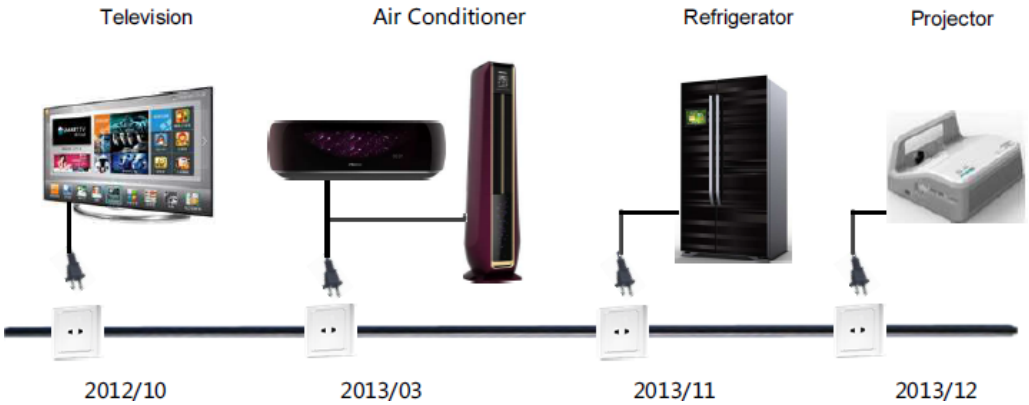
Introduction to Internet of Things



Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

These slides and audio/video recordings of this class lecture are at:
http://www.cse.wustl.edu/~jain/cse570-13/

Overview

1. What are "Things" and why IoT is important
2. Recent Protocols for IoT
3. IEEE 1901 - Power Line Communication (PLC)
4. IEEE 1905.1 - Convergent Digital Home Network

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

Machine-to-Machine (M2M)

- 1.1 Billion smart phones
- 244 Million smart meters
- 487 Million e-readers and tablets
- 2.37 Billion networked office devices
- 86 Million medical devices
- 45 Million connected automobiles
- 547 Million connected appliances
- 105 Million connected military devices
- 431 Million information technology devices
- 45 Million supervisory control and data acquisition (SCADA)
- 5+ Billion other (non-phone/tablet/e-reader) electronic devices

Ref: H. Zhou, "The Internet of Things in the Cloud: A Middleware Perspective," CRC Press, 2013, 365 pp., ISBN: 9781439892992 (Safari Book)

Internet of Things

- Only 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
  Industrial Internet by GE
  Cyber-Physical Systems (CPS)
  Internet of European Things (more popular in Europe)

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

Research Funding for IoT

- 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
  - Models, tools, and architectures for highly dependable CPS
  - Safety models and designs for CP medical systems
  - Cloud enablement of CPS
  - Software verification and validation for large scale CPS, e.g., next generation air transportation

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

Cyber Physical Systems

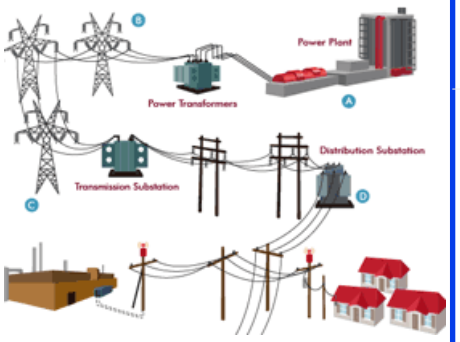
- CPS: Tight coupling between computing and physical components
  ⇒ Smart infrastructure
- Industrial Control Systems:
  - **Supervisory Control and Data Acquisition (SCADA)**: Over a large area spanning thousands of square kilometers, e.g., power grid, gas pipelines
  - **Distributed Control Systems (DCS)**: Within one location, e.g., wastewater treatment plant
  - **Programmable Logic Controllers**: Devices used in SCADA and DCS, e.g., assembly lines

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

CPS (Cont)

- **Electric Grid**: Smart Grid
- **Water Supply** and Waste Water
- **Chemical**: agricultural, pharmaceuticals, and other chemicals
- **Transportation**: Smart Bridges, Smart Cars, In-Aircraft systems
- **Healthcare**: Robotic assistance for the Elderly, tele-operational surgical robots
- Commercial **Buildings**

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

Recent Protocols for IoT

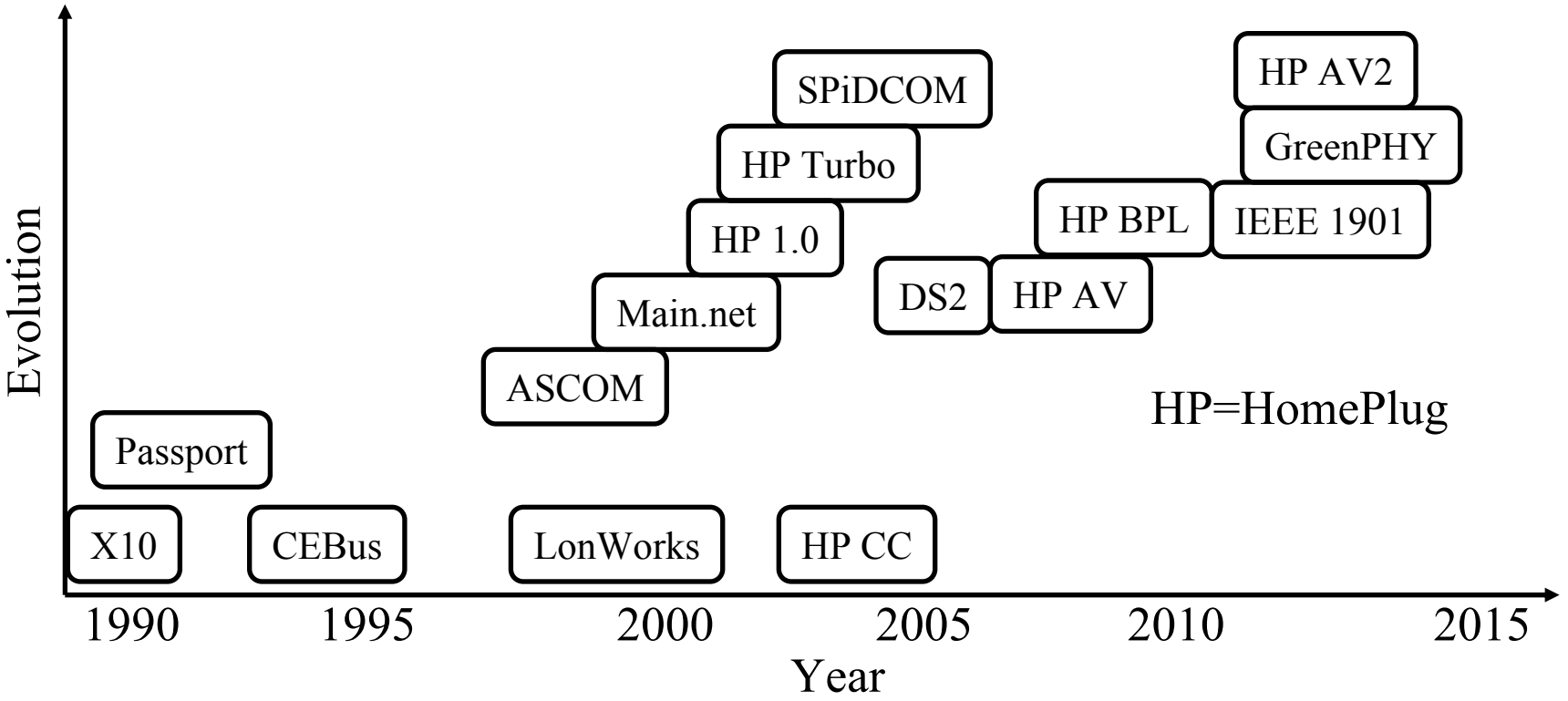
1. Powerline Communications (PLC)
2. IPv6 over Low Power Wireless Personal Area Network (6LowPAN)
3. Routing Protocol for Low Power and Lossy Networks (RPL)
4. ZigBee Smart Energy 2.0
5. ETSI M2M Architecture
6. MQ Telemetry Transport (MQTT)

Legacy IoT Protocols

- BACnet
- LonWorks
- ModBus
- KNX
- ZigBee
- Z-Wave
- M-Bus
- ANSI CI-12
- Device Language Message Specification (DLMS)/Company Specification for Energy Metering (COSEM)

Power Line Communication (PLC)

- Used in 1950 for remote ignition and lighting of street lights. 100 Hz and 1 kHz signals over electrical wires
- Two way systems using 3-148.5 kHz for reading electric meters, and home automation, alarms etc.



Ref: H. Chaouchi, "The Internet of Things: Connecting Objects," Wiley, Jun 2010, 288 pp., ISBN: 9781848211407 (Safari Book)

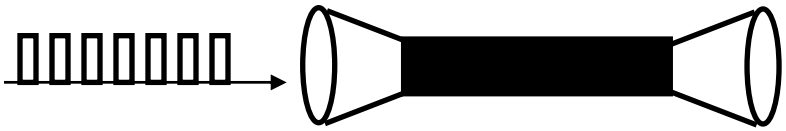
Broadband Over Power Lines (BPL)

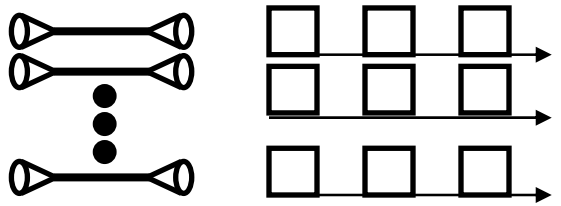
- High-speed internet connection using power lines (like DSL)
- IEEE 1901-2011 Broadband over Power Line standard
- Not cost competitive with optical fiber or DSL
  $\Rightarrow$ Suitable for remote locations
- High-frequency signal cannot pass through transformers and so the signal has to be bypassed using a repeater
- In US 1 transformer per house $\Rightarrow$ Very expensive
  In Europe: 1 transformer per 10-100 houses $\Rightarrow$ More cost effective
- Radio frequency interference with existing wireless services is avoided using OFDM

Ref: http://en.wikipedia.org/wiki/Broadband_over_power_lines

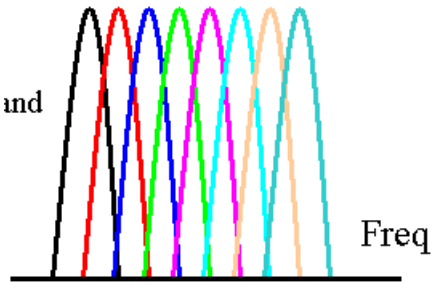
OFDM

- Orthogonal Frequency Division Multiplexing
- Ten 100 kHz channels are better than one 1 MHz Channel
  ⇒ Multi-carrier modulation





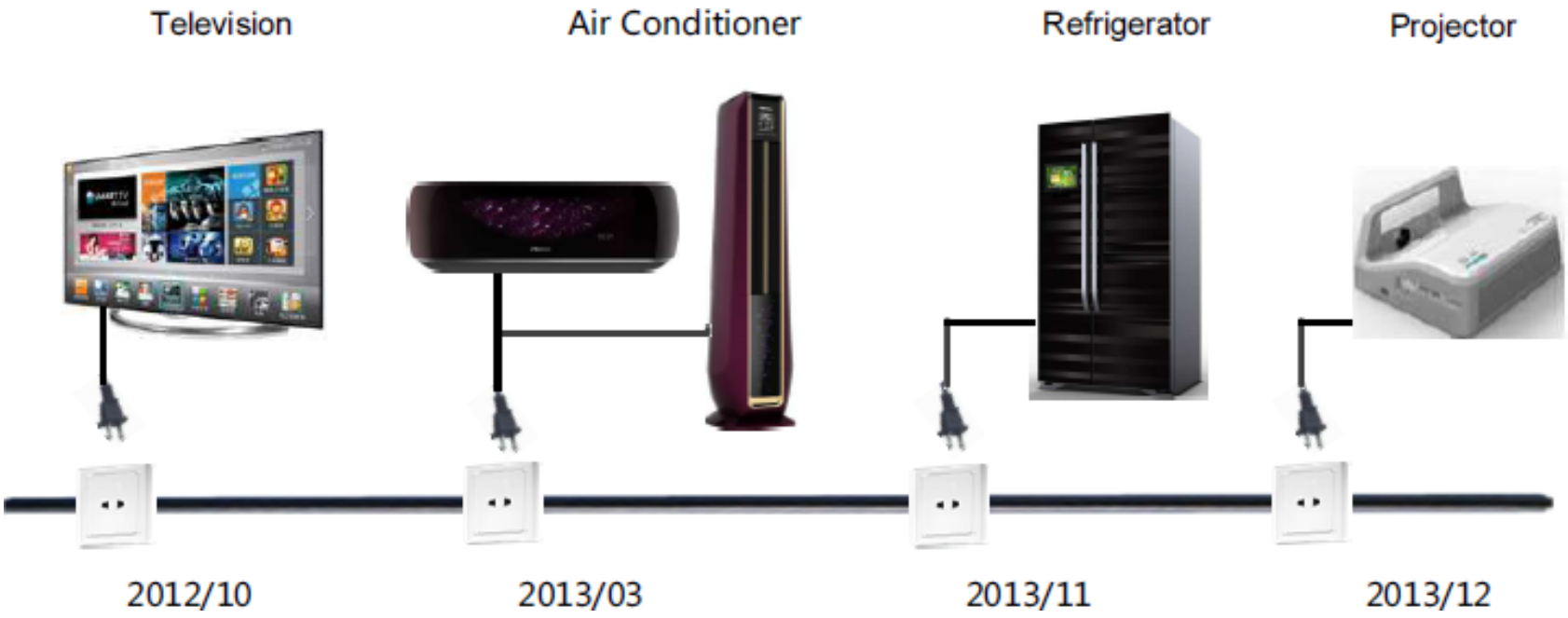
- Frequency band is divided into 256 or more sub-bands.
  Orthogonal ⇒ Peak of one at null of others
- Each carrier is modulated with a **BPSK** (2bps/Hz), **QPSK** (4 bps/Hz), **16-QAM** (8bps/Hz), **64-QAM** (16 bps/Hz) etc depending on the noise (Frequency selective fading)
- Used in 802.11a/g, 802.16,
  Digital Video Broadcast handheld (DVB-H)
- Easy to implement using FFT/IFFT



HomePlug

- HomePlug 1.0
- HomePlug AV
- HomePlug AV2
- HomePlug GP

Connected Home



Ref: HomePlug Alliance, "HomePlug Connected Home Summits 2013 Presentations," http://www.homeplug.org/tech/whitepapers/Connected_Home_Summits_2013.pdf

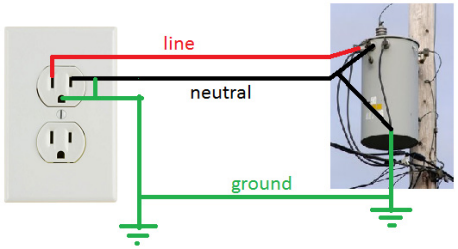
HomePlug AV

- Leading industry consortium for power line communications
  90% of PLC devices use HomePlug
- 1.8 MHz to 30 MHz spectrum = 28 MHz ⇒ 20 to 200 Mbps
- Multipath distortion
- **Orthogonal Frequency Division Multiplexing (OFDM):**
  Using 1155 carriers at 24.414 kHz spacing of which 917 are used for signal. Rest as pilots.
- **Adaptive bit loading**: Each carrier is modulated based on the noise level and multipath at that frequency.
  2-bits/symbol to 10 bits/symbol.
- **Tone Maps**: Each receiver keeps a table of signal strengths from each of the other receivers ⇒ n-1 tone maps in a n-device system

Ref: HomePlug Alliance, "HomePlug AV White Paper," http://www.homeplug.org/tech/whitepapers/HPAV-White-Paper_050818.pdf

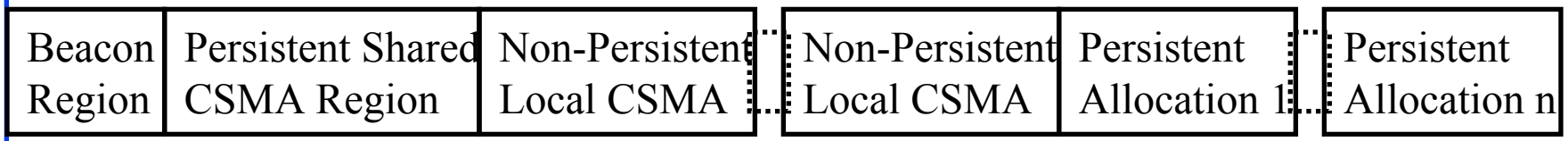
HomePlug AV (Cont)

- **Robust OFDM** (ROBO) mode for highly reliable transmission. The same information is transmitted on 2-5 subcarriers using a low-bit rate modulation
- Use only Line-neutral pair (ground is not used)
- Four channel access priorities
- MAC is similar to that of WiFi
  ⇒ **Carrier Sense Multiple Access (CSMA).**
- All devices part of the same trust domain form a "**AV Logical Network** (AVLN)."
- All members of the AVLN share a Network Membership Key 128-bit AES.
- Each AVLN has a **central coordinator (CCo)**



HomePlug AV (Cont)

- CCo transmits beacons containing schedule
- Long best effort transmissions declare their queues to CCo and use a pre-allocated **persistent shared CSMA** region
- Short best effort transmissions use **non-persistent CSMA** region.
- Real-time traffic uses periodic time division multiple access (TDMA) allocation in the **contention-free** period
- Before video transmission, the transmitter tests the channel for achievable throughput. Helps determine the required transmission interval per beacon period



HomePlug AV Security

- A station can participate in a AVLN if it has the **Network membership key (NMK)**.
  A station with multiple keys can participate in multiple AVLNs.
- All devices have a default NMK and so can form the network. Users should program the devices to use specific NMK.
- Once a devices has a NMK, it will be given the **network encryption key** which is used to encrypt the data.
- If there are multiple networks on the same wire, CCos coordinate their transmission schedules

HomePlug AV2

- Gigabit networking using home powerline wiring. Peak PHY rate of 1.256 Gbps. 600 Mbps net throughput.
- Can transmit multiple HD video streams
- Compatible with HomePlug AV devices on the same wires

1. **Additional Spectrum**: 2MHz-86MHz (84 MHz)
2. **Multiple-input Multiple-output (MIMO)**: transmissions using two wires with three-wire configuration (Line-Neutral, Line-Ground, Neutral-Ground)
3. **Beam forming**: Bit loading for each transmitter
4. **Lower overhead**: Shorter packet delimiter and delay acks.
5. **Efficient notching**: Of noisy carriers

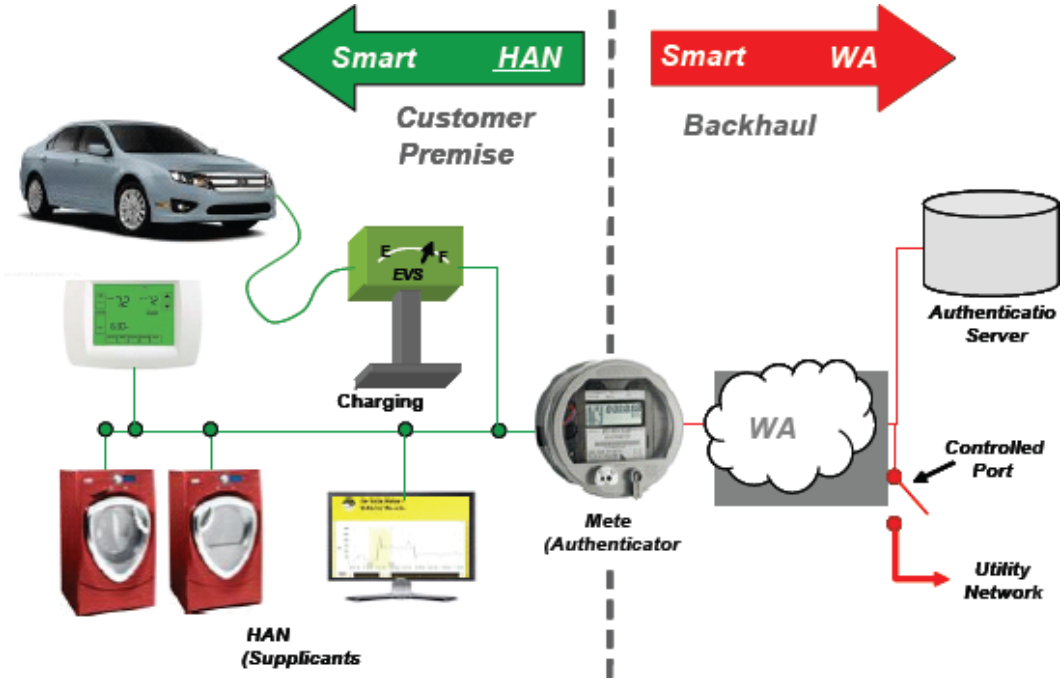
Ref: HomePlug Alliance, "HomePlug AV2 Technology," http://www.homeplug.org/tech/whitepapers/HomePlug_AV2_whitepaper_130909.pdf

HomePlug AV2 (Cont)

6. **Repeating**: Signal is demodulated and re-modulated at intermediate devices
7. **Better coding**: 12 bps/Hz and aggressive code rates (8/9)
8. **Power Control**: Manage transmission power to enhance coverage and throughput
9. **Power Save**: Stations can declare sleep periods. Other transmit only when the destination is awake.

HomePlug GreenPHY

- Designed for **home area network (HAN)** for monitoring and control of energy consuming/controlling devices including electric vehicle charging.
- Low cost. Low power. Low data rate version of HomePlug AV.



Ref: HomePlug Alliance, "HomePlug GreenPHY White Paper," http://www.homeplug.org/tech/whitepapers/HomePlug_Green_PHY_whitepaper_121003.pdf

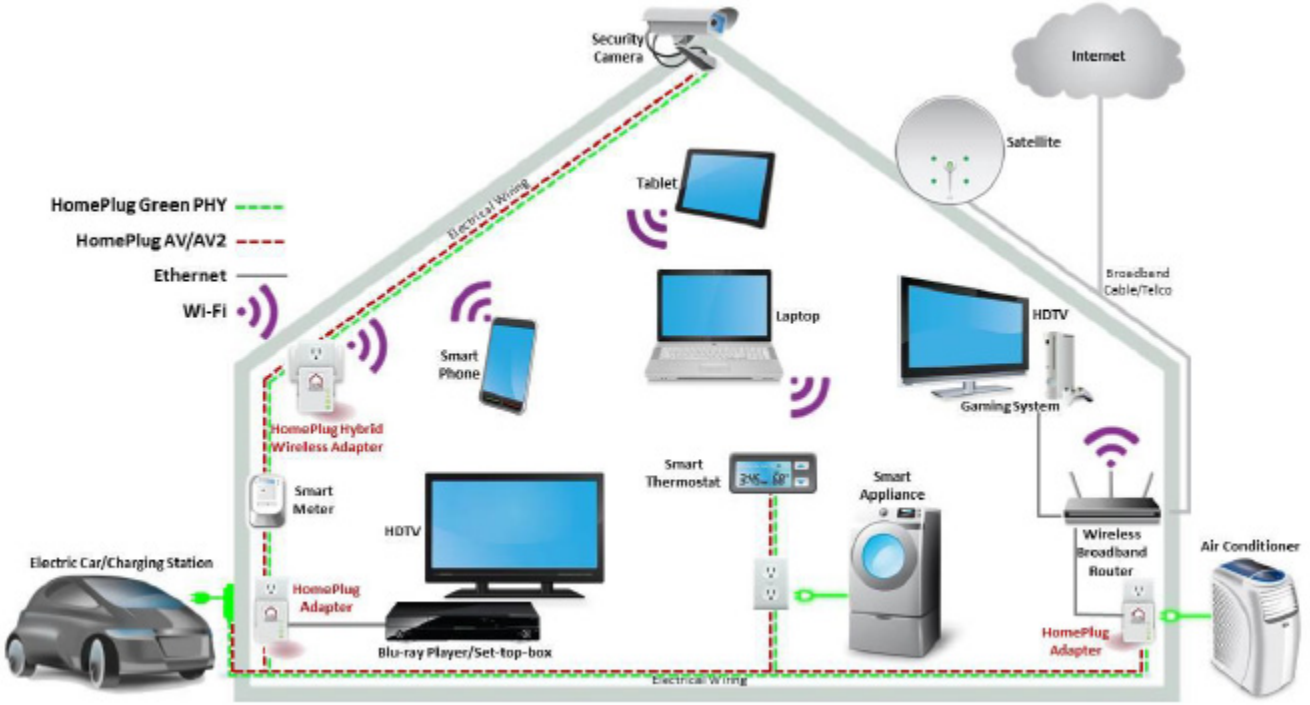
HomePlug GP (Cont)

- HomePlug GP is a profile of **IEEE 1901-2010** standard for Powerline Networks and is compatible with HomePlug AV and HomePlug AV2.
- 28 MHz ⇒ 256 kbps to 10 Mbps using only one modulation
  No tone maps.
- Use 75% less power than HomePlug AV.
  75% less bill of materials
- Devices coordinate their sleep cycle and may sleep for 2^n beacon intervals, n=1,..,10
- HomePlug GP 1.1 adds new power management and features for electric vehicles. Secure billing is possible at a public charging station.

Ref: HomePlug Alliance, "HomePlug GreenPHY Overview," http://www.homeplug.org/tech/whitepapers/HomePlug_GreenPHY_Overview.pdf

Convergent Digital Home Network

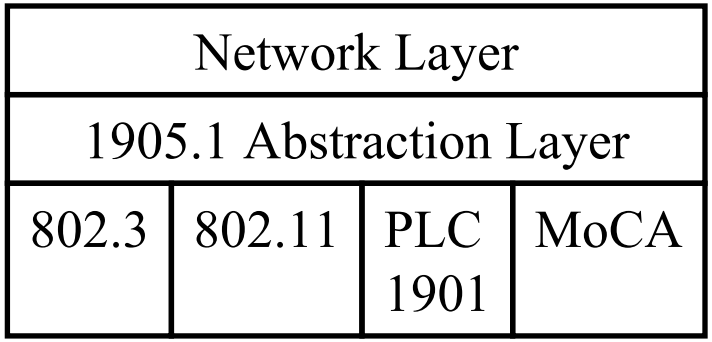
- IEEE 1905.1-2013 Convergent Digital Home Network for Heterogeneous Technologies
- Combined use of WiFi, HomePlug, Ethernet, Multimedia over Coax (MoCA) in a home



Ref: http://en.wikipedia.org/wiki/IEEE_1905

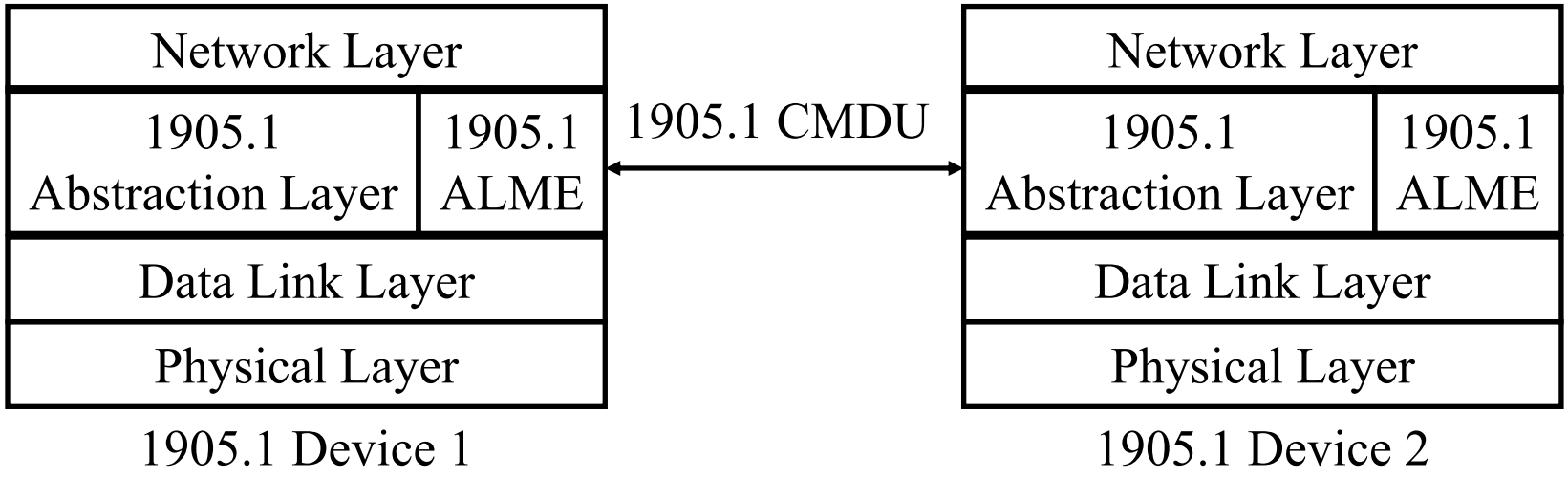
Convergent Digital Home (Cont)

- Entire home looks like a single network with automated provisioning, management, and operation
- Allows a device to aggregate throughput from multiple interfaces
- A link can be used fallback when another link fails
- An abstraction layer is used to exchange **Control Message Data Unit (CMDU)** among 1905.1 compliant devices
- No changes to underlying technologies is required.



IEEE 1905.1 Management

- 1905.1 compliant devices speak Abstraction Layer Management Entity (ALME) Protocol



1905.1 Device 1 1905.1 Device 2

IEEE 1905.1 Management (Cont)

- ALME has messages for
  - Neighbor discovery,
  - Topology exchange,
  - Topology change notification,
  - Measured traffic statistics exchange,
  - Flow forwarding rules, and
  - Security associations
- HomePlug AV2 can be used as a backbone for Wi-Fi
- Existing IEEE 802.1 bridging protocols are used for loop prevention and forwarding

IEEE 1905.1 Security and Configuration

- Security Setup:
  - **Push Button**: Press buttons on new and existing devices
    The new device gets the keys from the existing device
  - User can configure **passphrase/key** in the new device
  - **NFC**: User touches the new device with a NFC equipped smart phone which is existing member of the network
- Auto configuration:
  - New Access Points (APs) can get configuration information from existing APs
- The certification program for IEEE 1905.1 is called "**nVoy**"
  Connects disparate networks = Network Diplomat = Network Envoy
  $\Rightarrow$ nVoy
- Qualcomm Atheros products implementing IEEE 1905.1 are called **Hy-Fi** (for Hybrid Fidelity)

Netricity

- Long-range outside-the-home PLC for smart grid applications
- Certification for IEEE 1901.2 Low Frequency, Narrowband Powerline Communications Standard is called "Netricity"

Fieldbus

- Family of protocols for *short-range* real-time distributed industrial control systems standardized as IEC 61158
- Fieldbus connects programmable logic controllers to sensors, actuators, electric motors, console lights, switches, valves, and contractors
- Hundreds of nodes are connected to a single microcontroller using a *single* cable, e.g., 250 nodes on 13.2 km cable⇒ High-level Datalink Control (HDLC)-like master-slave communication with polling

Ref: H. Zhou, "The Internet of Things in the Cloud: A middleware Perspective," CRC Press, 2013, 366pp., ISBN:9781439892992 (Safari Book)
Ref: http://en.wikipedia.org/wiki/Fieldbus

Fieldbus (Cont)

- Collection of 8 different *incompatible* "Types"
  1. Foundation Fieldbus H1
  2. ControlNet
  3. PROFIBUS
  4. P-NET
  5. FOUNDATION Fieldbus High Speed Ethernet
  6. SwiftNet
  7. WorldFIP
  8. Interbus
- Only PHY, Datalink, and application layer
  $\Rightarrow$ No routing $\Rightarrow$ Need Ethernet/IP from microcontroller

Industrial Ethernet

- Same as regular Ethernet but with rugged connectors and designed for extended temperature/humidity environment
- Full duplex links (no CSMA/CD)
- Optical fibers (electrical interference)
- Min frame size of 64 byte may be too big for some applications

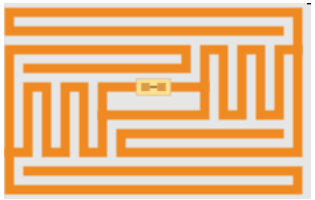
Ref: http://en.wikipedia.org/wiki/Industrial_Ethernet

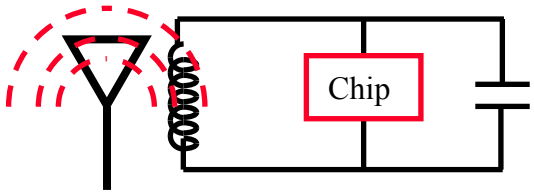
IEEE 1451

- Set of smart transducer interface for sensors and actuators
- Transducer electronic data sheets (TEDS) is a memory device that stores transducer id, calibration, correction data, and manufacturer information
- Allows access to transducer data regardless of wired or wireless connection
- XML based ⇒ Allows manufacturers to change the contents

Ref: http://en.wikipedia.org/wiki/IEEE_1451

Smart Cards





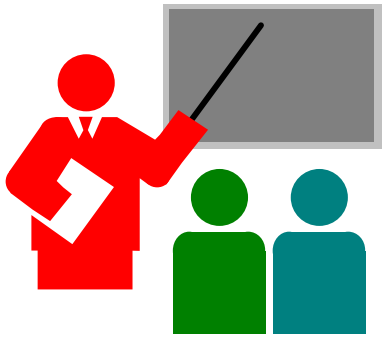
- Smart ⇒ With a processor
- Radio Frequency ID (RFID) is a subset
- Reader queries using RF, ID sends its ID using RF
- Used for retail loss prevention, toll collection, bus/rail passes, passports
- May have battery (active), no battery (passive), small battery (semi-passive)
- Get power from the reader by inductive or capacitive coupling
- Standards: ISO 14443 (Proximity ~10cm), ISO15693 (vicinity ~50cm), ECMA 340 (near field communication transceiver)
- More details in CSE 574 wireless networking course http://www.cse.wustl.edu/~jain/cse574-10/index.html

Smart Card Security Issues

1. Skimming: Read w/o knowledge of owner
2. Eavesdropping or sniffing: Man-in-the-middle
3. Data Tampering: Erasing or changing data
4. Spoofing: Mimic another source
5. Cloning: Making a copy of data
6. Malicious Code: Insertion of executable virus code
7. Denial of Service: Overwhelm the receiver's capacity
8. Killing: Disable
9. Jamming: Interfere with a strong signal
10. Shielding: Mechanically prevent reading

Ref: H. Zhou, "The Internet of Things in the Cloud: A middleware Perspective," CRC Press, 2013, 366pp., ISBN:9781439892992 (Safari Book)
Ref: http://en.wikipedia.org/wiki/Radio-frequency_identification#Security_concerns

Summary



1. Only 1% of things are connected ⇒ Big opportunity for IoT
2. Smart Grid and Energy management is leading the change.
3. HomePlug Powerline communication can provide up to 600 Mbps over electrical power lines
4. IEEE 1905.1 allows combining WiFi, Ethernet, and PLC, and Cable communication in a home
5. Fieldbus and Industrial Ethernet are used in manufacturing environments.
6. Smart cards including RFID allow short distance communication using active, passive, or semi-passive modes

Reading List

- HomePlug Alliance, "HomePlug AV White Paper," http://www.homeplug.org/tech/whitepapers/HPAV-White-Paper_050818.pdf
- HomePlug Alliance, "HomePlug AV2 Technology," http://www.homeplug.org/tech/whitepapers/HomePlug_AV2_whitepaper_130909.pdf
- HomePlug Alliance, "HomePlug Connected Home Summits 2013 Presentations," http://www.homeplug.org/tech/whitepapers/Connected_Home_Summits_2013.pdf
- HomePlug Alliance, "HomePlug GreenPHY Overview," http://www.homeplug.org/tech/whitepapers/HomePlug_GreenPHY_Overview.pdf
- HomePlug Alliance, "HomePlug GreenPHY White Paper," http://www.homeplug.org/tech/whitepapers/HomePlug_Green_PHY_whitepaper_121003.pdf
- 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

Wikipedia Links

- http://en.wikipedia.org/wiki/IEEE_1905
- http://en.wikipedia.org/wiki/IEEE_1901
- http://en.wikipedia.org/wiki/Broadband_over_power_lines
- http://en.wikipedia.org/wiki/Power_line_communication
- http://en.wikipedia.org/wiki/HomePlug
- http://en.wikipedia.org/wiki/Cyber-physical_system
- http://en.wikipedia.org/wiki/HomePlug_Powerline_Alliance
- http://en.wikipedia.org/wiki/MIMO
- http://en.wikipedia.org/wiki/SCADA
- http://en.wikipedia.org/wiki/Smart_grid
- http://en.wikipedia.org/wiki/G.hn
- http://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiplexing
- http://en.wikipedia.org/wiki/IEEE_Smart_Grid
- http://en.wikipedia.org/wiki/Fieldbus
- http://en.wikipedia.org/wiki/Industrial_Ethernet
- http://en.wikipedia.org/wiki/IEEE_1451

Wikipedial Links (Cont)

- http://en.wikipedia.org/wiki/List_of_broadband_over_power_line_deployments
- http://en.wikipedia.org/wiki/Qualcomm_Atheros
- http://en.wikipedia.org/wiki/G.9972
- http://en.wikipedia.org/wiki/Home_network
- http://en.wikipedia.org/wiki/SPiDCOM
- http://en.wikipedia.org/wiki/Smart_meter
- http://en.wikipedia.org/wiki/IEC_62196

References

- H. Chaouchi, "The Internet of Things: Connecting Objects," Wiley, Jun 2010, 288 pp., ISBN: 9781848211407 (Safari Book)
- H. Zhou, "The Internet of Things in the Cloud: A Middleware Perspective," CRC Press, 2013, 365 pp., ISBN: 9781439892992 (Safari Book)
- NITRD, http://www.nitrd.gov/
- NITRD, "FY 2014 Supplement to the President's Budget," http://www.nitrd.gov/Publications/PublicationDetail.aspx?pubid=48
- "Gartner Identifies Top 10 Strategic Technologies," http://www.cioinsight.com/it-news-trends/gartner-identifies-top-10-strategic-technologies.html
- Workshop on Future Directions in CPS Security, July 2009, http://www.ee.washington.edu/faculty/radha/dhs_cps.pdf

Acronyms

- 6LowPAN IPv6 over Low Power Wireless Personal Area Network
- AES Advanced Encryption Standard
- ALME Abstraction Layer Management Entity
- APs Access Points
- AV Audio-Visual
- AVLN Audio-Visual Logical Network
- BPL Broadband Over Power Lines
- BPSK Binary Phase-Shift Keying
- CCo Central Coordinator
- CMDU Control Message Data Unit
- CP Cyber Physical
- CPS Cyber Physical Systems
- CSIA Cyber Security and Information Assurance
- CSMA Carrier Sense Multiple Access
- DARPA Defense Advance Research Project Agency
- DCS DIstributed Control Systems
- DOE Department of Energy

Acronyms (Cont)

- DVB-H Digital Video Broadcast handheld
- FFT Fast Fourier Transform
- GE General Electric
- GP GreenPHY
- GreenPHY Green Physical Layer
- HAN Home Area Network
- HCSS High Confidence Software and Systems
- HD High Definition
- HDLC High-Level Datalink Control
- HEC High-End Computing
- HPAV HomePlug Audio-Visual
- IEEE Institution of Electrical and Electronic Engineers
- IFFT Inverse Fast Fourier Transform
- IM Information Management
- IoT Internet of Things
- IPv6 Internet Protocol V6
- IT Information Technology

Acronyms (Cont)

- kHz Kilo Hertz
- LSN Large Scale Networking
- MAC Media Access Control
- MHz Mega Hertz
- MIMO Multiple-input Multiple-output
- MoCA Multimedia over Coax
- MQTT MQ Telemetry Transport
- NASA National Aeronautical and Space Administration
- NFC Near Field Communication
- NIH National Institute of Health
- NITRD Networking and Info Technology Res and Development
- NMK Network Membership Key
- NSF National Science Foundation
- OFDM Orthogonal Frequency Division Multiplexing
- ONR Office of Naval Research
- PHY Physical Layer

Acronyms (Cont)

- PLC Power Line Communication
- QAM Quadrature Amplitude Modulation
- QPSK Quadrature Phase Shift Keying
- RFID Radio Frequency Identification
- RPL Routing Protocol for Low Power and Lossy Networks
- SCADA Supervisory Control and Data Acquisition
- SDP Software Design and Productivity
- TDMA Time division multiple access
- TEDS Transducer electronic data sheets