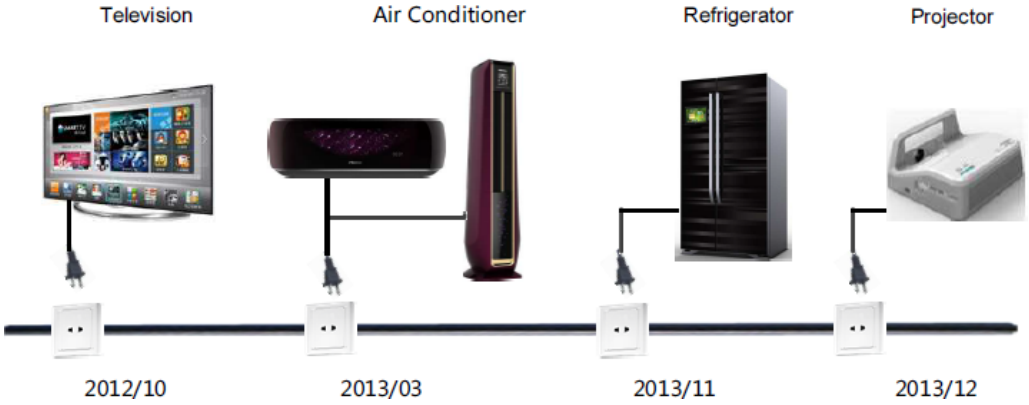
Introduction to Internet of Things



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These slides and audio/video recordings of this class lecture are at:
http://www.cse.wustl.edu/~jain/cse570-18/

Overview

1. What are Things?
2. What's Smart and Why IoT Now?
3. IoT Research Challenges including Datalink and Networking Issues
4. Recent Protocols for IoT
5. Fog Computing and Multi-Cloud Management

Note: This is part 1 of a series of class lectures on IoT. MQTT, 6LowPAN, and RPL are covered in other parts.

What are Things?

- Thing = Not a computer
- Phone, watches, thermostats, cars, Electric Meters, sensors, clothing, band-aids, TV,…
- Anything, Anywhere, Anytime, Anyway, Anyhow (5 A's)

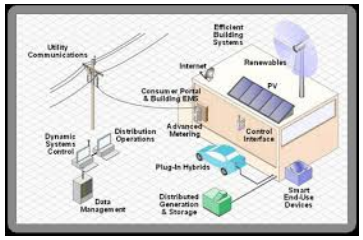
Ref: http://blog.smartthings.com/iot101/iot-adding-value-to-peoples-lives/

Internet of Things

- Less than 1% of things around us is connected.
  Refrigerator, car, washing machine, heater, a/c, garage door, should all be connected but are not.
- From 10 Billion today to 50 Billion in 2020
  Should include processes, data, things, and people.
- $14 Trillion over 10 years
  ⇒ Third in the list of top 10 strategic technologies by Gartner
  (After Mobile devices, Mobile Apps, but before Clouds, …)
- a.k.a. **Internet of Everything** by Cisco
  Smarter Planet by IBM

Ref: "Gartner Identifies Top 10 Strategic Technologies,"
http://www.cioinsight.com/it-news-trends/gartner-identifies-top-10-strategic-technologies.html
Ref: J. Bradley, "The Internet of Everything: Creating Better Experiences in Unimaginable Ways," Nov 21, 2013,
http://blogs.cisco.com/ioe/the-internet-of-everything-creating-better-experiences-in-unimaginable-ways/#more-131793

Sample IoT Applications



Smart Grid

Smart Health

Smart Home

Smart Cities

Smart Industries

Smart TV

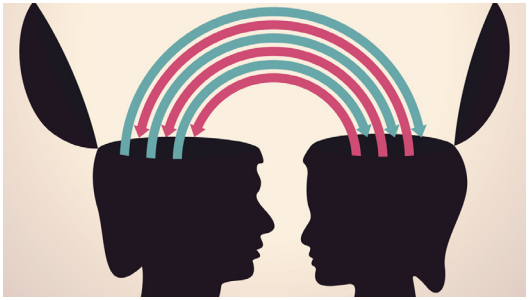
Smart Watch

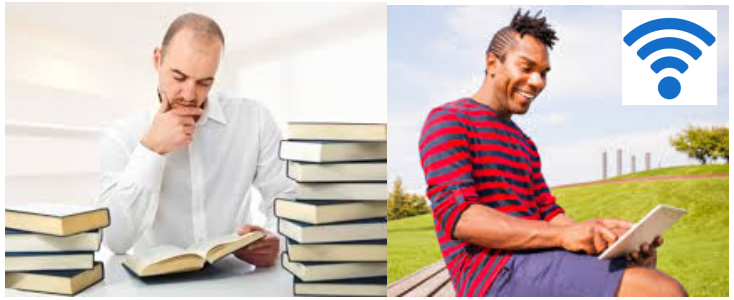
Smart Car

Smart Kegs

What's Smart?

- Old: Smart = Can think ⇒ Computation
  = Can Recall ⇒ Storage
- Now: Smart = Can find quickly, Can Delegate
  ⇒ Communicate = Networking
- Smart Grid, Smart Meters, Smart Cars, Smart homes, Smart Cities, Smart Factories, Smart Smoke Detectors, …





Not-Smart Smart

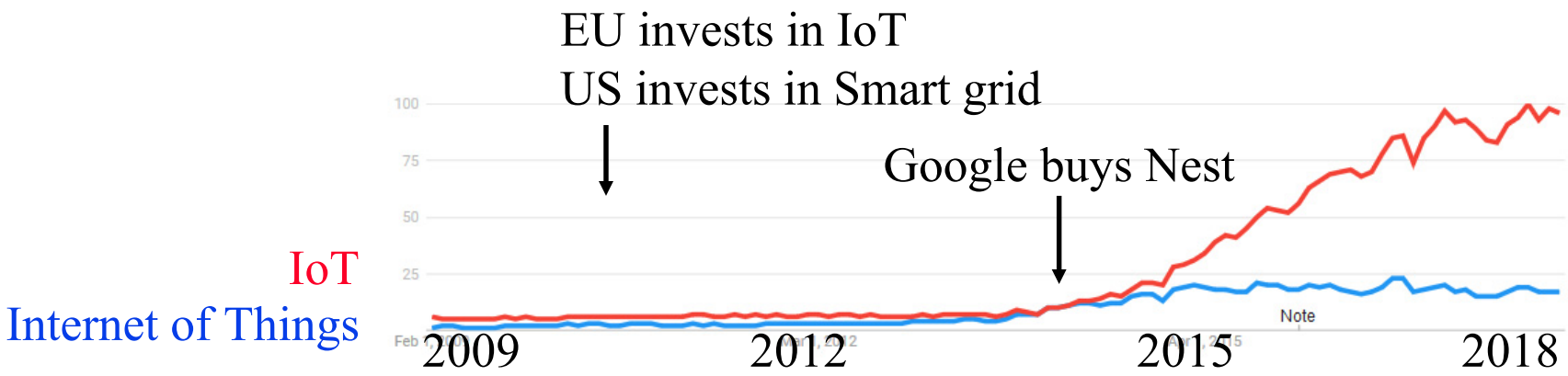
Why IoT Now?

- IoT = Sensing + Communication + Computation

1. Micro-Sensors: Temperature, Moisture, Pressure, air quality, …
2. Tags: Radio Frequency Id (RFID), Quick Response (QR) Codes, …
3. Energy Efficient Communication: Small or no batteries, Personal area communication (PAN), Bluetooth, ZigBee, …
4. Micro-Computing: Micro multi-core chips, Raspberry Pi, Intel Galileo, Arduino, …
5. Cloud Computing: Little or no local computing
6. Open/Small operating systems: Linux

Ref: CTIA, "Mobile Cyber security and the Internet of Things,"
http://www.ctia.org/docs/default-source/default-document-library/ctia-iot-white-paper.pdf

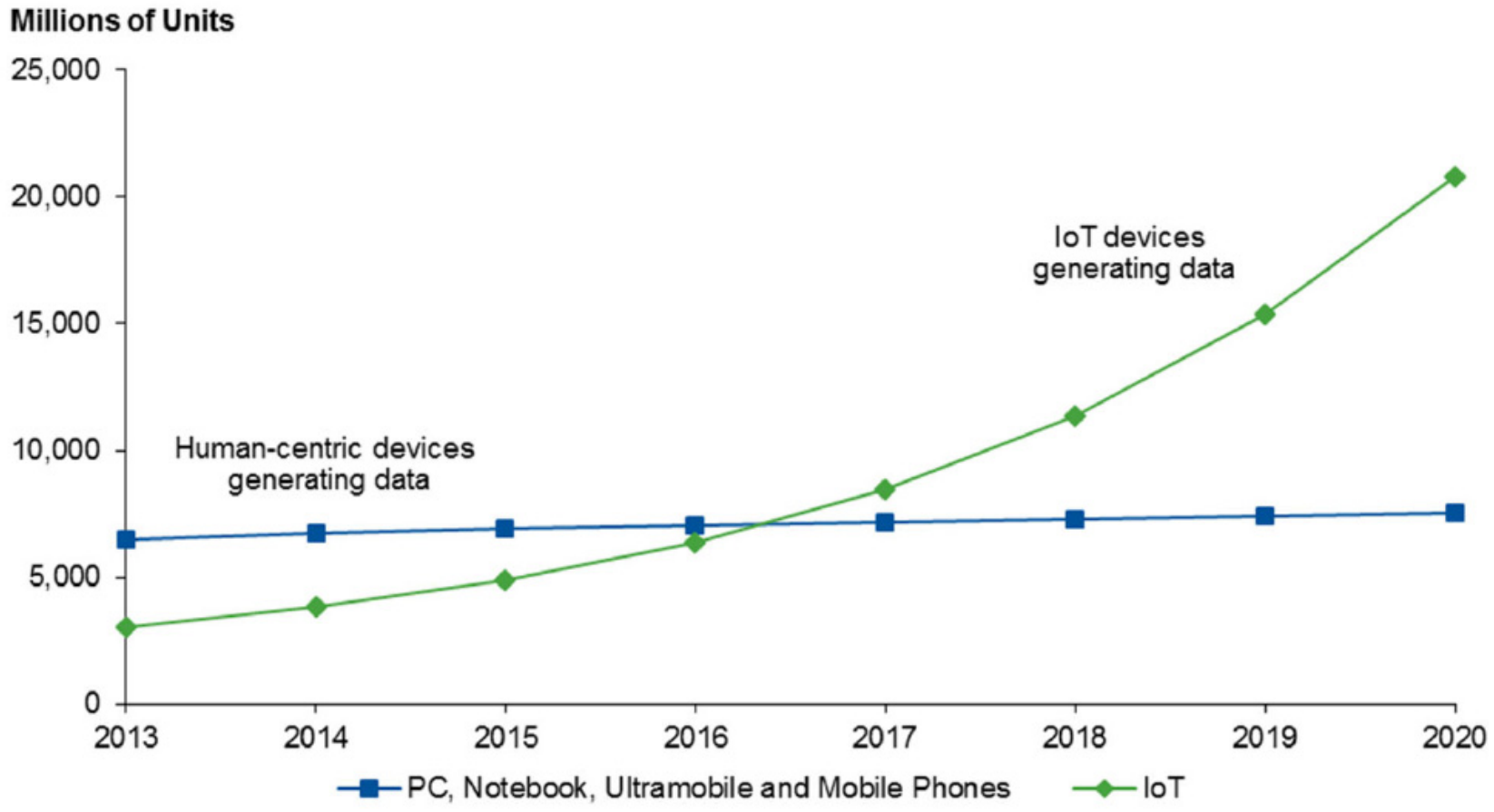
Google Trends



- IERC-European Research Cluster on the Internet of Things funded under 7th Framework in 2009

  $\Rightarrow$ "Internet of European Things"
- US interest started in 2009 w $4B funding for **smart grid** in American Recovery and Reinvestment Act of 2009
- Venture capital interest jumped when Google bought Nest for $3.2B in 2014.

Computing vs. IoT



- 21 Billion devices by 2020

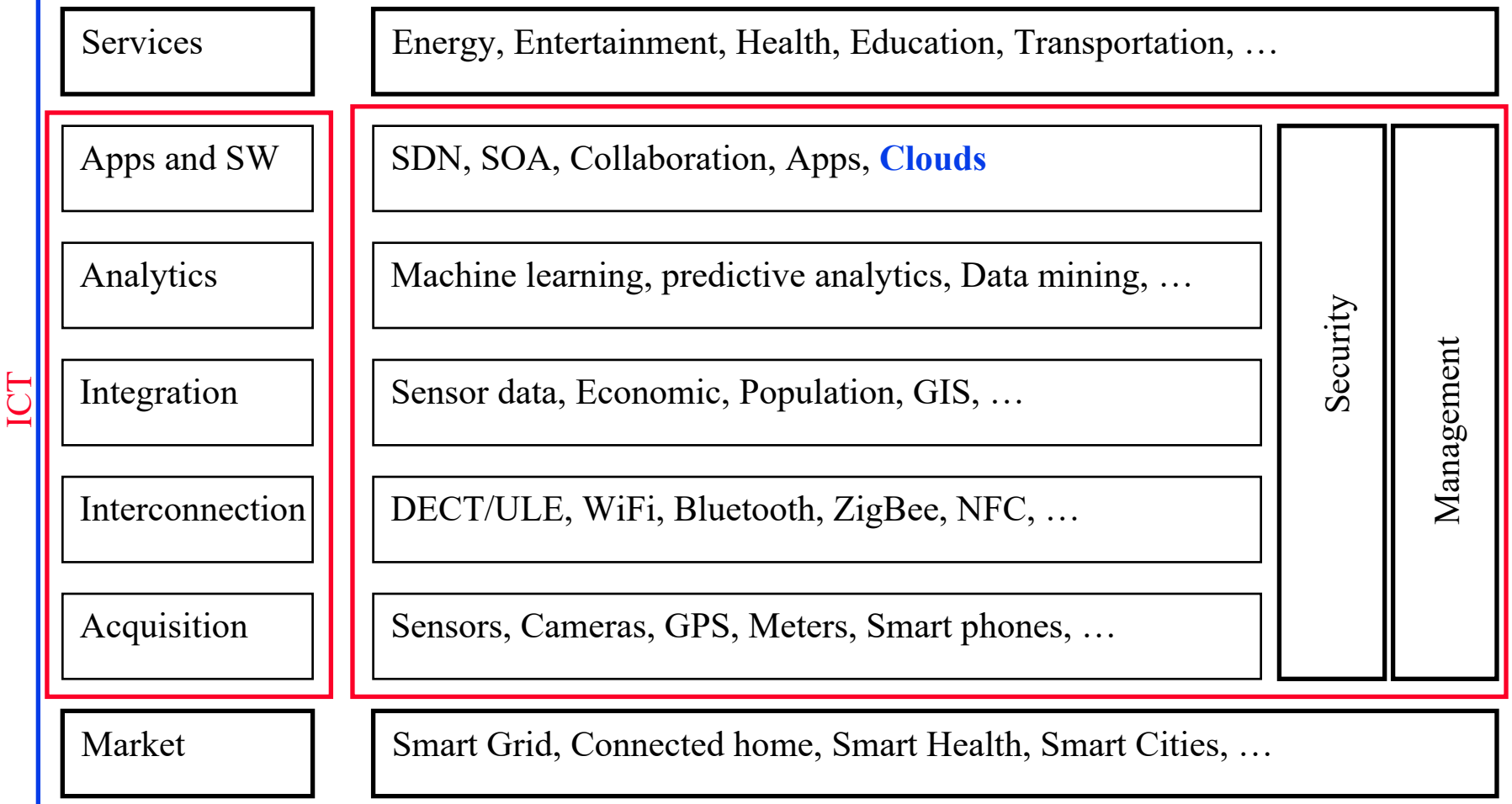
Ref: M. Moran, "Why the Internet of Things Will Dwarf Social (Big Data)," Gartner Report #G00289622, February 2016

IoT Business Opportunity

- $1.7 Trillion by 2020 - IDC
- $7.1 Trillion - Gartner
- $10-15 Trillion just for Industrial Internet – GE
- $19 Trillion – Internet of Everything - Cisco

Ref: http://www.forbes.com/sites/gilpress/2014/08/22/internet-of-things-by-the-numbers-market-estimates-and-forecasts/
http://www.forbes.com/sites/gilpress/2014/08/22/internet-of-things-by-the-numbers-market-estimates-and-forecasts/

A 7-Layer Model of IoT



Areas of Research for IoT

1. **PHY**: Smart devices, sensors giving real-time information, *Energy Harvesting*
2. **Datalink**: WiFi, Bluetooth, ZigBee, 802.11ah, … Broadband: DSL, FTTH, Wi-Fi, 5G, …
3. **Routing**: *Multiple interfaces,* Mesh networking, …
4. **Analytics**: Big-data, data mining, Machine learning, Predictive analytics, …
5. **Apps & SW**: SDN, SOA, Cloud computing, Web-based collaboration, Social networking, HCI, Event stream processing, …
6. **Applications**: Remote health, On-line education, on-line laboratories, …
7. **Security:** Privacy, Trust, Identity, Anonymity, …

Internet of Harmful Things

Imagine, as researchers did recently at Black Hat, someone hacking your connected toilet, making it flush incessantly and closing the lid repeatedly and unexpectedly.

News

Worm may create an Internet of Harmful Things, says Symantec (Take note, Amazon)

Security firm Symantec says it has found a Linux worm aimed at Internet of Things devices

By Patrick Thibodeau
December 3, 2013 01:22 PM ET Add a comment

Share 6 g+1 Like 7 More

Computerworld - Security researchers are gradually raising warnings that the Internet of Things will increase, by multitudes, the number of things that can be hacked and attacked.

The Hitchcockian plotlines are endless. Replace *The Birds* with flying Amazon delivery drones. Or imagine, as researchers did recently at Black Hat, someone hacking your connected toilet, making it flush incessantly and closing the lid repeatedly and unexpectedly.

Privacy Issue: Beacons

- Advertizing based on proximity
- Peripherals (your phone) broadcasts its presence if Bluetooth is turned on
- Primary aim of these broadcasts is to allow device discovery
- Advertising packets consist of a header and max 27B of payload with multiple TLV-encoded data items
  - May include signal strength ⇒ Distance
- iOS7 iPhones can send/received iBeacons
- Can be used for customized advertising, indoor location, geofencing
- PayPal uses this to identify you. You can pay using a PIN and your phone.

Datalink Issues

- Energy efficiency
  - ⇒ Need to decrease energy/bit by a factor of 1000
  - Energy/bit has gone down by a factor of 2 per year
  - Either wait ten years or design better protocols
- Small messages ⇒ Need low overhead
- Limited computing ⇒ Light weight protocols
  ⇒ lightweight Encryption, authentication, security
- Quality of Information (QoI)

Power per MB

Type	Bit rate	TX Power	mJoules/MB
802.11b	11Mb	50mW	36.4
802.11g	54Mb	50mW	7.4
802.11a	54Mb	200mW	29.6
802.15.1 Bluetooth	1Mb	1mW	8.0
802.15.3	55Mb	200uW	0.03

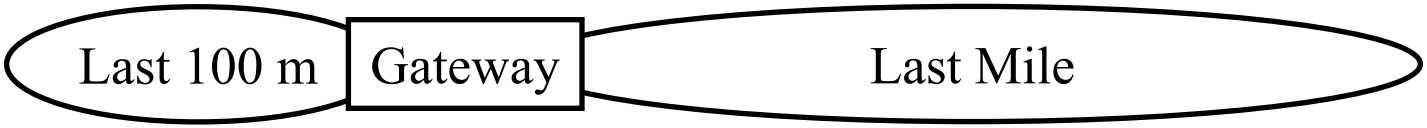
- Once connected, Bluetooth classic maintains connections even when there is no data. Low power but not low enough.

Networking Issues

- Large number ⇒ 32-bit or 48-bit addressing not sufficient
- 32-bit IPv4 addresses too small
- 48-bit IEEE 802 too small
- 128-bit IPv6 addresses too large. Tiny things do not have energy to transmit such large addresses.
- 16-bit local addresses and 64-bit global addresses
- 6LowPAN, 6-to-NonIP

Last 100m Protocols

- The Last Mile: Mobile and Broadband Access revolution
  Smart Grid, Smart Cities, Smart Industries
- The last 100m: Smart home
- The last meter: Smart Healthcare, Smart Wearable's



Legacy IoT Protocols

- **BACnet**: Building Automation and Control Network
- **LonWorks**: Local Operating Network (like BACnet)
- **ModBus**: Modicon (Schneider Electric)'s Serial Bus (www.modbus.org)
- **KNX**: Home and Building Automation Standard
- **Z-Wave**: Wireless Communication for Home Automation
- **M-Bus**: Bus for remote reading of gas and electric meters
- **ANSI CI12.20**: Electric Meter Accuracy and Performance
- **DLMS**: Device Language Message Specification
- **COSEM**: Company Specification for Energy Metering
- **DALI**: Digital Addressable Lighting Interface
- **EIB**: European Installation Bus
- **WirelessHART**: Wireless Highway Addressable Remote Transducer Protocol (www.hartcomm.org)

Ref: IEC 61158: Fieldbus for use in industrial control systems, Part 1 to 6, 2008

Recent Protocols for IoT

Session	MQTT, SMQTT, CoRE, DDS, AMQP , XMPP, CoAP, IEC, IEEE 1888, …	**Security**	**Management**
Network	Encapsulation 6LowPAN, 6TiSCH, 6Lo, Thread… Routing RPL, CORPL, CARP	IEEE 1888.3, TCG, Oath 2.0, SMACK, SASL, EDSA, ace, DTLS, Dice, …	IEEE 1905, IEEE 1451, IEEE 1377, IEEE P1828, IEEE P1856
Datalink	WiFi, Bluetooth Low Energy, Z-Wave, ZigBee Smart, DECT/ULE, 3G/LTE, NFC, Weightless, HomePlug GP, 802.11ah, 802.15.4e, G.9959, WirelessHART, DASH7, ANT+, LTE-A, LoRaWAN, ISA100.11a, DigiMesh, WiMAX, …		

Ref: Tara Salman, Raj Jain, "A Survey of Protocols and Standards for Internet of Things," Advanced Computing and Communications, Vol. 1, No. 1, March 2017, http://www.cse.wustl.edu/~jain/papers/iot_accs.htm

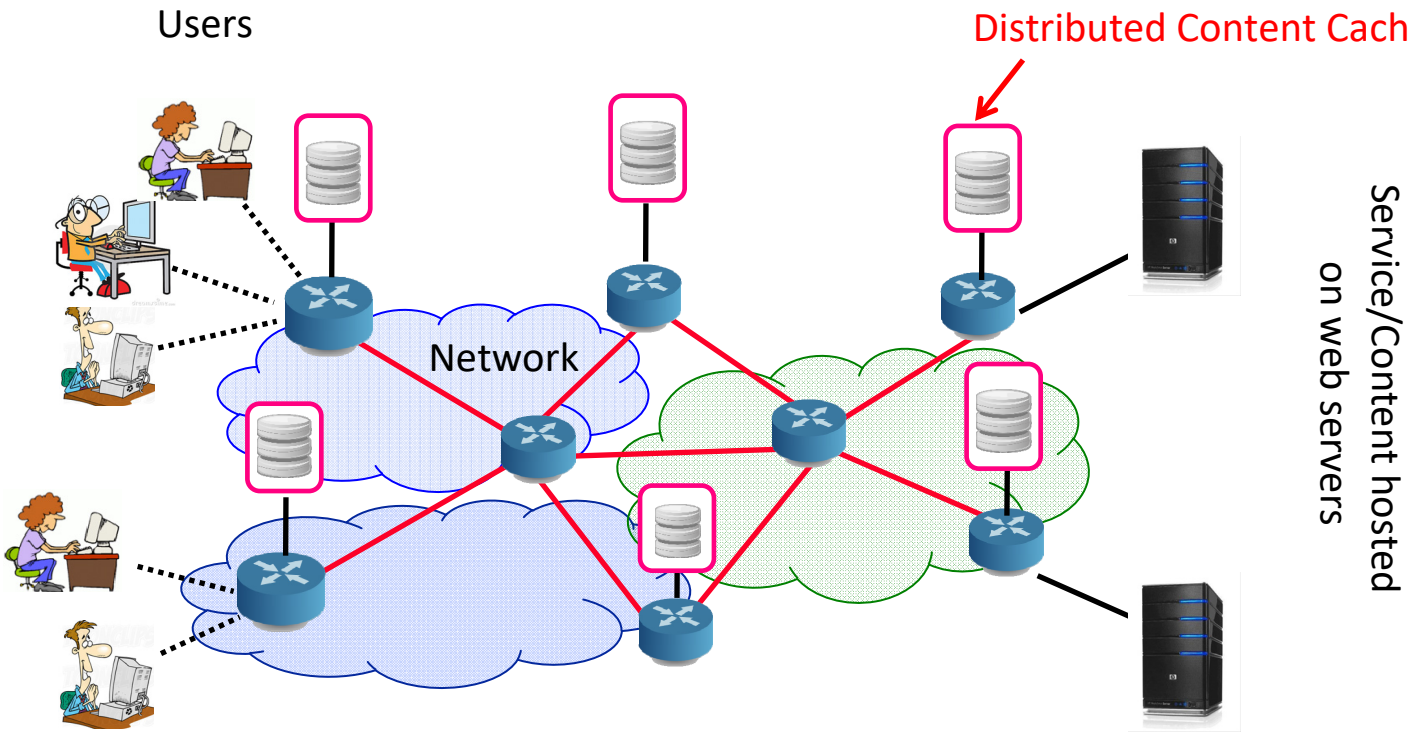
Standardization

- Almost every standards body is working on IoT:
  - IEEE: 802.11, 802.15.4, HomePlug
  - ZigBee Alliance: ZigBee Smart
  - Bluetooth SIG: Bluetooth Smart
  - IETF: RPL, 6LowPAN
  - ITU:
  - ETSI: DECT/ULE
  - IPSO, …
- Seven organizations joined together to avoid duplication: ARIB, ATIS, CCSA, ETSI, TIA, TTA, TTC ⇒ oneM2M

Ref: http://www.onem2m.org

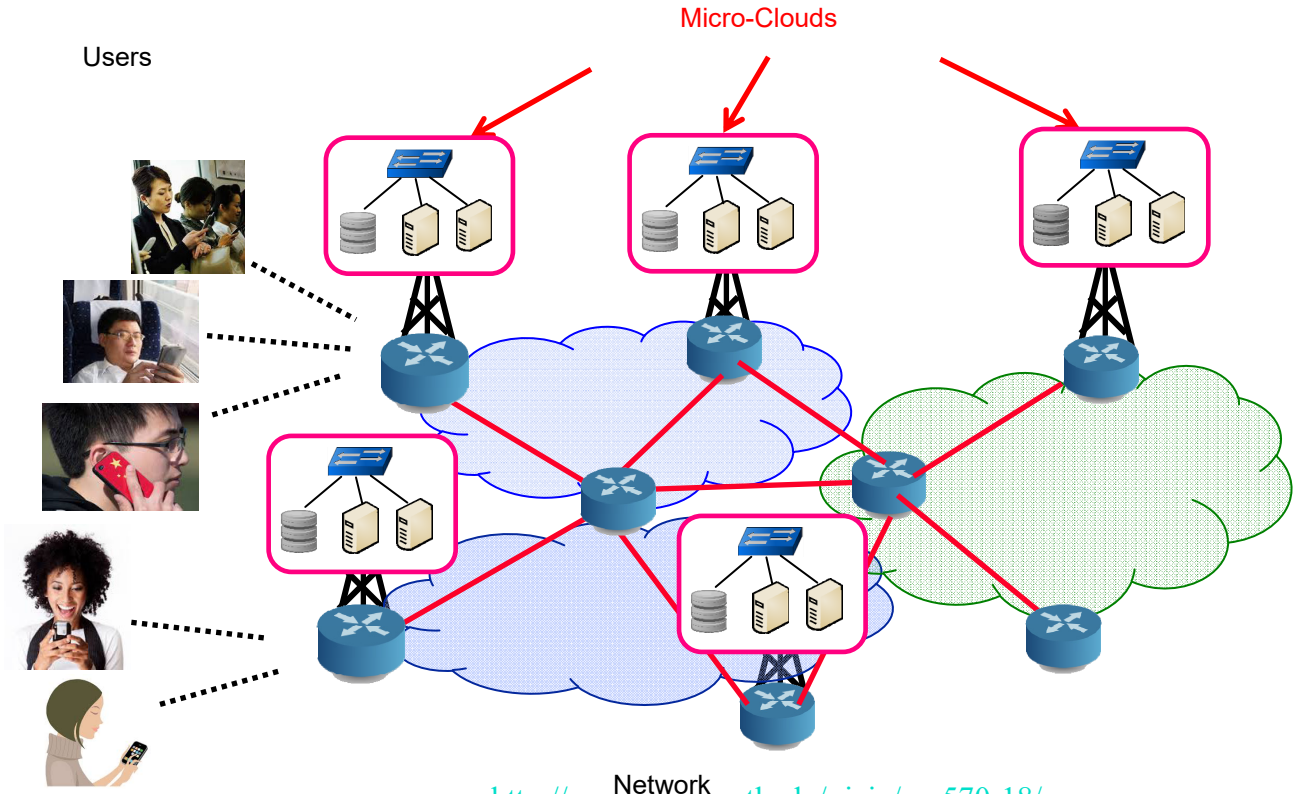
Past: Data in the Edge

- To serve world-wide users, latency was critical and so the data was replicated and brought to edge



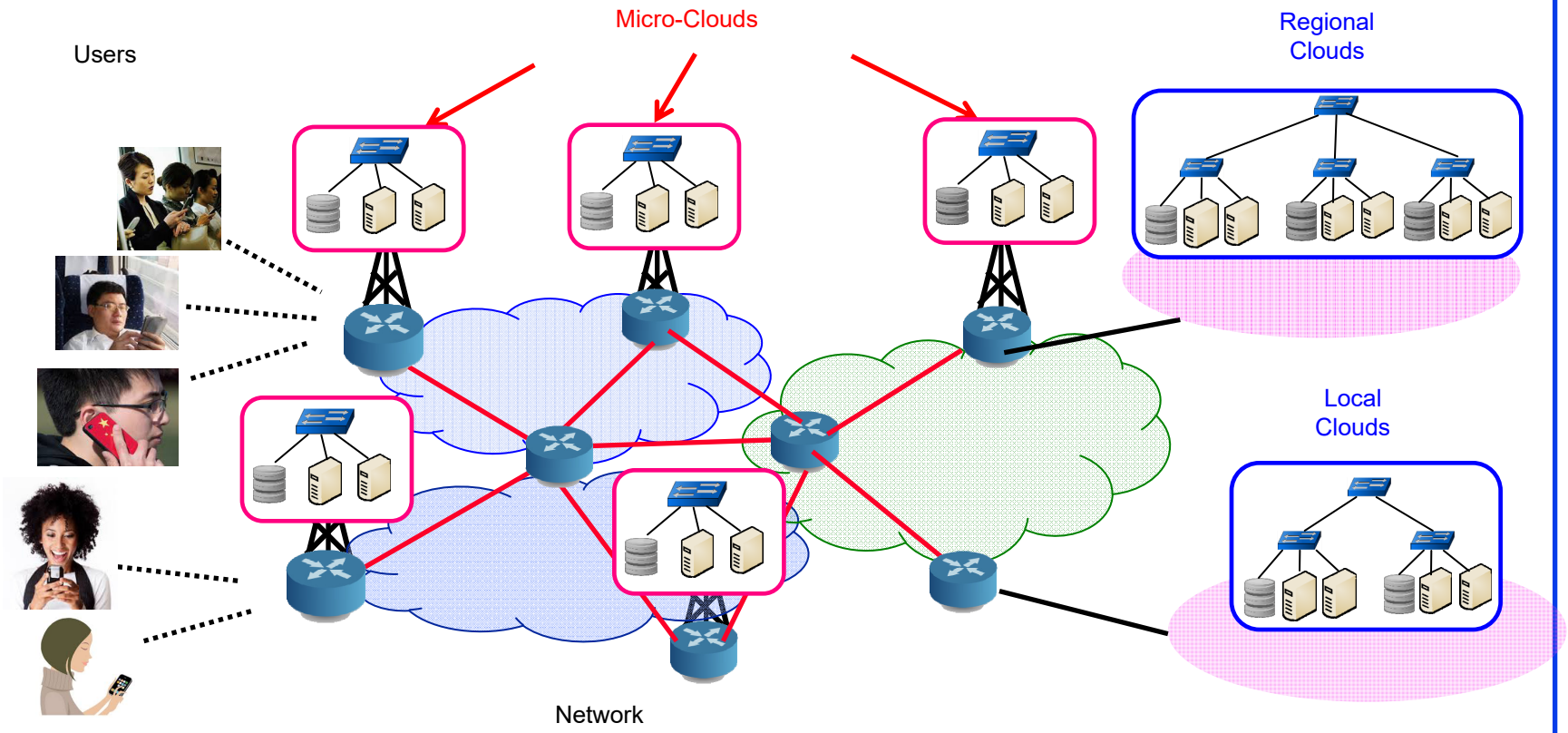
Trend: Computation in the Edge

- To service mobile users/IoT, the computation needs to come to edge ⇒ Micro-cloud on the tower
  ⇒ Mobile-Edge Computing

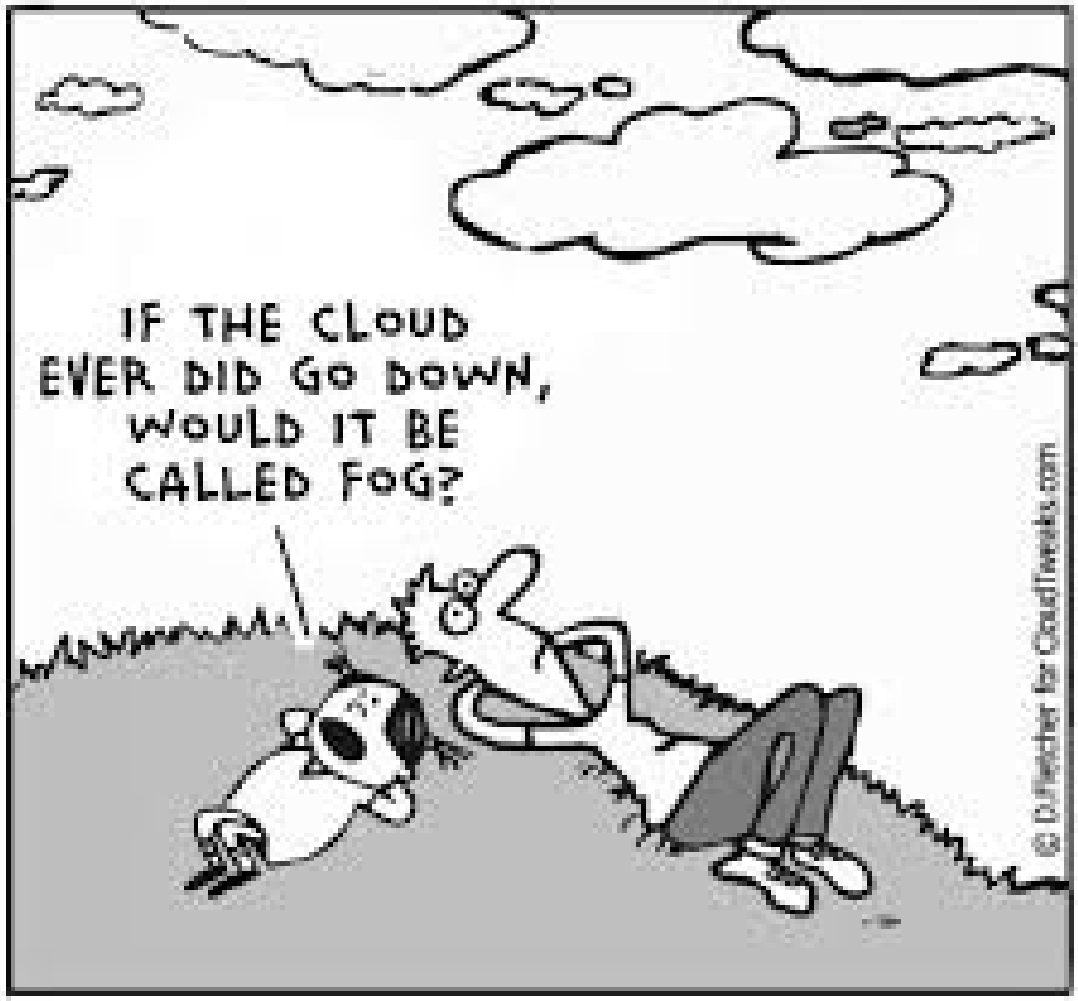


Trend: Multi-Cloud

- Larger and infrequent jobs serviced by local and regional clouds ⇒ Fog Computing



Fog Computing



Ref: http://community.spiceworks.com/topic/254392-fog-computing-replaces-cloud-as-new-tech-buzzword

Fog Computing (Cont)

- Location Aware and Location Sensitive
  ⇒ Low latency ⇒ Computing in micro clouds
  ⇒ Computing in the edge ⇒ Computing everywhere
  ⇒ Fog
- Geographically distributed => Everywhere/Anywhere
- Large Scale
- Mobility
- Real-Time

Ref: F. Bonomi, et al., "Fog Computing and Its Role in the Internet of Things," ACM MCC'12, August 17, 2012, Helsinki, Finland

Mobile Healthcare Use Case

Medical Application Service Provider

Home sensors for patient monitoring

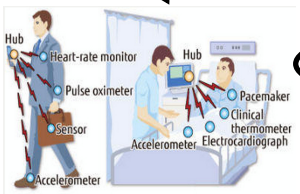
Multi-Cloud Mobile Application Deployment and Optimization Platform

Hospital Cloud

…

SDN Controller

Insurance Co Cloud

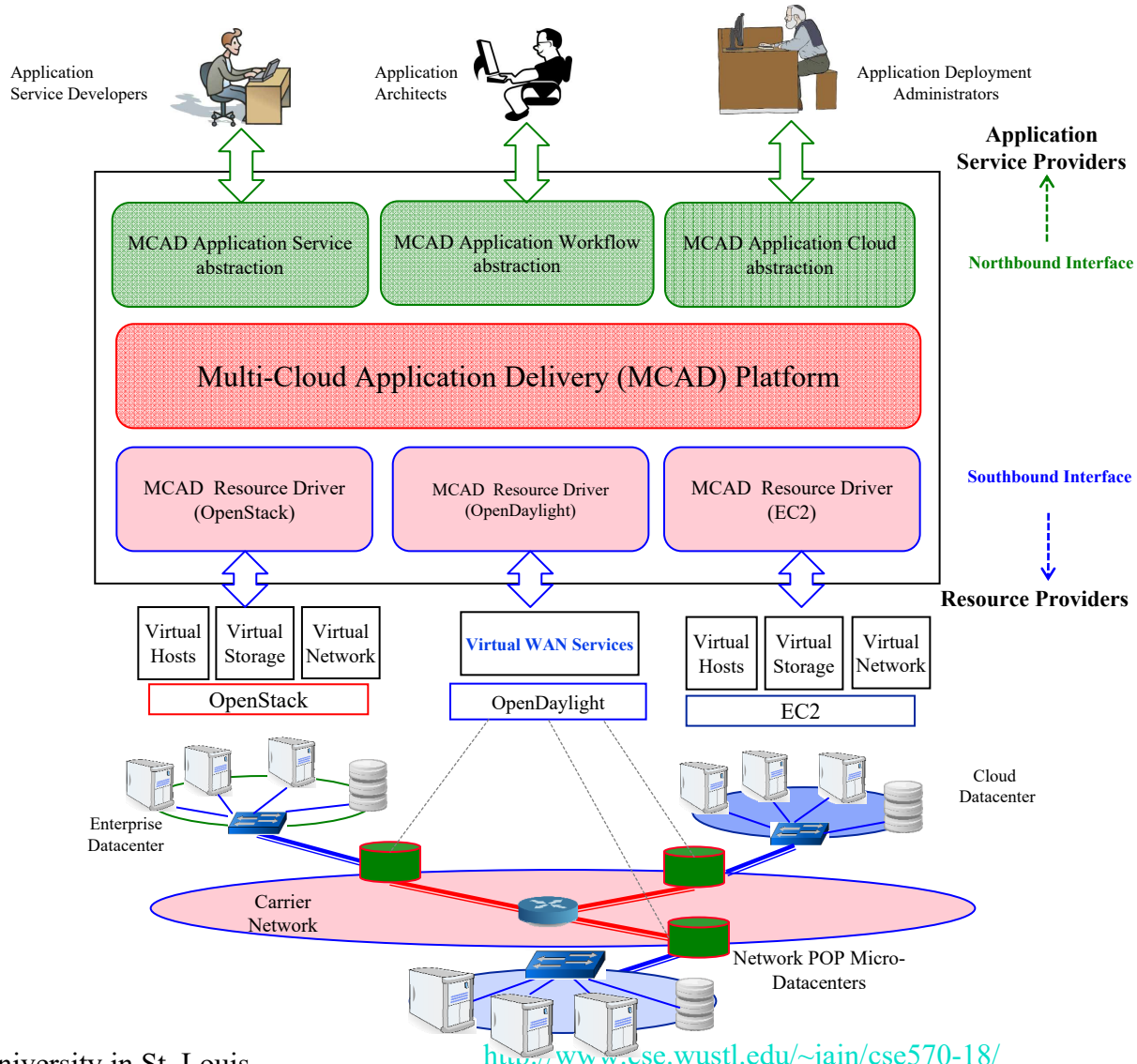


Body Area Network for mobile patient

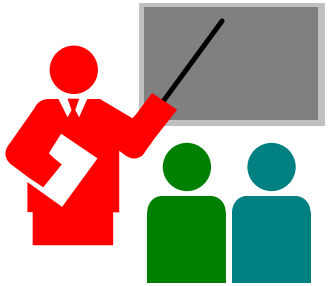
5G Carrier

Mobile Doctor

Multi-Cloud Management



Summary



1. Less than 1% of things are connected
   ⇒ IoT is a big opportunity for academics and industry
2. Smart Grid and Energy management lead the change.
3. Smartness comes from communication capability since the computation can be delegated
4. Right at the knee: Academic and Startup Research opportunities in almost subfields of computing including hardware development, data analytics, security, and networking.
5. Cloud computing everywhere leads to fog computing and multi-cloud computing ⇒ our MCAD project

Reading List

- Tara Salman, Raj Jain, "**A Survey of Protocols and Standards for Internet of Things**," Advanced Computing and Communications, Vol. 1, No. 1, March 2017, http://www.cse.wustl.edu/~jain/papers/iot_accs.htm

Additional Reading

- Honbo Zhou, "The Internet of Things in the Cloud: A Middleware Perspective," CRC Press, October 2012, 391 pp., ISBN:978-1-4398-9299-2 (Safari Book).
- Olivier Hersent; David Boswarthick; Omar Elloumi, "The Internet of Things: Key Applications and Protocols," John Wiley & Sons, February 1, 2012, 370 pp., ISBN:978-1-119-99435-0 (Safari Book).
- Francis daCosta, "Rethinking the Internet of Things: A Scalable Approach to Connecting Everything," Apress, January 2014, 192 pp., ISBN:1-4302-5740-7 (Safari Book).
- Hakima Chaouchi, "The Internet of Things: Connecting Objects," John Wiley & Sons, June 2010, 288 pp., ISBN:978-1-848-21140-7 (Safari Book).
- Nitesh Dhanjani, "Abusing the Internet of Things," O'Reilly Media, Inc., August 2015, 250 pp., ISBN:978-1-4919-0233-2 (Safari Book).

Wikipedia Links

- https://en.wikipedia.org/wiki/Fog_computing
- https://en.wikipedia.org/wiki/Industrial_Internet
- https://en.wikipedia.org/wiki/Internet_of_Things
- https://en.wikipedia.org/wiki/IPSO_Alliance
- https://en.wikipedia.org/wiki/Machine_to_machine
- https://en.wikipedia.org/wiki/Multicloud
- https://en.wikipedia.org/wiki/Nearables
- https://en.wikipedia.org/wiki/Smart_device
- https://en.wikipedia.org/wiki/SmartThings
- https://en.wikipedia.org/wiki/Ubiquitous_computing
- https://en.wikipedia.org/wiki/Wearable_technology
- https://en.wikipedia.org/wiki/Web_of_Things

Acronyms

- 6LowPAN IPv6 over Low Powered Personal Area Network
- ACM Automatic Computing Machinery Association
- AMQP Advanced Message Queueing Protocol
- ANSI American National Standards Institute
- ANT A proprietary open access multicast wireless sensor network
- ANT+ Interoperability function added to ANT
- API Application Programming Interface
- ARIB Association of Radio Industries and Businesses (Japan)
- BACnet Building Automation and Control Network
- CI12.20 ANSI Standard for Electric Meter Accuracy and Performance
- CoAP Constrained Application Protocol
- COSEM Company Specification for Energy Metering
- CPS Cyber Physical Systems
- CPU Central Processing Unit
- CTIA Cellular Telecommunication Industries Association
- DARPA Defense Advance Research Project Agency
- DASH7 ISO 18000-7 RFID standard for sensor networks

Acronyms (Cont)

- DECT Digital Enhanced Cordless Communication
- DLMS Device Language Message Specification
- DoE Department of Energy
- EC2 Elastic Compute Cloud 2 (by Amazon)
- ETSI European Telecommunications Standards Institute
- EU European Union
- FP7 Framework Program 7
- GP GreenPHY
- GreenPHY Green Physical Layer
- HomePlug-GP HomePlug Green PHY
- IEEE Institute for Electrical and Electronic Engineers
- IERC IoT-European Research Cluster
- IETF Internet Engineering Task Force
- iOS iPhone Operating System
- IoT Internet of Things
- IP Internet Protocol

Acronyms (Cont)

- IPSO IP for Smart Objects
- IPv4 Internet Protocol version 4
- IPv6 Internet Protocol version 6
- ISP Internet Service Provider
- ITU International Telecommunications Union
- KNX Building automation protocol
- MB Mega-byte
- MCAD Multi-Cloud Application Deployment Platform
- MQTT Message Queue Telemetry Transport
- NASA National Aeronautical and Space Administration
- NEST Name of a product
- NFC Near field communication
- NIH National Institute of Health
- NITRD Networking and Info Tech Research and Development
- NonIP Non-Internet Protocol
- NSF National Science Foundation

Acronyms (Cont)

- OAuth Open Authorization protocol from IETF
- oneM2M One Machine to Machine
- ONR Office of Naval Research
- PAN Personal area network
- PIN Personal Identification Number
- PLC Power Line Communication
- PoP Point of Presence
- QoI Quality of information
- QR Quick Response
- RFID Radio Frequency Identifier
- RPL Routing Protocol for Low Power and Lossy Networks
- SDN Software Defined Networking
- SIG Special Interest Group
- TLV Type-Length-Value
- TV Television
- UK United Kingdom

Acronyms (Cont)

- ULE Ultra Low Energy
- US United States
- VC Venture Capital
- WAN Wide Area Network
- WiFi Wireless Fidelity
- XML eXtensible Markup Language
- ZB Ziga-Byte

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Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),

https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Wireless and Mobile Networking (Spring 2016),
https://www.youtube.com/playlist?list=PLjGG94etKypKeb0nzyN9tSs_HCd5c4wXF

CSE571S: Network Security (Fall 2011),

https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw