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

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

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

http://www.cse.wustl.edu/~jain/cse574-20/

**Student Questions**

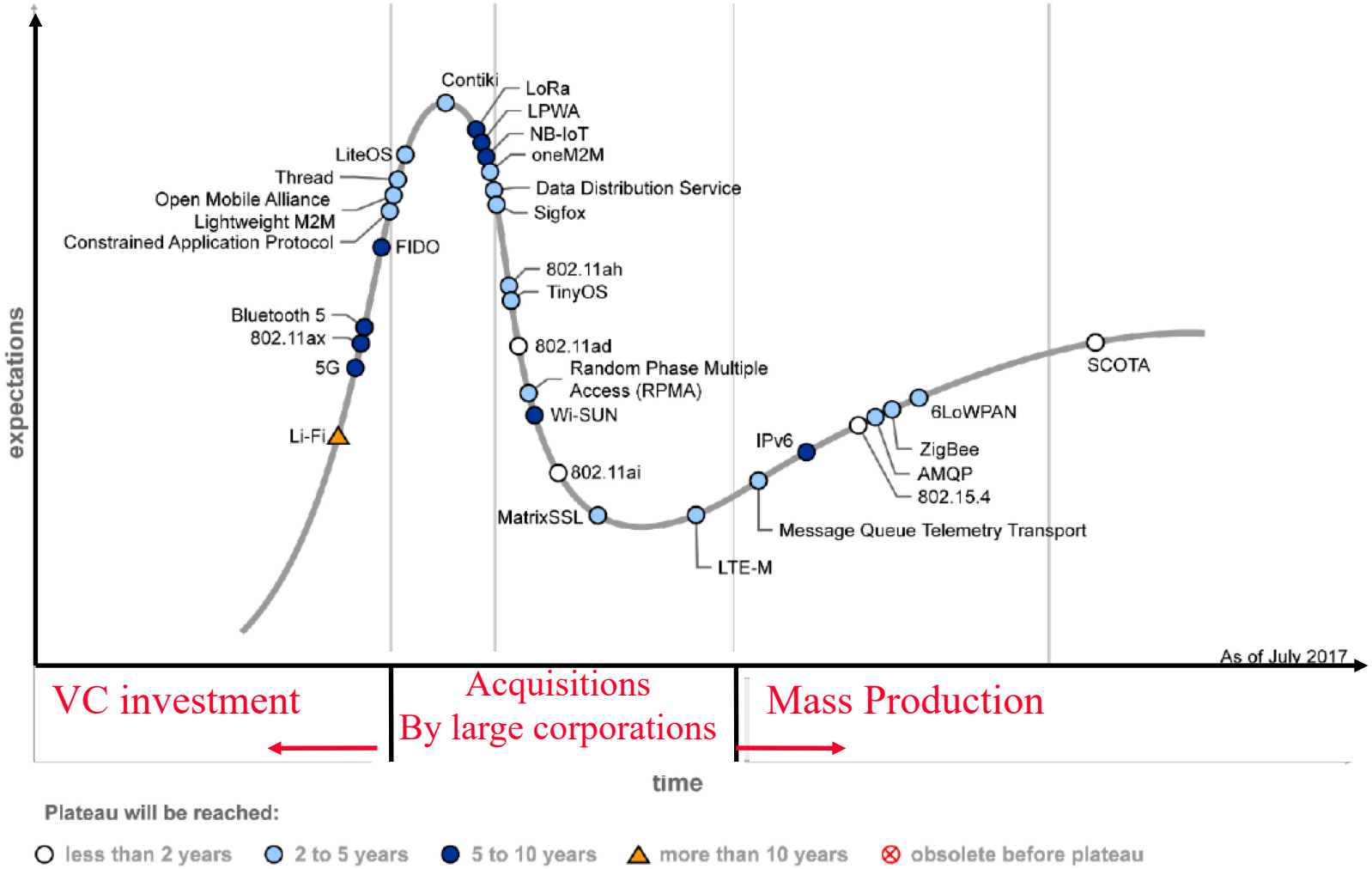
# Overview

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**

# 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.





## Student Questions

# 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

## 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*

# 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

**Student Questions**

# 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/





**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**

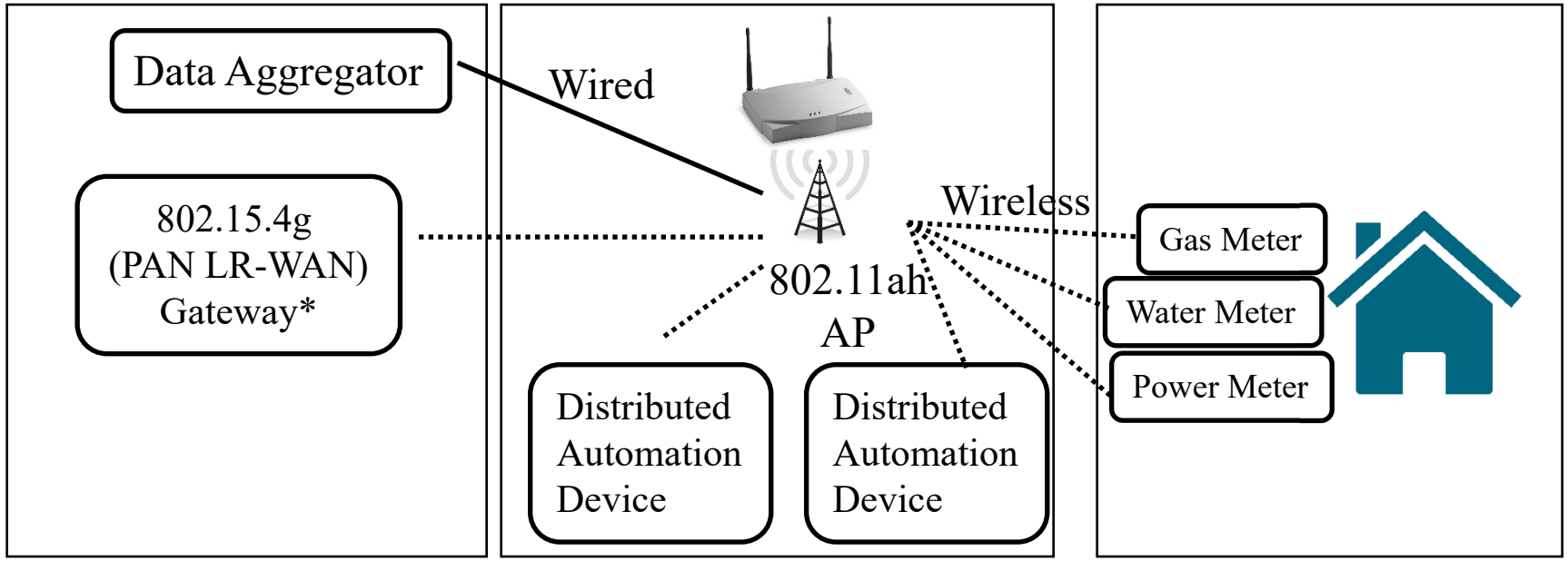
Ref: [1] https://en.wikipedia.org/wiki/TinyOS
[2] https://en.wikipedia.org/wiki/Contiki
[3] https://en.wikipedia.org/wiki/LiteOS

# 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**

# 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

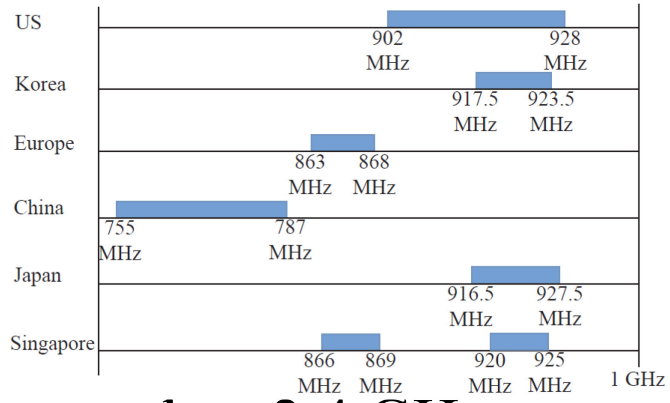




## Student Questions

# 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)

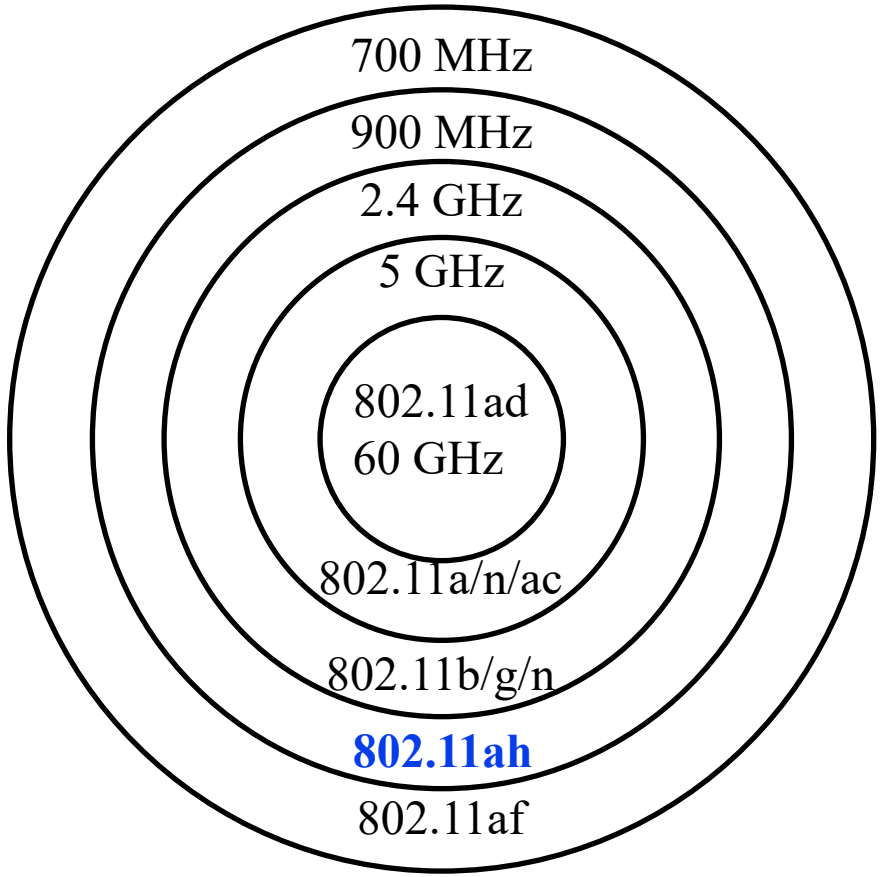



- **Sub-GHz frequency** ⇒ Longer range than 2.4 GHz, Less congested, better penetration
- Low bit rate for IoT, Short data transmissions, Power savings, Efficient MAC
- Goal: Support at least **4X devices** per AP than legacy 802.11

**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

## 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

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





**Student Questions**

# 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





**Student Questions**

# 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

# 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**

# 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

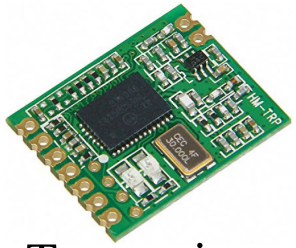




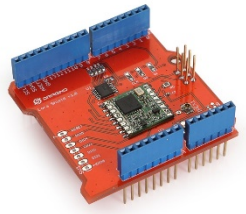
**Student Questions**

# 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

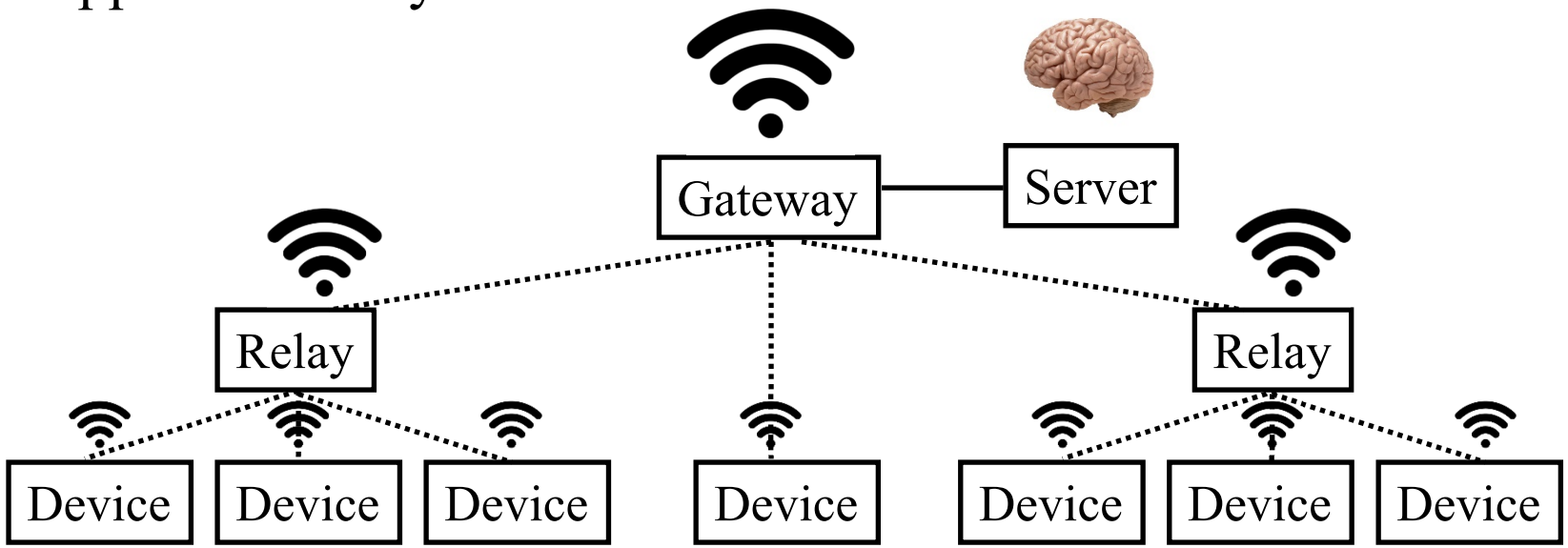
Connectivity Kit for
Arduino, Waspmote,
Raspberry Pi

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

**Student Questions**

# 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**

# LoRa Frequency Band

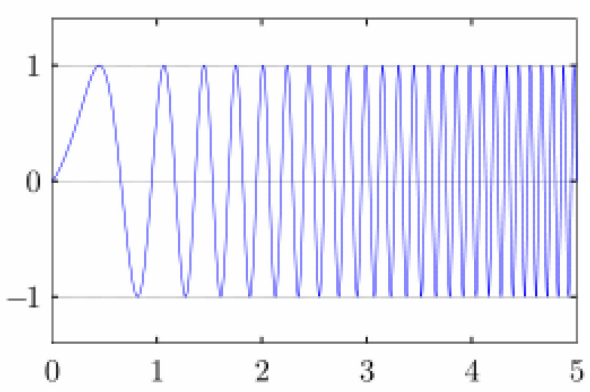
- Uses ISM license-exempt band:
  - 915 MHz MHz in US. Power limit. No duty cycle limit.
  - 868 MHz in Europe. 1% and 10% duty cycle limit
  - 433 MHz in Asia
- Same techniques can be used in 2.4GHz or 5.8 GHz
- Currently suitable for public (single) deployment in an area
  - All gateways report to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

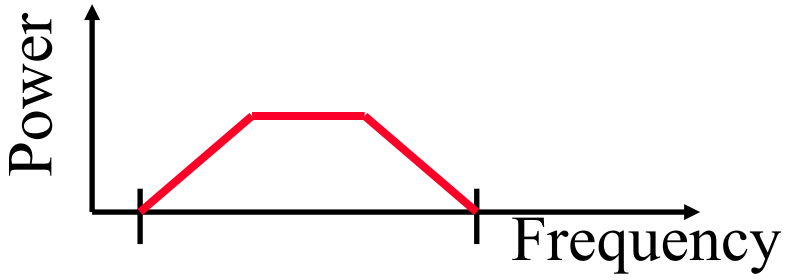
**Student Questions**

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

# 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



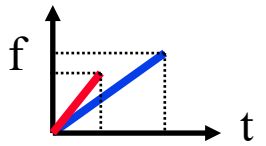




Ref: Z. Ianelli, "Introduction to Chirp Spread Spectrum (CSS) Technology," IEEE 802 Tutorial, http://www.ieee802.org/802_tutorials/03-November/15-03-0460-00-0040-IEEE-802-CSS-Tutorial-part1.ppt

**Student Questions**

# 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

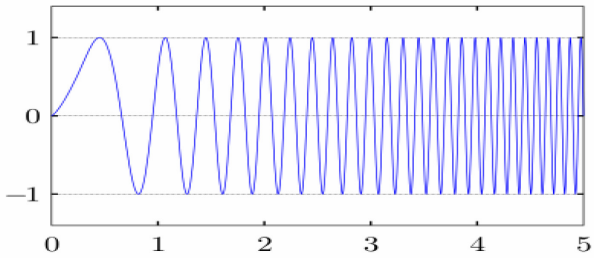




## Student Questions

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

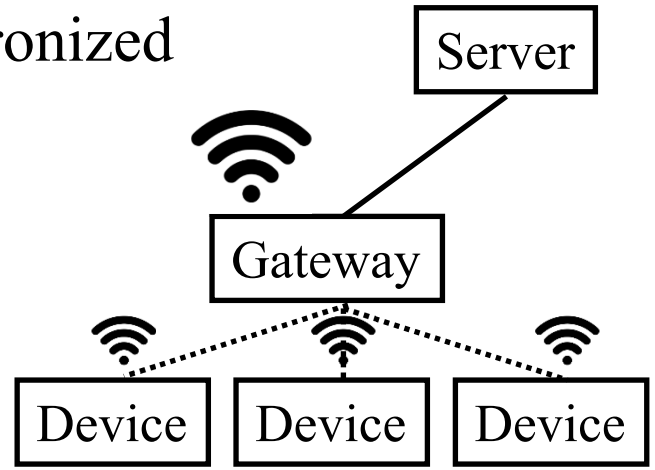
*The following figure shows how frequency increases with time. Slope of increase (as shown on the left) determines 0 or 1.*




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

# 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**

# 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*

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

# 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**

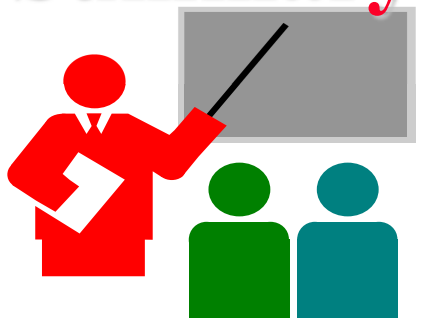
Ref: Brian Ray, "SigFox Vs. LoRa: A Comparison Between Technologies & Business Models," *May 31, 2018,* *https://www.link-labs.com/blog/sigfox-vs-lora*

# LoRa vs. Sigfox (Cont)

| Issue | LoRa | Sigfox |
|---|---|---|
| Business Model | Sell LoRa chips and silicon | Network as a Service<br>Royalty from network service providers |
| Technology | LoRa Modulation | Ultra-narrowband (100 kHz) with BPSK |
| Symmetry | Uplink = Downlink | 12 B payload in uplink<br>8 B payload in downlink<br>140 Messages/day/device uplink<br>4 messages/day/device downlink |
| Cost | Gateway and end points cost comparable | Expensive base stations<br>Cheap end-points |
| Openness | Any one can make either or both end devices | Anyone can make end-points.<br>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**

# 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
- Note: The version specified above is free and is sufficient for this lab. Higher versions of InSSIDer are either not free or require getting a code after creating a free a/c. The MAC version is currently beta. See: https://www.metageek.com/support/downloads/
- **B. Download Wireshark from**:
  - https://www.wireshark.org/#download
- Run a trace packets on your wireless network
- Submit a screen capture

**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


**Student Questions**

# References


- 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


**Student Questions**

# 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
- https://en.wikipedia.org/wiki/IEEE_802.1ah-2008
- https://en.wikipedia.org/wiki/Li-Fi
- https://en.wikipedia.org/wiki/LiteOS
- https://en.wikipedia.org/wiki/LPWAN
- https://en.wikipedia.org/wiki/MatrixSSL
- https://en.wikipedia.org/wiki/NarrowBand_IOT
- https://en.wikipedia.org/wiki/OMA_LWM2M

## Student Questions

# 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)

**Student Questions**

# 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 |

## Student Questions

# 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

**Student Questions**

# 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

**Student Questions**

# 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

**Student Questions**

# 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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Raj Jain
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