Lecture 12: CPS Networking

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Based on the Slides from Edward Lee

Review

- Processing units
  - Energy/power consumption
    - Parallel execution
    - DPM
    - DVFS
  - Application-specific processors (DS, GPU, …)
  - Real-time capability
  - Multi-core processors
  - MPSoCs

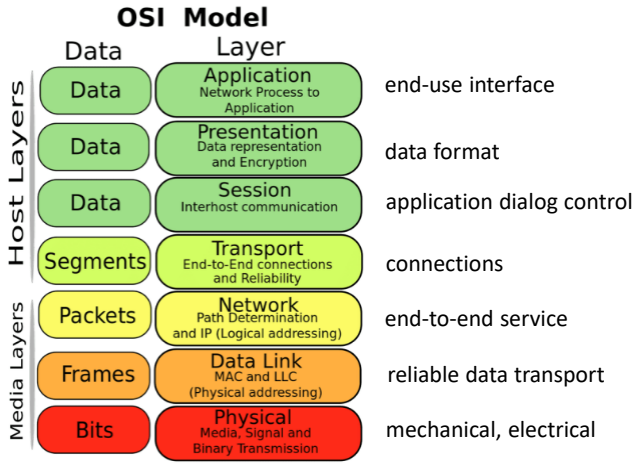
Outline

- Network layers in embedded systems
- Wired and wireless networks

The Alphabet Soup

- 1588
- 6LoWPAN
- 802.15.4
- 802.1(AS)
- 802.11
- AVB
- BLE
- CAN
- CoAP
- CSMA/CA
- GSM
- HART
- HTTP
- IoT
- IPv6
- LTE
- MAC
- PAN
- PTP
- QoS
- REST
- TDMA
- TSMP
- TSN
- TTEthernet
- TTP
- WAN
- WLAN
- WPAN

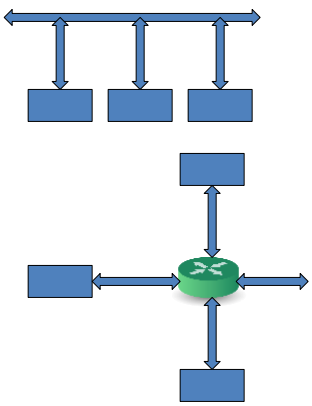
Communications Layers



Physical Layer Technologies

Specifies

- Electrical characteristics
- How to map signals <-> data
- Network topology
  - Busses
    - Shared physical medium
    - MAC protocol dominates
  - Star networks
    - Private medium
    - MAC protocol is less important
    - Routing protocols become important
    - Buffers in routers



MAC: Media Access Control CSMA/CA vs. Time Slotted

Carrier Sense Multiple Access / Collision Avoidance

Basis of Ethernet and WiFi

- Listen for idle channel
- Send
- Wait for ack, retransmit if no ack after some timeout

Time Division Multiple Access (TDMA)

Basis of TTA, TTEthernet, FlexRay/

- Wait your turn
- Send when it's your turn
- Add various schemes to recover unused slots
- Maybe add slots for CSMA/CA

Frequency Division Multiple Access (FDMA)

- Protocol supports multiple "channels" each at a different frequency
- Send on a specific channel to not conflict with others

Network Layer

- How devices are named (addressed)?
- How are messages routed?

- Issues with routing
  - Buffering
    - Buffer overflow can cause packet drops. — Reliability
  - Routing tables
    - To which port should the router send a packet? — Security
  - Priorities
    - Which packet queued for a port to send first? — QoS

Wired Networks

- Ethernet (CSMA/CD)
- CAN: Controller Area Network (Bosch, 1983)
- TTP: Time-Triggered Protocol (Vienna U. of Tech.)
- FlexRay (Automotive industry, deployed 2006…)
- TTEthernet (Time-triggered Ethernet)
- TSN (Time-sensitive networks)

- Control over timing, guaranteed bandwidth, redundancy, and fault tolerance, are all issues that loom large in embedded systems.
- Ethernet networks are acquiring high resolution clock synchronization, which can make them more suitable.

Wired Networks

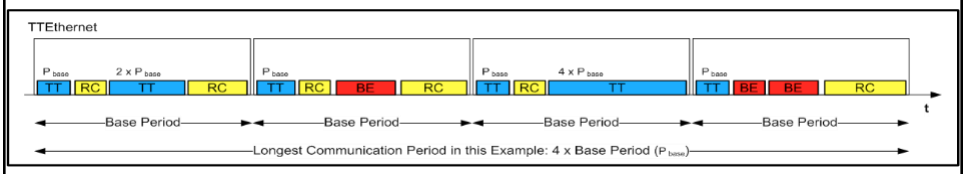
Not good enough for everything:

- UART
  - Slow. Usually no shared bus.
- I^2C
  - Slow. Master-initiated communication. Short distance.
- SPI
  - Master-initiated communication. Lots of pins.

Time-Slotted Networks: Example: TTEthernet (marketed by TTTech)

Combines three traffic types over Ethernet:

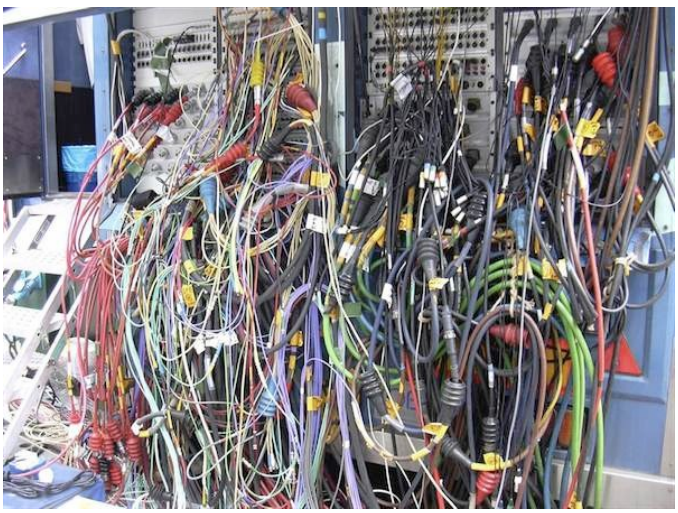
- TT: Time triggered
- RC: Rate constrained
- BE: Best effort



TSN: Time-Sensitive Networks

Before 2012, called AVB: Audio-Video Bridging.

Developed to solve this problem:



Broadcasting van. Photo by Gael Mace, licensed under creative commons attribution 3.0

TSN: Audio Video Bridging (AVB)

(Priority-based routing over Ethernet with reservations)

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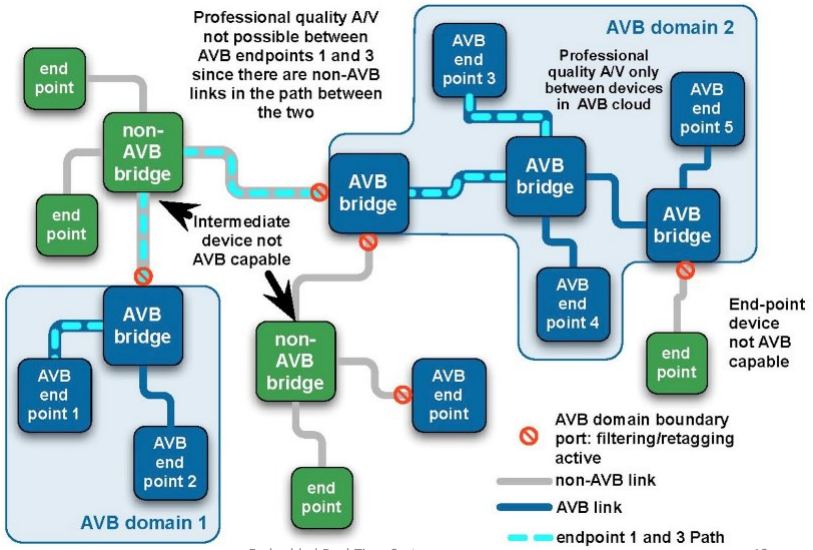
Part of IEEE 802.1 (Ethernet) family of standards.



Application of TSN

Meyer Sound CAL
(Column Array Loudspeaker),
using IEEE 1588 over Ethernet

Enabler: Precision Time Protocols (PTP)
(IEEE 1588 and 802.1AS on Ethernet)

Press Release October 1, 2007

National Semiconductor
The Sight & Sound of Information

NEWS RELEASE

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Industry's First Ethernet Transceiver with IEEE 1588 PTP Hardware Support from National Semiconductor Delivers Outstanding Clock Accuracy

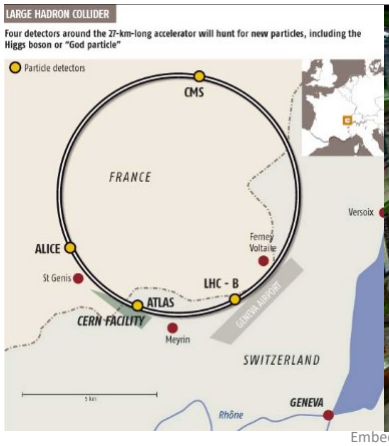
Using DP83640, Designers May Choose Any Microcontroller, FPGA or ASIC to Achieve 8- Nanosecond Precision with Maximum System Flexibility

It is becoming routine for physical network interfaces (PHY) to provide hardware support for PTPs.

With this first generation PHY, clocks on a LAN agree on the current time of day to within 8ns, far more precise than GPS older techniques like NTP.

An Extreme Example: The Large Hadron Collider

The WhiteRabbit project at CERN is synchronizing the clocks of computers 10 km apart to within about 80 psec using a combination of GPS, IEEE 1588 PTP and synchronousEethernet.



How PTP Synchronization works

Precision Time Protocols

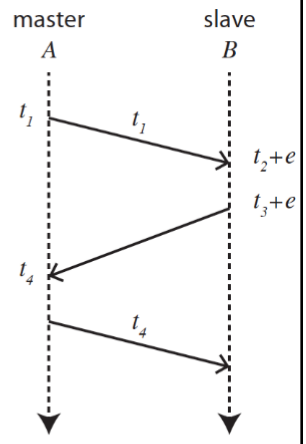
Round-trip delay:

$$r = (t_4 - t_1) - ((t_3 + e) - (t_2 + e)).$$

where e is the clock error in the slave. Estimate of the clock error is

$$\tilde{e} = (t_2 + e) - t_1 - r/2.$$

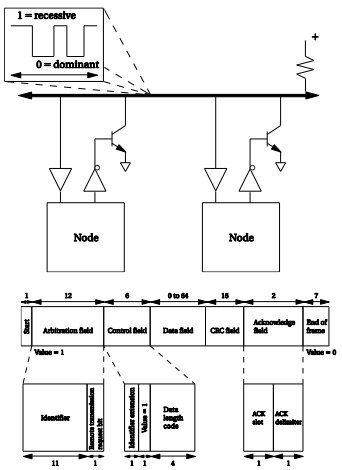
If communication latency is exactly symmetric, then $\tilde{e} = e$, the exact clock error. B calculates $\tilde{e}$ and adjusts its local clock.



IEEE 1588,
IEEE 802.1AS

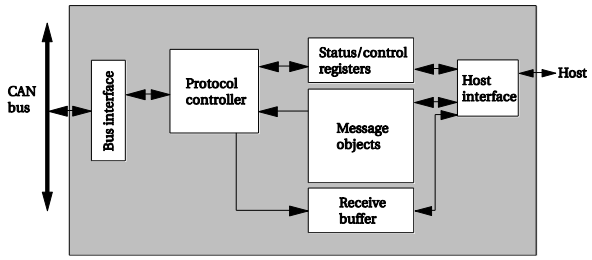
CAN Bus

- First used in 1991.
- Serial bus, 1 Mb/sec up to 40 m.
- Synchronous bus.
- Logic 0 dominates logic 1 on bus.
- Arbitrated with CSMA/AMP:
  - Arbitration on message priority.
- Data frame
  - 11 bit destination address/message id.
  - RTR bit determines read/write from/to destination.
  - Any node can detect bus error, interrupt packet for retransmission.



CAN controller

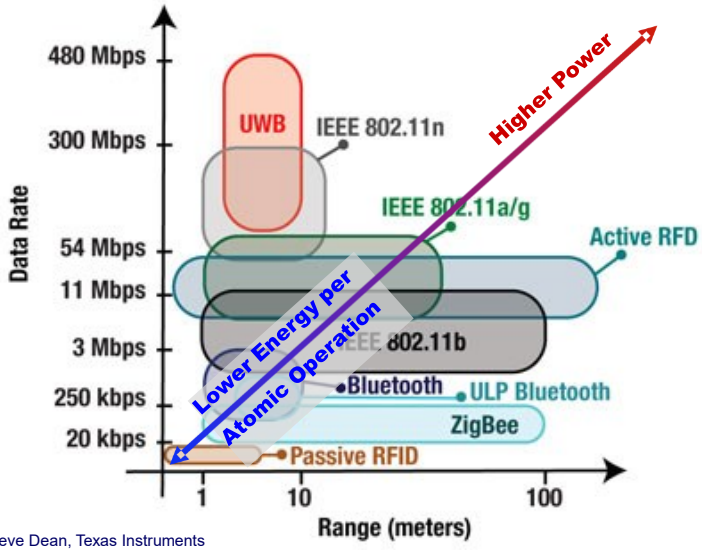
- Controller implements physical and data link layers.
- No network layer needed---bus provides end-to-end connections.



Wireless

- Personal Area Networks (PANs)
  - Bluetooth, BLE
- Local Area Networks (LANs)
  - WiFi (IEEE 802.11.*)
  - Zigbee, et al. (IEEE 802.15.4*)
- Wide Area Networks (WANs)
  - GSM (for voice, some data)
  - LTE and 5G (for audio, video)
  - Sigfox, Lora, LTE-M (for Machine-to-Machine, M2M, IoT)

Radio Technologies



Source: Steve Dean, Texas Instruments
http://eecatalog.com/medical/2009/09/23/current-and-future-trends-in-medical-electronics/

RFID

- RFID tag can provide object ID (Electronic Product Code, etc.), other information.
- Many tags are read-only, some are writable.
- Two types of tags
  - Passive transmits only when it receives a request.
  - Active tag both transmits independently and responds to requests.
- Passive may also be used to refer to tags with no internal power source.
- RFID tags may operate in several different bands and at different ranges.

Growing set of smart and connected devices

IEEE 802.15.4 (a.k.a. "ZigBee" stack)
- Workhorse radio technology for sensornets
- Widely adopted for low-power mesh protocols
- Middle (6LoWPAN, RPL) and upper (CoAP layers)
- Can last for years on a pair of AA batteries
- 850 million chipset sales in 2016 expected

Bluetooth Low-Energy (BLE)
- Short-range RF technology
- On phones and peripherals
- Can beacon for years on coin cells
- 3 billion chipset sales in 2014

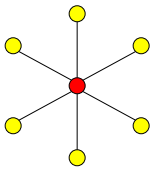
Near-Field Communications (NFC)
- Asymmetric backscatter technology
- Small (mobile) readers in smartphones
- Large (stationary) readers in infrastructure
- Ambient backscatter now emerging

IEEE 802.15.4

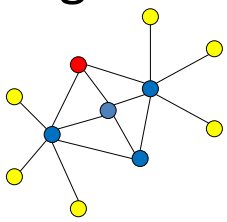
Physical and MAC layer standard for
- low-rate wireless personal area networks (WPAN)
- for energy constrained devices.

Provides the basis for:
- Zigbee: Adds mesh network and encryption
- WirelessHART: Highway Addressable Remote Transducer Protocol (HART)
  - Integrates TSMP, Time Synchronized Mesh Protocol, developed by Dust Networks.
- 6LoWPAN: IPv6 over low power WPAN

Network Topologies

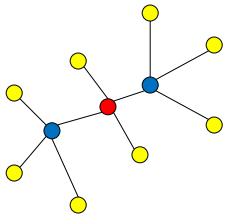


Star



Mesh

- Coordinator
- End device
- Router / End device

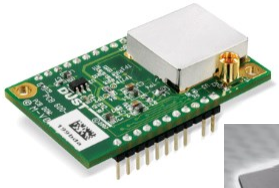


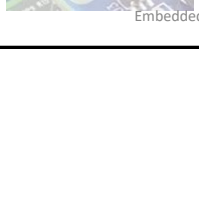
Cluster Tree

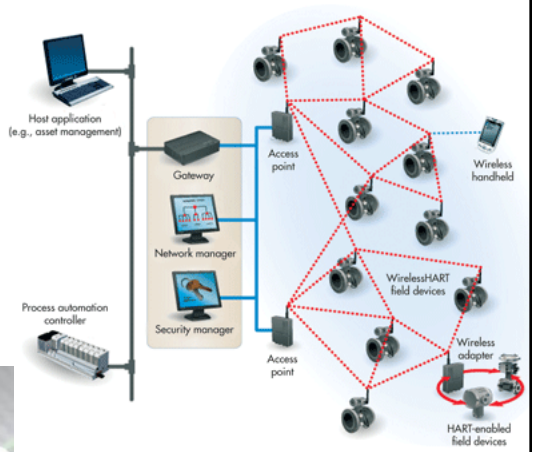
End devices capable of routing and/or coordinating are called peer-to-peer devices.

Energy Efficiency

Wireless HART uses Time Synchronized Mesh Protocol (TSMP) in a Mote-on-Chip (MoC), from Dust Networks Inc.



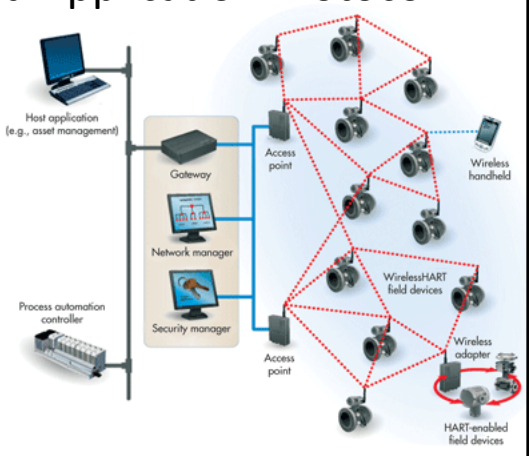




IEEE 802.15.4e

Routing to Energy-Constrained Devices
CoAP: Constrained Application Protocol

Access to low-power, mesh networked devices via a gateway to give them an Internet presence (IPv6).

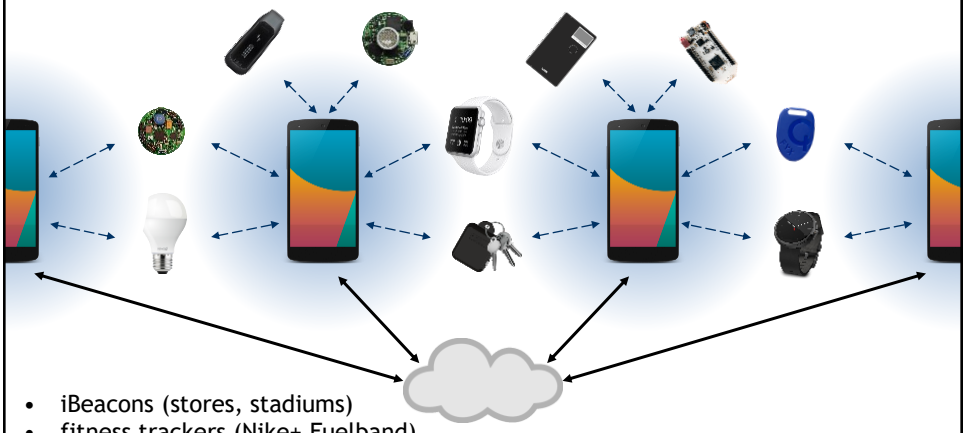


Gateway translates IPv6 128-bit (vs 32-bit in IPv4) addresses to 16-bit, locally unique addresses.

Bluetooth

- Developed by Ericsson, Lund, Sweden, in 1994, to replace serial port wired connections over short distances.
- Standardized as IEEE 802.15.1
- Operates in unlicensed industrial, scientific and medical (ISM) radio bands, 2.4 to 2.485 GHz, same as WiFi.
- Bluetooth v4.0 includes Bluetooth Low Energy (BLE) (aka Bluetooth Smart, introduced by Nokia in 2006). Designed for low-cost, energy constrained devices.
- One application of BLE is proximity sensing, as in Apple's iBeacon technology.

Smartphones with BLE have kick-started consumer IoT

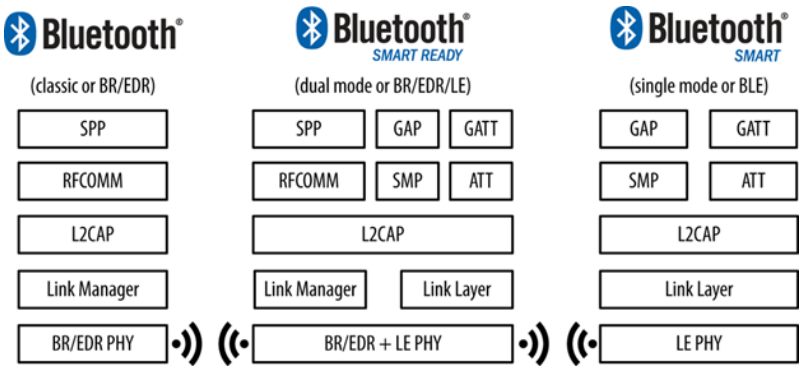


- iBeacons (stores, stadiums)
- fitness trackers (Nike+ Fuelband)
- medical devices (ConnectBlue)
- keys (Kwikset's Kevo)

Introduction to BLE

Classic Bluetooth vs BLE

- Bluetooth was originally created for continuous streaming of data
- Classic Bluetooth is for larger amounts of data
- Not directly compatible with each other, only dual-mode devices can use both



WiFi

- WLAN: Wireless Local Area Network (~20 meters)
- Developed in the 1990s (AT&T plus others)
- Access points provide gateways to wired networks
- Operates in 2.4 and 5 GHz unlicensed bands

- Requires larger antennas and more energy than Bluetooth or 802.15 networks.

Example Processor ESP 8266

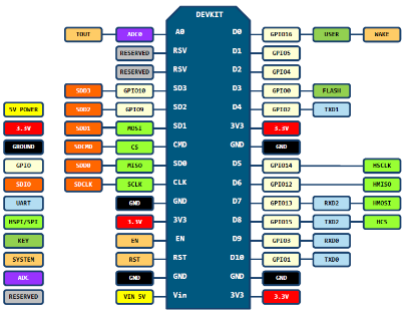
ESP8266

- CPU
  - 32 bit
  - 26MHz-52MHz
  - 64KB instruction RAM, 64KB boot ROM
  - 96KB data RAM
- WiFi
  - 802.11b/g/n
  - Access Point or Station
  - WEP
- GPIO, UART, ADC, I2C, SPI, PWM
- Made by Expressif

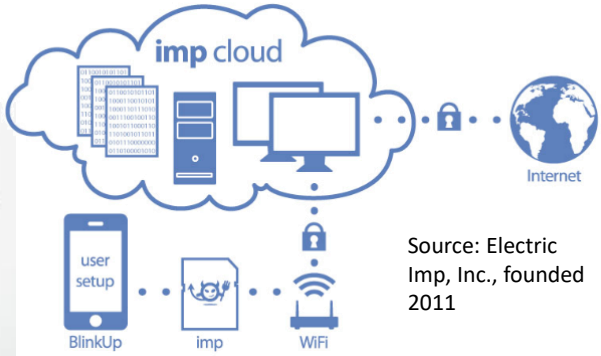
NodeMCU

- Arduino IDE
- Library support

PIN DEFINITION



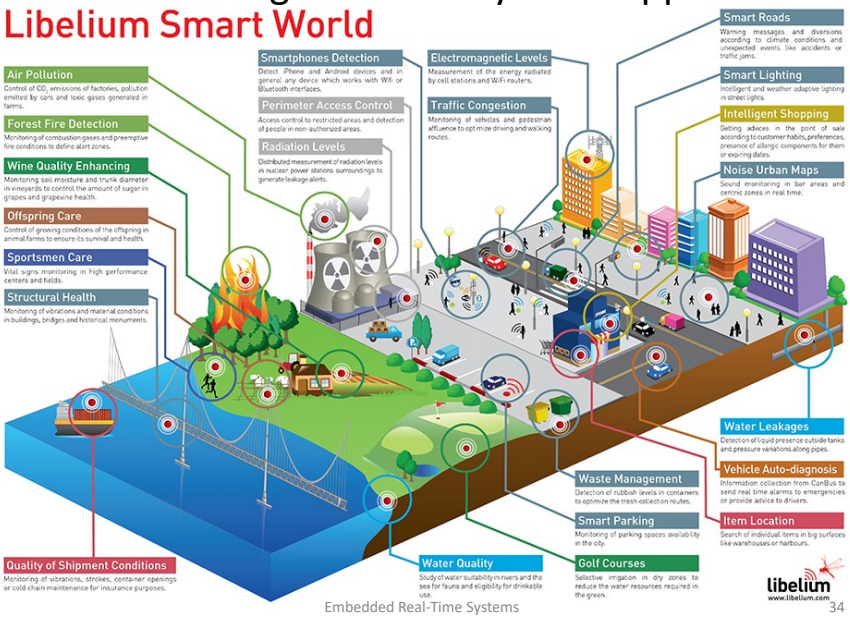
Example IoT Technology using WiFi: Electric Imp



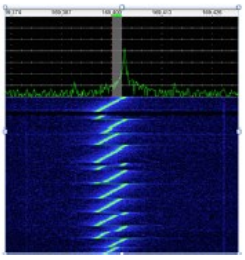
Source: Electric Imp, Inc., founded 2011

Publishes sensor data from built-in ADCs to the cloud, and then provides a RESTful interface to the data.

IoT is advancing towards city-scale applications



LoRaWAN

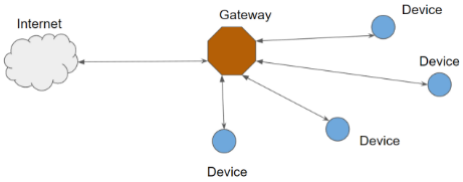


- LoRa
  - Physical layer protocol
  - Chirp, spread-spectrum modulation
  - Sub-GHz RF bands like 169, 433, 868, 915 MHz.
- LoRaWAN
  - Data-link layer protocol
  - Specifies when to transmit and receive data over LoRa

LoRaWAN

Network Architecture

- All communication is two or from a gateway
  - Similar to master/slave relationship in BLE
  - Devices do not directly communicate with each other



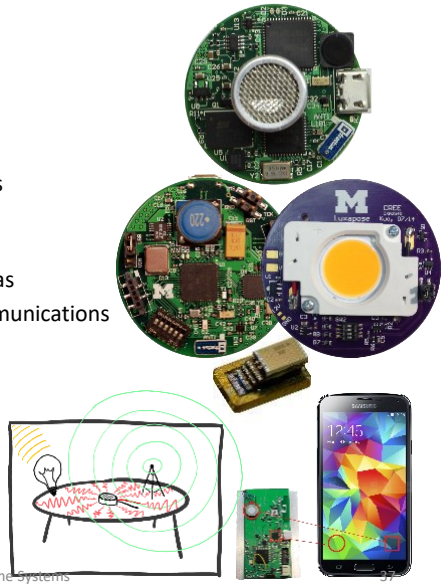
Data Rate and Distance

- LoRaWAN trades off distance and data rate

Name	Data Rate (bits/second)	Theoretical Range (kilometers)
Data Rate 0	980	25
Data Rate 1	1760	21
Data Rate 2	3125	13
Data Rate 3	5470	12
Data Rate 4	12500	9

Emerging set of proximal communication interfaces

- Ultrasonic
  - Small, low-power, short-range
  - Supports very low-power wakeup
  - Can support pairwise ranging of nodes
- Visible Light
  - Enabled by pervasive LEDs and cameras
  - Supports indoor localization and communications
  - Easy to modify existing LED lighting
- Vibration
  - Pervasive accelerometers
  - Pervasive vibration motors
  - Bootstrap desktop area context

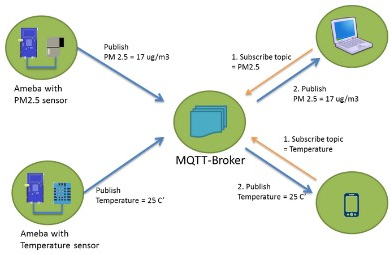


Example of an IoT Protocol: MQTT

- Machine-to-machine (M2M)/"Internet of Things" connectivity protocol
- Small code footprint
- Publish/subscribe message exchange pattern
- Works on top of TCP/IP
- Client libraries for Android, Arduino, C, C++, C#, Java, JavaScript, .NET
- Persistence: MQTT has support for persistent messages stored on the broker
- Applications: Home automation, Healthcare, Industrial automation, Automotive, etc.

MQTT Publish/Subscribe Scheme

- Multiple clients connect to a broker and subscribe to topics that they are interested in.
- Clients connect to the broker and publish messages to topics.
- Topics are treated as a hierarchy, using a slash (/) as a separator.
- Example: sensors/COMPUTER_NAME/temperature/HARDDRIVE_NAME



Conclusion

The hot trend today is towards

- "smart sensors and actuators"
- that are equipped with network interfaces (wired or wireless)
- and are accessed via
  - *web technologies* (specifically HTTP)
  - or *wirelessly* via bluetooth.

➢ But quality of service (QoS) is hard to control, so these mechanisms are not always suitable.