IoT Fundamentals & Applications

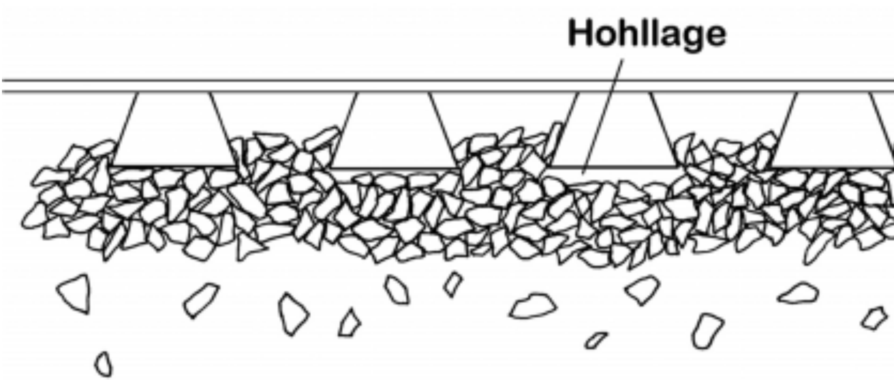
Gökçe Aydos, 2019, content influenced by Cisco IoT fundamentals course

Intro and Examples

Example - Tesla Model S

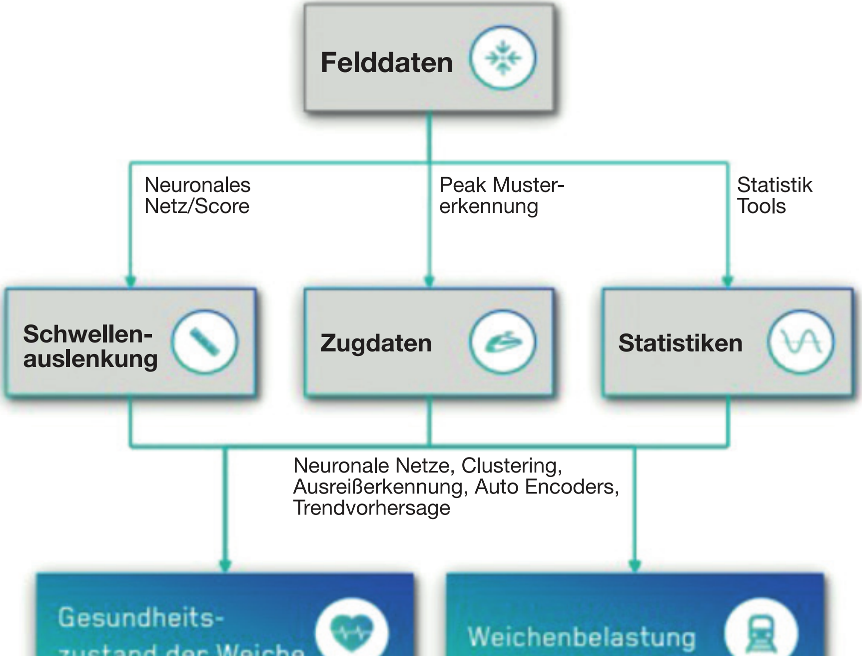
- *computer on wheels*
- sensors like camera, radar, ultrasonic proximity sensors
- operational info like energy use, position of wheels, brakes, door handles, speed
- persistent internet connection, 4G, Wi-Fi
- over-the-air update support
  - the manufacturer can avoid costly recalls
- the car has an API

Example - Rail Maintenance



Example - Rail Maintenance II

Example - Rail Maintenance III



Example - Cattle Tracking System

- tail and neck attached device Moocall from Ireland
- calving sensor
  - measures tail movement patterns and labor contractions (Geburtswehen)
  - 4G connection
- heat sensor
  - measures if the cows are in heat

IoT Origins - History

- until 1980s - *large mainframe computers*
- miniaturization => *personal computers (PC)*
- computers interacting with physical environment => *embedded systems*
  - more emphasis on physical interaction => *cyber-physical system*
- interconnected and collaborating embedded systems => *Internet of Things (IoT)*

What is IoT

Fundamental components:

- *things*, at least *sensors*
- *data*
- *internet* (not necessarily worldwide web, but represents interconnection of devices)
- collect *data* and manipulate *things* over the *internet*
- integration between the physical world and computer-based systems => leads to efficiency, accuracy, economic benefit

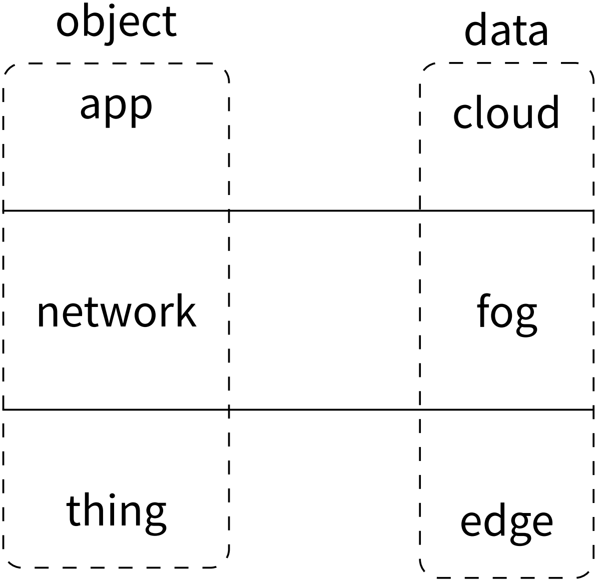
IoT Vision

- today's internet is more **internet of people** mainly connecting applications that are used by people (vs connecting things with things)
- *people take actions* based on *notifications from connected applications*
- IoT emphasizes *things* <-> *things* (but not people)
- IoT refers to anything connected over the Internet

IoT Use Cases

- connected building & facility management
- Industry 4.0
- remote industries (e.g., oil & gas)
- logistics & tracking
- smart agriculture
- smart metering
- smart lighting
- smart parking
- traffic & waste management

IoT Simplified Model

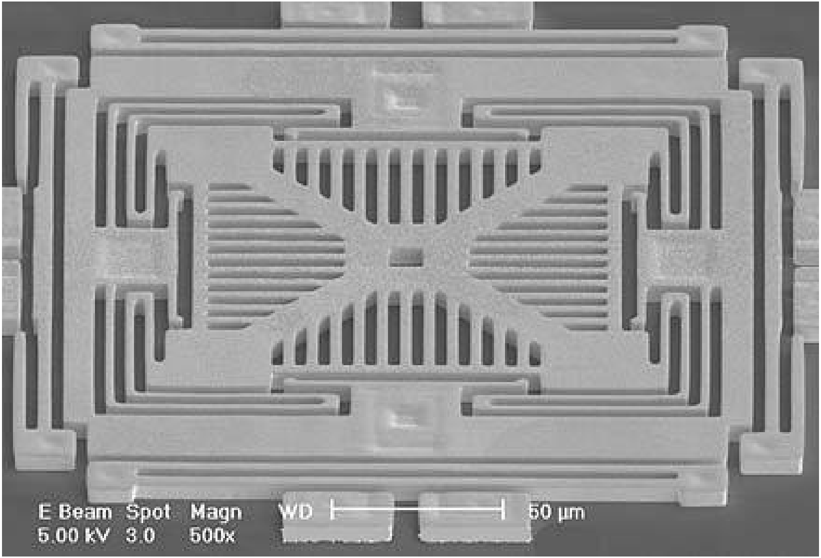


Core Elements

Sensors

- sensors
  - sense something..., e.g., magnetic field, your mood
  - analyzing vs sensing
  - *physical quantities => digital representation*

Accelerometer



Actuators

- relais
- valve
- motors
- robots

IoT Connectivity

- things generate data
- connectivity is obvious
  - 2G/3G/4G
  - ZigBee
  - WiFi etc
- data get processed in the cloud
- cloud controls the things (environment)

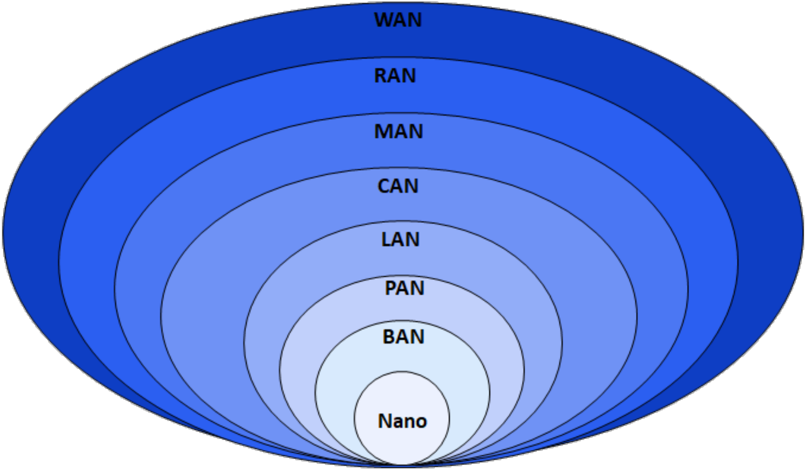
Wireless Communication - Concerns

- does the device have power constraints?
  - => *low power network*
- do we have hundreds of devices?
  - => *wireless network*
- do we have real-time requirements?
  - => *time-sensitive network*
- do we have to cover a large area?
  - => *mesh & long-range wireless network*

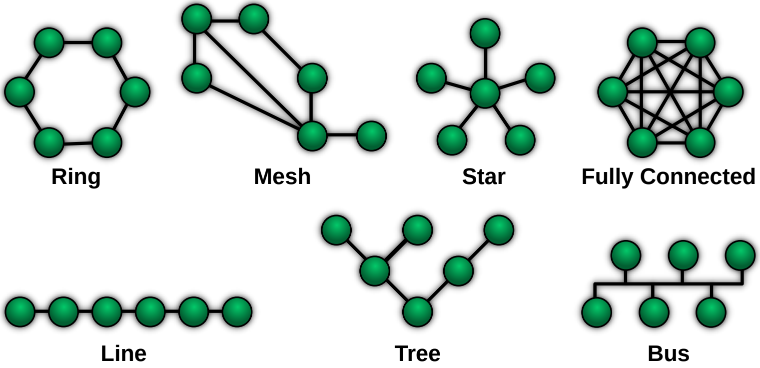
Wireless Communication Protocols

- short range
  - Bluetooth
- medium range
  - Wi-Fi bgn, ac, ah
  - ZigBee
- long range
  - 2/3/4/5G

Data Network Types - Spatial Classification



Data Network Types - Topologies



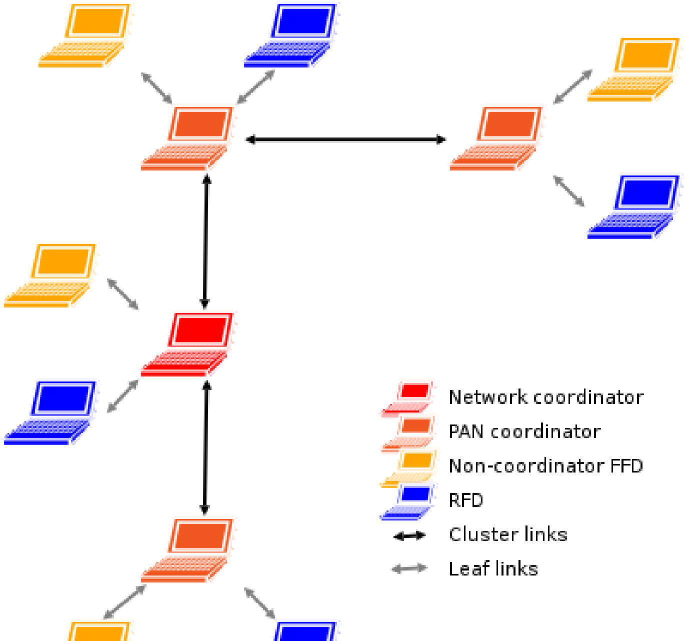
Mesh Network Example - Freifunk

- Freifunk Berlin community
- Freifunk Rhein-Neckar community

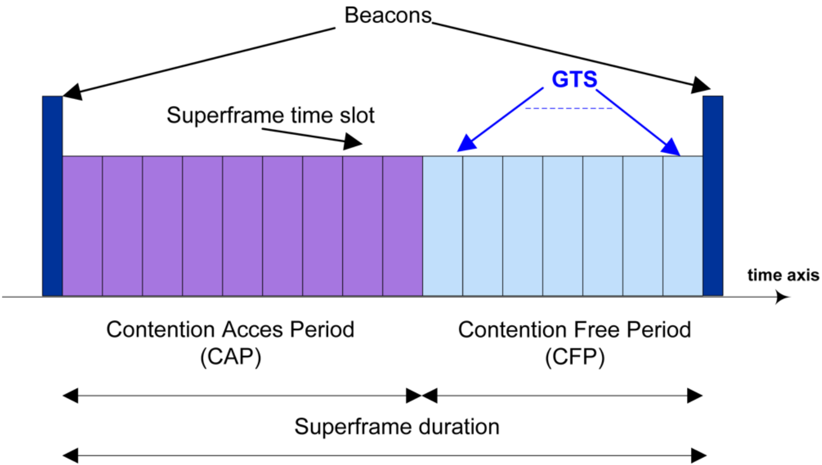
Connectivity using IEEE 802.15.4

- low rate wireless personal area network, upto ~10m range
- for factory and building automation
- IoT-friendly features
  - low data rate
  - scalable, new devices are easily integrated
  - low power and low cost operation
  - scheduled media access

802.15.4 Example Topology



IEEE 802.15.4 Determinism



IEEE 802.15.4 Use Cases

- e.g., utility metering, charging infrastructure, outdoor lighting, transformer monitoring
- WirelessHART, ISA 100.11a, Wi-SUN, Zigbee
- ZigBee
  - emerged from house to industry automation => many domains
  - from industrial sensors to PC peripherals like keyboard

ZigBee Compatibility

IPv6

- IPv4
  - 2^{32} addresses
  - ~4 billion
- IPv6
  - 2^{128} addresses ~= 10^{38}
- *we can give about 7 IPv6 addresses to each atom of every human*
- source

Apps (in the Cloud)

- software as a service (SaaS)
  - e.g., Gmail, Apple iCloud
- platform as as service (PaaS)
  - enables convenient app deployment for developers
  - e.g., Cloudfoundry, Google IoT, Siemens Insights Hub
- infrastructure as a service
  - processing capacity for rent
  - e.g., Amazon Web Services (AWS), Azure

IoT Security

- more connected devices $=>$ more hacking opportunities
  - IoT search engine

Security Incidents on Industrial Systems

- Stuxnet - 2012
  - infected motor controllers of nuclear centrifuges in Iran through USB sticks
  - spread to other plants in other countries without significant impact
- Ukraine power grid attack - 2015
  - taking network under control, switching 30 substations off
  - 230k people without electricity for hours

Making Use of Data

Analytics

- interconnection of things is *not the only goal*
  - it is about *data analytics*
- data analytics and big data allow:
  - automation for faster results
  - detection of hidden patterns
  - data driven decisions

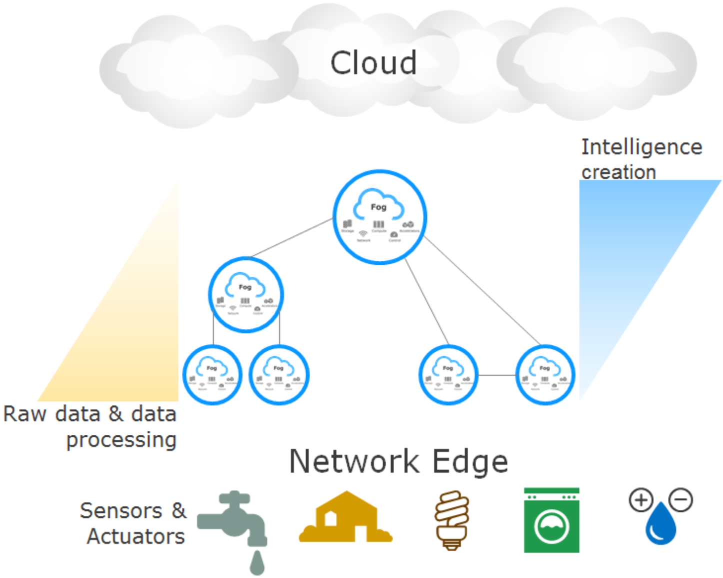
Unstructured vs Structured Data

- structured
  - relational databases, e.g., Oracle, SQL
  - data is already categorized in tables
- unstructured
  - the relationship between data is not well understood
  - e.g., text files, images, audio, social media
- most of the data available is unstructured
- Berners-Lee dream about semantic web unrealized

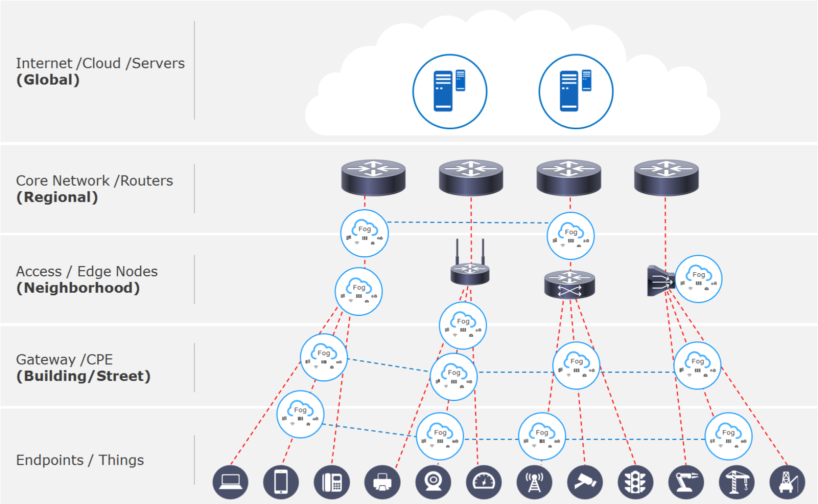
Data Analytics Types

- *descriptive* - what is happening?
- *diagnostic* - why did it happen?
- *predictive* - what is likely to happen?
- *prescriptive* - what should I do about it?

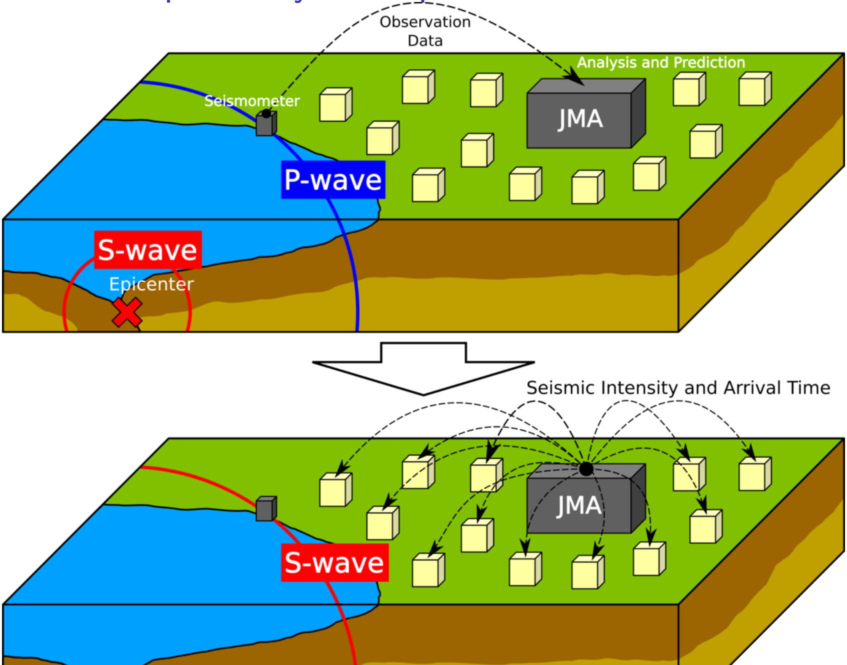
Fog and Edge Computing



Fog and Edge Computing II



Use Case - Japan Early Earthquake Detection



Summary

Appendix

Utilities and Smart Grid

- Edison in a power station vs Bell uses a smartphone
  - high potential for digital disruption
- power generation & consumption must be kept in balance
- utilities generate big data, there is need for data analytics
- interconnection between smart meters & distribution elements => automation
- distributed SCADA systems are being networked
- distributed energy generation through renewables

Mobility

- *self-driving car* vs *connected car*
- sensors in a car
  - tire pressure, oil levels, temperature
  - allow predictive maintenance
  - fleet management for car sharing companies
- software updates according to country
- V2X - vehicle to *anything* communication
  - V2V - vehicle to vehicle
  - V2I - vehicle to infrastructure
    - better bridge inspection through mobile sensors

Manufacturing

- more business value through data analytics
- more insights through material tracking
- from proprietary to Ethernet-based networks
    - eases data aggregation

Smart Cities

- energy efficiency through smart buildings
- safety and real-time billing through gas monitoring
- real-time visibility and billing through smart parking
    - 30% of car driving time spent for parking search
- water pipe leakage detection
- automatic payment for dense and congested roads

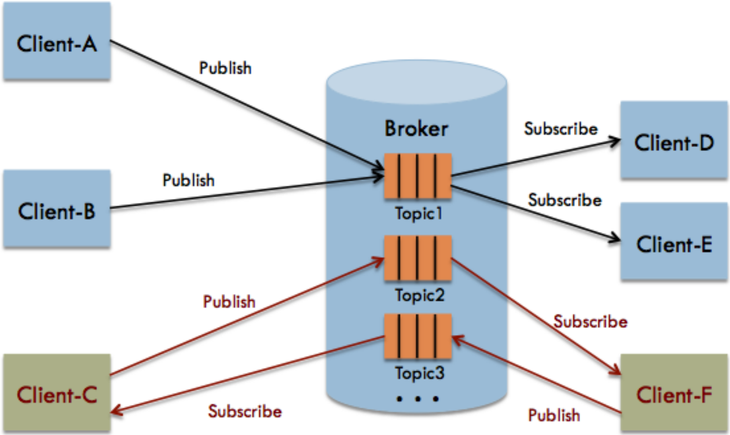
Construction

- distributed sensors for safety and monitoring
  - temperature, humidity for construction quality
  - temperature for worker's health
- speech analysis for mood and automated daily reports
- camera image analysis for billing and safety
  - example: automated truck detection

Message Queue Telemetry Transport (MQTT)

- based on TCP and HTTP
- sensor publishes info as an address
- compared to CoAP
  - distribution to many subscribersption
- but TCP limits the sleep time
  - MQTT-S => MQTT over UDP

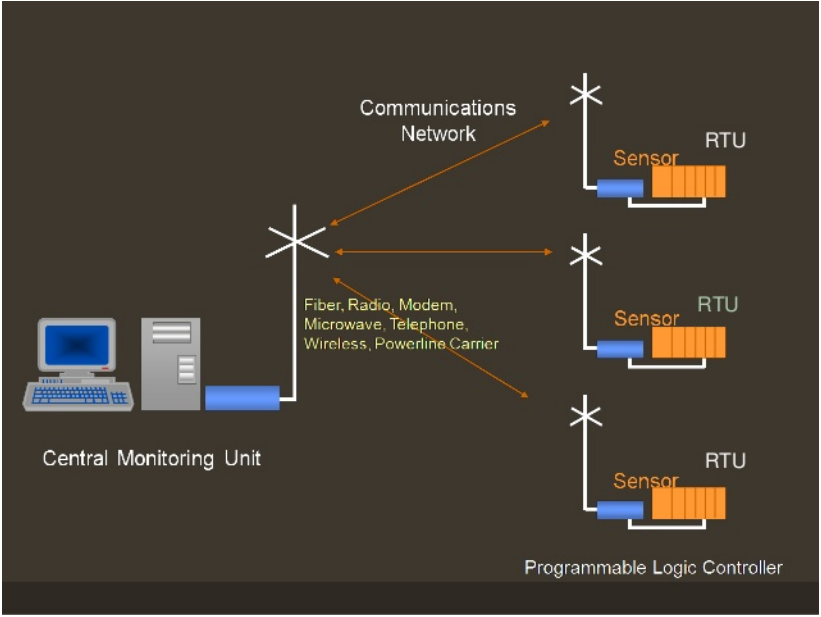
MQTT Example



Supervisory Control and Acq. of Data (SCADA)

- exists since 1960s
- direct connection to industrial utilities for control
  - remote terminal unit (RTU) for A/D conversion
- initially used serial protocols like RS-232 or RS-485
- nowadays IP is used
- common protocols
  - Modbus
  - DNP3 (USA)
  - IEC 60870-5-101

SCADA Overview



TCP vs UDP

- *Transmission Control Protocol* vs *User Datagram Protocol*
- TCP is connection-oriented
  - 3 packets required at the beginning
  - retransmission in case of lost packets
  - ordering of packets ensured
- UDP does not care about if sent packets arrived
- UDP is fast when the round-time is high

Number of Connected Devices Forecast

2019 world population $\sim$ 7.7 billion .. image:: visuals/2019-iot-count-forecast.png

Examples

- smart home
  - Alexa
  - Nest
- smart wear
  - smart t-shirt

Stages of Industrial Revolutions

1. *mechanical assistance*
    - 18th to 19th centuries
    - agrarian, rural societies => industrial, urban
    - water wheel, steam engine
2. *mass production*
    - 1870 to 1914
    - growth especially in steel, oil, electricity industry. use of electricity for mass production
    - telephone, light bulb, phonograph, internal combustion engine
3. *digital revolution through electronics & control*
    - started 1980
    - analog electronic and mechanical systems => digital
    - personal computer (PC), Internet, information and communications tech. (ICT)
    - potential fundamental change through

IoT overview

Personal level: - Outlook: *all the things in our environment are connected to the Internet, and seamlessly communicate with each other for a collective intelligence* - Goal: *enable objects around us to efficiently sense our surroundings, communicate, create a better environment: objects act based on what we need and like without explicit instructions* - e.g., advanced health monitoring, enhanced learning, improved security

Business level: - automatic sensing and prompt analysis of product- or service-related parameters + taking action before a service experience or product operation is impacted. - collecting and analyzing massive amounts of structured and unstructured data, e.g., social media, to offer better services or products. - e.g., new business models (Mindsphere by Siemens,

Just consider the impact the Internet has had!

WILL IoT create the largest technology opportunity?

History of the term IoT

- 1999 - first coined by Kevin Ashton in a talk at Procter & Gamble. RFID + Internet
- 2001 - MIT Auto-ID center presents their IoT vision
- 2005 - ITU formally introduces the term in their *Internet Report*

IoT from Engineer Perspective

- How do I monitor and control things from anywhere in the world?
- Why?
- Who?
- Security?

How?

- communication ability
  - Wi-Fi
  - mobile
- unique identity
  - IP address
  - physically unclonable function (PUF)
- sensing ability
  - sensors

Why?

- giving control to remote experts
  - monitoring patient's temperature or blood pressure by the doctor
- learning about and interacting with things
  - pointing a smartphone to a thing of interest to *ask questions*
  - *where are my keys*
- managing remote infrastructure
  - smart cities
- entertainment and games
  - Pokèmon Go

Who?

- person
  - homeowner remotely checks if oven is turned on
- machine
  - home automation software turns off the light after 22:00 using WebThings API

IoT Reference Framework

- devices
- network
- services platform
- applications
  - business logic like accounting and billing, business intelligence
- TODO: visual

IoT Reference Framework - Advantages

- reduced complexity, simplified education
  - a sensor manufacturer does not have to understand how the sensor data is sent to a server
- standardized components and interfaces
  - engineers can communicate in a more convenient way
- interoperability, module engineering
  - a software engineer writes an IoT application which can be used by many customers
- innovation acceleration
  - a developer can just concentrate on his business application without having to set up the IoT network

Why is IoT Important Now?

- convergence of IT and OT
- rise of internet-based businesses
- mobile device explosion
- social network explosion
- analytics at the edge

Convergence of IT and OT

- information technology (IT)
  - information systems focusing on computing, data storage, networking
  - e.g., organizing employees' payments, VoIP communication
- operation technology
  - automation equipment with sensors and actuators for industrial needs
  - e.g., sorting of parcels in Amazon, city water filtration system
- IoT leads to the merger of IT and OT
  - IT professionals must pay attention to the OT requirements
  - e.g., mission-critical infrastructure, slow adoption of new software updates in OT

Rise of Internet-based Businesses - Uber

- internet-based platform connecting passengers with car drivers
- smartphone's accelerometer and GPS allows tracking of driver's behavior

Rise of Internet-based Businesses - Square

- convenient payment services for business owners utilizing smartphones or tablets
- leverages smartphone's motion sensor to detect if the credit card is failing

Analytics Moving to the Edge

- Motivation: in some mission-critical applications doing analytics in the data center is no longer viable.
  - e.g., a traffic camera differentiating between pedestrians and vehicles
- Analytics 1.0
  - structured data (data that can fit in rows and columns, e.g., customer data)
  - processed centrally, e.g., data center
- Analytics 2.0
  - structured + unstructured data (difficult to organize, e.g., images, call center logs)
- Analytics 3.0
  - can also be processed at the edge
  - possible real-time requirements

Rise of Cloud Computing

- on-demand computing, pay what you use
- Amazon AWS, Microsoft Azure, Google Compute Engine, Alibaba Cloud
- *public*, *private*, *hybrid* cloud
- *infrastructure as a service*, *platform as a service*, *software as a service*
- advent of *virtualization*
  - e.g., Docker, Linux containers

Rise of Easily Accessible IoT Platforms

- as personal computers become cheaper, more people could tinker with software
- the same happend with hardware and IoT platforms
  - e.g., Raspberry Pi, Arduino
- common hardware available, but *Android* like IoT OS needed to avoid fragmentation

Digital Transformation

- started with *move to paperless operation*
  - e.g., Docusign
- digitalization enables data analysis
- introduction of *chief digitalization officer* in traditional companies

Rise of Enhanced User Interfaces

- user experience (UX), user interface (UI)
- best UX is a system without UI
- voice interfaces like Alexa, Siri

Number of IoT Devices

- Gartner - market analysis company
- 21 billion devices in 2020

Interesting IoT Ideas

- Refrigerdating

The Quantified Self

- incorporating technology into data acquisition on aspects of a person's daily life
  - e.g, food consumed, quality of surrounding air

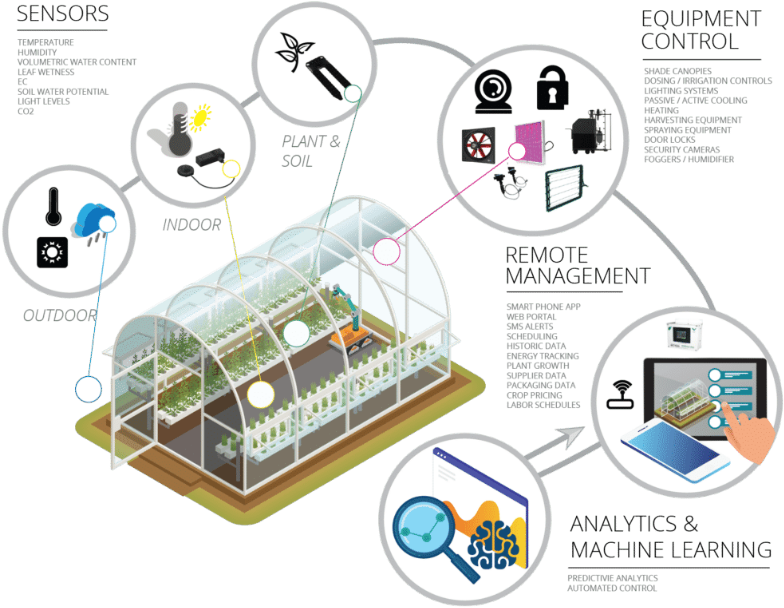
Cattle Tracking System - Ida

- collar worn tracking device ida from Amsterdam
- sensor
  - battery life 3-5 years
  - narrow band RFID
  - can sense eating, ruminating, chewing, walking ...
  - range $>$1km
- cloud cattle analytics as a service
  - e.g., cow is very active
  - $2.5 per cow

Cattle Tracking System - Quantified AG

- ear tag from Quantified AG (US)
- sensor
  - temperature
  - accelerometer
- analytics in the cloud

Smart Greenhouse Monitoring



Greenhouse Monitoring - Smartbeecontrollers

- indoor grow rooms monitoring from Smartbeecontrollers

Greenhouse Monitoring - Smartbeecontrollers II

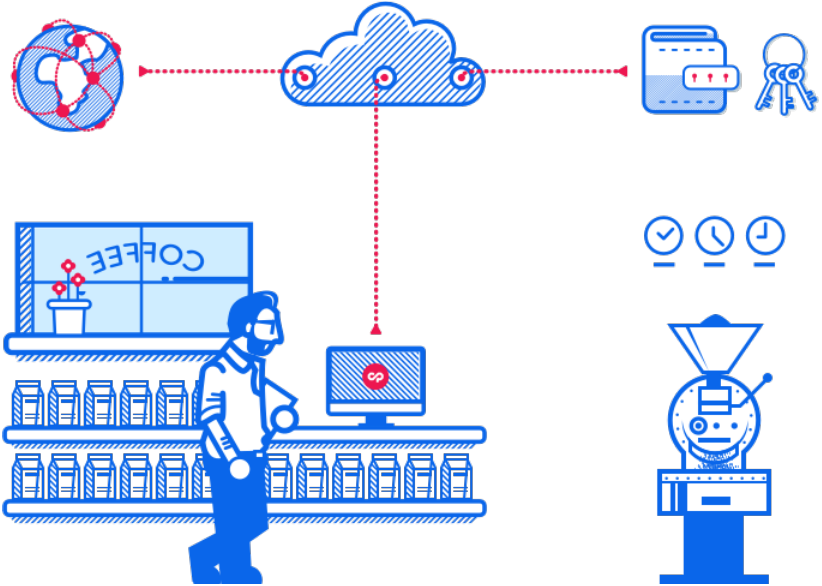
- sensor
  - Zigbee wireless mesh networking
  - temperature, humidity, CO_2, light
  - solar panels

Outlook - Distributed Autonomous Corporations

Outlook - Device Democracy

- winners in the IoT economy will enable decentralized peer-to-peer systems that allow for very low cost, privacy and long term sustainability in exchange for less direct control of data
- a transaction system requires:
  - communication
  - data storage
  - role and permission arbitration
- a decentralized IoT solution should support:
  - trustless peer-to-peer communication
  - distributed data sharing
  - scalable device coordination
- Source: IBM Institute for Business Value, 2014

Decentralized Data Storage - Blockchain



- altcoins, sidechains

Decentralized Data Storage - IPFS

- interplanetary file system (IPFS) aims to replace HTTP
- *content-addresable* and *peer-to-peer* data storage

Outlook - Incentivize IoT devices through Federated Learning

- With OpenMined, an AI model can be governed by multiple owners and trained securely on an unseen, distributed dataset

Smart Objects

- smart sensors
- smart devices
- IoT devices
- intelligent devices
- things
- smart things
- intelligent nodes
- intelligent things
- intelligent products
- ubiquitous things
- mote => a sensor in a sensor network

SANET

- sensor and actuator network
- often small networks, simple deployment, cheap
- e.g., smart homes
- can be wired or wireless

WSN

- wireless sensor network
- purely wireless
- limited power, processing power, memory
- limitation can be relieved by redundancy

Data Rate vs Throughput

- TODO better look at the Wikipedia
  - wikipedia does mention throughput and goodput. is there a difference between throughput and data rate?
- modulation & bandwidth => *data rate*
- *throughput (goodput)* « *data rate*
  - throughput => bits that pass the link per second
  - goodput is the *useful* data only, excludes retransmissions

OSI Layers

- host layers
  - *application* high-level API
  - *presentation* translation of data between network service and application e.g., character encoding
  - *session* session management, continous exchange of info between two nodes
  - *transport* reliable transmission of data segments between points on a network, e.g., acknowledgment
- media layers
  - *network* structuring a multi-node network, e.g., addressing, routing
  - *data link* reliable transmission of data frames between two nodes connected by a physical layer
  - *physical* transmission of raw bit streams over a physical medium

Internet Protocol Suite Layers

- application layer
  - e.g., DHCP, DNS, FTP, HTTP
- transport layer
  - e.g., TCP, UDP
- internet layer (internetworking between independent networks)
  - IP, ICMP, IPSec
- link layer
  - ARP, PPP, MAC

Signal to Noise Ratio (SNR)

- 10*log10(P1/Pbase) => for power comparison
- 20*log10(A1/Abase) => for amptlitude comparison
- dBm => compared to 1 mW => 10*log10(P/1mW)
- SNR can be negative => more noise than signal
  - how do we extract then the desired signal?
  - but spread spectrum schemes spread the signal in frequency. When the signal is spread, power spectral density of the signal goes under the noise power level. Now the signal is hidden under the noise, the same spreading codes can be used to despread the signal at the receptor end.

IEEE 802.11ah

- sub-1 GHz
- extended range upto 1km
- minimizes contention
- little power
- thousands of devices

Functional vs Non-functional Requirements

- **what** vs **how** should the system do?
- **specific behavior** vs **judging the operation of a system**
- **system design** vs **system architecture**
- examples:
  - a system must send an email whenever a certain condition is met (functional)
  - emails should be sent with a latency of no greatre than 12 hours (non-functional)

Example - Smart Jacket

- Jacquard from Google

Wireless Communication - Waves

- frequency affects your communication
- lower frequency => longer wavelength
- lower frequency => larger antenna (for efficient communication)
- larger antenna => longer range at same power
  - Wi-Fi 2.4 vs 5 GHz
- larger antenna => larger reception area => larger energy collection
- more power => larger reception area => less wireless devices
- frequency preference depends on the regulations

IPv6 - Other IoT-related Features

- stateless address autoconfiguration (SLAAC)

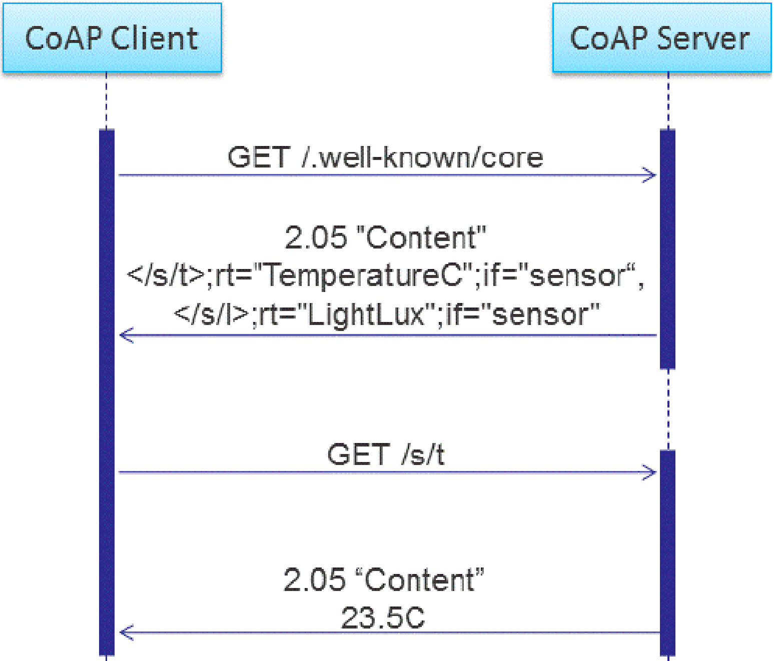
IoT Management Protocols

- how do I manage thousands of sensors
  - configuration
  - software update
  - need for a *data concentrator* which standardizes different data encodings
- what about HTTP?
  - header too big
  - many unneded methods for IoT

Constrained Application Protocol (CoAP)

- lightweight HTTP
- UDP based
  - confirmable vs unconfirmable messages
- $<$10 bytes header
- implements just *GET*, *POST*, *PUT*, *DELETE*
- publish/subscribe model *OBSERVE*
- resource discovery

CoAP Example - Request & Response



CoAP Example - Observation

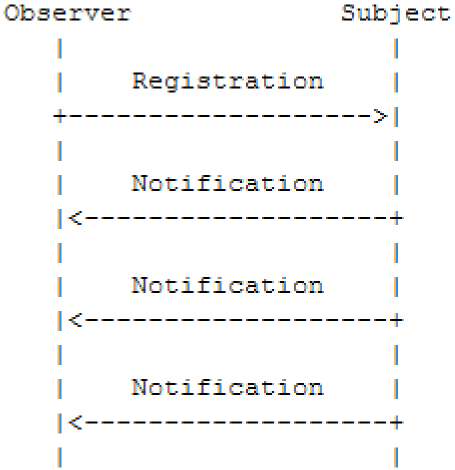
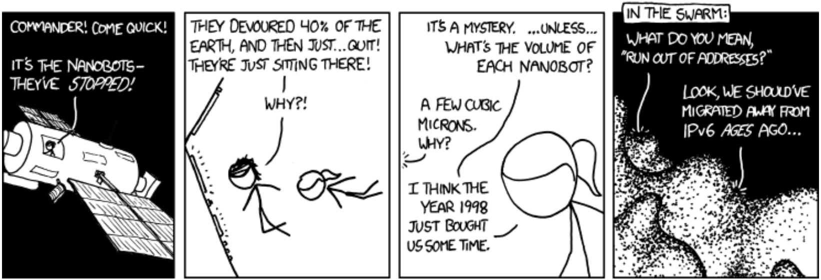


Figure 1: The Observer Design Pattern

IPv6 - Limited for a Reason?

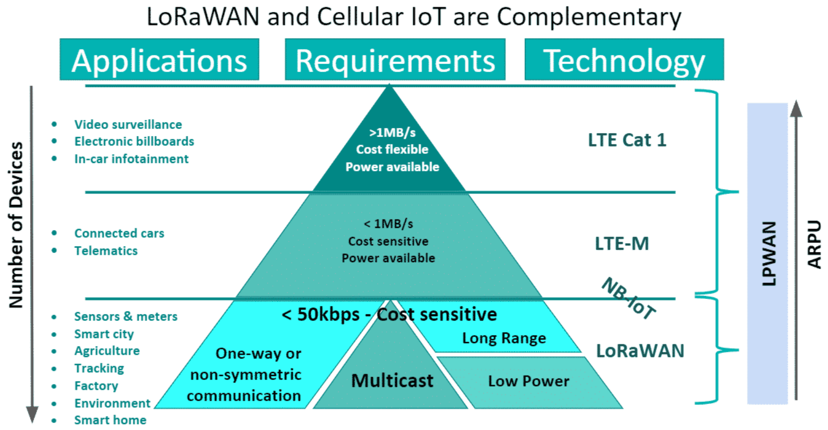


- volume of earth: 10^12 km^3 = 10^39 m^3
- volume of a nanobot: 1 m^3
- explanation

6LoWPAN

- IPv6 over low-power wireless personal area networks
- IETF group working on solutions for integrating 802.15.4 devices into the internet
- 802.15.4 packet size vs IPv6 max. MTU
  - 127 vs at least 1280 bytes
- Led to the creation of 6Lo - *IPv6 over Networks of Resource-constrained Nodes*

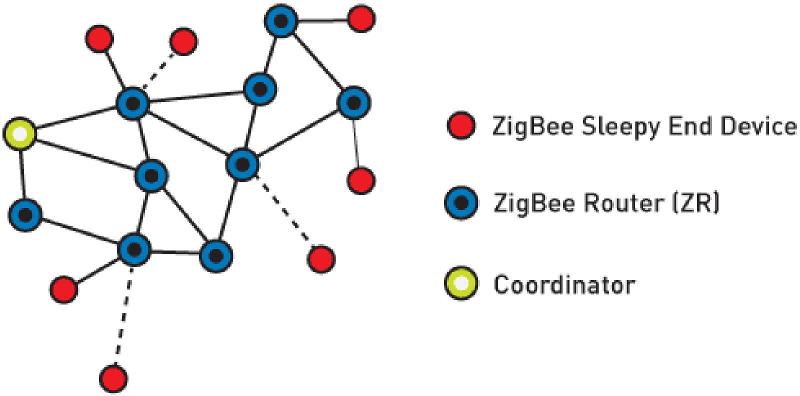
LoRaWAN & Cellular IoT are Complementary



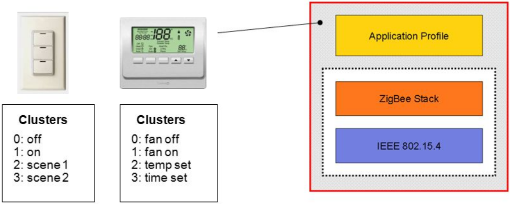
ZigBee

- ZigBee makes use of 802.15.4 PHY and MAC layers
- emerged from house to industry automation
- similar to 802.15.4 ZigBee supports *star*, *tree*, *mesh* networks
- three kinds of devices
  - *coordinator*
  - *router*
  - *end device*

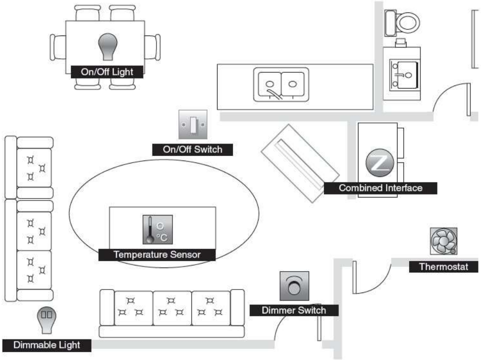
ZigBee Device Types



ZigBee Application Profile Example



ZigBee Home Automation Example



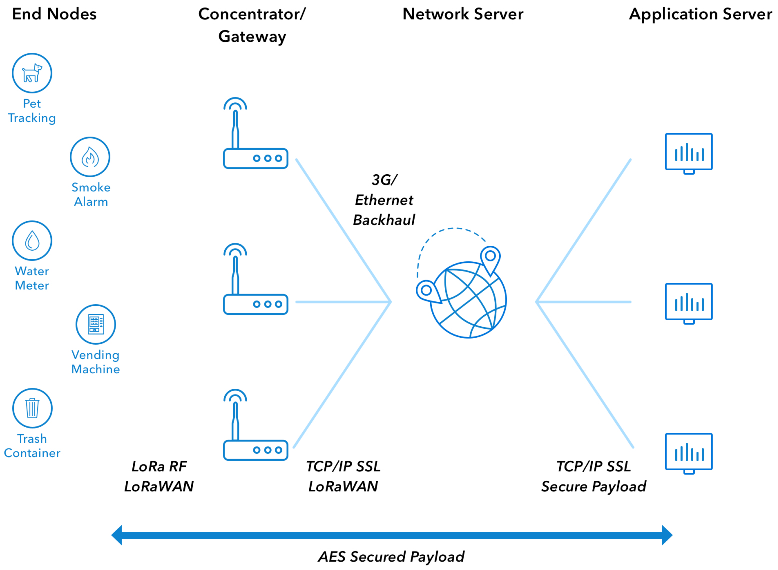
ZigBee Application Profiles

- Industrial Plan Monitoring
- Home Automation
- Commercial Building Automation
- Telecom Applications
- Personal Home & Hospital Care
- Advanced Metering Initiative

Low Power Wide Area Network (LPWAN)

- normal approach
  - sensors connect via medium range link (Wi-Fi, ZigBee) to a gateway
  - gateway connects via cellular backhaul to the cloud
- alternative
  - sensors connect to the backhaul directly
  - => example LoRaWAN

LoRaWAN - Overview



LoRaWAN - Features

- 1000s of devices
- communication over unlicensed 125 and 500 kHz channels
- range up to 15 km
- low data rates 300 bit/s to 5400 bit/s
- cost about 20 EUR per node, no operational costs
- no IP - devices and applications have a 64bit id
  - but IETF explores way to integrate IPv6

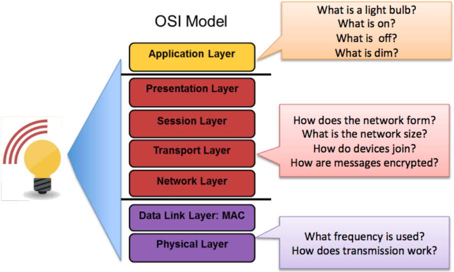
LoRaWAN - Anti-Features

- not for:
  - realtime data
  - phone calls
  - controlling lights
  - sending photos

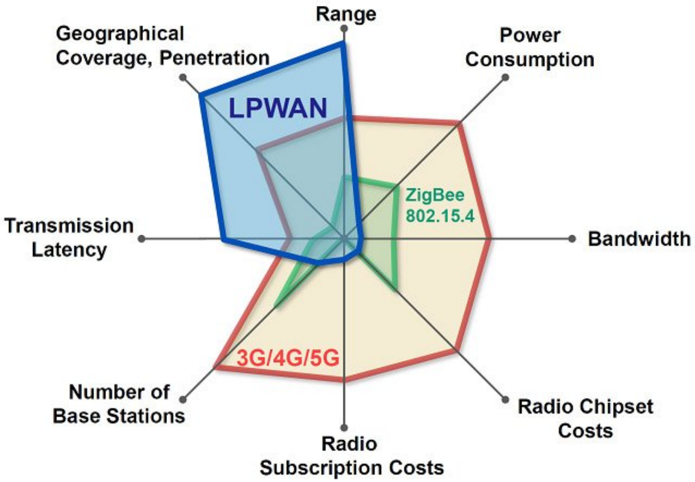
LPWAN Use Cases

- remote metering
  - connect gas, power, water meters via LoRa
- grid fault management
  - sensors over power lines
- asset tracking
  - track expensive utilities, e.g, cable reel

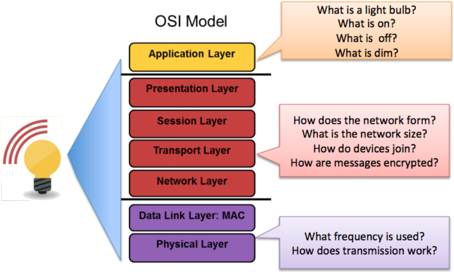
OSI Model with Regards to IoT



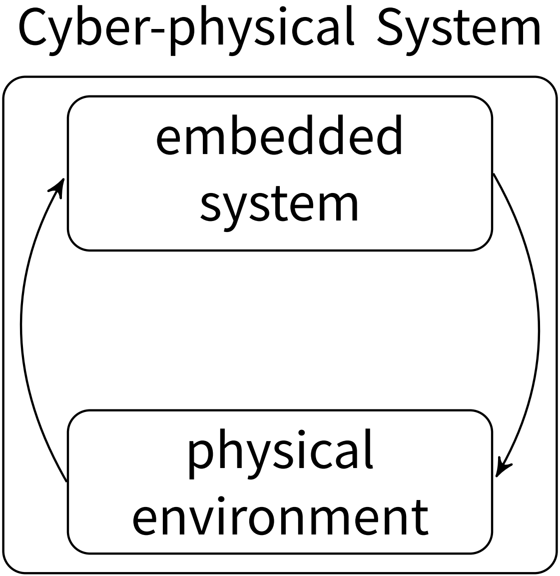
LPWAN vs Zigbee vs Cellular



OSI Model with Regards to IoT



Cyber-physical System



Cyber-physical System - Example