Low Power WAN Protocols for IoT: IEEE 802.11ah, LoRaWAN, Sigfox

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Audio/Video recordings of this class lecture are available at:

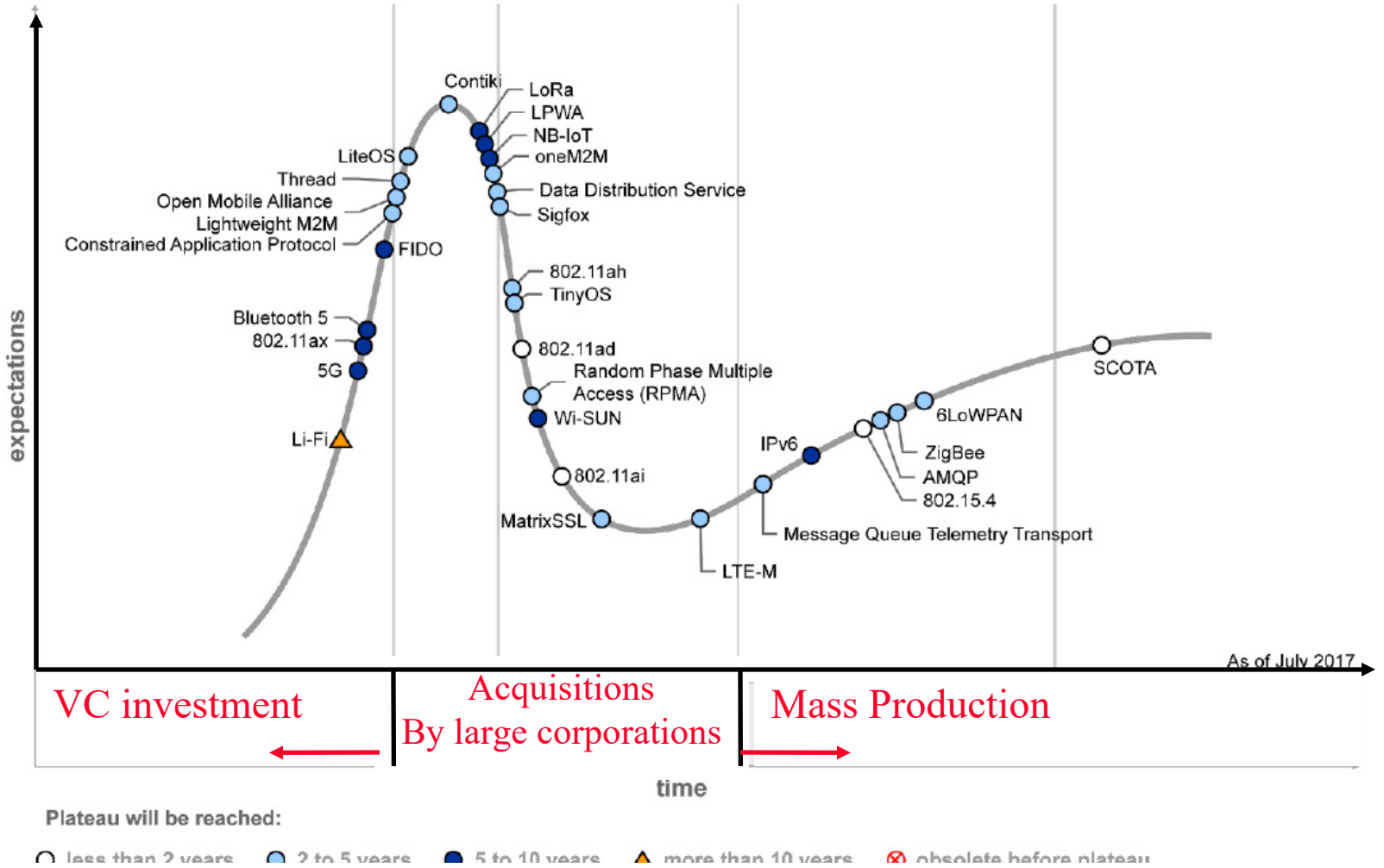
http://www.cse.wustl.edu/~jain/cse574-18/

Overview

1. IoT Protocols on the Hype
2. Low-Power WANs
3. IEEE 802.11ah
4. LoRaWAN
5. Sigfox

Note: This is the 6th lecture in series of class lectures on IoT. Bluetooth, Bluetooth Smart, IEEE 802.15.4, ZigBee, 6LowPAN, RPL were covered in the previous lectures.

Gartner's Hype cycle for IoT Standards and Protocols 2017



Ref: Bill Ray, "Hype Cycle for IoT Standards and Protocols, 2018," Gartner Report ID G00338610, Aug 30, 2018, 61 pp.

IoT Protocols on the Hype

- Li-Fi: Light Fidelity. Optical wireless at 100+ Gbps[1]
- IEEE 802.11ax: Successor to IEEE 802.11ac with 11 Gbps throughput and larger number of nodes[2]
- Thread: Networking over 802.15.4 using IPv6 over 6LowPAN[3]
- LPWA: Low Power Wide Area Network[4]
  - **Lora**: Long-Range
  - **Sigfox**
  - **802.11ah**
  - RPMA: Random Phase Multiple Access. Proprietary LPWA by Ingenu[5]

Ref: [1] https://en.wikipedia.org/wiki/Li-Fi
[2] https://en.wikipedia.org/wiki/IEEE_802.11ax
[3] https://en.wikipedia.org/wiki/Thread_(network_protocol)
[4] https://en.wikipedia.org/wiki/LPWAN
[5] C. McClelland, "RPMA – Overview of Ingenu's LPWAN Technology," Apr 20, 2017, https://medium.com/iotforall/rpma-overview-of-ingenus-lpwan-technology-3d72c47f0461

IoT Protocols on the Hype (Cont)

- Wi-SUN: Wireless Smart Ubiquitous Network. Field area network for utility industry. Used by Tokyo Electric Power[1]
- Cellular: **5G**, **NB-IoT**, **LTE-M**
- OneM2M: Consortium of eight standards organization for IoT (Machine to Machine)[2]
- Security:
  - MatrixSSL: Open source TLS/SSL implementation for IoT devices[3]
  - FIDO: Fast Identity Online authentication protocol[4]
  - IEEE 802.11ai-2016: Secure and fast Link setup[5]

Ref: [1] https://tools.ietf.org/id/draft-heile-lpwan-wisun-overview-00.html
[2] https://en.wikipedia.org/wiki/OneM2M
[3] https://en.wikipedia.org/wiki/MatrixSSL
[4] https://fidoalliance.org/approach-vision/
[5] https://en.wikipedia.org/wiki/IEEE_802.11ai

IoT Protocols on the Hype (Cont)

- Lightweight M2M: By Open Mobile Alliance and IPSO Alliance for smart object management and interoperability[1]
- Application Support Layer:
  - MQTT: Message Queuing Telemetry Transport[2]
  - AMQP: Advanced Message Queuing Protocol[3]
  - SCOTA (Software/firmware compnents/updates over the air)[4]
  - CoAP: Constrained Application Protocol. Web transfer protocol for constrained (IoT) devices[5]
  - DotDot: Network independent version of Zigbee's cluster library[6]

Ref: [1] https://en.wikipedia.org/wiki/OMA_LWM2M
[2] http://www.cse.wustl.edu/~jain/cse570-18/m_14mqt.htm
[3] https://en.wikipedia.org/wiki/Advanced_Message_Queuing_Protocol
[4] https://en.wikipedia.org/wiki/Over-the-air_programming
[5] https://en.wikipedia.org/wiki/Constrained_Application_Protocol
[6] https://www.zigbee.org/zigbee-for-developers/dotdot/

IoT Protocols on the Hype (Cont)

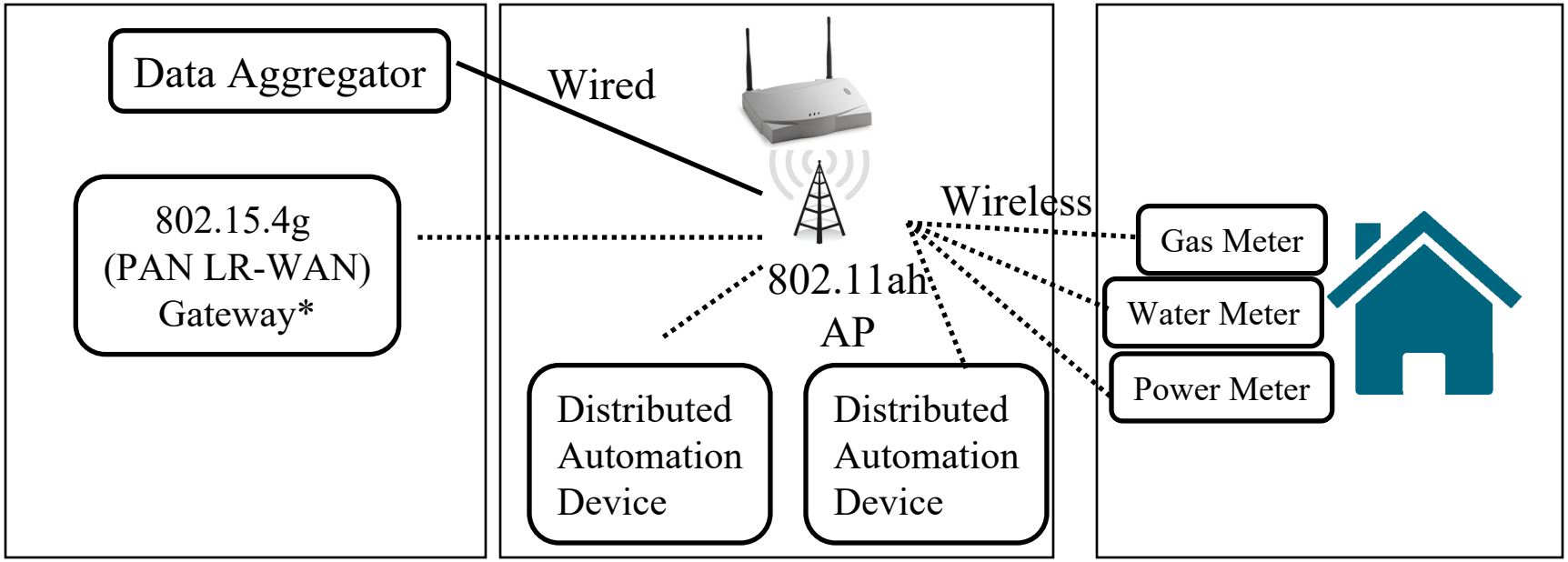
- Operating Systems:
  - TinyOS: Open source operating system for IoT[1]
  - Contiki: Open source OS/networking stack for IoT[2]
  - LiteOS: Huawei Real-time operating systems for IoT[3]

Ref: [1] https://en.wikipedia.org/wiki/TinyOS
[2] https://en.wikipedia.org/wiki/Contiki
[3] https://en.wikipedia.org/wiki/LiteOS

Low-Power WAN Applications

- Sensors:
  - Smart Grid – meter reading
  - Agriculture monitoring
  - Industrial sensors
  - Building automation
- Machine to Machine (M2M) Communication:
  - Factory automation
  - Traffic Control
  - Medical devices

Sample LPWAN Application

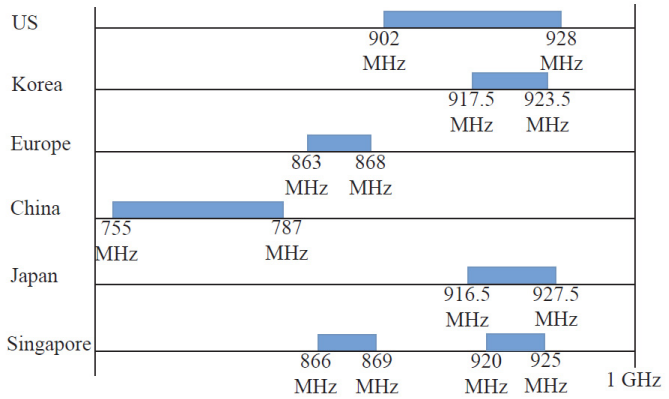


* 802.15.4g is no longer active

Ref: H. Wei, "Self-Organizing Energy Efficient M2M Communications," http://cc.ee.ntu.edu.tw/~ykchen/1123-HWei.pdf

IEEE 802.11ah Features

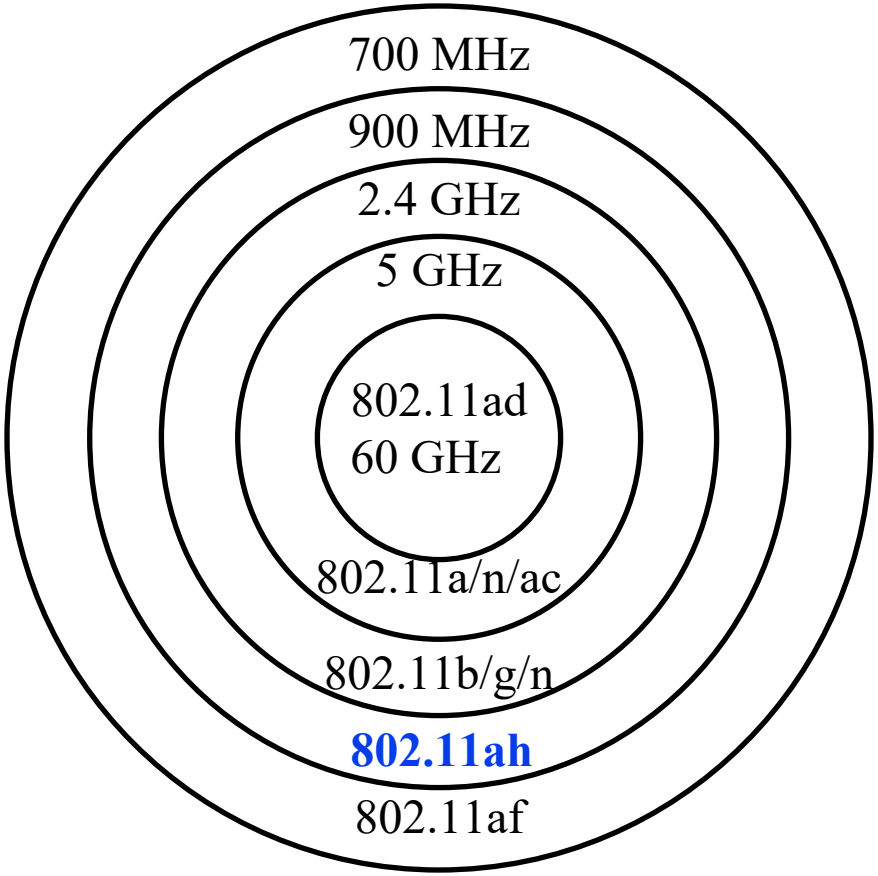
- *Aka "WiFi HaLow"* by WiFi Alliance.
- IEEE spec for Low-rate long-range IoT applications. Currently in 2nd Sponsor ballot (March 2016).
- **Spectrum**: Sub-Giga Hertz license-exempt spectrum. Not including TV white spaces (700 MHz for 802.11af).
  - 902-928 MHz (USA)
  - 863-868.6 MHz (Europe)
  - 916.5-927.5 MHz (Japan)
  - 755-787 MHz (China)
  - 917.5-923.5 MHz (Korea)



- **Sub-GHz frequency** ⇒ Longer range than 2.4 GHz, Less congested, better penetration
- Low bit rate for IoT, Short data transmissions, Power savings, Efficient MAC
- Goal: Support at least **4X devices** per AP than legacy 802.11

IEEE 802.11ah Range

- 150 kbps to 78 Mbps per spatial stream (up to 4 streams)



Ref: J. DeLisle, "What's the difference between 802.11af and 802.11ah," Microwave and RF, Oct 2015, http://mwrf.com/active-components/what-s-difference-between-ieee-80211af-and-80211ah

IEEE 802.11ah PHY

1. 802.11ac PHY **down clocked** by 10X
   - 2/4/8/16 MHz channels in place of 20/40/80/160 MHz in ac
   - 20 MHz 11ac and 2 MHz 11ah both have 64 FFT size and 48 data subcarriers + 4 pilots $\Rightarrow$ 1/10th inter-carrier spacing
     $\Rightarrow$ 10X longer Symbols $\Rightarrow$ Allows 10X delay spread
     $\Rightarrow$ All times (SIFS, ACKs) are 10x longer
   - New 1 MHz PHY with 32 FFT and 24 data subcarriers
2. **Adjacent channel bonding**: 1MHz+1MHz = 2 MHz
3. All stations have to support 1MHz and 2MHz
4. Up to **4 spatial streams** (compared to 8 in 11ac)
5. 1 MHz also allows a new MCS 10 which is MCS0 with 2x repetition $\Rightarrow$ Allows 9 times longer reach than 2.4GHz
6. **Beam forming** to create sectors

Ref: W. Sun, M. Choi, and S. Choi, "IEEE 802.11ah: A Long Range 802.11 WLAN at Sub 1 GHz," River Journal, 2013, pp. 1-26, http://riverpublishers.com/journal/journal_articles/RP_Journal_2245-800X_115.pdf

IEEE 802.11ah MAC

- **Large number of devices** per Access Point (AP)
  - Hierarchical Association Identifier (AID)
  - 802.11g/n/ac allow ~2^{11} stations, 802.11ah designed to allows ~2^{14} stations eventually
- **Relays** are used to allow connectivity outside the coverage area. Limited to 2-hops.
- **Power Savings Enhancements**:
  - Allows stations to sleep and save energy.
  - AP negotiates a Target Wake Time (TWT) for individual stations
- **Speed frame exchange** allows stations to exchange a sequence of frames for a TXOP.

Ref: E. Khorov, et al., "A survey on IEEE 802.11ah: An enabling networking technology for smart cities," Computer Communications, 2014, http://dx.doi.org/10.1016/j.comcom.2014.08.008

MAC Protocol Versions

- Protocol Version 0 (PV0) is same as that for b/a/g/n/ac
- Protocol version 1 (PV1) is optimized for IoT
  - Short headers
  - Null Data packets: Only PHY, No MAC. For Acks.
  - Speed frame exchange: Multi-frame transmissions
  - Improved channel access

Ref: R. Jain, "Lower Power WAN Protocols for IoT: IEEE 802.11ah, LoRAWAN," 2016, http://www.cse.wustl.edu/~jain/cse574-16/j_14ahl.htm

802.11ah: Summary

1. 802.11ah runs at 900 MHz band ⇒ Longer distance
2. 802.11ah is 802.11ac down by 10x.
   It uses OFDM with 1/2/4/8/16 MHz channels.
   Longer symbols ⇒ Longer multi-path
3. MAC is more efficient by eliminating reducing header, aggregating acks, null data packets, speed frame exchanges
4. Saves energy by allowing stations and AP to sleep longer
5. Slow adoption by industry
   ⇒ No products by major companies

Other LPWANs

Low Power Wide Area Networks (LPWANs)

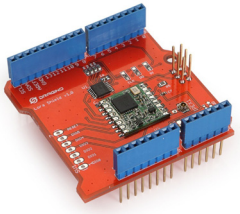
- **LoRaWAN**, https://www.lora-alliance.org
- SIGFOX, http://www.sigfox.com/
- Weightless-N (Narrowband), http://www.weightless.org/
- Weightless-P (High Performance), http://www.weightless.org/
- NWAVE, http://www.nwave.io/nwave-network/
- OnRamp Wireless, http://www.onrampwireless.com/
- PLATANUS, http://www.m2comm-semi.com/our-protocol/#
- Telensa, http://www.telensa.com/unb-wireless/
- M-Bus by Amber Wireless, https://www.amber-wireless.com/en/products/wireless-m-bus.html
- M2M Spectrum, http://m2mspectrum.com

Ref: C. Pham, "Long-Range Technology Overview," Dec 2015, http://web.univ-pau.fr/~cpham/LORA/WAZIUP-LoRa-overview.pdf

LoRaWAN

- Long Range Wide Area Network.
- Originally developed by Cyclos in France.
  Acquired by Semtech corporation, which formed **LoRa Alliance**.
  Now 160+ members.
- V1.0 spec dated January 2015. Released to public July 2015.
- Rapid Adoption: Products already available on Amazon.

Transceiver



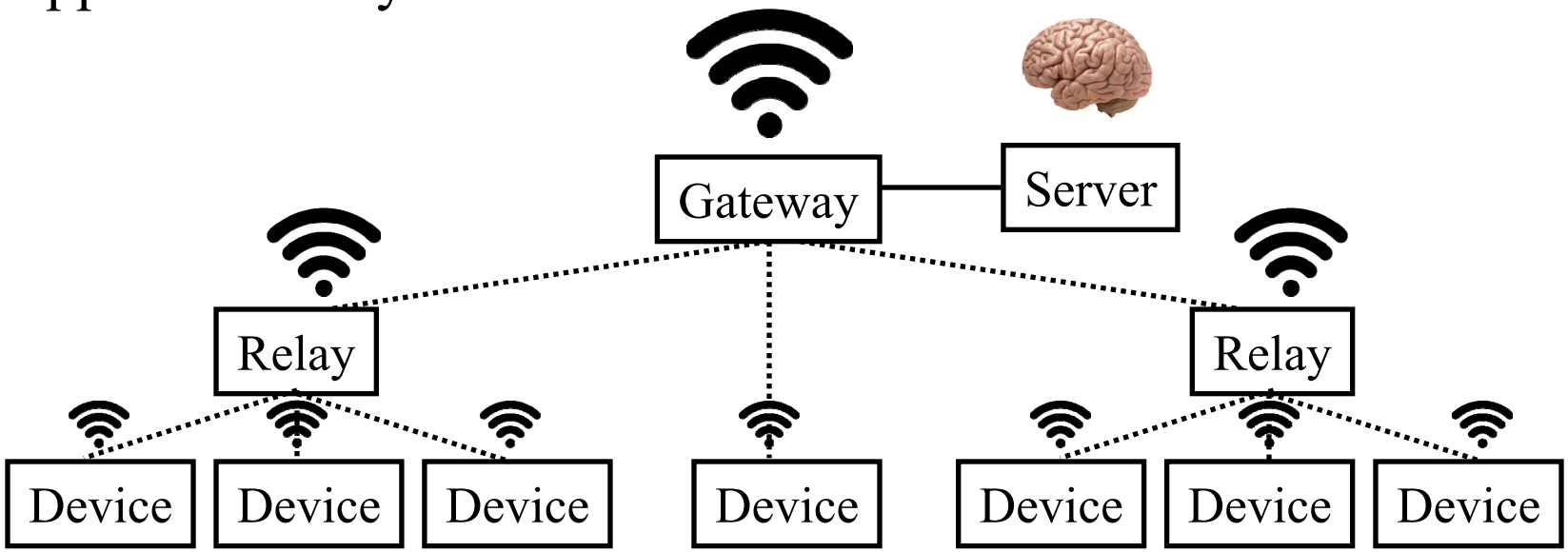
Arduino
Radio Shield

Connectivity Kit for
Arduino, Waspmote,
Raspberry Pi

Ref: https://www.lora-alliance.org/What-Is-LoRa/Technology

Key Features of LoRaWAN

- **Bidirectional** communication
  Low Rate: 0.3 kbps to 22 kbps in Europe, 0.9 kbps in US
- **Star of Stars Topology**: Gateways are transparent bridges. Server is the brain. Simple devices. Relays are optional.
- **Secure**: EUI128 Device Key, EUI64 Network Key, EUI64 Application Key



Ref: https://www.lora-alliance.org/What-Is-LoRa/Technology

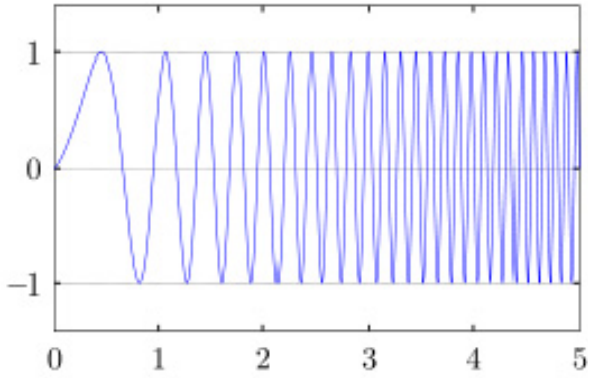
LoRa Frequency Band

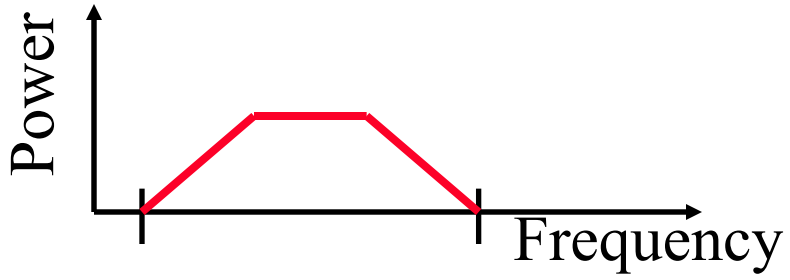
- Uses ISM license-exempt band:
  - 915 MHz MHz in US. Power limit. No duty cycle limit.
  - 868 MHz in Europe. 1% and 10% duty cycle limit
  - 433 MHz in Asia
- Same techniques can be used in 2.4GHz or 5.8 GHz
- Currently suitable for public (single) deployment in an area
  - All gateways report to the same server
  - A device can talk to any gateway
  - All devices use the same frequency

Ref: http://www.link-labs.com/what-is-lora/
http://www.radio-electronics.com/info/wireless/lora/lorawan-network-architecture.php

Chirp Spread Spectrum

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

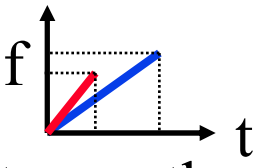




Ref: Z. Ianelli, "Introduction to Chirp Spread Spectrum (CSS) Technology," IEEE 802 Tutorial, http://www.ieee802.org/802_tutorials/03-November/15-03-0460-00-0040-IEEE-802-CSS-Tutorial-part1.ppt

LoRa Modulation

- Designed to achieve high sensitivity using a cheap crystal
- Allows low power transmissions over long distances
- A form of Chirp spread spectrum.
- Data is encoded using the frequency increase/decrease rate
  $\Rightarrow$ Data rate and link condition determines the frequency bandwidth required

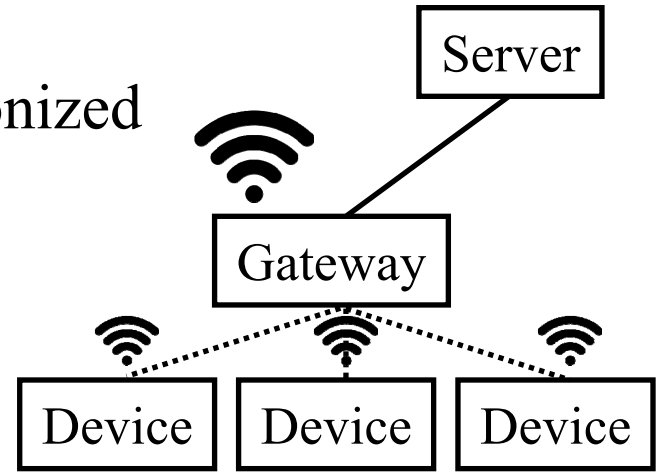


- Multiple parallel transmissions with different data rates on the same frequency
- Can receive signals **19.5 dB below** noise floor with forward error correction (FEC)
- Power level is determined adaptively based on data rate and link condition. Fast communication is used to save battery.

Ref: "LoRA Physical Layer and RF Interface," Radio-Electronics,
http://www.radio-electronics.com/info/wireless/lora/rf-interface-physical-layer.php

LoRaWAN MAC

- LoRaWAN: MAC function over LoRa PHY (Other MACs can be used over LoRA PHY)
- Server manages the network and runs MAC
  - Assigns each device is a frequency, spreading code, data rate
  - Eliminates duplicate receptions
  - Schedules acknowledgements
  - Adapts data rates
- All gateways of a network are synchronized
- Data rate is determined by distance and message duration
- Server determines the data rate using an adaptive data rate (ADR) scheme
- Competition: Sigfox, NB-IoT



LoRaWAN: Summary

1. LoRaWAN is the new MAC standardized by LoRa Alliance
2. LoRa modulation is a variation of chirp spread spectrum where the rate of frequency increase/decrease is modulated by symbol
   ⇒ Increases its resistance to noise
   ⇒ Allows multiple parallel transmissions in one frequency
3. Centralized management and media access control using a "server"
4. Devices broadcast to all gateways. The best gateway replies back.

Sigfox

- Proprietary protocol developed by Sigfox for 900 MHz ISM band
- Ultra-narrowband spectrum:
  100 Hz per user => Long symbols => resistance to noise
- Simple BPSK Modulation => 100-600 bps
- Inexpensive end-point radio, sophisticated base station
- Receiver sensitivity on the end-point is less => downlink capacity is less
- Network in the process of being deployed in 60 countries
- 6 million objects by end of 2018
- Covers 24 of top 25 metropolitan areas in US

Ref: Sigfox, "SIgfox Technology Overview," https://www.sigfox.com/en/sigfox-iot-technology-overview
Washington University in St. Louis http://www.cse.wustl.edu/~jain/cse574-18/

LoRa vs. Sigfox

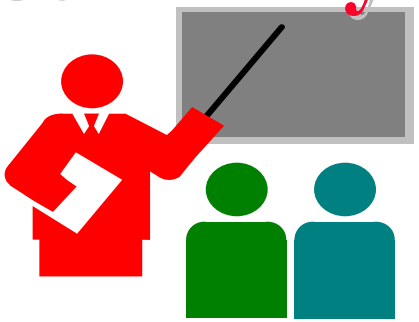
- Common:
  - Both have proprietary technology
  - Both use 900/868 MHz ISM band
  - Both use star network architecture
  - Multiple base stations/gateways listen to the packets from IoT devices

Ref: Brian Ray, "SigFox Vs. LoRa: A Comparison Between Technologies & Business Models," *May 31, 2018,* https://www.link-labs.com/blog/sigfox-vs-lora

LoRa vs. Sigfox (Cont)

Issue	LoRa	Sigfox
Business Model	Sell LoRa chips and silicon	Network as a Service Royalty from network service providers
Technology	LoRa Modulation	Ultra-narrowband (100 kHz) with BPSK
Symmetry	Uplink = Downlink	12 B payload in uplink 8 B payload in downlink 140 Messages/day/device uplink 4 messages/day/device downlink
Cost	Gateway and end points cost comparable	Expensive base stations Cheap end-points
Openness	Any one can make either or both end devices	Anyone can make end-points. Sigfox makes the basestations.
Service Provider	Anyone can setup a network	Sigfox sets up the network
Location	Can use everywhere	Only in markets where Sigfox has a network

Summary



1. IoT protocol space is very crowded. Many protocols are being hyped
2. Low Power WANs are used for Utility and citywide applications.
3. IEEE 802.11ah was standardized but seeing limited use
4. LoRaWAN uses LoRa modulation and has many products
5. Sigfox is betting on Network as a service.

Lab 1

A. Download InSSIDer v3.1.2.1 from:

- http://www.techspot.com/downloads/5936-inssider.html or
- http://www.filecroco.com/download-inssider

- Measure the signal levels of various WiFi networks
- Submit a screen capture

B. Download Wireshark from:

- https://www.wireshark.org/#download

- Run a trace packets on your wireless network
- Submit a screen capture

Reading List

- E. Khorov, et al., "A survey on IEEE 802.11ah: An enabling networking technology for smart cities," Computer Communications, 2014, http://www.freepaperdownload.us/1752/Article5078210.htm
- W. Sun, M. Choi, and S. Choi, "IEEE 802.11ah: A Long Range 802.11 WLAN at Sub 1 GHz," River Journal, 2013, pp. 1-26, http://riverpublishers.com/journal/journal_articles/RP_Journal_2245-800X_115.pdf
- http://www.link-labs.com/what-is-lora/
- "LoRA Physical Layer and RF Interface," Radio-Electronics, http://www.radio-electronics.com/info/wireless/lora/rf-interface-physical-layer.php
- https://www.lora-alliance.org/What-Is-LoRa/Technology

References

- C. Pham, "Long-Range Technology Overview," Dec 2015, http://web.univ-pau.fr/~cpham/LORA/WAZIUP-LoRa-overview.pdf
- GreenPeak, http://www.greenpeak.com/Company/Opinions/CeesLinksColumn36.pdf
- H. Wei, "Self-Organizing Energy Efficient M2M Communications," http://cc.ee.ntu.edu.tw/~ykchen/1123-HWei.pdf
- http://www.radio-electronics.com/info/wireless/lora/lorawan-network-architecture.php
- J. DeLisle, "What's the difference between 802.11af and 802.11ah," Microwave and RF, Oct 2015, http://mwrf.com/active-components/what-s-difference-between-ieee-80211af-and-80211ah
- 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 Links

- https://en.wikipedia.org/wiki/Chirp_spread_spectrum
- https://en.wikipedia.org/wiki/Delivery_traffic_indication_message
- https://en.wikipedia.org/wiki/IEEE_802.11ah
- https://en.wikipedia.org/wiki/IEEE_802.1ah-2008
- https://en.wikipedia.org/wiki/LPWAN
- https://en.wikipedia.org/wiki/Traffic_indication_map

Wikipedia Links (Optional)

- https://en.wikipedia.org/wiki/6LoWPAN
- https://en.wikipedia.org/wiki/Comparison_of_wireless_data_standards
- https://en.wikipedia.org/wiki/DASH7
- https://en.wikipedia.org/wiki/Distributed_coordination_function
- https://en.wikipedia.org/wiki/IEEE_802.11_RTS/CTS
- https://en.wikipedia.org/wiki/NarrowBand_IOT
- https://en.wikipedia.org/wiki/Network_allocation_vector
- https://en.wikipedia.org/wiki/On-Ramp_Wireless
- https://en.wikipedia.org/wiki/Short_Interframe_Space
- https://en.wikipedia.org/wiki/Sigfox
- https://en.wikipedia.org/wiki/Weightless_(wireless_communications)

Acronyms

- 6Lo — IPv6 over Networks of Resource Constrained Nodes
- 6LoWPAN — IPv6 over Low Power Wireless Personal Area Networks
- 6TiSCH — IPv6 over Time Slotted Channel Hopping Mode of IEEE 802.15.4e
- AC — Alternating Current
- ACK — Acknowledgement
- ADR — adaptive data rate
- AID — Association Identifier
- AMQP — Advanced Message Queuing Protocol
- AP — Access Point
- CARP — Channel-Aware Routing Protocol
- CoAP — Constrained Application Protocol
- CORPL — Cognitive RPL
- CSS — Chirp Spread Spectrum
- CTS — Clear to Send
- DASH-7 — Named after last two characters in ISO 18000-7

Acronyms (Cont)

- dB DeciBel
- EDCF Enhanced Distributed Coordination Function
- EUI Extended Unique Identifier
- FFT Fast Fourier Transform
- GHz Giga Hertz
- GP Green PHY
- GPS Global Positioning System
- HAN Home Area Network
- ID Identifier
- IEC International Engineering Council
- IEEE Institution of Electrical and Electronic Engineers
- IoT Internet of Things

Acronyms (Cont)

- ISA International Society of Automation
- ISM Instrumentation Scientific and Medical
- kHz Kilo Hertz
- LoRa Long Range
- LoRaWAN Long Range Wide Area Network
- LowPAN Low Power Personal Area Network
- LPWANs Low Power Wide Area Network
- LTE-A Long-Term Evolution Advanced
- LTE Long-Term Evolution
- MAC Media Access Control
- MCS Modulation and Coding Scheme

Acronyms (Cont)

- MHz Mega Hertz
- MQTT Message Queue Telemetry Transport
- NAN Neighborhood Area Network
- NAV Network Allocation Vector
- NDP Null Data Packet
- NFC Near Field Communication
- NWAVE Name of a company
- OFDM Orthogonal Frequency Division Multiplexing
- OMA Open Mobile Alliance
- OneM2M One committee for Machine to Machine
- PAN Personal Area Network
- PHY Physical Layer
- PLATANUS Name of a company
- PV0 Protocol Version 0
- PV1 Protocol Version 1

Acronyms (Cont)

- RF Radio Frequency
- RID Response Indication Deferral
- RPL Routing Protocol for Low Power and Lossy Networks
- RTS Request to Send
- SCOTA Software components over the air
- SMACK Simple Mandatory Access Control Kernel for Linux
- SSL Secure Session Layer
- TCG Trusted Computing Group
- TLS Transport Layer Security
- TV Television
- TWT Target Wake Time
- TXOP Transmission Opportunity
- US United States
- VC Venture Capitalist

Acronyms (Cont)

- WAN Wide Area Network
- WiFi Wireless Fidelity
- WiMAX Worldwide Interoperability of Microwave Access
- WLAN Wireless Local Area Networks

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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