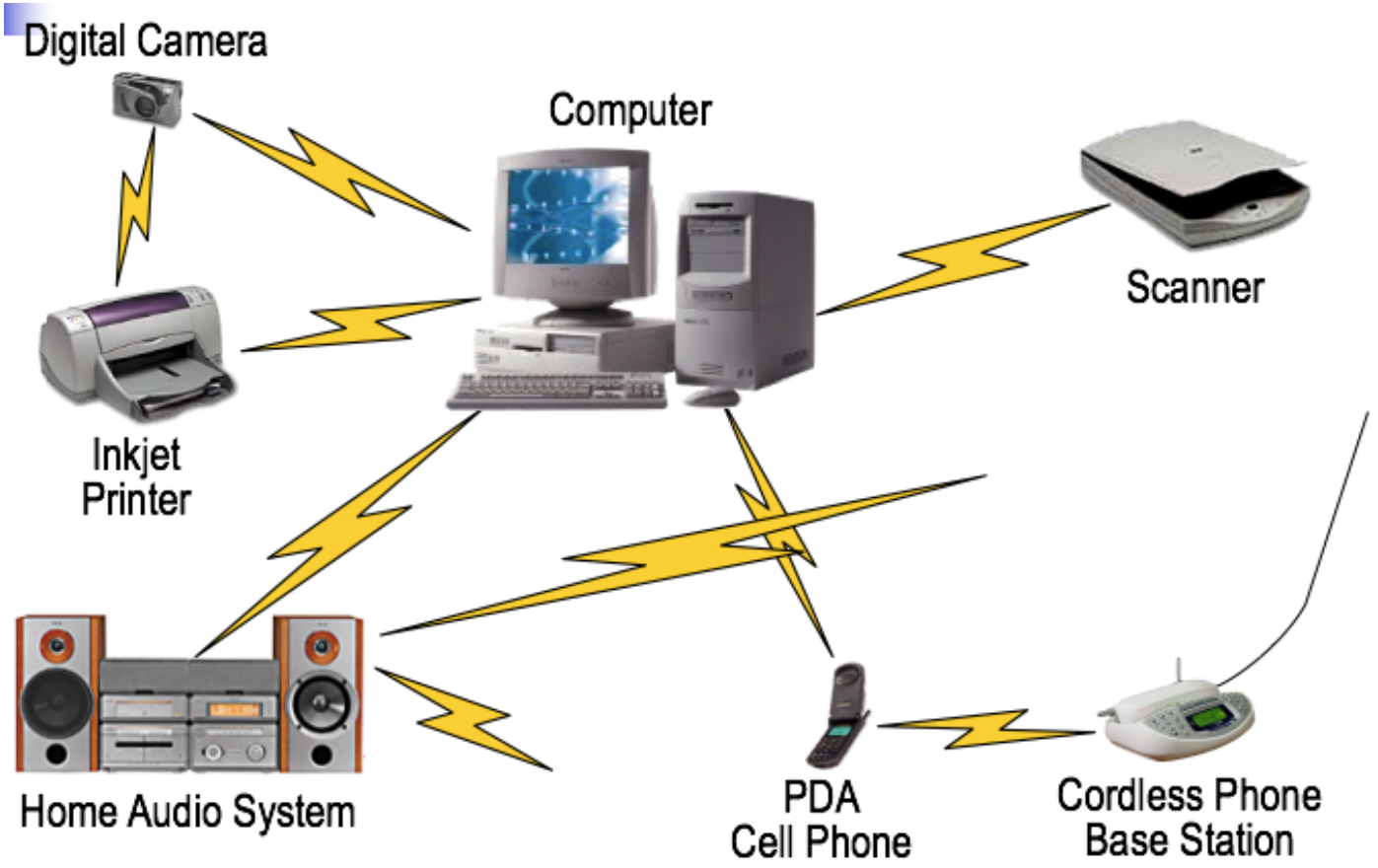
Wireless Personal Area Network (WPAN)

Wireless Personal Area Networks

- Person centered short-range wireless connectivity



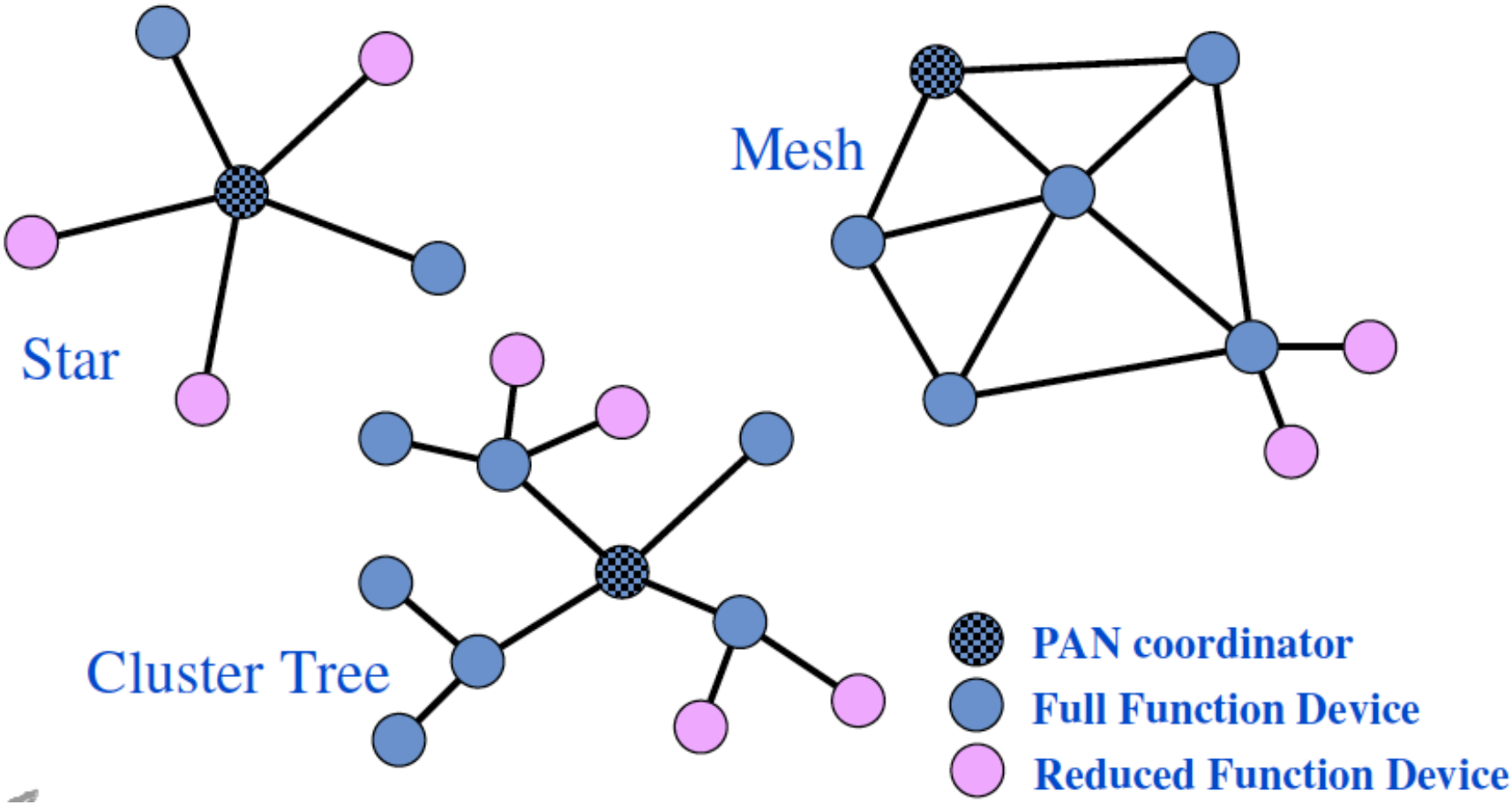
IEEE Definition of WPAN

- WPANs are used to convey information over short distances among a private, intimate group of participant devices
- Unlike a WLAN, a connection made through a WPAN involves little or no infrastructure or direct connectivity to the world outside the link
- This allows small, power-efficient, inexpensive solutions to be implemented for a wide range of devices

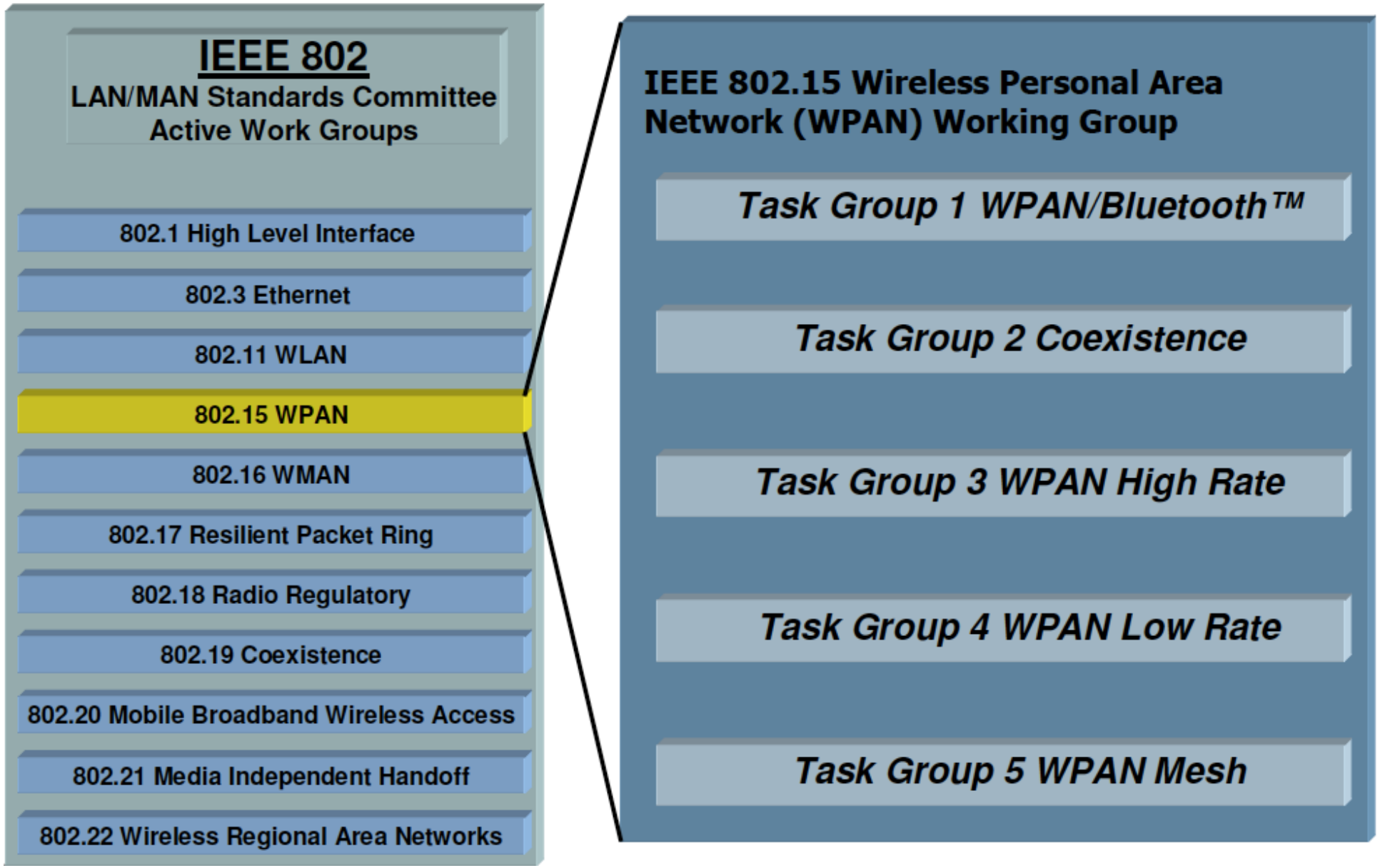
Applications

- Applications include
  - Short-range (< 10 m) connectivity for multimedia applications
    - PDAs, cameras, voice (hands free devices)
    - High QoS, high data rate (IEEE 802.15.3)
  - Industrial sensor applications
    - Low speed, low battery, low cost sensor networks (IEEE 802.15.4)
- Common goals
  - Getting rid of cable connections
  - Little or no infrastructure
  - Device interoperability

WPAN Topologies



IEEE 802.15 WPAN Working Group



IEEE 802.15 WPAN Standards

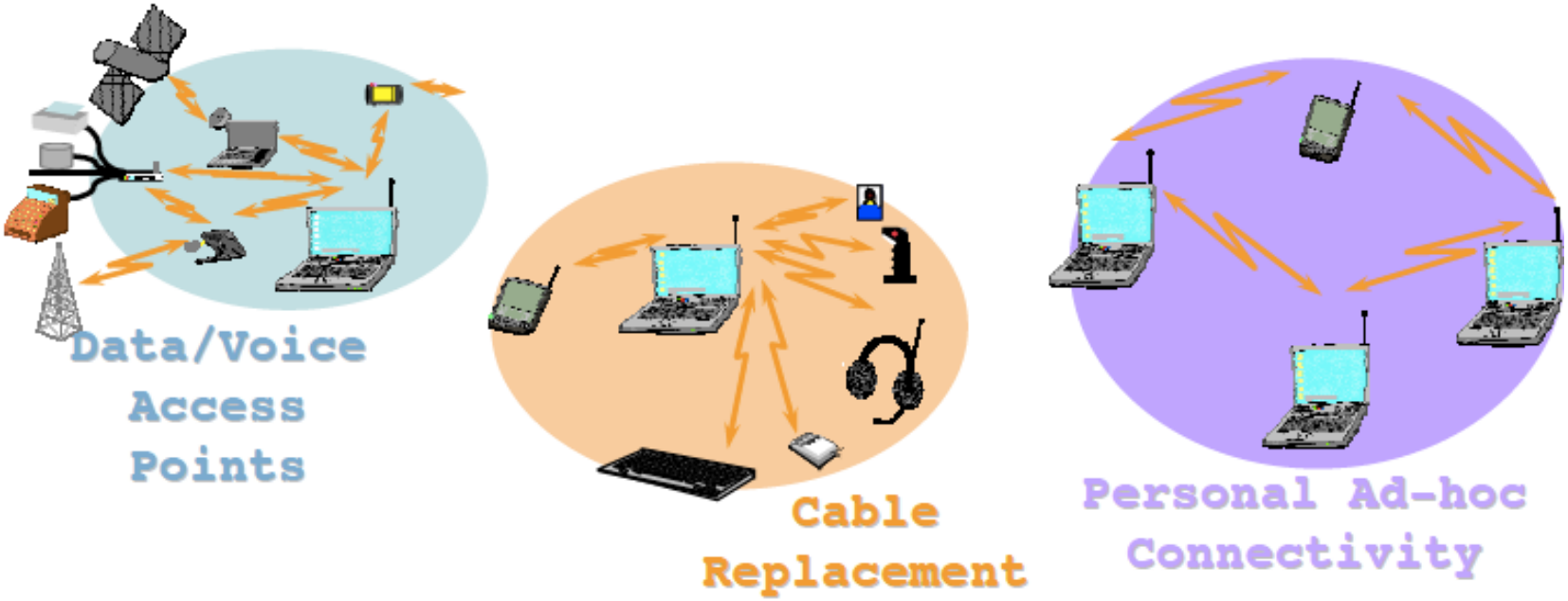
IEEE standard	Topic	Data throughput	Suitable applications	QoS needs
802.15.1	Bluetooth	1Mbp	Cell phones, Computers, Personal Digital Assistants (PDAs)/Handheld Personal Computers (HPCs), printers, microphones, speakers, headsets, bar code readers, sensors, displays, pagers, and cellular & Personal Communications Service (PCS) phones.	QoS suitable for voice applications
802.15.2	Coexistence of Bluetooth and 802.11b	N/A	N/A	N/A
802.15.3	High-rate WPAN	>20Mbps	Low power, low cost solutions for portable consumer of digital imaging and multimedia applications	Very high QoS
802.15.4	Low-rate WPAN	< 0.25 Mbps	Industrial, agricultural, vehicular, residential, medical applications, sensors and actuators with very low power consumption and low cost	Relaxed needs for data rate and QoS

Bluetooth ≈ IEEE 802.15.1

- A widely used WPAN technology is known as Bluetooth (version 1.2 or version 2.0)
- The IEEE 802.15.1 standard specifies the architecture and operation of Bluetooth devices, but only as far as physical layer and medium access control (MAC) layer operation is concerned (the core system architecture)
- Higher protocol layers and applications defined in usage profiles are standardized by the *Bluetooth SIG*

Bluetooth - Dominating Standard

- Bluetooth is the base for IEEE Std 802.15.1-2002 (rev. 2005)
  - Data rate of 1 Mbps (2 or 3 Mbps with enhanced data rate)
  - Robust short range communications

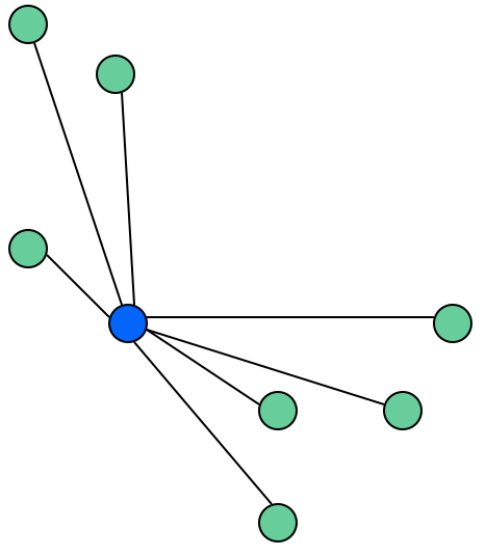


Piconets

- Bluetooth enabled electronic devices connect and communicate wirelessly through short-range, ad hoc networks known as piconets

ad hoc => no base station

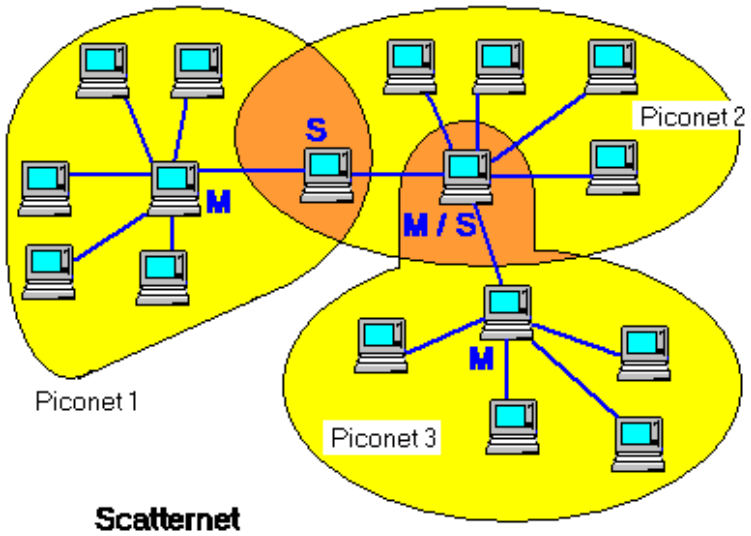
- Piconets are established dynamically and automatically as Bluetooth enabled devices enter and leave radio proximity
- Up to 8 devices in one piconet (1 master and up to 7 slave devices)
- Max range 10 m



- The **piconet master** is a device in a piconet whose clock and device address are used to define the piconet physical channel characteristics
- All other devices in the piconet are called **piconet slaves**
- All devices have the same timing and frequency hopping sequence
- At any given time, data can be transferred between the master and one slave
- The master switches rapidly from slave to slave in a round-robin fashion
- Any Bluetooth device can be either a master or a slave
- Any device may switch the master/slave role at any time

Scatternet

- Any Bluetooth device can be a master of one piconet and a slave of another piconet at the same time (scatternet)
- Scatternet is formed by two or more Piconets
- Master of one piconet can participate as a slave in another connected piconet
- No time or frequency synchronization between piconets

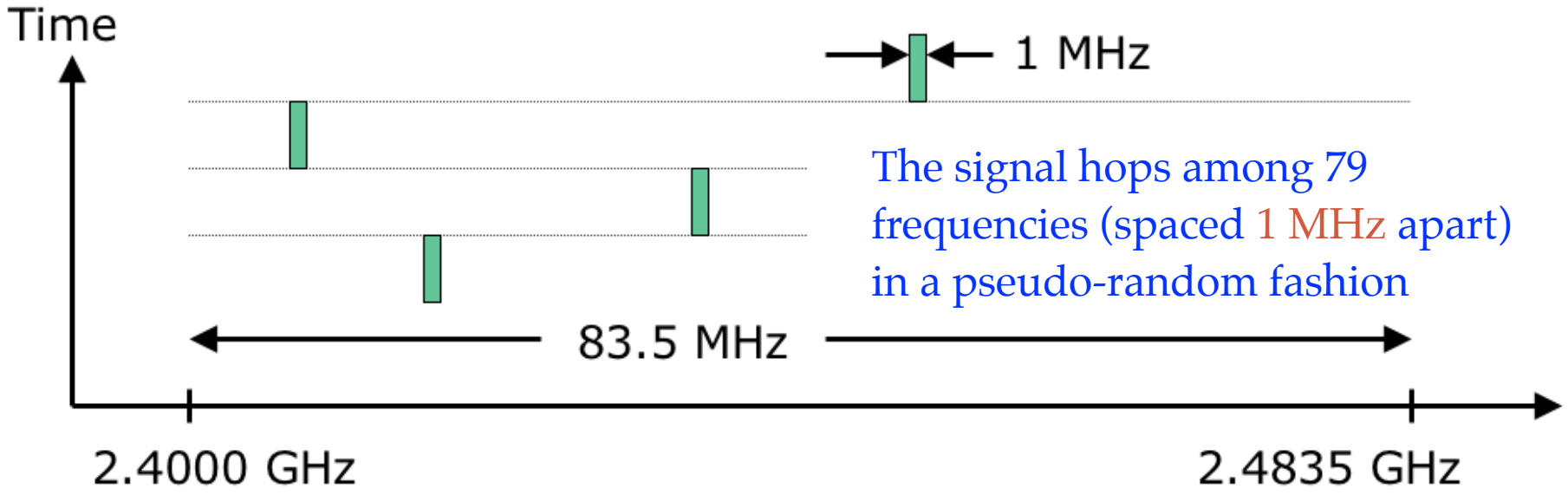


Bluetooth Radio and Baseband Parameters

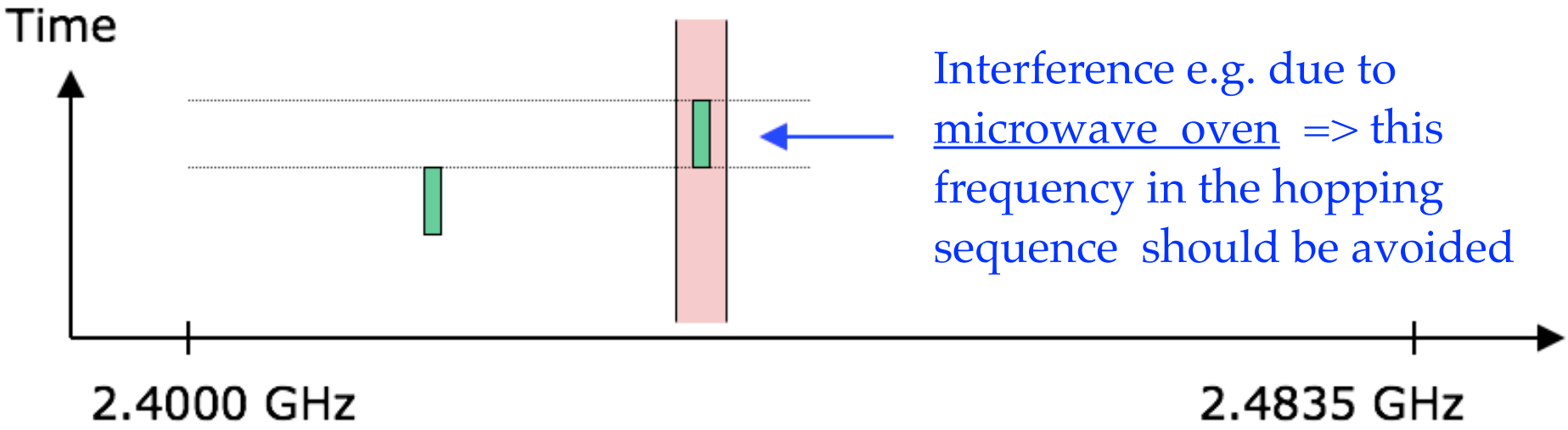
*	Topology	Up to 7 simultaneous links
	Modulation	Gaussian filtered FSK
	RF bandwidth	220 kHz (-3 dB), 1 MHz (-20 dB)
*	RF band	2.4 GHz ISM frequency band
*	RF carriers	79 (23 as reduced option)
	Carrier spacing	1 MHz
*	Access method	FHSS-TDD-TDMA
*	Freq. hop rate	1600 hops/s

Frequency Hopping Spread Spectrum (FHSS)

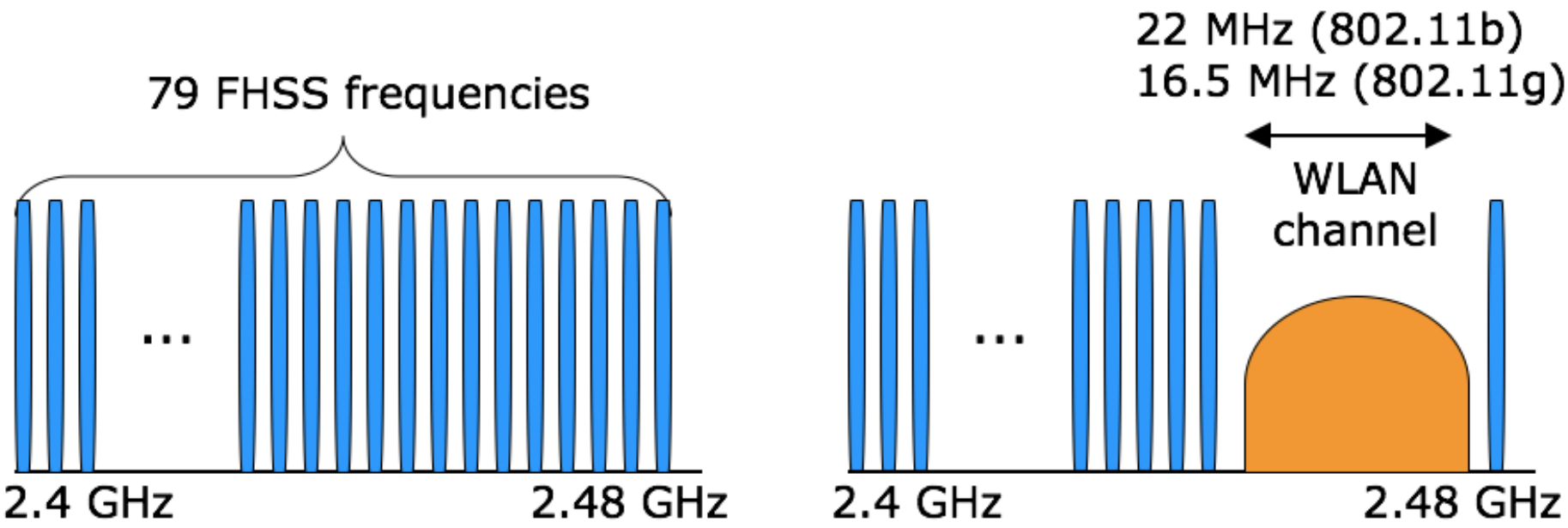
- Bluetooth technology operates in the 2.4 GHz ISM band, using a spread spectrum, frequency hopping, full-duplex signal at a nominal rate of 1600 hops/sec



- The adaptive frequency hopping (AFH) feature (from Bluetooth version 1.2 onward) is designed to reduce interference between wireless technologies sharing the 2.4 GHz spectrum

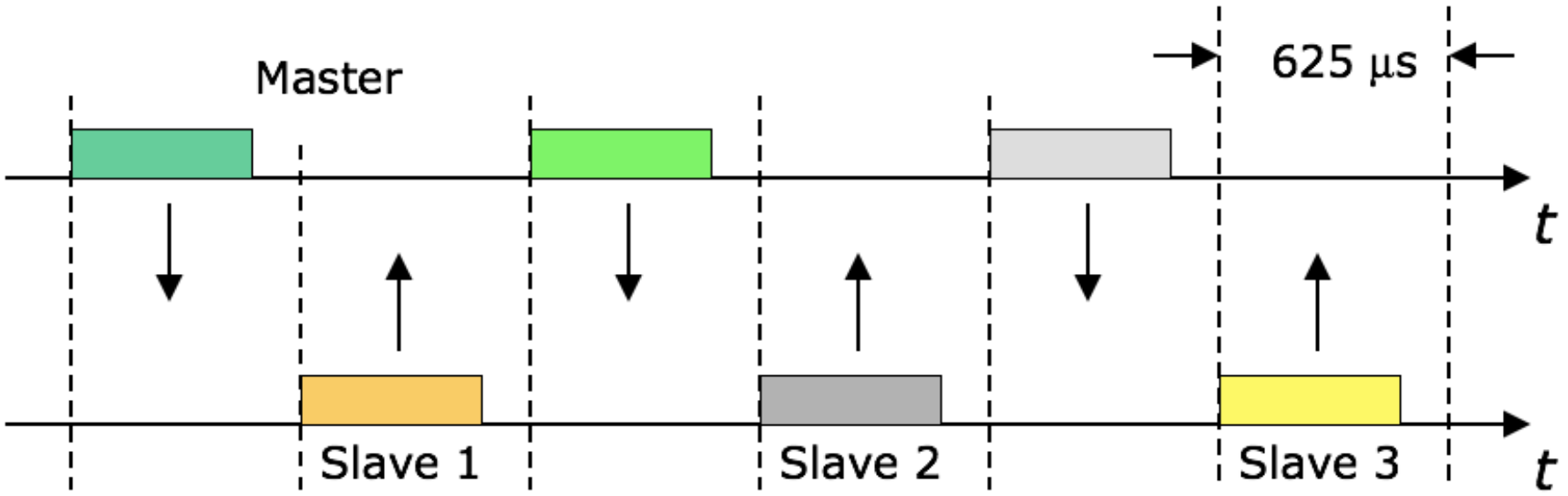


- In addition to avoiding microwave oven interference, the adaptive frequency hopping (AFH) feature can also avoid interference from WLAN networks

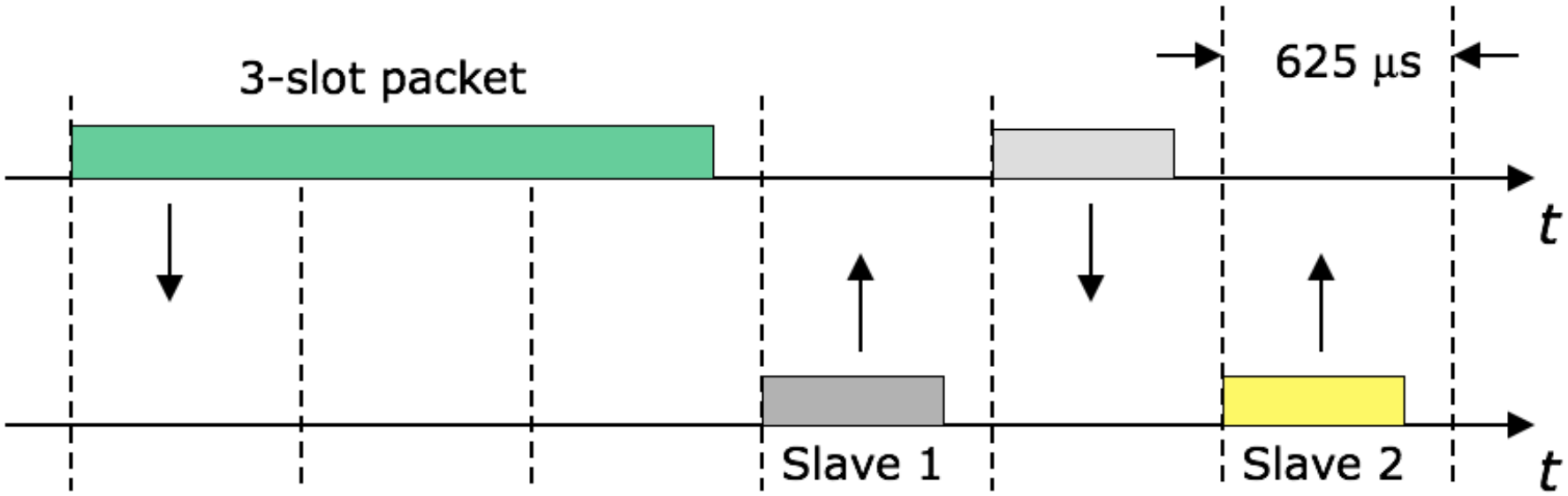


Frequency Hopping in Action

- The piconet master decides on the frequency hopping sequence
- All slaves must synchronize to this sequence
- Then transmission can take place on a TDD-TDMA basis



- The packet length can be 1, 3 or 5 slots
- Note that the following transmissions are synchronized to the hopping sequence



Power Classes

- Bluetooth products are available in one of three power classes

Class	Power	Range	
Class 1	100 mW	~100 m	Industrial usage
Class 2	2.5 mW	~10 m	Mobile devices
Class 3	1 mW	~10 cm	

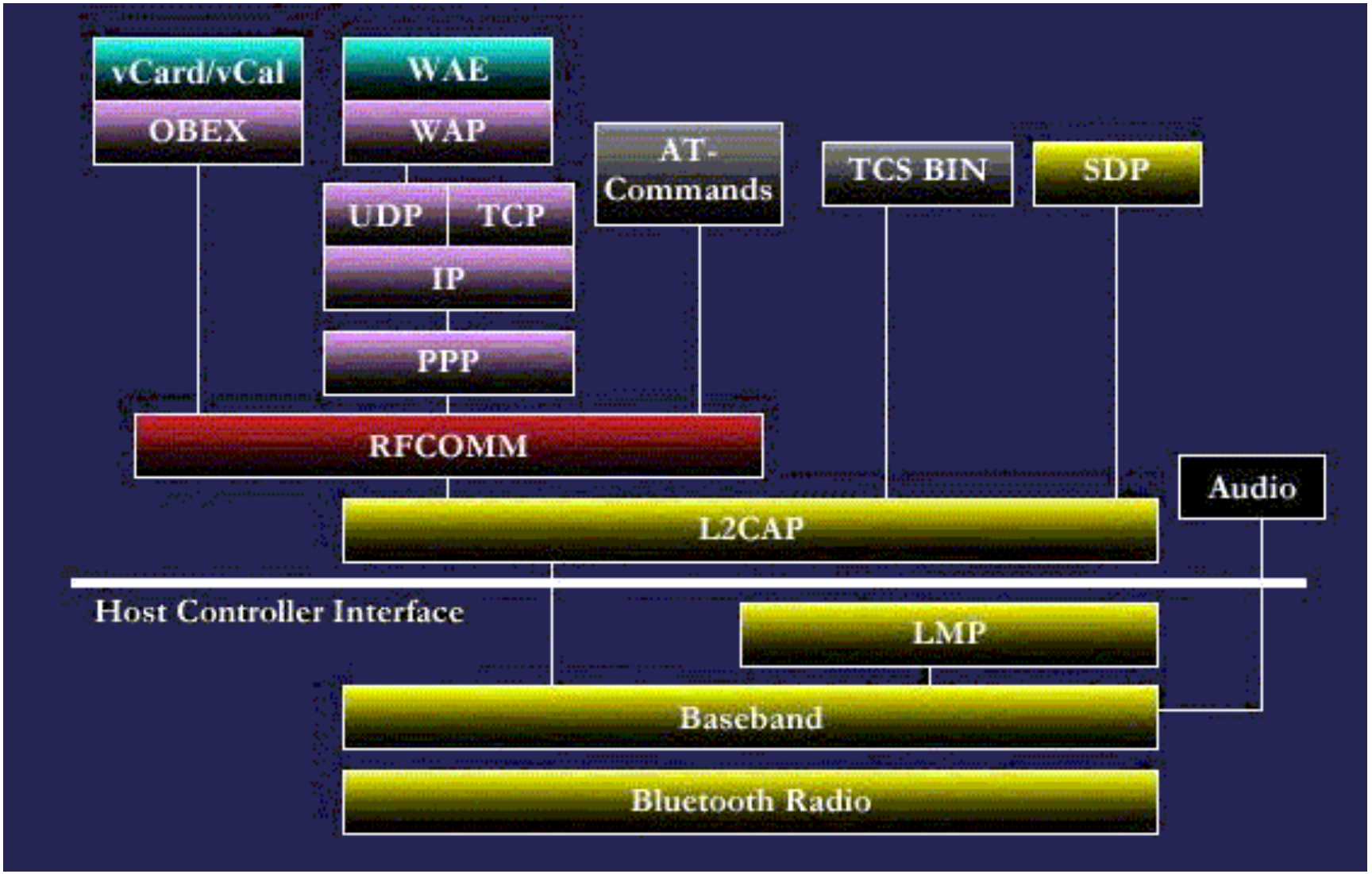
Data Rates

- Channel data rates
  - Bluetooth version 1.2 offers a bit rate of **1 Mbps**
  - Bluetooth version 2.0 offers a bit rate of **3 Mbps**
- Achievable user bit rates are much lower, (among others) due to the following reasons
  - overhead resulting from various protocol headers
  - interference causes destroyed frequency bursts => information has to be retransmitted

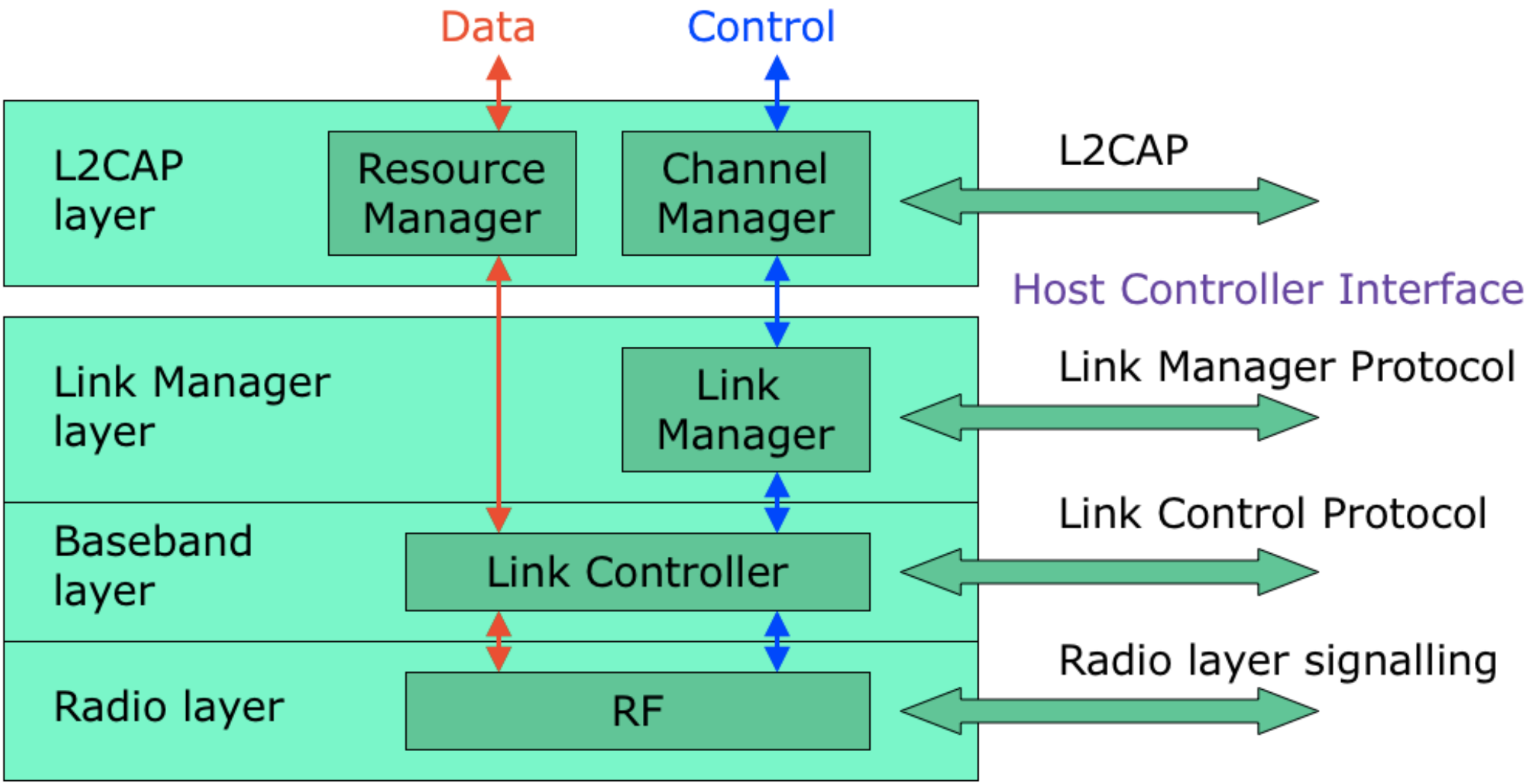
Link Delivery Services

- Two types of links can be established between the piconet master and one or more slaves
- Synchronous connection-oriented (SCO) [circuit switch]
  - Link allocates a fixed bandwidth for a **point-to-point** connection involving the piconet master and a slave
  - Up to three simultaneous SCO links are supported in a piconet
- Asynchronous connectionless or connection-oriented (ACL) [packet switch]
  - Link is a **point-to-multipoint** link between the master and all the slaves in the piconet
  - Only one single ACL link can exist in the piconet

Bluetooth Protocol Stack

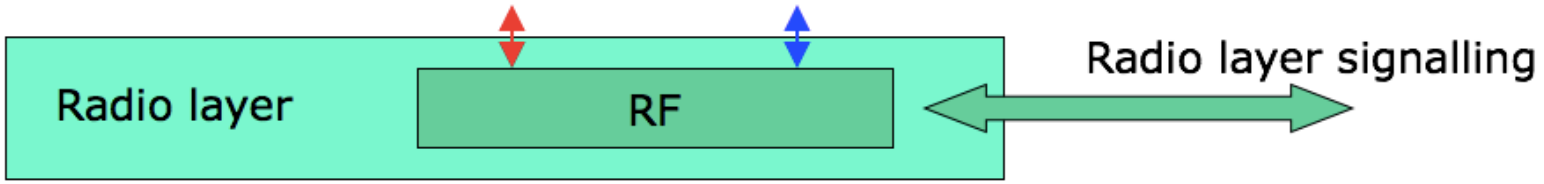


Bluetooth Core System Architecture



Radio Layer (Physical Layer)

- The radio layer specifies details of the air interface, including the usage of the frequency hopping sequence, modulation scheme, and transmit power



- The radio layer FHSS operation and radio parameters

Topology	Up to 7 simultaneous links
Modulation	Gaussian filtered FSK
RF bandwidth	220 kHz (-3 dB), 1 MHz (-20 dB)
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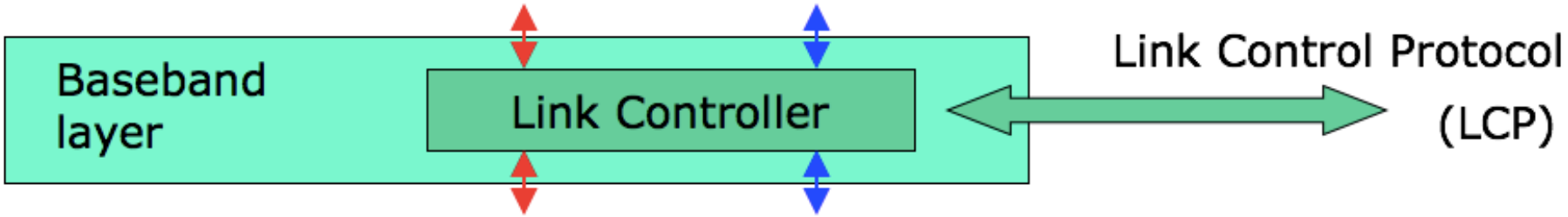
RF carriers	79 (23 as reduced option)
Carrier spacing	1 MHz
Access method	FHSS-TDD-TDMA
Freq. hop rate	1600 hops/s

Baseband Layer

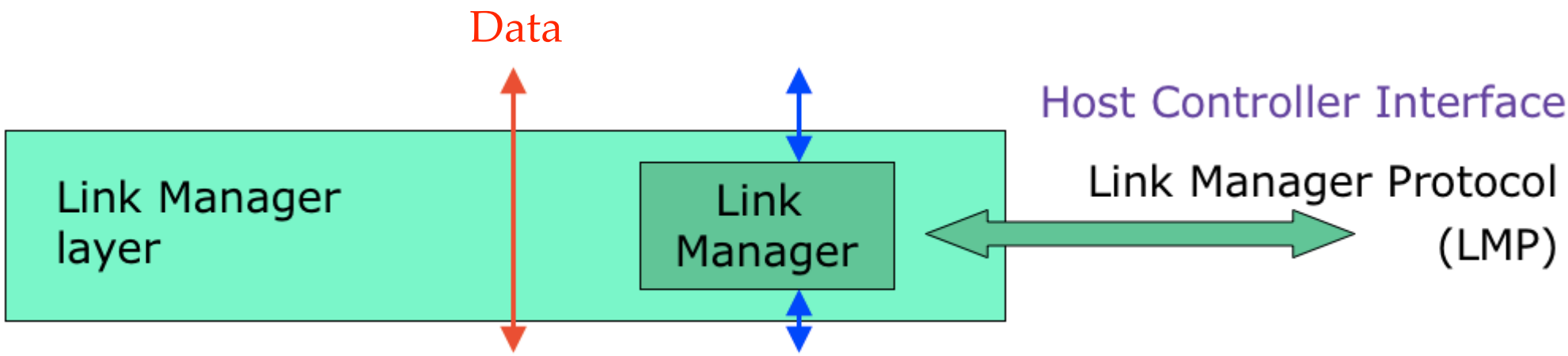
- The baseband layer specifies the lower level operations at the bit and packet levels, e.g.,
  - Forward Error Correction (FEC) operations
  - Encryption, Cyclic Redundancy Check (CRC) calculations
  - Retransmissions using the Automatic Repeat Request (ARQ) Protocol



Link Manager layer

- The link manager layer specifies the establishment and release of SCO and ACL links, authentication, traffic scheduling, link supervision, and power management tasks
- Responsible for all the physical link resources in the system
  - Handles the control and negotiation of packet sizes used when transmitting data
- Sets up, terminates, and manages baseband connections between devices
  - Establishes different types of links (SCO / ACL) dependent on requests from the L2CAP layer

- These are "control plane" tasks
- This layer is not involved in "user plane" tasks (i.e., handling of the user data)



SCO Links

- SCO links provides a **circuit-switched connection** where data is regularly exchanged
- SCO links are used primarily for carrying time-bounded **real-time data** (audio, video) where large delays are not allowed (so that retransmission cannot be used) and occasional data loss is acceptable
- The guaranteed data rate is achieved through reservation of slots
- The master maintains the SCO link by using reserved slots at regular intervals
- The basic unit of reservation is two consecutive slots - one in each transmission direction
- An ACL link must be established (for signaling) before an SCO link can be used

ACL Link

- The ACL link offers **packet-switched data transmission**, where data is exchanged sporadically as and when data is available from higher up the stack
- No bandwidth reservation is possible and delivery may be guaranteed through error detection and retransmission
- A slave is permitted to send an ACL packet in a slave-to-master slot only if it has been addressed in the preceding master-to-slave slot
- Data can be sent in two ways
  - **unprotected** : although Automatic Repeat-reQuest (ARQ) can be used at a higher layer
  - **protected** : with a 2/3 rate Forward Error Correction (FEC) code

Achievable User Data Rates (ACL)

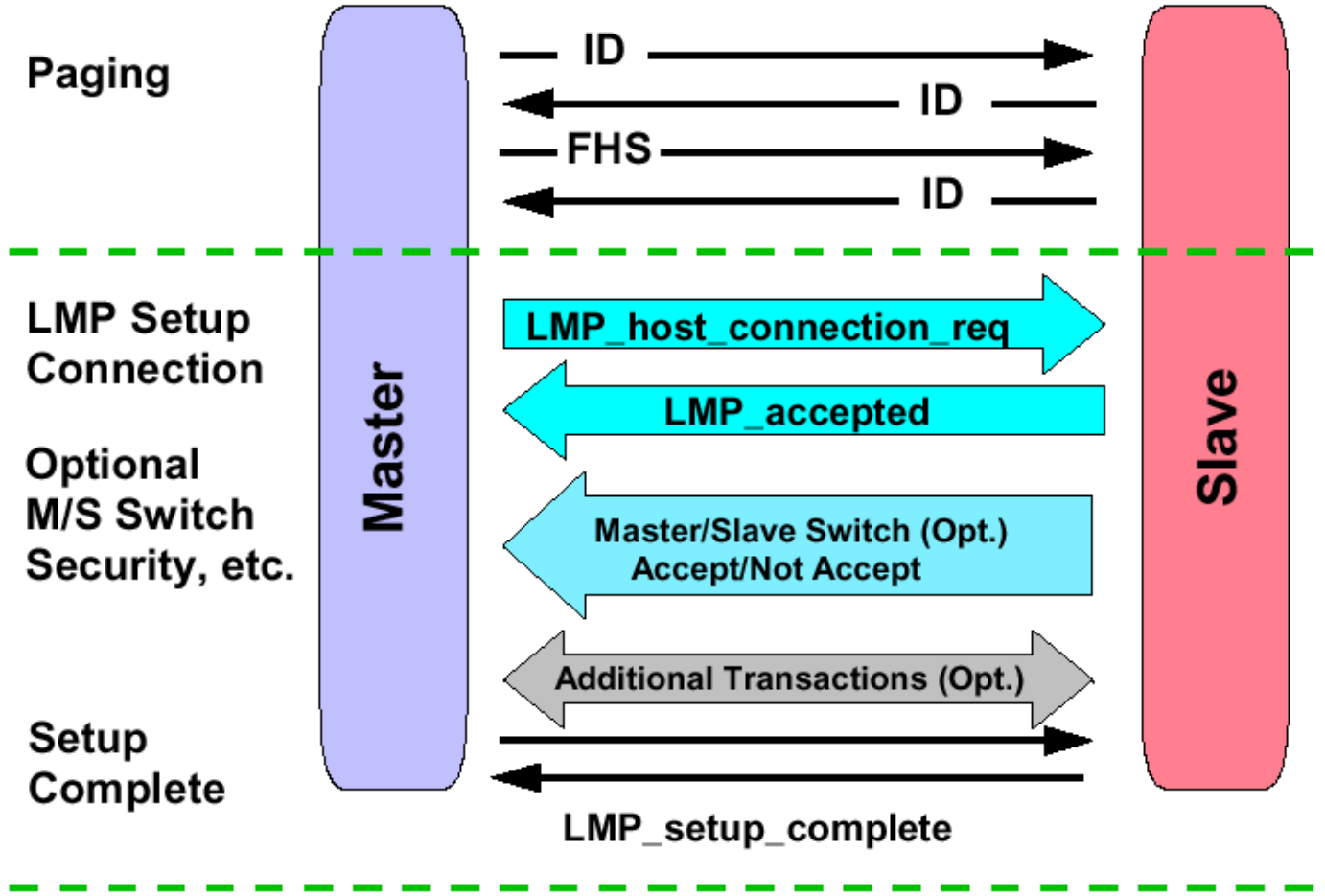
Type	*Symmetric (kbit/s)*	*Asymmetric (kbit/s)*	
DM1	108.8	108.8	108.8
DH1	172.8	172.8	172.8
DM3	256.0	384.0	54.4
DH3	384.0	576.0	86.4
DM5	286.7	477.8	36.3
DH5	432.6	721.0	57.6

DMx = x-slot FEC-encoded (relatively low)
DHx = x-slot unprotected (relatively high)

SCO Links vs. ACL Links

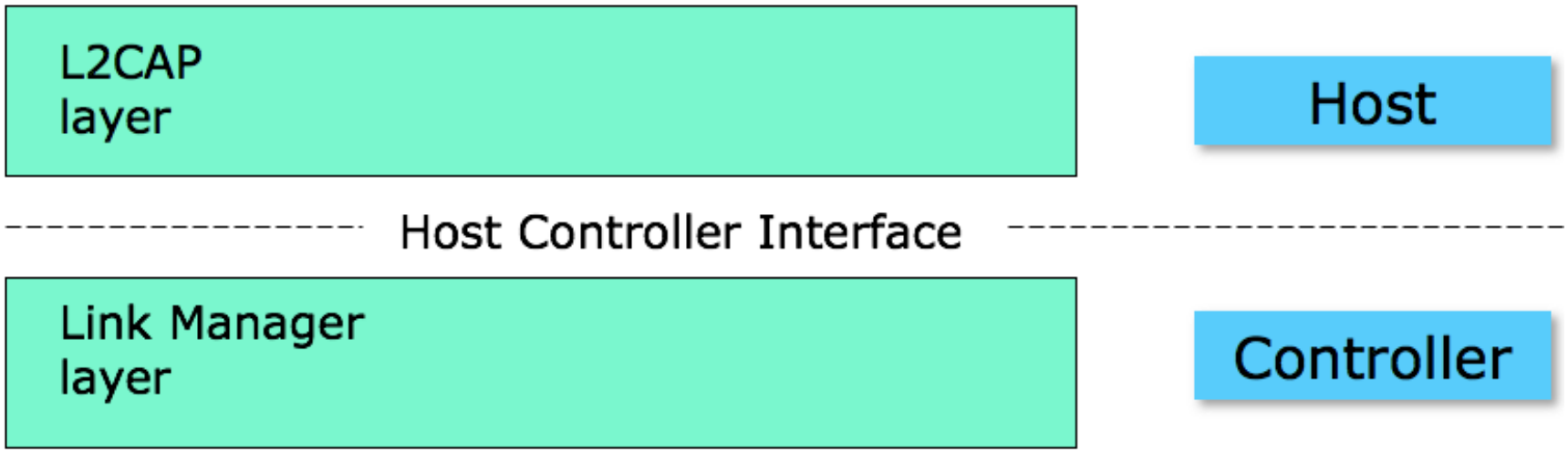
	Intended Traffic Type	Retransmission	Max # links between master and slave	Supported during hold mode	Switched connection type
ACL	Data	Yes	1	No	Packet
SCO	Time bounded info (Audio or Video)	No	3	Yes	Circuit

ACL Setup under LMP

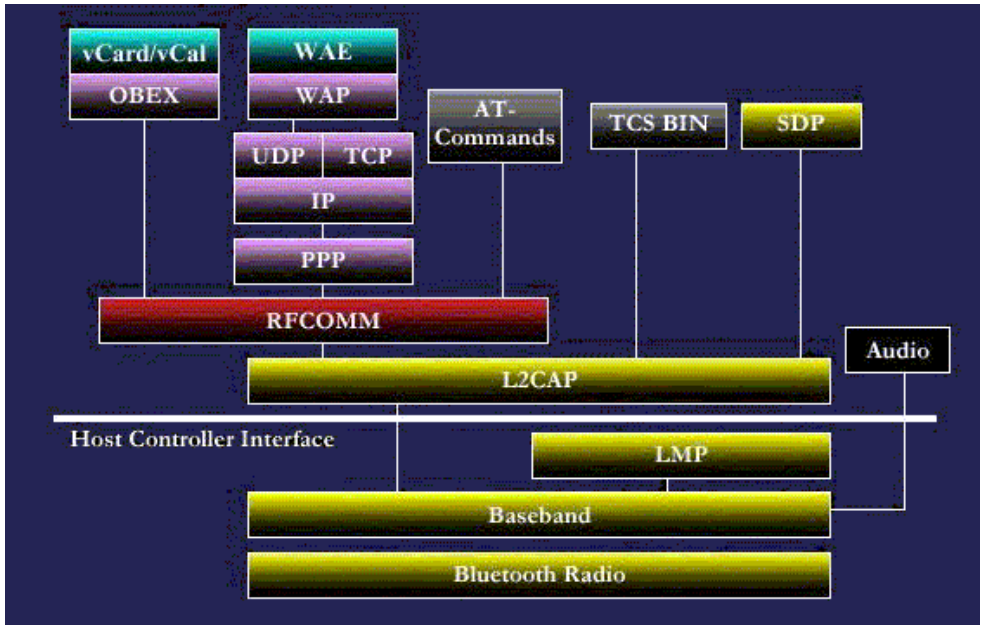


Host Controller Interface (HCI)

- The open host controller interface resides between the Bluetooth controller (e.g. PC card) and Bluetooth host (e.g. PC)
- In integrated devices such as Bluetooth-capable mobile devices this interface has little or no significance

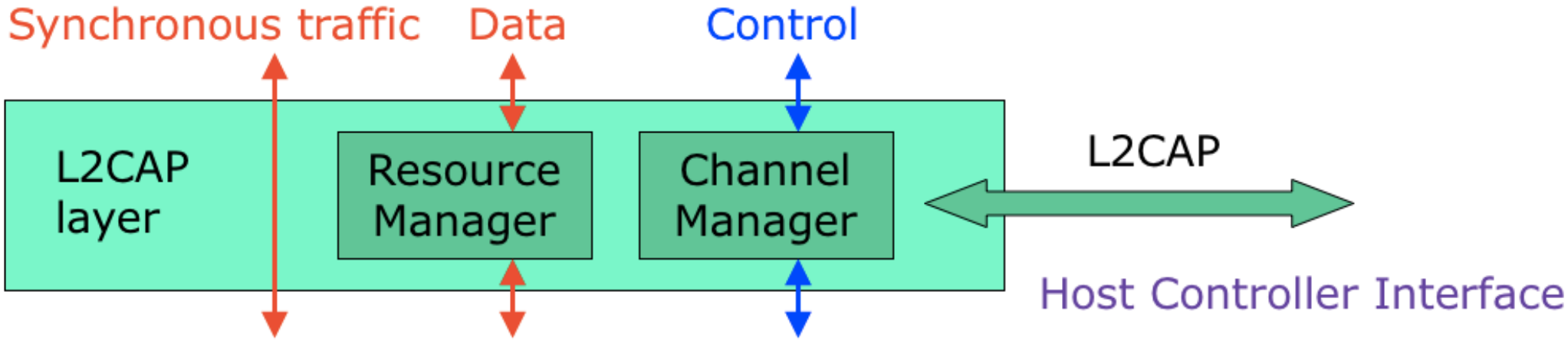


- Most Bluetooth systems consist of two processors
  - The **higher layers** of the protocol stack (**L2CAP, SDP, RFCOMM**) are run on the host device's processor
  - The **lower layers** of the protocol stack (**Baseband** and **radio**) are run on specific Bluetooth hardware
- HCI provides an interface between the higher and the lower layers of the protocol stack

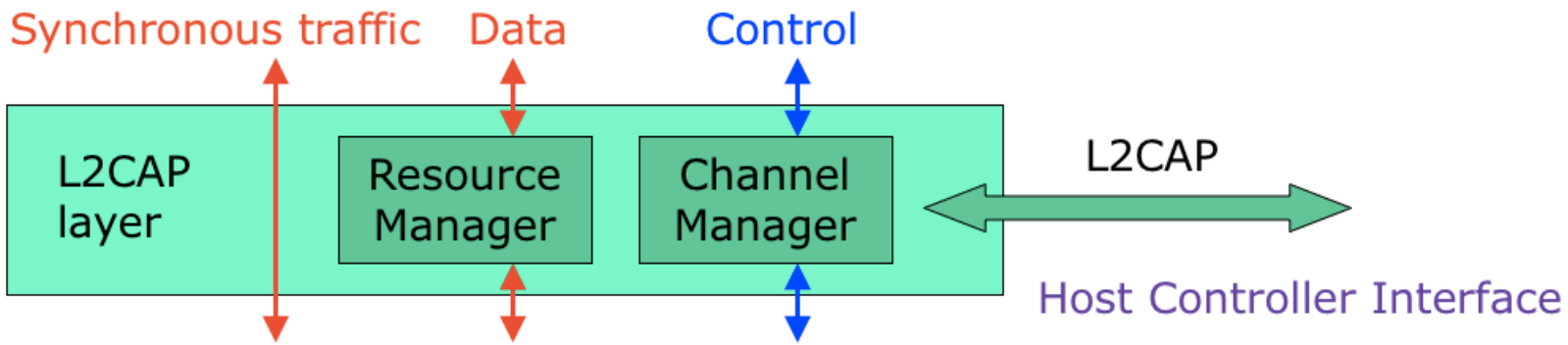


L2CAP layer

- The Logical Link Control and Adaptation Protocol (L2CAP) layer handles the multiplexing of higher layer protocols and the segmentation and reassembly (SAR) of large packets
- The L2CAP layer provides both connectionless and connection-oriented services



- L2CAP performs 4 major functions
  - Managing the creation and termination of logical links for each connection through **channel** structures
  - Enforcing and defining QoS requirements
  - Adapting Data, for each connection, between application (APIs) and Bluetooth Baseband formats through Segmentation and Reassembly (SAR)
  - Performing Multiplexing to support multiple concurrent connections over a single common radio interface (multiple apps. using link between two devices simultaneously)



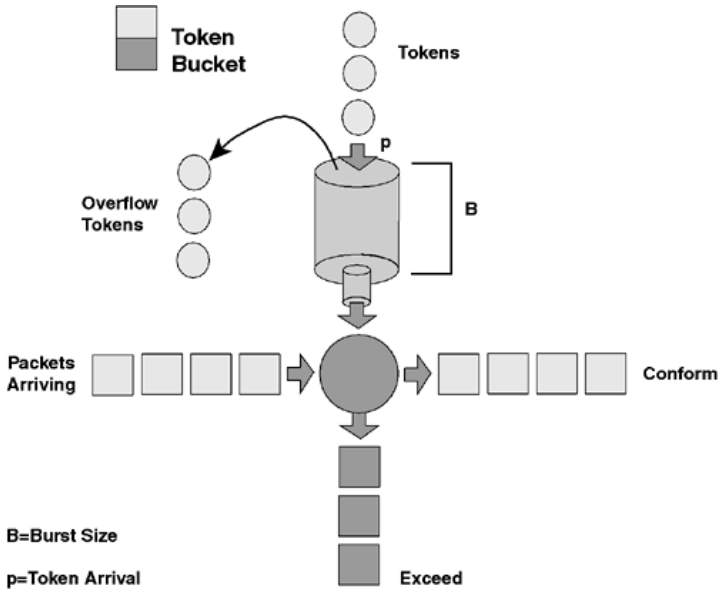
Segmentation/Reassembly

- Baseband packet size is limited
  - Can handle payload of 2745 bits
- L2CAP accepts packet size up to 64kb
- L2CAP segments large packets into smaller baseband manageable packets
- Smaller received baseband packets are reassembled coming back up the protocol stack

Quality of Service

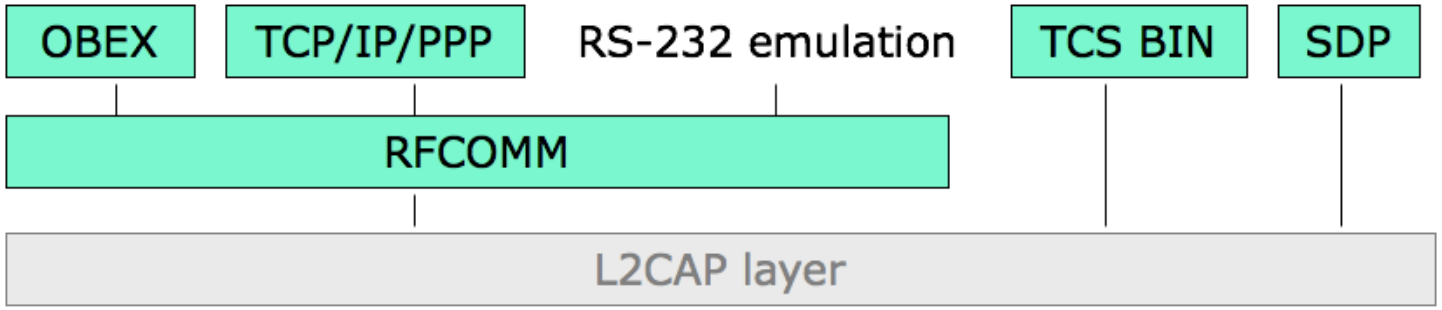
- Applications may demand QoS on specific parameters
  - Peak bandwidth
  - Latency
  - Delay variation
  - Token rate
  - Token bucket size
- L2CAP provides requested QoS if possible and notifies application if link can not support demands

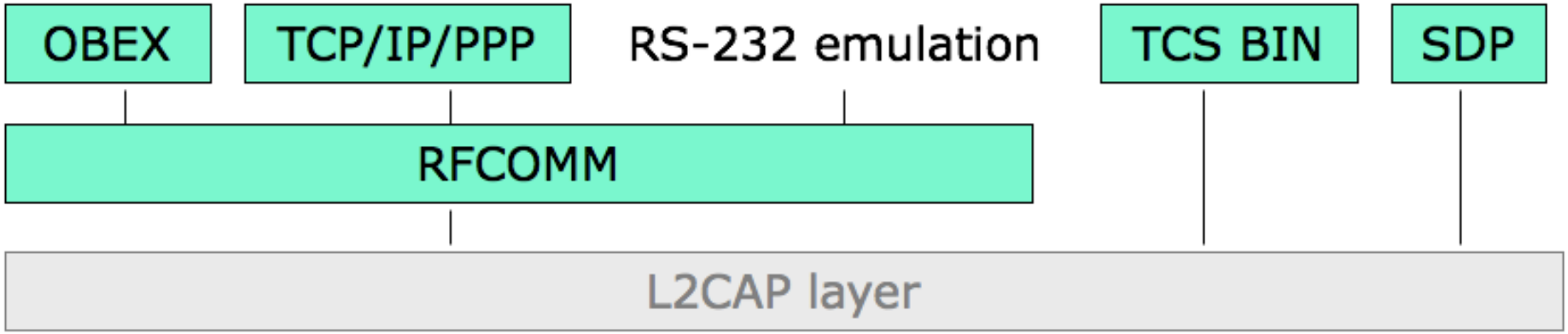
- Note: **token bucket**
  - The token bucket is an algorithm used in packet switched computer networks and telecommunications networks
  - It can be used to check that data transmissions, in the form of packets, conform to defined limits on bandwidth and burstiness (a measure of the unevenness or variations in the traffic flow)
  - It can also be used as a scheduling algorithm to determine the timing of transmissions that will comply with the limits set for the bandwidth and burstiness

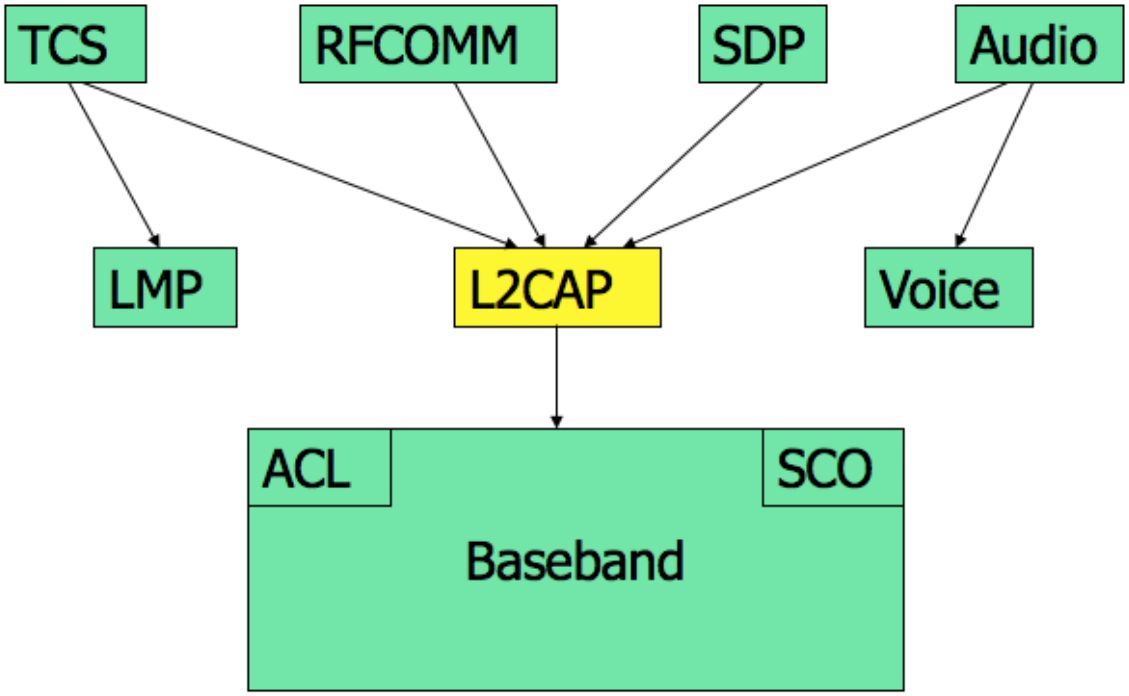


Protocol Multiplexing

- Applications may access L2CAP through different support protocols
  - Service Discovery Protocol (SDP)
  - RFCOMM
  - Telephony Control Protocol Specification (TCS)
- Baseband is not concerned with operation protocols meaning L2CAP must distinguish between them

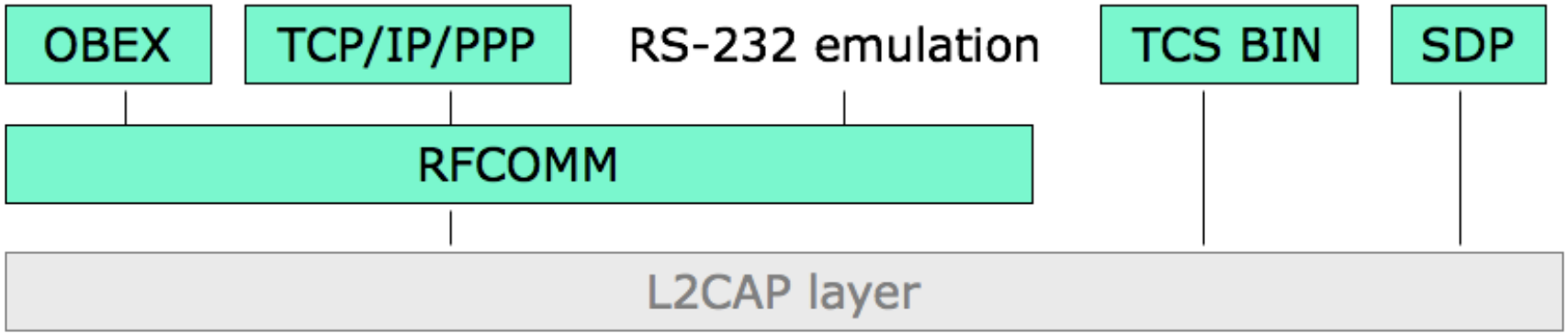



OBEX
TCP/IP/PPP
RS-232 emulation
TCS BIN
SDP
RFCOMM
L2CAP layer


TCS
RFCOMM
SDP
Audio
LMP
L2CAP
Voice
ACL
SCO
Baseband

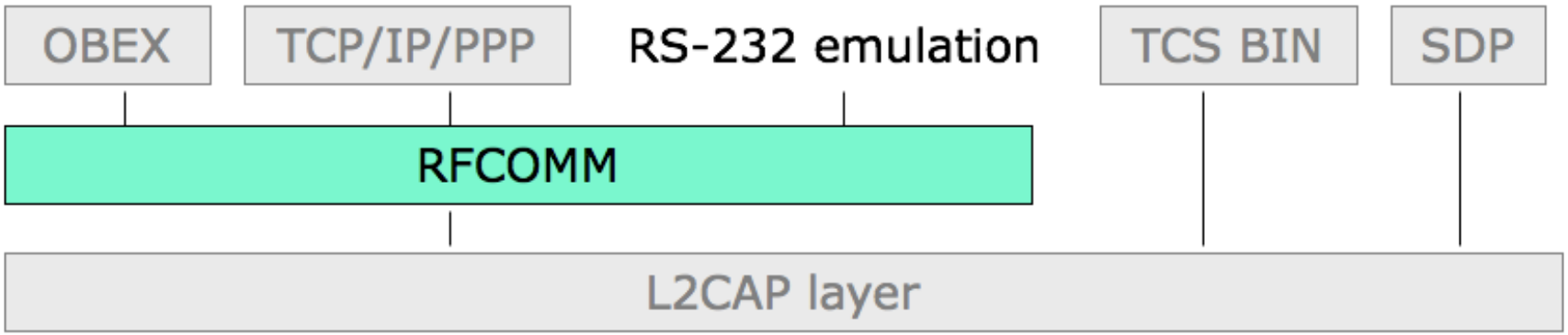
Higher Protocol Layers

- The operation of higher protocol layers is outside the scope of the IEEE 802.15.1 standard (but included in the Bluetooth SIG standards)
- The usage of these protocols depends on the specific Bluetooth profile in question
- A large number of Bluetooth profiles have been defined

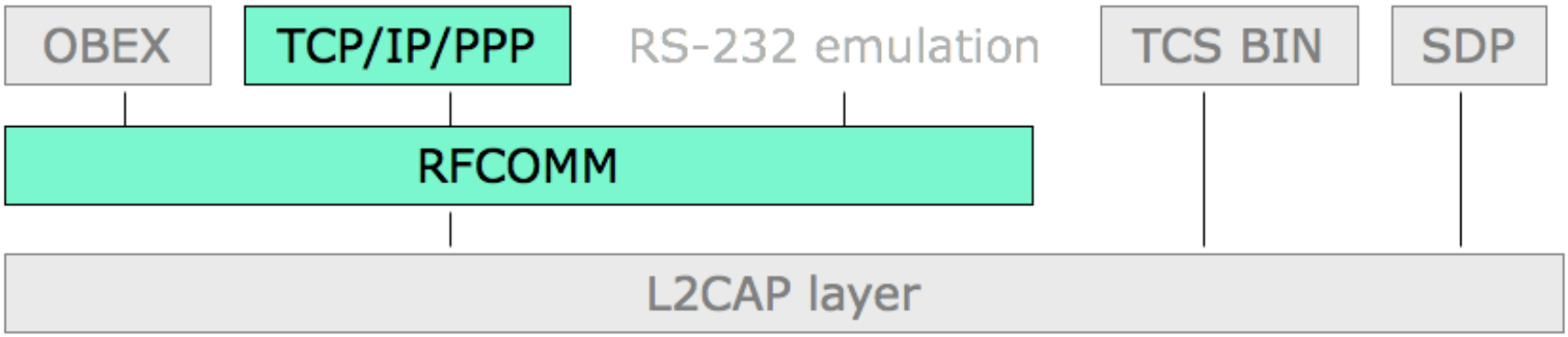


- The radio frequency communication protocol **RFCOMM** enables the replacement of serial port cables (carrying RS-232 control signals such as *TxD*, *RxD*, *CTS*, *RTS*, etc.) with wireless connections

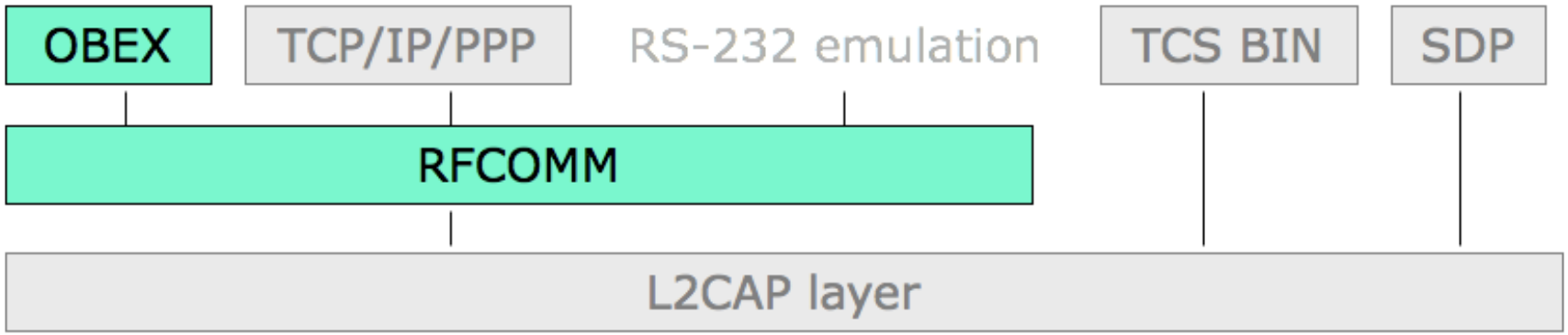
- Several tens of serial ports can be multiplexed into one Bluetooth device



- **TCP/IP** based applications, for instance information transfer using the Wireless Application Protocol (WAP), can be extended to Bluetooth devices by using the **Point-to-Point Protocol** (**PPP**) on top of **RFCOMM**

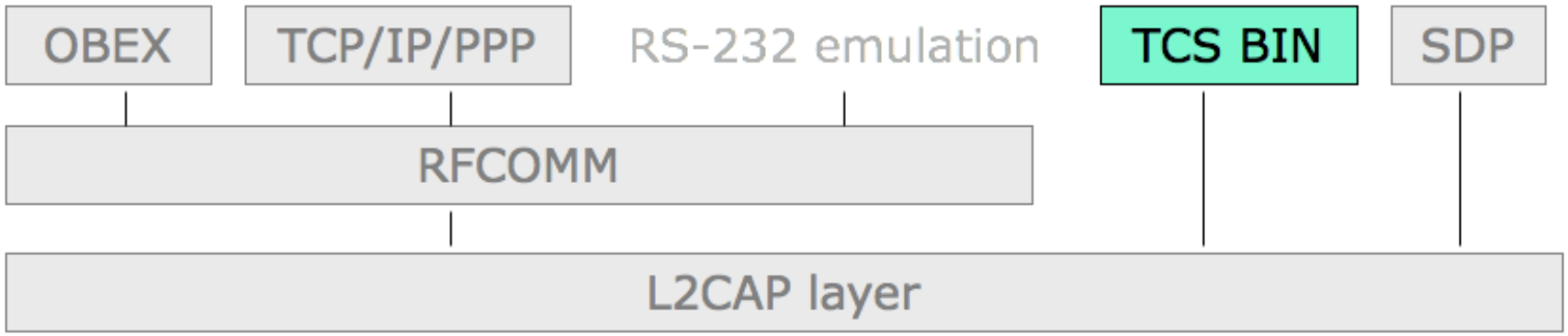


- The **Object Exchange Protocol** (**OBEX**) is a session-level protocol for the exchange of objects
- This protocol can be used for example for phonebook, calendar or messaging synchronization, or for file transfer between connected devices

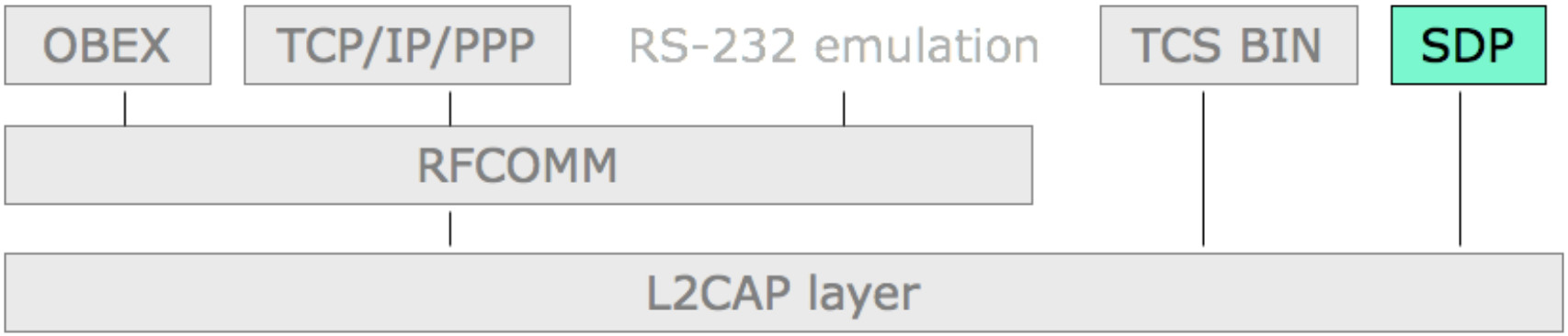


- The **telephony control specification - binary** (**TCS BIN**) protocol defines the call-control signaling for the establishment of speech and data calls between Bluetooth devices

- In addition, it defines mobility management procedures for handling groups of Bluetooth devices



- The **Service Discovery Protocol** (**SDP**) can be used to access a specific device (such as a digital camera) and retrieve its capabilities, or to access a specific application (such as a print job) and find devices that support this application

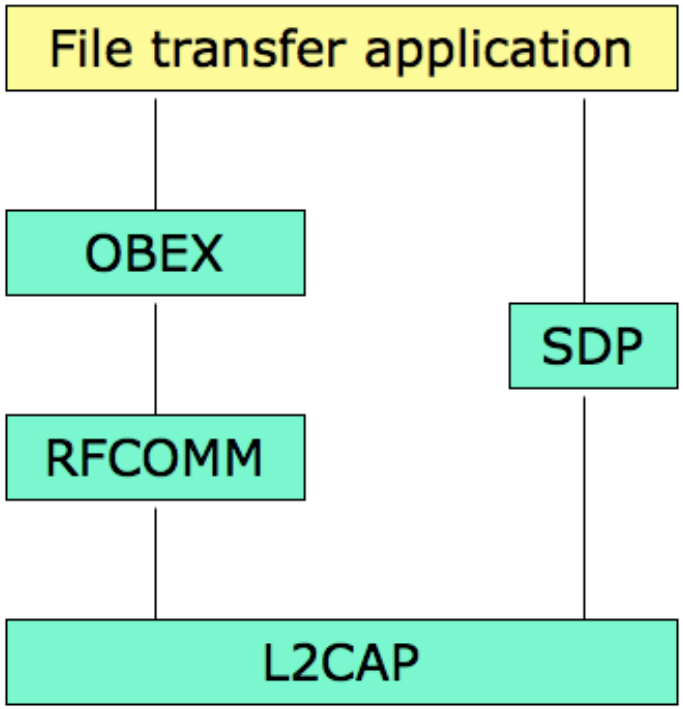


Usage Models

- A number of usage models are defined in Bluetooth profile documents
- A usage model is described by a set of protocols that implement a particular Bluetooth-based application
- Examples
  - File transfer
  - LAN access
  - Wireless headset
  - Cordless (three-in-one) phone

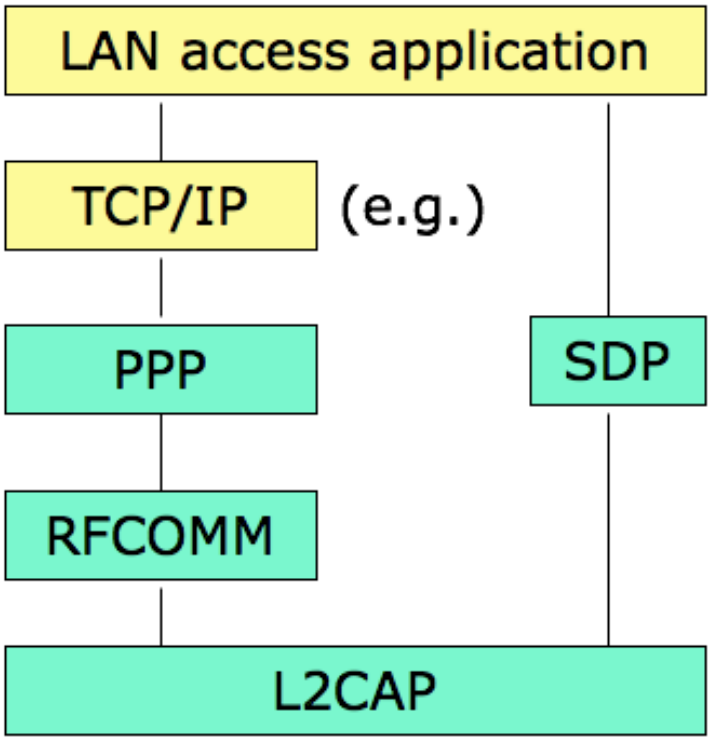
File Transfer Application

- Using the **file transfer** profile
  - A Bluetooth device can browse the file system of another Bluetooth device, can manipulate objects (e.g. delete objects) on another Bluetooth device, or - as the name implies - files can be transferred between Bluetooth devices



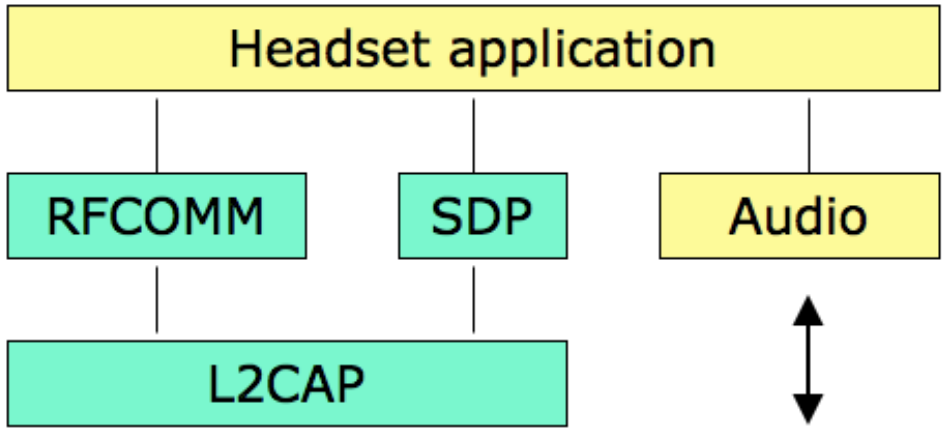
LAN Access Application

- Using the **LAN** profile
  - A Bluetooth device can access LAN services using (for instance) the TCP/IP protocol stack over Point-to-Point Protocol (PPP)
  - Once connected, the device functions as if it were directly connected (wired) to the LAN



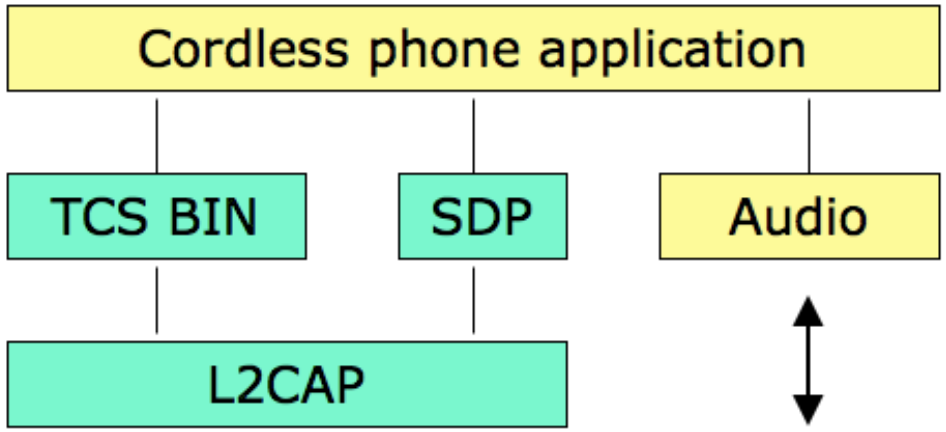
Wireless Headset Application

- Using the **headset** profile
  - According to this usage model, the Bluetooth-capable headset can be connected wirelessly to a PC or mobile phone, offering a full-duplex audio input and output mechanism
  - This usage model is known as the ultimate headset



Cordless (three-in-one) Phone Application

- Using the **cordless telephone** profile
  - A Bluetooth device using this profile can set up phone calls to users in the PSTN (e.g. behind a PC acting as voice base station) or receive calls from the PSTN
  - Bluetooth devices implementing this profile can also communicate directly with each other



IEEE 802.15 WPAN Standards

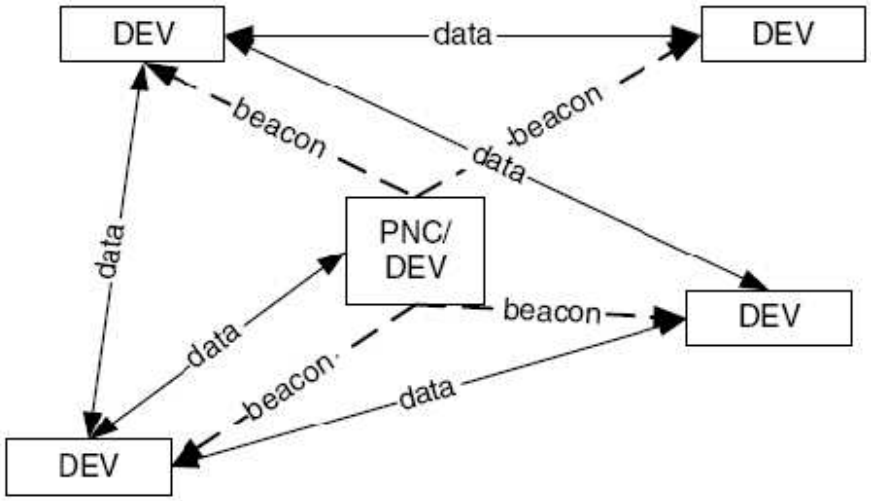
IEEE standard	Topic	Data throughput	Suitable applications	QoS needs
802.15.1	Bluetooth	1Mbp	Cell phones, Computers, Personal Digital Assistants (PDAs)/Handheld Personal Computers (HPCs), printers, microphones, speakers, headsets, bar code readers, sensors, displays, pagers, and cellular & Personal Communications Service (PCS) phones.	QoS suitable for voice applications
802.15.2	Coexistence of Bluetooth and 802.11b	N/A	N/A	N/A
802.15.3	High-rate WPAN	>20Mbps	Low power, low cost solutions for portable consumer of digital imaging and multimedia applications	Very high QoS
802.15.4	Low-rate WPAN	< 0.25 Mbps	Industrial, agricultural, vehicular, residential, medical applications, sensors and actuators with very low power consumption and low cost	Relaxed needs for data rate and QoS

IEEE 802.15 WPAN High Rate (HR) Task Group 3

- Task Group 3
  - First high rate WPAN standard: IEEE Std 802.15.3-2003 (HR-WPAN)
- Task Group 3a
  - Alternative PHY using UWB
- Task Group 3b
  - Improved implementation and interoperability of the IEEE Std 802.15.3 MAC
- Task Group 3c
  - WPAN at mm-waves (57-64 GHz)

IEEE Std 802.15.3-2003 (HR)

- WPAN with high data rate (HR) IEEE Std 802.15.3-2003
  - Data rates from 11 Mbps to 55 Mbps
  - Ad hoc peer-to-peer networks (piconets)
  - Each piconet is controlled by piconet coordinator (PNC)
    - Sends beacon for piconet information and timing
    - Controls superframe structures



IEEE Std 802.15.3-2003 (HR)

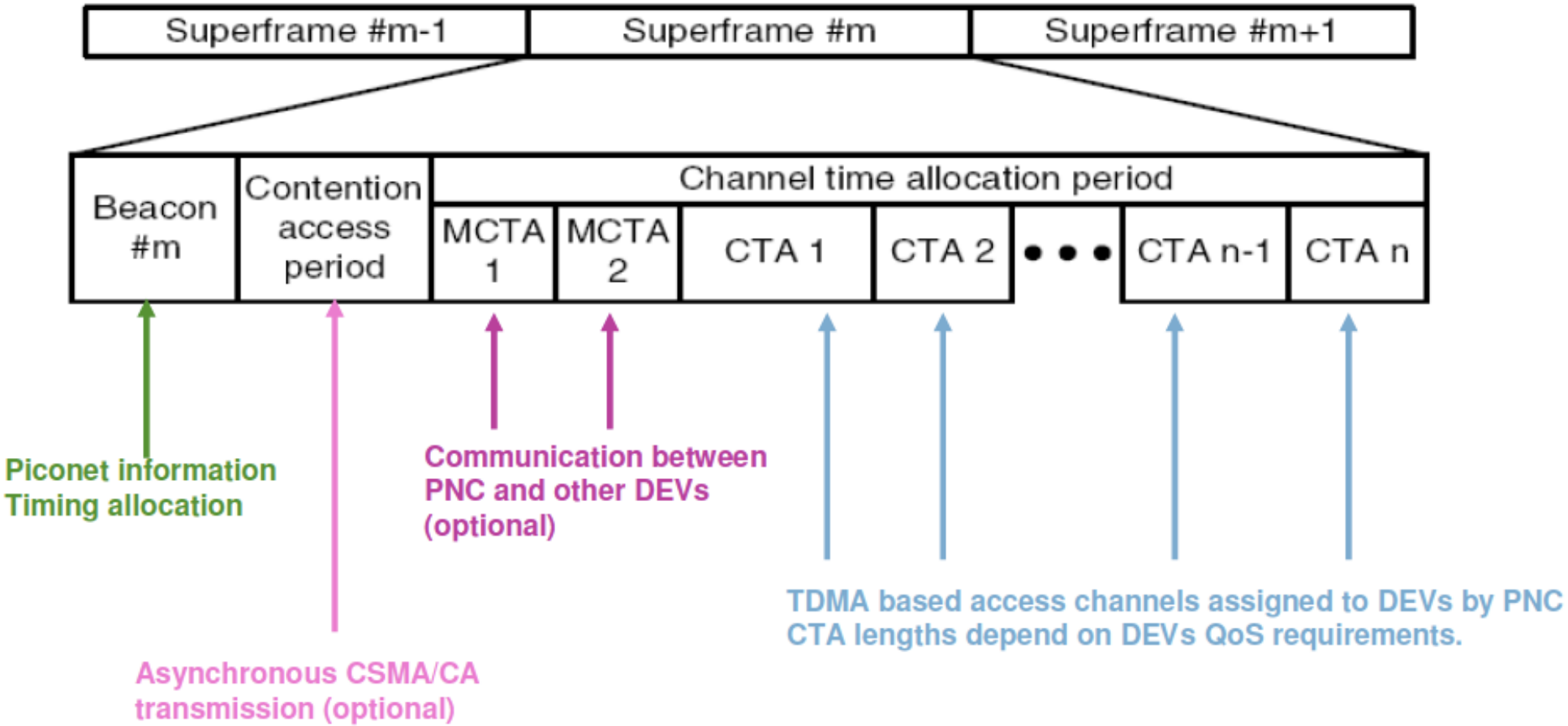
- Single carrier of 15 MHz bandwidth and Trellis Coded Modulation (TCM)

Modulation type	Coding	Data rate
QPSK	8-state TCM	11 Mb/s
DQPSK	none	22 Mb/s
16-QAM	8-state TCM	33 Mb/s
32-QAM	8-state TCM	44 Mb/s
64-QAM	8-state TCM	55 Mb/s

- Frequency band of 2.4-2.4835 GHZ
  - Coexistence with 802.11b
    - Passive scanning
    - Dynamic channel selection
    - A channel plan that minimize channel overlap
    - Transmit power control

CHNL_ID	Center frequency	High-density	802.11b coexistence
1	2.412 GHz	X	X
2	2.428 GHz	X	
3	2.437 GHz		X
4	2.445 GHz	X	
5	2.462 GHz	X	X

- Piconet timing is based on superframes



CSMA/CA：Carrier Sense Multiple Access with Collision Avoidance
PNC：PicoNet Coordinator
CTA：Channel Time Allocation
MCTA：Management Channel Time Allocation

IEEE 802.15 WPAN Standards

IEEE standard	Topic	Data throughput	Suitable applications	QoS needs
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IEEE 802.15 WPAN Low Rate (LR) Task Group 4

- Task Group 4
  - LR-WPAN Standard: IEEE Std 802.15.4-2003 (LR WPAN)
  - Also known as **ZigBee**
- Task Group 4a
  - Alternative PHYs: UWB Impulse Radio and Chirp Spread Spectrum (CSS)
- Task Group 4c
  - Specific enhancements and clarifications to the IEEE Std 802.15.4-2003

IEEE 802.15.4 LR-WPAN (ZigBee)

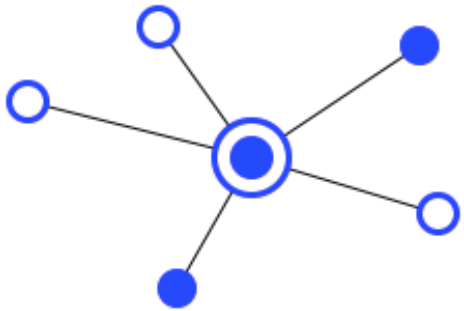
- ZigBee technology is simpler (and less expensive) than Bluetooth
- The main objectives of an LR-WPAN like ZigBee are ease of installation, reliable data transfer, short-range operation, extremely low cost, and a reasonable battery life, while maintaining a simple and flexible protocol
- The raw data rate will be high enough (max of 250 kbps) to satisfy a set of simple needs such as interactive toys, but is also scalable down to the needs of sensor and automation needs (20 kbps or below) using wireless communications

Network Topologies

- Two or more devices communicating on the same physical channel constitute a WPAN
- The WPAN network must include at least one FFD that operates as the PAN coordinator
- PAN coordinator
  - The primary controller of the PAN
  - Initiates, terminates, or routes communication around the network
- The WPAN may operate in either of two topologies
  - Star topology
  - Peer-to-peer topology

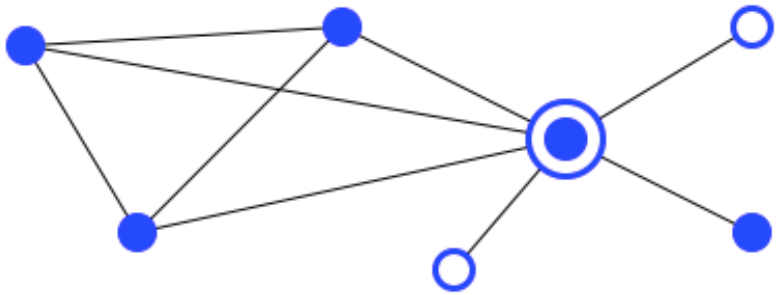
Star Topology

- In a star network, after an FFD is activated for the first time, it may establish its own network and become the PAN coordinator
- The PAN coordinator can allow other devices to join its network



Peer-to-Peer Topology

- In a peer-to-peer network, each FFD is capable of communicating with any other FFD within its radio sphere of influence
- One FFD will be nominated as the PAN coordinator
- A peer-to-peer network can be ad hoc, self-organizing and self-healing, and can combine devices using a mesh networking topology



ZigBee PHY and MAC parameters

Topology	Ad hoc (central PAN coordinator)
RF band	2.4 GHz ISM frequency band
RF channels	16 channels with 5 MHz spacing
Spreading	DSSS (32 chips / 4 bits)
Chip rate	2 Mchip/s
Modulation	Offset QPSK

Access method	CSMA/CA (or slotted CSMA/CA)

IEEE Std 802.15.4-2003 (LR)

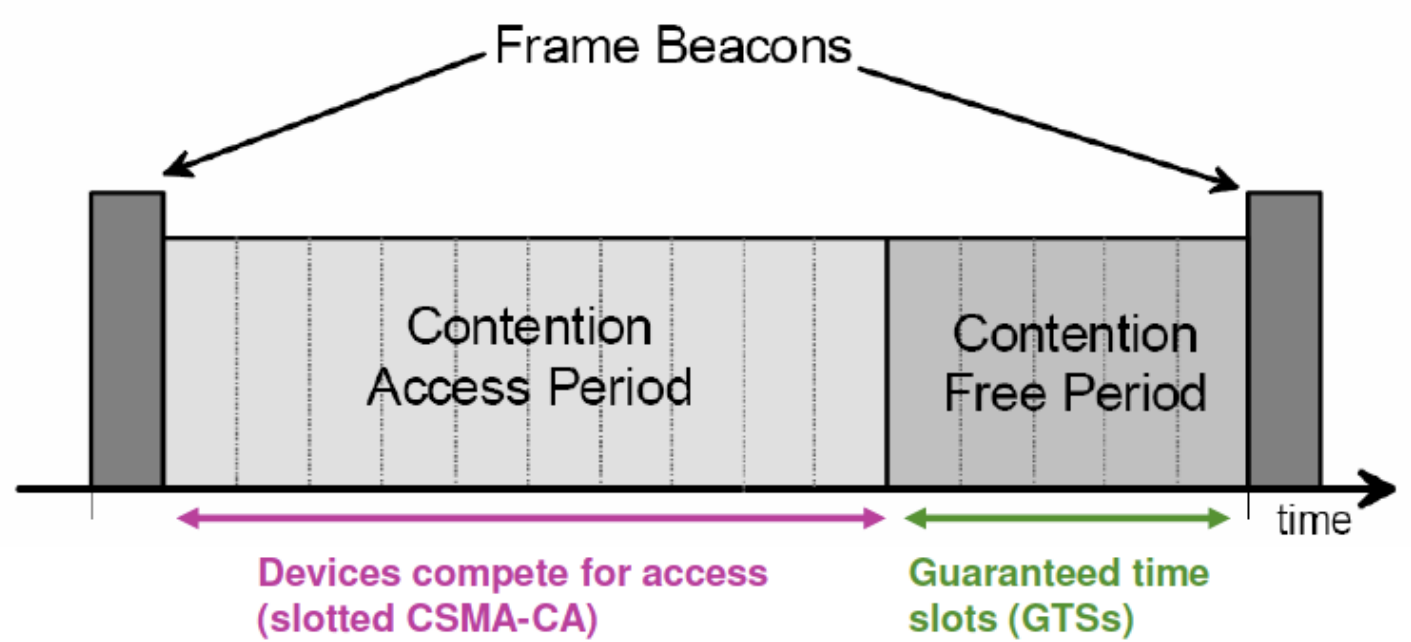
- WPAN for low data rate (LR-WPAN) IEEE Std 802.15.4-2003
  - Low complexity
  - Multi-month to multi-year battery life
  - Peer-to-peer and star topologies
  - Data rates from 20 kb/s (@868 MHz) to 250 kb/s (@2450 MHz)
- Applications
  - Sensors, interactive toys (joysticks etc.), remote controls

PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868/915	868–868.6	300	BPSK	20	20	Binary
	902–928	600	BPSK	40	40	Binary
2450	2400–2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

LR-WPAN Device Types

- Two different device types can participate in an LR-WPAN network
  - Full-function devices (FFD) can operate in three modes serving as a personal area network (PAN) coordinator, a coordinator, or a device
  - Reduced-function devices (RFD) are intended for applications that are extremely simple
- An FFD can talk to RFDs or other FFDs, while an RFD can talk only to an FFD

- FFD performs as PAN coordinator
  - Controls an optional superframe structure
    - Provides beacons for synchronization and optional guaranteed time slots for low-latency applications

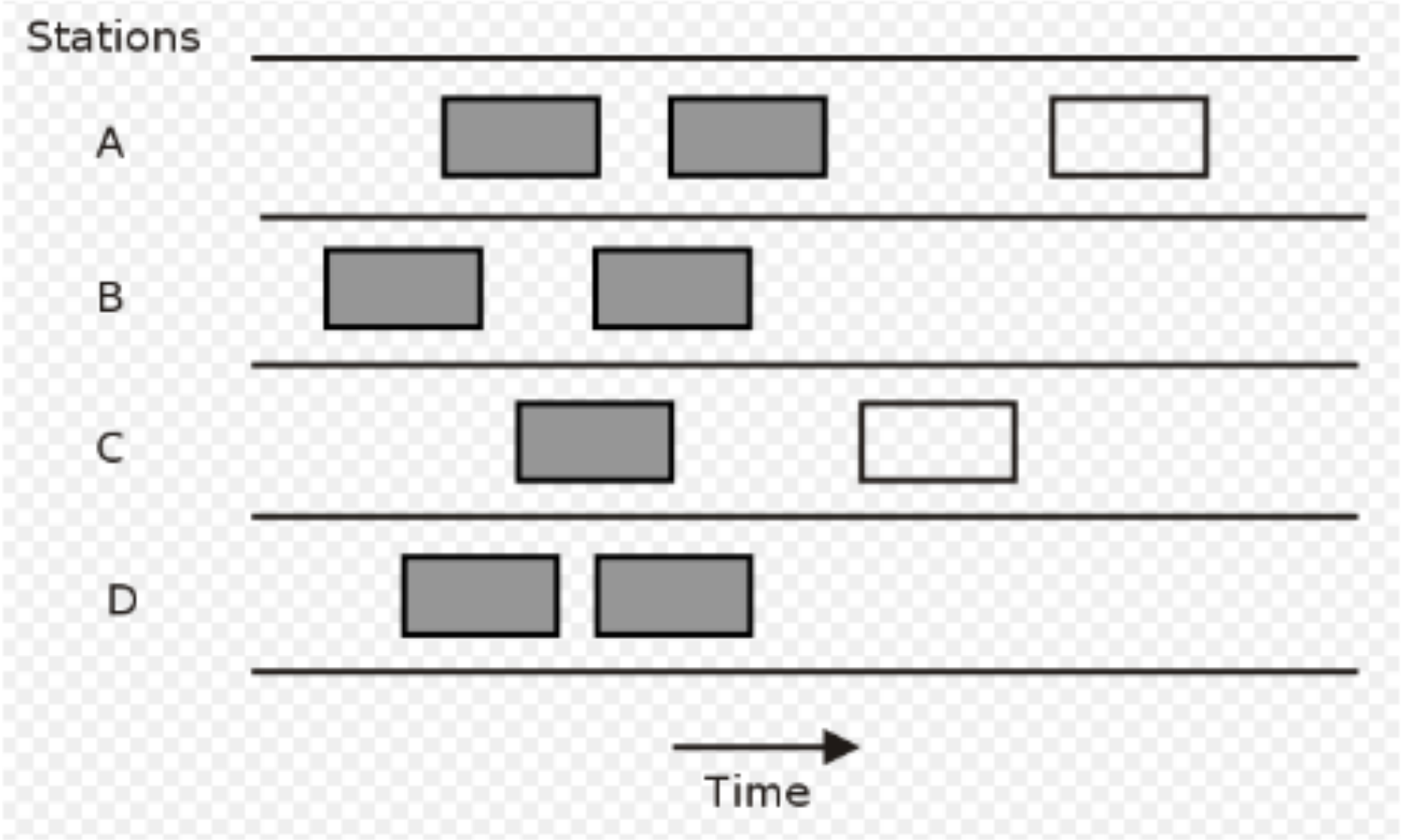


Beacon Frames

- The LR-WPAN standard allows the optional use of a superframe structure
- The format of the superframe is defined by the coordinator
- The superframe is bounded by network beacons, sent by the coordinator, and is divided into 16 equally sized slots
- The beacon frame is transmitted in the first slot of each superframe
- If a coordinator does not wish to use a superframe structure, it may turn off the beacon transmissions
- The beacons are used to synchronize the attached devices, to identify the PAN, and to describe the superframe structure

CSMA/CA Operation

- **Nonbeacon-enabled networks** use an unslotted CSMA-CA channel access mechanism
- Each time a device wishes to transmit data frames or MAC commands, it shall wait for a random period
  - If the channel is found to be idle, following the random backoff, the device shall transmit its data
  - If the channel is found to be busy, following the random backoff, the device shall wait for another random period before trying to access the channel again
- Acknowledgment frames shall be sent without using a CSMA-CA mechanism.



Pure ALOHA protocol (shaded frames indicate collision)

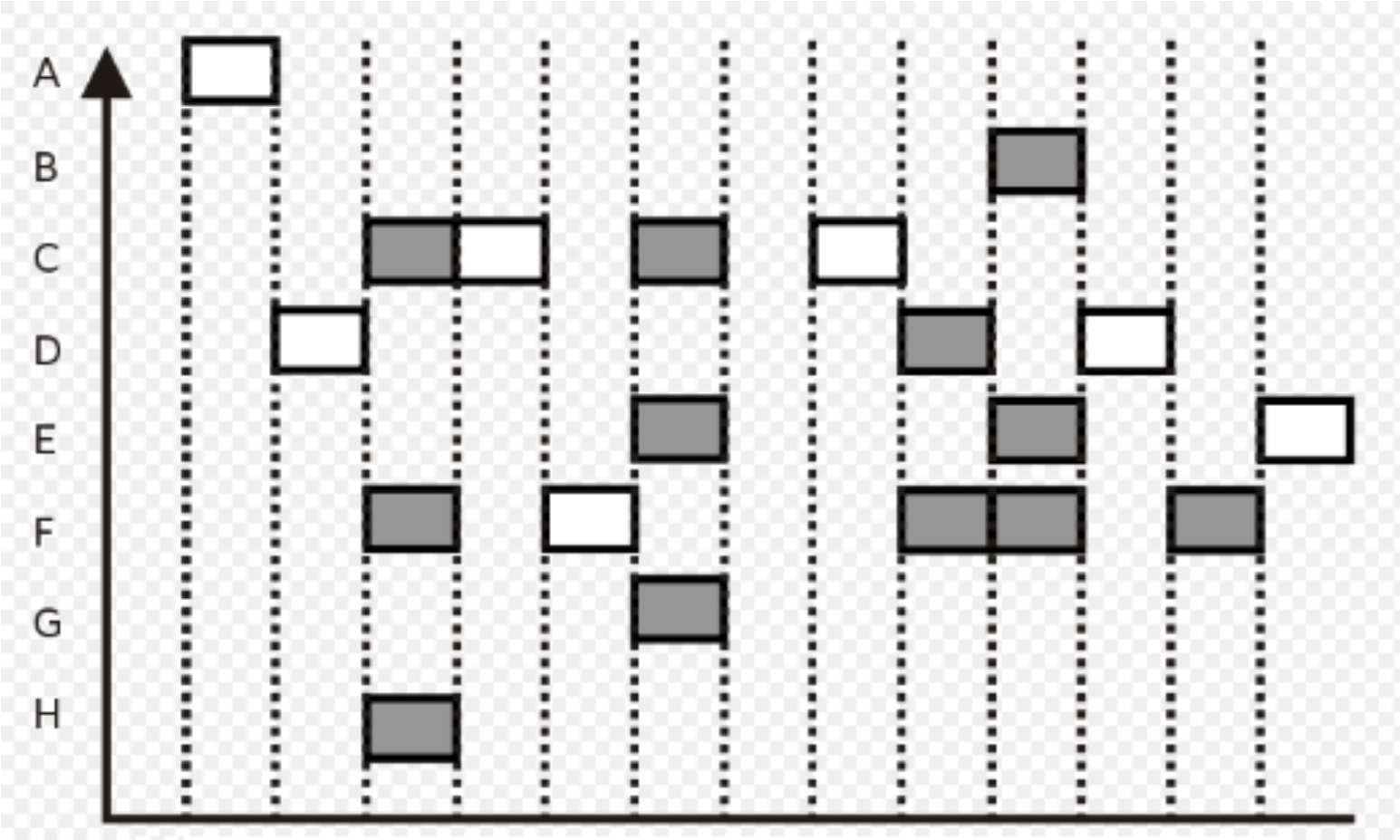
Source: wikipedia

- **Beacon-enabled networks** use a slotted CSMA-CA channel access mechanism, where the backoff slots are aligned with the start of the beacon transmission

- Each time a device wishes to transmit data frames, it shall wait for a random number of backoff slots

  - If the channel is busy, following this random backoff, the device shall wait for another random number of backoff slots before trying to access the channel again

  - If the channel is idle, the device can begin transmit on the next available backoff slot boundary



Slotted ALOHA protocol (shaded slots indicate collision)

Source: wikipedia

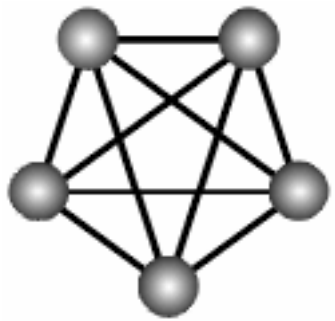
Differences: Bluetooth vs. ZigBee (TG4)

- Modulation technique
  - Bluetooth: Frequency Hopping Spread Spectrum (FHSS)
  - ZigBee: Direct Sequence Spread Spectrum (DSSS)
- Protocol stack size
  - Bluetooth: 250K bytes
  - ZigBee: 28K bytes
- Battery
  - Bluetooth: intended for frequent recharging
  - ZigBee: not rechargeable (one reason batteries will last for up to 10 years)

- Maximum network speed
  - Bluetooth: 1M bps
  - ZigBee: 250K bps
- Network range
  - Bluetooth: 1 or 100 meters, depending on radio class
  - ZigBee: up to 70 meters
- Typical network join time
  - Bluetooth: 3 seconds
  - ZigBee: 30 milliseconds

IEEE 802.15 WPAN Task Group 5 (TG5)

- PHY and MAC layer mechanisms for mesh networking

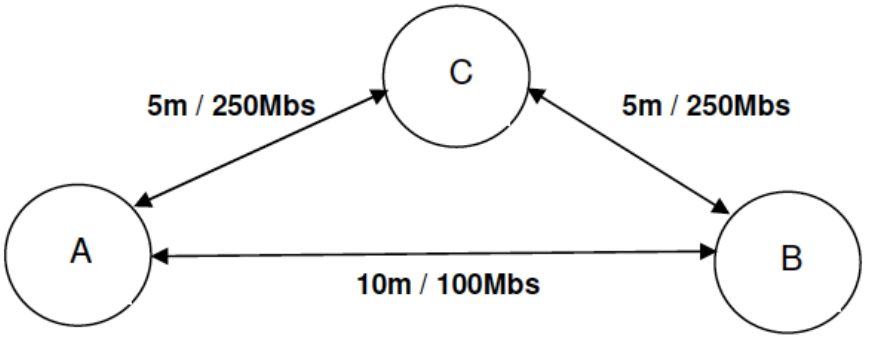


Mesh network

- Mesh topology allows
  - Network coverage extension
  - Enhanced reliability via route redundancy
  - Easier network configuration
  - Battery life due to fewer retransmissions

IEEE 802.15.5 WPAN Mesh

- Additional promises made by the Mesh Task Group
  - Extends distance and communication speed
  - Allows effortless installation of a communications infrastructure
  - Self-configures, is self diagnostic and self-healing
  - Provides resiliency, with no single point of failure



Enhancing communication speed