Bluetooth

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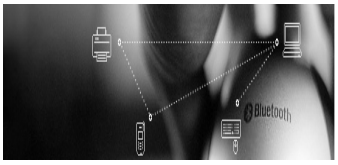
What is Bluetooth

- **It is an always on, low power, short ranged radio link for communication between mobile devices**
- **Developed in 1994 by the Swedish company Ericsson to enable laptops make calls over mobile phones**
- **Also known as 802.15, it employs the 2.4 GHz unlicensed band, the same as 802.11b wireless, but does not interfere with it**
- **Provides data rates of up to 720 Kbps**
- **Power output is around 1 milliwatt, compared to the average cell phone's 500 milliwatt power output**

Bluetooth Applications

- **Major use in consumer electronics**
- **Embedded in a whole slew of electronic products ranging from on PDAs, cellphones and printers, to automobiles**



Bluetooth Characteristics

- Allows up to 8 devices to communicate in a local network called a Piconet, also known as a Personal Area Network or PAN
- Because of its low power consumption, its range is limited to 10 m.
- However, range can be increased to 100 m by employing a scatternet topology or a higher powered antenna
- Three classes of Bluetooth devices
  - Class 1 – 100 m ≤ 20 dBm power
  - Class 2 – 10m ≤ 4 dBm power
  - Class 3 – 10 cm @ 0 dBm power

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The Bluetooth Standard

- The Bluetooth standard is maintained and published by the Bluetooth Special Interest Group (SIG)
- Includes thousands of member companies
- Covers topics such as interoperability, testing and qualification of bluetooth devices
- Most important, outlines the specifications for:
  - Bluetooth Radio
  - Baseband
  - LMP – Link Manager Protocol
  - HCI – Host Controller Interface
  - L2CAP – Logical Link Control & Adaptation Protocol
  - RFCOMM
  - Profiles

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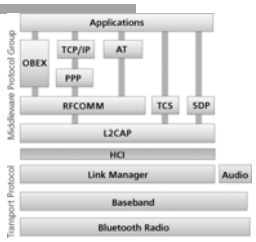
The Bluetooth Stack



Note: Baseband really means Baseband + Link Controller
•LC is responsible for carrying out link level operations over several data packet duration
•Baseband is responsible for channel codec and management of the link over a single data packet

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Bluetooth Radio

- Bluetooth uses a 74 MHz slice of the 2.4 GHz radio band.
- This is shared by not only 802.11 WiFi, but also by garage door openers and baby monitors!
- Does this mean that baby monitors interfere with bluetooth?
  - Unlike a baby monitor, bluetooth employs a Frequency Hopping strategy
- Frequency Hopping is a method where the signal is switched from one channel to another in accordance with a pre-established pseudo-random pattern
- This not only reduces interference from other sources, but also provides security by preventing eavesdropping

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Frequency Hopping

- The Bluetooth bit rate is 1Mbps ±1ppm
- However, headers and handshaking overhead take up about 20% of this bandwidth
- Frequency Hopping happens at 1600 times a second over 79 channels (United States and Europe) or 23 channels (Japan)
- Each time-slot is 625 μs long
- Packets can take up to 5 time-slots
- Data packets can be up to 2745 bits long
- Two modes for transmission
  - SCO – Synchronous Connection Oriented
  - ACL – Asynchronous Connectionless

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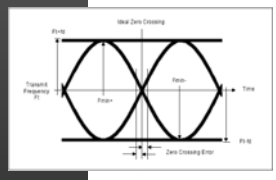
Bluetooth Radio



- Bluetooth uses a TDD (Time Division Duplex) protocol to transmit information in one time-slot and receive in another
- Employs a Gaussian Frequency Shift Keying (GFSK) modulation mechanism to transmit bits, where:
  - Binary 0 is represented by a negative frequency deviation
  - Binary 1 is represented by a positive frequency deviation

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Baseband

- **Baseband is the Physical Layer of Bluetooth and manages the following. We will discuss only the highlighted items:**
  - ✓ **Physical Channels**
  - ✓ **Physical Links**
  - ✓ **Packets**
  - • **Error Correction**
  - • **Logical Channels**
  - • **Data Whitening**
  - • **Transmit/Receive Routines & Timing**
  - • **Channel Control & Hop Selection**
  - • **Bluetooth Audio**
  - ✓ **Bluetooth Addressing**
  - • **Bluetooth Security**

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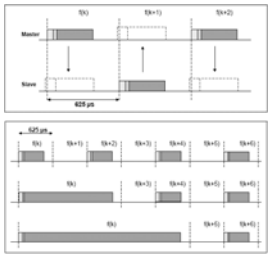
Baseband – Physical Channel

- **Each channel is represented by a pseudo-random hopping frequency, determined by the master, through 79 or 23 RF channels**
- **The channel is divided into time slots, each 625 µs in length**
- **Time slots are numbered according to the bluetooth clock of the master ranging from 0 to 2^{27}-1 cyclically**
- **Master transmits on even time-slots, while slaves transmit on odd time-slots**



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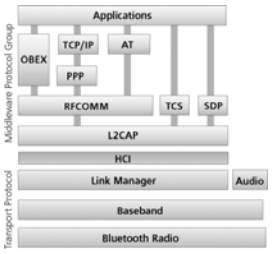
Baseband – Physical Link

- **Baseband is the physical link of the Bluetooth protocol**
- **It handles two types of links:**
  - **SCO – Synchronous Connection Oriented**
  - **ACL – Asynchronous Connectionless**



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Baseband - SCO

- SCO is a symmetric point-to-point link between a master and a single slave in the piconet
- The SCO link is maintained by the master by its use of timeslots at regular intervals
- The Master can support up to 3 simultaneous SCO links, while the slaves can support 2 or 3 links
- SCO packets are never retransmitted, and are typically employed in time constraint applications such as voice
- Are used in 64Kbps speech transmission
- A SCO link can be considered as a circuit-switched connection

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Baseband - ACL

- Point-to-multipoint link between master and all slaves in the piconet
- ACL link can be established on per slot basis
- In the slots which are not reserved for SCO transmission, the master can establish an ACL link with any slave, including the slaves which are already engaged in SCO communication
- Unlike SCO where multiple SCO links can be established, only one ACL Link can be established between two nodes
- ACL packets which are lost are always retransmitted

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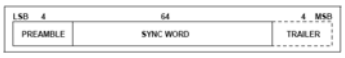
Baseband - Packets

- The Bluetooth general packet format is comprised of three parts: Access Code, Header, and Payload

- Access Code
  - Can be 68 or 72 bits wide, depending on whether a packet header follows or not
  - Used for synchronization, DC offset compensation, and identification



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Baseband - Packets

- There are three categories of Access Codes:
  - Channel Access Code (CAC): Defines a piconet
  - Device Access Code (DAC): Used for paging
  - Inquiry Access Code (IAC): There are two variations of General (GIAC) and Dedicated (DIAC), the latter is used only in identifying Bluetooth devices sharing a common characteristic
- Payload data is dependent on the Bluetooth application (voice, data, …)
- The Packet Header consists Link Control (LC) and is comprised of 6 fields:

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Baseband - Packets

- The 6 fields are as follows:
  - AM_ADDR is a 3-bit active member address used to distinguish between the active members of a piconet
  - Type is a 4-bit type code used to distinguish between one of 16 different packet types, such as ID Packet, POLL packet, or NULL Packet.
  - Flow is a bit used for flow control over ACL. When the receiver buffer is full, a STOP indication is returned by means of FLOW = 0 to prevent further transmission
  - ARQN is the acknowledgement bit for CRCed packets
  - SEQN provided sequencing for multiple data packets
  - HEC is the Header Error Check used to verify header integrity

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Link Controller

- The Link Controller carries out higher level operations such as paging and inquiries
- It is responsible for device discoverability, as well as establishing and maintaining connections with other devices
- Handling corrupted data:
  - Each packet has an ARQN flag which indicates the status of the previously received packet
  - ARQN value of 1 is an ACK, and 0 is a NAK
- All new packets change the value of SEQN, however retransmitted packets maintain SEQN

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Link Controller

- **At any given time, the Link Controller is in one of several states**
  - ***Standby*: The device is inactive, the radio is switched off, and no data is being transferred**
  - ***Inquiry*: The device attempts to discover all BT devices in its local vicinity**
  - ***Inquiry Scan*: Another part of the inquiry procedure. Devices listen for a long time, which is important because they don't have knowledge of the frequency hop or timing of an inquiring device, for GIAC and DIAC inquiry packets**

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Link Controller

- ***Page*: For a device to establish connection and become master, it needs to transmit page messages until a slave device acknowledges the pages**
- ***Paging Scan*: Consequently, a device needs to enter page scan periodically to allow paging devices to establish connection with it**
- ***Connection*: Connection has four states: *active, hold, sniff*, and *park*.**
  - **In Active mode, the bluetooth module is actively participating in channel communication. The master schedules transmissions based on its traffic demands, but also maintains regular transmissions to keep synchronized slaves alive**

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Link Controller

- **Hold mode is a low power mode where only the internal timer of the slave is running. Slave units can demand to be put into hold mode, but only the master can put a slave into hold mode**
- **In sniff mode the slave device simply listens to all packets on a predefined time slot until a time out occurs. This occurs at a reduced rate than it would normally listen to traffic.**
- **The sniff interval is is programmable**
- **Park mode is used for low power modes where the device only occasionally listens for traffic, but is still synchronized to the channel**

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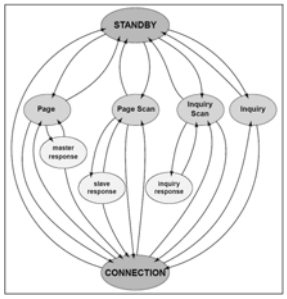
Link Controller State Diagram



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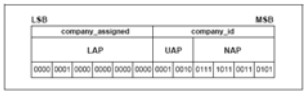
Bluetooth Addressing

- **Each Bluetooth transceiver is allocated a unique 48-bit device address (BD_ADDR)**
  - **LAP is the 24-bit Lower Address Part**
  - **UAP is the 8-bit Upper Address Part**
  - **NAP is the 16-bit Non-significant Address Part**



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Bluetooth Addressing

- **Asides from the BD_ADDR there are three other addressing functions**
  - **<u>AM_ADDR</u> is the 3-bit Active Member address assigned to each slave in a Piconet. It is only valid while the slave is Active (not parked, or disconnected)**
  - **The all-zero AM_ADDR is the broadcast packet**
  - **The Piconet Master does not have an AM_ADDR. It is distinguishable by its transmit time-slot**
  - **<u>PM_ADDR</u> is an 8-bit Parked Member Address that differentiates between parked slaves**
  - **<u>AR_ADDR</u> is the Access Request Packet used in slave activated unparking**

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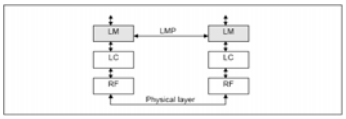
Link Manager Protocol (LMP)

- The Link Manager provides messages that are used in link setup, security and control
- Link Manager Protocols take a higher priority over data traffic
- Messages are interpreted at the LM level and are not passed further up through the stack



- The LMP is a collection of Protocol Data Units (PDUs) sent from one device to another:

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Link Manager Protocol

- The LM manages:
  - Attaching and detaching slaves to a piconet, and allocating active member addresses
  - Establishing ACL or SCO links
  - Putting a connection into low power mode (hold, sniff, or park)
- A Link Manager communicates with another Link Manager on a different device via the Link Manager Protocol (LMP), and transmitted as Protocol Data Units (PDUs)

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Link Manager Protocol - PDUs

- General Response
- Authentication
- Pairing
- Change Link Key
- Change Current Link Key
- Encryption
- Slot Offset Request
- Clock Offset Request
- Timing Accuracy Info Req.
- LMP Version
- ✓ Supported Features
- Switch Master/Slave
- Paging Scheme
- ✓ Name Request
- ✓ Detach
- ✓ Hold Mode
- Sniff Mode
- ✓ Park Mode
- ✓ Power Control
- Channel Quality-Driven Change
- Quality of Service
- SCO Links
- Control of Multi-Slot Packets
- Connection Establishment
- Test Mode
- Error Handling
- Link Supervision

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Link Manager Protocol - PDUs

- **Supported Features**
  - **The Bluetooth radio and Link Controller could support only a limited number of packet types and features**
  - **Therefore a device cannot send any packets other than ID, FHS, NULL, POLL, DM1 and DH1 until a target device capabilities are identified**
- **Name Request**
  - **Name Request receives a user-friendly name associated with a Bluetooth device in a maximum string length of 248 characters encoded in the UTF-8 standard.**
- **Detach**
  - **A command which can be initiated by the master or the slave in order to close a connection. A message can be transferred to indicate the reason as to closure of link.**

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Link Manager Protocol - PDUs

- **Hold Mode**
  - **Used in ACL mode, it is intended to prevent the Master from sending further ACL packets for a specified hold time. The transceiver can then be turned off in order to save power.**
- **Park Mode**
  - **If a slave does not need to participate in a channel, it can be placed in park mode. In this mode all PDUs sent from the Master are broadcast PDUs.**
- **Power Control**
  - **A device can request to increase or decrease another devices transmit power. A request in a multi-slave scenario affects only for the requesting slave.**

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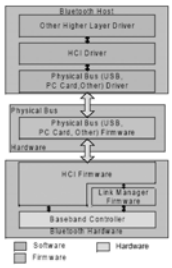
Host Controller Interface (HCI)

- **HCI's most important function is to provide a uniform method for accessing Bluetooth baseband capabilities**
- **It separates the higher levels of the Bluetooth Stack (software) from the lower levels of the Bluetooth stack (firmware and hardware)**



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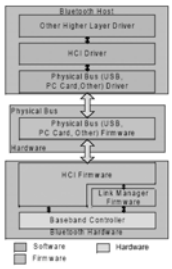
Host Controller Interface (HCI)

- HCI is an interface between higher and lower levels of the protocol, e.g. PCMCIA card
- For example, a PCMCIA card can implement the lower levels of the protocol, and to save cost interface with the host PC for higher levels of the protocol
- Why not implement some of the lower levels on host PC? Because of stringent timing requirements
- However something like a headset needs to implement all levels of the protocol



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Host Controller Interface (HCI)

- HCI employs three different packet types
  - Command Packets – go from Host to the BT module
  - Event Packets –go from the BT module to the Host
  - Data Packets – which travel in both directions
- Through these commands, HCI enables the host to fully control a BT module
  - Control links – configure, setup, teardown
  - Access local & remote modules via LMP exchanges
  - Invoke the BT test module for factory test
- HCI provides three transport layers
  - USB
  - RS232 – which provides error correction
  - UART – which does not provide error correction

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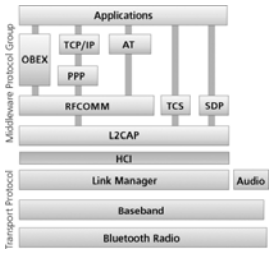
In case you've forgotten…



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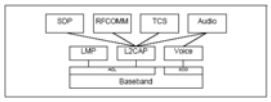
Logical Link Control and Adaptation Protocol (L2CAP)

- L2CAPs function is to take data from a higher level application and to pass it down to the lower stack
- L2CAP supports both connection oriented and connectionless data services to upper protocols
- It allows higher level protocols to transmit and receive data of up to 64 Kbytes.
- L2CAP is in charge of protocol multiplexing as well as Segmentation and Reassembly (SAR) of packets.



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Other L2CAP Functions

- **L2CAP is also in charge of…**
  - Multiplexing between different higher level protocols
  - Segmentation and Reassembly to allow transfer of larger packets than lower levels can support
  - Group management, provides one-way transmission to a group of BT devices
  - QoS management for higher protocols

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RFCOMM

- RFCOMM is used to emulate the functions of a serial port (RS232) over bluetooth
- RFCOMM provides multiple concurrent connections by relying on the L2CAP services to handle multiplexing over a single connection
- RFCOMM lacks the ability to validate data integrity, and therefore relies on the bluetooth baseband to provide reliable and in-sequence delivery of byte streams

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RFCOMM

- Traditional serial interfaces rely on a Universal Asynchronous Receiver Transmitters (UARTs) to translate parallel data into a serial stream and vice versa.
- RFCOMM emulates this process
- There are two types of devices:
  - Type 1 is an internally emulated serial port
  - Type 2 is an intermediate device which is actually connected to a serial port

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RFCOMM

- RFCOMM needs to first establish an L2CAP connection, after which time the RFCOMM control and data frames can be sent back and forth
- RFCOMM can support up to 30 different data channels at once, however in reality most devices limit the number of channels due to lack of resources

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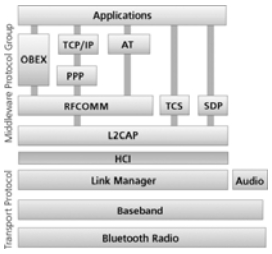
Service Discovery Protocol (SDP)

- Service Discovery Protocol is one of the higher level protocols which provides the means for an application to discover which services are available
- Keep in mind that the list of services which are available changes dynamically due to environmental factors (RF proximity), or functional factors…



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Service Discovery Protocol (SDP)

- The way bluetooth connects to devices is unlike the way devices connected on a LAN
- For example, you can find a printer on the local network and connect to it with a PC. Once connected, this is a connection which remains in place for a very long time
- Bluetooth on the other hand was designed for an environment where connections changed frequently
- Therefore it needs a mechanism to allow it to quickly discover devices, use their services, and forget about them once they have been used
- This is provided by the *Service Discovery Protocol*

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Profiles

- Profiles are specifications which describe how bluetooth should be used in a specific application and as such ensures that all devices from different manufacturers can seamlessly work with one another
- There are about a dozen profiles:
  - Generic Access, Serial Port, Dialup Networking, FAX, Headset, LAN Access Point, Generic Object Exchange (OBEX), File Transfer,Object Push, Synchronization, Cordless Telephony, and Intercom
- More profiles are under discussion within various Bluetooth SIG groups, and there is a whole other spec dedicated to Bluetooth Profiles

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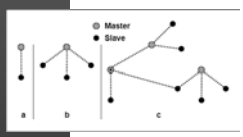
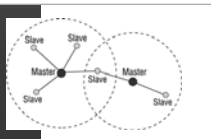
Piconet





- A Piconet or a Personal Area Network (PAN) is comprised of one master and seven slaves
- A device can be a slave in two different Piconets
- A device can also be a master in one Piconet while a slave in another
- Piconet communication always takes place as point-to-point or point-to-multipoint
- Joining more than one Piconet together forms a scatternet

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Piconet

- The ability of Bluetooth to setup and tear down piconet networks *ad-hoc* makes it both very flexible, and more complex than traditional wired networks
- This is also why the Bluetooth Link Controller provides specific functions to help detect new in-range devices and to easily establish connection with them

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Inquiry Example

- The inquiry procedure enables a device to discover which devices are in range, and determine the addresses and clocks for the devices.
  - The inquiry procedure involves a unit (the source) sending out inquiry packets (inquiry state) and then receiving the inquiry reply
  - The unit that receives the inquiry packets (the destination), will hopefully be in the inquiry scan state to receive the inquiry packets.
  - The destination will then enter the inquiry response state and send an inquiry reply to the source.
- After the inquiry procedure has completed, a connection can be established using the paging procedure.

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Paging Procedure

- It is with the paging procedure that an actual connection can be established.
- The paging procedure typically follows the inquiry procedure. Only the Bluetooth device address is required to set up a connection.
- A unit that establishes a connection will carry out a page procedure and will automatically be the master of the connection.

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Paging Procedure (cont.)

- **The procedure occurs as follows:**
  - **A device (the source) pages another device (the destination). [Page state]**
  - **The destination receives the page. [Page Scan state]**
  - **The destination sends a reply to the source. [Slave Response state]**
  - **The source sends an FHS packet to the destination. [Master Response state]**
  - **The destination sends it's second reply to the source. [Slave Response state]**
  - **The destination & source then switch to the source channel parameters.**

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Have a nice weekend!

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