wustl.edu/~jain/cse574-16/j_13zgb.htm)

Low Power WAN Protocols for IoT,

[http://www.cse.wustl.edu/~jain/cse574-16/j\\_14ahl.htm](http://www.cse.wustl.edu/~jain/cse574-16/j_14ahl.htm)



Audio/Video Recordings and Podcasts of  
Professor Raj Jain's Lectures,

<https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw>