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/cse574-24/

Student Questions

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Next Q 12



Overview

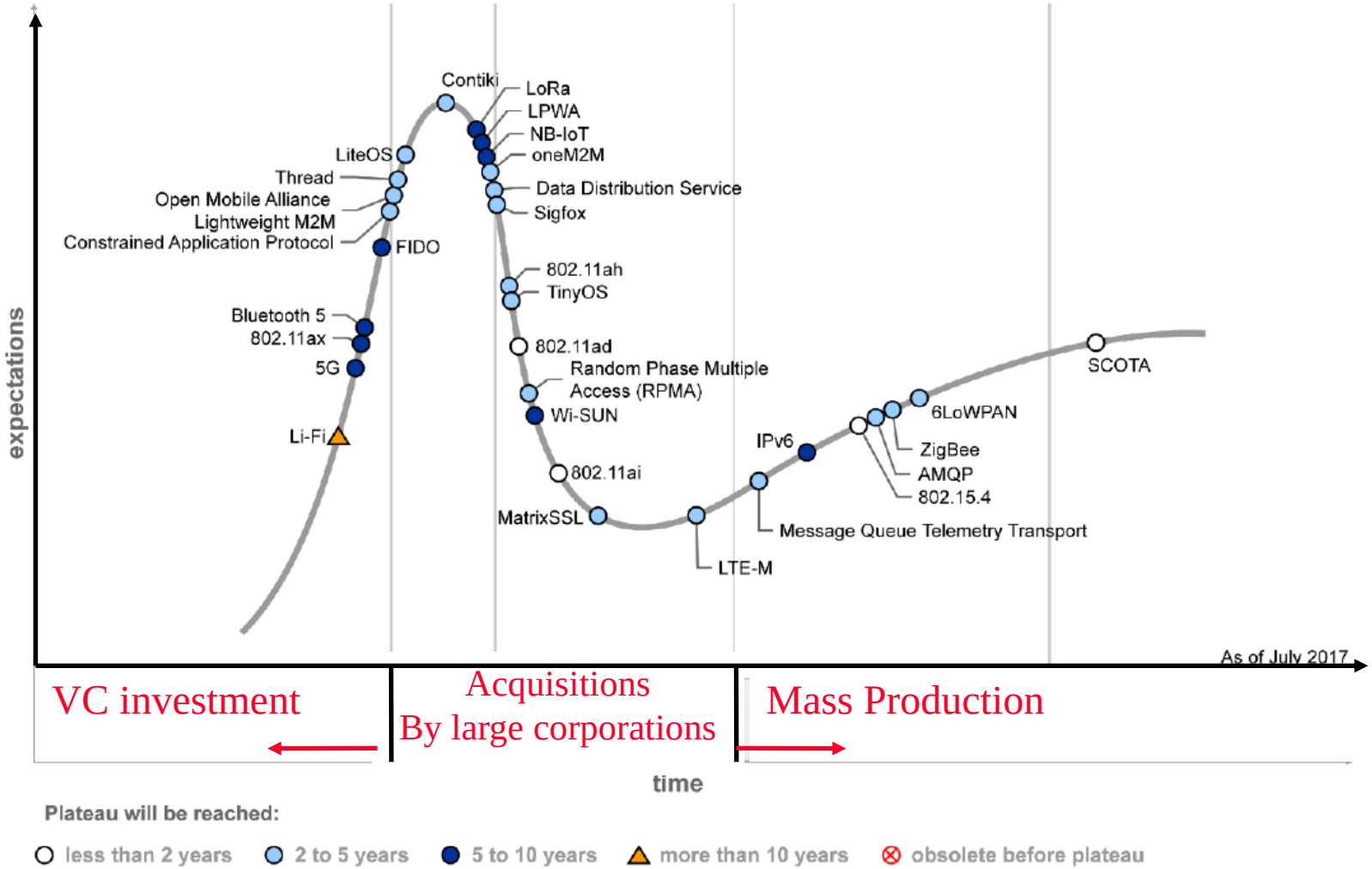
1. IoT Protocols on the Hype
2. Low-Power WANs
3. IEEE 802.11ah
4. LoRaWAN
5. Sigfox

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.

Student Questions

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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.

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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]

Student Questions

- Why hasn't LiFi made any significant advancements over the past decade? Is there some fundamental issue that's preventing its development?

Not yet cost effective

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

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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

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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/

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Student Questions

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]

Student Questions

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

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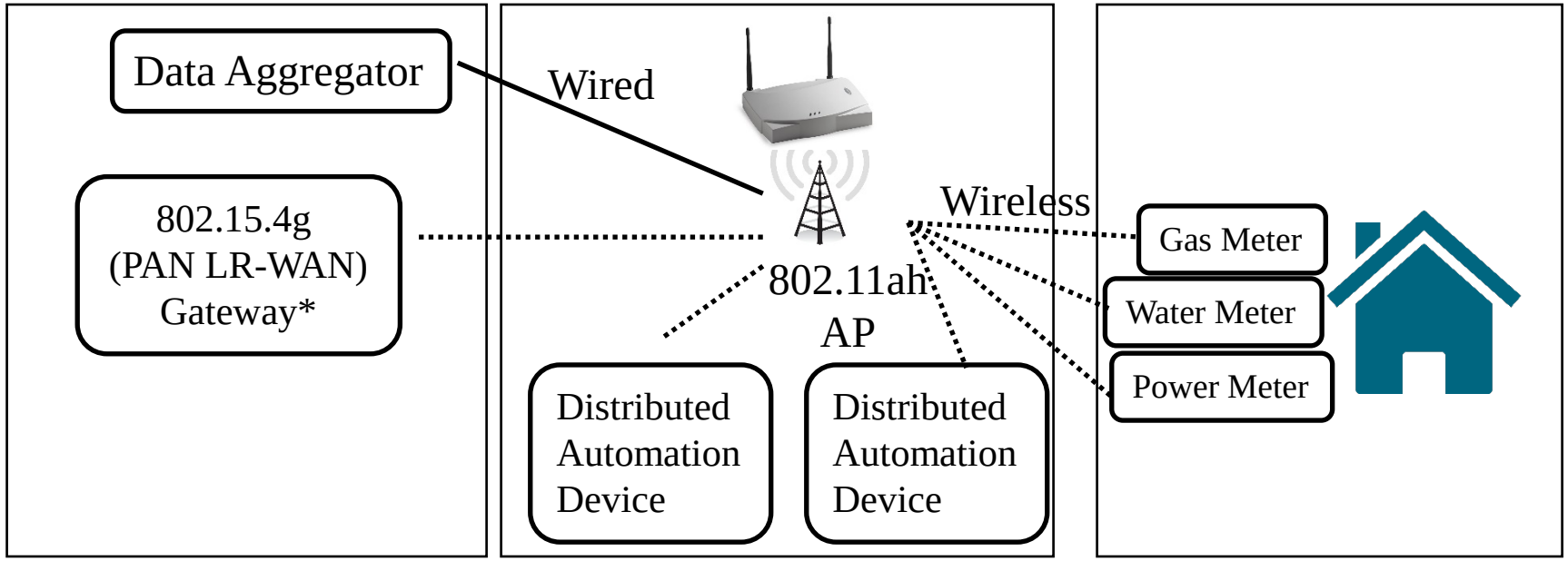
Low-Power WAN Applications

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

Student Questions

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Sample LPWAN Application



Wide Area Network (WAN)

Neighborhood Area Network (NAN)

Home Area Network (HAN)

* 802.15.4g is no longer active

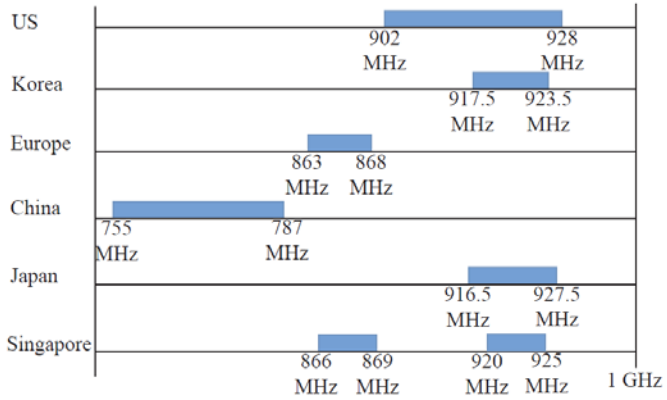
Ref: H. Wei, "Self-Organizing Energy Efficient M2M Communications," http://cc.ee.ntu.edu.tw/~ykchen/1123-HWei.pdf

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Student Questions

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)

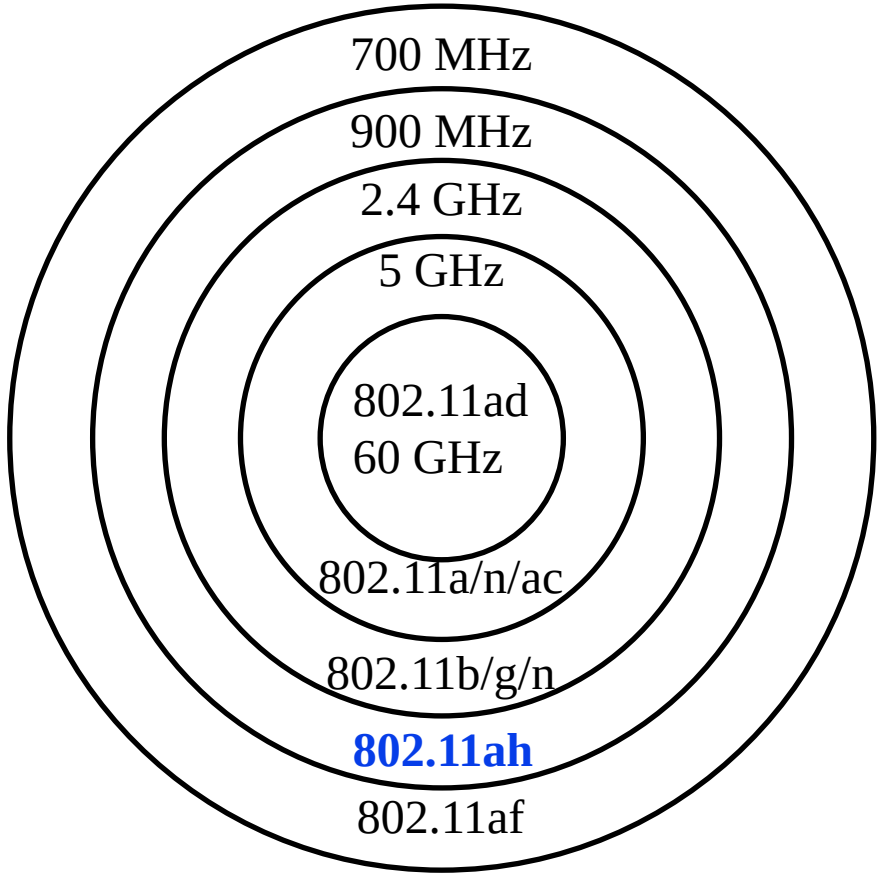


- **Sub-GHz frequency** ⇒ Longer range than 2.4 GHz, Less congested, better penetration
- Low bit rate for IoT, Short data transmissions, Power savings, Efficient MAC
- Goal: Support at least **4X devices** per AP than legacy 802.11

Student Questions

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

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Student Questions

- Where would ax be on this graph?

Along with a/n/ac

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 ⇒ $1/10^{th}$ inter-carrier spacing
     ⇒ 10X longer Symbols ⇒ Allows 10X delay spread
     ⇒ 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 ⇒ Allows 9 times longer reach than 2.4GHz
6. **Beam forming** to create sectors

Student Questions

- Can the doppler shift from the motion of the meter reader cause inter-carrier interference?

The data collector could be moving or stationary on a pole. Motion will cause some deterioration but speed is controlled to avoid unacceptable interference.

- Why exactly is this PHY layer down clocked by 10x?

Longer distance need longer symbols to avoid intersymbol interference. Longer bit means slower clock.

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

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Next Q 21b

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.

Student Questions

- Can you explain more on efficient MAC?
- *AID Devices are grouped into smaller groups with specific time slots =>Minimizes contention*
- *Relays extend the range.*
- *Power savings*
- *Speed frame exchange => Lower overhead*

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

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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

Student Questions

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

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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

Student Questions

- In the time since the lecture was recorded, has any developments in the adoption of 802.11ah been made?

LoraWAN is still more prevalent.

- Are there any recent products that indicate a future for 802.11ah or is the market relatively set? I'm curious as to how relevant 802.11ah is or if there is any renewed interest.

There is some interest but the LoraWAN's deployments have slowed the progress.

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   ⇒ No products by major companies

Student Questions

- This slide said that the industry and no products by major companies are slowly adopting 802.11ah. Based on this point and compared to the Hype cycle on page 3, why are there still acquisitions related to 802.11ah by large corporations?

Everyone bets on the future but no one knows the future. It is yet to be seen.

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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/
- 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: J. Phinnegan, "A Comparative Survey of LPWA Networking," ArXiv, https://arxiv.org/pdf/1802.04222

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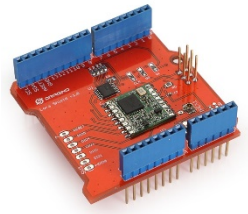
Student Questions

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

Student Questions

- Since LoRaWAN is not an IEEE standard, is interoperability with any IEEE technologies completely off the table? If interoperability is not possible, what does this say about the longevity of the standard?

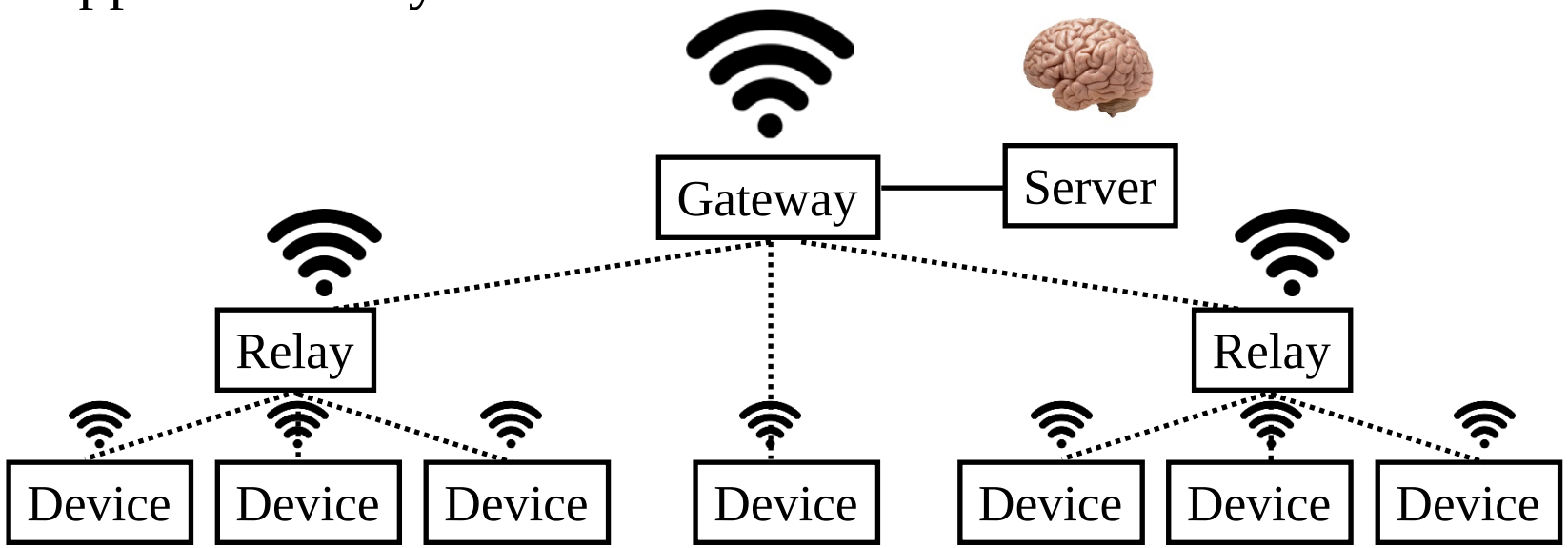
Interoperability is required in technologies serving the same market space. Bluetooth and Zigbee are also not IEEE standards and have no interoperability with IEEE802.11 but they are surviving.

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

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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

Student Questions

- Is LoRaWAN used in daily lives?

Smart agriculture, live stock monitoring, smart cities, smart parking solutions, smart waste management, smart utility (electricity/water/gas) usage monitoring.

- What is the scenario in which a device key is insufficient and a network key is needed?

Network key is shared by all members of the network and provides less security than device keys.

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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

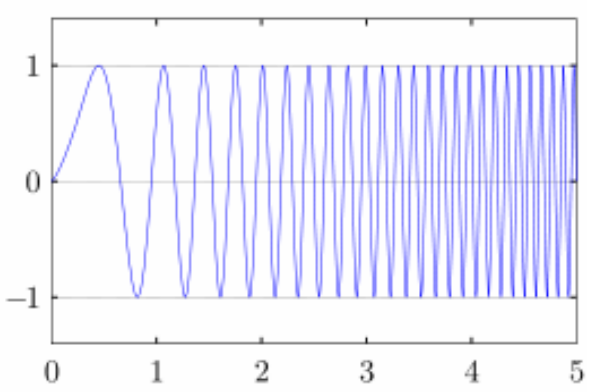
Student Questions

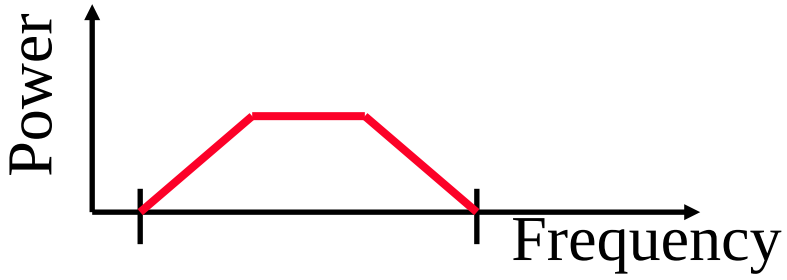
Ref: http://www.link-labs.com/what-is-lora/
http://www.radio-electronics.com/info/wireless/lora/lorawan-network-architecture.php

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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





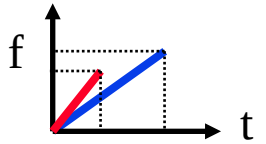
Ref: Z. Ianelli, "Introduction to Chirp Spread Spectrum (CSS) Technology," IEEE 802 Tutorial, http://www.ieee802.org/802_tutorials/03-November/15-03-0460-00-0040-IEEE-802-CSS-Tutorial-part1.ppt

Student Questions

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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
  ⇒ 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.

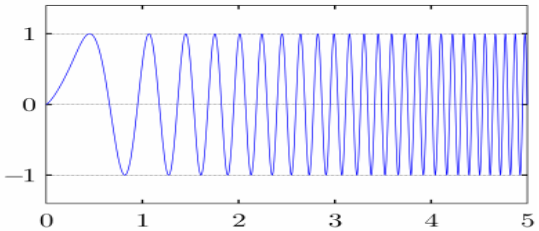
Ref: "LoRA Physical Layer and RF Interface," Radio-Electronics, http://www.radio-electronics.com/info/wireless/lora/rf-interface-physical-layer.php

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Student Questions

- Can you clarify how the frequency slope indicates whether it is a 0 or a 1?

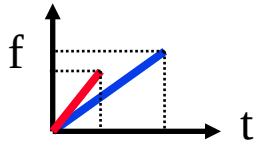
The following figure shows how frequency increases with time. Slope of increase (as shown on the left) determines 0 or 1.



Ref: https://en.wikipedia.org/wiki/Chirp_spread_spectrum

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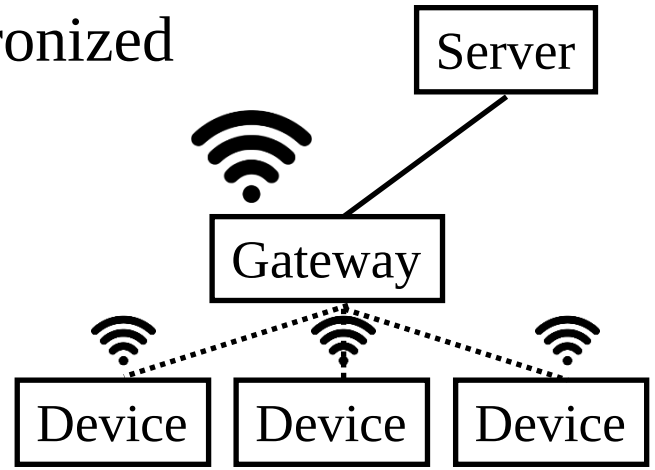
❖How does LoRa allow multiple parallel transmissions with different data rates? How this translates to a higher data rate?

Encoding uses frequency increase/decrease rates as shown in the figure. The effect of multiple users on the same frequency is similar to that of MIMO. Total data rate is higher.

End of Q

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



Student Questions

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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.

Student Questions

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

Student Questions

- Who is using Sigfox/for what?

Both Sigfox and LoraWAN are addressing the same market of "smart city." I saw a demo of garbage collection in Dubai using LoraWAN

What type of customers does Sigfox attract? Why did they base their business model this way?

Wide area sensing requires cheap sensors.

- In bullet 5 - what does receiver sensitivity mean? Unable to filter noise?

Yes, ability to filter noise

- Why is lower receiver sensitivity on Sigfox endpoints acceptable, and how does it impact overall network performance?

In almost all protocols, receivers are limited and therefore download capacity is less.

Ref: Sigfox, "SIgfox Technology Overview," https://www.sigfox.com/en/sigfox-iot-technology-overview

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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

Student Questions

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

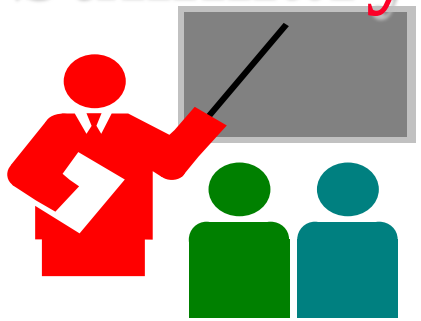
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LoRa vs. Sigfox (Cont)

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

Student Questions

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.

Student Questions

Reading List

- 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

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References

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- 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

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Wikipedia Links

- https://en.wikipedia.org/wiki/6LoWPAN
- https://en.wikipedia.org/wiki/Advanced_Message_Queuing_Protocol
- https://en.wikipedia.org/wiki/Chirp_spread_spectrum
- https://en.wikipedia.org/wiki/Constrained_Application_Protocol
- https://en.wikipedia.org/wiki/Contiki
- https://en.wikipedia.org/wiki/DASH7
- https://en.wikipedia.org/wiki/IEEE_802.11ah
- https://en.wikipedia.org/wiki/IEEE_802.11ai
- https://en.wikipedia.org/wiki/IEEE_802.11ax
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Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/OneM2M
- https://en.wikipedia.org/wiki/Over-the-air_programming
- https://en.wikipedia.org/wiki/Sigfox
- https://en.wikipedia.org/wiki/Thread_(network_protocol)
- https://en.wikipedia.org/wiki/TinyOS
- https://en.wikipedia.org/wiki/Weightless_(wireless_communications)

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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

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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

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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

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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

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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

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Acronyms (Cont)

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

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https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
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Recent Advances in Networking (Spring 2013),
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Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw

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