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/cse574-16/

1. What are Things?
2. Business Opportunities for IoT
3. IoT Research Challenges
4. Recent Protocols for IoT
5. Datalink Issues

Note: This is part 1 of a series of class lectures on IoT.

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)

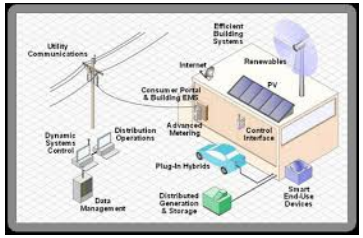
Ref: http://blog.smartthings.com/iot101/iot-adding-value-to-peoples-lives/

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?

- IoT = Instrument, Interconnect, Intelligently process (3 I's)
- Old: Smart = Can think ⇒ Can compute
- Now: Smart = Can find quickly, Can Delegate
  ⇒ Communicate = Networking
- Smart Grid, Smart Meters, Smart Cars, Smart homes, Smart Cities, Smart Factories, Smart Smoke Detectors, …

Think

Communicate

Why IoT Now?

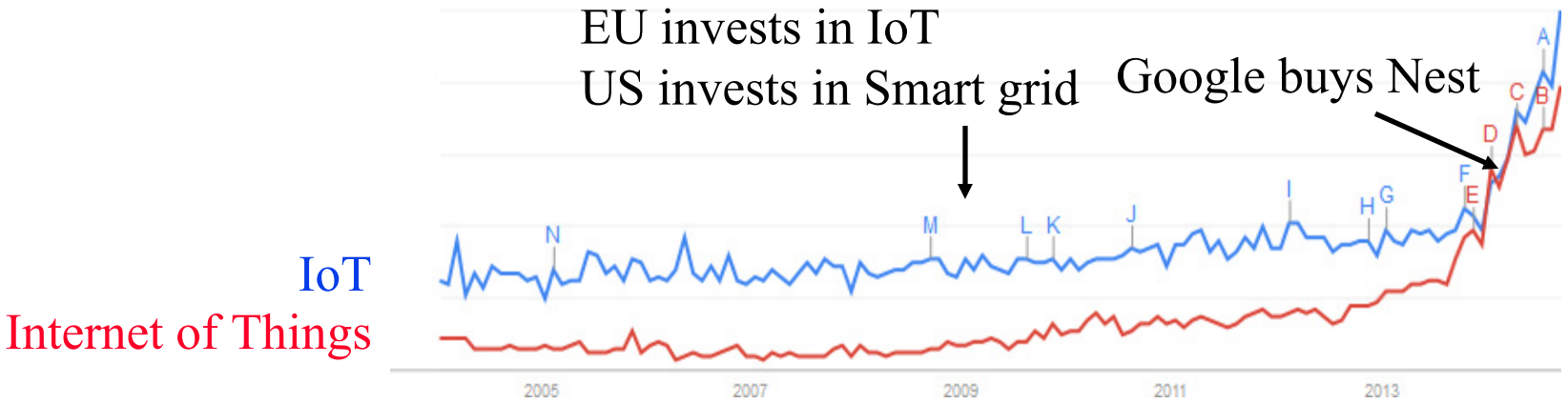
- IoT = Sensing + Communication + Computation

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

Funding

Google Trends



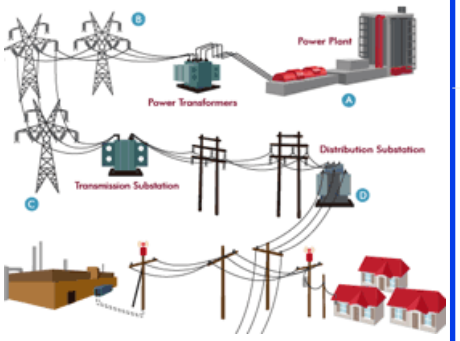
- Around for 10 years
- IERC-European Research Cluster on the Internet of Things funded under 7th Framework in 2009
  $\Rightarrow$ "Internet of European Things"
- US interest started in 2009 w $4B funding for **smart grid** in American Recovery and Reinvestment Act of 2009

Research Funding for IoT

- 70 M € in European Research program FP7
  ⇒ Internet of European Things
- Networking and Information Technology Research and Development (NITRD)
  - Group of 15 Federal agencies: NSF, NIH, NASA, DOE, DARPA, ONR, …
  - Recommends supplement to the president's annual budget
  - CPS is one of the areas recommended by NITRD starting 2012 ⇒ Smart infrastructure
    - Smart Grid, Smart Bridges, Smart Cars, tele-operational surgical robots, Smart **Buildings**
- March 2014: £45M for IoT research in UK by David Cameron

Ref: NITRD, http://www.nitrd.gov/

Smart Grid

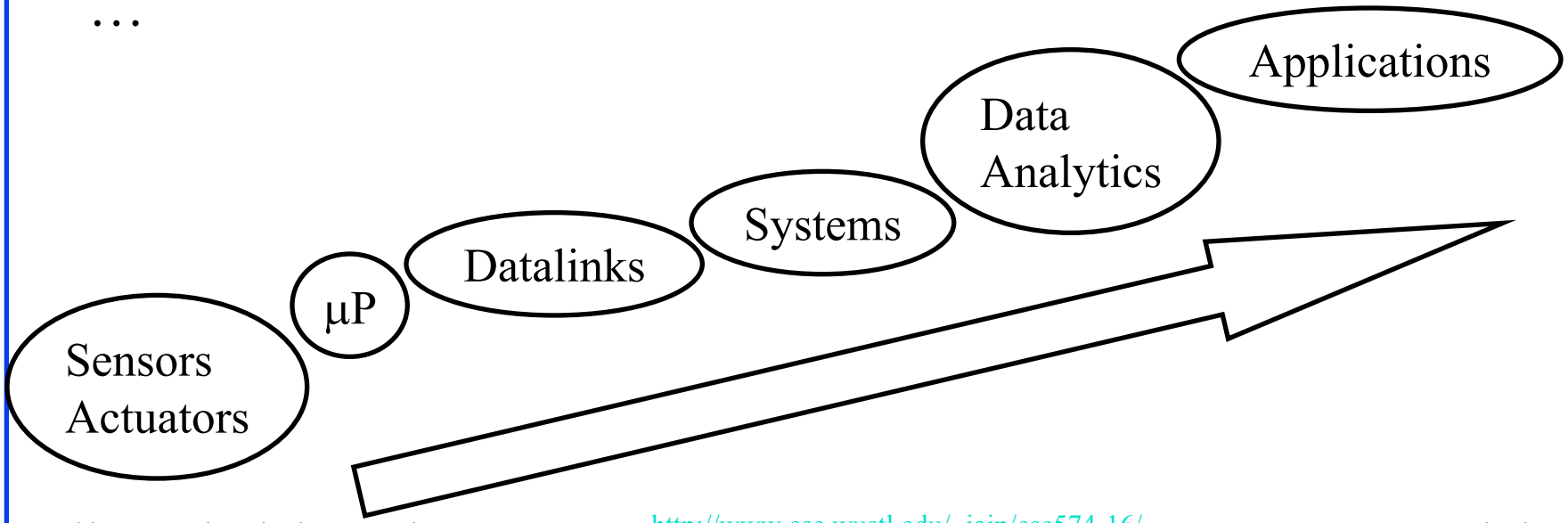


- $4B funding in Economic Recovery Act
- Smart Grid can
  - Identify surges, outages, and failure points
  - Contain damage and reroute power around failure
  - Accommodate new off-grid energy sources
  - Load balance dynamically
  - Be less vulnerable to accidental or malicious harms
- Meters that provide features needed for energy control
- Efficient cryptographic communication between substations and control centers
- Protocols for publishing/subscribing of system data

Ref: Workshop on Future Directions in CPS Security, July 2009, http://www.ee.washington.edu/faculty/radha/dhs_cps.pdf

Business Opportunities

- Components: Sensors, wireless radios, protocols,
- Smart Objects: Smart TV, Camera, Watch, …
- Systems: Buildings, Cars, Health, …
- Network service providers: ISP
- Application Service Providers: Monitoring, Analytics, Apps, …



IoT is a Data ($) Mine

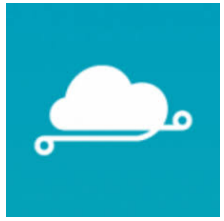
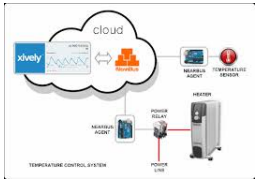
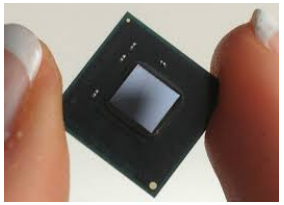
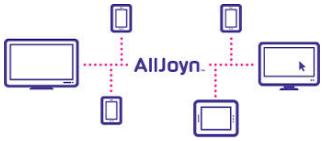
Ref: https://www.pinterest.com/iofficecorp/humor/

Venture Activities in IoT

- $1.1B invested in IoT startups by VCs in 153 deals in 2013
  - Quantified Self: Know your body and mind
  - Healthcare sensors: Wearable clock, sleep monitors
  - Energy management
  - Home Automation: Kitchenware, locks,
  - Environmental monitoring: Air Quality sensors, personal weather stations
- January 2014: Google buys NEST for 3.3B
- May 2014: $150M in VC investments in IoT by Cisco

Ref: http://www.cbinsights.com/blog/internet-of-things-investing-snapshot/
http://www.zdnet.com/cisco-invests-150m-in-internet-of-things-startups-7000028964/

Recent IoT Products

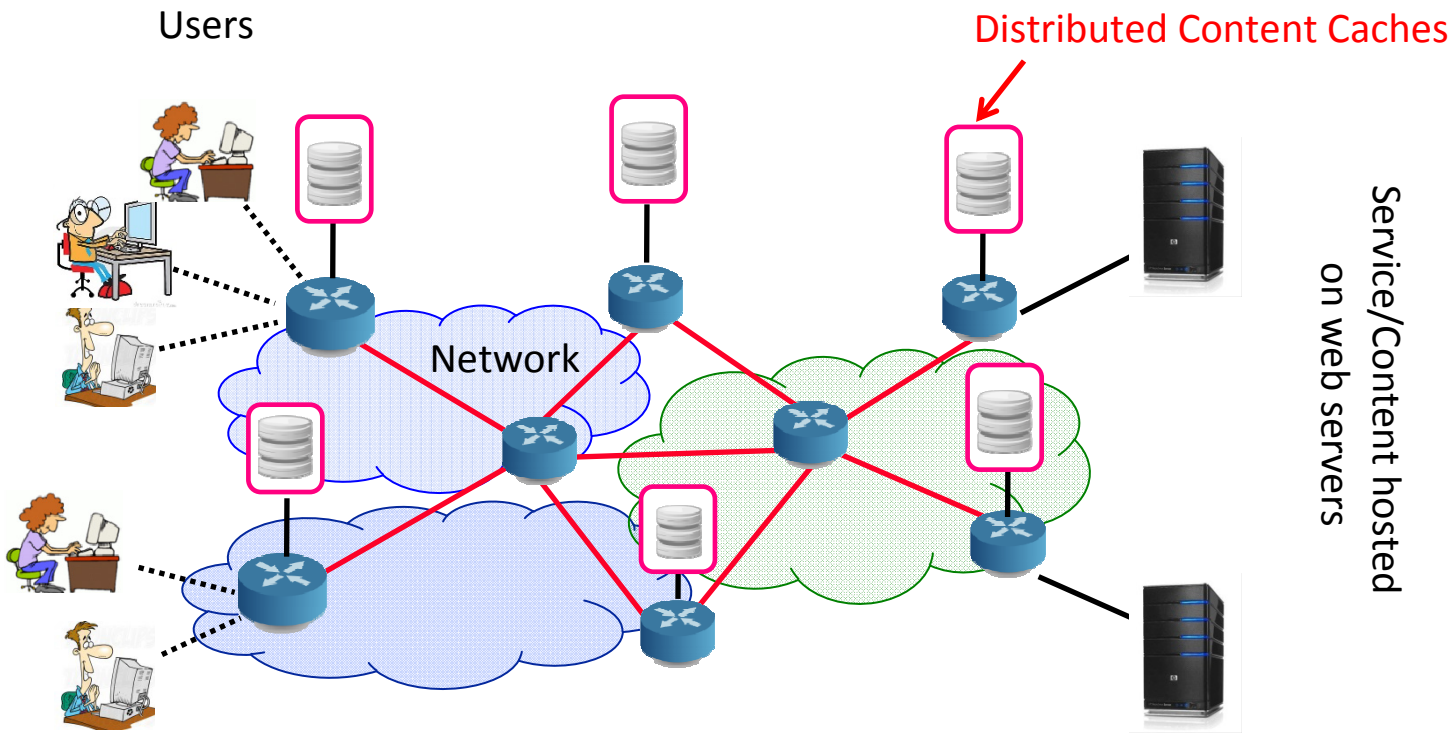
 NEST Thermostat	 Corventis: Wireless Cardiac Monitor	 WEMO Remote	 Tractive Pet Tracker
 Ninja Blocks	 Revolve Home Automation	 ThingWorx Application Platform	 Lings Cloud Platform
 Mbed Development Platform	 Xively Remote Access API	 Intel Quark Processor	 AllJoyn S/W Framework

IoT Research Challenges

1. **Naming and Addressing**: Advertising, Searching and Discovery
2. Service Orchestration
3. Power/Energy/Efficient resource management.
   Energy harvesting
4. **Things to Cloud**: Computation and Communication Gateways
5. **Miniaturization**: Sensors, CPU, network
6. **Big Data Analytics**: 35 ZB of data $2B in value by 2020
7. **Semantic technologies**: Information and data models for interoperability
8. **Virtualization**: Multiple sensors aggregated, or a sensor shared by multiple users
9. **Privacy/Security**/Trust/Identity/Anonymity
   Target Pregnancy Prediction
10. Heterogeneity/Dynamics/**Scale**

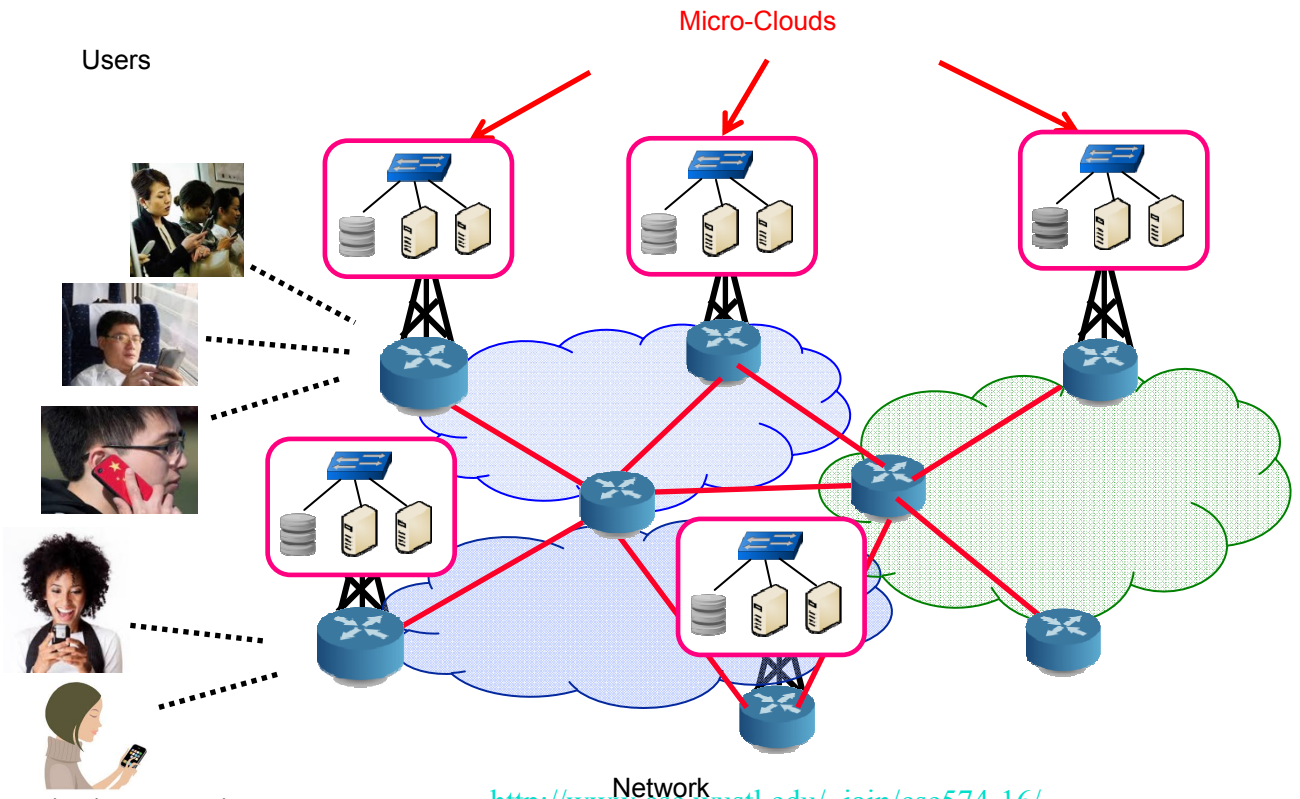
Past: Data in the Edge

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

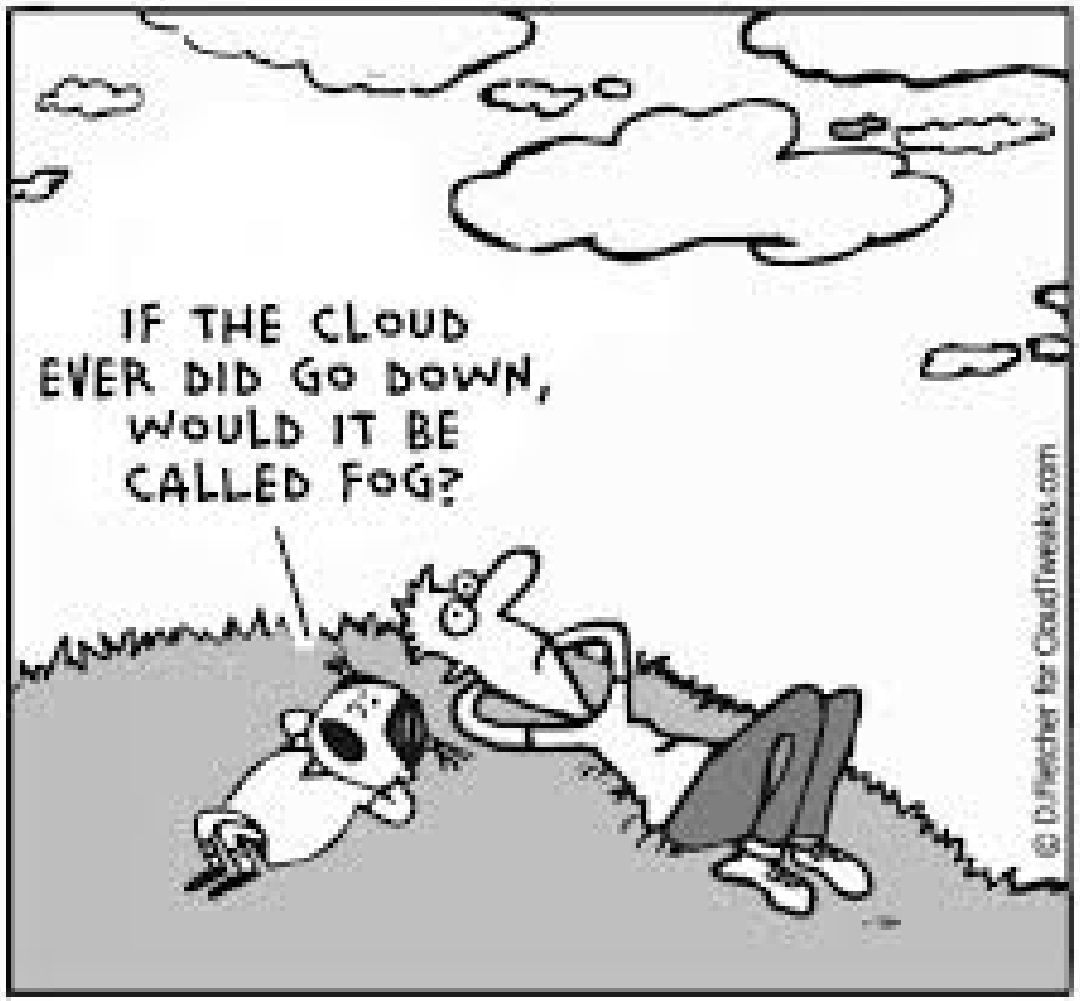


Trend 2: Computation in the Edge

- To service mobile users/IoT, the computation needs to come to edge ⇒ Mobile Edge Computing, Fog Computing



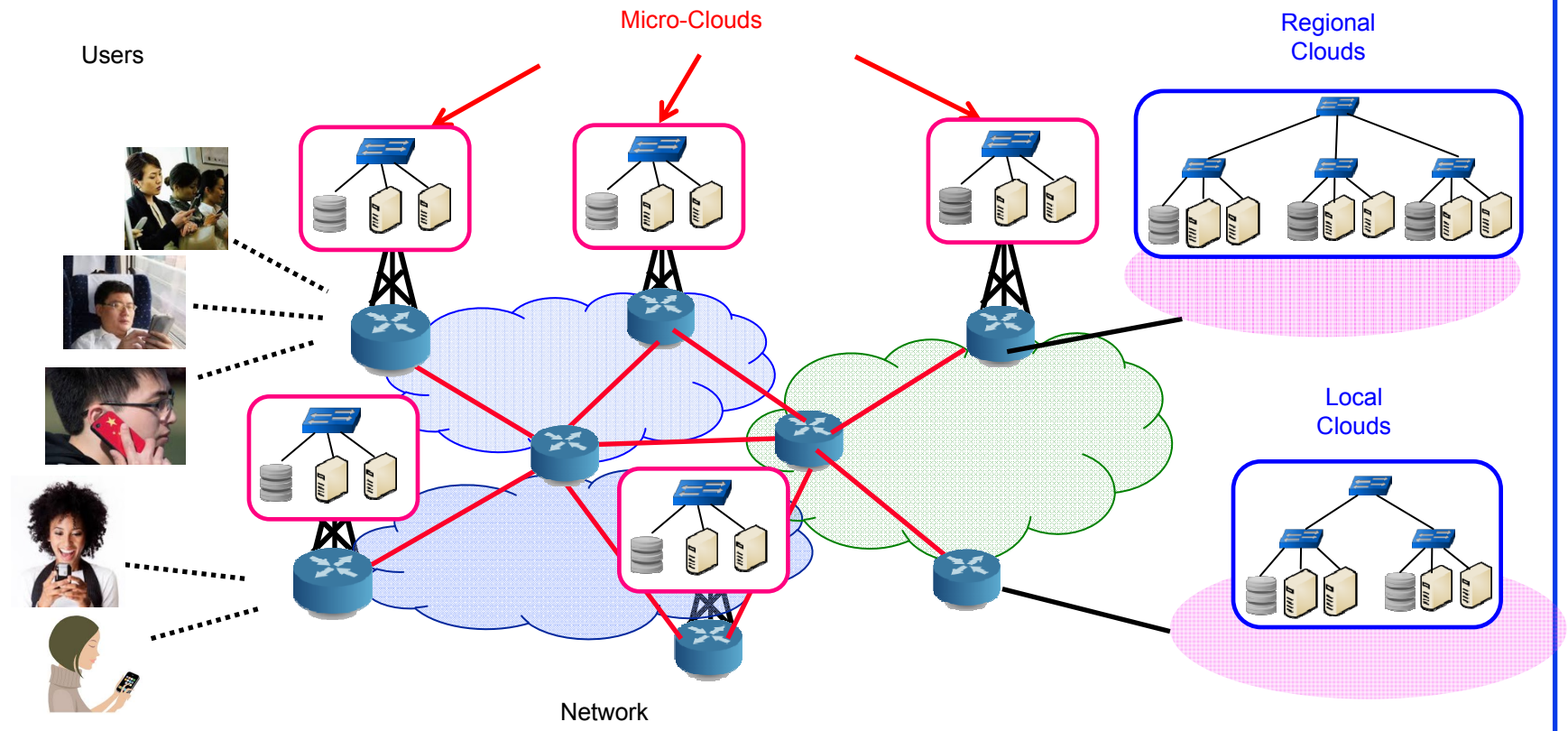
Fog Computing



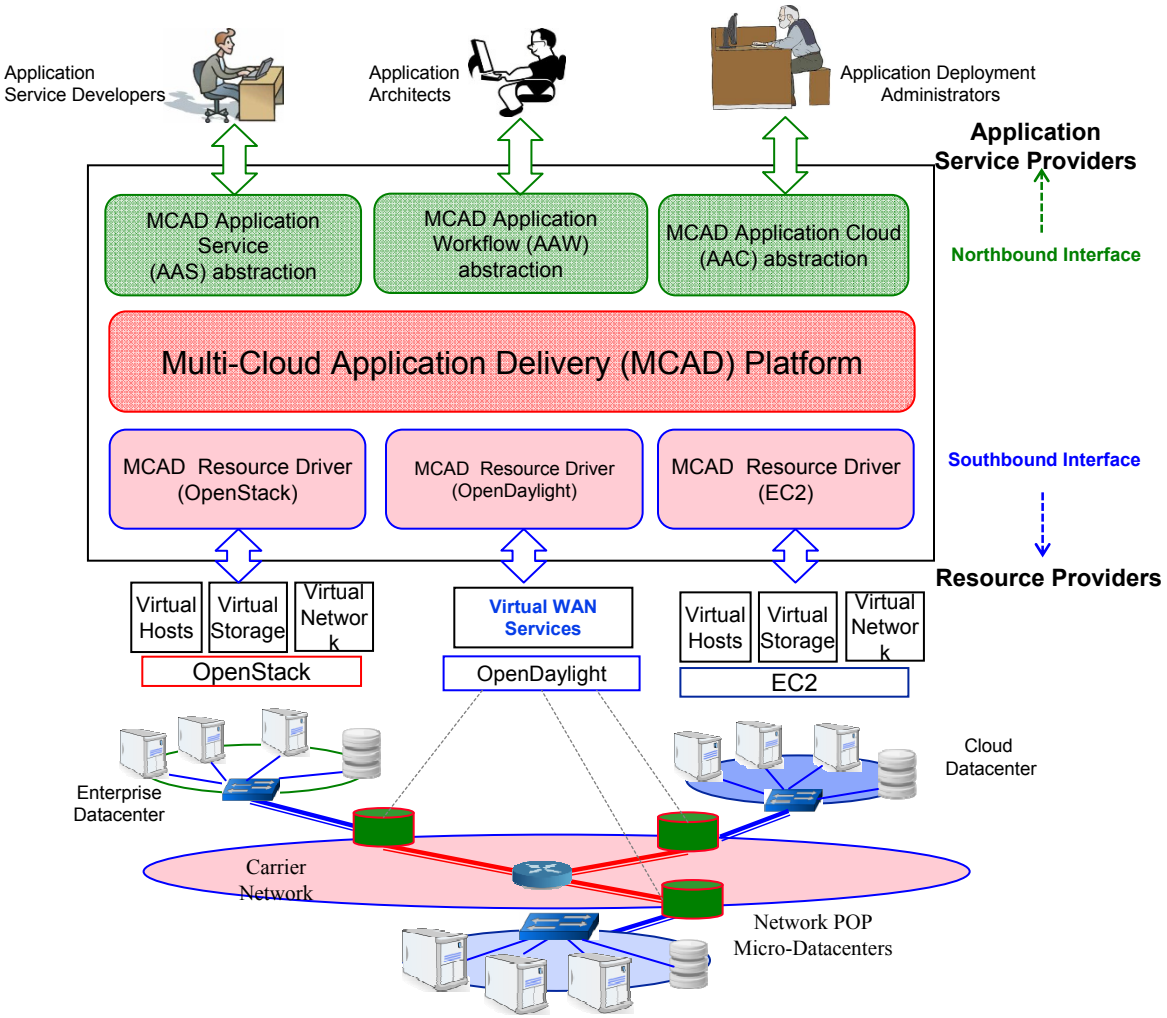
Ref: http://community.spiceworks.com/topic/254392-fog-computing-replaces-cloud-as-new-tech-buzzword

Trend 3: Multi-Cloud

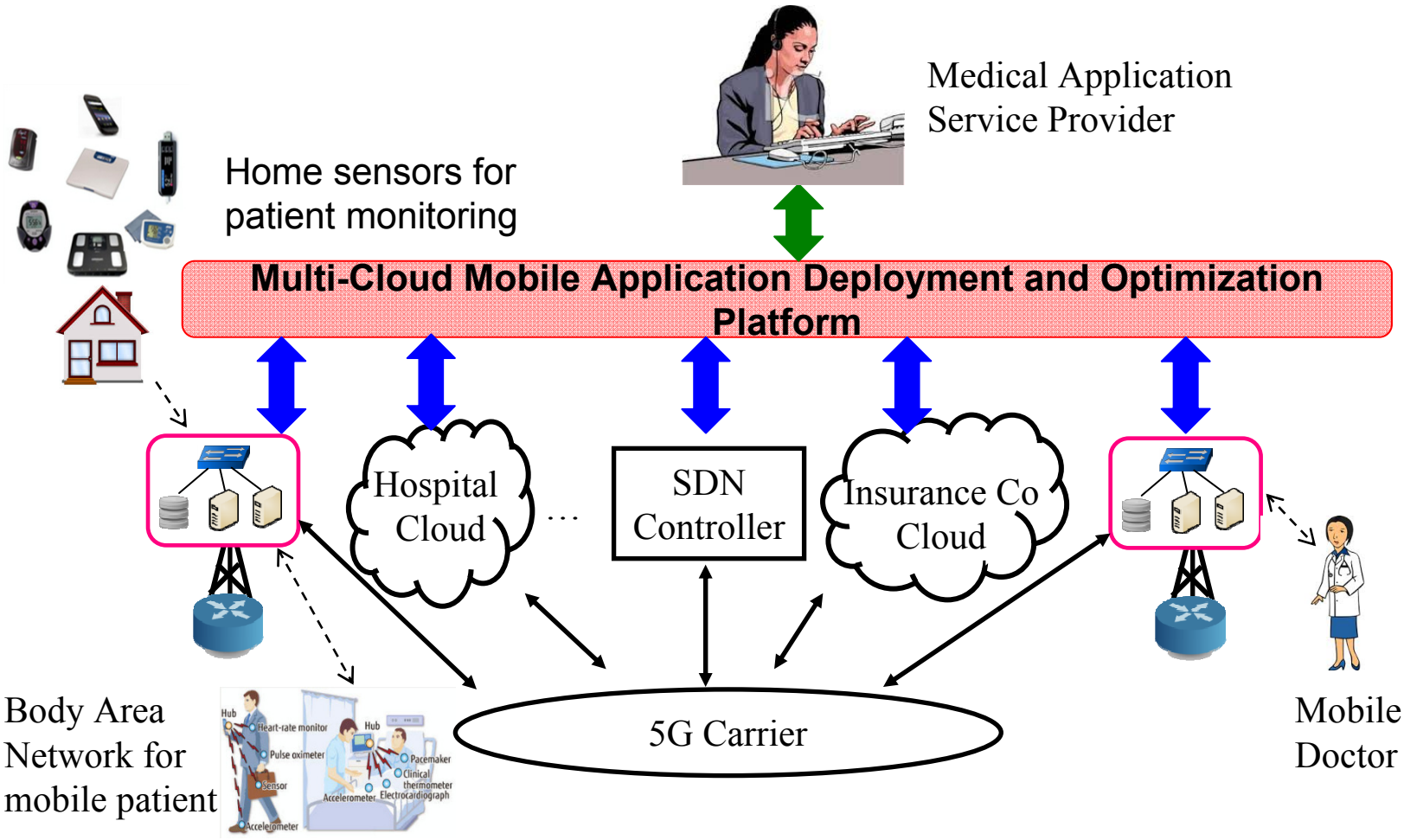
- Larger and infrequent jobs serviced by local and regional clouds ⇒ Fog Computing



Software Defined Multi-Cloud Application Management



Mobile Healthcare Use Case



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,…	**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, 802.11ah, Bluetooth Low Energy,** Z-Wave**, ZigBee Smart, DECT/ULE, 3G/LTE**, NFC, **Weightless,** HomePlug GP**, 802.15.4e, G.9959, WirelessHART, DASH7, ANT+, LTE-A, LoRaWAN,** ISA100.11a**,** DigiMesh**,** WiMAX, …		

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

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

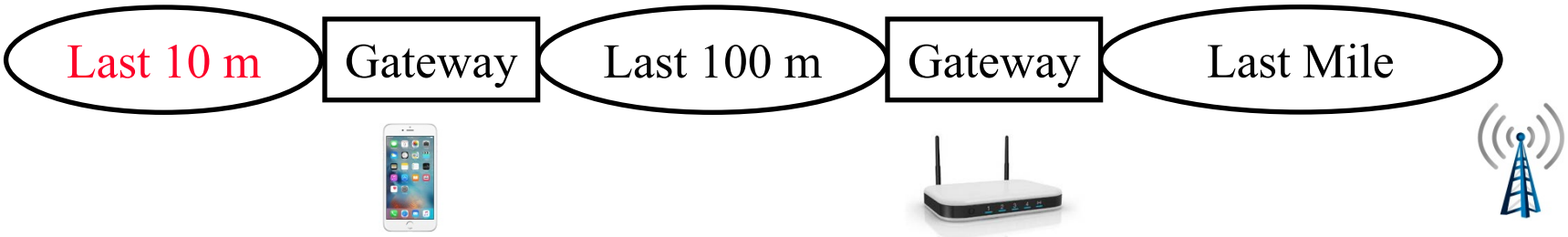
- Once connected, Bluetooth classic maintains connections even when there is no data. Low power but not low enough.

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

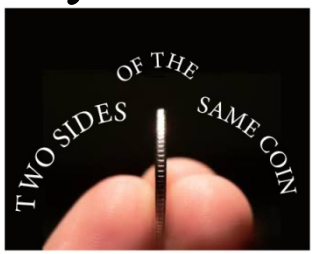
Last 100m Protocols

- The Last Mile: Mobile and Broadband Access revolution
  Smart Grid, Smart Cities, Smart Industries
- The last 100m: Smart home
- The last 10 meter: Smart Healthcare, Smart Wearable's



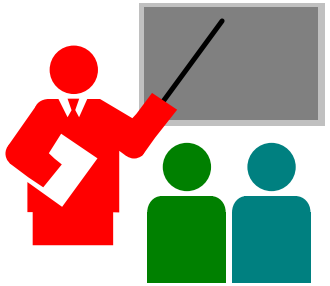
Machines vs. Human

- IoT will enable machines to handle many tasks currently handled by humans ⇒ Comfort + Unemployment
- Gartner predicts that by 2018:
  - 20% of business content authored by machines
  - 6B support calls from connected things
  - Digital assistants will recognize individuals by faces and voice
  - 3M (small) workers supervised by a "roboboss"
  - 2M (small) employees will be required to wear health tracking devices
  - 50% of fast growing companies will have fewer employees than smart machines



Ref: Gartner, "Top Strategic Predictions for 2016 and Beyond: The Future Is a Digital Thing," October 2015

Summary



1. Less than 1% of things are connected
   ⇒ IoT is a big opportunity for academics and industry
2. Smart Grid and Energy management is leading 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 ⇒ AppFabric

Reading List

- 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).

Optional:

- 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

Wikipedia Links (Cont)

- http://en.wikipedia.org/wiki/ANT%2B
- http://en.wikipedia.org/wiki/Near_field_communication,
- http://en.wikipedia.org/wiki/Weightless_%28wireless_communications%29
- https://en.wikipedia.org/wiki/Highway_Addressable_Remote_Transducer_Protocol
- https://en.wikipedia.org/wiki/Li-Fi
- https://en.wikipedia.org/wiki/LoRaWAN
- https://en.wikipedia.org/wiki/Thread_(network_protocol)
- https://en.wikipedia.org/wiki/Weightless_(wireless_communications)

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

Introduction to Vehicular Wireless Networks,
http://www.cse.wustl.edu/~jain/cse574-16/j_08vwn.htm

Introduction to 5G,
http://www.cse.wustl.edu/~jain/cse574-16/j_195g.htm

Wireless Protocols for IoT Part III: ZigBee,
http://www.cse.wustl.edu/~jain/cse574-16/j_13zgb.htm

Low Power WAN Protocols for IoT,
http://www.cse.wustl.edu/~jain/cse574-16/j_14ahl.htm

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