

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/cse570-21/>

Student Questions



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.

Student Questions

Internet of Things

- ❑ Less than 1% of things around us were connected in 2013. Refrigerator, car, washing machine, heater, a/c, garage door, should all be connected but may be not.
- ❑ From 10 Billion in 2013 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,"

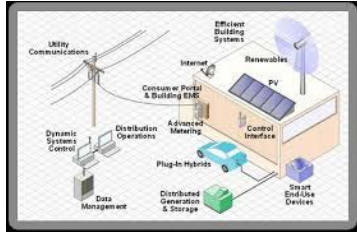
<http://www.cioinsight.com/it-news-trends/gartner-identifies-top-10-strategic-technologies.html>

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>

Student Questions

Sample IoT Applications



Smart Grid



Smart Health



Smart Home



Smart Cities



Smart Industries



Smart TV



Smart Watch



Smart Car



Smart Kegs

Student Questions

What's Smart?

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



Not-Smart

Smart

Student Questions

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>

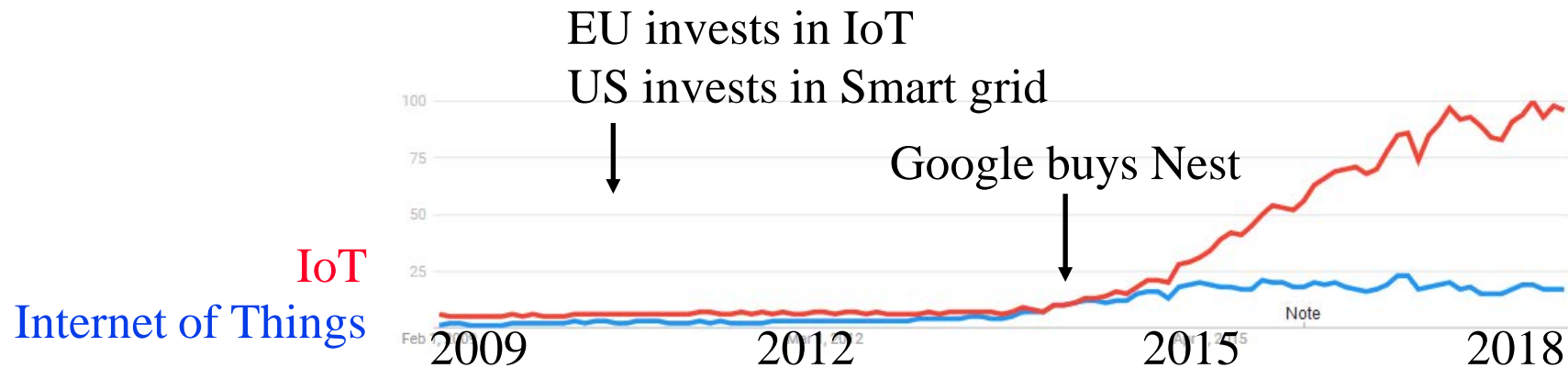
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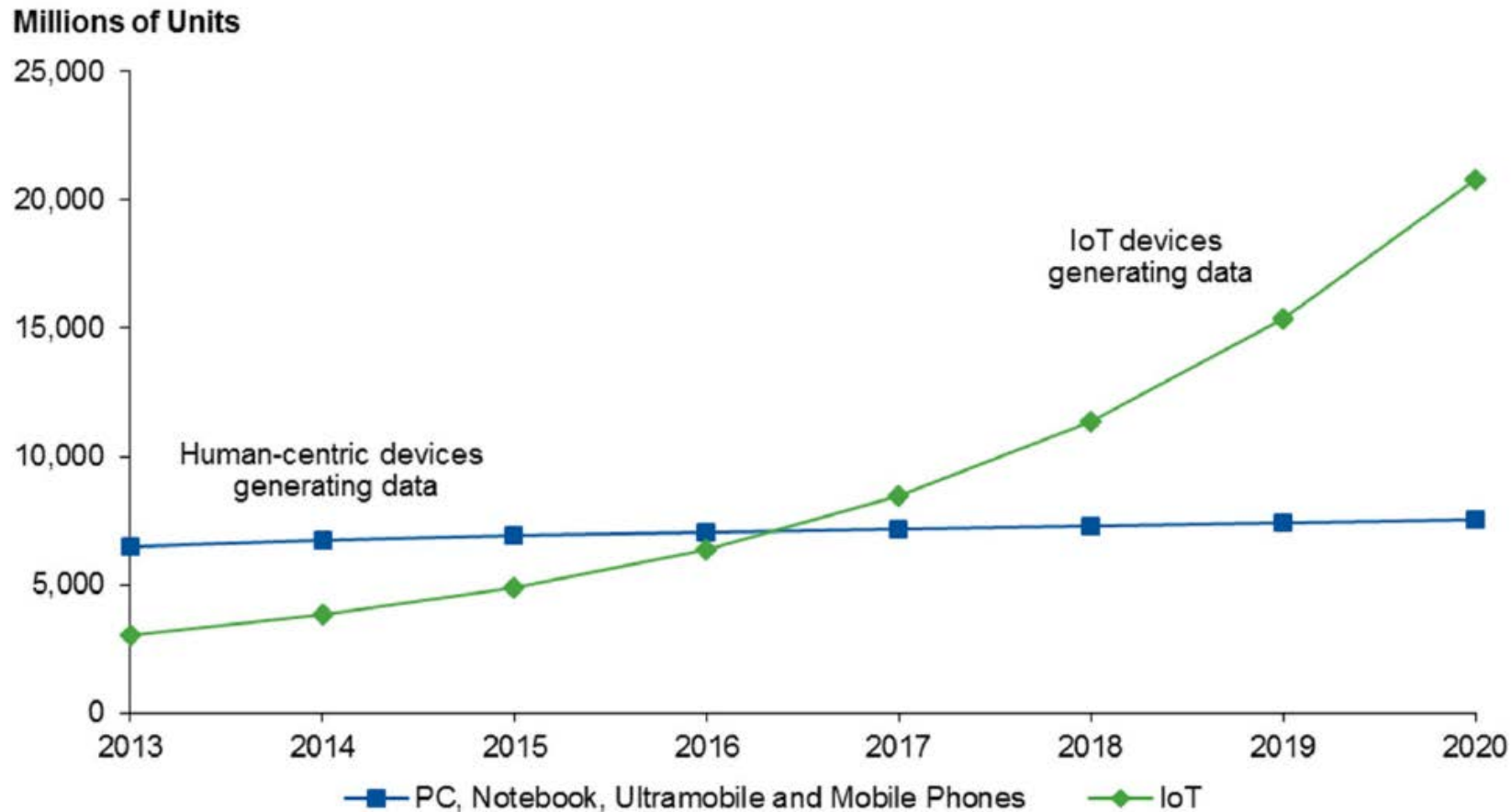
Google Trends



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

Student Questions

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

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Student Questions

IoT Business Opportunity

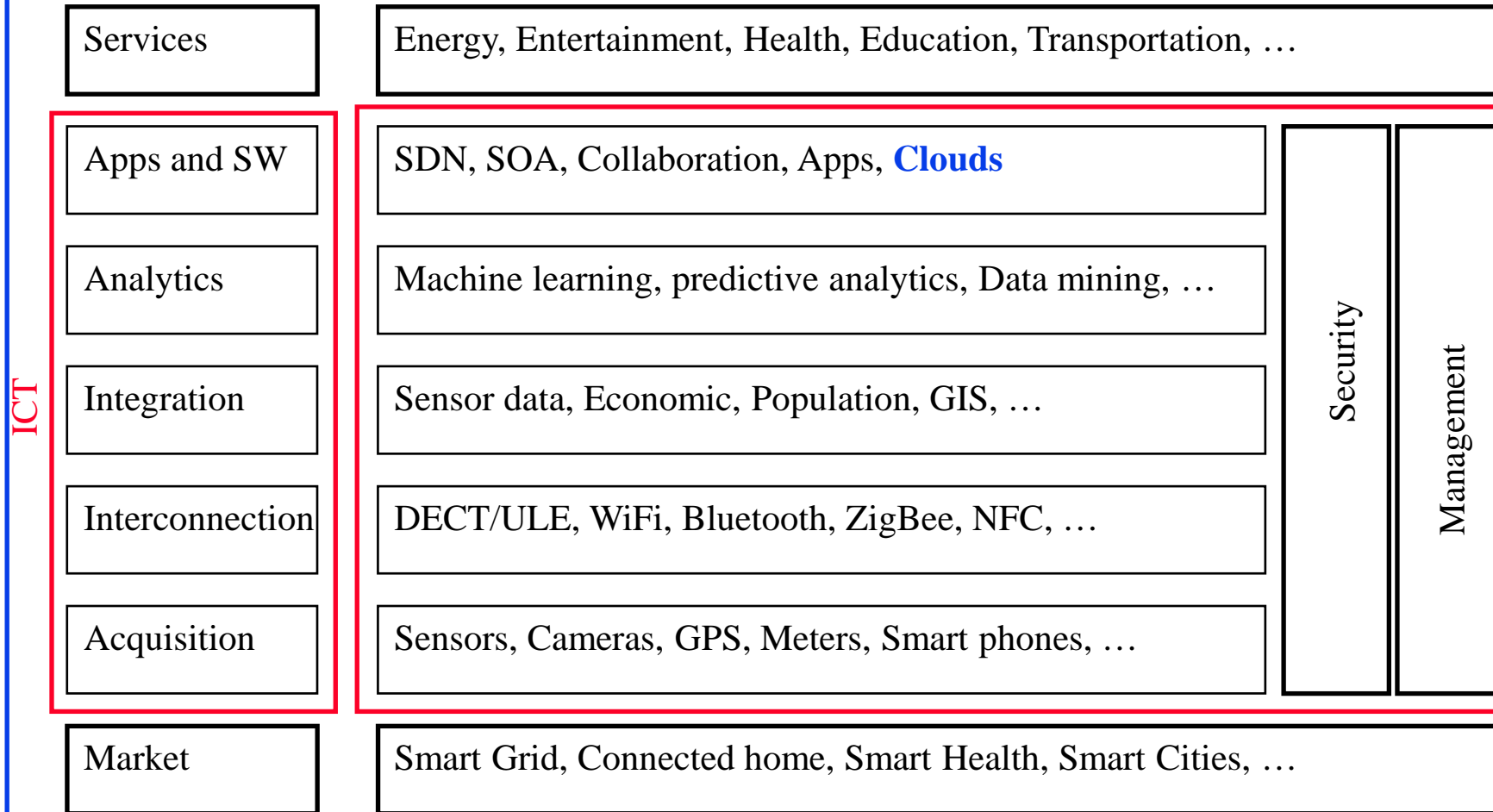


- ❑ \$1.7 Trillion by 2020 - IDC
- ❑ \$7.1 Trillion - Gartner
- ❑ \$10-15 Trillion just for Industrial Internet – GE
- ❑ \$19 Trillion – Internet of Everything - Cisco

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/>

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A 7-Layer Model of IoT



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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, ...

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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](#)



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.



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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 \Rightarrow 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.



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Datalink Issues

- ❑ Energy efficiency
 - \Rightarrow 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 \Rightarrow Need low overhead
- ❑ Limited computing \Rightarrow Light weight protocols
 - \Rightarrow lightweight Encryption, authentication, security
- ❑ Quality of Information (QoI)

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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.

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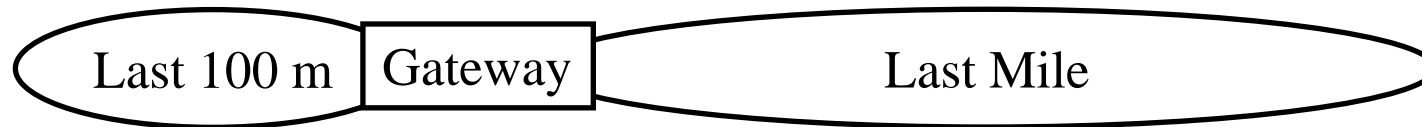
Networking Issues

- ❑ Large number \Rightarrow 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

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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



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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

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IoT Ecosystem

Applications	Smart Health, Smart Home, Smart Grid Smart Transport, Smart Workspaces, ...	Security TCG, Oath 2.0, SMACK, SASL, ISASecure, ace, CoAP, DTLS, Dice	Management IEEE 1905, IEEE 1451, ...
Session	MQTT , CoRE, DDS, AMQP , ...		
Network	Encapsulation 6LoWPAN , 6TiSCH, ... Routing RPL , CORPL, CARP		
Datalink	WiFi, Bluetooth Smart, ZigBee Smart, Z-Wave, DECT/ULE, 3G/LTE, NFC, Weightless, HomePlug GP , 802.11ah, 802.15.4 , G.9959, WirelessHART, DASH7, ANT+ , LoRaWAN, ...		
Software	Mbed, Homekit, AllSeen, IoTvity, ThingWorks, EVERYTHING , ...		
Operating Systems	Linux, Android, Contiki-OS, TinyOS, ...		
Hardware	ARM, Arduino , Raspberry Pi, ARC-EM4, Mote, Smart Dust, Tmote Sky, ...		

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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

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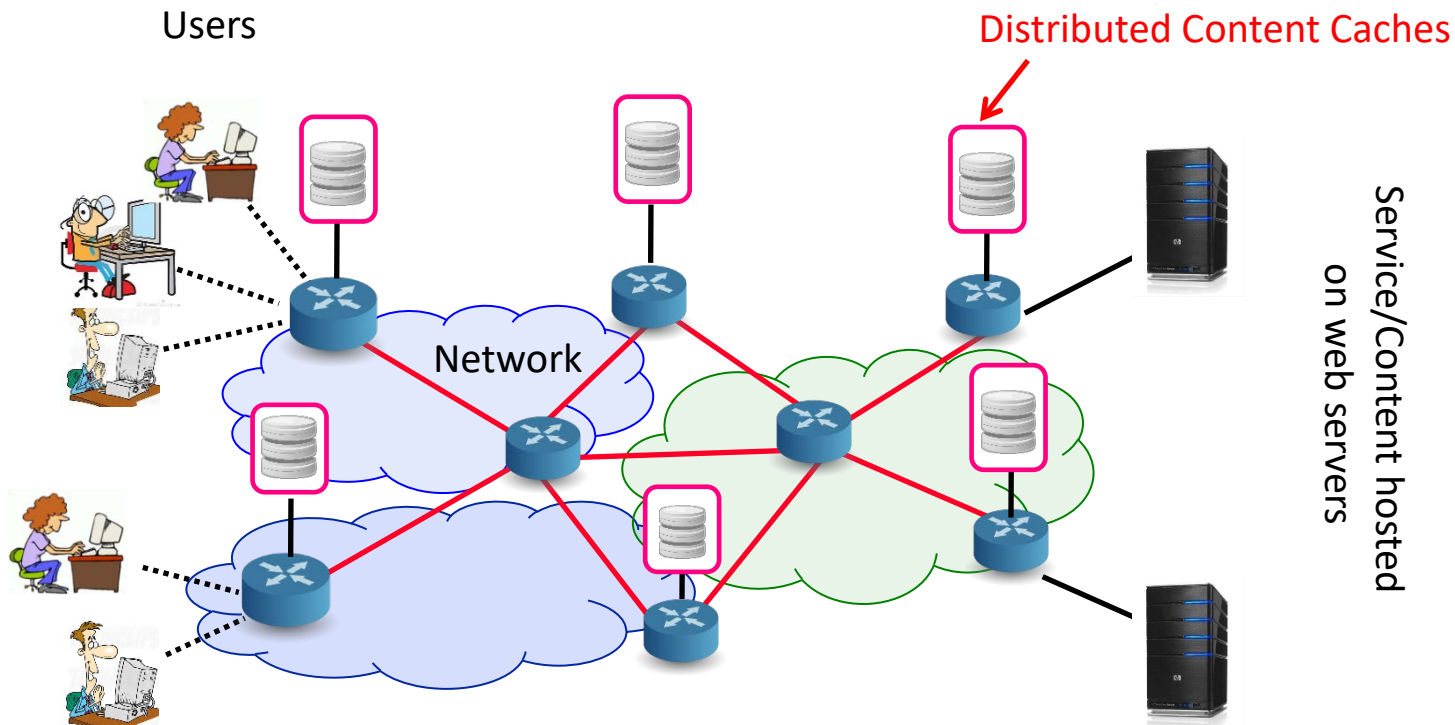
Standardization

- ❑ 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: oneM2M (see below)
 - ETSI: DECT/ULE
 - IPSO, ...
- ❑ Seven organizations joined together to avoid duplication:
ARIB, ATIS, CCSA, ETSI, TTA, TTC ⇒ oneM2M

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Past: Data in the Edge

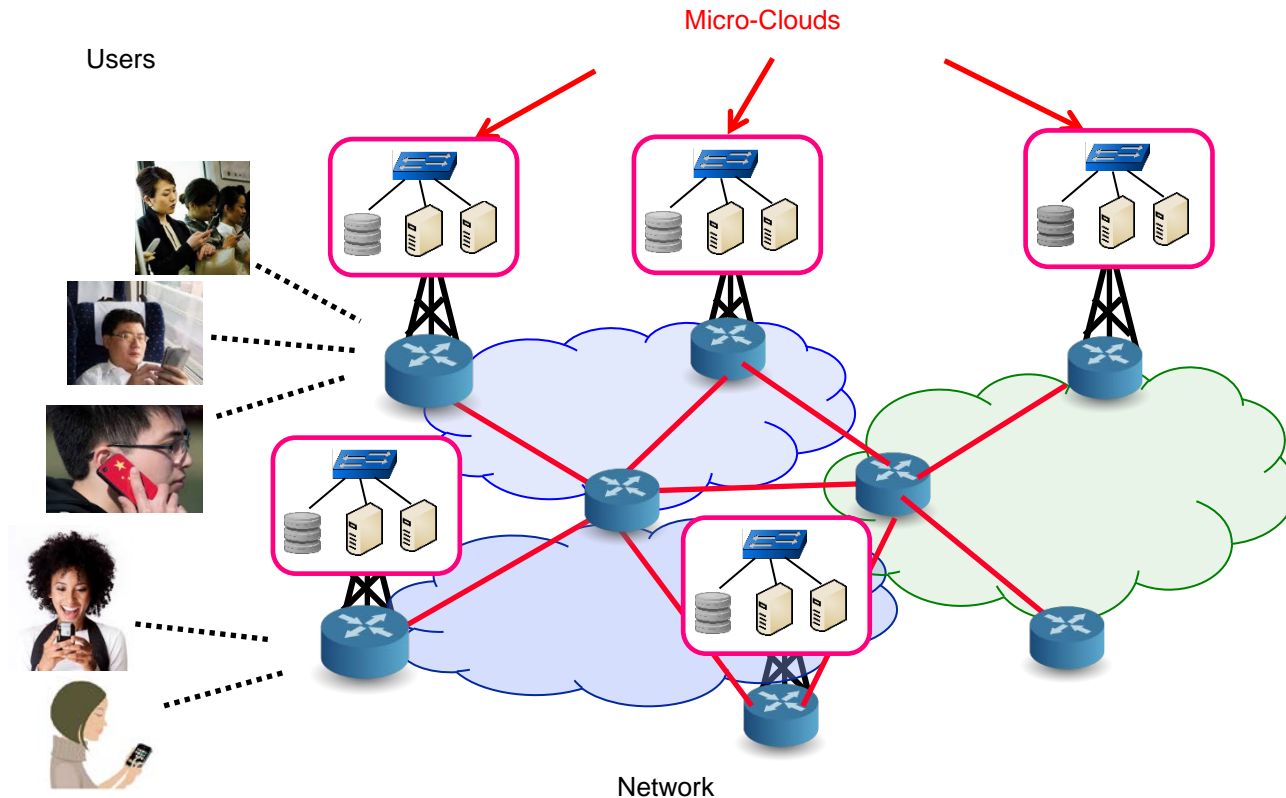
- ❑ To serve world-wide users, latency was critical and so the data was replicated and brought to edge



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Trend: Computation in the Edge

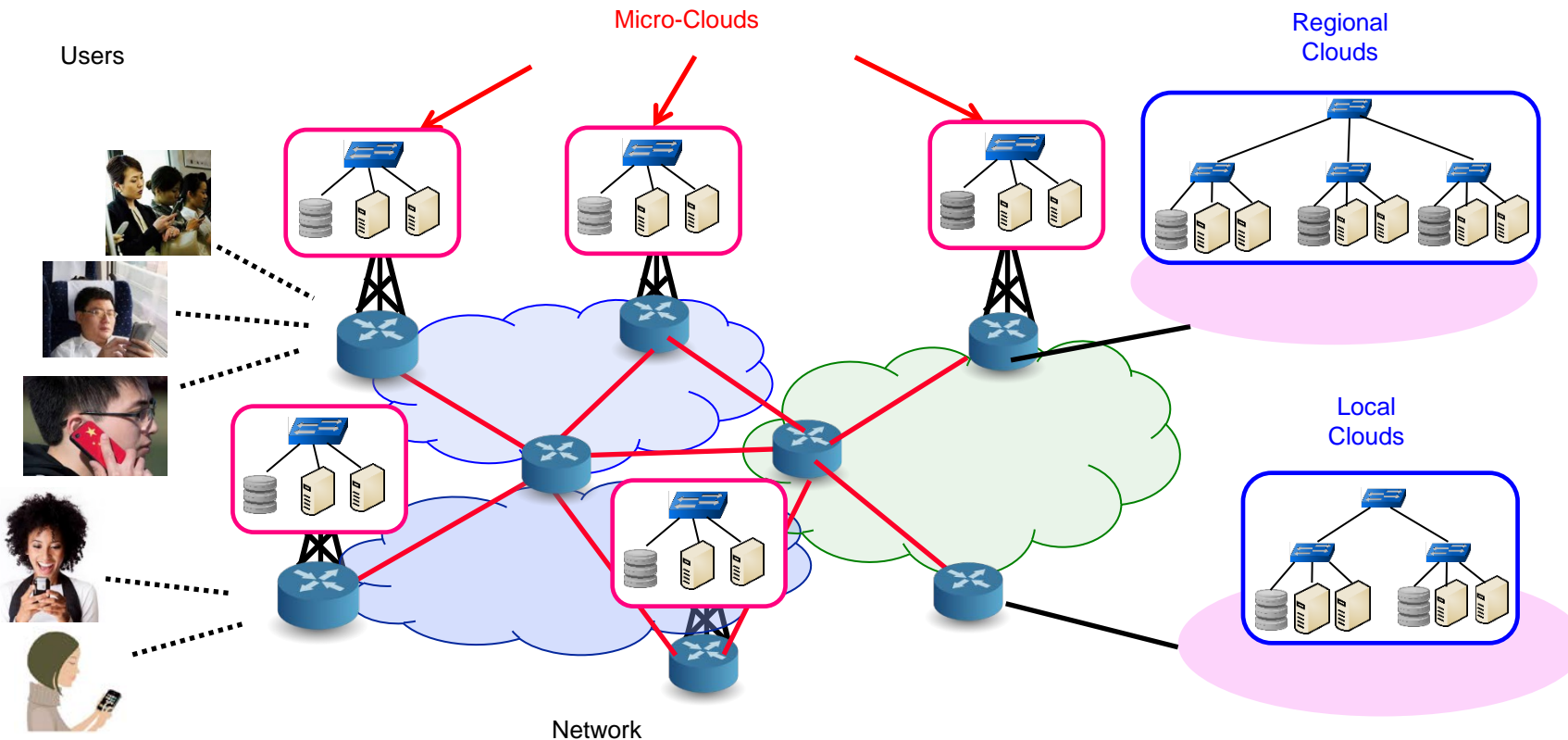
- To service mobile users/IoT, the computation needs to come to edge \Rightarrow Micro-cloud on the tower \Rightarrow Mobile-Edge Computing



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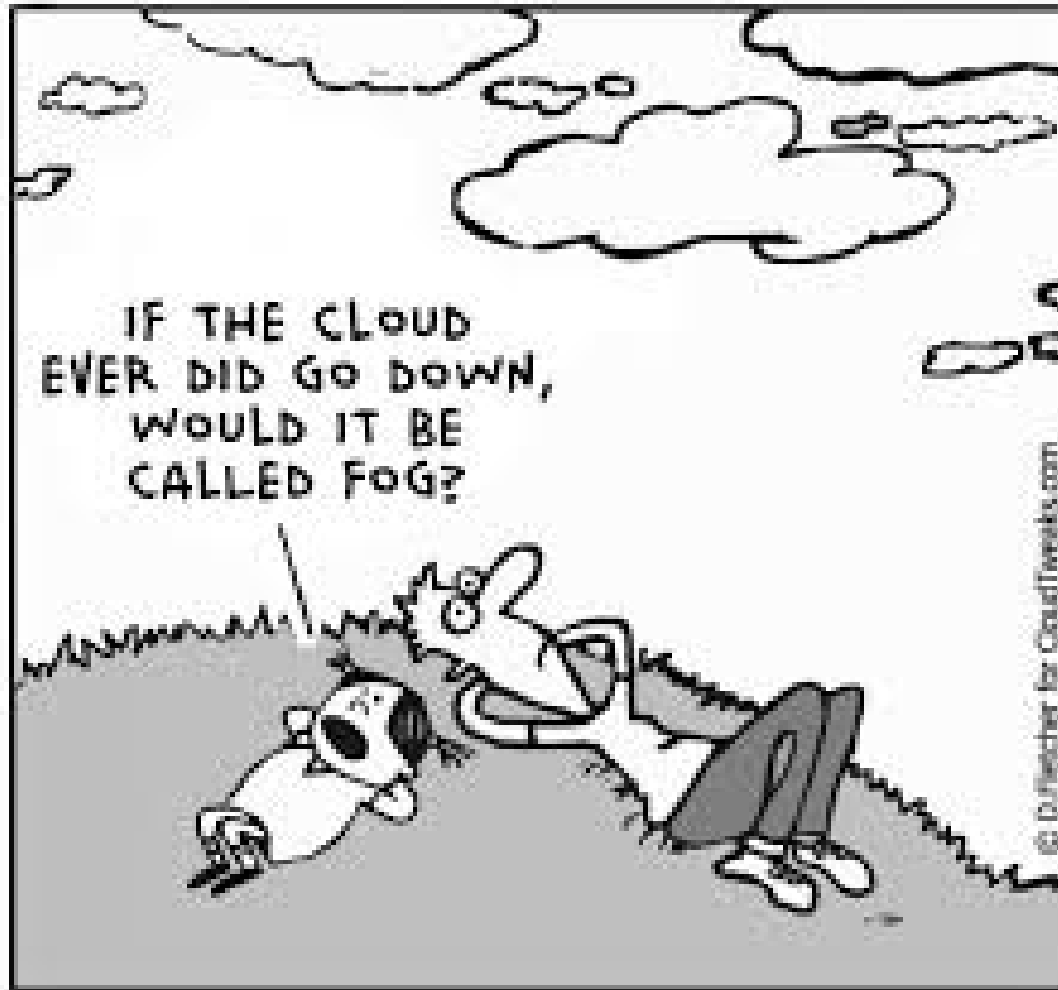
Trend: Multi-Cloud

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



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Fog Computing



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

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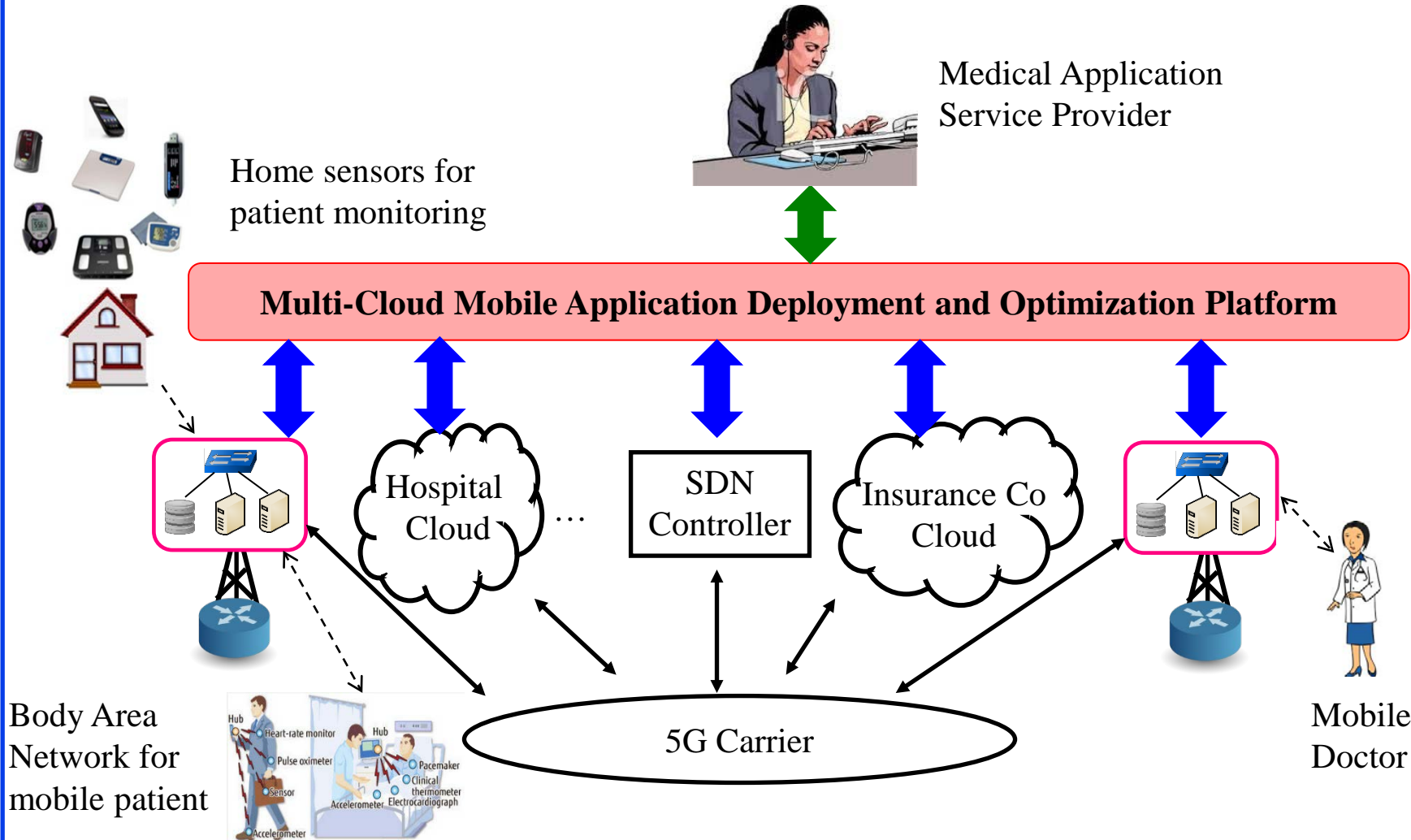
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Fog Computing (Cont)

- ❑ 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

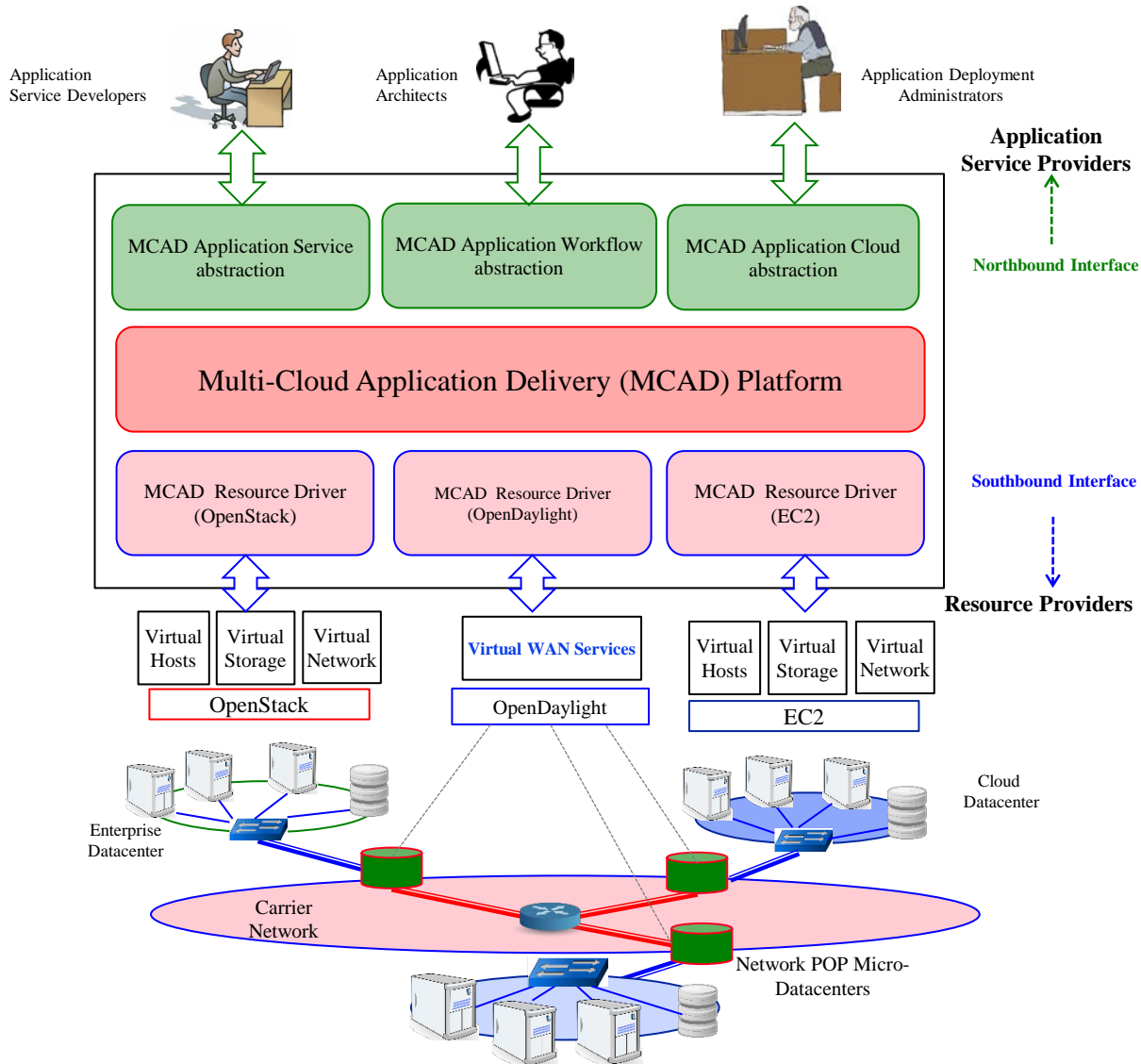
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Mobile Healthcare Use Case



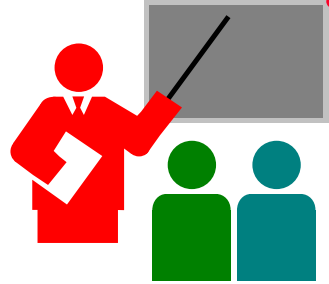
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Multi-Cloud Management



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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

Student Questions

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

Student Questions

References

- ❑ 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).

Student Questions

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

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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

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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

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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

Student Questions

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
- ❑ SOA Service Oriented Architecture
- ❑ TLV Type-Length-Value
- ❑ TV Television
- ❑ UK United Kingdom

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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

Student Questions

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<http://rajjain.com>

http://www.cse.wustl.edu/~jain/cse570-21/m_10iot.htm

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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=PLjGG94etKypJWOSPMh8Azcg5e_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>

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