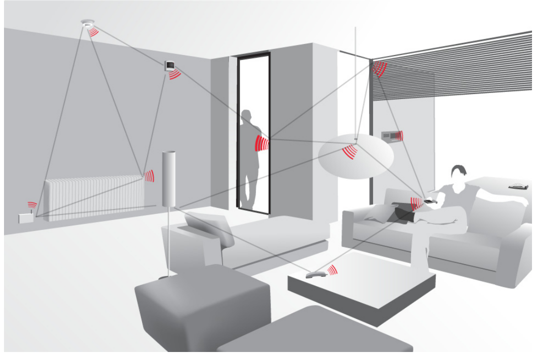
Wireless Protocols for Internet of Things: Part I – Wireless Personal Area Networks



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These slides and audio/video recordings of this class lecture are at:
http://www.cse.wustl.edu/~jain/cse574-14/

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 2nd 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.

Machine-to-Machine (M2M)

- 1.1 Billion smart phones
- 244 Million smart meters
- 487 Million e-readers and tablets
- 2.37 Billion networked office devices
- 86 Million medical devices
- 45 Million connected automobiles
- 547 Million connected appliances
- 105 Million connected military devices
- 431 Million information technology devices
- 45 Million supervisory control and data acquisition (SCADA)
- 5+ Billion other (non-phone/tablet/e-reader) electronic devices

Ref: H. Zhou, "The Internet of Things in the Cloud: A Middleware Perspective," CRC Press, 2013, 365 pp., ISBN: 9781439892992 (Safari Book)

Internet of Things

- Only 1% of things around us is connected.
  Refrigerator, car, washing machine, heater, a/c, garage door, should all be connected but are not.
- From 10 Billion today to 50 Billion in 2020
  Should include processes, data, things, and people.
- $14 Trillion over 10 years
  ⇒ Third in the list of top 10 strategic technologies by Gartner
  (After Mobile devices, Mobile Apps, but before Clouds, …)
- a.k.a. **Internet of Everything** by Cisco
  Smarter Planet by IBM
  Industrial Internet by GE
  Cyber-Physical Systems (CPS)
  Internet of European Things (more popular in Europe)

Ref: "Gartner Identifies Top 10 Strategic Technologies," http://www.cioinsight.com/it-news-trends/gartner-identifies-top-10-strategic-technologies.html
Ref: J. Bradley, "The Internet of Everything: Creating Better Experiences in Unimaginable Ways," Nov 21, 2013, http://blogs.cisco.com/ioe/the-internet-of-everything-creating-better-experiences-in-unimaginable-ways/#more-131793

Wireless Protocols for IoT

- IEEE 802.11*
- Bluetooth/Bluetooth Smart*
- ZigBee/ZigBee Smart Energy 2.0
- IEEE 802.15.6-2012: Body Area Networking
- Wireless HART (Highway Addressable Remote Transducer Protocol)
- International Society of Automation (ISA) 100.11a
- Z-Wave
- MiWi (Microchip Technology Wireless)
- ANT+
- Wireless MBUS

*Note: Already covered in previous lectures of this course.

Other Protocols for IoT

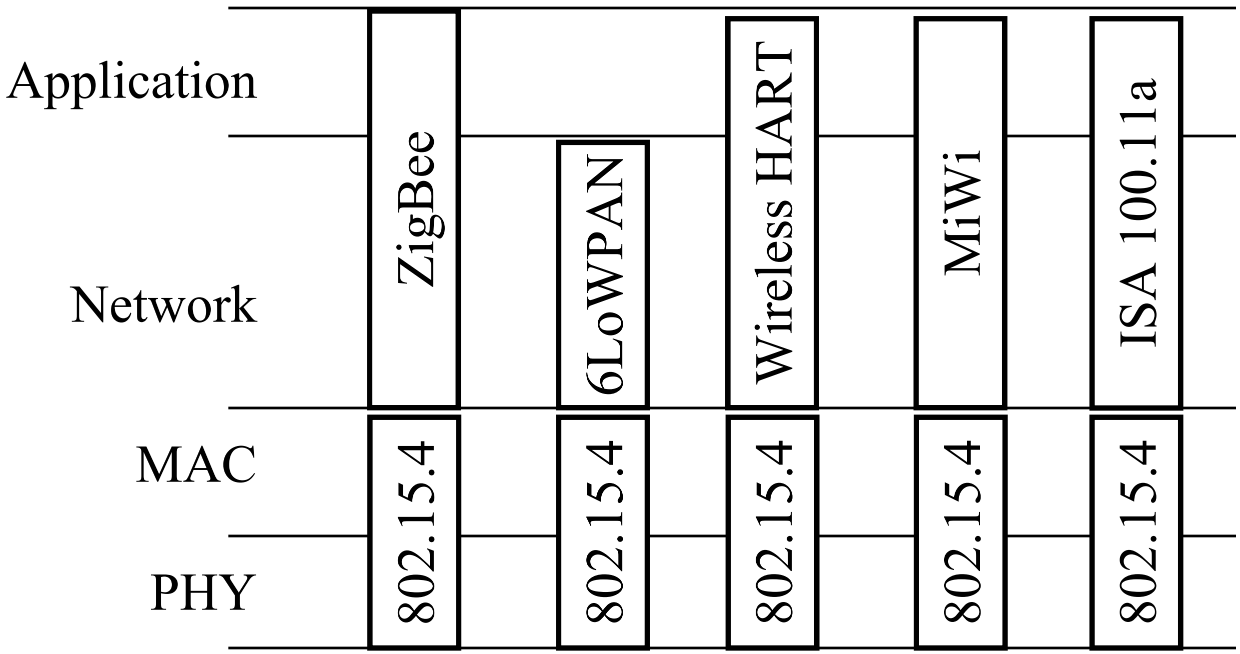
- Powerline Communications (PLC)*
- 6LowPAN (IPv6 over Low Power Personal Area Networks)§
- Routing Protocol for Low Power and Lossy Networks (RPL)§
- ETSI M2M Architecture
- MQ Telemetry Transport (MQTT)
- BACnet
- LonWorks
- ModBus
- KNX
- ANSI CI-12
- Device Language Message Specification (DLMS)/ Company Specification for Energy Metering (COSEM)

*Ref: R. Jain, "Introduction to Internet of Things," Class Lecture, Fall 2013, http://www.cse.wustl.edu/~jain/cse570-13/j_18iot.htm

§Ref: R. Jain, "Networking Protocols for Internet of Things," Class Lecture, Fall 2013, http://www.cse.wustl.edu/~jain/cse570-13/j_19lpn.htm

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

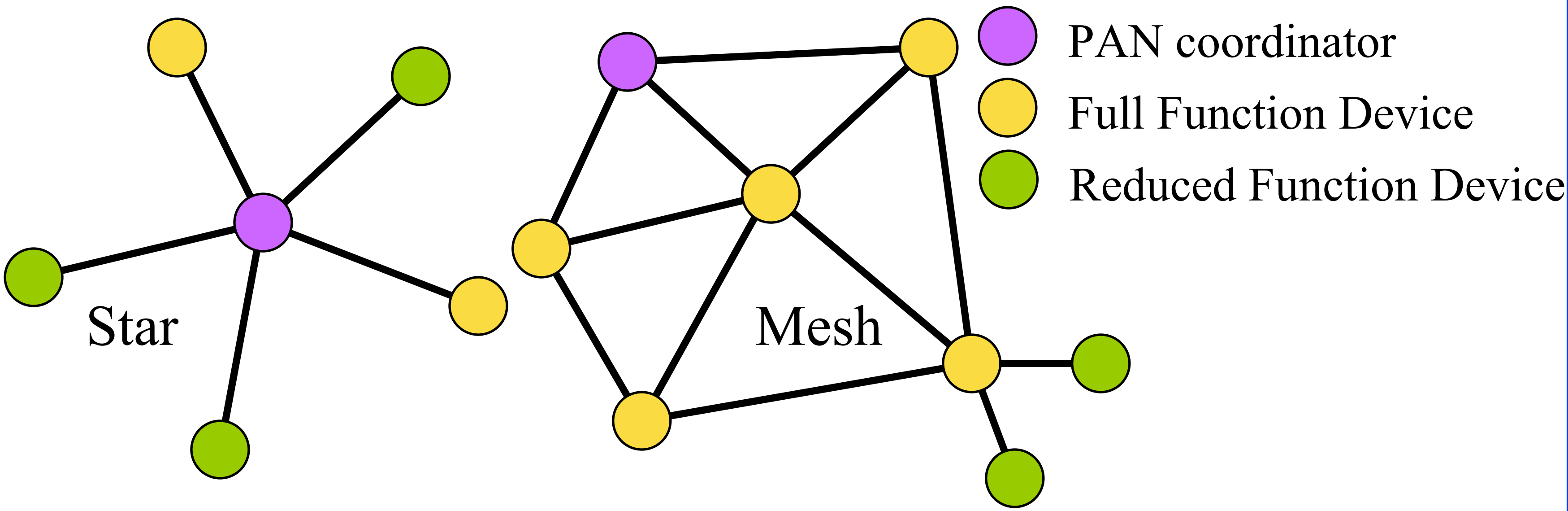
- Low Rate Wireless Personal Area Network (LR-WPAN)
- 2.4 GHz (most common). 16 5-MHz channels
- 250 kbps PHY ⇒ 50 kbps application data rate
- Peak current depends upon symbol rate ⇒ multilevel 4b/symbol)
- Similar to 802.11: Direct Sequence Spread Spectrum, CSMA/CA, Backoff, Beacon, Coordinator (similar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

U/M	G/L	OUI	40 bits assigned by the manufacturer
1b	1b	22b	40b

- 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)



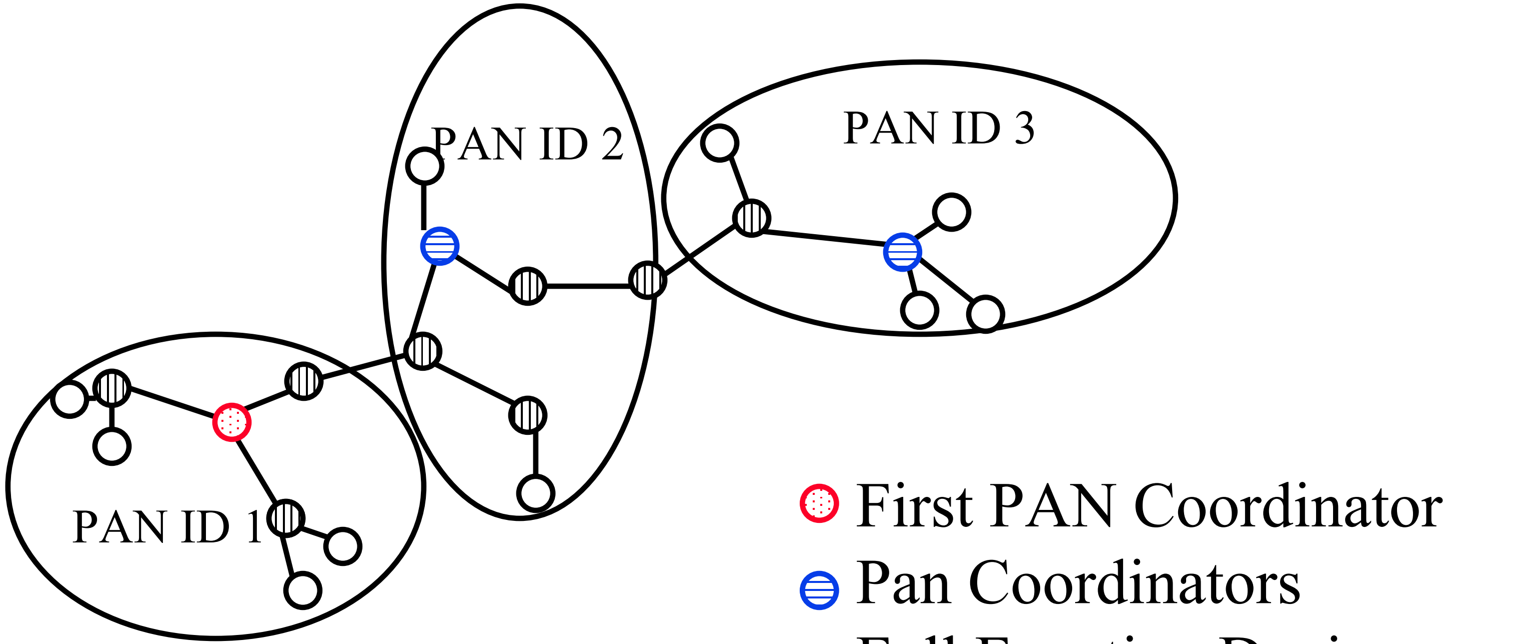
Ref: IEEE 802.15.4-2011

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

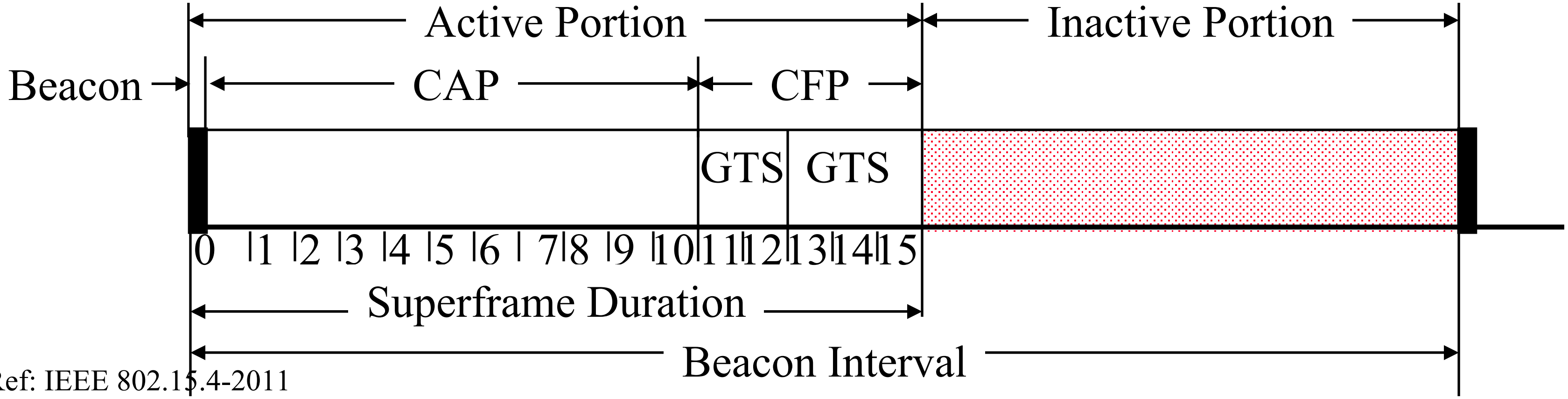


Ref: IEEE 802.15.4-2011

IEEE 802.15.4 MAC

Beacon-Enabled CSMA/CA

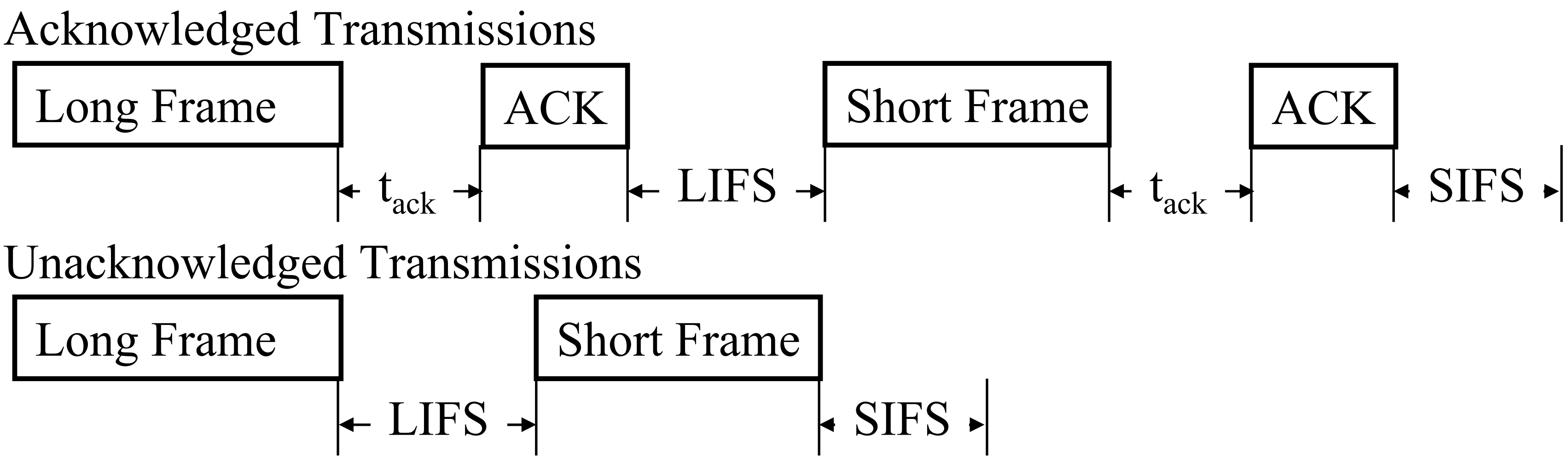
- Coordinator sends out beacons periodically
- Part of the beacon interval is inactive ⇒ Everyone sleeps
- Active interval consists of 16 slots
- Guaranteed Transmission Services (GTS): For real-time services. Periodic reserved slots.
- Other slots are available for contention. Slotted CSMA.



Ref: IEEE 802.15.4-2011

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)



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.

MAC Frame Format

Frame Control	Seq. #	Dest. PAN Id	Dest. Addr.	Src PAN Id	Src Addr.	Aux. Security Header	Payload	FCS
16b	8b	0/16b	0/16/64b	0/16b	0/16/64b	0/40/48/80/70b		16b

Frame Type	Security enabled	Frame Pending	Ack Reqd	PAN Id Compression	Rsvd	Dest. Addr. Mode	Frame version	Src. Addr. mode
3b	1b	1b	1b	1b	3b	2b	2b	2b

Frame Type:

000	Beacon
001	Data
010	Ack
011	MAC Command
Other	Reserved

Dest. Addr. Mode / Src. Addr. mode:

00	PAN Id and Addr no present
01	Reserved
10	16-bit short address
11	64-bit extended address

Ref: IEEE 802.15.4-2011

IEEE 802.15.4-2011 PHY Bands

PHY (MHz)	Band (MHz)	kchip/s	Modulation	kb/s	ksymbols/s
2450 DSSS	2400-2483.5	2000	O-QPSK	250	62.5
2450 CSS	2400-2483.5			250	167
				1000	167
915 (USA)	902-928	600	BPSK	40	40
	902-928	1600 (PSS)	ASK	250	50
	902-928	1000	O-QPSK	250	62.5
868 (Europe)	868-868.06	300	BPSK	20	20
	868-868.06	400 (PSS)	ASK	250	12.5
	868-868.06	400	O-QPSK	100	25
780 (China)*	779-787	1000	O-QPSK	250	62.5
	779-787	1000	MPSK	250	62.5
950 (Japan)	950-956	-	GFSK	100	100
	950-956	300	BPSK	20	20
UWB Sub-GHz	250-750				
UWB Low Band	3244-4742				
UWB High Band	5944-10234				

* Note: 314-316 MHz and 430-434 MHz bands are also used in China.

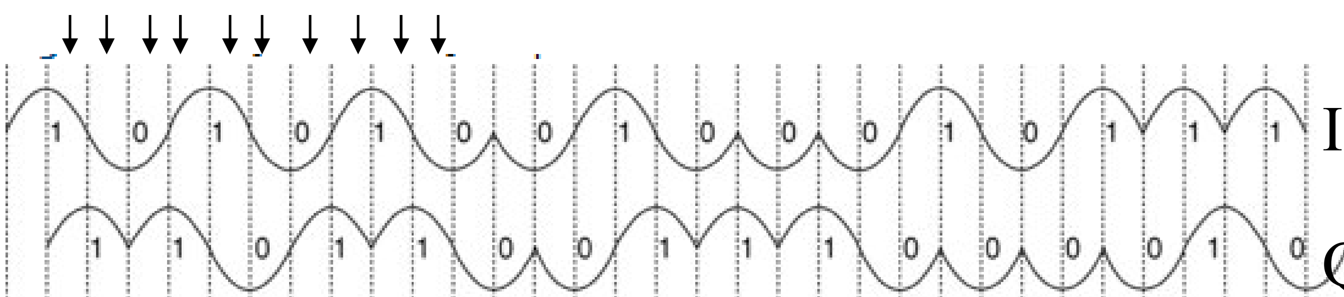
IEEE 802.15.4-2011 PHYs

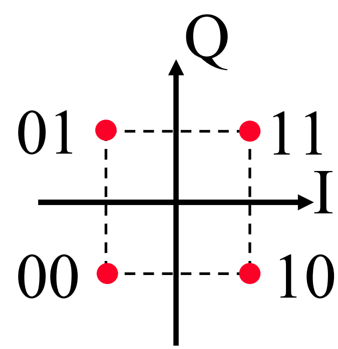
1. **Offset Quadrature Phase Shift Keying** (O-QPSK) modulation with Direct Sequence spread spectrum (DSSS) DSSS reduces the settling time and lock time.
2. **Binary Phase Shift Keying** (BPSK) modulation with DSSS Phy
3. **Amplitude Shift Keying** (ASK) with Parallel Sequence Spread Spectrum (PSSS)
4. **Chirp Spread Spectrum** (CSS) with Differential Quadrature Phase-shift keying (DQPSK) modulation
5. **Ultra-Wide Band** (UWB) with combined Burst Position modulation (BPM) and BPSK modulation
6. **m-ary Phase-Shift Keying** (MPSK) modulation ($m=4 \Rightarrow$ QPSK)
7. **Gaussian Frequency-Shift Keying** (GFSK)

Offset-QPSK

- Offset-QPSK: QPSK ⇒ Max 180 phase difference
  ⇒ Large amplitude shifts after low pass filtering
- O-QPSK ⇒ Change 1-bit at a time
  1st-bit of the 2-bit symbol is used to change I-component
- 2nd-bit of the 2-bit symbol is used to change Q-Component
  and Q is offset by 1 bit ⇒ Max 90 phase difference
  ⇒ Smaller amplitude shifts after filtering

11 01 10 01 11 00 00 11 01 01 00 10 00 10 11 10

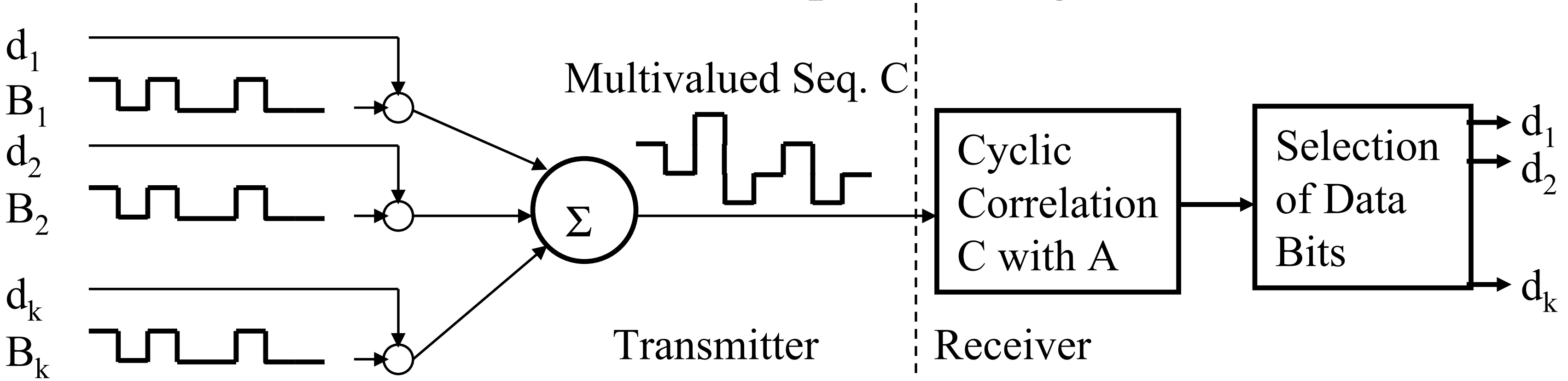




Ref: O. Hersent, et al., "The Internet of Things: Key Applications and Protocols," Wiley, 2012, 344 pp., ISBN:9781119994350

Parallel Sequence Spread Spectrum

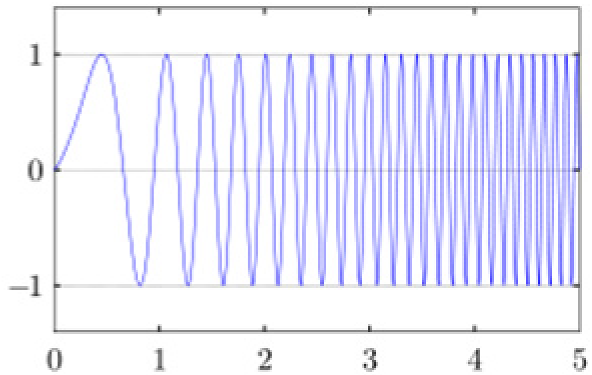
- Direct Sequence Spread Spectrum uses a L-bit bi-polar spreading code $A = \{a_1, a_2, \ldots, a_L\}$, $a_k \in \{+1, -1\}$
- By cyclically shifting the spreading code, k other uni-polar spreading codes are obtained: $B_i=\{b_{i,1}, b_{i,2}, \ldots, b_{i,L}\}$, $b_{i,k} = (a_{(k+i) \bmod L} + 1)/2 \in \{1, 0\}$
- These spreading codes are applied to the data sequence in parallel and a k-ary sum is transmitted
- Increases the resistance to multipath fading

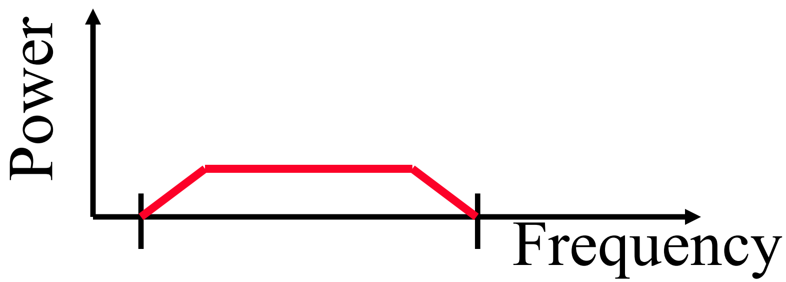


Ref: H. Schwetlick, "PSSS-Parallel Sequence Spread Spectrum – A Potential Physical Layer for OBAN?," http://oban.tubit.tu-berlin.de/5-PSSS-Schwetlick.pdf

Chirp Spread Spectrum

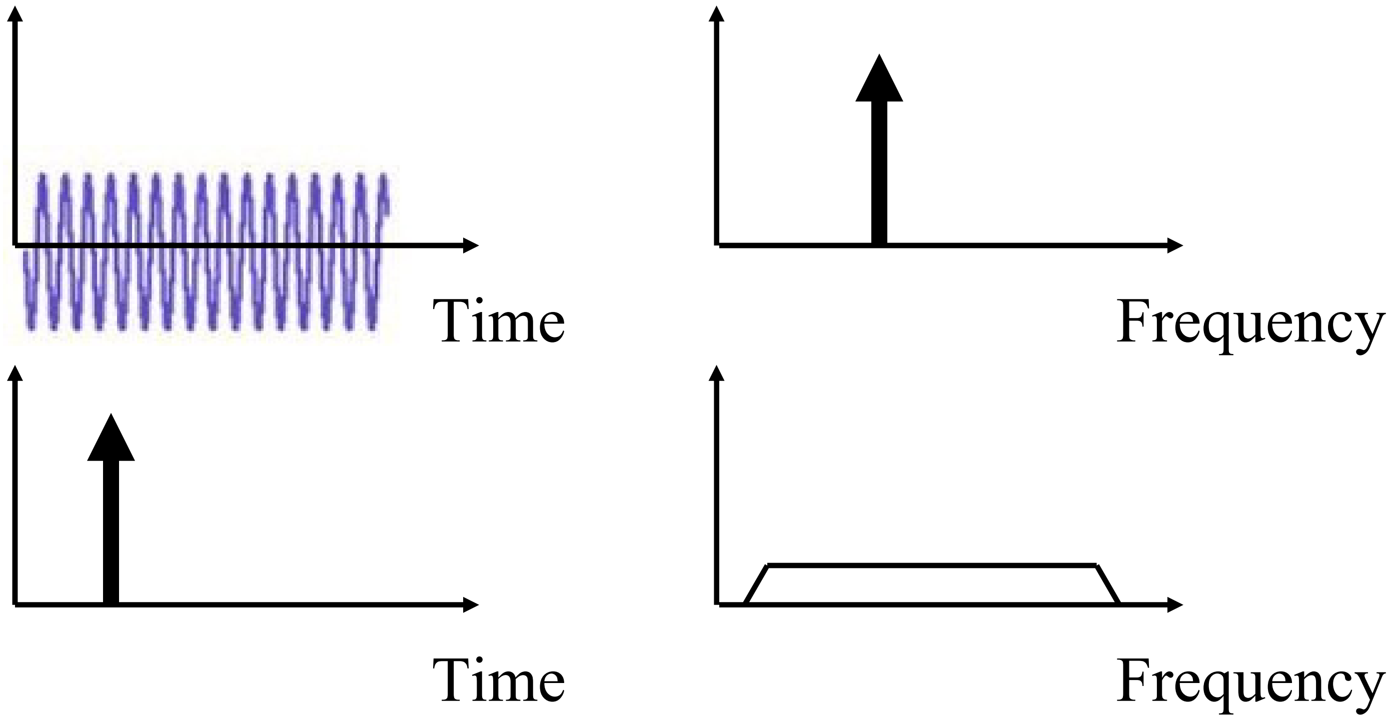
- **Chirp**: A signal with continuously increasing (or decreasing) frequency (Whale sound)
- **Chirp Spread Spectrum**: signal is frequency modulated with frequency is increasing (or decreasing) from min to max (or max to min) ⇒ power is *spread* over the entire spectrum





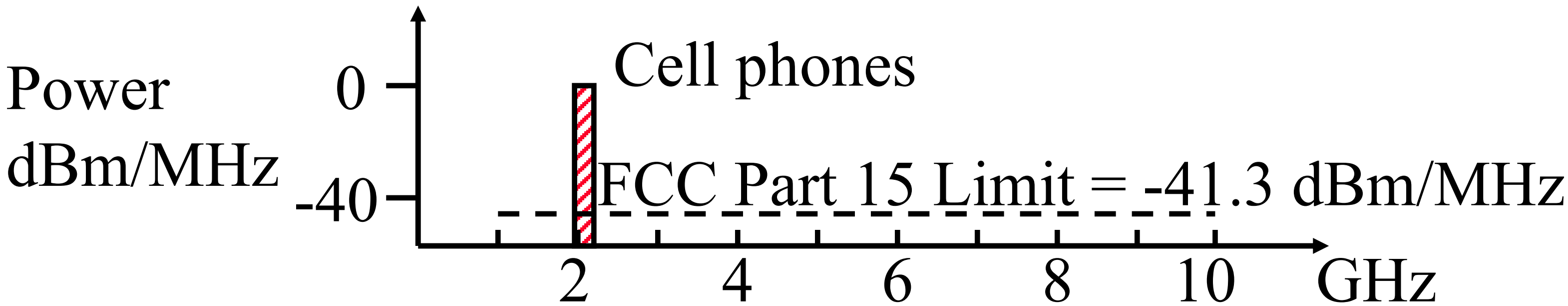
Ref: Z. Ianelli, "Introduction to Chirp Spread Spectrum (CSS) Technology," IEEE 802 Tutorial, http://www.ieee802.org/802_tutorials/03-November/15-03-0460-00-0040-IEEE-802-CSS-Tutorial-part1.ppt

Ultra-Wideband



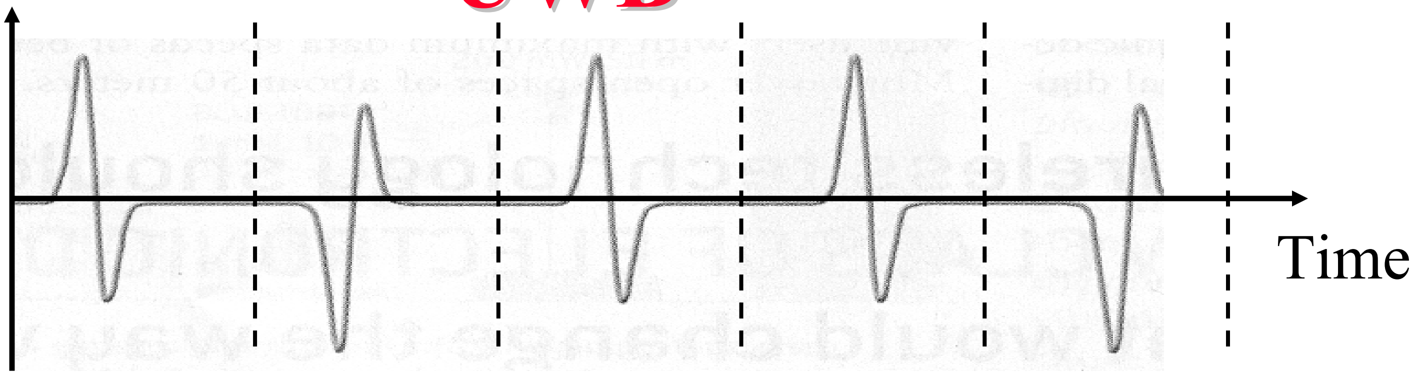
- An impulse in time domain results in a ultra wide spectrum in frequency domain and essentially looks like a white noise to other devices

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

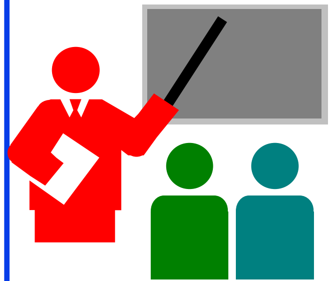
- Very low energy consumption: Good Watts/Mbps
- Line of sight not required. Passes through walls.
- Sub-centimeter resolution allows precise motion detection
- Pulse width much smaller than path delay
  ⇒ Easy to resolve multipath
  ⇒ Can use multipath to advantage
- Difficult to intercept (interfere)
- All digital logic ⇒ 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 $\Rightarrow$ 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. Uses slotted/unslotted CSMA/CA.Supports Guaranteed transmission services for low-latency application.
4. Newer PHYs use Chirp-spread spectrum and Parallel Sequence Spread spectrum.
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.
- 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

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., 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

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