Networking

EECE.4520/5520 Microprocessor II and Intro to Embedded Systems

Prof. Yan Luo

Agenda

- Wired Networking
- Wireless Networking

Acknowledgement
slides are based on the ones by Lee and Seshia

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Networking and Communications

- Goal of lecture
- Want you to be aware of communication options and choices

- Outline
- Communications model
- Wired networks
- Wireless networks

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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

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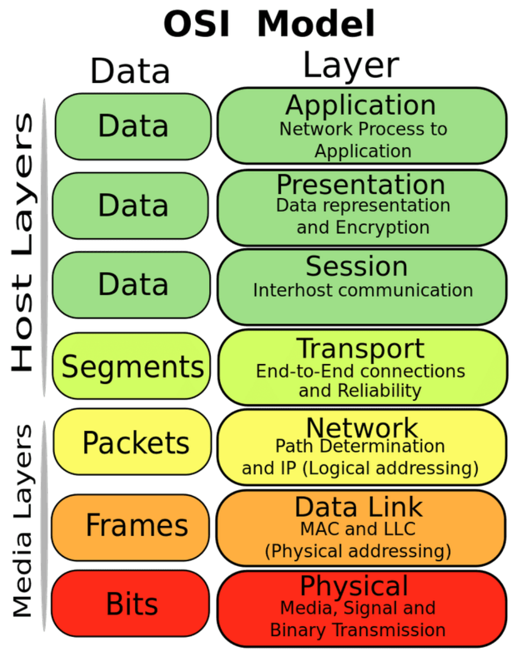
Communications Layers



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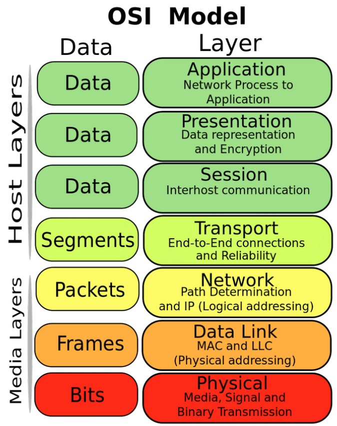
Physical Layer Technologies



- Specifies electrical characteristics
  - Voltages
  - Frequencies

- Specifies how to map signals to data
  - Example low voltage = 0 and high voltage = 1
  - Example oscillation at a high frequency = 0, low = 1

- Specifies network topology as well

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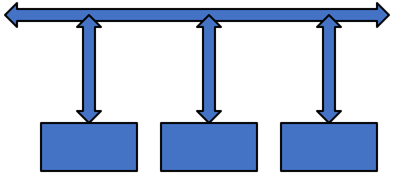
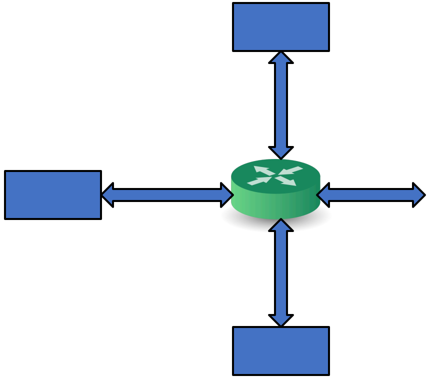
Network Topology

- Busses
  - Shared physical medium
  - MAC protocol dominates



- Star networks
  - Private medium
  - MAC protocol is less important
  - Routing protocols become important
  - Buffers in routers



•Is radio a bus?

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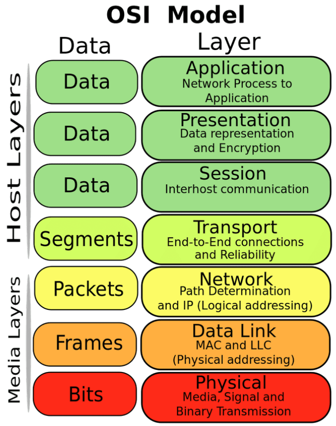
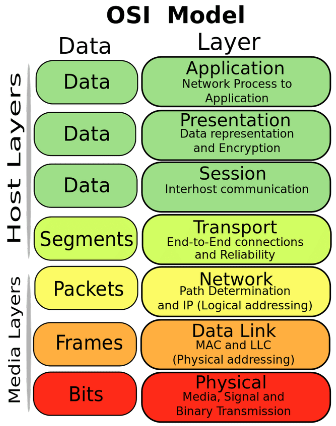
Medium Access Controls

- How do multiple devices share the same transmission technology?



Medium Access Controls



- How do multiple devices share the same transmission technology?

- Don’t worry about it, let collisions happen
- Listen for others and don’t transmit if they are
- Coordinate with others and transmit at different times
- Transmit at different frequencies

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

Basis of Ethernet and WiFi

- Carrier Sense Multiple Access / Collision Avoidance
- Listen for idle channel
- Send
- Wait for ack, retransmit if no ack after some timeout

- Time Division Multiple Access (TDMA)
- Wait your turn
- Send when it's your turn
- Add various schemes to recover unused slots
- Maybe add slots for CSMA/CA

Basis of TTA, TTEthernet, FlexRay/

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MAC: Media Access Control
FDMA

- Frequency Division Multiple Access
- Protocol supports multiple “channels” each at a different frequency
- Send on a specific channel to not conflict with others

- There are many other methods of sharing as well

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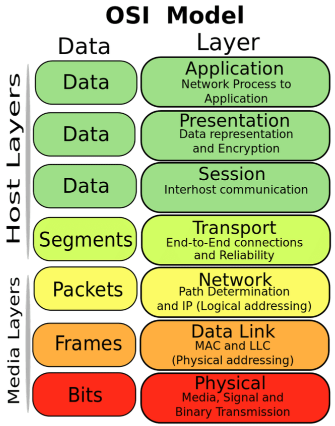
Network Layer

- How do I get a message to the correct device?

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

- Example: IP



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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

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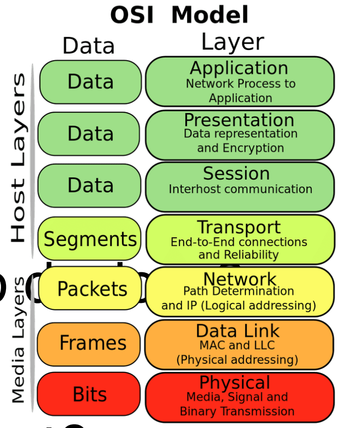
Transport Layer Reliability



- How do I reliably get messages between two
  - What if the message is too big for one packet?
  - How do I know if the recipient got the message?

- Example: TCP and UDP

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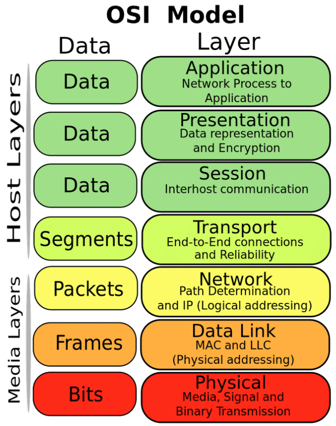
Higher Layers



- How do we handle data?

- Includes:
- maintaining connections across computers
- deciding what messages to send
- data compression and encryption

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Wired Networks

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Wired Networks

- Ethernet
- 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.

I^2C, UART, and SPI

- Why aren't these good enough for everything?
- UART
- I^2C
- SPI

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I^2C, UART, and SPI

- Why aren't these good enough for everything?

- UART
- Slow. No shared bus.

- I^2C
- Slow. Master-initiated communication. Short distance.

- SPI
- Master-initiated communication. Lots of pins.

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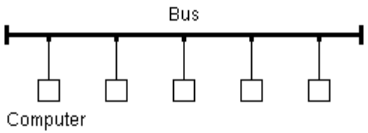
Ethernet

- Shared network between peers
- Open contention for network CSMA/CD
  - Detect collisions as they occur

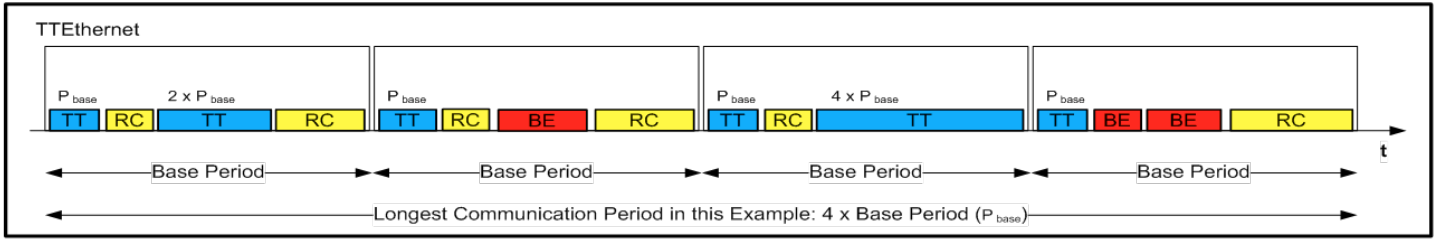


- Problem: collisions slow down the network

•Note: this is all original Ethernet design

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

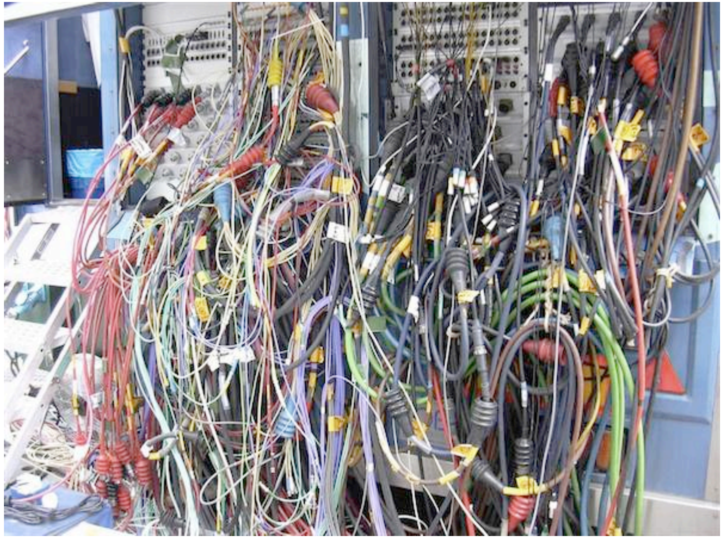
- Combines three traffic types over Ethernet:
- TT: Time triggered
- RC: Rate constrained
- BE: Best effort



TSN: Time-Sensitive Networks

- Before 2012, called AVB: Audio-Video Bridging.

- Developed to solve this problem:



Broadcasting van.
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TSN: Time-Sensitive Networks (aka AVB)

(Priority-based routing over Ethernet with reservations)

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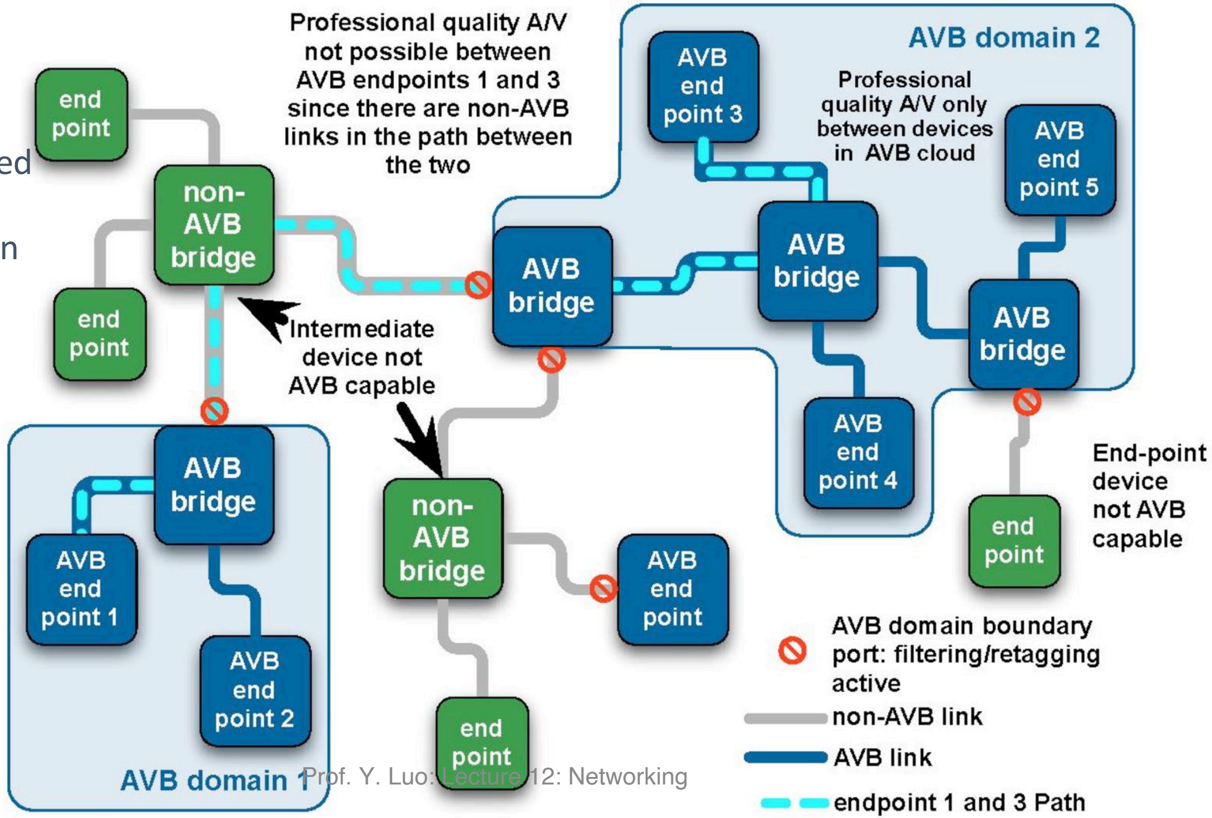

Part of IEEE 802.1 (Ethernet) family of standards.

Application of TSN

Meyer Sound CAL
(Column Array Loudspeaker), based on research at CNMAT (UC Berkeley), using IEEE 1588 over Ethernet

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

Press Release October 1, 2007

It is b … aces (PHY) to provide
hard…

With t… current time of day to within 8ns,
far mo…

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

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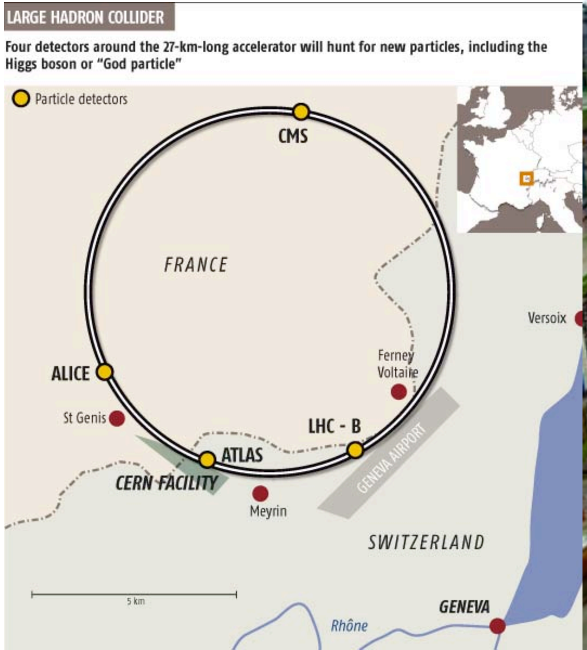
An Extreme Example: The Large Hadron Collider

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 synchronous ethernet.

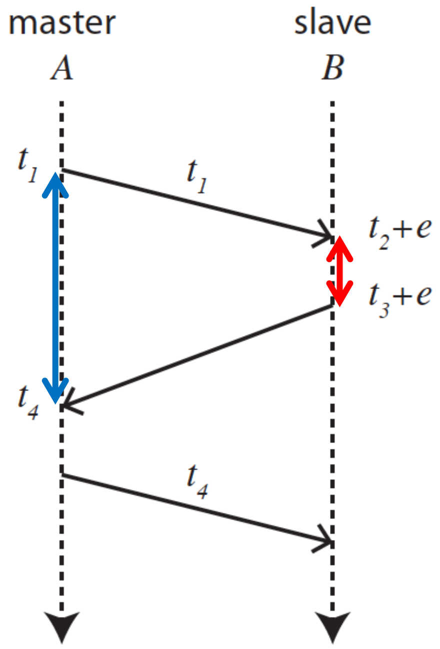


PTP Example

- The slave synchronizes to the master

1. Measure round-trip delay
   1. Master sends a packet along with time that packet was sent (t_1)
   2. Slave receives packet at ($t_2 + e$)
   3. Slave sends response at ($t_3 + e$)
   4. Master receives packet at t_4
   5. Master sends t_4 to slave

RTT = (t_4 - t_1) – (($t_3 + e$) - ($t_2 + e$))



IEEE 1588,

IEEE 802.1AS

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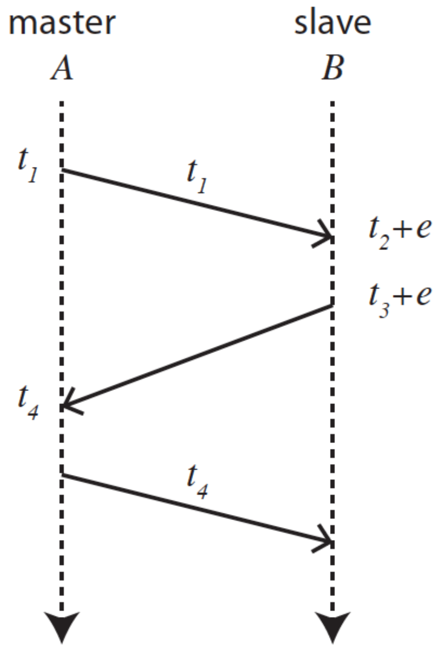
PTP Example

1. Assume symmetric delay
   One-way delay = $\frac{RTT}{2}$

2. Estimate error
   $t_2 = t_1 + \frac{RTT}{2}$
   $\tilde{e} = (t_2 + e) - (t_1 + \frac{RTT}{2})$

3. Adjust slave clock accordingly
4. Repeat periodically!



IEEE 1588,
IEEE 802.1AS

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How PTP Synchronization works

Precision Time Protocols

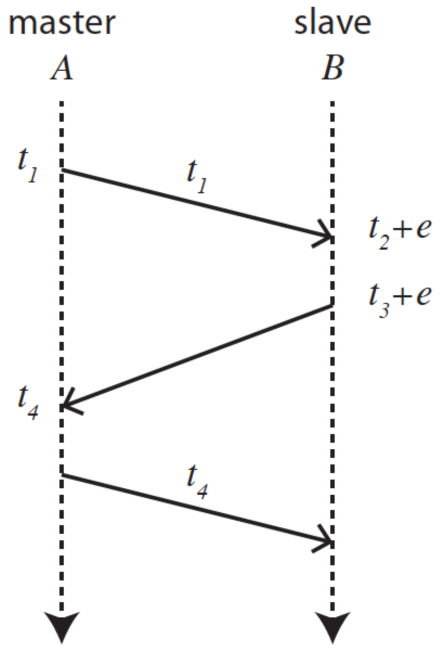
Round-trip delay:

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

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

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Wireless Networks

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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)

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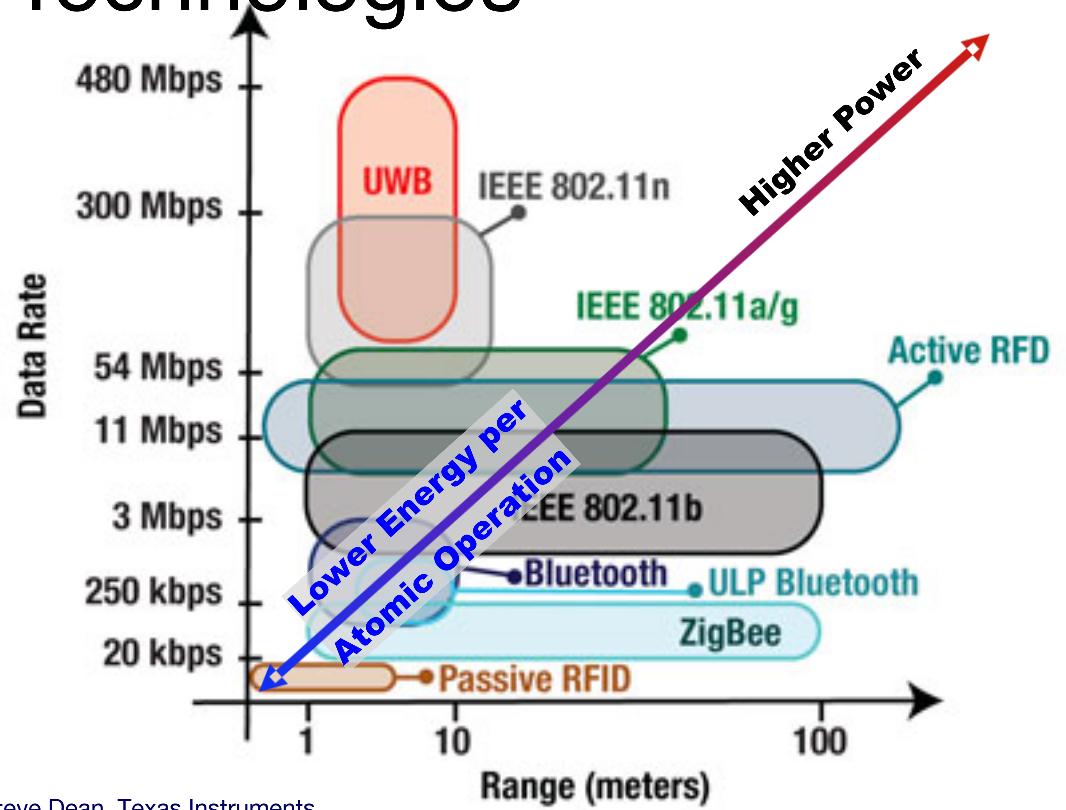
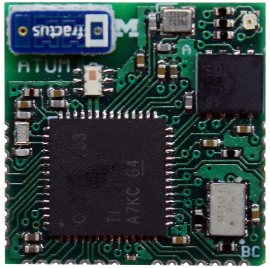
Radio Technologies



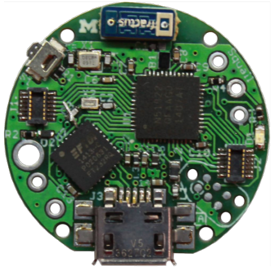
Source: Steve Dean, Texas Instruments
http://eecatalog.com/medical/2009/09/23/current-and-future-trends-in-medical-electronics/

Growing set of smart and connected devices

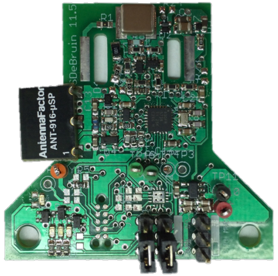
- IEEE 802.15.4 (a.k.a. "ZigBee" stack)
  - Workhorse radio technology for sensornets
  - Widely adopted for low-power mesh protocols
  - Middle (6LoWPAN, RPL) and upper (CoAP layers)
  - Can last for years on a pair of AA batteries
  - 850 million chipset sales in 2016 expected



- 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



Slide courtesy of Prabal Dutta

Wireless Networks

Personal Area Networks – Bluetooth Low Energy

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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.

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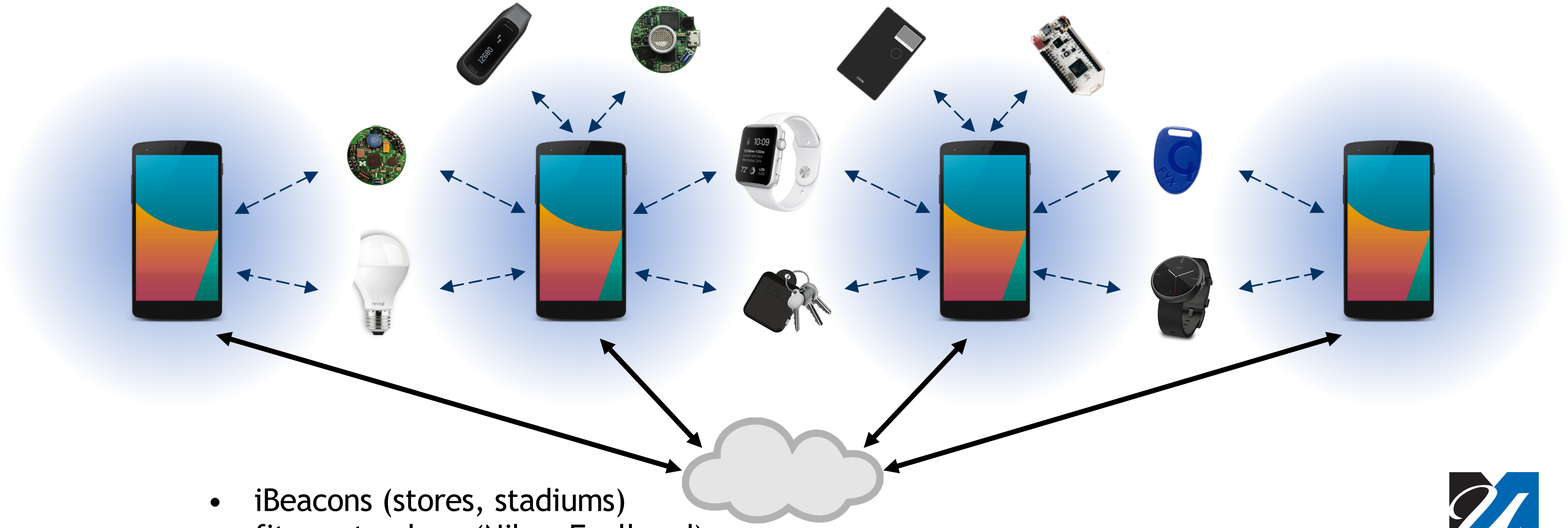
Smartphones with BLE have kick-started consumer IoT



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

Slide adapted from Prabal Dutta

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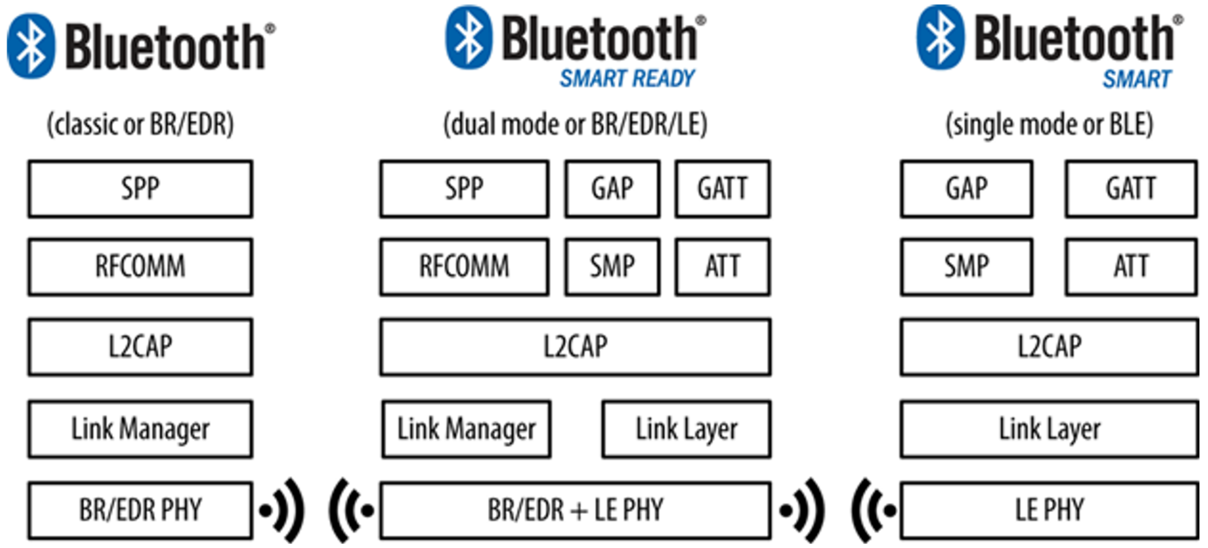
Introduction to BLE

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



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Slide courtesy of Prabal Dutta

BLE High-level Architecture

- Centrals are high-power master devices
  - Such as laptops or smartphones
  - They listen for peripherals and choose to connect to them
  - Sometimes termed Scanners outside of a connection
- Peripherals are low-power slave devices
  - They advertise their presence and can be connected to
  - Sometimes termed Advertisers outside of a connection

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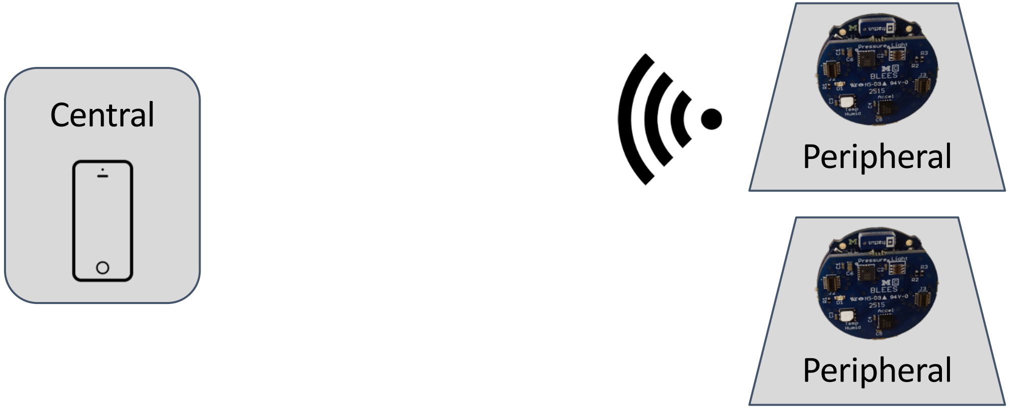
BLE Advertisements

- Peripherals send out advertisement packets
  - Periodic, broadcast transmission on three channels
  - Enable device discovery
  - Transmit up to 31 Bytes of data



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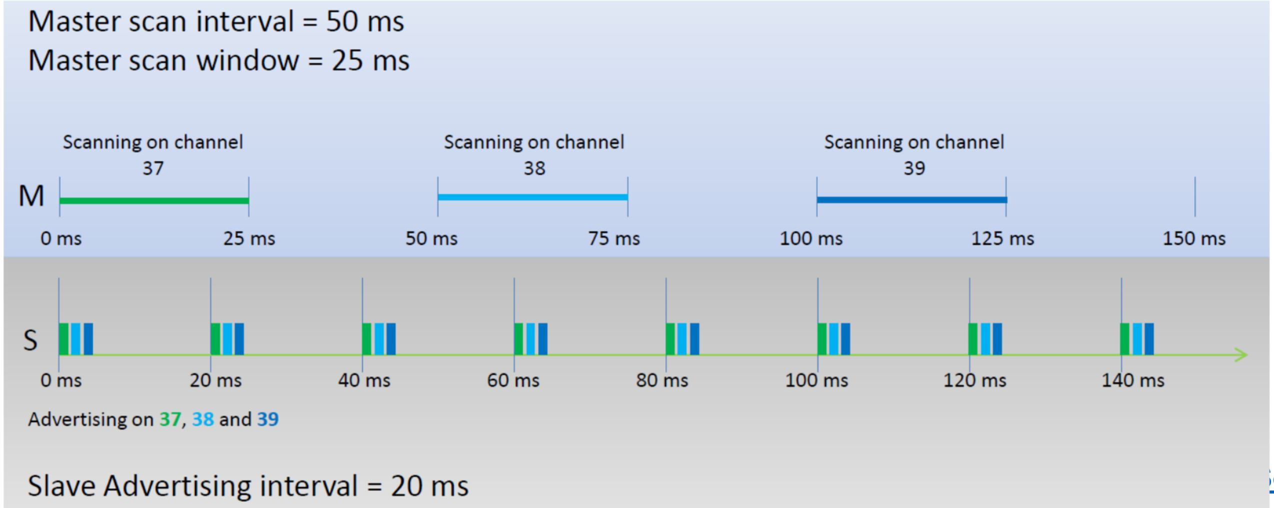
BLE Advertisements

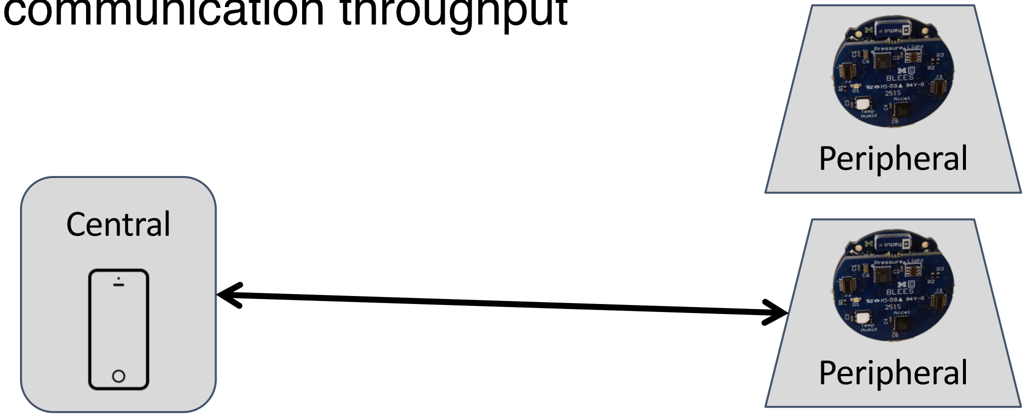


emiconductor

- What are the advantages to end nodes of this transmission scheme?
- What are the disadvantages?

BLE Connections

- Centrals can connect to peripherals
  - In response to an advertisement
  - Forms private connection with end node
  - Hops over 37 data channels
  - Schedule receive and transmit windows
  - Higher communication throughput



What makes it low energy?

- Asymmetric relationship
- End nodes are slaves
- Master of connection burden is placed on phones

- End devices rarely listen for data
- When not in a connection, listen only after transmit

- Data rate is low
- 270 kbps when in a connection

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BLE Security

A device can request a secure one-to-one connection using the Security Manager Protocol (SMP)

Two steps are needed to get a secure connection:

- Pair
- Bond

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Slide courtesy of Prabal Dutta

BLE Security: Pairing

Set up a secure connection using a Short Term Key (STK)

STK is relatively insecure, used only to protect the key exchange in the Bonding process

Three ways to pair devices and share a STK:

1. Just Works
   - Not secure, STK passed in plain text between devices
2. Passkey Display
   - User passes 6-digit passkey between devices, used to generate the STK
3. Out Of Band
   - Uses NFC or some other method to pass the STK

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Slide courtesy of Prabal Dutta

BLE Security: Bonding

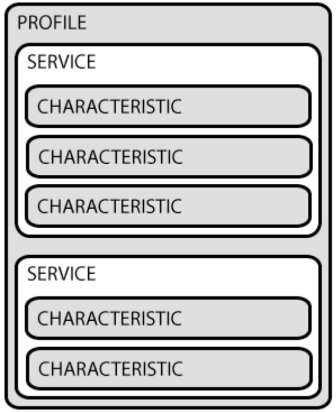
Devices then “Bond” by exchanging a stronger pair of keys, called “secret keys”

Secret key transmission is encrypted using the STK created in the pairing process

The secret keys are then stored in non-volatile memory, so the bonded devices can easily reconnect to each other later without having to pair or bond again

BLE Services

- Services are used to exchange data in connections
  - Both centrals and peripherals can have services
  - Services can be thought of as a group of device data
  - There are many standardized services
    - Environmental sensing, heart rate monitoring, etc.
- Services have characteristics
    - Specific data which can be read or written
    - Up to 512 Bytes in length



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BLE Service Example

- As an example, the [Environmental Sensing Service]()
- Characteristics
  - Temperature, Elevation, Humidity, Pollen Concentration, etc.
  - Read-only to get measurement value
- Descriptors
  - Measurement frequency, Measurement range
  - Often read-only to understand how the sensor works
  - Occasionally writable to change how the sensor works

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BLE Standardization

- What do we gain from all the standardization?

- What do we lose?

BLE Standardization

- What do we gain from all the standardization?
- Interoperability!

- What do we lose?
- Complexity
- Flexibility

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Wireless Networks

Wide Area Networks – LoRaWAN

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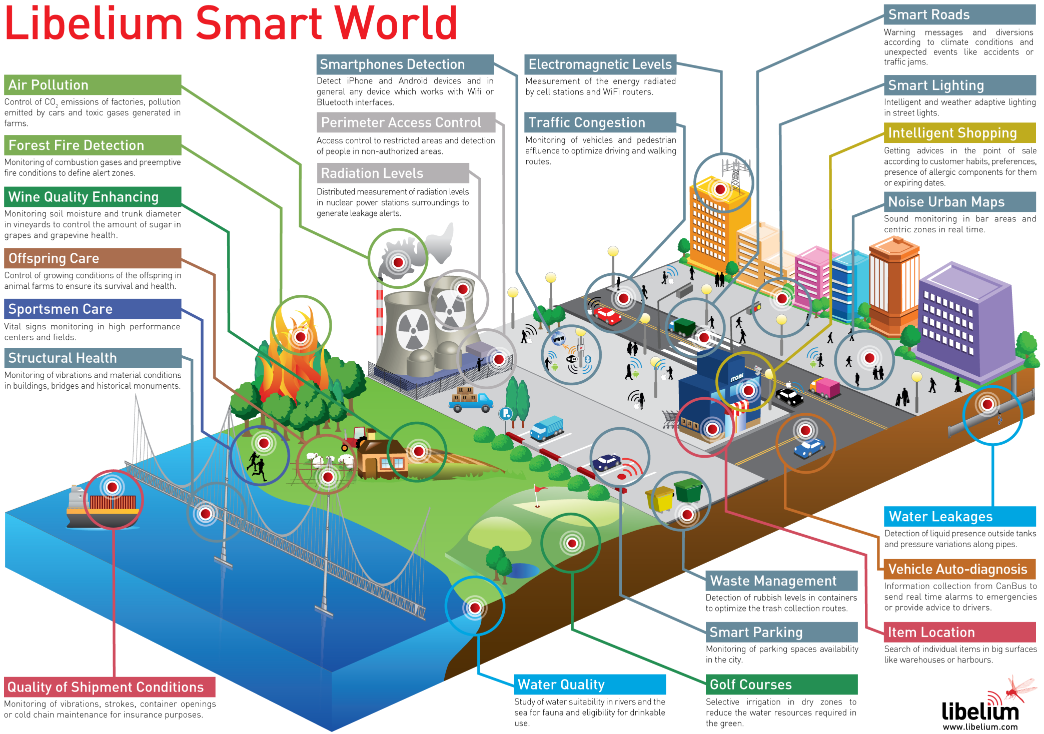
IoT is advancing towards city-scale applications

- Example by Libelium



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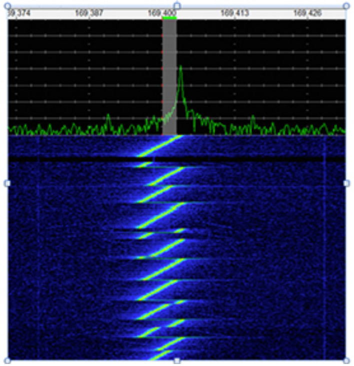
Systems are still resource-constrained

- Need low-power, low-bandwidth, but still long range

LoRaWAN



- LoRa
  - Physical layer protocol
  - Chirp, spread-spectrum modulation
  - 915 MHz in the United States (ISM band)

- LoRaWAN
  - Data-link layer protocol
  - Specifies when to transmit and receive data over LoRa

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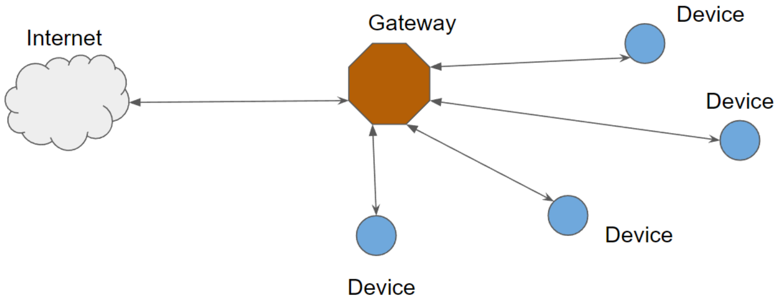
LoRaWAN Network Architecture

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



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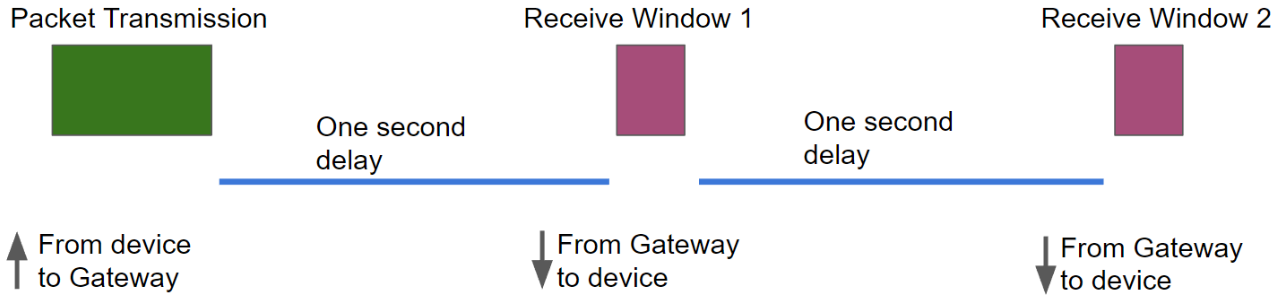
LoRaWAN Packet Transmission

- The network expects mostly uplink transmissions
- End nodes listen twice after each transmission

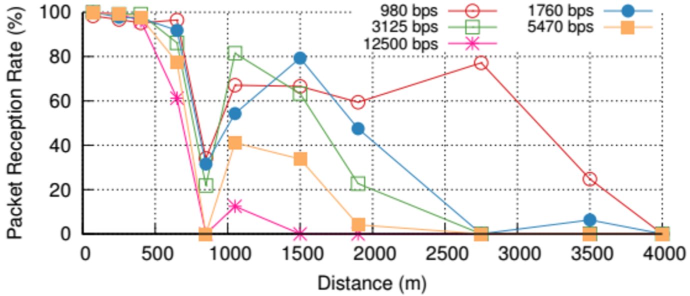


LoRaWAN Data Rate and Distance

- 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

Testing on campus and downtown



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Wireless Networks

Local Area Networks – 802.15.4 and WiFi

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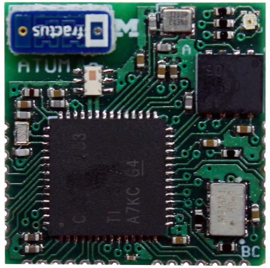
Growing set of smart and connected devices

- 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



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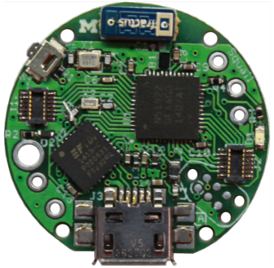
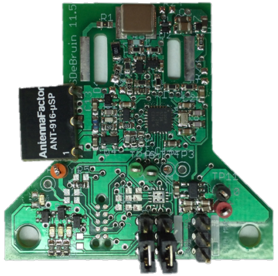


- Near-Field Communications (NFC)
  - Asymmetric backscatter technology
  - Small (mobile) readers in smartphones
  - Large (stationary) readers in infrastructure
  - Ambient backscatter now emerging



Slide courtesy of Prabal Dutta

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

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The New York Times

Thursday, November 3, 2016 | Today's Paper | Video

- "The worm spreads by jumping directly from one l… ZigBee wireless connectivity and their physical pro… …ngle infected bulb anywhere in the city, an… enabling the attacker to turn all the ci… …a massive DDOS attack."

FEATURED

Why Light Bulbs May Be the Next Hacker Target

By JOHN MARKOFF

Carlos Gonzalez for The New York Times

The Internet of Things, activated through apps, promises tremendous convenience to homeowners. But it may also prove irresistible to hackers.

Wireless "smart" devices may be the tech wave of the future, but researchers have found flaws that let hackers spread malicious code through them.

IoT Goes Nuclear: Creating a ZigBee Chain Reaction

Eyal Ronen(✉)[*], Colin OFlynn[†], Adi Shamir[*] and Achi-Or Weingarten[*]

PRELIMINARY DRAFT, VERSION 0.9

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coflynn@dal.ca

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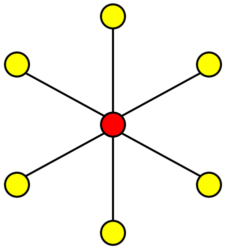
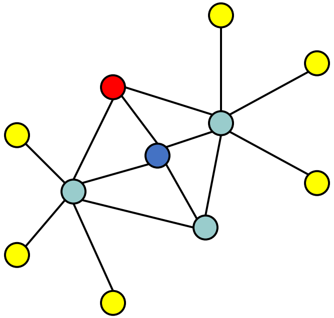
Network Topologies

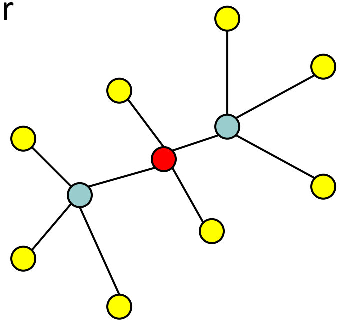
- Coordinator
- End device
- Router / End device



Star



Mesh



Cluster Tree

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

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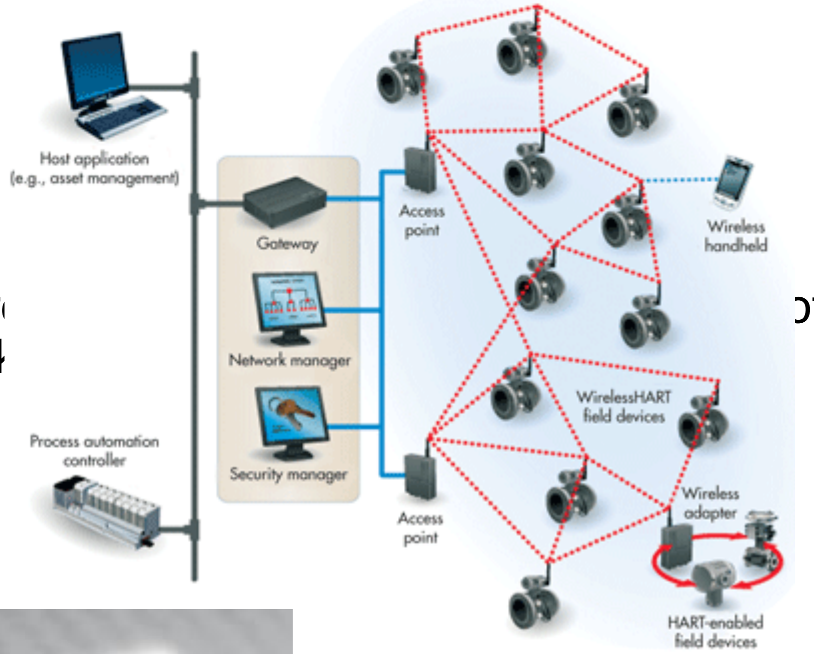
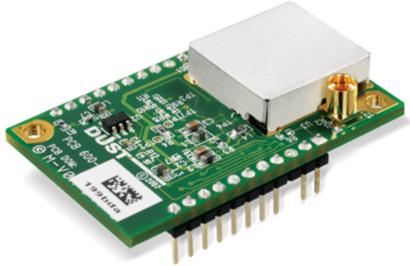
Unslotted vs. Slotted Modes

- Unslotted:
  - All nodes are always listening, or
  - Leaf nodes poll the coordinator for available data (coordinator and routers are always listening)
- Slotted: Typically has superframe with two periods:
  - Contention access period uses CSMA/CA
  - Contention-free period has assigned time slots
  - Requires clock synchronization or always-on radios

Energy Efficiency

Wireless HART uses Time Synchr ote-
on-Chip (MoC), from Dust Networ





IEEE 802.15.4e

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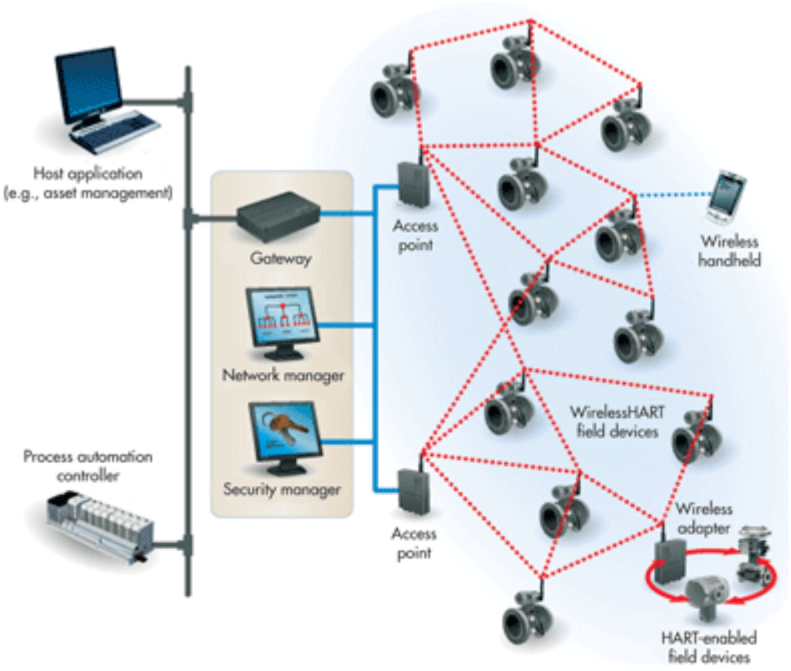
Routing to Energy-Constrained Devices CoAP: Constrained Application Protocol

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

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



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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.

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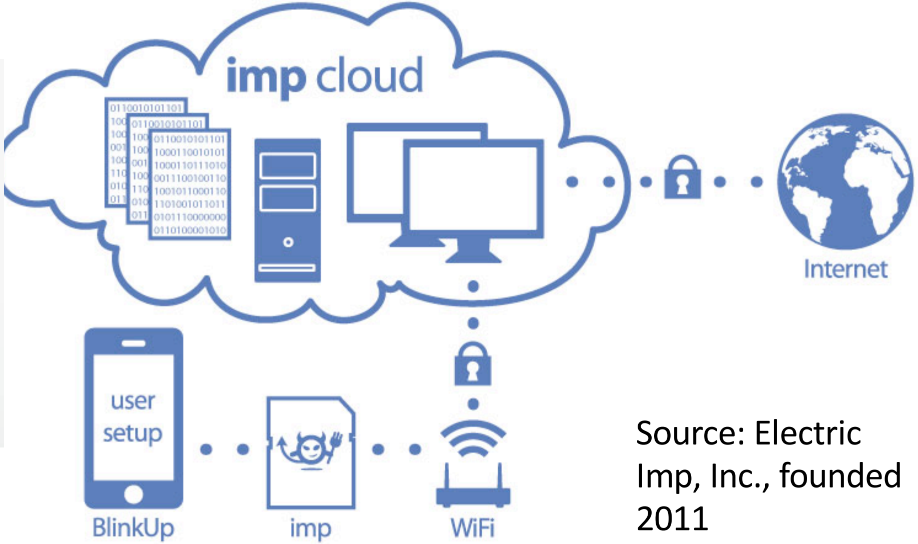
Example IoT Technology using WiFi: Electric Imp

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



Source: Electric Imp, Inc., founded 2011

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RESTful Interfaces

- Representational State Transfer (REST) [1] uses web technology

- Example:
  - http://ptolemy.org:8077/sensor/get?id=A1243ADsA3209

- [1] Fielding, R. T. and R. N. Taylor (2002). "Principled Design of the Modern Web Architecture." ACM Transactions on Internet Technology (TOIT) **2**(2): 115-150.

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Communication and The Internet of THings

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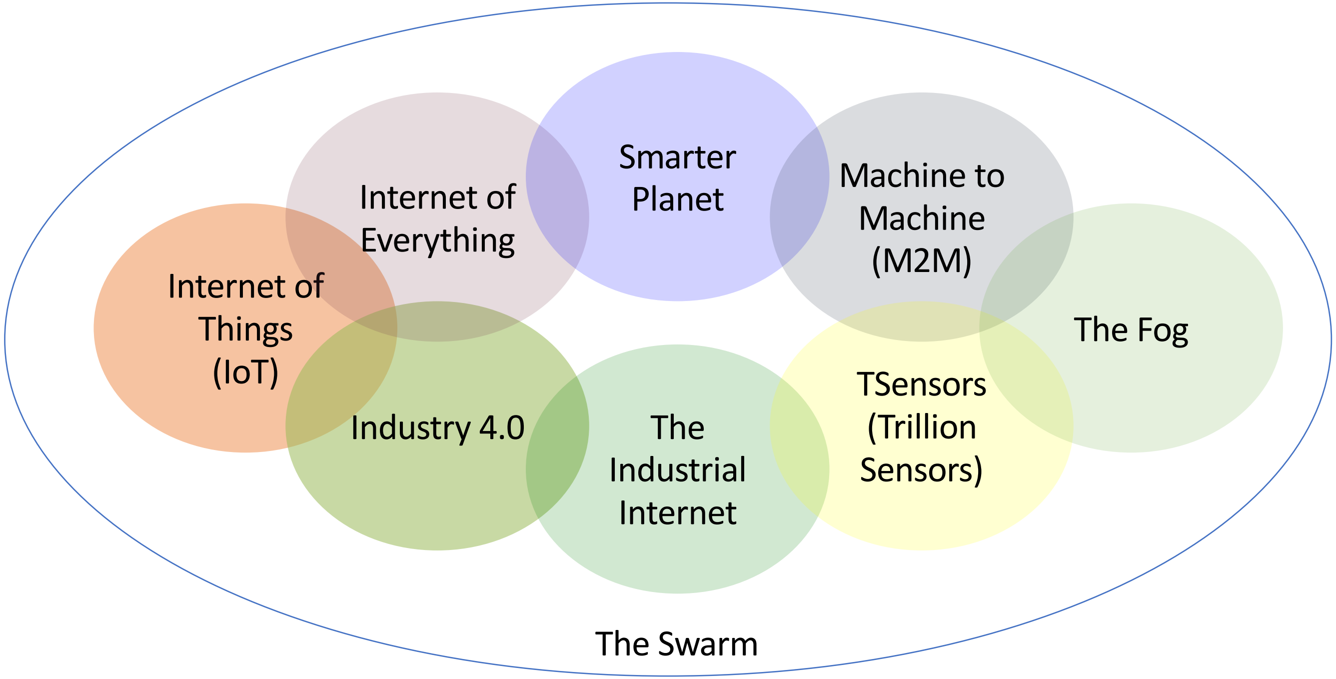
"Swarm" Technology
The Buzz around the Swarm



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Typical IoT Architectures Today

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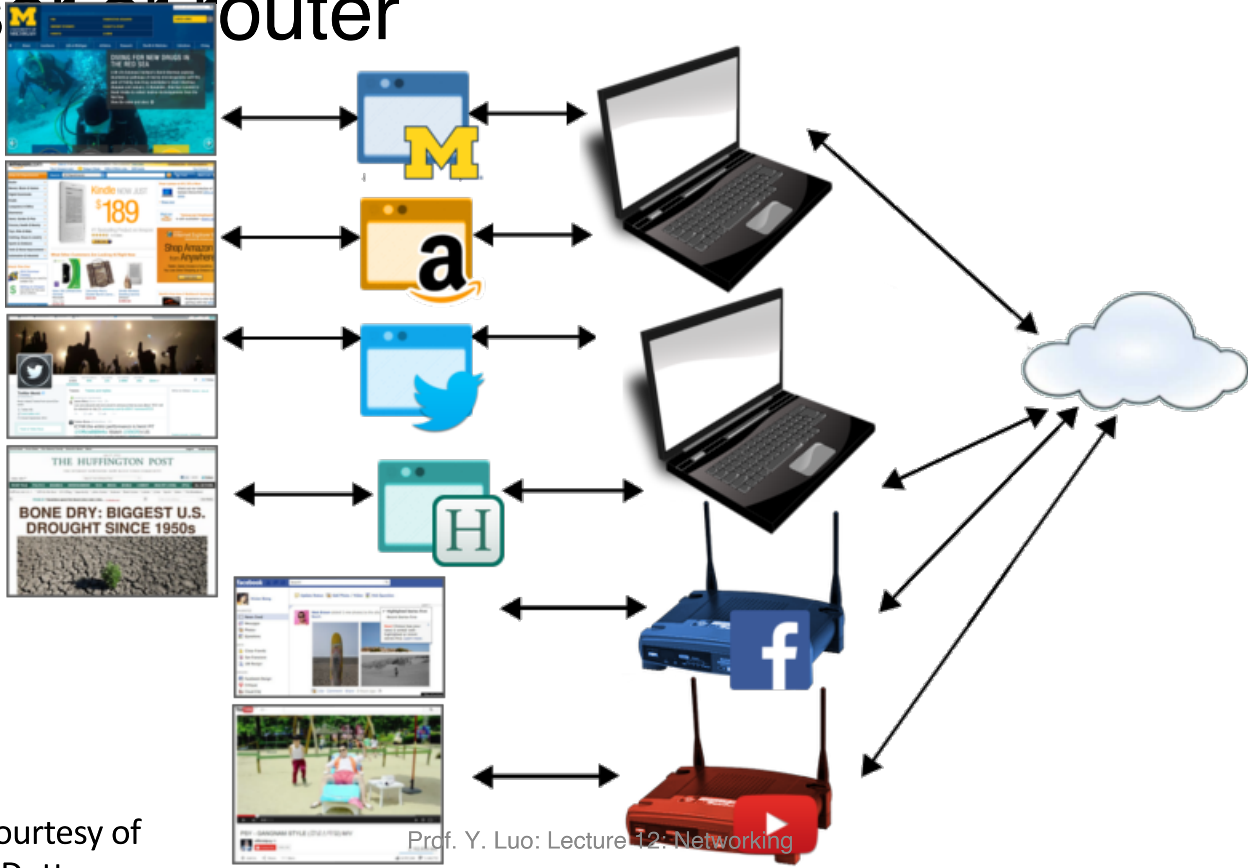
Imagine if every website required its own browser or router



Slide courtesy of
Prabal Dutta

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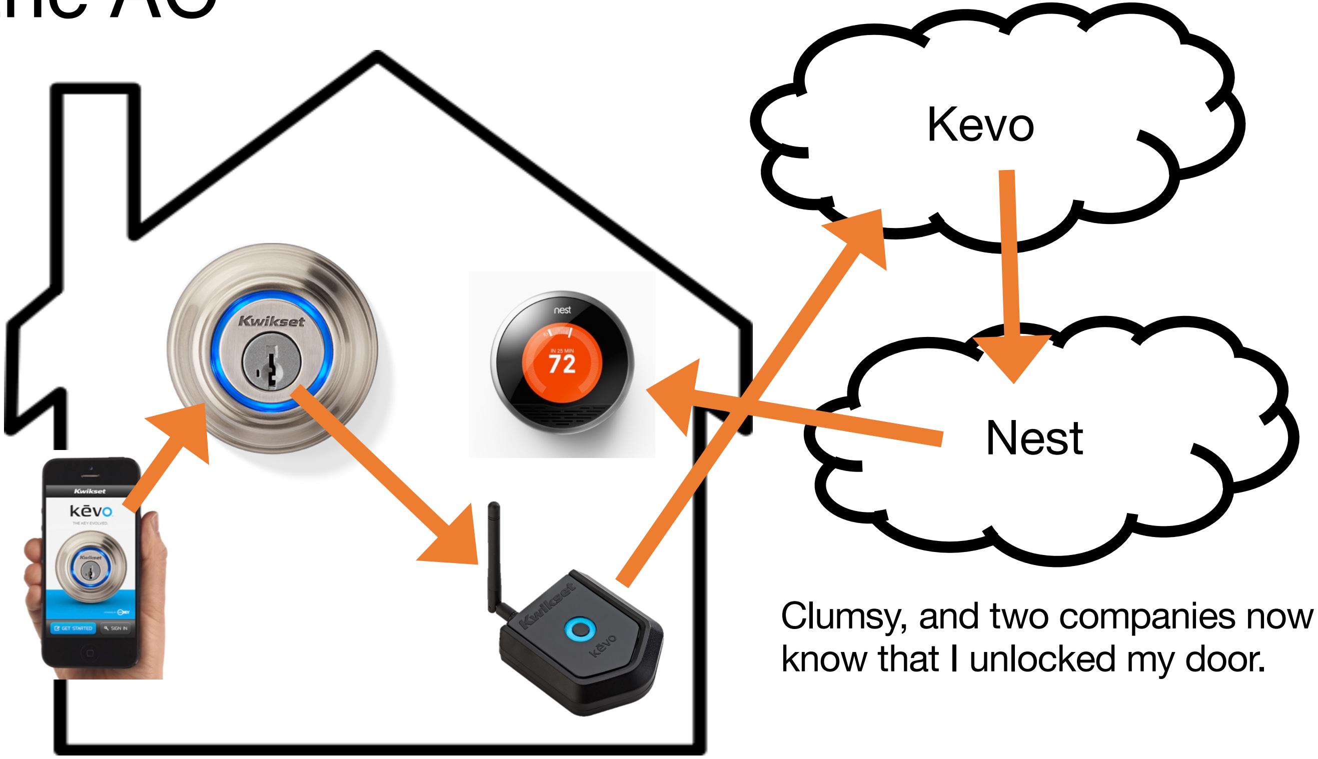
Orchestration: when I enter my house, turn on the AC

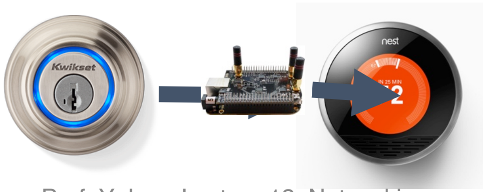


Clumsy, and two companies now know that I unlocked my door.

Slide courtesy of Prabal Dutta

Initial setup, configuration, and authorization may require complex interactions and cloud interaction

…but device interactions likely do not.



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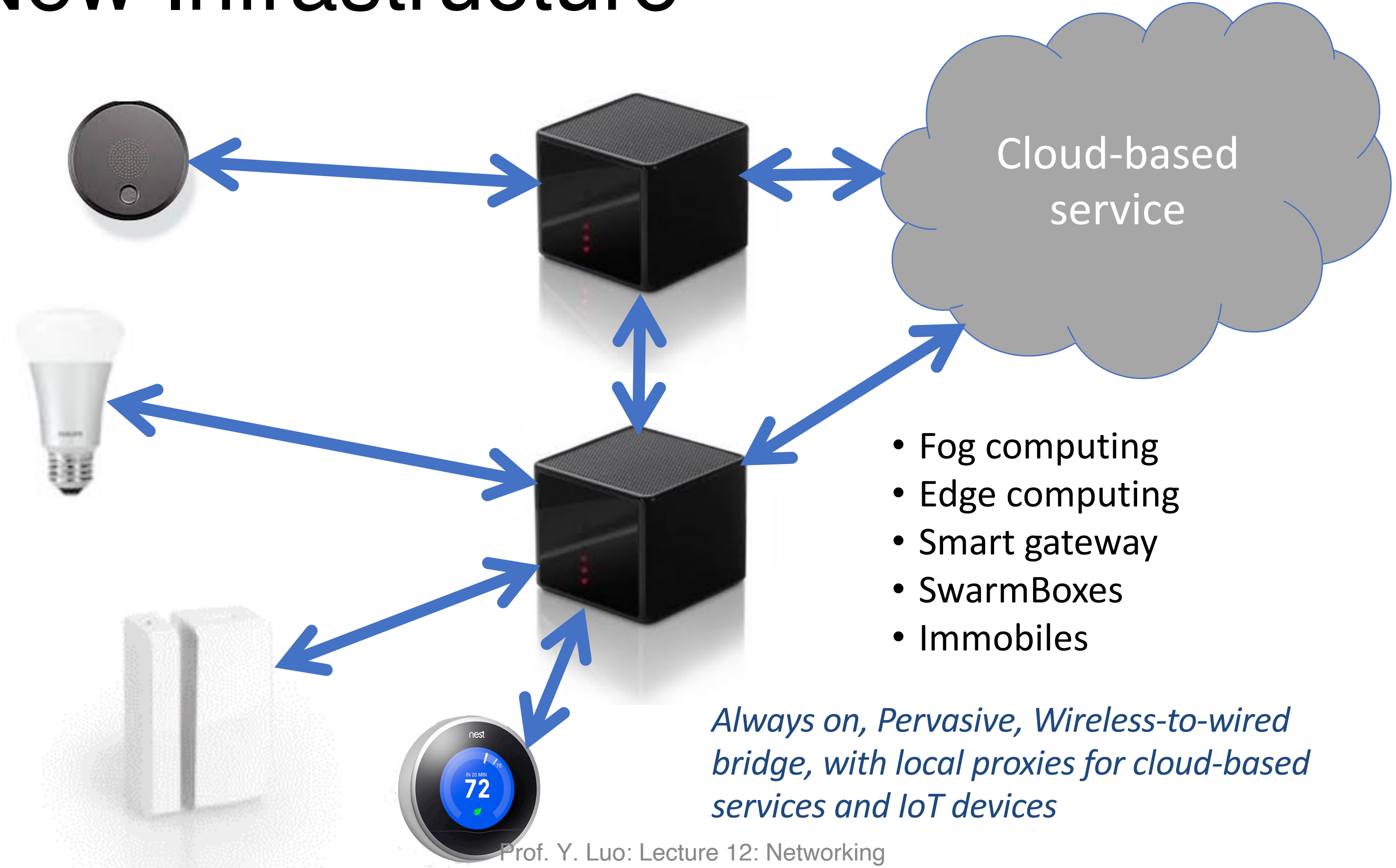
Challenges

- Smartphone apps proliferate, increasing user complexity.
- Vendor-specific gateways don't scale well to many vendors.
- Latency of cloud-based services can be substantial.
- Composition of services can only be done in the cloud (e.g. using IFTTT), increasing latency.
- Many moving parts makes systems less reliable, and tracking the source of problems can be hard.

A New Infrastructure



- Fog computing
- Edge computing
- Smart gateway
- SwarmBoxes
- Immobiles

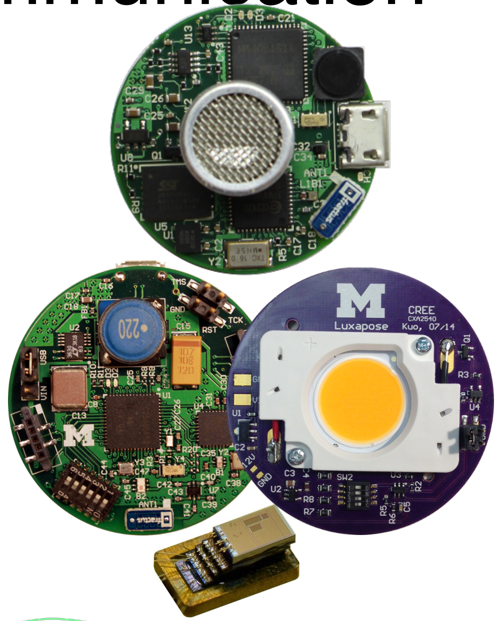
Always on, Pervasive, Wireless-to-wired bridge, with local proxies for cloud-based services and IoT devices

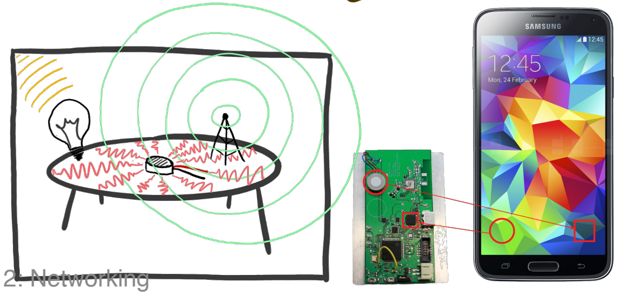
Emerging set of proximal communication interfaces

- 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 comms
  - Easy to modify existing LED lighting

- Vibration
  - Pervasive accelerometers
  - Pervasive vibration motors
  - Bootstrap desktop area context





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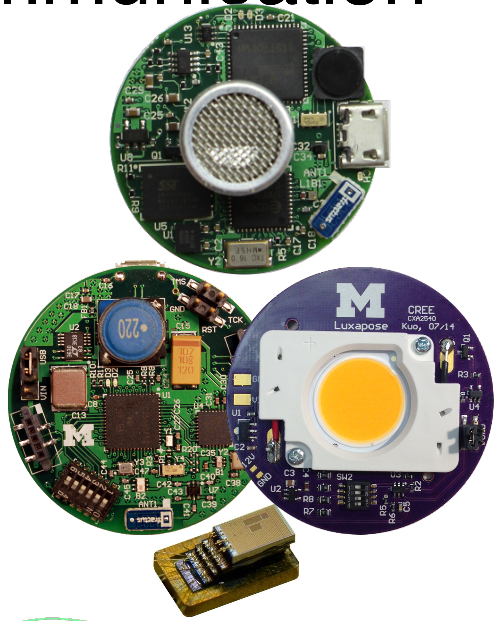

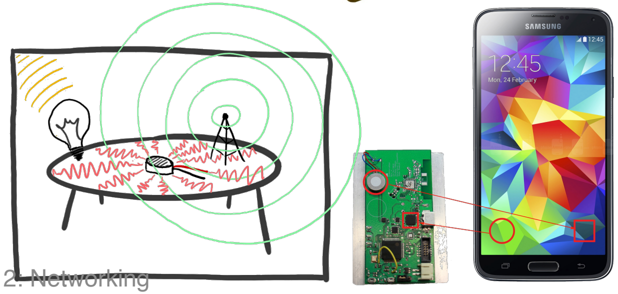

Slide courtesy of Prabal Dutta

Emerging Retail Environment

- Often have line-of-sight to lighting
  - Groceries
  - Drugstores
  - Megastores
  - Hardware stores
  - Enterprise settings
- Lots of overhead lighting in retail
- Retailers deploying LED lighting
- Customers using phones in stores
  - Surf, Scan, Share
- Customers installing retailer apps
  - Maps, Barcodes, Deals, Shopping

Slide courtesy of Prabal Dutta

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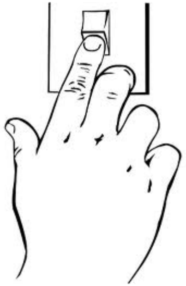
Going from milli-Hz to mega-Hz switching

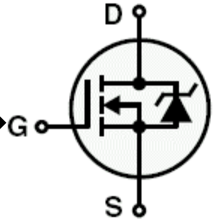
≠

~10^{-3} Hz



~10^{7} Hz

00010100 →



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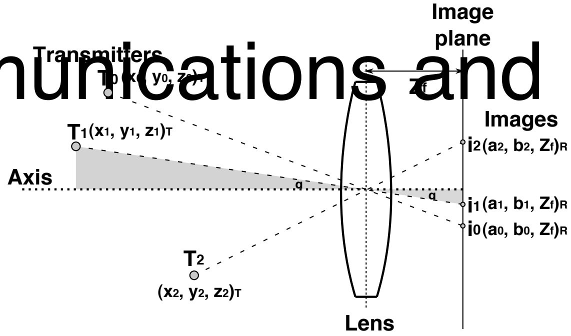
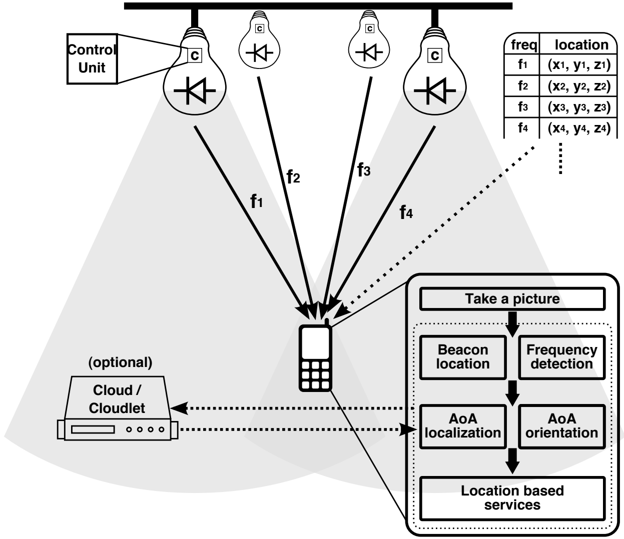
VLCP: visible light communications and positioning



- LED luminaires
  - Slightly-modified
  - Transmit beacons
  - Identities or coordinates



- Smart phones
  - Run background mobile app
  - Take images periodically
  - Perform local processing
  - Offload to cloud/cloudlet

- Cloud/cloudlet server
  - Do photogrammetry
  - Do AoA Localization
  - Estimate location
  - Estimate orientation
  - Provide location-based services

Ye-Sheng Kuo, Pat Pannuto, Ko-Jen Hsiao, and Prabal Dutta, "Luxapose: Indoor Positioning with Mobile Phones and Visible Light," In Proceedings of the 20th Annual International Conference on Mobile Computing and Networking (MobiCom'14), Maui, HI, Sep. 7-11, 2014.

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Indoor localiza

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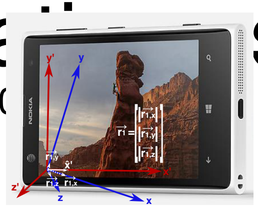
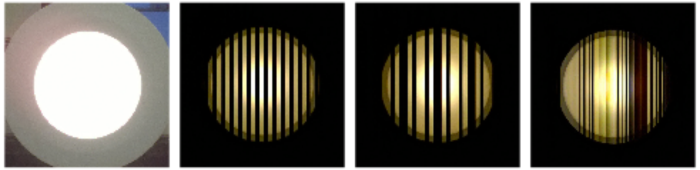
LED Luminaire

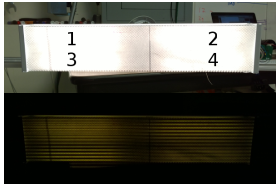


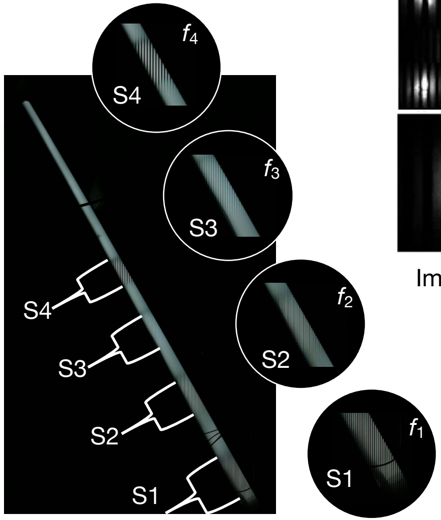
Smart Phone



Illuminate | Idle | TX <66> | TX packet

Captured using a rolling shutter





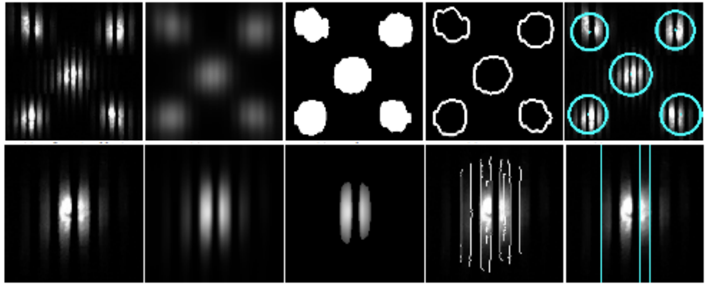


Image processing extracts beacon locations and frequencies

$$
\begin{aligned}
d_{0,1}^2 &= (u_0-u_1)^2+(v_0-v_1)^2+(w_0-w_1)^2 \\
&= (K_0a_0-K_1a_1)^2+(K_0b_0-K_1b_1)^2+Z_f^2(K_0-K_1)^2 \\
&= K_0^2\left|\overrightarrow{Oi_0}\right|^2+K_1^2\left|\overrightarrow{Oi_1}\right|^2-2K_0K_1(\overrightarrow{Oi_0}\cdot\overrightarrow{Oi_1}) \\
&= (x_0-x_1)^2+(y_0-y_1)^2+(z_0-z_1)^2,
\end{aligned}
$$

Compute

$$
\sum_{m=1}^{N}\{(T_x-x_m)^2+(T_y-y_m)^2+(T_z-z_m)^2-K_m^2(a_m^2+b_m^2+Z_f^2)\}^2
$$

Minimiz
e

Ye-Sheng Kuo, Pat Pannuto, Ko-Jen Hsiao, and Prabal Dutta, "Luxapose: Indoor Positioning with Mobile Phones and Visible Light," In Proceedings of the 20th Annual International Conference on Mobile Computing and Networking (MobiCom'14), Maui, HI, Sep. 7-11, 2014.

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Bigger picture: Software-Defined Lighting

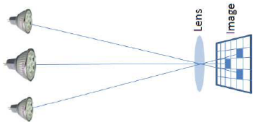
Illumination

Entertainment

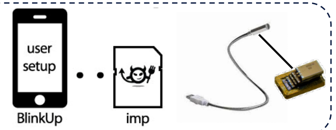
Communications

01100101000

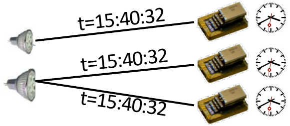
Indoor Positioning



Device Configuration



Clock Synchronization



Slide courtesy of Prabal Dutta

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
- VLCP
- WAN
- WLAN
- WPAN

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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.

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