Bluetooth and Bluetooth Smart

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Audio/Video recordings of this class lecture are available on-line at:

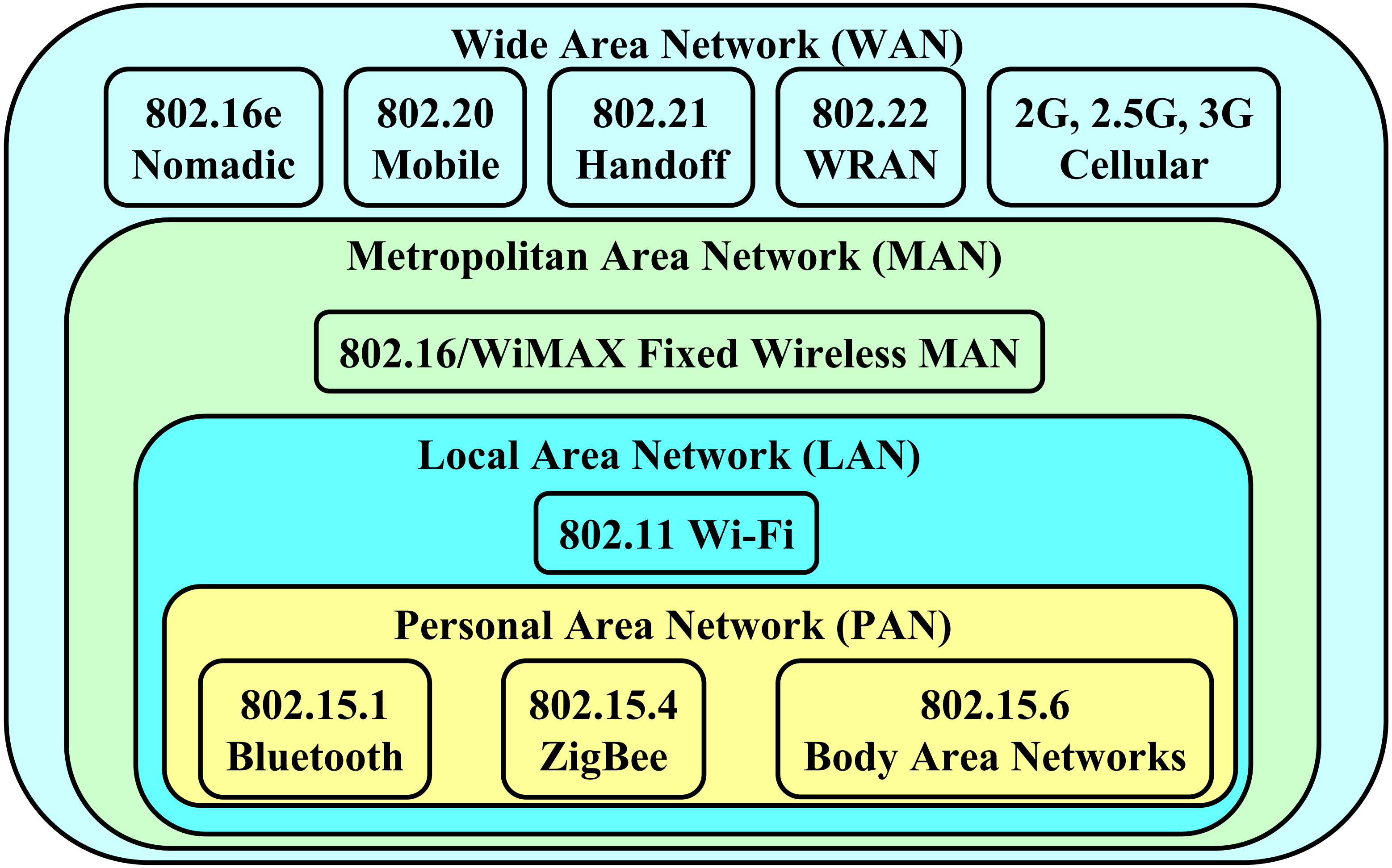
http://www.cse.wustl.edu/~jain/cse574-14/

1. Wireless Personal Area Networks (WPANs)
2. IEEE 802.15 Projects
3. Bluetooth: Packet Format, Energy Management
4. Bluetooth Protocol Stack, Application Profiles
5. Bluetooth LE: Protocol Stack, PHY, MAC
6. Bluetooth and WiFi Coexistence

Note: This is 1st in a series of lectures on WPANs. ZigBee and other networks are discussed in subsequent lectures.

Wireless Personal Area Networks (WPANs)

- 10m or less



WPAN: Design Challenges

- **Battery powered**: Maximize battery life. A few hours to a few years on a coin cell.
- **Dynamic topologies**: Short duration connections and then device is turned off or goes to sleep
- **No infrastructure**
- **Avoid Interference** due to larger powered LAN devices
- **Simple and Extreme Interoperability**: Billions of devices. More variety than LAN or MAN
- **Low-cost**: A few dollars

IEEE 802.15 Projects

- **IEEE 802.15.1-2005**: **Bluetooth** 1.2
- **IEEE 802.15.2-2003**: Coexistence Recommended Practice
- **IEEE 802.15.3-2003**: High Rate (55 Mbps) Multimedia WPAN
- IEEE 802.15.3a: Ultra-Wide Band Phy - disbanded
- **IEEE 802.15.3b-2005**: MAC Interoperability
- **IEEE 802.15.3c-2009**: High Rate (>1Gbps) mm Wave PHY
- **IEEE 802.15.4-2011**: Low Rate (250kbps) WPAN - **ZigBee**
- IEEE 802.15.4a-2007: Higher data rate PHY
- IEEE 802.15.4b: Enhancements and clarifications to 802.15.4-2003 (Completed and incorporated in 802.15.4-2006)
- IEEE 802.15.4c-2009: Sub 1 GHz PHY for China
- IEEE 802.15.4d-2009: Sub 1 GHz PHY for Japan
- **IEEE 802.15.4e-2012**: MAC Enhancements

IEEE 802.15 Projects (Cont)

- **IEEE 802.15.4f-2012**: PHY for Active RFID
- **IEEE 802.15.4g-2012**: PHY for Smart Utility Networks
- IEEE 802.15.4h: 802.15.4 Corrigendum 1
- IEEE 802.15.4i: 802.15.4 Roll-up to include 15.4a, c & d
- IEEE 802.15.4j-2013: Medical Body Area Network 2.36-2.4 GHz
- **IEEE 802.15.4k-2013**: Low Energy Critical Infrastructure Monitoring PHY
- **IEEE P802.15.4m**: TV White Spaces PHY
- IEEE P802.15.4n: China Medical Band PHY
- IEEE P802.15.4p: Positive Train Control (Rail Communications & Control) PHY
- IEEE P802.15.4q: Ultra Low Power PHY

IEEE 802.15 Projects (Cont)

- IEEE 802.15.4r: 15.4 Roll up for e, f, g, j, and k
- **IEEE 802.15.5-2009**: Mesh Networking. Full/partial meshes. Range Extension
- **IEEE 802.15.6-2012**: Body Area Networking. Medical and entertainment. Low power
- **IEEE 802.15.7-2011**: Visible Light Communications
- IEEE P802.15.8: New standard for Peer Aware Communications
- IEEE P802.15.9: Key Management Protocol
- IEEE P802.15.10: Layer 2/Mesh Under Routing
- IEEE 802.15 SG4r: Common Ranging Protocol Study Group
- IEEE 802.15 SG4s: EU Regional PHY support Study Group

IEEE 802.15 Projects (Cont)

- IEEE 802.15 SG7a: Optical Camera Comm. Study Group
- IEEE 802.15 SGsru: Spectrum Resources Usages in WPANs Study Group
- IEEE 802.15 IGdep: Enhanced Dependability Interest Group
- IEEE 802.15 IGled: LED-ID system for 15.7 Interest Group
- IEEE 802.15 SCmag: Maintenance Group Standing Committee
- IEEE 802.15 SCwng: Wireless Next Generation Standing Committee
- IEEE 802.15.IGthz: Tera-Hertz Interest Group
- IEEE 802.15 IG6T: 6TiSCH IETF Liaison Interest Group
- IEEE 802.15 SG100G: 100 Gbps Wireless Study Group

Bluetooth Products

Headsets

Audio

Game Controller

Keyboard

GPS

- Printers, faxes, digital cameras…
- 720 kbps to 10m initially
- Competes with infrared, which has a range of 1m, requires line of sight and has a low data rate

Bluetooth

- Started with Ericsson's Bluetooth Project in 1994 for radio-communication between cell phones over short distances
- Named after Danish king Herald Blatand (AD 940-981) who was fond of blueberries
- Intel, IBM, Nokia, Toshiba, and Ericsson formed Bluetooth SIG in May 1998
- Version 1.0A of the specification came out in late 1999.
- IEEE 802.15.1 approved in early 2002 is based on Bluetooth Later versions handled by Bluetooth SIG directly
- Key Features:
  - Lower Power: 10 μA in standby, 50 mA while transmitting
  - Cheap: $5 per device
  - Small: 9 mm^2 single chips

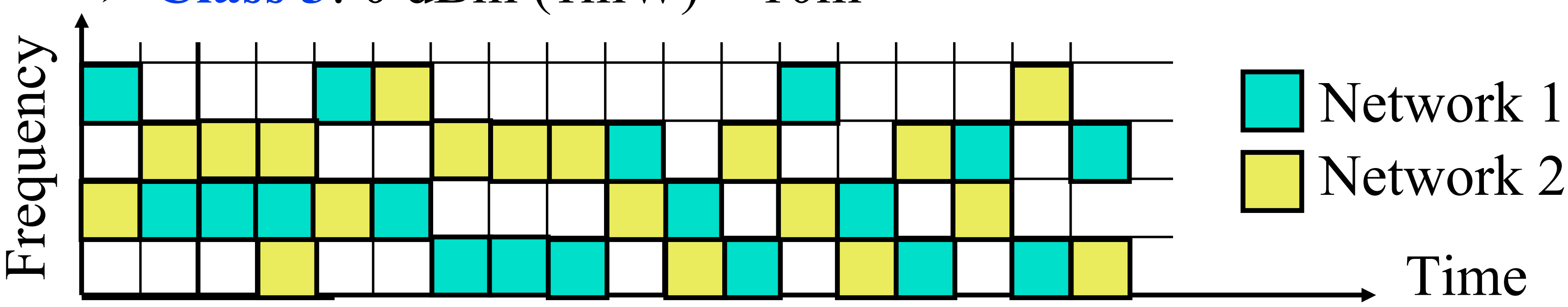
Bluetooth Versions

- **Bluetooth 1.1**: IEEE 802.15.1-2002
- **Bluetooth 1.2**: IEEE 802.15.1-2005. Completed Nov 2003. Extended SCO, Higher variable rate retransmission for SCO + Adaptive frequency hopping (avoid frequencies with interference).
- **Bluetooth 2.0** + Enhanced Data Rate (EDR) (Nov 2004): 3 Mbps using DPSK. For video applications. Reduced power due to reduced duty cycle
- **Bluetooth 2.1** + EDR (July 2007): Secure Simple Pairing to speed up pairing
- **Bluetooth 3.0**+ High Speed (HS) (April 2009): 24 Mbps using WiFi PHY + Bluetooth PHY for lower rates
- **Bluetooth 4.0** (June 2010): Low energy. Smaller devices requiring longer battery life (several years). New incompatible PHY. Bluetooth Smart or BLE
- **Bluetooth 4.1**: 4.0 + Core Specification Amendments (CSA) 1, 2, 3, 4

Ref: ITL, "Security of Bluetooth Systems and Devices," http://csrc.nist.gov/publications/nistbul/august-2012_itl-bulletin.pdf

Bluetooth: Details

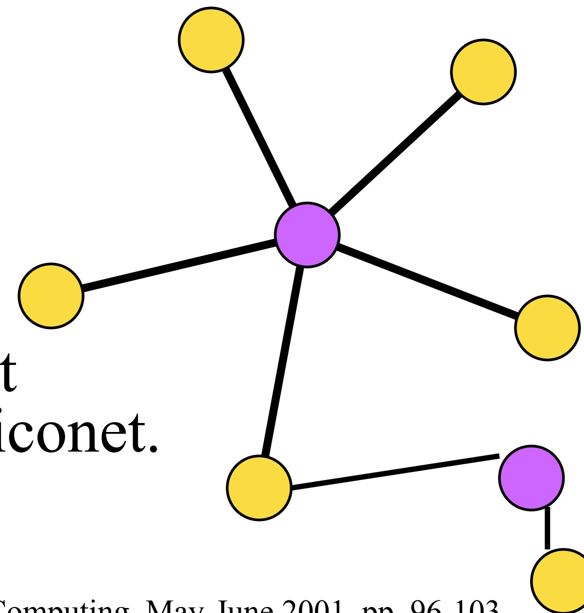
- **Frequency Range:** 2402 - 2480 MHz (total 79 MHz band) 23 MHz in some countries, e.g., Spain
- **Data Rate:** 1 Mbps using 1 MHz (Nominal) 720 kbps (User)
- **Radio Frequency hopping:** 1600 times/s $\Rightarrow$ 625 µs/hop
- **Security:** Challenge/Response Authentication. 128b Encryption
- **TX Output Power:**
  - Class 1: 20 dBm Max. (0.1W) – 100m
  - Class 2: 4 dBm (2.5 mW)
  - **Class 3**: 0 dBm (1mW) – 10m



Ref: http://www.bluetooth.com/, http://www.bluetooth.org/, http://grouper.ieee.org/groups/802/15/index.html

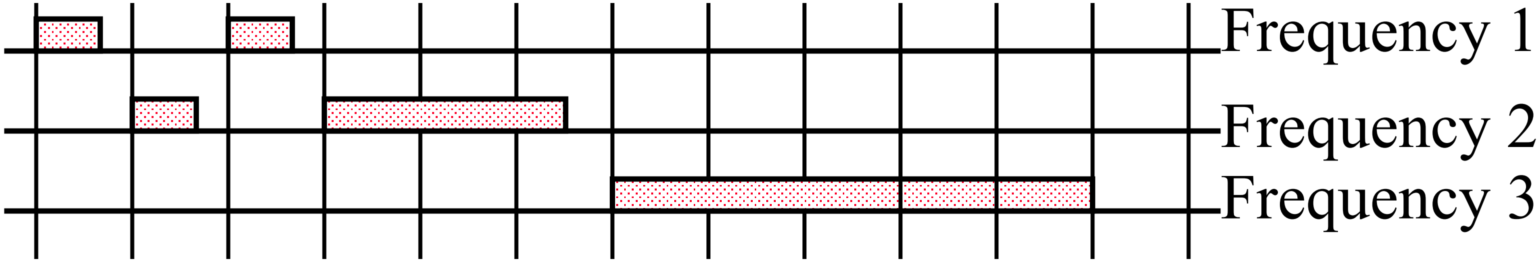
Piconet

- Piconet is formed by a master and many slaves
  - Up to 7 active slaves.
    Slaves can only transmit when requested by master
  - Up to 255 Parked slaves
- Active slaves are polled by master for transmission
- Each station gets a 8-bit parked address
  $\Rightarrow$ 255 parked slaves/piconet
- The parked station can join in 2ms.
- Other stations can join in more time.
- **Scatter net**: A device can participate in multiple Pico nets $\Rightarrow$ Timeshare and must synchronize to the master of the current piconet. Routing protocol not defined.



Ref: P. Bhagwat, "Bluetooth Technology for short range wireless Apps," IEEE Internet Computing, May-June 2001, pp. 96-103, bluetooth.pdf (Must read)

Frequency Hopping Sequences



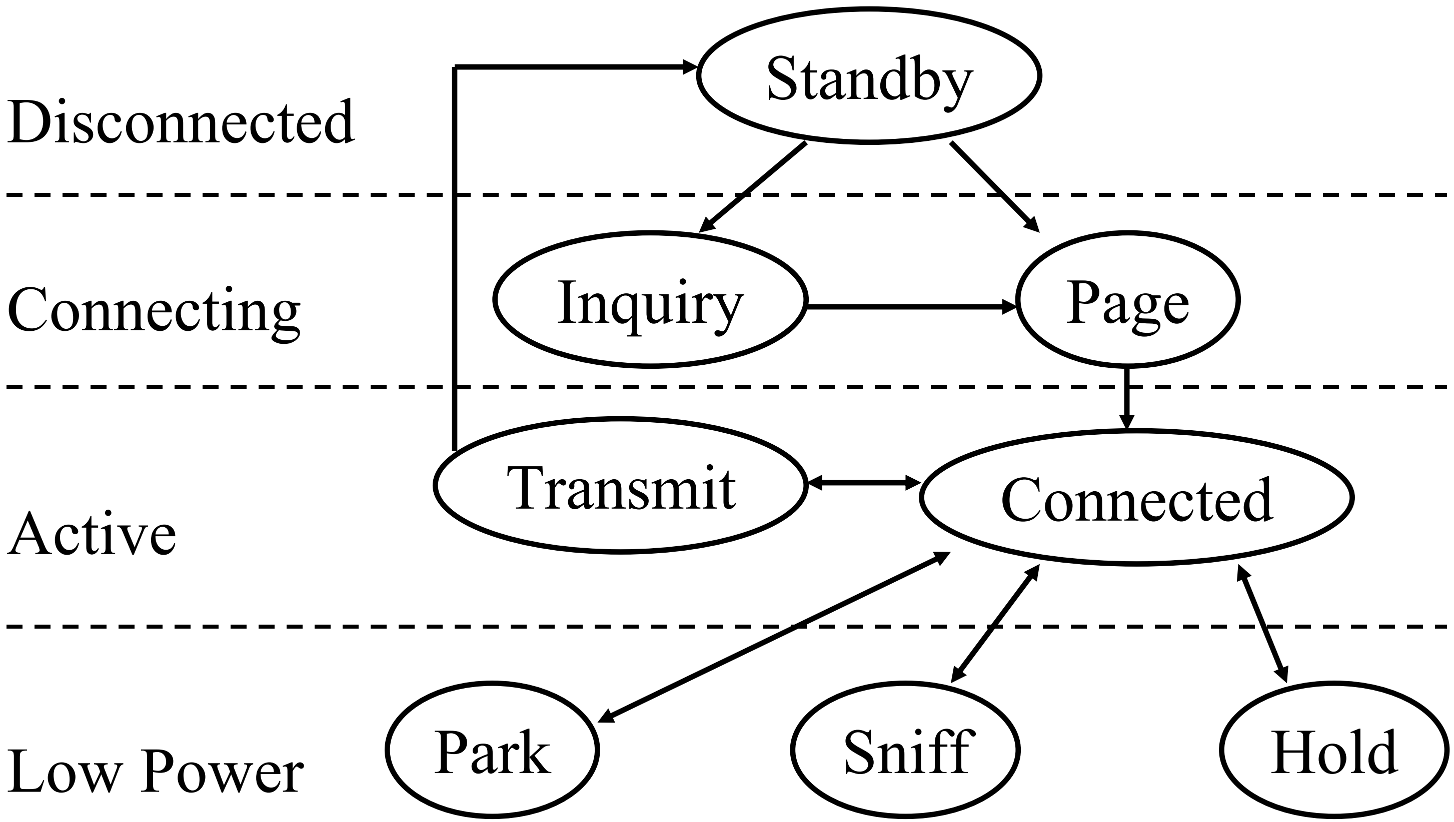
- 625 μs slots using a 312.5 μs clock
- Time-division duplex (TDD)
  ⇒ Downstream and upstream alternate
- Master starts in even numbered slots only.
- Slaves start in odd numbered slots only
- Slaves can transmit in one slot right after receiving a packet from master
- Packets = 1 slot, 3 slot, or 5 slots long
- The frequency hop is skipped during a packet.

Bluetooth Packet Format

Access Code	Baseband/Link Control Header	Data Payload
72b	54b	0-2745b

- Packets can be up to five slots long. 5 slots =3125 bits.
- Access codes:
  - Channel access code identifies the piconet
  - Device access code for paging requests and response
  - Inquiry access code to discover units
- Header: member address (3b), type code (4b), flow control, ack/nack (1b), sequence number, and header error check (8b) 18b Header is encoded using 1/3 rate FEC resulting in 54b
- Synchronous traffic has periodic reserved slots.
- Other slots can be allocated for asynchronous traffic

Bluetooth Operational States



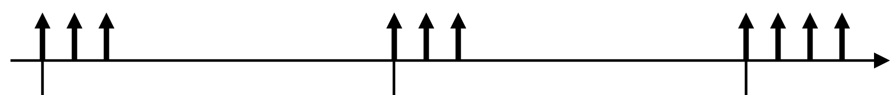
Bluetooth Operational States (Cont)

- **Standby**: Initial state
- **Inquiry**: Master sends an inquiry packet. Slaves scan for inquiries and respond with their address and clock after a random delay (CSMA/CA)
- **Page**: Master in page state invites devices to join the piconet. Page message is sent in 3 consecutive slots (3 frequencies). Slave enters page response state and sends page response including its device access code.
- Master informs slave about its clock and address so that slave can participate in piconet. Slave computes the clock offset.
- **Connected**: A short 3-bit logical address is assigned
- **Transmit**:

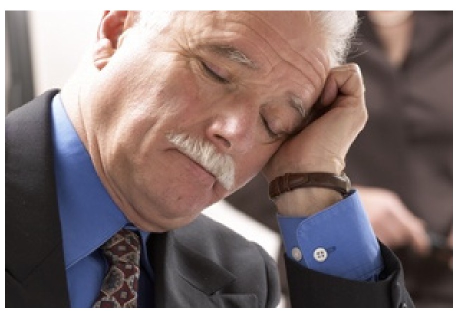
Energy Management in Bluetooth

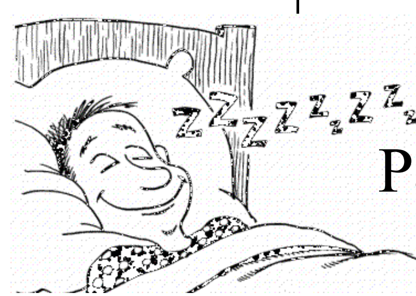
Three inactive states:

1. **Hold**: No Asynchronous Connection List (ACL). Synchronous Connection Oriented (SCO) continues.
   Node can do something else: scan, page, inquire
2. **Sniff**: Low-power mode. Slave listens after fixed sniff intervals.
3. **Park**: Very Low-power mode. Gives up its 3-bit active member address and gets an 8-bit parked member address. Wake up periodically and listen to beacons. Master broadcasts a train of beacons periodically



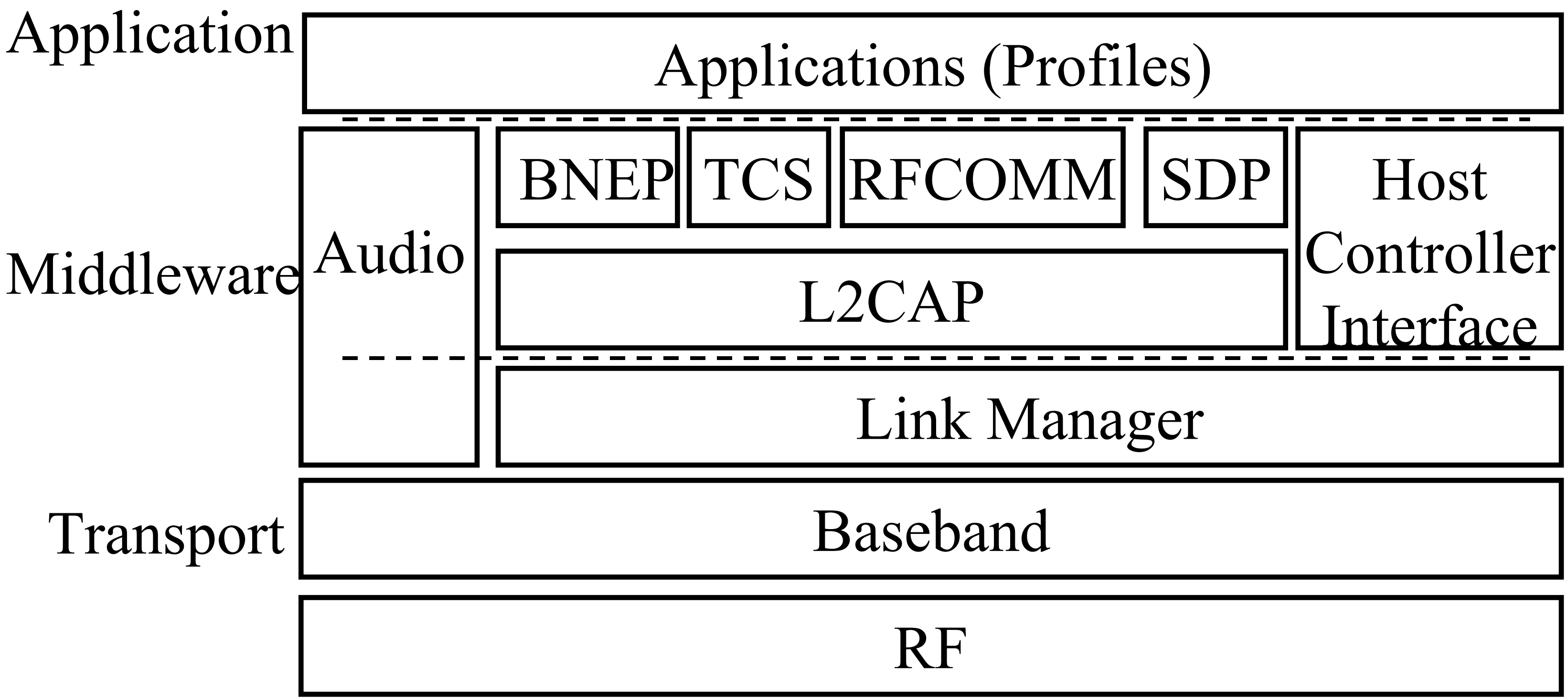
Sniff





Park

Bluetooth Protocol Stack



- **RF**: Frequency hopping Gaussian Frequency Shift Keying (GFSK) r
- **Baseband**: Frequency hop selection, connection, MAC

Baseband Layer

- Each device has a 48-bit IEEE MAC address
- 3 parts:
  - Lower address part (LAP) – 24 bits
  - Upper address part (UAP) – 8 bits
  - Non-significant address part (NAP) - 16 bits
- UAP+NAP = Organizationally Unique Identifier (OUI) from IEEE
- LAP is used in identifying the piconet and other operations
- Clock runs at 3200 cycles/sec or 312.5 µs (twice the hop rate)

Upper Address Part	Non-sig. Address Part	Lower Address Part
8b	16b	24b

Bluetooth Protocol Stack (Cont)

- **Logical Link Control and Adaptation Protocol (L2CAP)**:
  - Protocol multiplexing
  - Segmentation and reassembly
  - Controls peak bandwidth, latency, and delay variation
- Host **Controller Interface**: Chip independent interface to Bluetooth chip. Allows same software to run on all chips.
- **RFCOMM Layer**:
  - Presents a virtual serial port
  - Sets up a connection to another RFCOMM
- **Service Discovery Protocol (SDP):** Devices can discover the services offered and their parameters
- **Bluetooth Network Encapsulation Protocol (BNEP):** To transport Ethernet/IP packets over Bluetooth

Bluetooth Protocol Stack (Cont)

- **IrDA Interoperability protocols**: Allow existing IrDA applications to work w/o changes
- IrDA object Exchange (IrOBEX) and Infrared Mobile Communication (IrMC) for synchronization
- **Audio** is carried over 64 kbps over SCO links over baseband
- **Telephony control specification binary (TCS-BIN)**: implements call control including group management (multiple extensions, call forwarding, and group calls)
- **Application Profiles**: Set of algorithms, options, and parameters. Standard profiles: Headset, Cordless telephony, Intercom, LAN, Fax, Serial line (RS232 and USB).

Application Profile Examples

- Headset Profile
- Global Navigation Satellite System Profile
- Hands-Free Profile
- Phone Book Access Profile
- SIM Access Profile
- Synchronization Profile
- Video Distribution Profile
- Blood Pressure Profile
- Cycling Power Profile
- Find Me Profile
- Heart Rate Profile
- Basic Printing Profile
- Dial-Up Networking Profile
- File Transfer Profile

Ref: Bluetooth SIGn, "Adopted Bluetooth Profiles, Services, Protocols and Transports," https://www.bluetooth.org/en-us/specification/adopted-specifications

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.

Bluetooth and WiFi Coexistence

- Bluetooth frequency hops in 1 MHz carriers over 2402 - 2480 MHz (79 MHz total)
- WiFi uses OFDM with 52 subcarriers in 20 MHz channels in 2402-2480 MHz (3 non-overlapping channels)
- Most computers have both Bluetooth and WiFi
- Collaborative Strategies: Two networks on the same device
- Non-Collaborative Strategies: No common device

Collaborative Coexistence Strategies

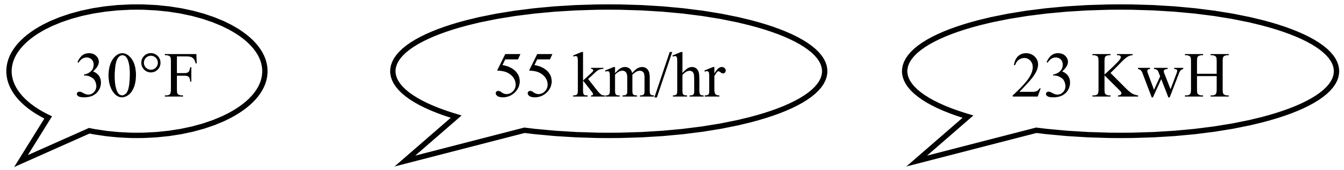
- Both networks on the same equipment (Laptop or IPhone):
  1. Time Division: Bluetooth skips slots when WiFi is busy, WiFi reserves time for Bluetooth between Beacons
  2. Packet Traffic Arbitration: Packets are prioritized and queued on a common queue for transmission
  3. Notch Filter: WiFi OFDM does not use subcarriers to which Bluetooth hops

Non-Collaborative Coexistence Strategies

- Measure noise level and error rate:
  Random bit errors $\Rightarrow$ Noise
  1. Adaptive Packet Selection: Bluetooth uses coding (FEC and Modulation) depending upon interference. Use FEC only if noise. No FEC if interference.
  2. Master Delay Policy: Bluetooth keeps track of error rates on various frequencies. Refrains from transmission on frequencies where interference is high
  3. Adaptive frequency hoping: Hop over only good frequencies
  4. Adaptive Notch Filter on WiFi

State

- Sensors periodically announce their "state"



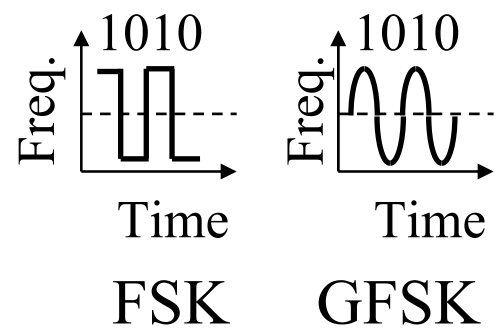
- Small data transfers
- Event triggered or polled.
- Gateway devices, e.g., cell phones, can transfer this data to Internet.
- Sensors do not need to speak IP.

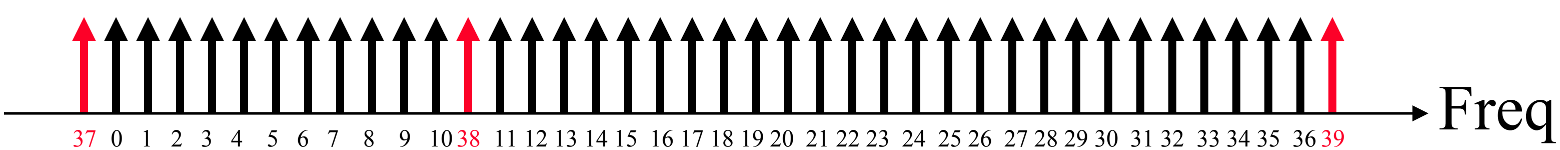
Bluetooth Smart

- **Low Energy**: 1% to 50% of Bluetooth classic
- **For short broadcast**: Your body temperature, Heart rate, Wearables, **sensors**, automotive, industrial.
  Not for voice/video, file transfers, …
- **Small messages**: 1Mbps data rate but throughput not critical.
- **Battery life**: In years from coin cells
- **Simple**: Star topology. No scatter nets, mesh, …
- **Lower cost** than Bluetooth classic
- New protocol design based on Nokia's **WiBree** technology
  Shares the same 2.4GHz radio as Bluetooth
  ⇒ Dual mode chips
- All new smart phones (iPhone, Android, …) have dual-mode chips

Bluetooth Smart PHY

- 2.4 GHz. 150 m open field
- Star topology
- 1 Mbps Gaussian Frequency Shift Keying
  Better range than Bluetooth classic
- Adaptive Frequency hopping. 40 Channels with 2 MHz spacing.
- 3 channels reserved for advertizing and 37 channels for data
- Advertising channels specially selected to avoid interference with WiFi channels

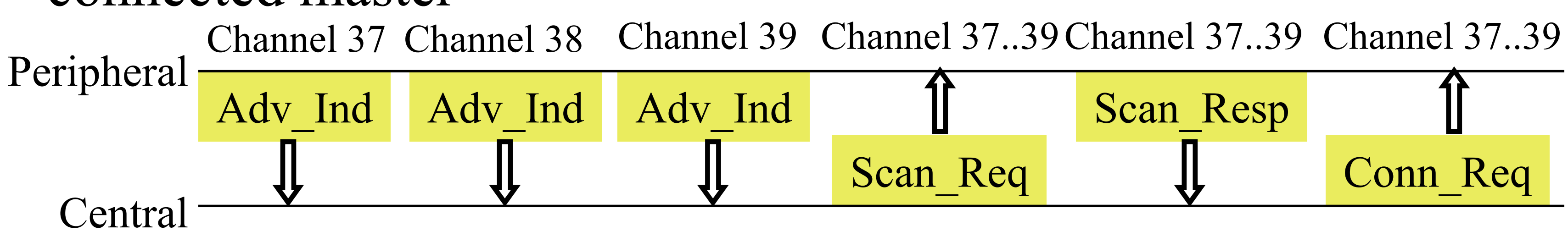




Ref: J. Decuir, "Bluetooth 4.0: Low Energy,'2010, http://chapters.comsoc.org/vancouver/BTLER3.pdf

Bluetooth Smart MAC

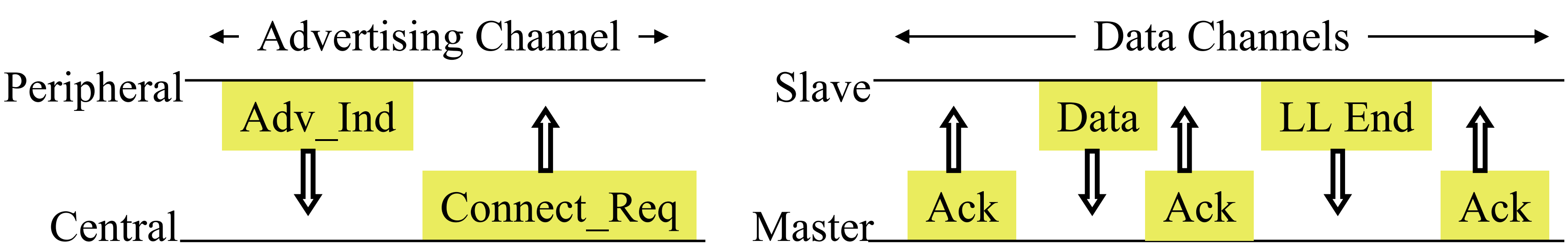
- Two Device Types: "**Peripherals**" simpler than "**central**"
- Two PDU Types: Advertising, Data
- **Non-Connectable Advertising**: Broadcast data in clear
- **Discoverable Advertising**: Central may request more information. Peripheral can send data without connection
- **General Advertising**: Broadcast presense wanting to connect. Central may request a short connection.
- **Directed Advertising**: Transmit signed data to a previously connected master



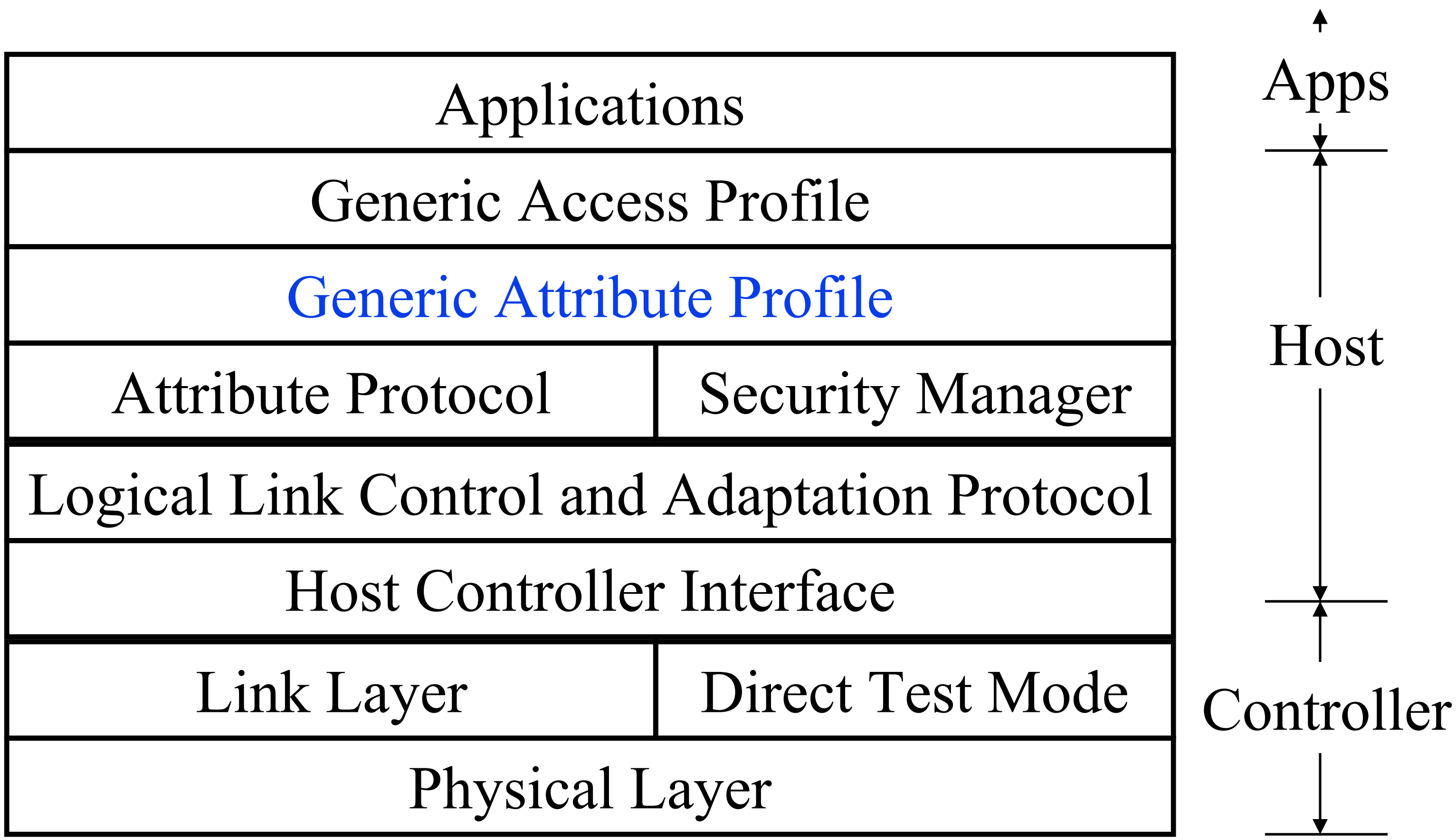
Ref: J. Decuir, "Bluetooth 4.0: Low Energy,'2010, http://chapters.comsoc.org/vancouver/BTLER3.pdf

Bluetooth Smart MAC (Cont)

- After connecting, master tells slave about hopping sequence and wake up cycle
- All subsequent data transfers in 37 data channels
- Both devices can sleep between transactions
- Data can be encrypted.
- ~3 ms per transaction, 15 mW Power = 10 mA using 1.5V
  $\Rightarrow$ 30μAs/transaction
  $\Rightarrow$ 21.6 M transactions using 180 mAh battery
  $\Rightarrow$ 41.1 years with 1 transaction/minute



Bluetooth Smart Protocol Stack



Ref: J. Decuir, "Bluetooth 4.0: Low Energy,'2010, http://chapters.comsoc.org/vancouver/BTLER3.pdf

Generic Attribute (GATT) Profile

- Defines data formats and interfaces with the Attribute Protocol
- Type-Length-Value (TLV) encoding is used
- Each attribute has a 16-bit Universally Unique ID (UUID) standardized by Bluetooth SIG
- 128-bit UUID if assigned by a manufacturer
- Allows any client to find a server, read/write data
  Allows servers to talk to generic gateways
- Allows security up to AES-128
- Each to encode in XML
- Makes profile (application) development easier

Bluetooth Gateway Devices

- A gateway device helps connect a Bluetooth device to the Internet. Smart phone, Tablets, PC, …
- A generic app can forward the data to the URL sent by the device

Bluetooth Smart Applications

- Proximity: In car, In room 303, In the mall
- Locator: Keys, watches, Animals
- Health devices: Heart rate monitor, physical activities monitors, thermometer
- Sensors: Temperature, Battery Status, tire pressure
- Remote control: Open/close locks, turn on lights

Ref: E. Vlugt, "Bluetooth Low Energy, Beacons and Retail," Verifone White paper, 2013, 12 pp., http://www.verifone.com/media/3603729/bluetooth-low-energy-beacons-retail-wp.pdf

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.

Summary

1. Bluetooth basic rate uses frequency hoping over 79 1-MHz channels with 1, 3, 5 slots packets.
2. Three inactive states: hold, sniff, park. Has a fixed set of applications called "Profiles"
3. Bluetooth and WiFi co-exist by time-sharing or adaptive frequency notching
4. Bluetooth Smart is designed for short broadcasts by sensors. 39 2-MHz channels with 3 channels reserved for advertising. One or two-message exchanges
5. Generic attribute profile allows new applications using UUID for data types

Homework 11

- Submit answer to the following Problem:
  Assume that in one slot in Bluetooth 256 bits of payload could be transmitted. How many slots are needed if the payload size is (a) 512 bits, (b) 728 bits, and (c) 1024 bits. Assume that the non-payload portions do not change.

Reading List: Bluetooth

- J. Decuir, "Bluetooth 4.0: Low Energy," 2010, 62 pp., http://chapters.comsoc.org/vancouver/BTLER3.pdf
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- B. Chatschik, "An overview of the Bluetooth wireless technology", Volume 39, Issue 12, Page(s):86 - 94, IEEE Communications Magazine, 2001, http://ieeexplore.ieee.org/iel5/35/20896/00968817.pdf?tp=&arnumber=968817&isnumber=20896

Acronyms

- ACL — Asynchronous Connection List
- AES-128 — Advanced Encryption Standard w 128 bit keys
- BLE — Bluetooth Low Energy
- BNEP — Bluetooth Network Encapsulation Protocol
- CAP — Connection Access Profile
- CSA — Core Specification Amendment
- dBm — Deci-bel milli-watt
- DPSK — Differential Phase Shift Keying
- EDR — Enhanced Data Rate,
- EU — European Union
- FEC — Forward Error Correction
- FSK — Frequency Shift Keying
- GATT — Generic Attribute
- GFSK — Gaussian Frequency Shift Keying
- GHz — Giga Hertz
- GPS — Global Positioning System
- HS — High Speed,

Acronyms (Cont)

ID	Identifier
IEEE	Institution of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IG	Interest Group
iOS	Apple's idevices Operating System
IP	Internet Protocol
IPv6	Internet Protocol version 6
IrDA	Infrared Data Association
IrMC	Infrared Mobile Communications
IrOBEX	Infrared Object Exchange
LAN	Local Area Network
LAP	Lower address part
LE	Low Energy
LTE	Long Term Evolution
MAC	Media Access Control
MAN	Metropolitan Area Network

Acronyms (Cont)

MB	Mega Byte
MHz	Mega Hertz
mW	milli Watt
NAP	Non-significant address part
OFDM	Orthogonal Frequency Division Multiplexing
OUI	Organizationally Unique Identifier
PAL	Protocol Adaptation Layer
PAN	Personal Area Network
PC	Personal Computer
PDU	Protocol Data Unity
PHY	Physical Layer
PIN	Personal Identification Number
RF	Radio Frequency
RFCOMM	Radio Frequency Communication
RFID	Radio Frequency Identifier
SC	Standing Committee

Acronyms (Cont)

- SCO Synchronous Connection Oriented
- SDP Service Discovery Protocol
- SG Study Group
- SIG Special Interest Group
- SIM Subscriber Identity Module
- TCS Telephony Control Specification
- TDD Time-division duplex
- TLV Type-Length-Value
- TV Television
- TX Transmit
- UAP Upper address part
- UCD Unicast Connectionless Data
- URL Uniform Resource Locator
- USB Universal Serial Bus
- UUID Universally Unique Identifier
- uW Micro-Watt

Acronyms (Cont)

- WAN Wide Area Network
- WBS Wide Band Speed
- WiFi Wireless Fidelity
- WiMax Worldwide Interoperability for Microwave Access
- WPAN Wireless Personal Area Networks
- WRAN Wireless Regional Area Network
- XML Extensible Markup Language