Lecture 3. Bluetooth Communications (07/05)

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5. Bluetooth Radio	a. Piconet formation b. Bluetooth Physical link c. Scatternet d. Piconet channels e. Multiple Access Scheme
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1. Bluetooth Communications. 802.15

Bluetooth is considered as a secure short-range wireless network.

- A cable replacement technology
- 1 Mb/s symbol rate
- Range 10+ meters
- Single chip radio at low power & low price ($5)

Why not use Wireless LANs?
- power
- cost

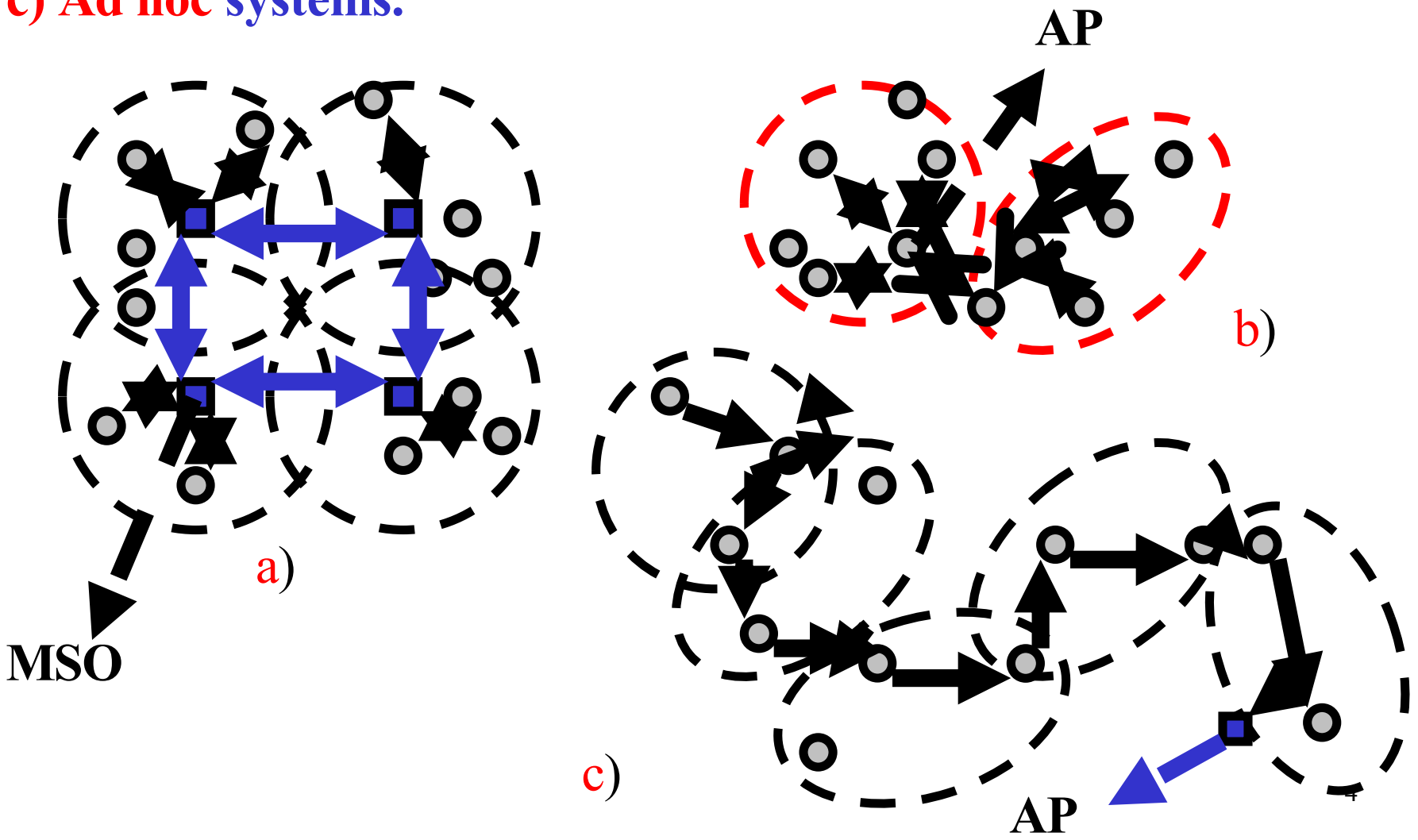
No Another wireless LAN

a. 802.11

- Replacement for Ethernet
- Supported data rates
  - 11, 5.5, 2, 1 Mbps; and recently up to >20 Mbps in 2.4 GHz
  - up to 54 Mbps in 5.7 GHz band (802.11 a)
- Range
  - Indoor 20 - 25 meters
  - Outdoor: 50 – 100 meters
- Transmit power up to 100 mW
- Cost:
  - Chipsets $ 35 – 50
  - AP $200 - $1000

b. Wireless Positioning

a) Cellular radio systems;
b) Bluetooth systems;
c) Ad hoc systems.



Wireless Positioning (cont)

Wireless LAN

- On-campus:
  Office, School, Airport, Hotel, Home

Cellular

- Off-Campus:
  Global Coverage

Bluetooth

- Person Space:
  Office, Room, Briefcase, Pocket, Car
- Short Range/Low Power
- Voice and Data
- Low-cost
- Small form factor,
- Many Co-located Notes
- Universal Bridge

c. Bluetooth working group history

- February 1998: The **B**luetooth **S**pecial **I**nterest **G**roup promoter: **Ericsson, IBM, Intel, Nokia, Toshiba.**
- May 1998:
- July 1999: version **1.0A** is released.
- December 1999: version **1.0B** is released.
- March 2001: version **1.1** is released
- **Where Did the Name Come From?**
- Herald Blatant "Bluetooth II "–King of Denmark 940-981 AC.
- Noted for unifying Denmark and Sweden.

Applications

User benefits

- Multiple device access (phone, music)
- Cordless phone benefits
- Hands free operation
- Conference Table
- Cordless Computer
- Business Card Exchange
- Instant Postcard
- Computer Speakerphone

Bluetooth Profiles

- Generic Access
- Service Discovery
- Cordless Telephone
- Intercom
- Serial Port
- Headset
- Dial-up Networking
- Fax
- LAN Access
- Generic Object Exchange
- Object Push
- File Transfer
- Synchronization

2. Technical Overview

a. Principles of SS modulation

The most important parameter in any SS system is the processing gain *Gp*:

$$G_p = \frac{W}{C}$$

$$C = W \cdot \log_2\left[1 + \frac{S}{N}\right]$$

This value measures the ratio of:

Transmitted RF bandwidth W

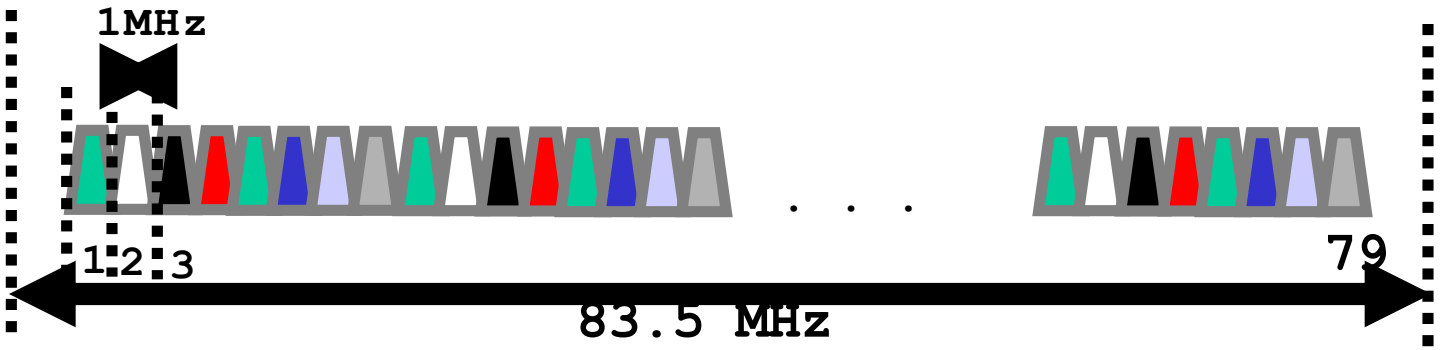
to the narrowband information rate C.

A system with a low signal-to-noise ratio must have a high processing gain Gp in order to recover the original signal.

Types of Spread Spectrum Modulation:

- Direct Sequence Spread Spectrum (DSSS)
- Frequency Hopping Spread Spectrum (FHSS)

b. Bluetooth radio link



- frequency hopping spread spectrum
  - **2.402 GHz + k x1MHz, k=0, …, 78=79**
  - **1,600 hops per second (1:1600=625 μs= Dwell time**
- GFSK modulation - 1 Mb/s symbol rate
- Transmit power - 0 dBm (up to 20dBm with power control)

$$G_p = \frac{W}{C} = 79$$

FHSS/TDD channel applied in Bluetooth.

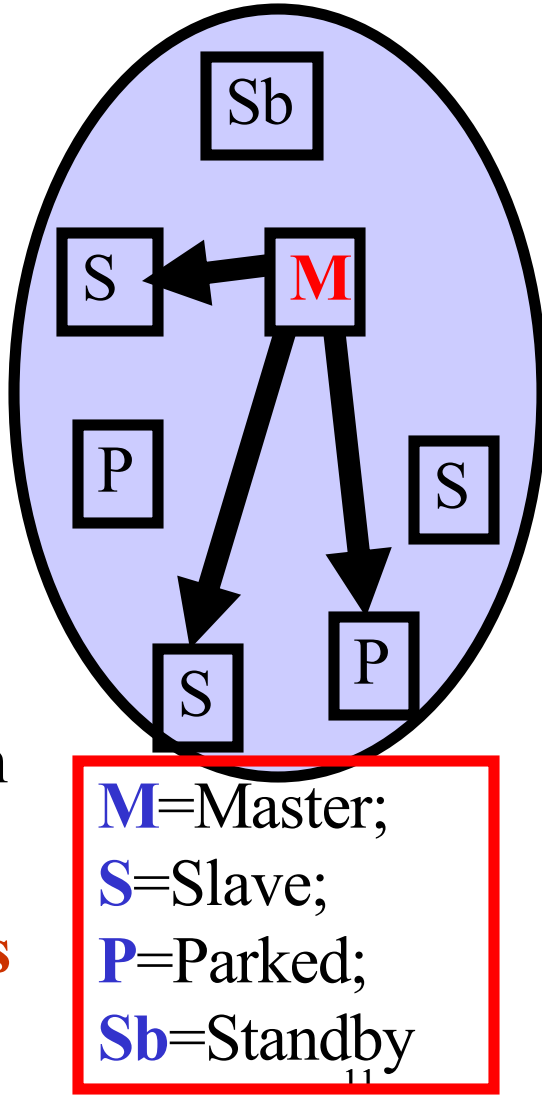
Multiple Ad hoc links will make use of different hopping channels with different hopping sequences and have **misaligned slot timing**

c. Bluetooth Architecture, Piconets and Scatternets

A Piconet is collection of devices connected to the Master.

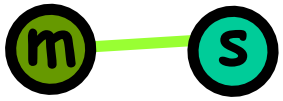
- One unit will act as a **Master** (the device, which initiates an exchange of data) and the others as **Slaves** (the device, which responds to the Master)
- Master sets the **clock, dwell time, hopping pattern**.
- **Each piconet** has a unique **hopping pattern/ID**
- Each master can connect to 7 active (specification limits) or 255 inactive (parked) slaves per piconet

A Scatternet is collection of the Piconets connected in an Ad-Hoc fashion.

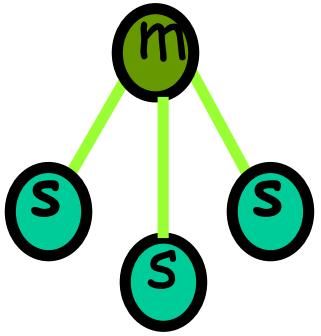


b. Bluetooth Physical link

- Point-to-point link
  - master - slave relationship
- Piconet
- Each Piconet has max capacity
  = **1 Mbps**



Fast frequency hopping 1600 hops/sec

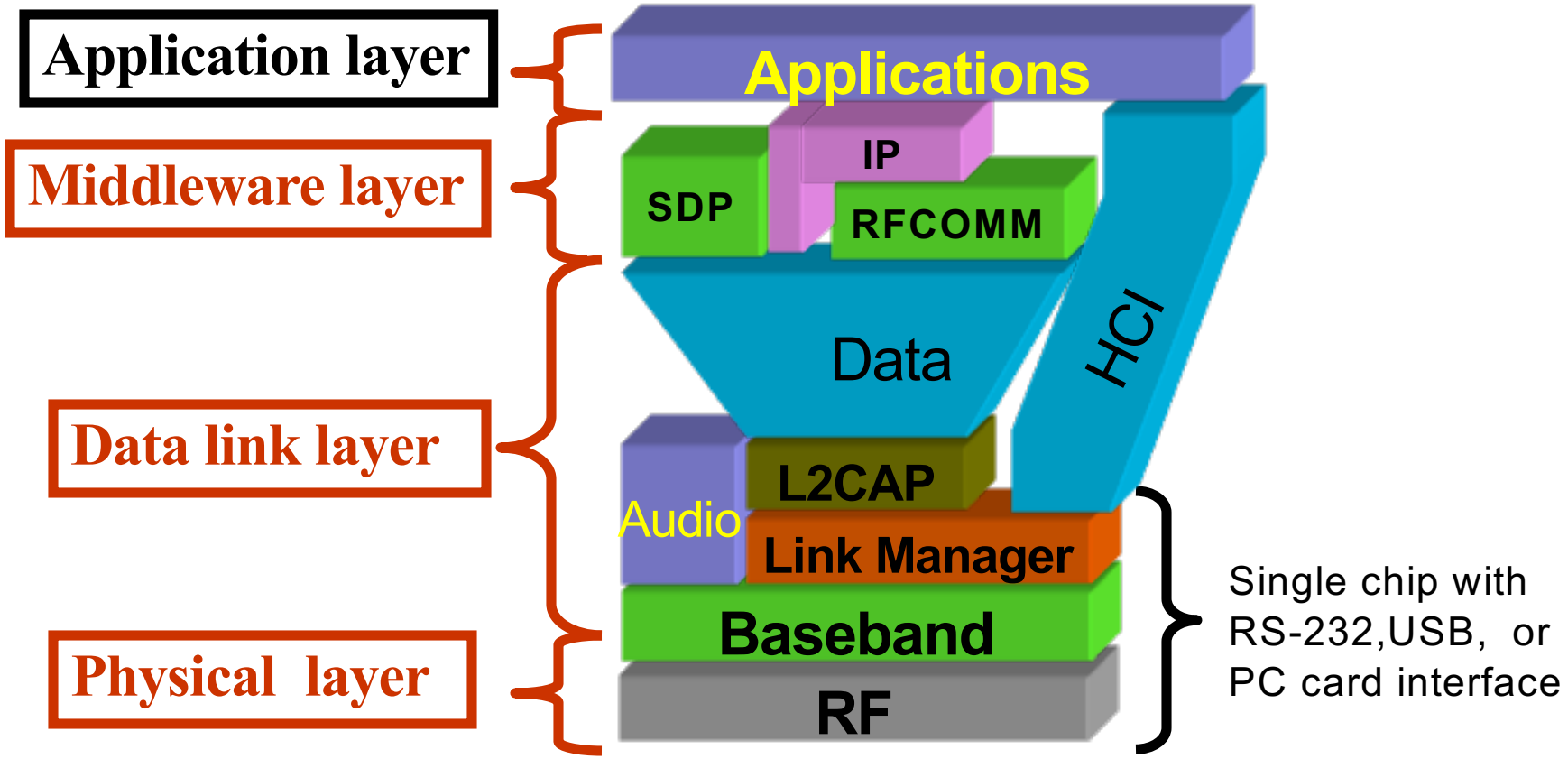


•**All devices** in a Piconet **hop together**. To form Piconet: master gives slaves its **clock** and device **ID**; Hopping pattern (**48-bit**); determined by device **ID**; Hopping pattern determined by Clock.

•A Piconet is centralized **TDD** system, with the master controlling the clock and determined which device gets to communicate in which time slot.

•The **baseband part** of the Bluetooth specification **describes an algorithm which can calculate a frequency hop sequence from a Bluetooth device address and a Bluetooth clock.**

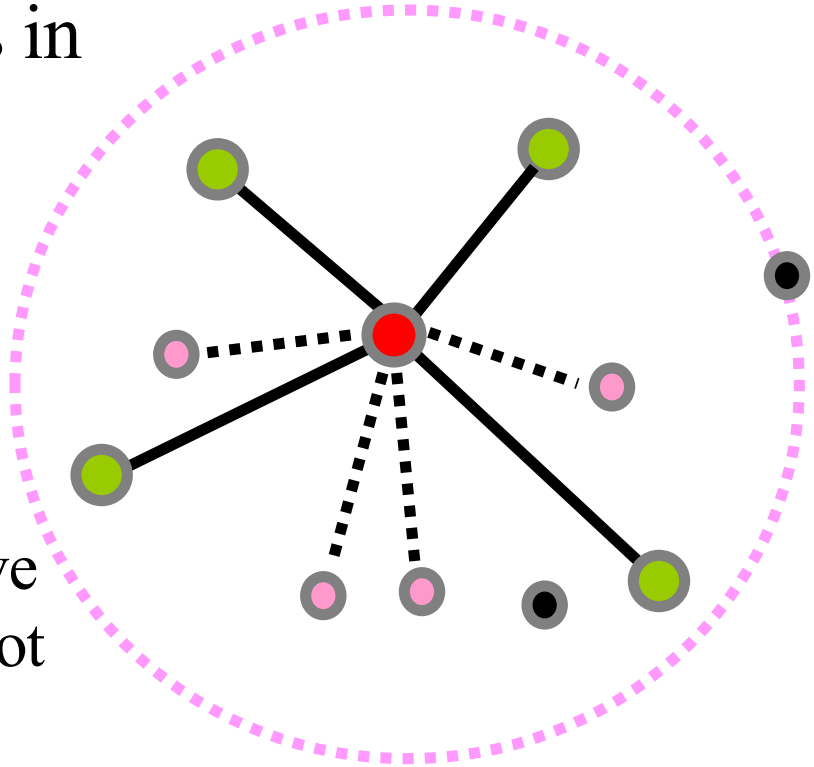
Bluetooth protocol stack



The Bluetooth protocol stack is a series of layers, there are some features which cross several layers.

a. Piconet formation

- Page - scan protocol
  - to establish links with nodes in proximity



Master

Active Slave

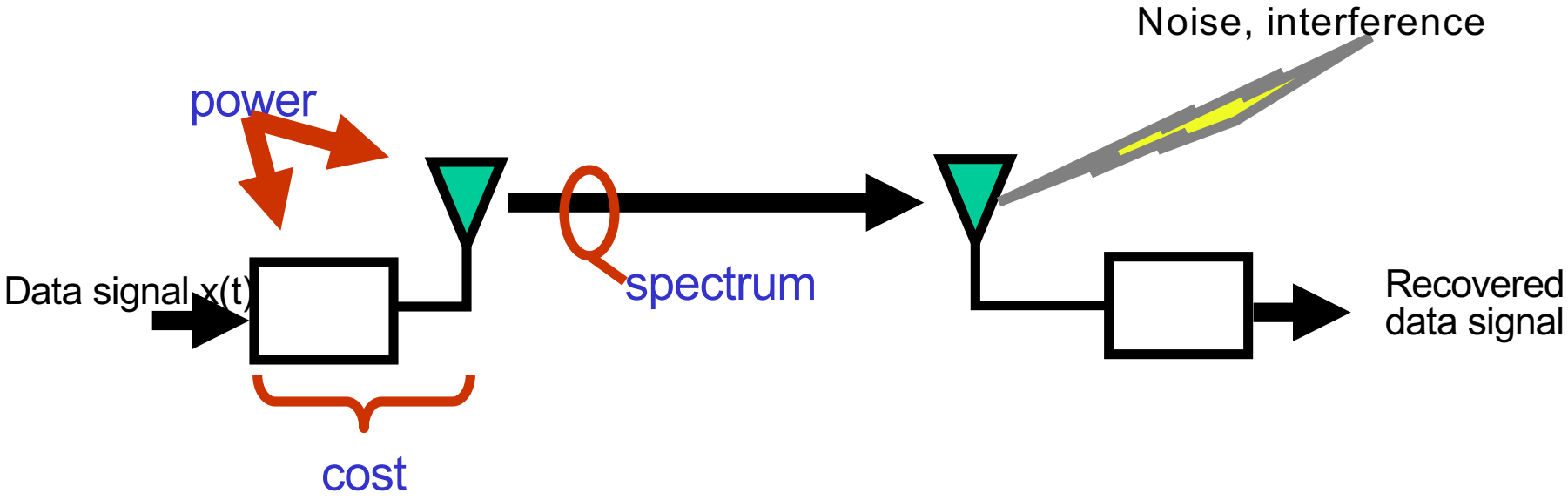
Parked Slave

Standby

Direct, slave-to-slave communication is not possible.

Piconet Addressing:
Active Member Address (**AMA**, 3-bits);
Parked Members Address (**PMA**, 8-bits)

d. Radio connection

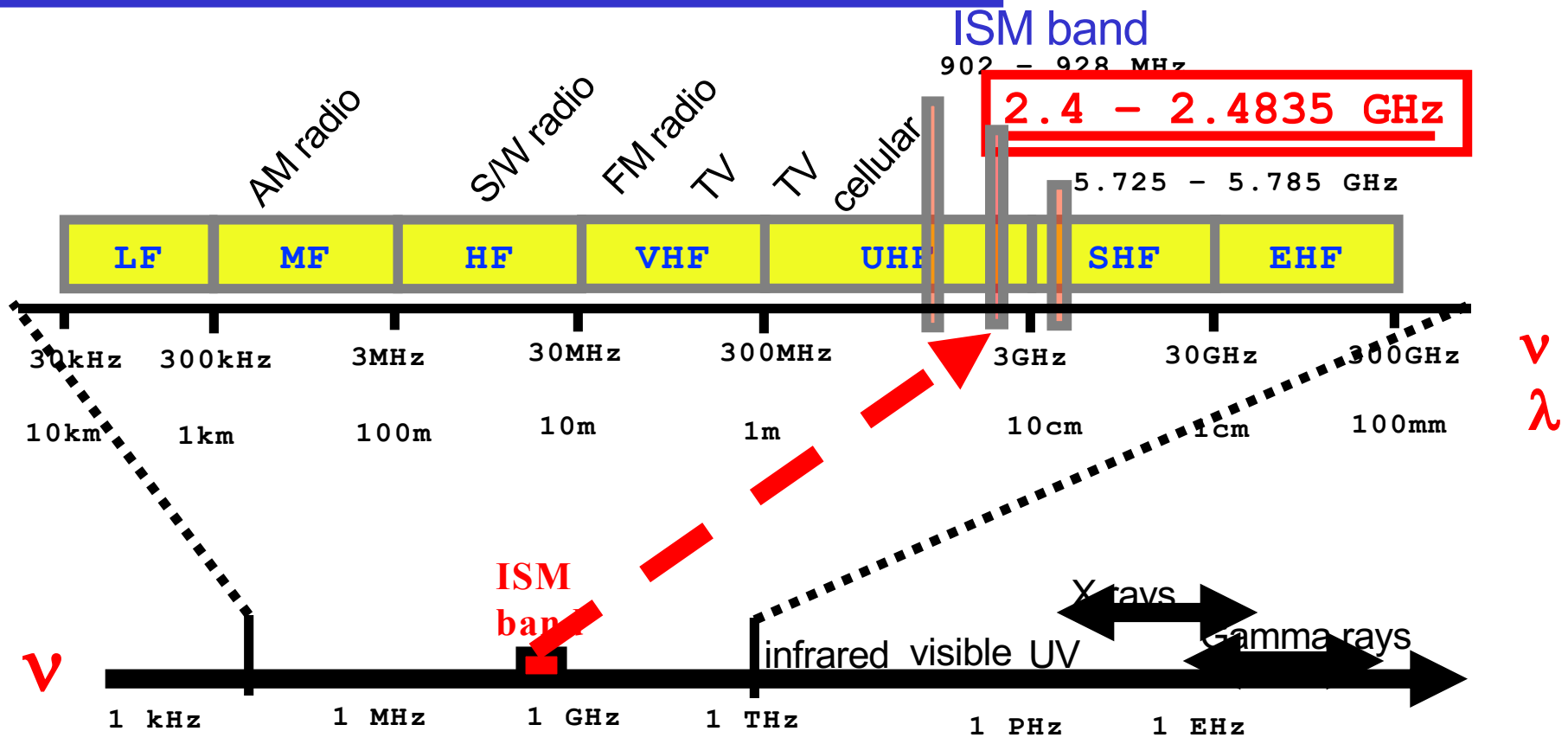


Goal:

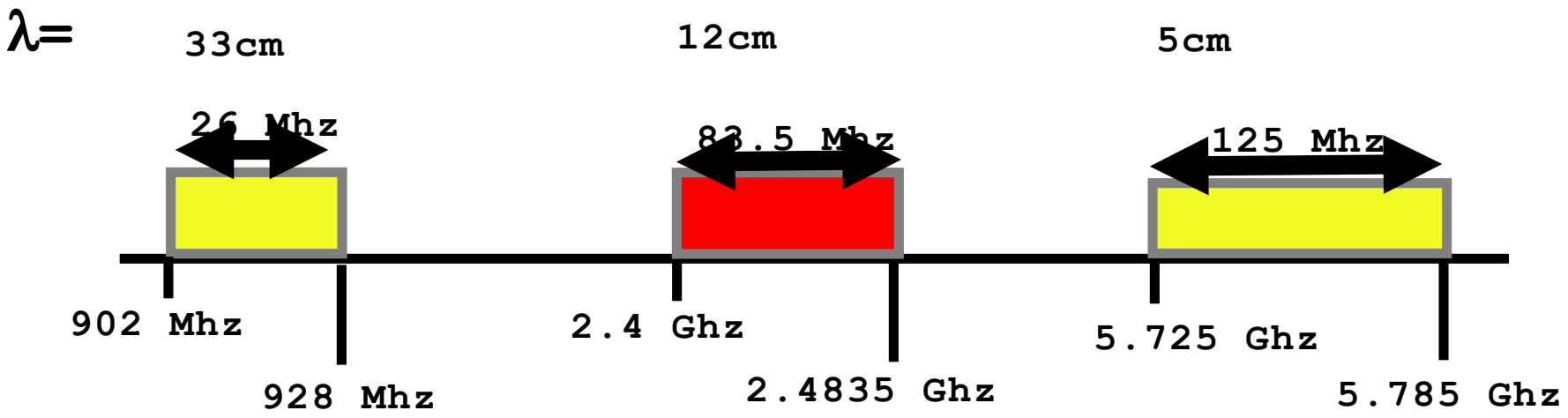
- **high bandwidth**
- **conserve battery power**
- **cost < $10**

3. EM Spectrum

Industrial, Science, Medicine = ISM band



a. Unlicensed Radio Spectrum

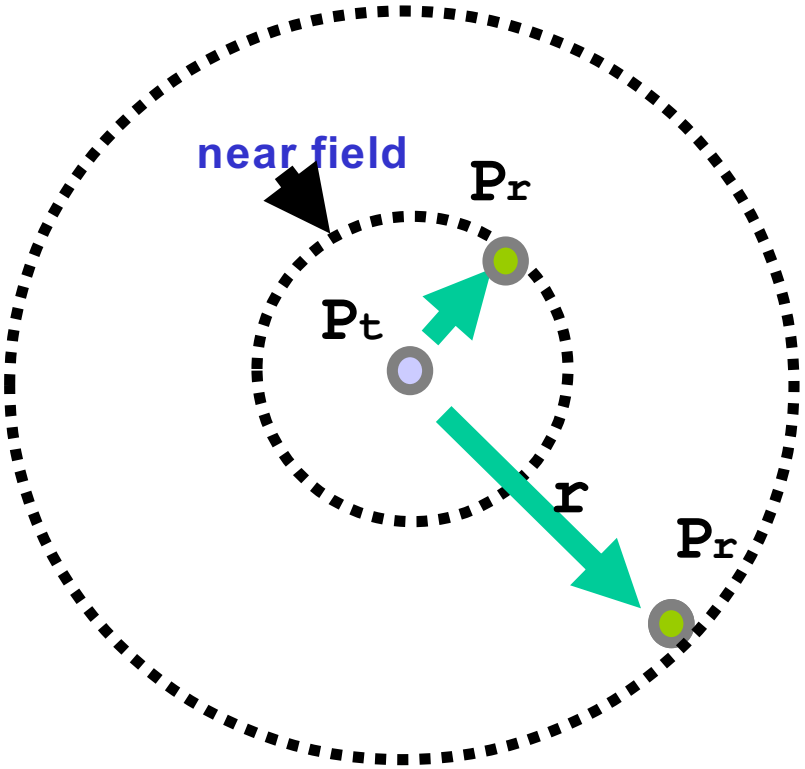


cordless phones,
baby monitors,
Wireless LANs

802.11 Cell.
802.15 Bluetooth,
Microwave oven

802.11a
HyperLan

b. Radio propagation: path loss



path loss in 2.4 Ghz band

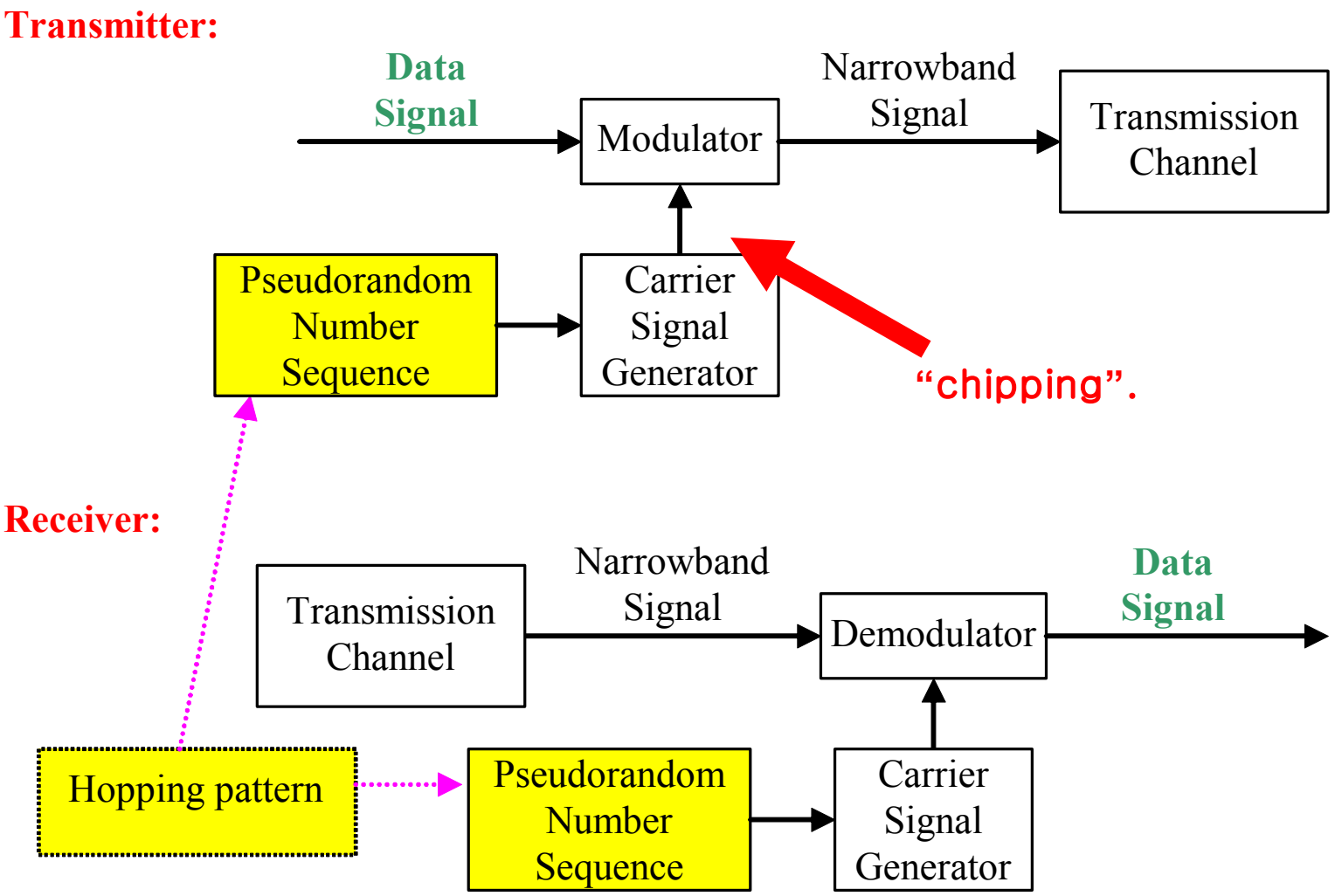
$r \leq 8m$: near field $\propto r^2$

$r > 8m$: far field $\propto r^{3.3}$

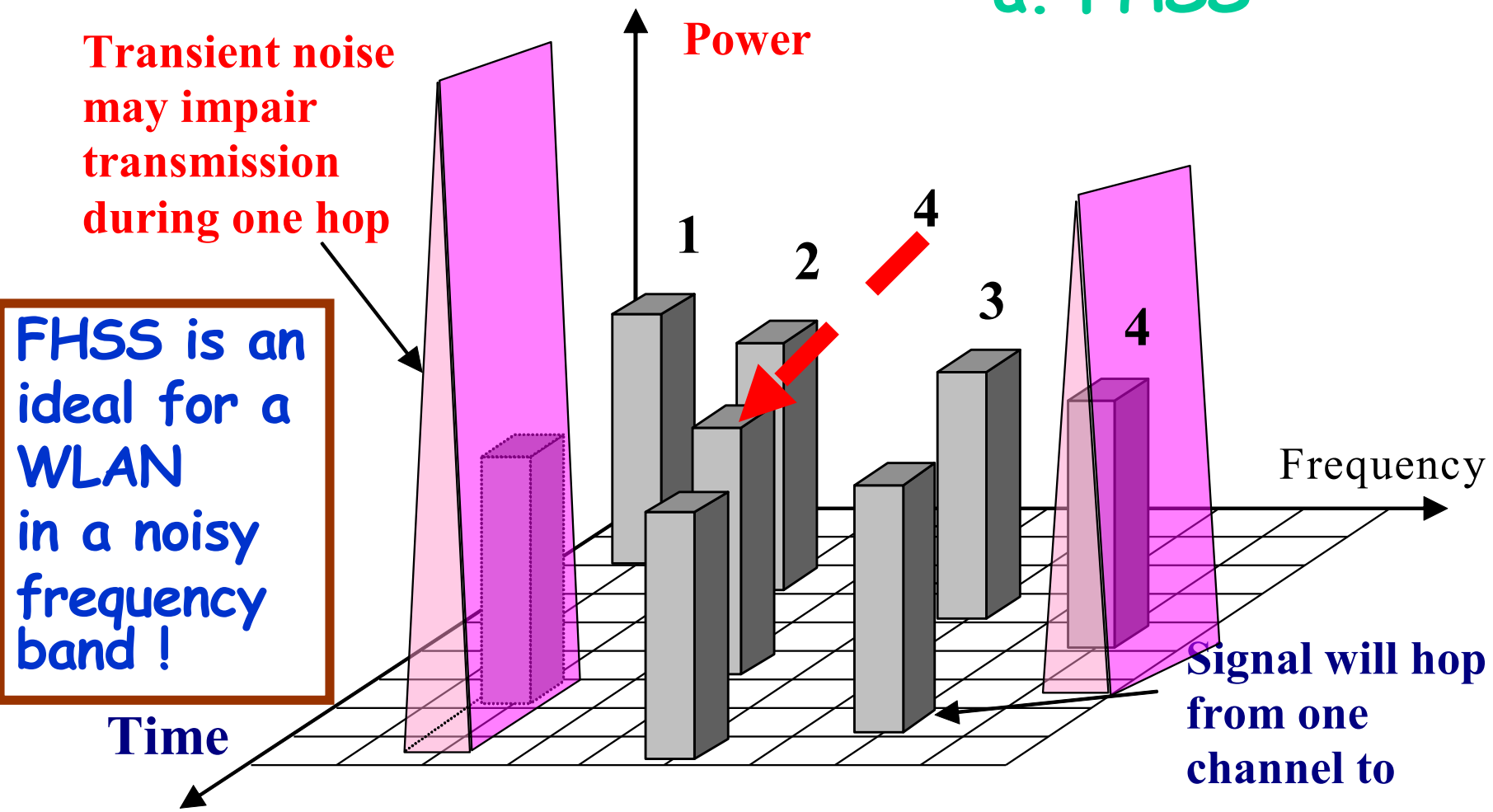
path loss $= 10 \log (4\pi r^2/\lambda)$ $\quad r \leq 8m$

$= 58.3 + 10 \log (r^{3.3}/8)$ $\quad r > 8m$

4. General model of FHSS modulation



a. FHSS

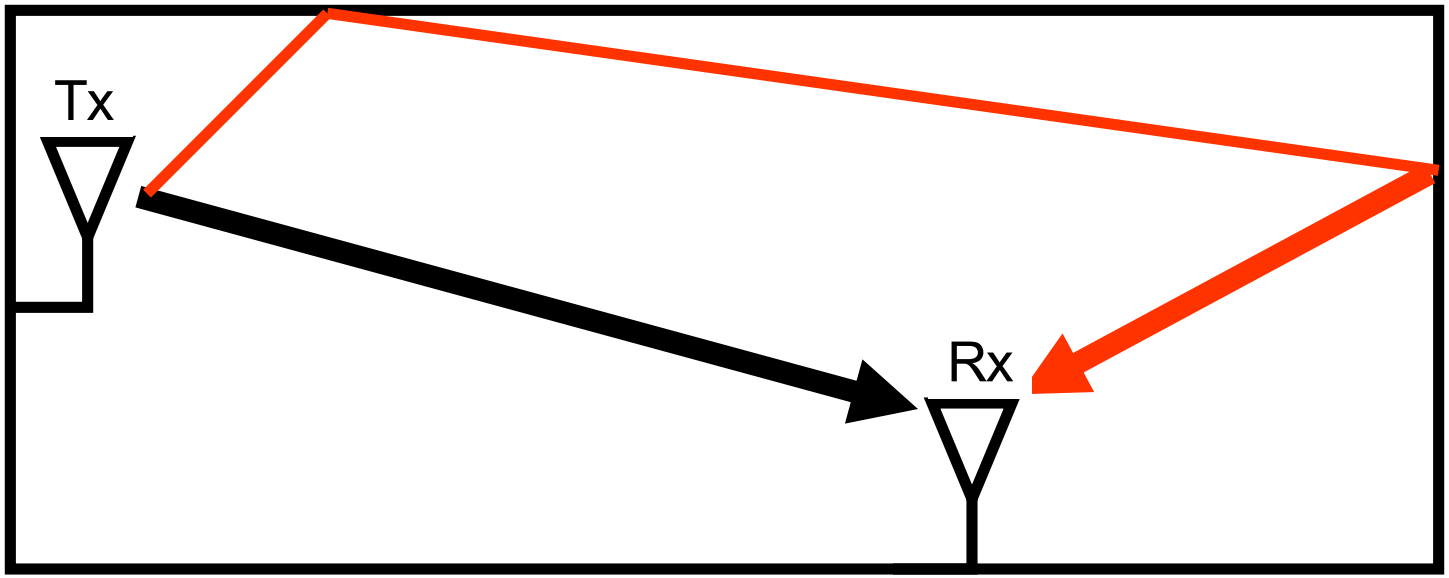


FHSS is an ideal for a WLAN in a noisy frequency band !

During any one hop, the signal is vulnerable to noise in th at frequency band, but it will soon move to another frequ ency with less noise. This new band will be sufficiently remov ed from the previous noisy band

b. Fading and multipath

Fading: rapid fluctuation of the amplitude of a radio signal over a short period of time or travel distance



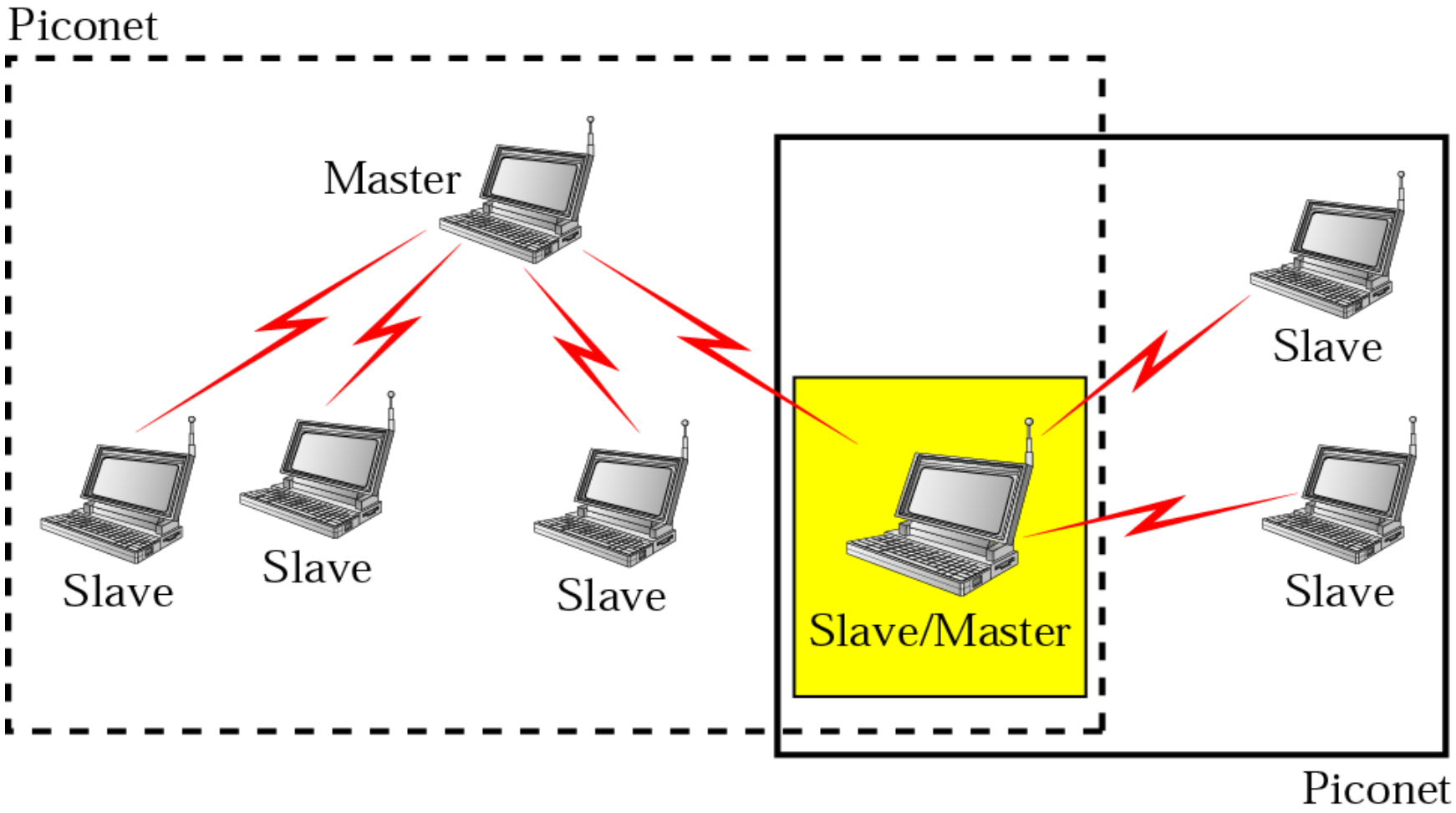
Effects of multipath

5. Bluetooth Radio

- **Low Power, Low Cost**
  - Standby modes wake up durations:
  - **Sniff, 10 ms**
  - **Hold, <1%**
  - **Park. <<1%**

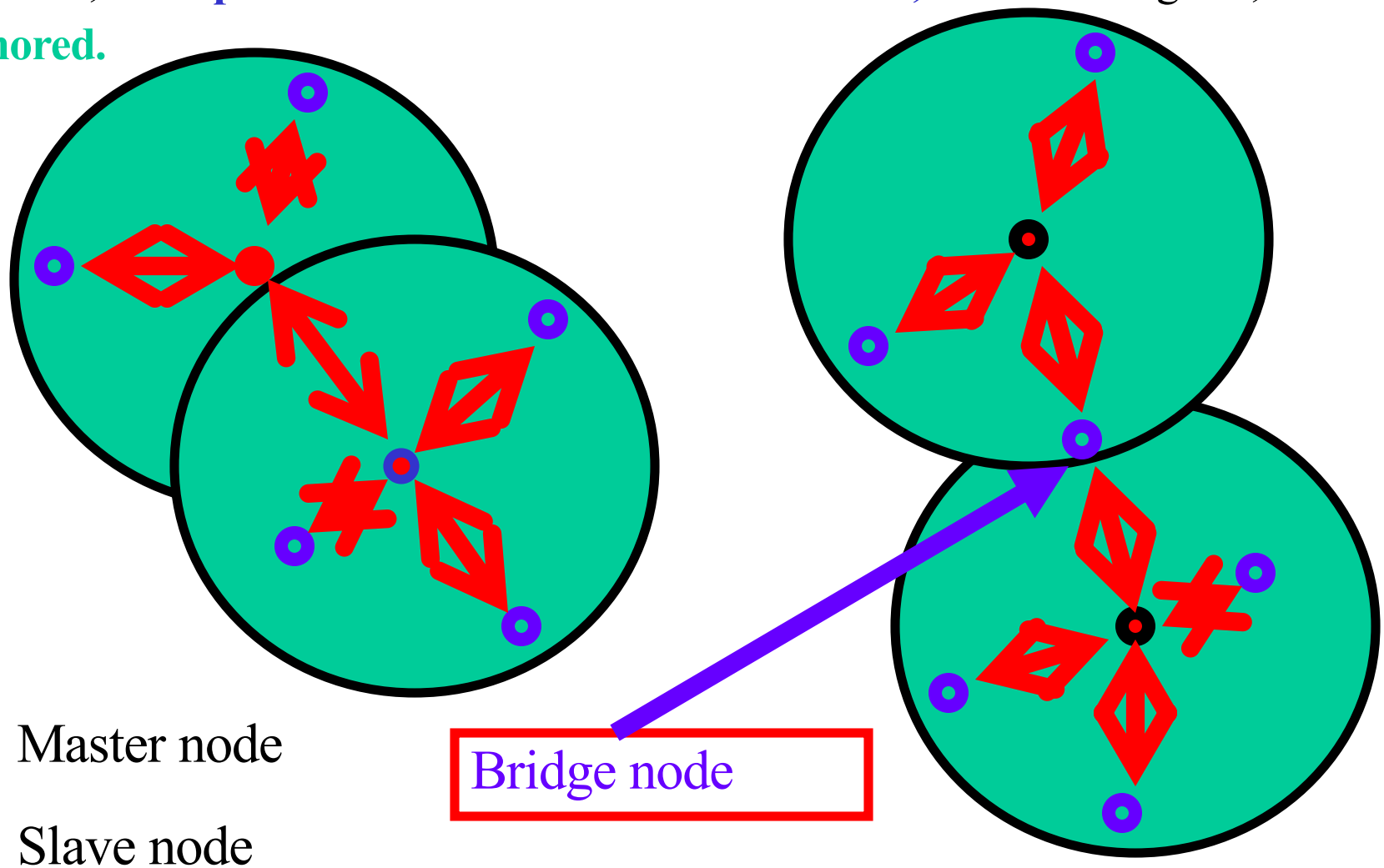
Power Class	Transmit Power	Nominal Range
1	100 mW (20 dBm)	100 m
2	2.5 mW (4 dBm)	20 m
3	1 m W (0 dBm)	10 m

c. Scatternet



Scatternet (cont)

If there are many independent piconets: there could be a collision on a particular channel, these **packets** will be lost and **retransmitted,** or if **voice** signals, it will be **ignored.**

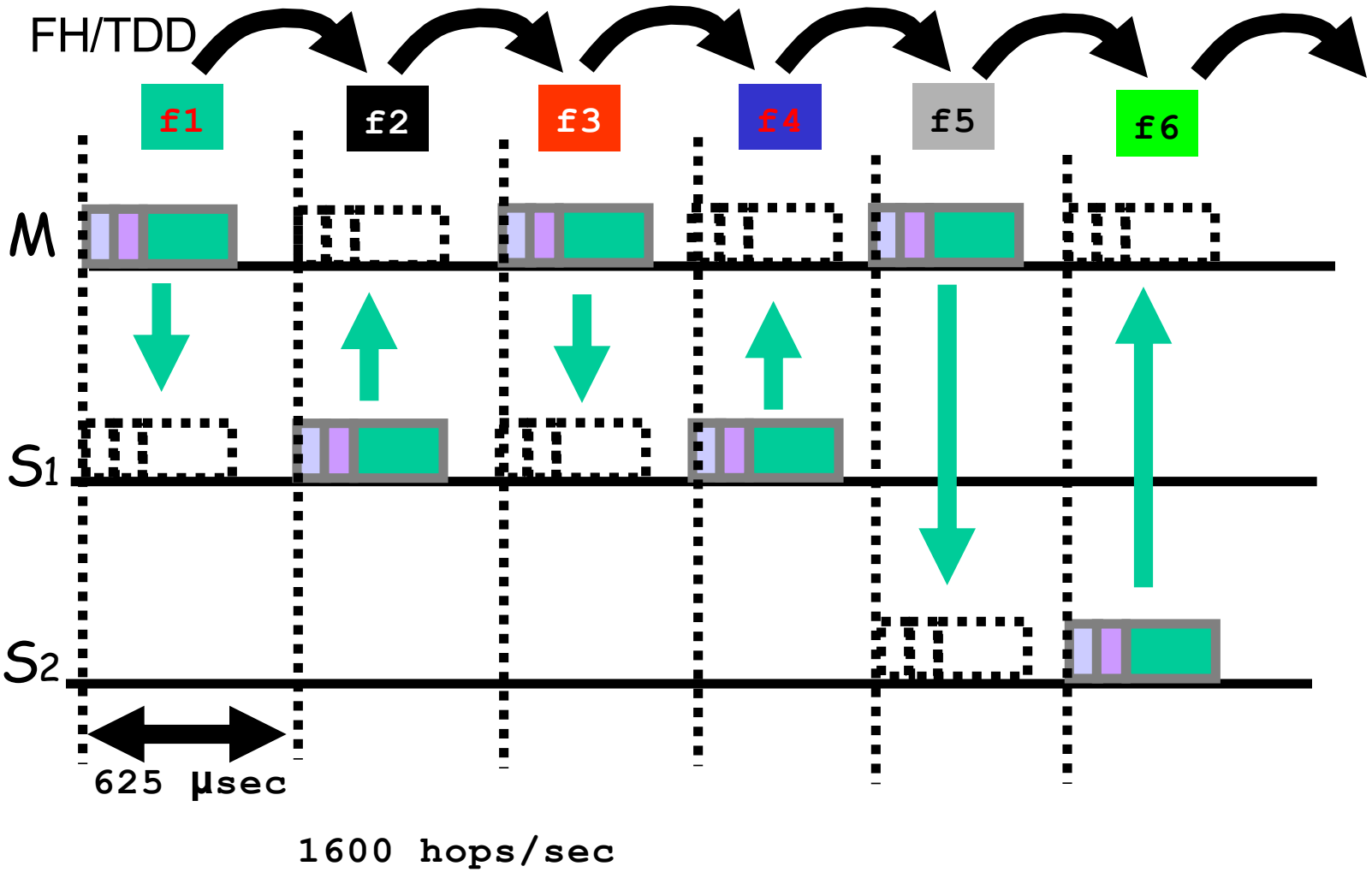


d. Characteristics

- Operates in the **2.4 GHz** band at a data rate of **720 Kb/s**
- Uses **FHSS**: Number of channels (**2.402-2.480 GHz = 79 channels).**
- Radio transceivers **hop** from one channel to another in a **pseudorandom fashion, determined by the master.**

Topology	**Supports up to 7 simultaneous links**	**Each link requires another cable**
Flexibility	**Goes through walls, bodies.**	**Line of sight**
Rate	**1Mb/s, 720 Kb/s**	**Varies with use and cost**
Power	**0.1 Watts active power**	**0.05 Watts or higher**
Range	**10 meters or less**	**Typically 1-2 meters**
Universal	**Work anywhere in the world**	**Cables vary with local customs**
Security	**link layer security**	**Secure (it's a cable)**

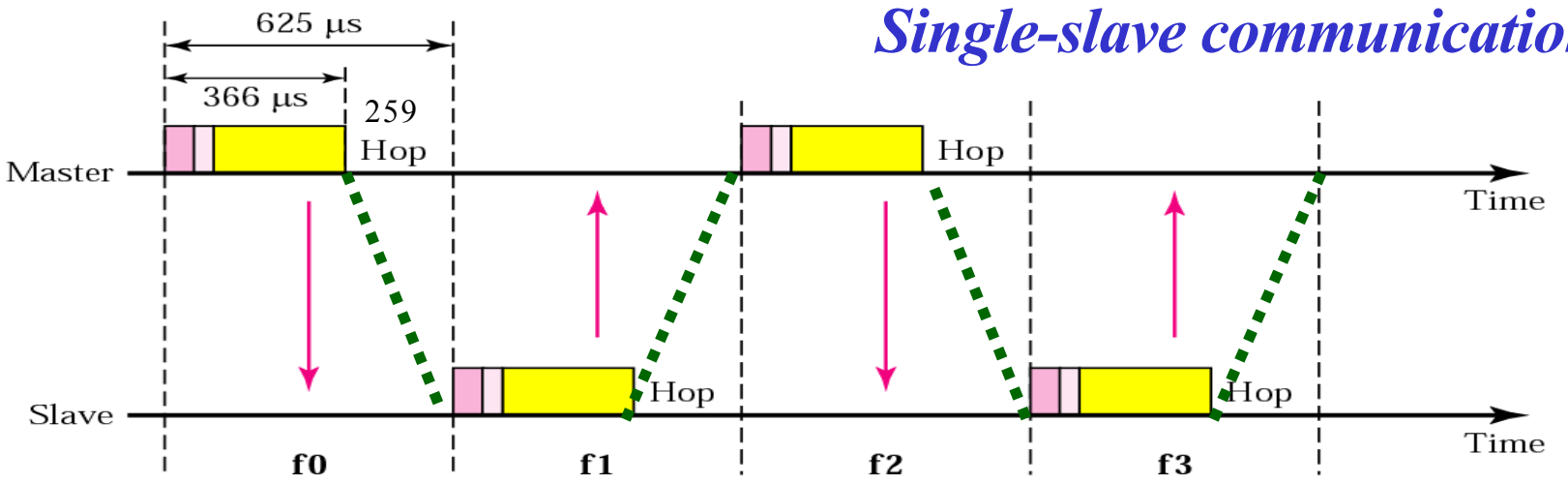
e. Piconet channels

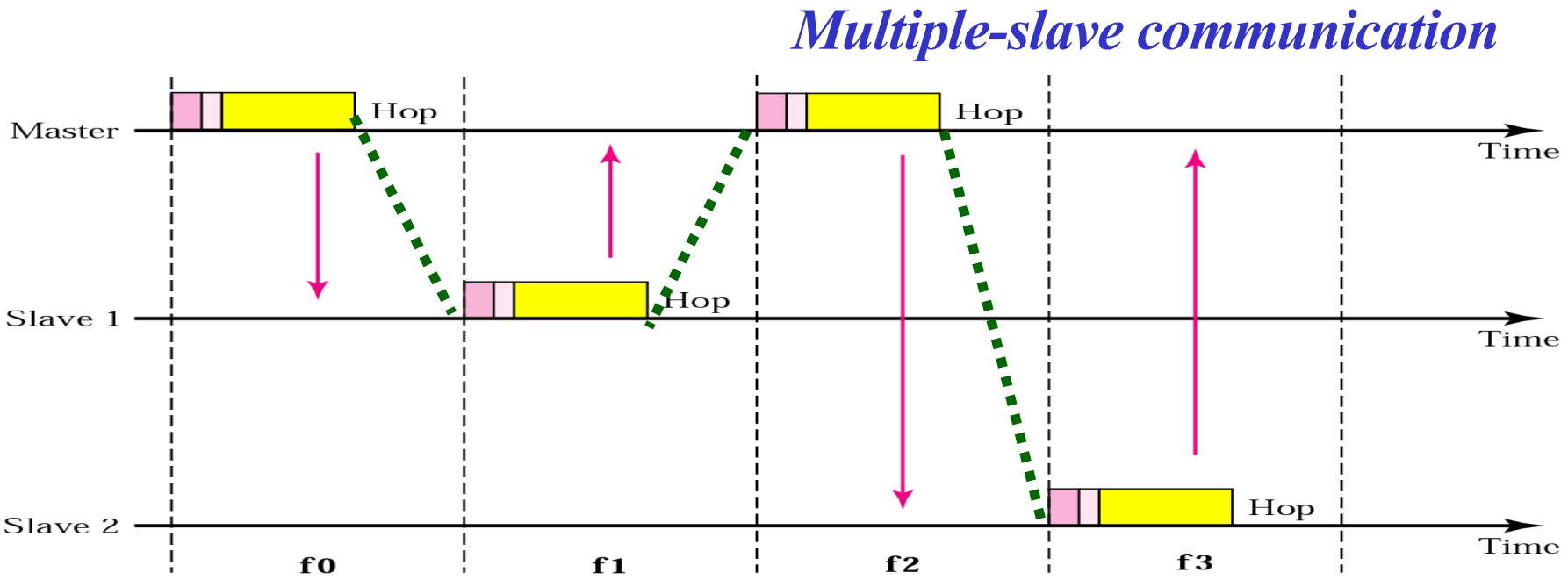


devices hop once per packet, which will be:

every slot, every 3 slots, or every 5 slots.

f. Multiple Access Scheme





6. The Modulation Scheme

- The operating band is divided into 1 MHz-spaced channels, each signaling data at 1 Mega-symbol per second **= 1 MB/s**.
- With the chosen modulation scheme of GFSK with **K_f= 0.3**.
- Binary **1 gives Fc +Δf** , while a binary **0 gives Fc -Δf.**
- After each packet, both **Tx & Rx** retune their radio to a different frequency, hopping **from channel to channel**.
- Bluetooth devices use the whole of the available band and if a interference occurred on one channel, the **retransmission will always be on a different** (hopefully clear) **channel.**
- Each Bluetooth time slot lasts **625 µs**, and devices hop once per packet: **every slot**, **every 3 slots**, or **every 5 slots.**

7. Medium Access Control

- Bluetooth with **79 channels** can support **79 Mb/s**.
- When a Piconet is established, the slaves **add offsets** to their native clocks to synchronize to the master.
- Each unit can become a **master or slave**. By definition, the **unit that establishes the Piconet becomes the master.**
- Access is completely **contention free**.
- The **master** implements **centralized control**;
- The **time slots** are alternately used for **master transmission and slave transmission.**

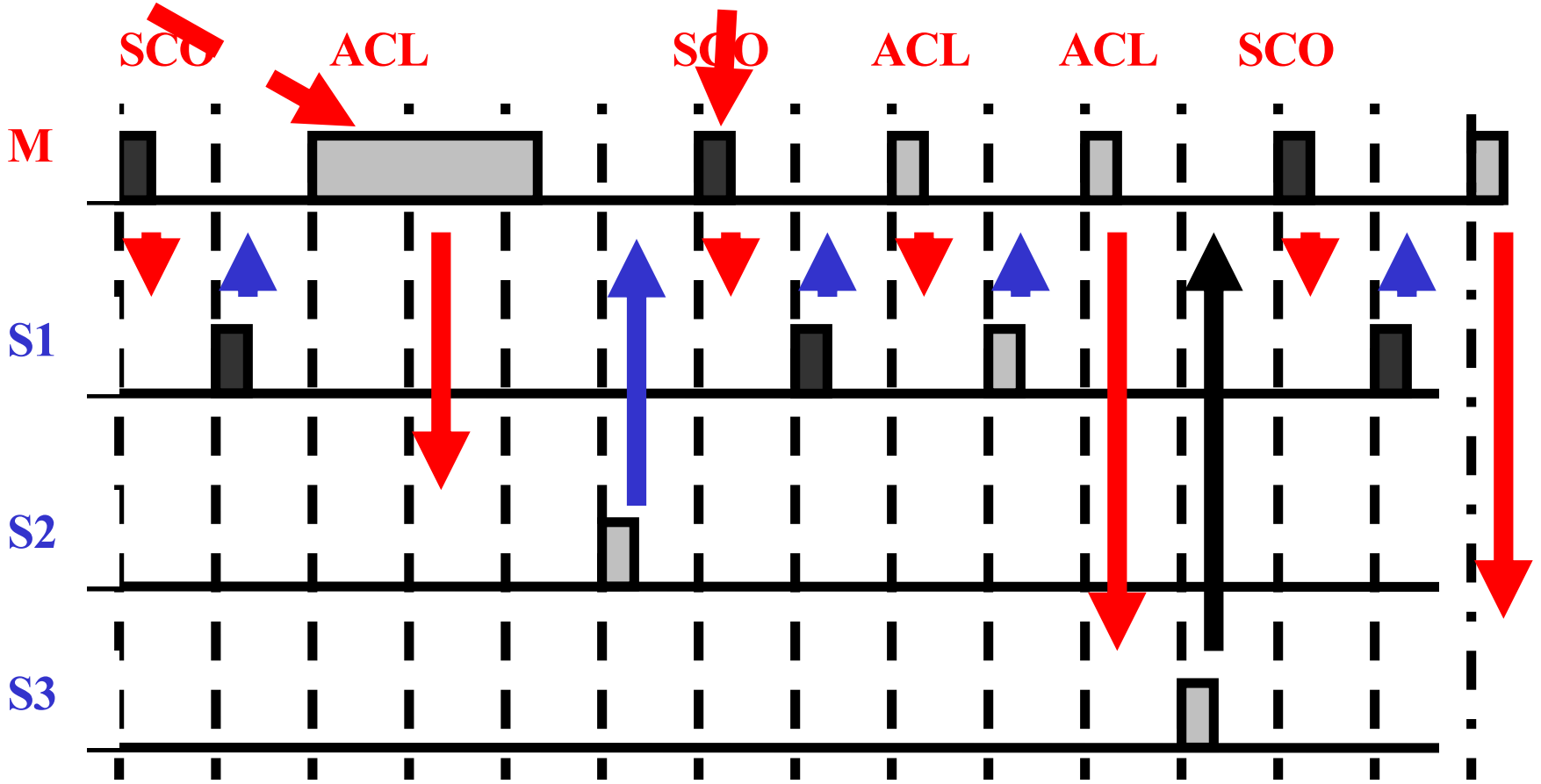
8. Voice and Data Links

- Bluetooth allows both **time sensitive** communication: **voice or audio**, and **time insensitive** packet: **data communication**.
- So, two different types of **links** are defined:
- **Synchronous Connection Oriented (SCO)** links

  for **voice communication**
- **Asynchronous Connectionless (ACL)** links

  for **data communication**.
- ACL data packets: a **72-bit access code**, a **54-bit packet header**, a **16-bit CRC** code, + **the payload data**.
- Different types of **packets** allow different amounts of data to be sent: The largest packet data payload is a **DH5 (Data High)** packet, with **5 slots**. A DH5 packet carry **339 bytes**, or **2712 bits** of data. So, 2858 bits are sent for 2712 bits of information, reply 1 slot = **asymmetric link.**

Mixing of synchronous SCO links and asynchronous ACL links on a single piconet channel.



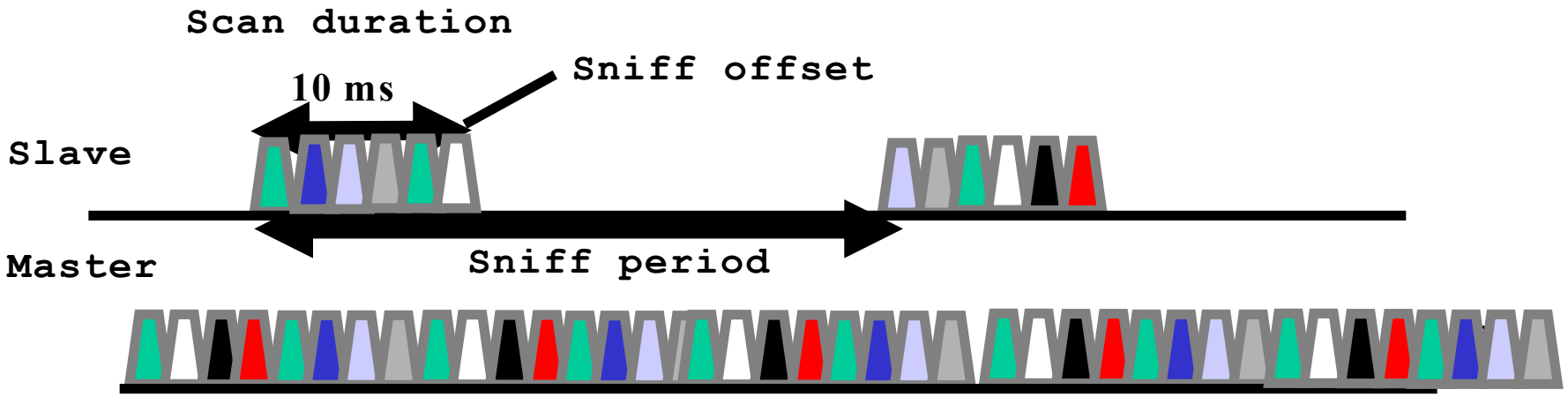
9. Communication Scenario

a. Connection Establishment

- **How to find each other**? **how do they make connections**?

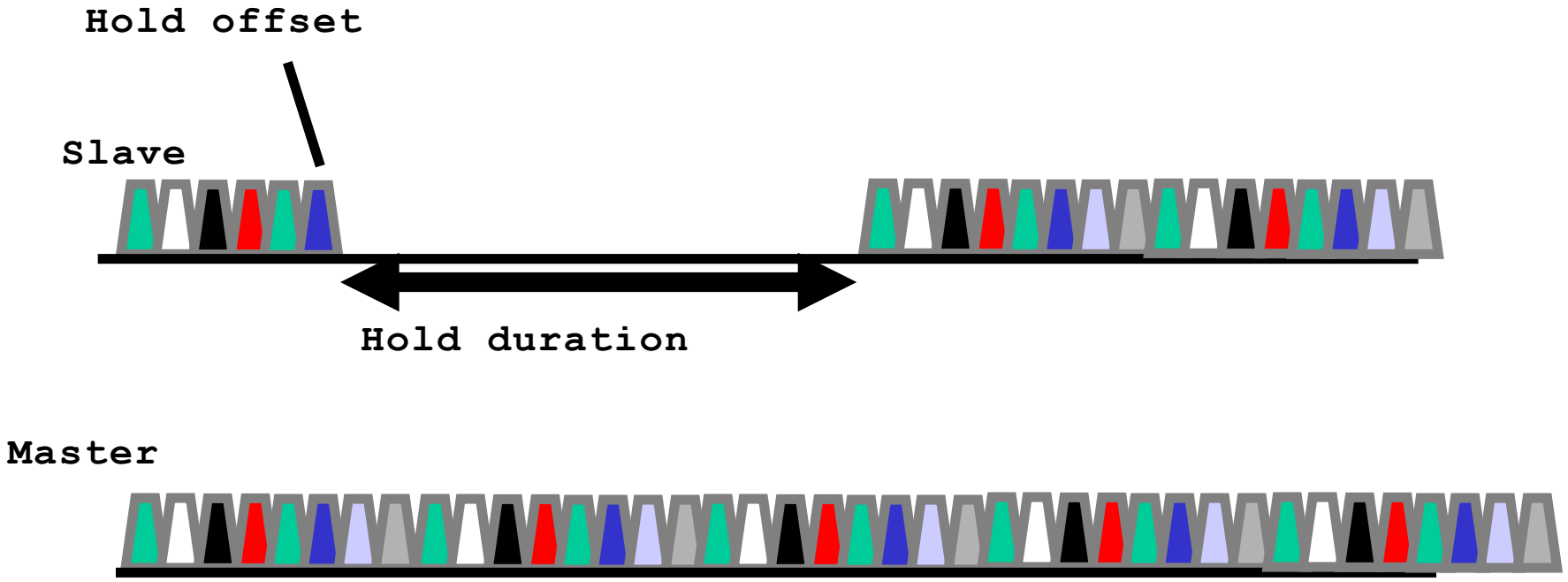
Scan, page, and inquiry support connection establishment:
In idle mode (**sniff**): the unit periodically **listens** if other units want **to connect**. The **scan** window is **about 10** ms.

At every **wake up**, it scans at a **different hop carrier**. The Bluetooth wake up hop sequence is only **32 hops** in length and is cyclic. All 32 hops in the wake up sequence **are unique**, and they scan at least **64 MHz** of the **79 MHz** available.



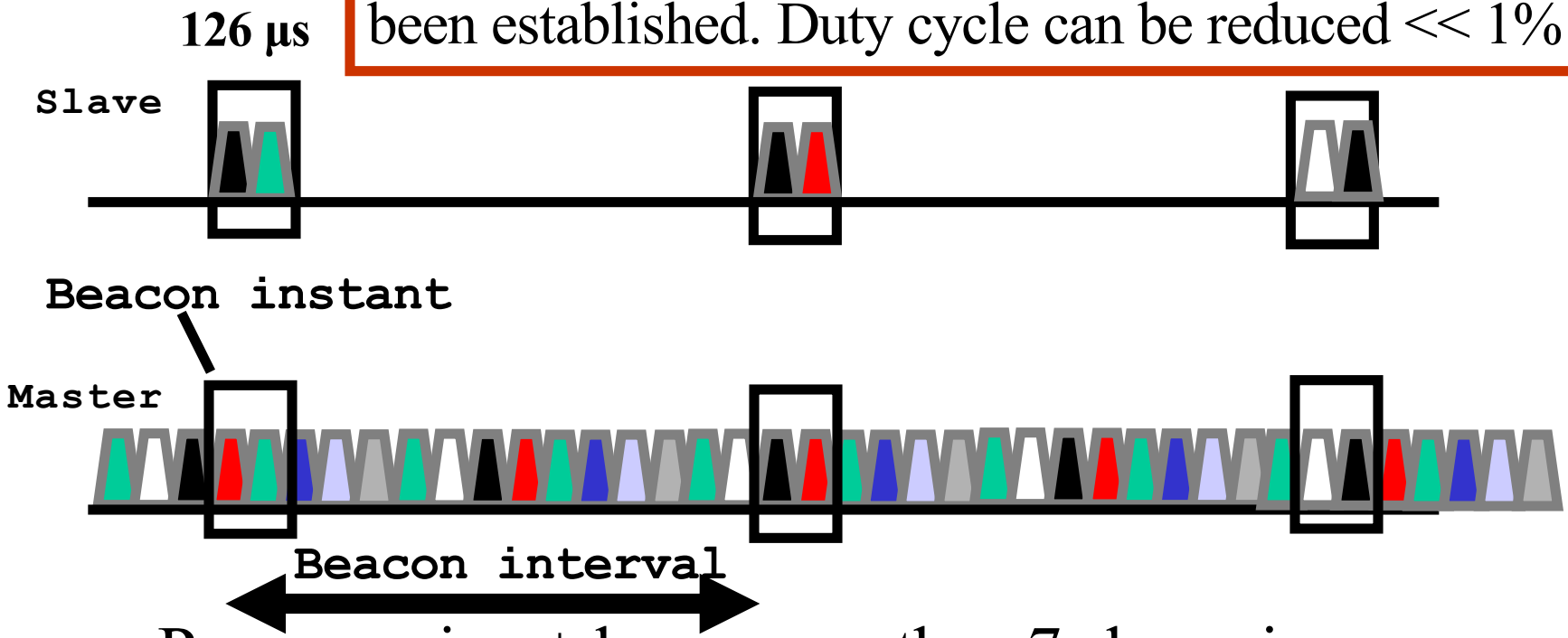
b. Power Management:
Low power mode (hold)

Duty cycle is well below 1 %



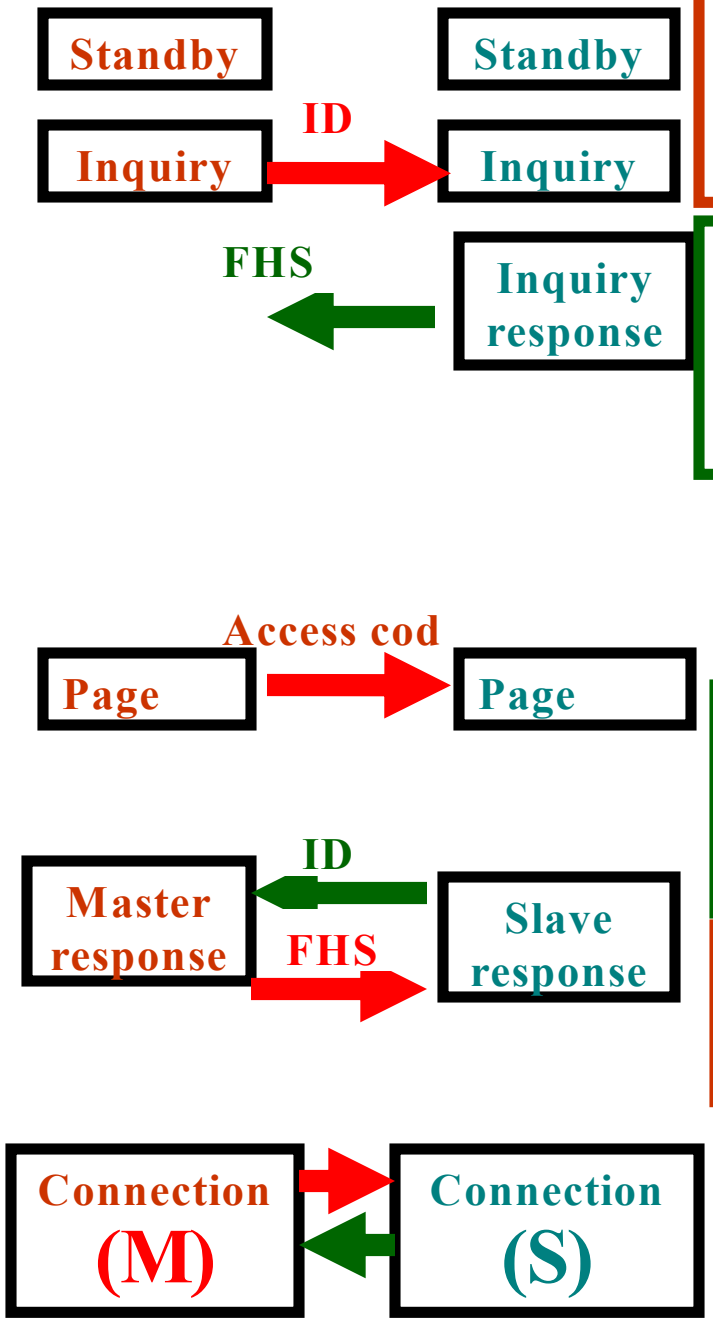
c. Power Management: (Park)

PARK mode can only be applied after the piconet has been established. Duty cycle can be reduced << 1%



- Power saving + keep more than 7 slaves in a piconet
- Give up active member address, maintain synchronization

Inquiry is the process where a device will attempt to discover all the Bluetooth enabled devices in its local area.



To make a connection unit broadcasts inquiry message with return address & clock information.

Idle units listens the inquiry, returns the inquiry and FHS packet which includes identity & clock information.

During page & inquiry, 32 hop used & access code is used for signaling

Slave ACKs the paging massage, switches to the Master's CLK & moves to Master's frequency hop and timing sequence

M enters the M response with its FHS packets.

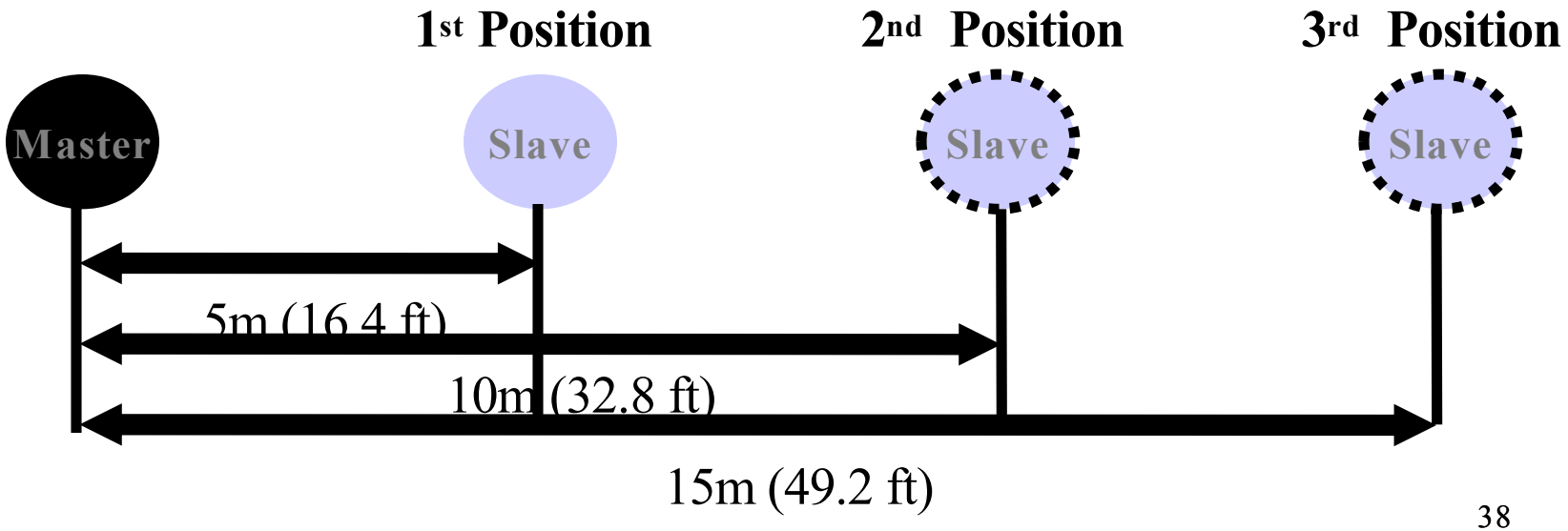
During connection state, various data exchange & logical channels are possible.

10. Bluetooth Experiment Goals

- Impact of distance and Bit Error Rate (BER) on throughput.
- Effect of one-to-many connection on throughput.
- Interference among Bluetooth devices.
- Interference and fairness between Bluetooth and IEEE 802.11 devices.

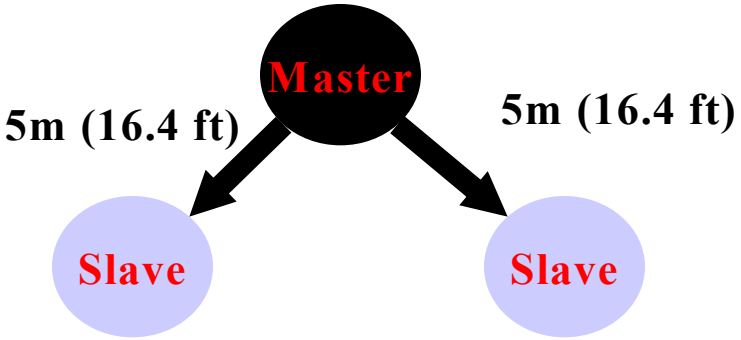
Experiments (1)

Measure TCP data throughput using Iperf measurement tool on one-to-one connection at different distance and packet type (DH1, DH3, and DH5).

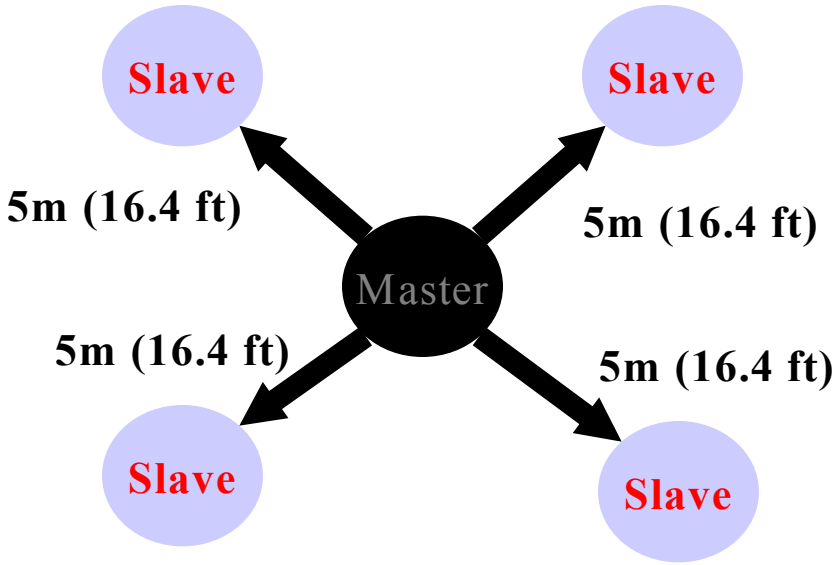


Experiments (2)

- Measure TCP data throughput on one-to-two and one-to-four connection.



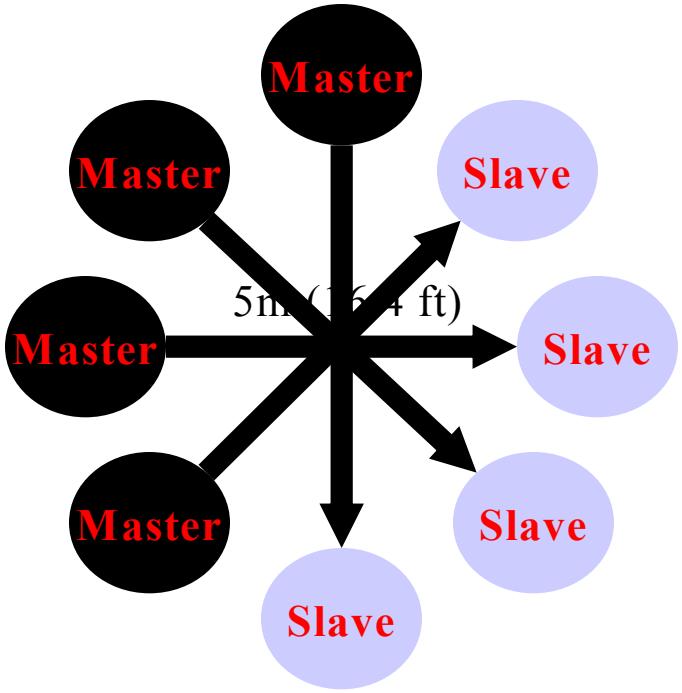
One-to-two Connection



One-to-four Connection

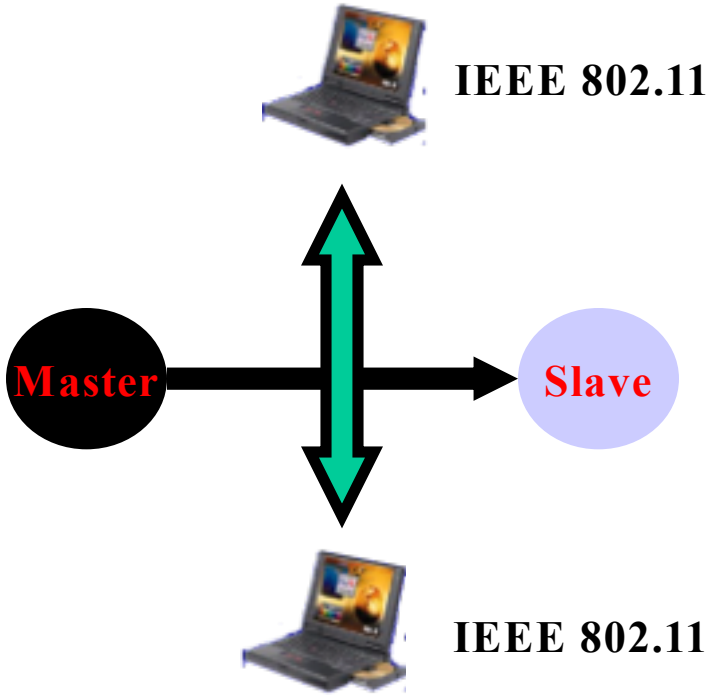
Experiments (3)

- Measure TCP data throughput in four crossed one-to-one connections.



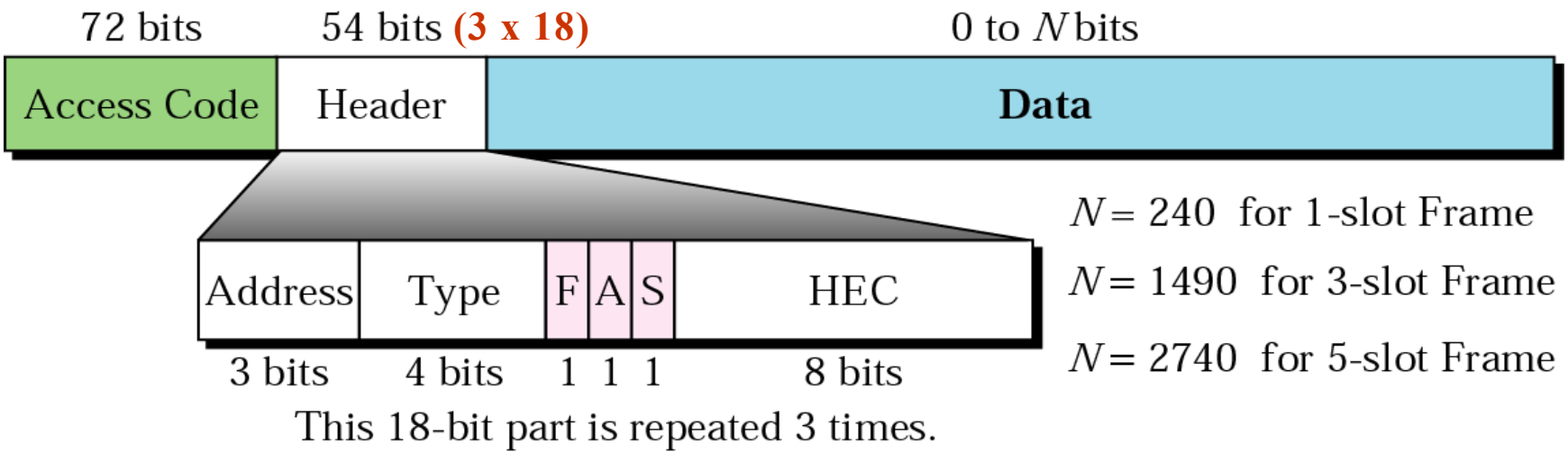
Experiments (4)

- Measure TCP data throughput for one-to-one connection crossed by IEEE 802.11 transfer.



THANK YOU!

Frame format types



The Address **- identifies which of the 8 active devices the frame is intended for.**

The Type **- frame type (ACL, SCO)**

The Flow **- is asserted by a slave when its buffer is full and cannot receive any more data**

The Ack-ment **bit is used for ACK**

The Sequence **- is used to number the frames for retransmissions. The protocol is stop-and-wait.**

Checksum **The 18-bit header is repeated 3 times for a total of 54 bits *Header***

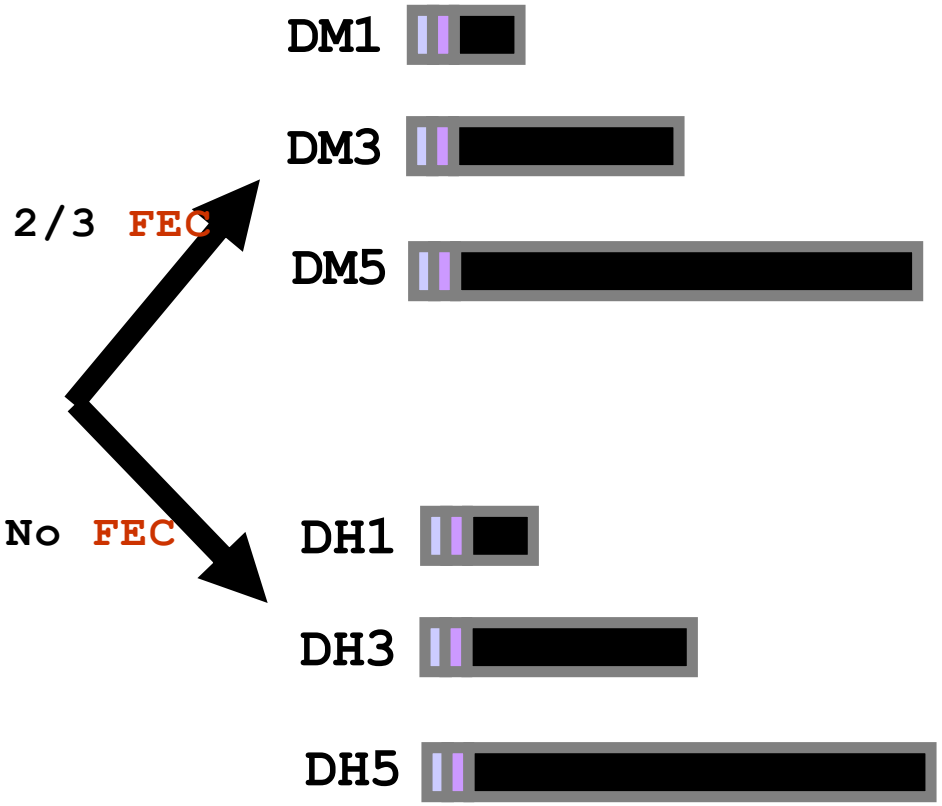
11. Materials for HW and the Report

Physical Link Definition

1. **SCO** link (voice traffic)
2. **ACL** link (data traffic)

- The SCO link is a point-to-point link between the **M** and a single S. The link is established by reservation of duplex slots at regular intervals. For **SCO links** only **single-slot** packets have been defined and supports a **full-duplex** link with a user rate **64 kbps** in both directions.
- The ACL link is a point-to-multipoint link between the **M** and **all the slaves** on the Piconet. The ACL link can use all of the remaining slots on the channel not used for SCO links. The traffic over the ACL link is scheduled by the M. The maximum user rate is **723.2 kbps**. In that case, a return link of **57.6 kbps** can be supported.

Data Packet Types (Details for calculations)



Symmetric	Asymmetric	
108.8	108.8	108.8
258.1	387.2	54.4
286.7	477.8	36.3

Symmetric	Asymmetric	
172.8	172.8	172.8
390.4	585.6	86.4
433.9	723.2	57.6

DM-Data Medium, with Forward Error Control

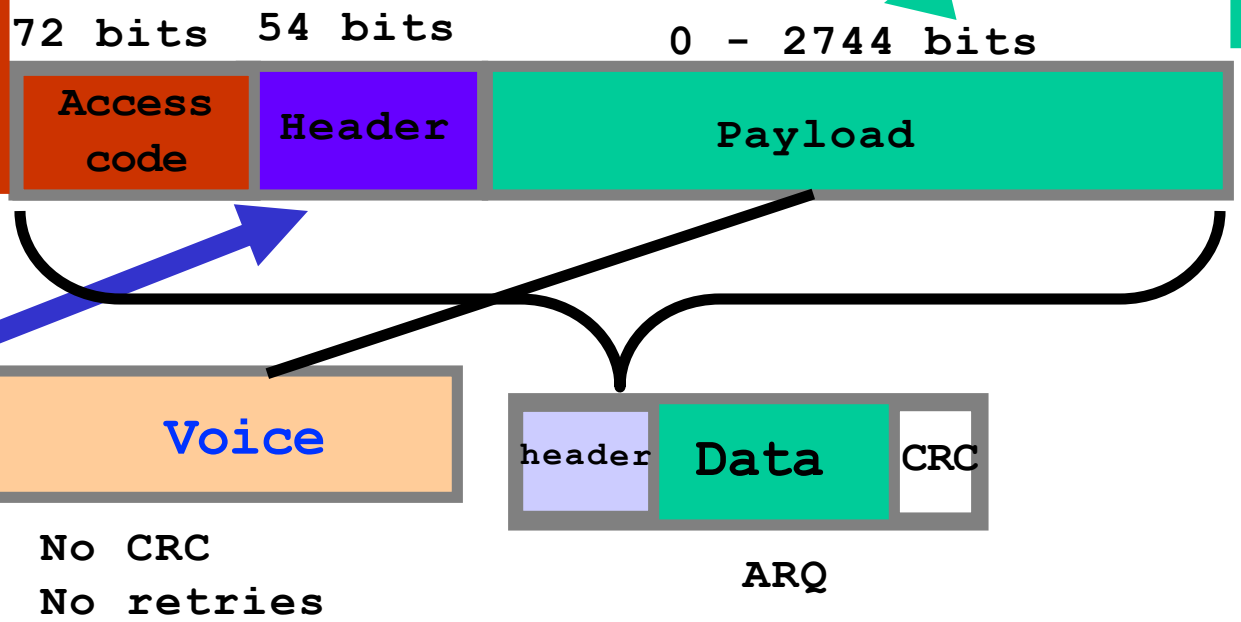
DH-Data High, no Forward Error Control

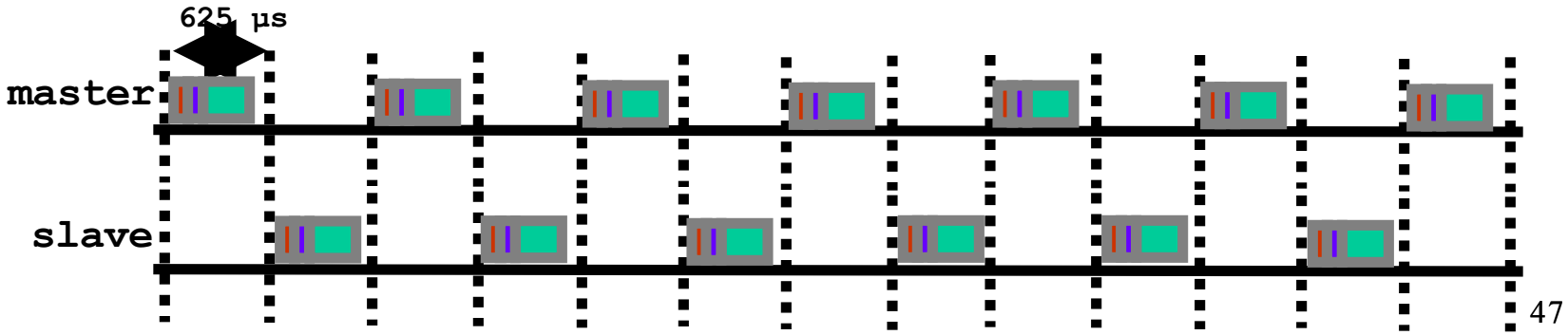
Packet Format

Identifies the master and slaves within radio range of two masters can tell which traffic is for them.

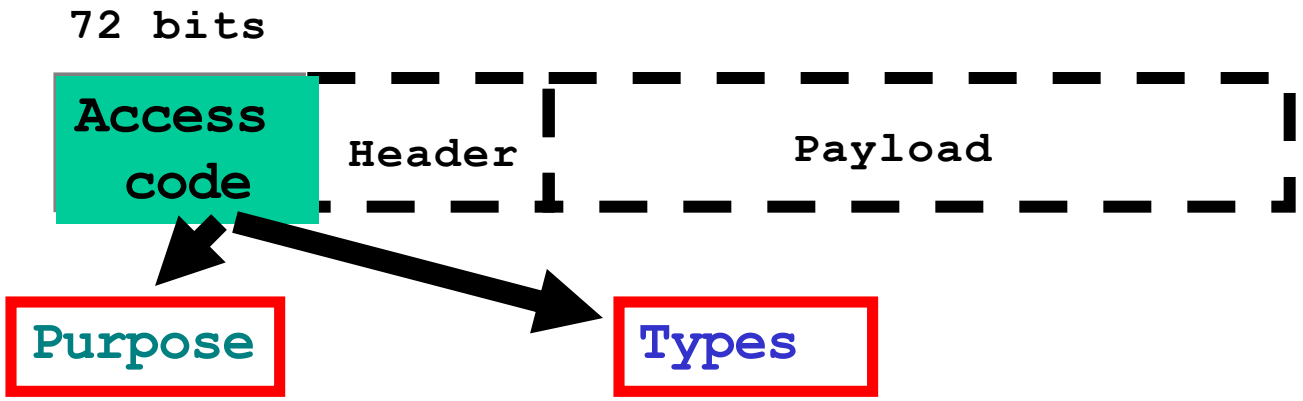
For a single time slot the data field is 240 bits.

Containing typical MAC sublayer fields



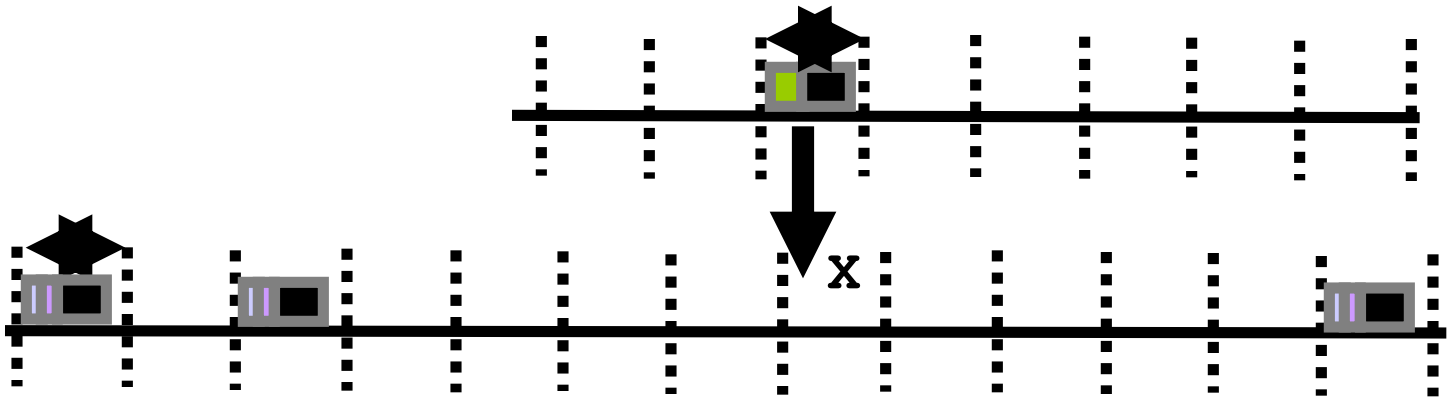


Access Code

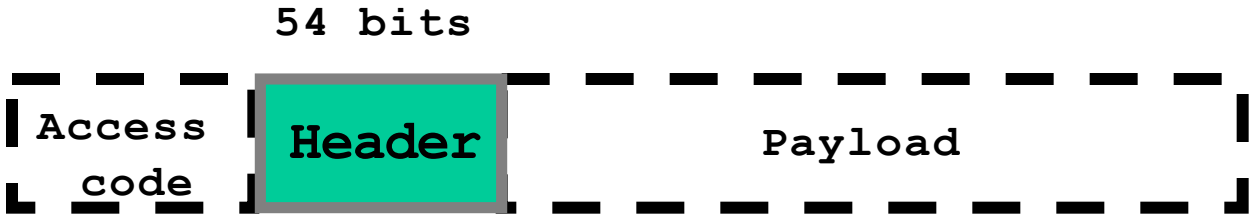


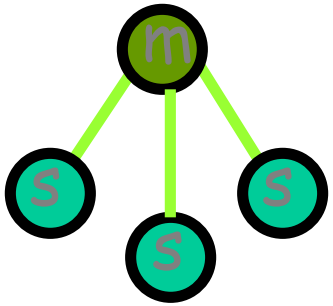
- Synchronization
- DC offset compensation
- Identification
- Signaling

- Channel Access Code (CAC)
- Device Access Code (DAC)
- Inquiry Access Code (IAC)



Packet Header





Purpose

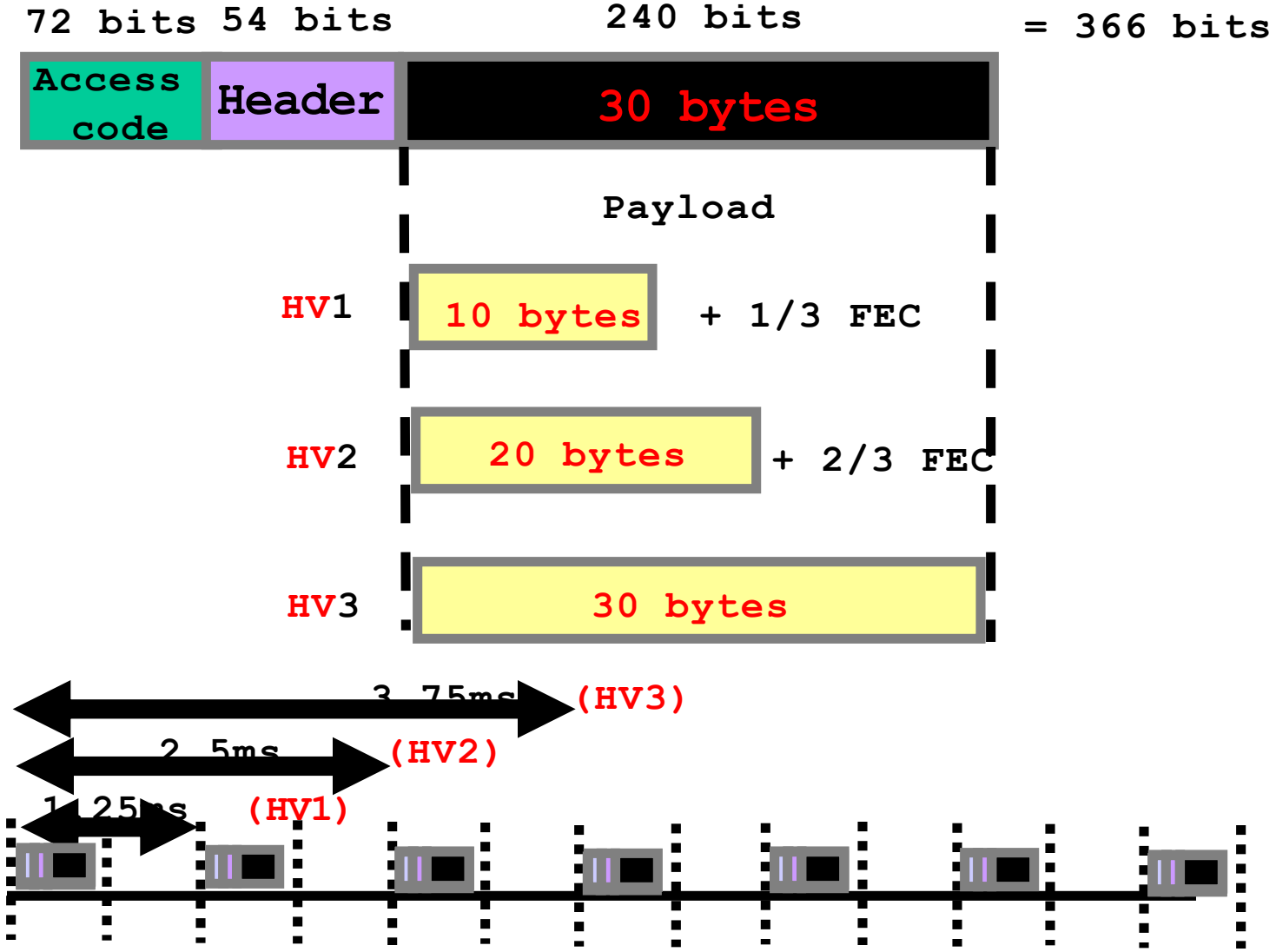
- **Addressing (3)** → Max 7 active slaves
- **Packet type (4)** → 16 packet types (some unused)
- **Flow control (1)**
- **1-bit ARQ (1)** → Broadcast packets are not ACKed
- **Sequencing (1)** → For filtering retransmitted packets
- **HEC (8)** → Verify header integrity (Header Error Control)

total 18 bits

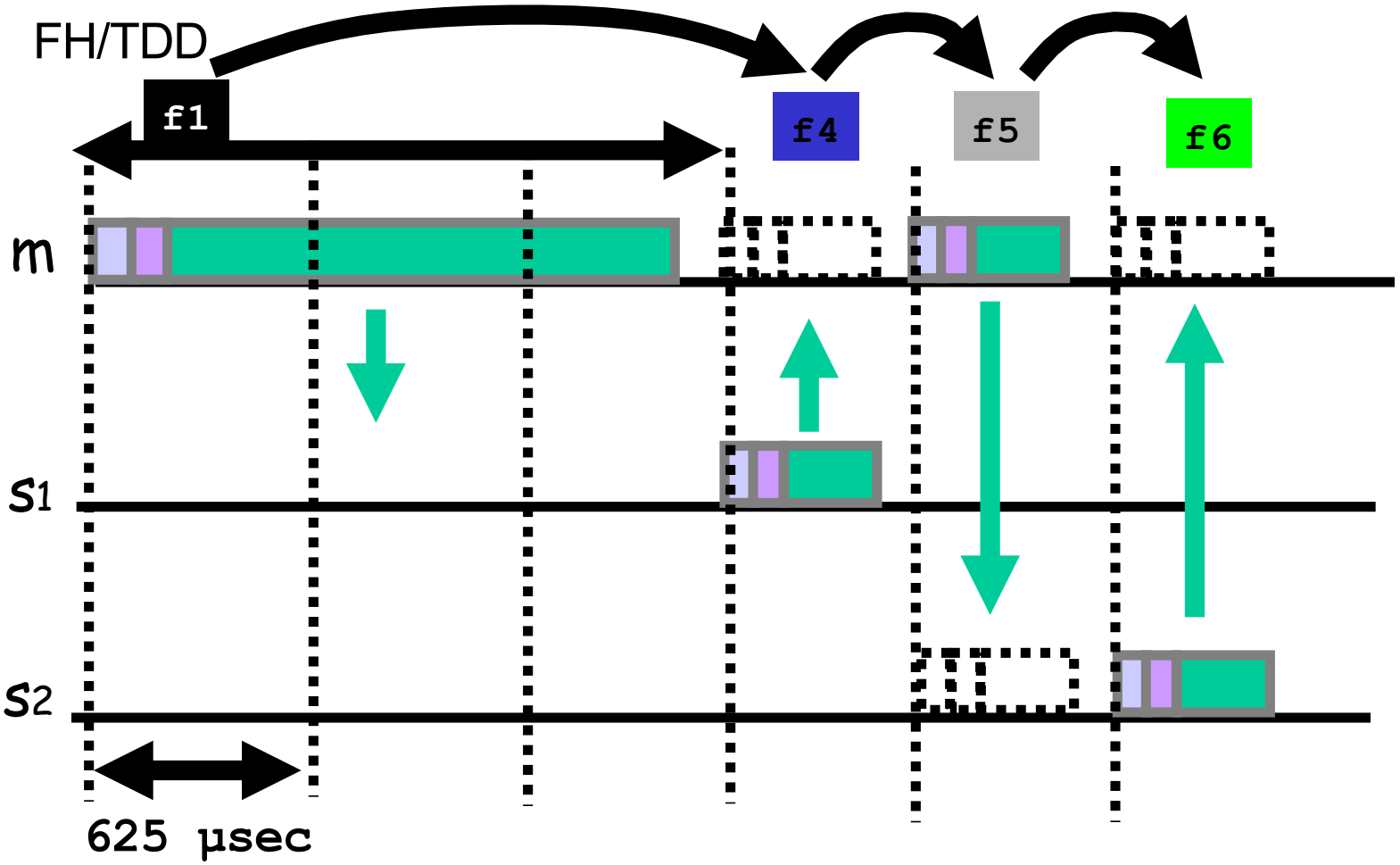
Encode with 1/3 FEC (**Forward Error Correction**) to get **54 bits**

Voice Packets (HV1, HV2, HV3)

HV-High Voice

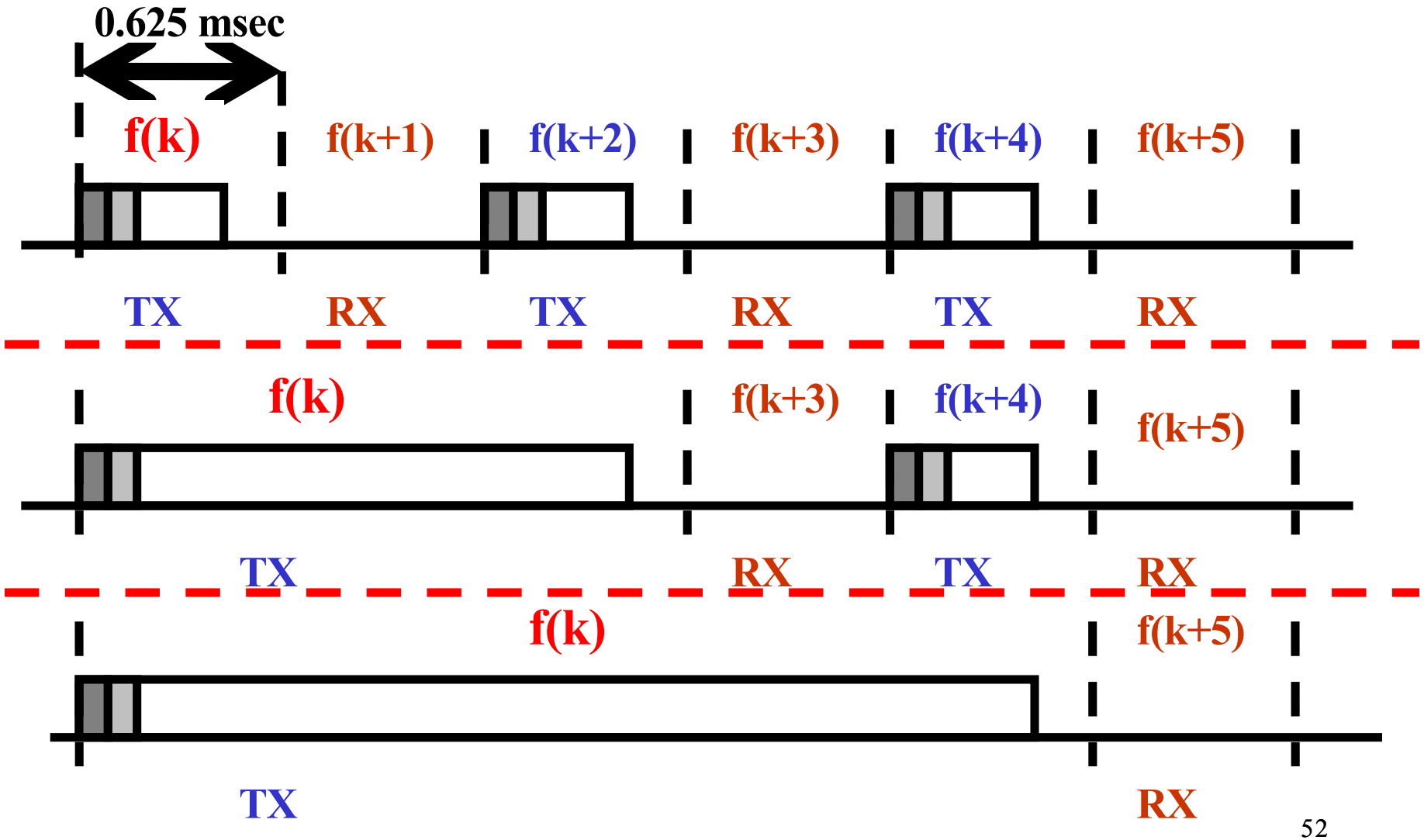


Multi slot packets

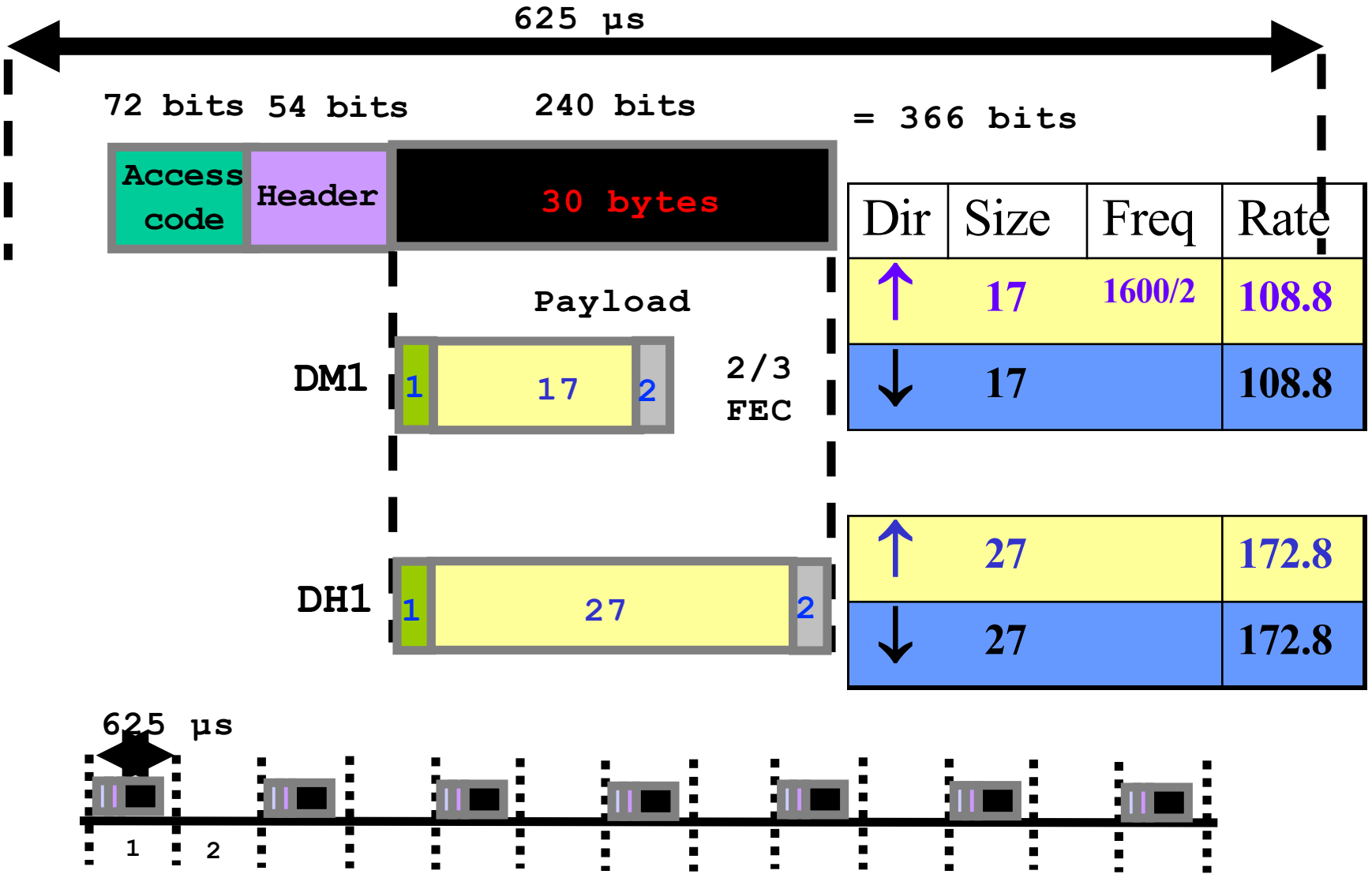


Data rate depends on type of packet

The frequency and timing characteristics of: single-slot, three-slot and five-slot packets

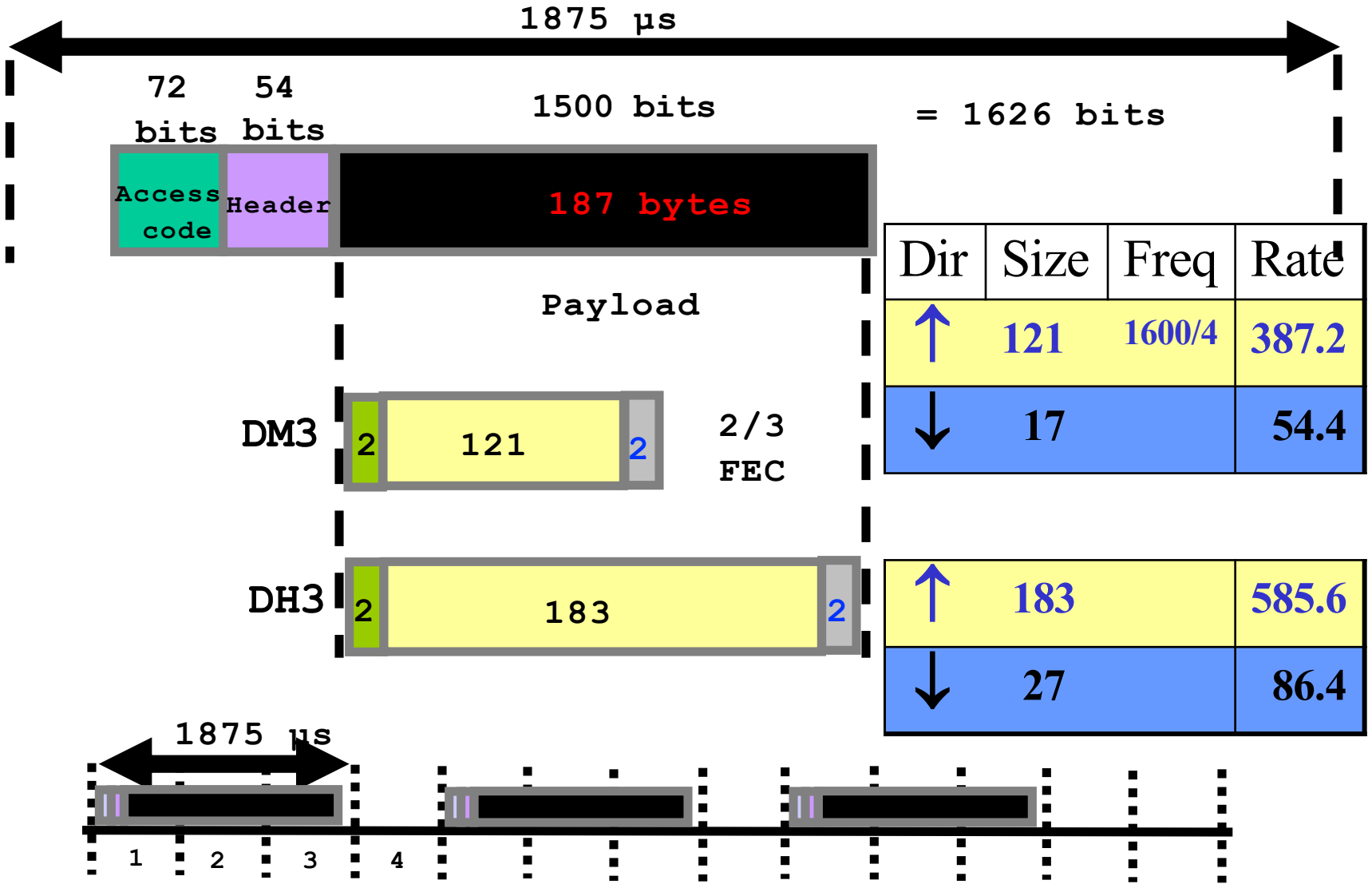


Data rate calculation: DM1 and DH1

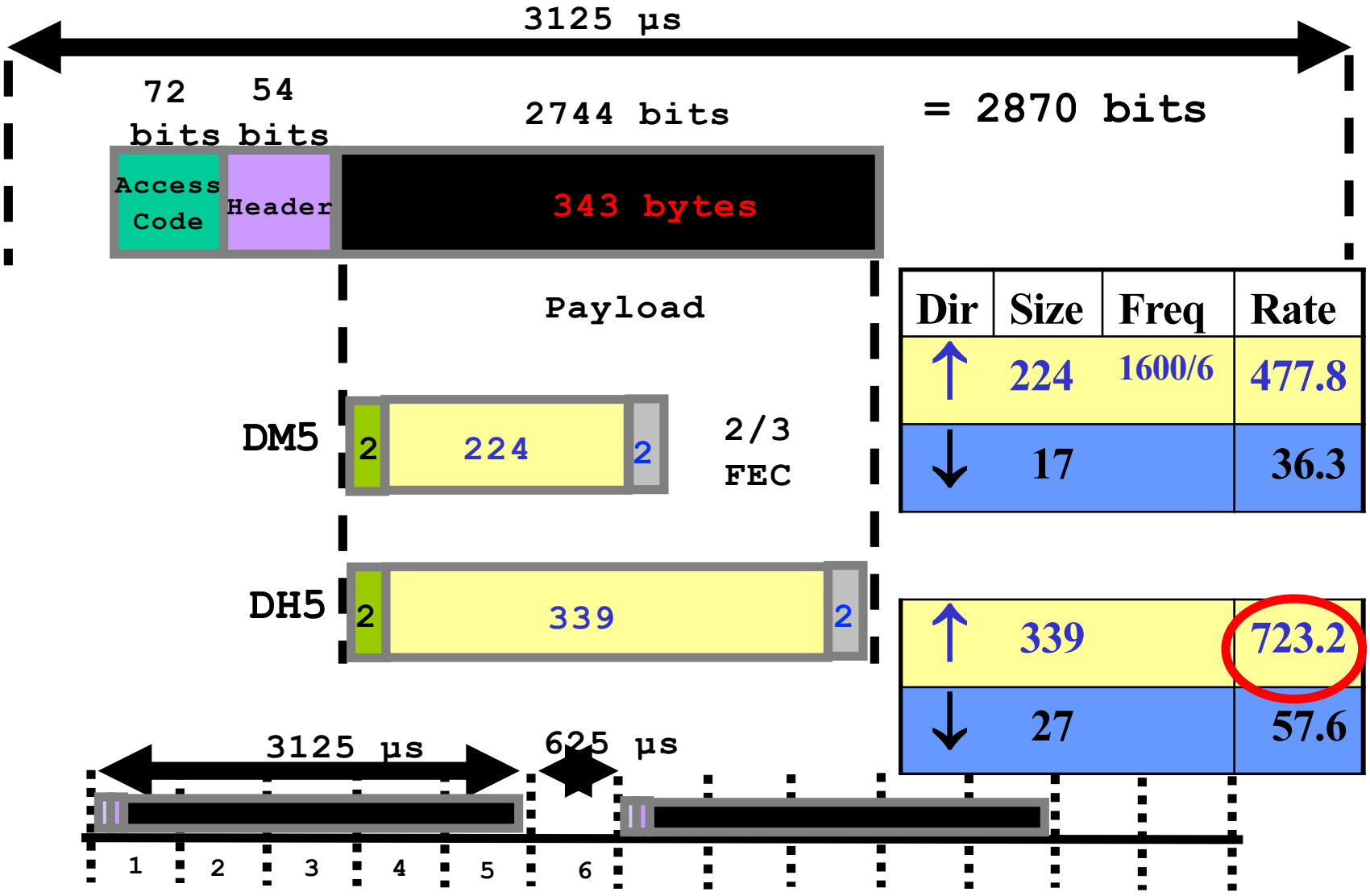


Dir	Size	Freq	Rate
↑	17	1600/2	108.8
↓	17		108.8
↑	27		172.8
↓	27		172.8

Data rate calculation: DM3 and DH3



Data rate calculation: DM5 and DH5



Z-B

Appendix. ZigBee and Bluetooth

B-T

Optimized for different applications

- **ZigBee 802.15.4**
  - Smaller packets over large network
  - Mostly Static networks with many, infrequently used devices
  - Home automation, toys, remote controls, etc.
- **Bluetooth 802.15**
  - Larger packets over small network
  - Ad-hoc networks
  - File transfer
  - Screen graphics, pictures, hands-free audio, Mobile phones, headsets, PDAs, etc.

Transceiver Comparisons

Z-B

- **Instantaneous Power Consumption**
  - 15.4 Transceivers are "similar" to Bluetooth Transceivers
    - **802.15.4**
      - **O-QPSK with shaping (Offset QPSK)**
      - **Max data rate 250 kbps over the air**
      - **2 M.chips/s over the Direct Sequence Spread Spectrum (62.5ksps*32 spread)**
      - **-90 dBm sensitivity**
    - **Bluetooth 802.15**
      - **FSK**
      - **Max data rate 720 kbps over the air**
      - **1 Msps over the Frequency Hop Spread Spectrum (79 channels @ 1600 hps)**
      - **-85dBm sensitivity**
- **Instantaneous power consumption will be similar for the raw transceivers without protocol**
- **Bluetooth's frequency hop makes it extremely difficult to create extended networks without large synchronization cost**

ZigBee and Bluetooth (cont)

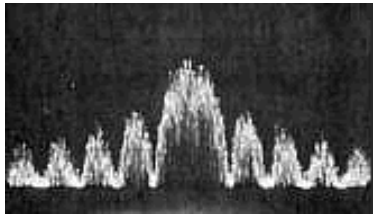
Air interface

- **ZigBee**
- **DSSS- 11 chips/ symbol**
- **62.5 K symbols/s**
- **4 Bits/ symbol**
- **Peak Information Rate**
- **~128 Kbit/second**

Bluetooth

- **FHSS**
- **1 M Symbol / second**
- **Peak Information Rate**

~720 Kbit / second



ZigBee and Bluetooth (cont)

Timing Considerations

- **ZigBee:**
- **Network join time = 30ms** typically
- **Sleeping slave changing to active = 15ms**
- **Active slave channel access time = 15ms**

Bluetooth:

- **Network join time = >3s**
- **Sleeping slave changing to active = 3s typically**
- **Active slave channel access time = 2ms typically**

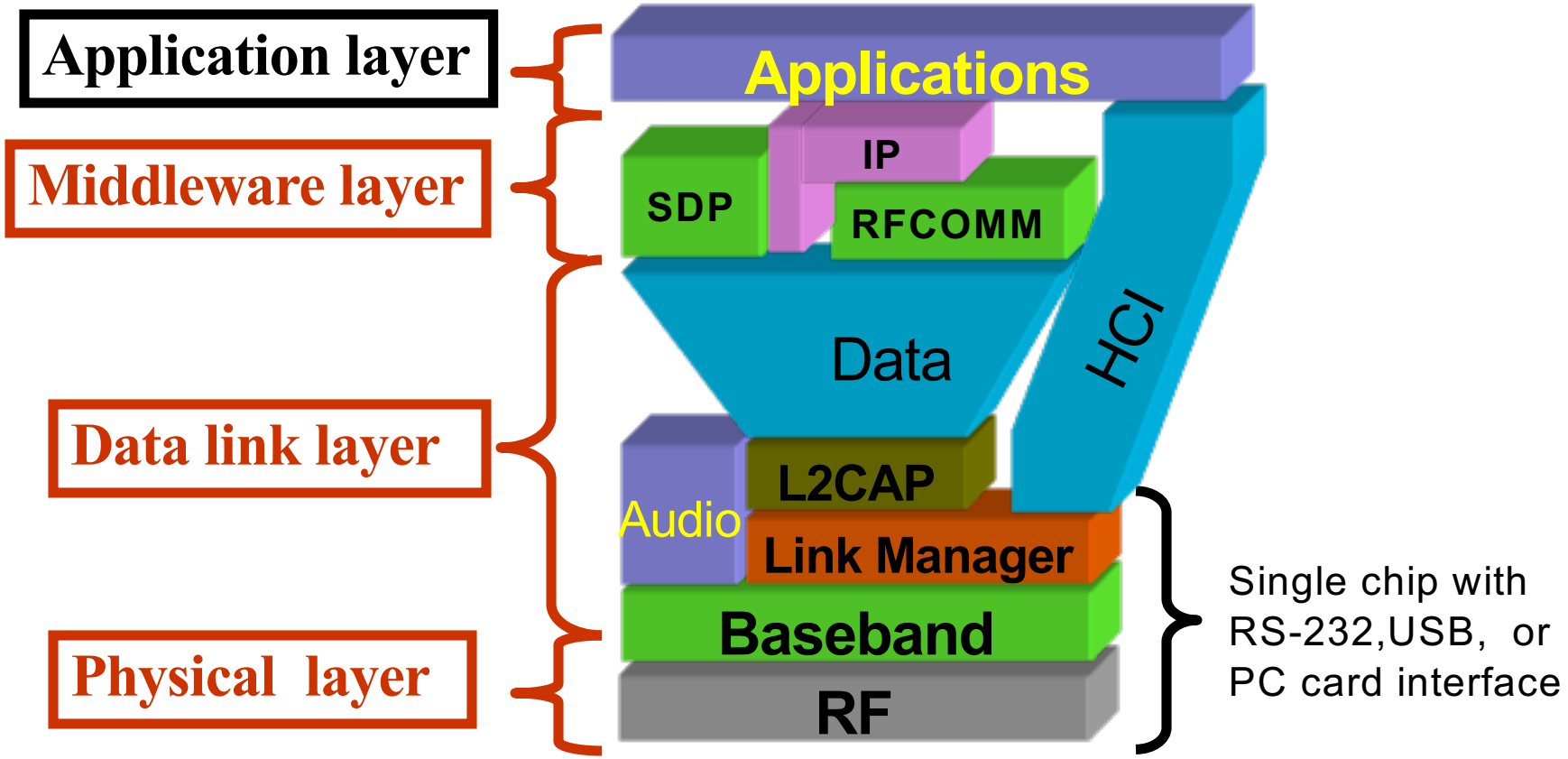
Light switch using ZigBee

- **With DSSS interface, only need to perform CSMA before transmitting**
  - **Only 200 μs of latency**
  - **Highly efficient use of battery power**

Z-B

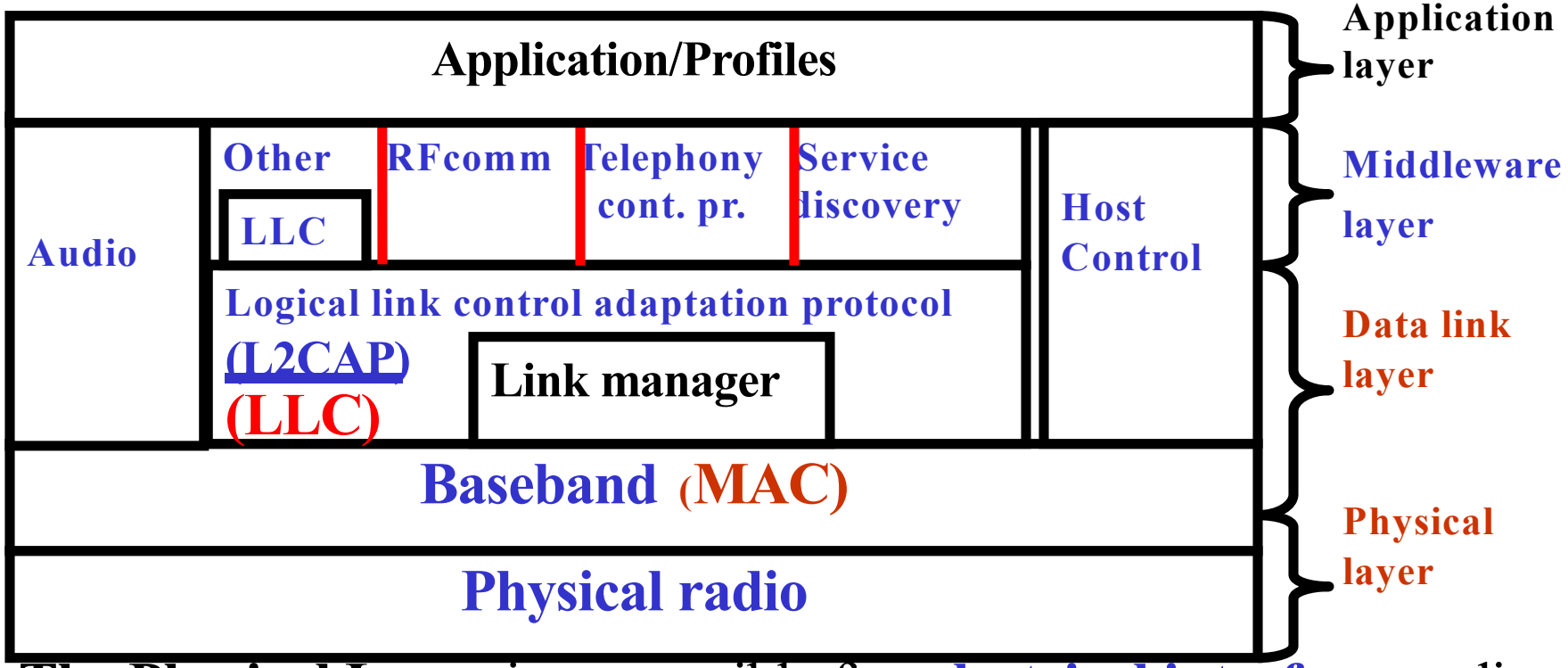
ZigBee offers longer battery life and lower latency than a Bluetooth equivalent.

Bluetooth protocol stack



Allocations of The Bluetooth protocol stack is a series of layers, through there are some features which cross several layers.

The Bluetooth Protocol Architecture

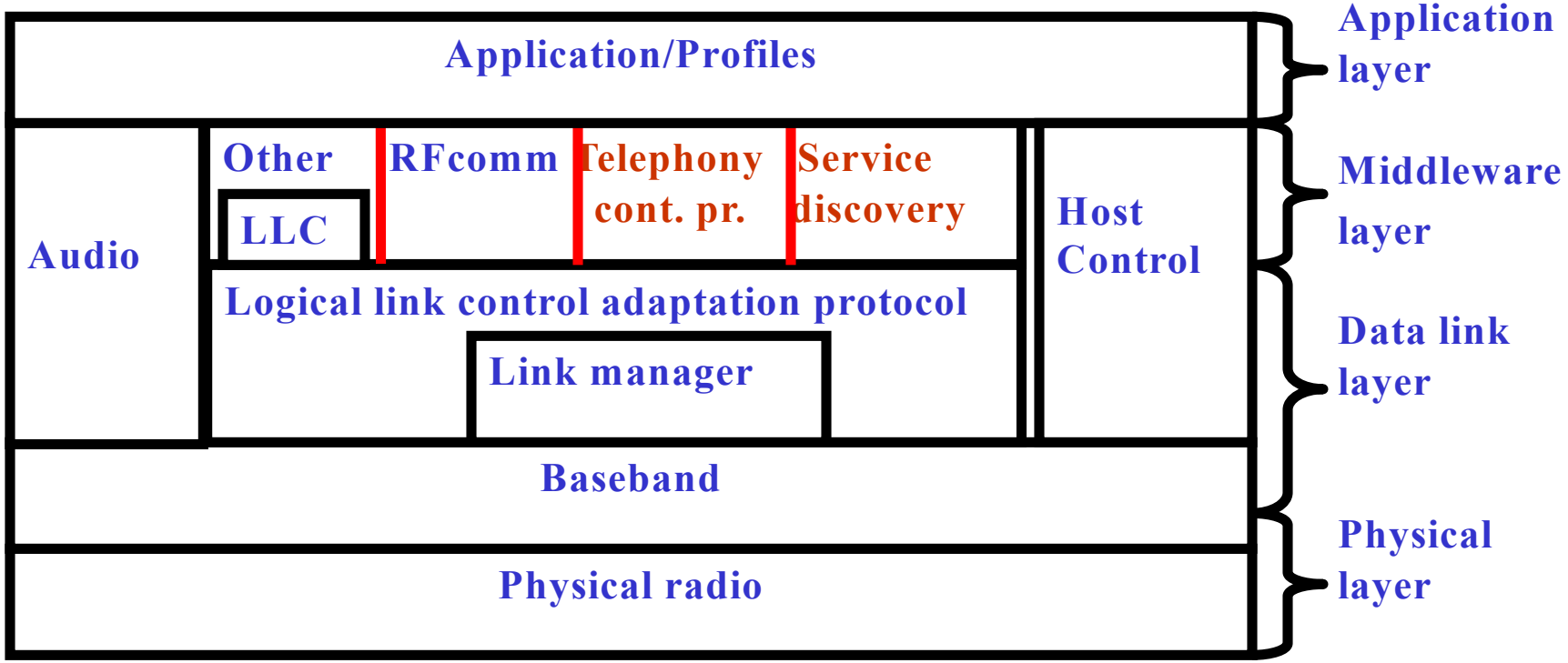


1. The Physical Layer is responsible for: **electrical interface** media, **modulation** & channel coding. It covers the radio and part of baseband and corresponds to the **physical layer** in the OSI and 802 models.

2. The Baseband Layer is analogous to the **MAC** sublayer + elements of the **physical layer**. It deals with how the **master controls time slots** and **how these slots are grouped into frames**.

3. L2CAP: analogous to the standard 802 **LLC** sublayer, but different.

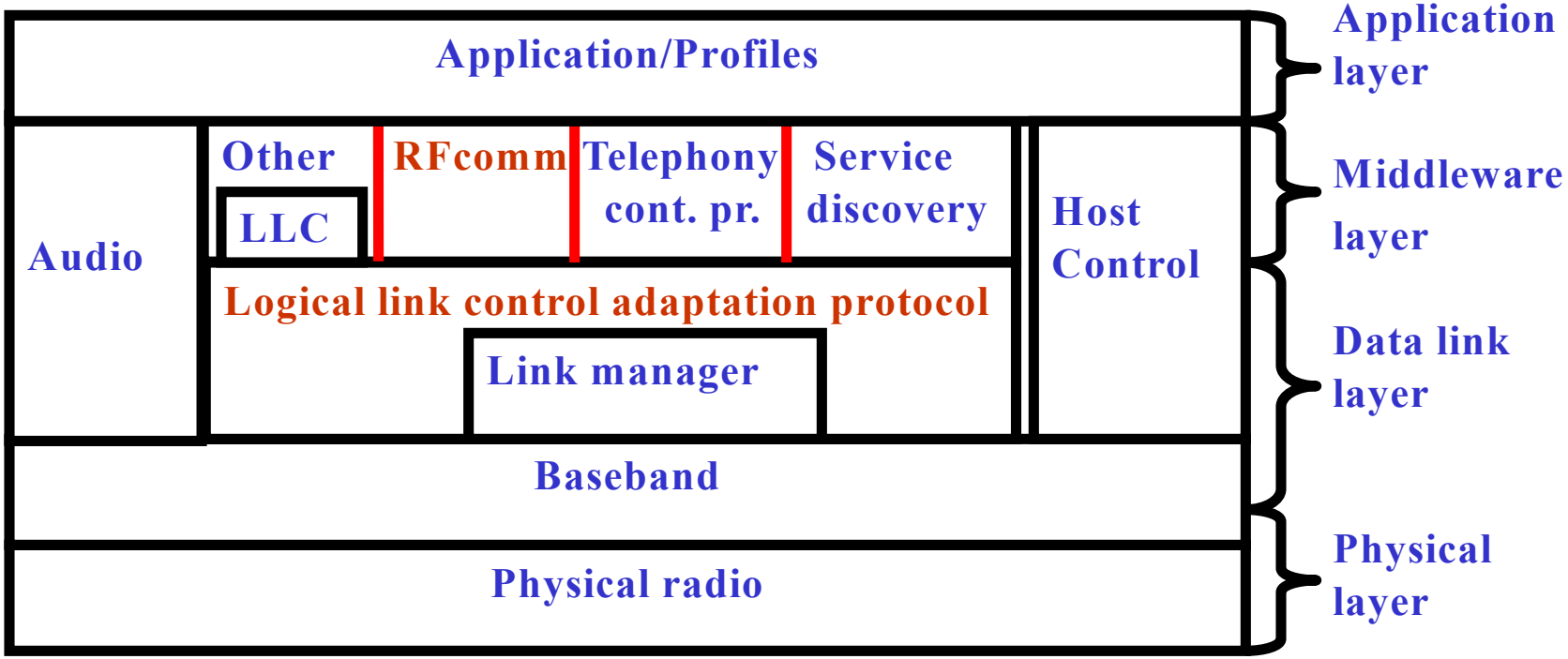
The Bluetooth Protocols



a. **Telephony** (TCS Telephony Control Protocol Specification) provides telephony services. Bluetooth's TCS defines how telephone calls should be sent across a Bluetooth link. It gives guidelines for the signaling needed to set up both point-to-point, and point-to-multipoint calls.

b. **SDP** (Service Discovery Protocol) lets Bluetooth devices to discover what services other Bluetooth devices support. In LAN, you find a connection to a printer, and once found, it stays in place. Bluetooth is designed to allow to walk into an area and find a printer, without having to pre-configure settings.

The Bluetooth Protocols (Cont)



c. RFCOMM is protocol for RS-232 serial cable. RS-232 serial ports have nine circuits, which can be used for transforming data and signaling. It provides multiple concurrent connections by relying on L2CAP to handle multiplexing over single connections, and to provide connections to multiple devices.

d. L2CAP (Logical Link Control and Adaptation Protocol). This provides segmentation and re-assembly services to allow large packets to pass across Bluetooth links, also takes data from higher layer of the Bluetooth stack and from applications and sends it over the lower layers of the stack.