COEN-4720 Embedded Systems

# Lecture 8
# BlueTooth

*Cris Ababei*
*Dept. of Electrical and Computer Engineering*
MARQUETTE UNIVERSITY
BE THE DIFFERENCE.



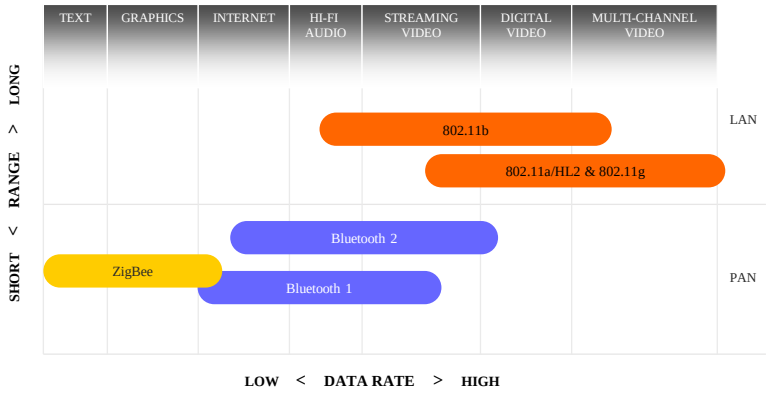


# Outline

- BlueTooth
  - Motivation, releases
  - Introduction and Specs
  - Basic idea
  - Protocol stack
  - Network topology
  - Security
  - Antennas
  - Bluetooth vs. Wi-Fi
- HC-06 BlueTooth Module
- Example Application + Demo

# Wireless Technologies: BlueTooth

- WiFi
- Bluetooth
- Cellular
- 3G (3rd Generation)
- UWB (Ultra Wide Band)
- FSO (Free Space Optics)
- WiMAX
- ZigBee
- …

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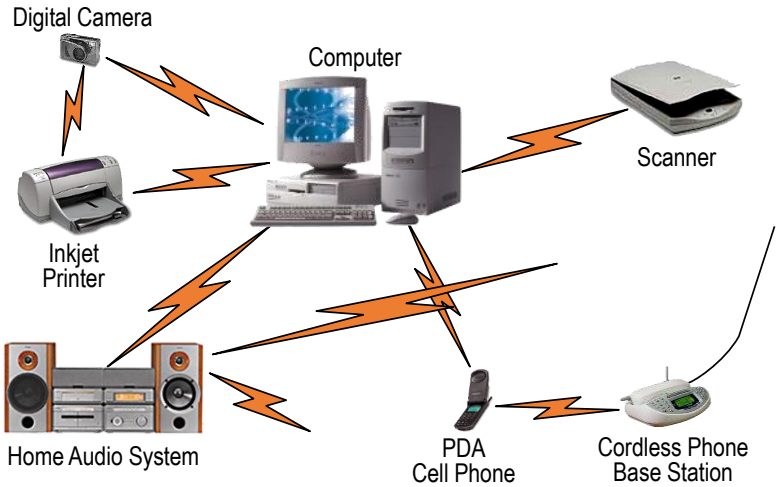
# BlueTooth - Motivation

- **Cable replacement**
- **Ad-hoc networking**

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# The Name - Bluetooth?

- The name is attributed to Harald “Blatand” (“Bluetooth”) Gormsen [son of Gorm], King of Denmark in the 10th century
- Choosing this name for the standard indicates how important companies from the Baltic region (nations including Denmark, Sweden, Norway and Finland) are to the communications industry?


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# BlueTooth - Intro

- BlueTooth (BT) is a wireless technology standard
- Invented by Dutch electrical engineer Jaap Haartsen working for Ericsson in 1994
- Initially intended as wireless alternative to RS-232 cables
- IEEE 802.15 committee standardized the physical and link layers
- Managed by Bluetooth Special Interest Group (SIG); >30,000 member companies
- Short distances
- Short-wavelength UHF radio waves in unlicensed ISM (industrial, scientific and medical) band, 2.400 to 2.485 GHz
- Fixed and mobile devices
- Building personal area networks (PANs)

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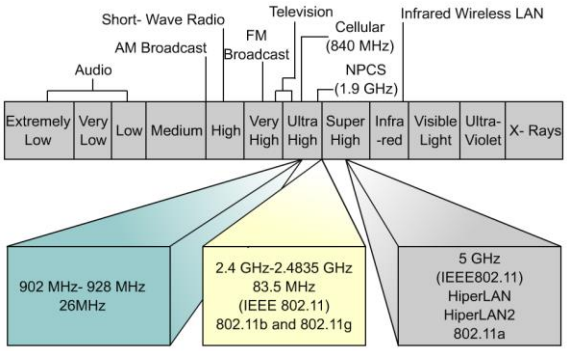
# US Frequency Bands




| Band | Frequency range |
|---|---|
| UHF ISM | 902-928 MHz |
| S-Band | 2-4 GHz |
| S-Band ISM | 2.4-2.5 GHz |
| C-Band | 4-8 GHz |
| C-Band satellite downlink | 3.7-4.2 GHz |
| C-Band Radar (weather) | 5.25-5.925 GHz |
| C-Band ISM | 5.725-5.875 GHz |
| C-Band satellite uplink | 5.925-6.425 GHz |
| X-Band | 8-12 GHz |
| X-Band Radar (police/weather) | 8.5-10.55 GHz |



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| BLUETOOTH STANDARD RELEASES & TIMELINE HISTORY | | |
|---|---|---|
| BLUETOOTH STANDARD VERSION | RELEASE DATE | KEY FEATURES OF VERSION |
| 1.0 | July 1999 | Draft version of the Bluetooth standard |
| 1.0a | July 1999 | First published version of the Bluetooth standard |
| 1.0b | Dec 1999 | Small updates to cure minor problems and issues |
| 1.0b + CE | Nov 2000 | Critical Errata added to issue 1.0b of the Bluetooth standard |
| 1.1 | February 2001 | First useable release. It was used by the IEEE for their standard IEEE 802.15.1 - 2002. |
| 1.2 | Nov 2003 | This release of the Bluetooth standard added new facilities including frequency hopping and eSCO for improved voice performance. Was released by the IEEE as IEEE 802.15.1 - 2005. This was the last version issued by IEEE. |
| 2.0 + EDR | Nov 2004 | This version of the Bluetooth standard added the enhanced data rate (EDR) to increase the throughput to 3.0 Mbps raw data rate. ***Read more about Bluetooth 2.*** |
| 2.1 | July 2007 | This version of the Bluetooth standard added secure simple pairing to improve security. |
| 3.0 + HS | Apr 2009 | Bluetooth 3 added IEEE 802.11 as a high speed channel to increase the data rate to 10+ Mbps |
| 4.0 | Dec 2009 | The Bluetooth standard was updated to include Bluetooth Low Energy formerly known as Wibree |



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# BlueTooth – Some Specs (1/2)

- Operates at frequencies between 2402 and 2480 MHz, or 2400 and 2483.5 MHz
- Uses radio technology called Frequency-Hopping Spread Spectrum (FHSS)
- 79 hops (i.e., BT channels) separated by 1 MHz (i.e., each channel has a bandwidth of 1 MHz).
- Maximum frequency hopping rate: 1600 hops/sec
- Bluetooth Low Energy uses 2 MHz spacing, which accommodates 40 channels
- Nominal range: 10 cm to 10 meters
- Divides transmitted data into packets, and transmits each packet on one of 79 designated BT channels
- One complete data packet can be transmitted within each 625 µs hop slot

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# BlueTooth – Some Specs (2/2)

- Bluetooth is a packet-based protocol with a master/slave architecture
- One master may communicate with up to 7 slaves in a piconet (ad-hoc computer network using BT technology)
- All devices share the master's clock
- Packet exchange is based on the basic clock (which ticks at 312.5 µs intervals), defined by the master
- Two clock ticks make up a slot of 625 µs
- Two slots make up a slot pair of 1250 µs
- In the case of single-slot packets, the master transmits in even slots and receives in odd slots. The slave, conversely, receives in even slots and transmits in odd slots
- Packets may be 1, 3 or 5 slots long, but in all cases the master's transmission begins in even slots and the slave's in odd slots

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- HC-06 BlueTooth Module
- Example Application + Demo

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# The Basic Idea

- Bluetooth is a standard for a small, cheap radio chip to be plugged into computers, printers, mobile phones, etc.
- Bluetooth chip is designed to replace cables; information is transmitted at a special frequency to a receiver Bluetooth chip.
- These devices can form a quick ad-hoc secure "piconet" and start communication.
- Connections in the "piconets" can occur even when mobile.

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# "Piconet"

- A collection of devices connected via Bluetooth technology in an ad-hoc fashion.
- A piconet starts with two connected devices, and may grow to eight connected devices.
- All Bluetooth devices are peer units and have identical implementations. However, when establishing a piconet, one unit will act as a Master and the other(s) as Slave(s) for the duration of the piconet connection.

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# Requirements

- Low cost as cables – chip $5
- Secure as cables – must support authentication and encryption
- Must support both data and voice
- Must connect to a variety of devices.
- Must be able to function in a noisy environment.
- Data rates – 721kbps, using the 2.45GHz radio frequency band – ISM (industrial, scientific and medical)
- Must support many simultaneous and private "piconets".
- Must be low power, compact and global.

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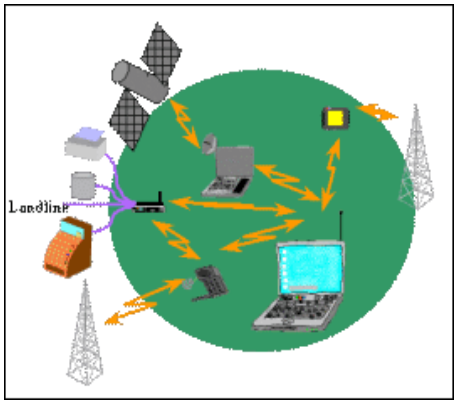
## Usage models - Voice/Data Access Points




- Connecting a computing device to a communicating device.
- Allows any device with a bluetooth chip to connect to the internet while located within the range of the access point.
- Example - a notebook could link to the internet using a mobile phone as an access point.

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## Usage models - Peripheral Interconnects

- Standard peripheral devices like keyboards, mice, headsets, etc. working over a wireless link.
- The same device can be used in multiple functions, e.g., a headset can access phones while in the office and can interface with a cellular phone when mobile.

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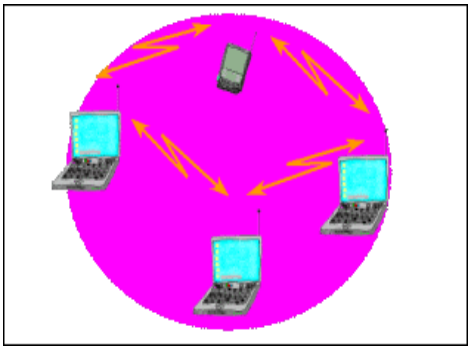
## Usage models - Personal Area Networking (PAN)



- Allows dynamic formation and breakdown of "PICONETS": ad-hoc personal networks.





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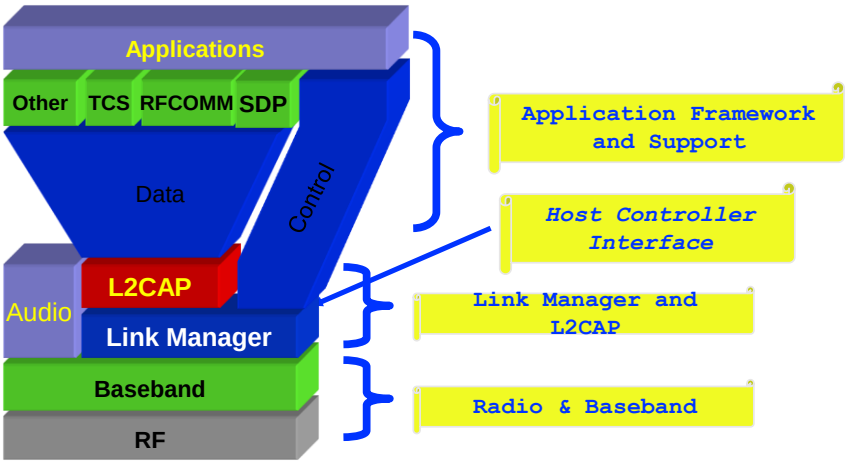
# Bluetooth Protocol Stack




- A hardware/software description
- An application framework

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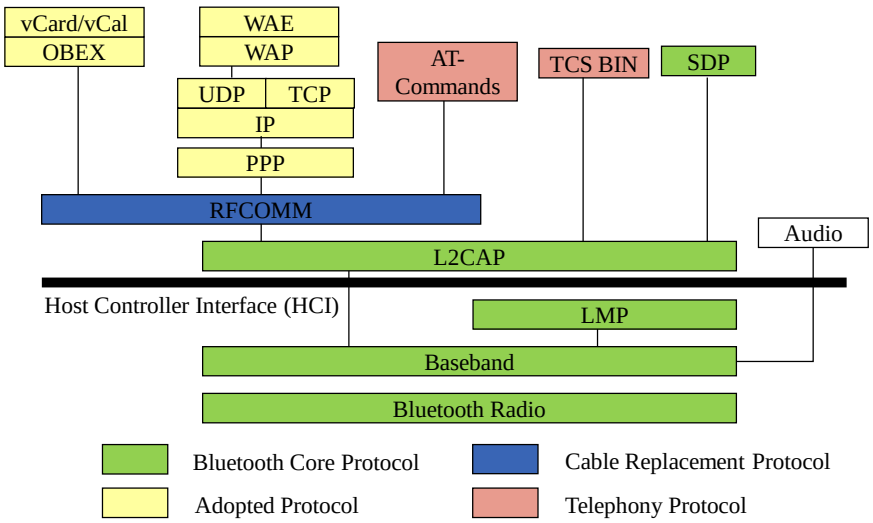
# Bluetooth Protocol Stack - Details

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## Layers

- Bluetooth Radio (RF Layer)
- Baseband
- LMP (Link Manager Protocol)
- HCI (Host Controller Interface)
- L2CAP (Logical Link Control and Adaptation Protocol)
- RFCOMM (Radio Frequency Communication)
- SDP (Service Discovery Protocol)

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## RF Layer

- The lowest defined layer of the Bluetooth specification
- It defines the requirements of the Bluetooth transceiver device operating in the 2.4 GHz ISM band
- It uses a packet switching protocol based on a technology called Frequency-hopping spread spectrum (FHSS) to spread the energy across the ISM band.

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- In order to minimize interference, the nominal antenna power is 1 mW which can be extended to 100 mW.
- The low power limits the range to about 10 centimeters to 10 meters.
- With higher power of 100 mW range of 100 meters can be achieved.
- 3 different power classes
  - Power Class1: long range (100m,100mW)
  - Power Class2: mid range (10m,1-2,5mW)
  - Power Class3: short range (0.1-10m,1mW)

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## Frequency-hopping spread spectrum (FHSS)

- FHSS is a method of transmitting radio signals by shifting carriers across numerous channels with a pseudorandom sequence which is already known to the sender and receiver.
- Divides the designated range of the ISM-band (2.402GHz to 2.480GHz) into 79 of 1 MHz channels.
- Every frequency is GFSK (Gaussian frequency-shift keying) modulated with channel width of 1MHz.

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## Frequency-hopping spread spectrum (FHSS)

- A device will use 79 individual (pseudo)randomly chosen frequencies, changing from one to another on a regular basis.
- Communication between devices switches between available channels. The frequency hopping is done at a rate of 1600 times a second. This:
  - Allows more devices to use the limited time slice
  - Reduces the chance of two transmitters being on the same frequency at the same time

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## Baseband Layer

- The physical layer of the Bluetooth that provides
  - Error correction
  - Flow control
  - Hopping sequence
  - Security
- Hopping through 79 channels
- Data is divided in packets
  - Access code: e.g. timing synchronization
  - Header: e.g. packet numbering, flow control, slave address
  - Payload: voice, data or both

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- Connection Modes
  - STANDBY: not connected in a piconet
  - ACTIVE: active participation on the channel
- Power Saving Modes
  - SNIFF: slave listens to the channel at a reduced rate (decreasing of duty cycle ) least power efficient
  - HOLD: data transfer is held for a specific time period, medium power efficient
  - PARK: synchronized to the piconet but does not participate in traffic

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- Security Modes
  - non-secure
  - encryption enforced by application layer
  - encryption enforced by link layer
- For devices
  - trusted device
  - untrusted device
- For services
  - require authorization and authentication
  - require authentication
  - open to all devices

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# Audio

- Two codecs: PCM and CVSD
- Both at 64kbit/s
- Synchronous connection oriented (SCO) links
- Time-critical
- No retransmission
- Errors appear as background noise

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# LMP (Link Manager Protocol)

- The Link Manager carries out link setup, authentication, link configuration and other protocols.
- It discovers other remote LM's and communicates with them via the Link Manager Protocol (LMP).
- To perform its service provider role, the LM uses the services of the underlying Link Controller (LC).

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# HCI (Host Controller Interface)

- HCI provides a command interface to baseband controller and link manager, and access to hardware status and control registers.
- Also to hardware status, control and event registers
- Bluetooth defined Host Controller Transport Layers:
  - UART (HCI over serial interface)
  - RS232 (HCI over serial interface)
  - USB (HCI over USB interface e.g. USB dongle)

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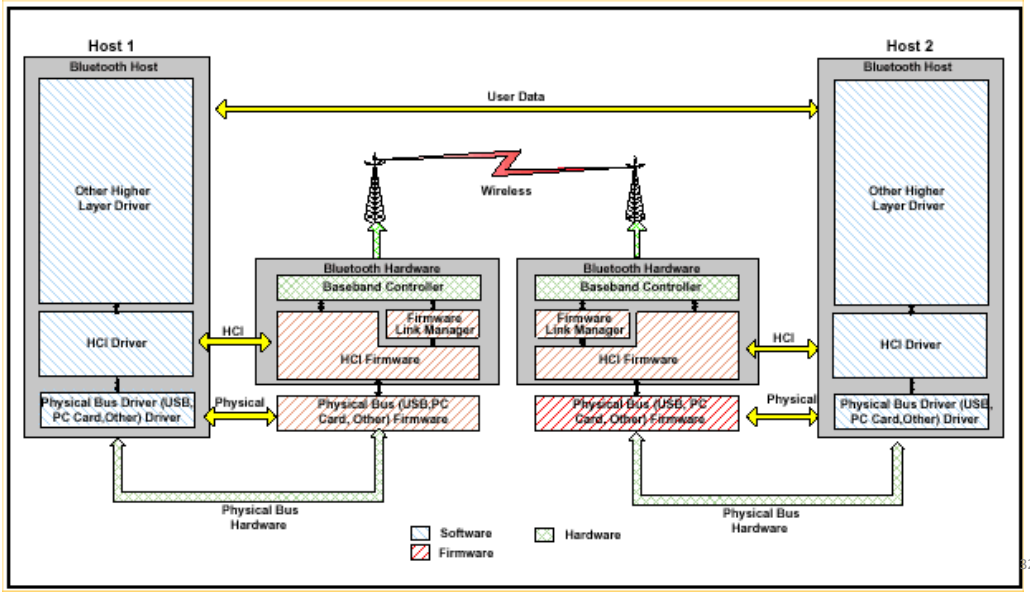
# HCI Functional Entities

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## L2CAP (Logical Link Control and Adaptation Protocol)

- L2CAP is layered over the Baseband Protocol and resides in the data link layer
- L2CAP provides connection-oriented and connectionless data services to upper layer protocols with quality-of-service functions using multiplexing, segmentation and reassembly
- Two link types are supported for the Baseband layer:
  - Synchronous Connection-Oriented (SCO)
  - Asynchronous Connection-Less (ACL)

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## RFCOMM (Radio Frequency Communication)

- Provides emulation of serial ports
- Supports up to 60 simultaneous connections
- Differentiates between two device types:
  - Type 1: communication end points (e.g. printer or headsets)
  - Type 2: devices which are part of communication (e.g. modems)
- But in the protocol itself no distinction is made, some information is for type 1 other for type 2

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# SDP (Service Discovery Protocol)

- Provides a means for applications to discover which services are available and to determine the characteristics of those available services
- Uses a request/response model where each transaction consists of one request protocol data unit (PDU) and one response PDU
- SDP is used with L2CAP
- Is optimized for the dynamic nature of bluetooth
- SDP does not define methods for accessing services

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# Network Topology

- All units have a unique global ID address (48 bits)
- The unit that initializes the connection is assigned as the master which controls the traffic of the connection.
- A master can simultaneously connect up to 7 slaves.
- A device can be a master in only one "piconet" at a time.
- The master/slave roles can be swapped.

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# Network Topology

- Piconet
  - Each piconet has one master and up to 7 simultaneous slaves
  - Master: device that initiates a data exchange
  - Slave: device that responds to the master
- Scatternet
  - Linking of multiple piconets through the master or slave devices
  - Bluetooth devices have point-to-multipoint capability to engage in Scatternet communication

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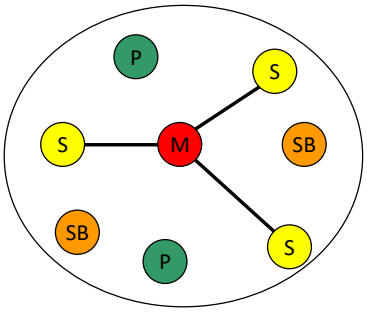
# Piconet

- All devices in a piconet hop together
  - Master gives slaves its clock and device ID
- Non-piconet devices are in standby




M = Master
P = Parked
S = Slave
SB = Standby

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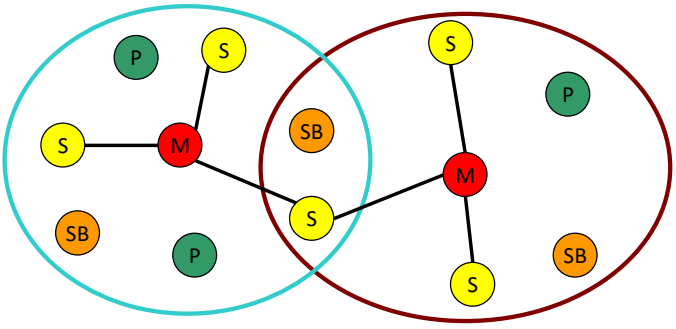
# Scatternet

- Devices can be slave in one piconet and master of another

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# Forming a piconet

- Needs two parameters
  - Hopping pattern of the radio it wishes to connect.
  - Phase within the pattern, i.e., the clock offset of the hops.
- The global ID defines the hopping pattern.
- The master shares its global ID and its clock offset with the other radios which become slaves.
- The global ID and the clock parameters are exchanged using a FHS (Frequency Hoping Synchronization) packet.

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- Devices not connected to a piconet are in *STANDBY* mode, using low power.
- A connection is made by either a *PAGE* command if the address is known or by the *INQUIRY* command followed by a *PAGE*
- When a radio sends an *INQUIRY* command, all the listening radios respond with their FHS packets, which tells the inquiring radio of all the radios in the area.
- All listening radios perform a page scan and/or an inquiry scan every 1.25 seconds.
- The master radio sends an FHS to the paged radio.

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- When a radio joins a piconet, it is assigned a 3 bit *Active Member Address (AMA).*
- Once the piconet has eight radios, the master can put/assign a radio into the *PARK* mode.
- This is one of the low power states, in which the radio releases its AMA for a 8 bit *PMA* (Passive Member Address).
- The freed AMA can be assigned to another radio wishing to join the piconet.
- Though up to 256 radios can actively reside on a piconet, only 8 of them with AMA's can transfer data.

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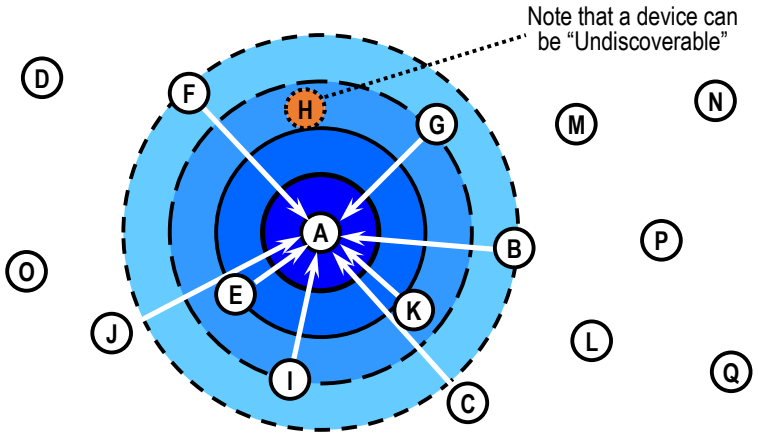
# Device Discovery Illustrated




**10 meters**

**After inquiry procedure, A knows about others within range**

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- Once a radio joins the piconet and has an AMA it can direct data to other devices on the piconet.
- In order to remain in the connected state within a piconet, the radio needs to maintain the frequency hopping pattern and offset while consuming low power.
- To achieve this the connected radios can be placed in either *PARK*, *HOLD* or *SNIFF* modes.

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PARK MODE

- The device has given up the AMA and has become passive.
- The parked device will occasionally listen to see if the master has sent any broadcast data asking it to become active.

HOLD MODE

- When data needs to be transmitted very infrequently, thus conserving power.
- In this mode only an internal timer is running.
- No data is transferred when in HOLD mode.
- The master can put slaves on HOLD mode.

SNIFF MODE

- A slave device listens to the piconet at a reduced rate.
- The SNIFF interval is programmable.
- In both the HOLD and SNIFF states the device retains its AMA.

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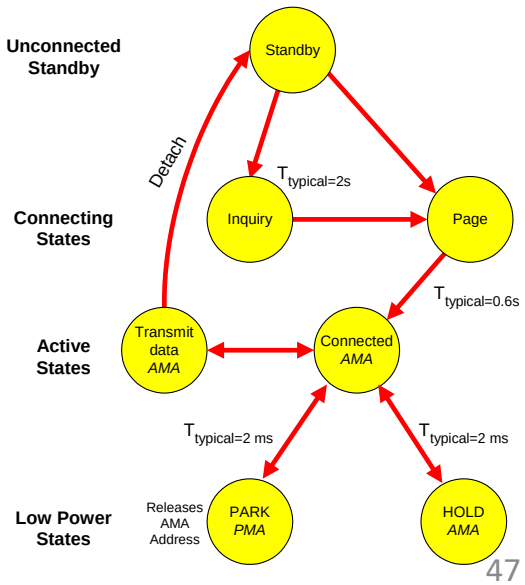
# Functional Overview

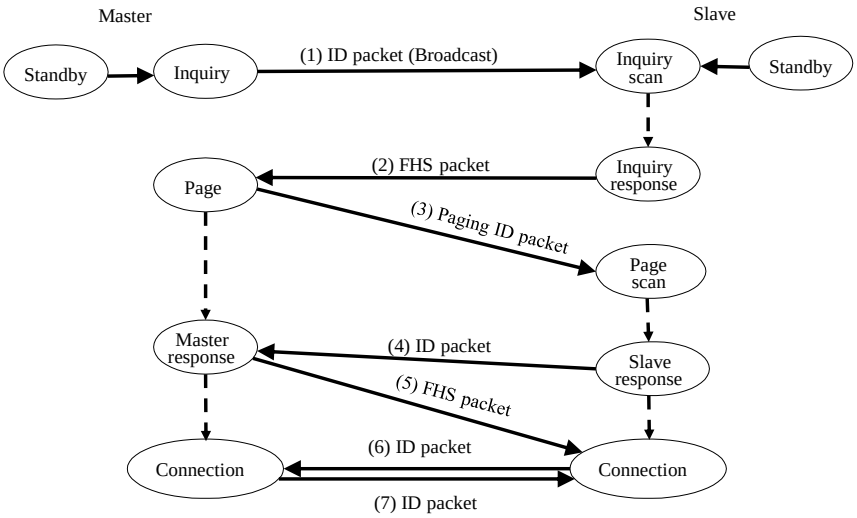
- Standby
  - Waiting to join a piconet
- Inquire
  - Ask about radios to connect to
- Page
  - Connect to a specific radio
- Connected
  - Actively on a piconet (master or slave)
- Park/Hold
  - Low Power connected states








# Connection: Inquiry and Paging



# Two Types of Links

- Baseband Layer handles two types of links:
  - Synchronous Connection Oriented (SCO)
    - Support symmetrical, circuit-switched, point-to-point connections
    - Typically used for voice traffic; do not use CRC and are not retransmitted
    - Data rate is 64 kbit/s
  - Asynchronous Connection-Less (ACL)
    - Support symmetrical and asymmetrical, packet-switched, point-to-multipoint connections
    - Typically used for data transmission
    - Up to 433.9 kbit/s in symmetric or 723.2/57.6 kbit/s in asymmetric

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# Security

- Bluetooth relies on PIN codes to establish trusted relationships between devices
- Supports Unidirectional or Mutual Encryption based on a secret link Key (128 bit) shared between two devices
- Security defined in 3 modes
  - Mode1 - No security
  - Mode 2 - Service level security: not established before channel is established at L2CAP
  - Mode 3 - Link level security: device initiates security before LMP (link management protocol) link is setup
- Devices and Services can be Set for Different Levels of Security
  - Two Trust Levels are Set for Devices
    - Trusted Device: Fixed Relationship and Unrestricted Access to All Services
    - Untrusted: No Permanent relationship and Restricted Services

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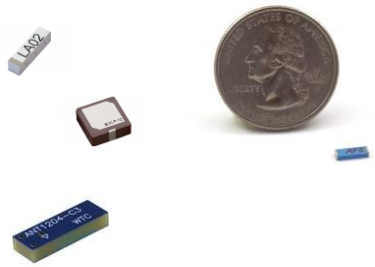
# Antennas

- Internal antennas
- External antennas

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# BlueTooth vs. Wi-Fi

- Similar applications
  - Setting up networks, printing, or transferring files
- Bluetooth
  - Intended for portable equipment and its applications (wireless personal area network, WPAN); ad-hoc connections
  - Also works for fixed location applications such as smart energy functionality in homes (thermostats, etc.)
  - Usually symmetrical, between two Bluetooth devices
  - Simple applications: headsets, remote controls, etc.
- Wi-Fi
  - Intended as replacement for high-speed cabling (wireless local area networks, WLAN)
  - Usually access point-centered, with asymmetrical client-server connection with all traffic routed through the access point
  - Applications where high speeds are required, especially for network access

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# BlueTooth vs. Wi-Fi

**Figure 1.**

**Select the Best Wireless Standard for Your Application**

| | ZigBee 802.15.4 | Bluetooth 802.15.1 | Wi-Fi 802.11b | GPRS/GSM 1XRTT/CDMA |
|---|---|---|---|---|
| System resource | 4-32 KB | 250 KB+ | 1 MB ± | 16 MB+ |
| Battery life (days) | 100-1,000+ | 1-7 | 0.1-5 | 1-7 |
| Nodes per network | 255/65,000+ | 7 | 30 | 1-1000 |
| Bandwidth (KBps) | 20-250 | 720 | 11,000+ | 64-128 |
| Range (meters) | 1-75+ | 1-10+ | 1-100 | 1000+ |

**Figure 2.**

**Which Wireless Standard?**

| | Application Focus | Success Metrics |
|---|---|---|
| ZigBee | Monitoring and control | Reliable, secure networking<br>Protocol simplicity<br>Low power consumption |
| Bluetooth | Cable replacement | Low incremental cost<br>Ease of use/convenience<br>Moderate data rate |
| Wi-Fi | Web, email, and video | High data throughput<br>Flexibility (work and home)<br>Hot Spot connectivity |
| GPRS / GSM | Wireless voice and data | Broad geographic coverage<br>Datacentric pricing plans<br>Network build-out |

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# Outline

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- HC-06 BlueTooth Module
- Example Application + Demo

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# HC-06 Module

- JY-MCU BT_BOARD V1.07 - referred to as HC-06 Module
  - Manual: http://www.ram-e-shop.com/ds/general/Bluetooth_TRx_Module_New.pdf
  - There are many similar others (including HC-03, HC-04, and HC-05)
- Wireless Bluetooth Transceiver Module – uses Bluetooth Specification v2.0
- Can work either as a master or a slave
- Built around the BC417 Bluetooth-to-Serial chip


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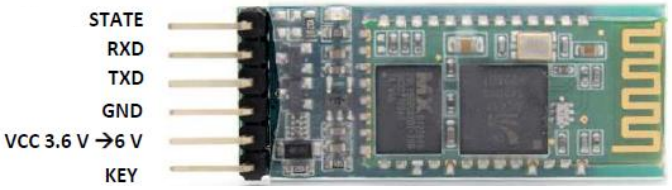
# HC-06 Pins

- The module has six pins:
  - **VCC:** supply voltage with range 3.6 V to 6 V (BC417 chip needs 3.3V generated with the help of a voltage regulator on the same PCB).
  - **GND**: ground.
  - **RXD**: Serial RX - would be connected to the TX pin of the Arduino board for example.
  - **TXD**: Serial TX - would be connected to the RX pin of the Arduino board.
  - **KEY**: Not used.
  - **STATE**: Not used.

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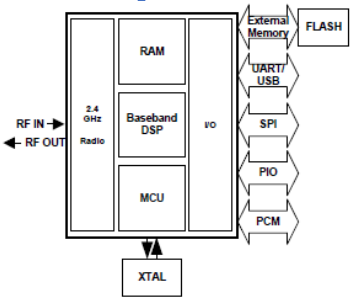
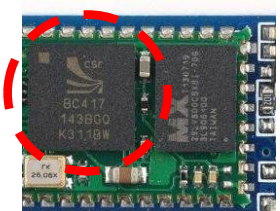
# BC417 BlueTooth-to-Serial Chip

- Single chip radio and baseband IC for Bluetooth 2.4 GHz systems
  - Datasheet: https://cdn.sparkfun.com/datasheets/Wireless/Bluetooth/CSR-BC417-datasheet.pdf
- Enhanced data rates (EDR) to 3Mbps
- Loaded with features
  - 1.8V core, 1.8 to 3.6V I/O
  - UART interface with programmable baud rate up to 3M baud
  - Low Power 1.8V operation
  - USB and Dual UART Ports
  - By default, it works as a Slave, 9600 baudrate, N, 8, 1, and Pincode 1234




System Architecture



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# Outline

- BlueTooth
- HC-06 BlueTooth Module
- Example Application + Demo

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# Examples of Projects that use HC-06

- Arduino based (can be ported to other MCU boards, such as Nucleo, LandTiger 2.0, etc. boards)
- Example #1
  - Send a text message from an MCU board to host-PC/smartphone
  - http://dejazzer.com/geen1200/resources/G1200_EECE_Lab3.pdf
- Example #2
  - Wireless data acquisition system (send Temp./Humidity data to host-PC/smartphone)
  - http://dejazzer.com/geen1200/resources/G1200_EECE_Lab3.pdf
- Example #3
  - Bluetooth Chat System: Android App ←→ Arduino + host-PC
  - Complete implementation available
  - http://www.dejazzer.com/eece4920/index.html

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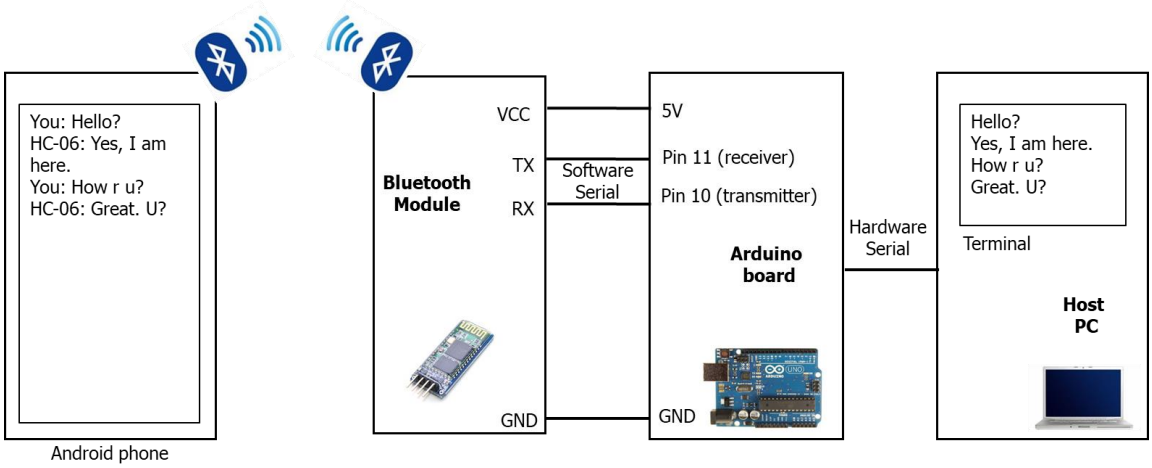
## Chat System:
## (Android App) talks to (HC-06 + Arduino + host-PC)

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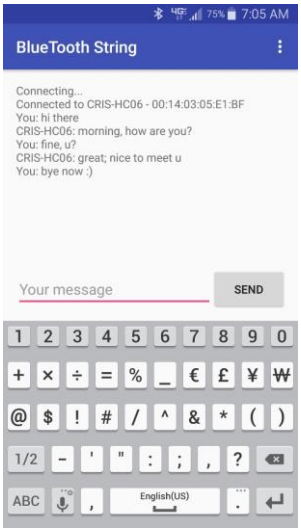
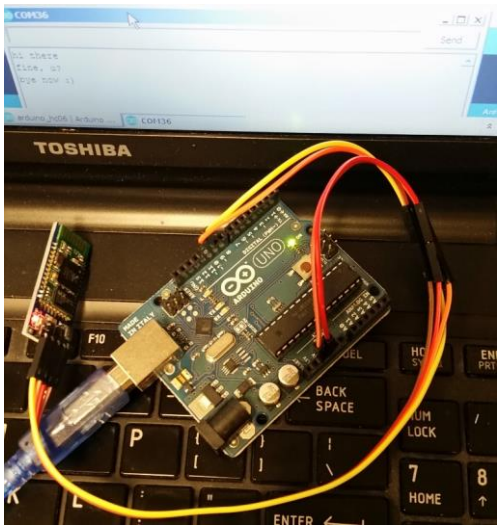
## Experimental Set-up

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# Credits and References


- https://en.wikipedia.org/wiki/Bluetooth
- https://www.bluetooth.com/what-is-bluetooth-technology/bluetooth-technology-basics
- https://www.amd.e-technik.uni-rostock.de/ma/gol/lectures/wirlec/bluetooth_info/radio.html
- http://www.radio-electronics.com/info/wireless/bluetooth/bluetooth_overview.php
- https://vdocuments.mx/wireless-personal-area-networks-wpans-bluetooth-ian-f-akyildiz-broadband.html
- https://www.scientificamerican.com/article/experts-how-does-bluetooth-work/
- Videos:
  - https://www.linkedin.com/learning/ethical-hacking-wireless-networks/understanding-bluetooth




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