Chapter 5 (Part 3)
LINK LAYER

Distributed
Computing
Group

Computer Networks
Summer 2007

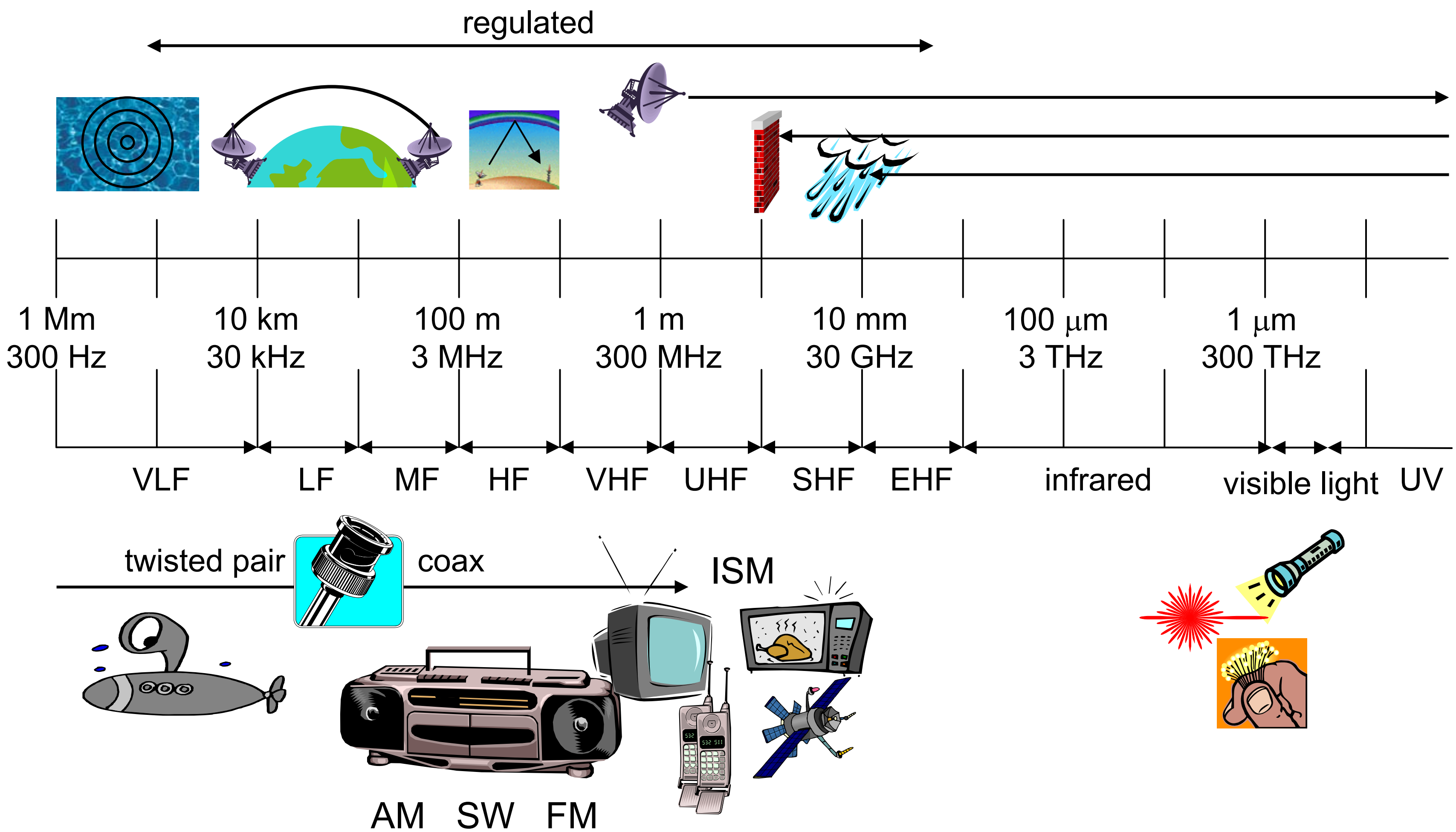
Overview

- More Wireless Basics

- IEEE 802.11
  - Architecture, Protocol
  - PHY, MAC
  - Cyclic Redundancy codes
  - Roaming, Security
  - a, b, g, etc.

- Bluetooth
- RFID

Physical Layer: Wireless Frequencies



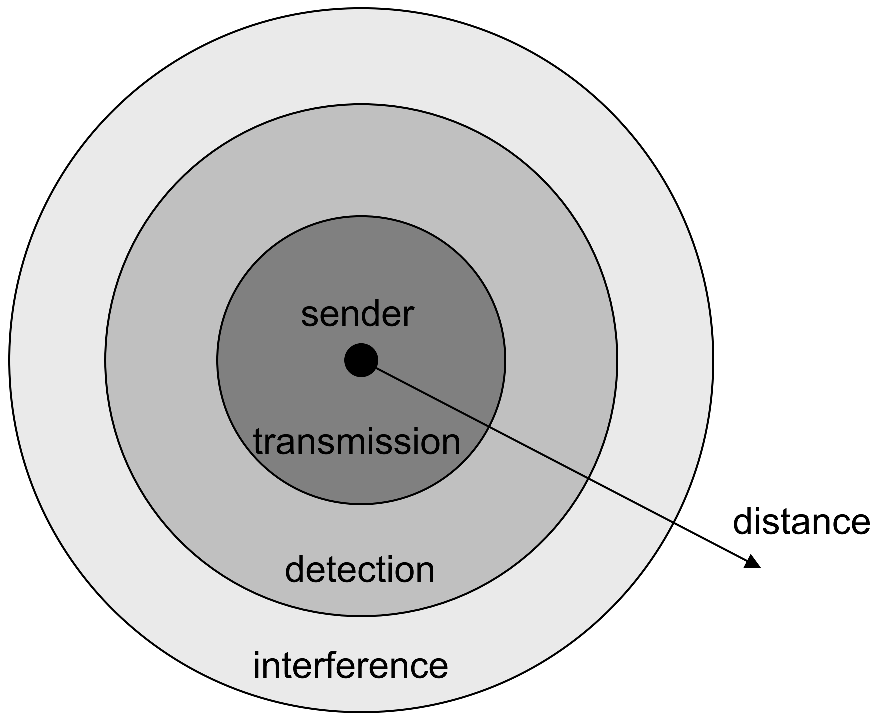
Frequencies and regulations

- ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences)

	Europe (CEPT/ETSI)	USA (FCC)	Japan
Mobile phones	**NMT** 453-457MHz, 463-467 MHz **GSM** 890-915 MHz, 935-960 MHz, 1710-1785 MHz, 1805-1880 MHz	**AMPS**, **TDMA**, **CDMA** 824-849 MHz, 869-894 MHz **TDMA**, **CDMA**, **GSM** 1850-1910 MHz, 1930-1990 MHz	**PDC** 810-826 MHz, 940-956 MHz, 1429-1465 MHz, 1477-1513 MHz
Cordless telephones	**CT1+** 885-887 MHz, 930-932 MHz **CT2** 864-868 MHz **DECT** 1880-1900 MHz	**PACS** 1850-1910 MHz, 1930-1990 MHz **PACS-UB** 1910-1930 MHz	**PHS** 1895-1918 MHz **JCT** 254-380 MHz
Wireless LANs	**IEEE 802.11** 2400-2483 MHz **HIPERLAN 1** 5176-5270 MHz	**IEEE 802.11** 2400-2483 MHz	**IEEE 802.11** 2471-2497 MHz

Signal propagation ranges

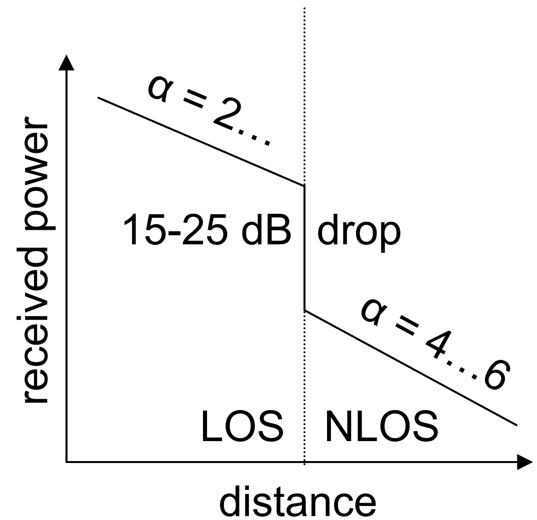
- Propagation in free space always like light (straight line)
- Transmission range
  - communication possible
  - low error rate
- Detection range
  - detection of the signal possible
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise



Attenuation by distance

- Attenuation [dB] = 10 $\log_{10}$ (transmitted power / received power)
- Example: factor 2 loss = 10 $\log_{10} 2 \approx 3$ dB

- In theory/vacuum (and for short distances), receiving power is proportional to $1/d^2$, where d is the distance.
- In practice (for long distances), receiving power is proportional to $1/d^\alpha$, $\alpha = 4\ldots6$. We call α the path loss exponent.



- Example: Short distance, what is the attenuation between 10 and 100 meters distance?
Factor 100 (=$100^2/10^2$) loss = 20 dB

Signal-to-Interference-Plus-Noise Ratio

- Communication theorists study complex fading and signal-to-noise-plus-interference (SINR)-based models
- Simplest case:

  → packets can be decoded if SINR is larger than β at receiver

Received signal power from sender

Power level of sender u

Path-loss exponent

$$\frac{\frac{P_u}{d(u,v)^\alpha}}{N+\sum_{w\in V\setminus\{u\}} \frac{P_w}{d(w,v)^\alpha}} \geq \beta$$

Minimum signal-to-interference ratio

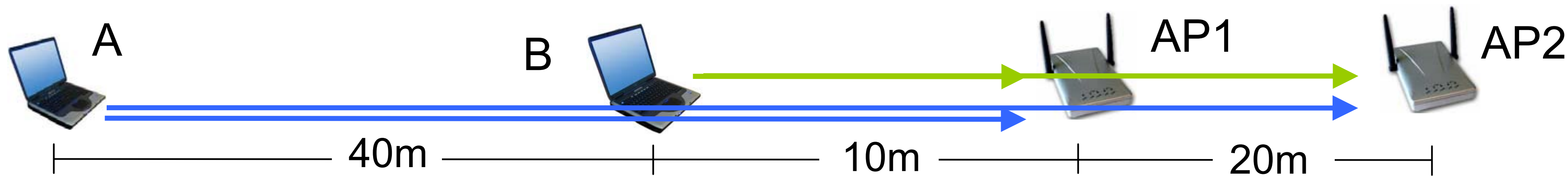
Noise

Received signal power from all other nodes (=interference)

Distance between two nodes

Example

- Clients A and B want to send (max. rate x kb/s)
- Assume there is a single frequency
- What total throughput („spatial reuse“) can be achieved...?



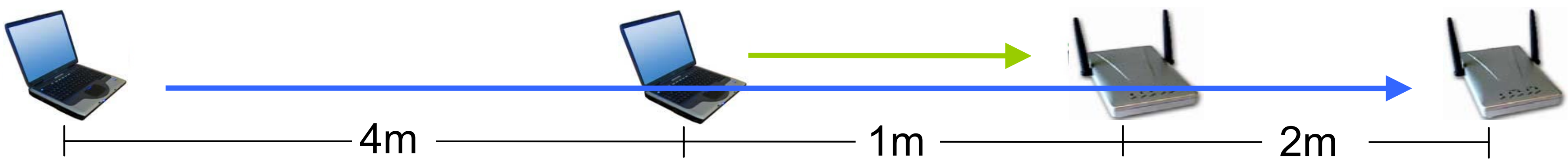
Total throughput at most: x kb/s

In graph-based models…

no spatial reuse seems possible…

Example

A sends to AP2, B sends to AP1 → (max. rate x kb/s)



- Assume a single frequency (and no fancy decoding techniques!)
- Let α=3, β=3, and N=10nW
- Set the transmission powers as follows P_B= -15 dBm and P_A= 1 dBm

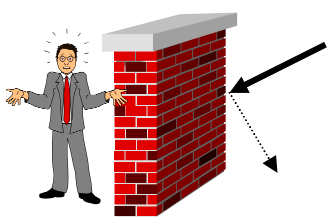
SINR of A at AP2: $$\frac{1.26mW/(7m)^3}{0.01\mu W + 31.6\mu W/(3m)^3} \approx 3.11 \geq \beta$$

SINR of B at AP1: $$\frac{31.6\mu W/(1m)^3}{0.01\mu W + 1.26mW/(5m)^3} \approx 3.13 \geq \beta$$

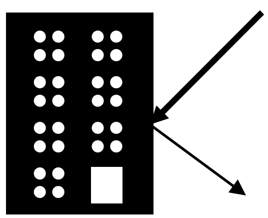
A total throughput of 2x kb/s is possible !

Attenuation by objects

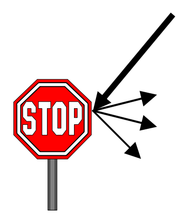
- Shadowing (3-30 dB):
  - textile (3 dB)
  - concrete walls (13-20 dB)
  - floors (20-30 dB)
- reflection at large obstacles
- scattering at small obstacles
- diffraction at edges
- fading (frequency dependent)



shadowing



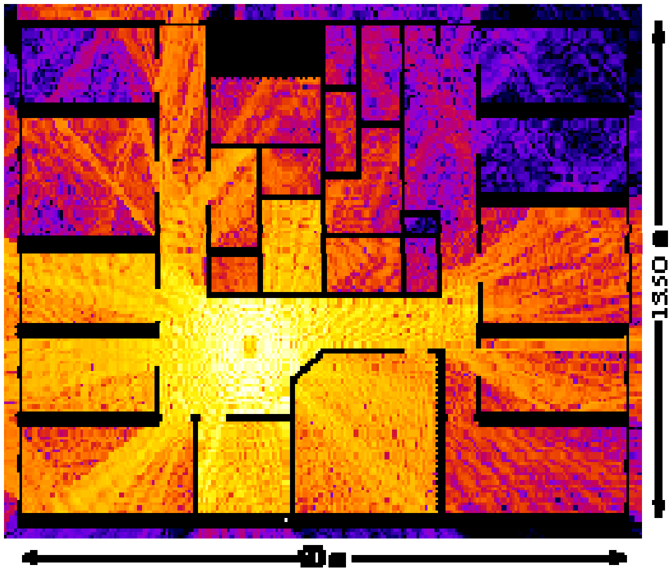
reflection

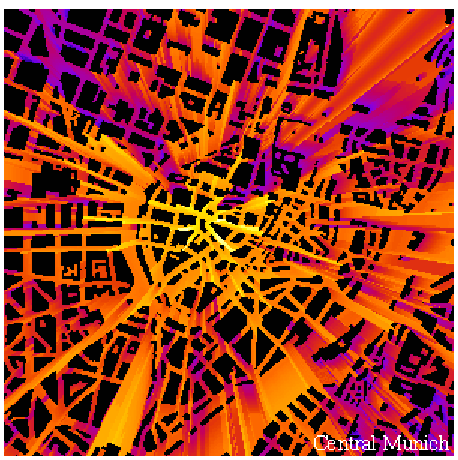


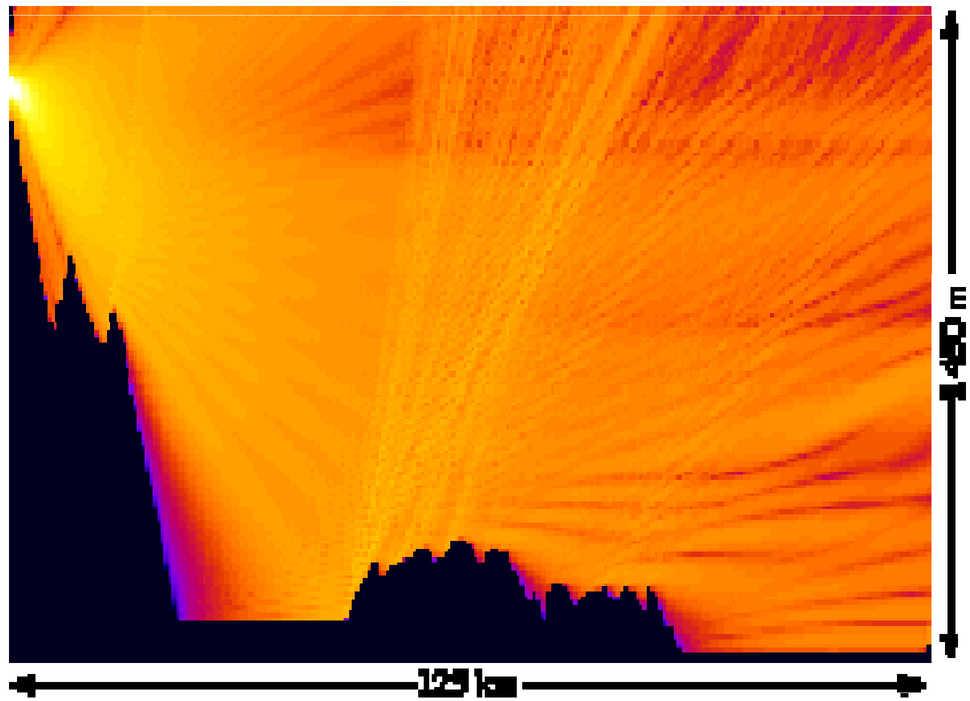
scattering

diffraction

Real World Examples

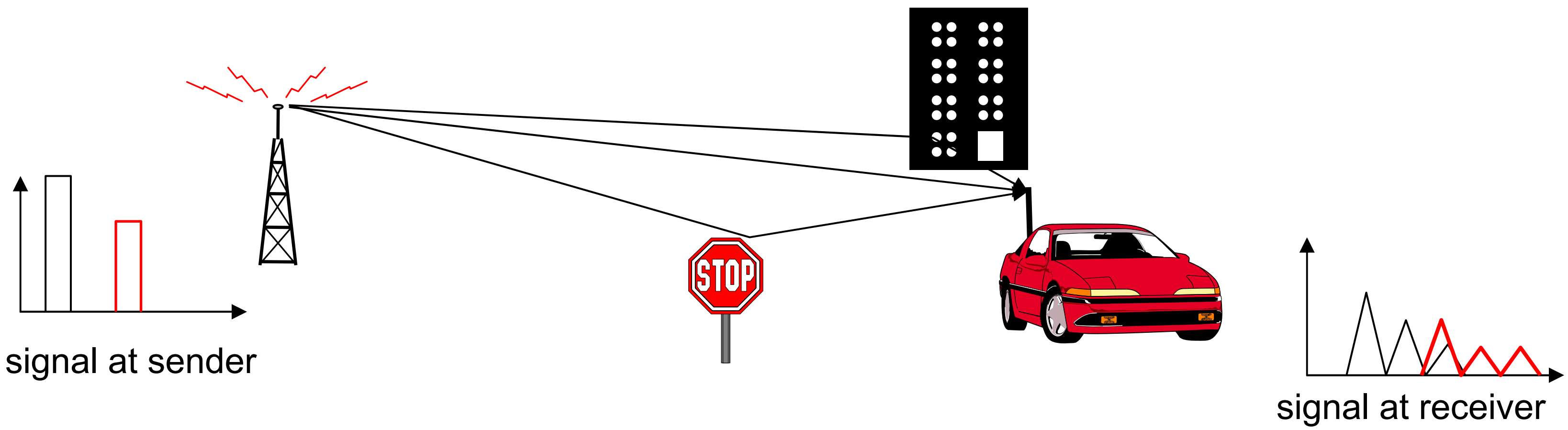






Multipath propagation

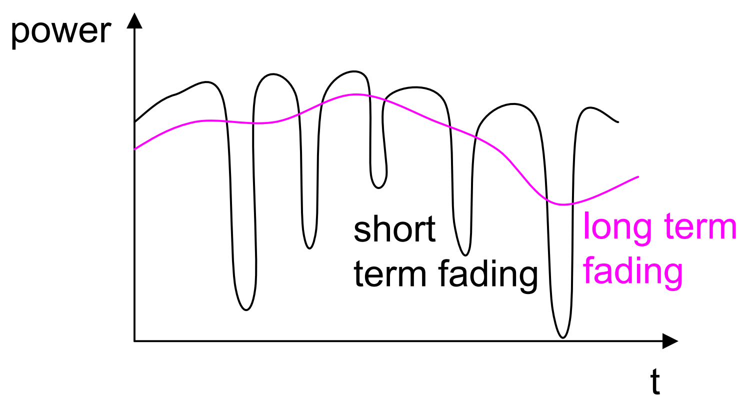
- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



- Time dispersion: signal is dispersed over time
- Interference with “neighbor” symbols: Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted
- Distorted signal depending on the phases of the different parts

Effects of mobility

- Channel characteristics change over time and location
  - signal paths change
  - different delay variations of different signal parts
  - different phases of signal parts
- quick changes in power received (short term fading)



- Additional changes in
  - distance to sender
  - obstacles further away
- slow changes in average power received (long term fading)

- Doppler shift: Random frequency modulation

Wireless LAN 802.11: Design goals

- Global, seamless operation
- Low power consumption for battery use
- No special permissions or licenses required
- Robust transmission technology
- Simplified spontaneous cooperation at meetings
- Easy to use for everyone, simple management
- Interoperable with wired networks
- Security (no one should be able to read my data), privacy (no one should be able to collect user profiles), safety (low radiation)
- Transparency concerning applications and higher layer protocols, but also location awareness if necessary

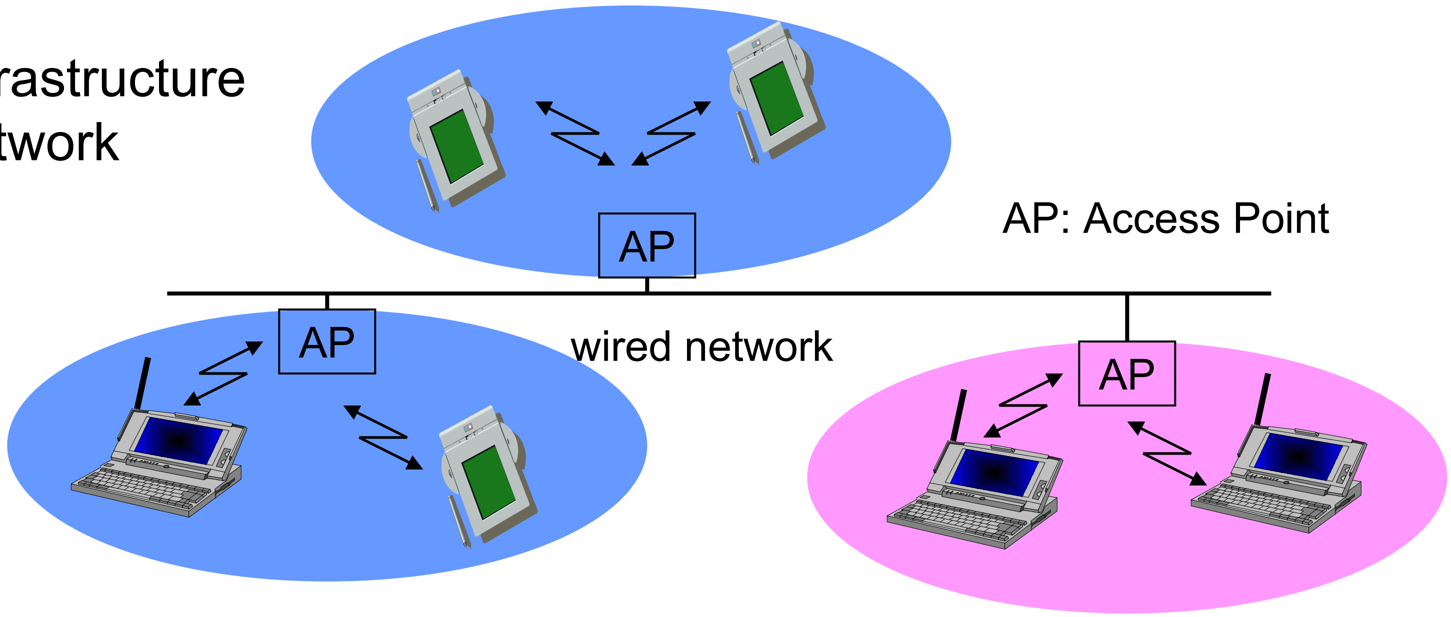
Wireless LAN 802.11: Characteristics

- \+ Very flexible (economical to scale)
- \+ Ad-hoc networks without planning possible
- \+ (Almost) no wiring difficulties (e.g. historic buildings, firewalls)
- \+ More robust against disasters or users pulling a plug

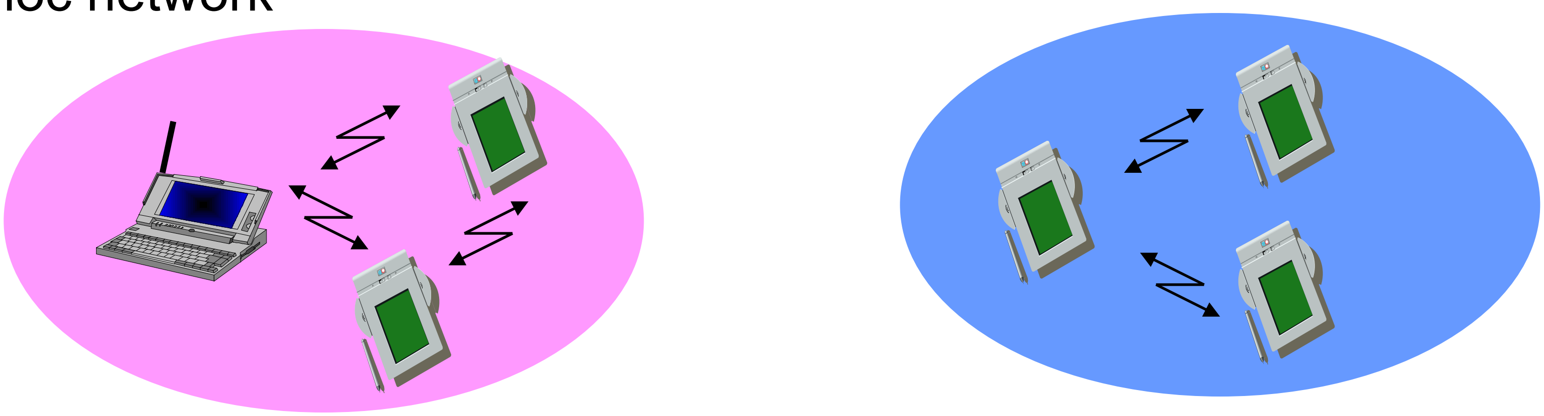
- – Low bandwidth compared to wired networks (10 vs. 100[0] Mbit/s)
- – Many proprietary solutions, especially for higher bit-rates, standards take their time
- – Products have to follow many national restrictions if working wireless, it takes a long time to establish global solutions (IMT-2000)
- – Security
- – Economy

Infrastructure vs. ad-hoc networks

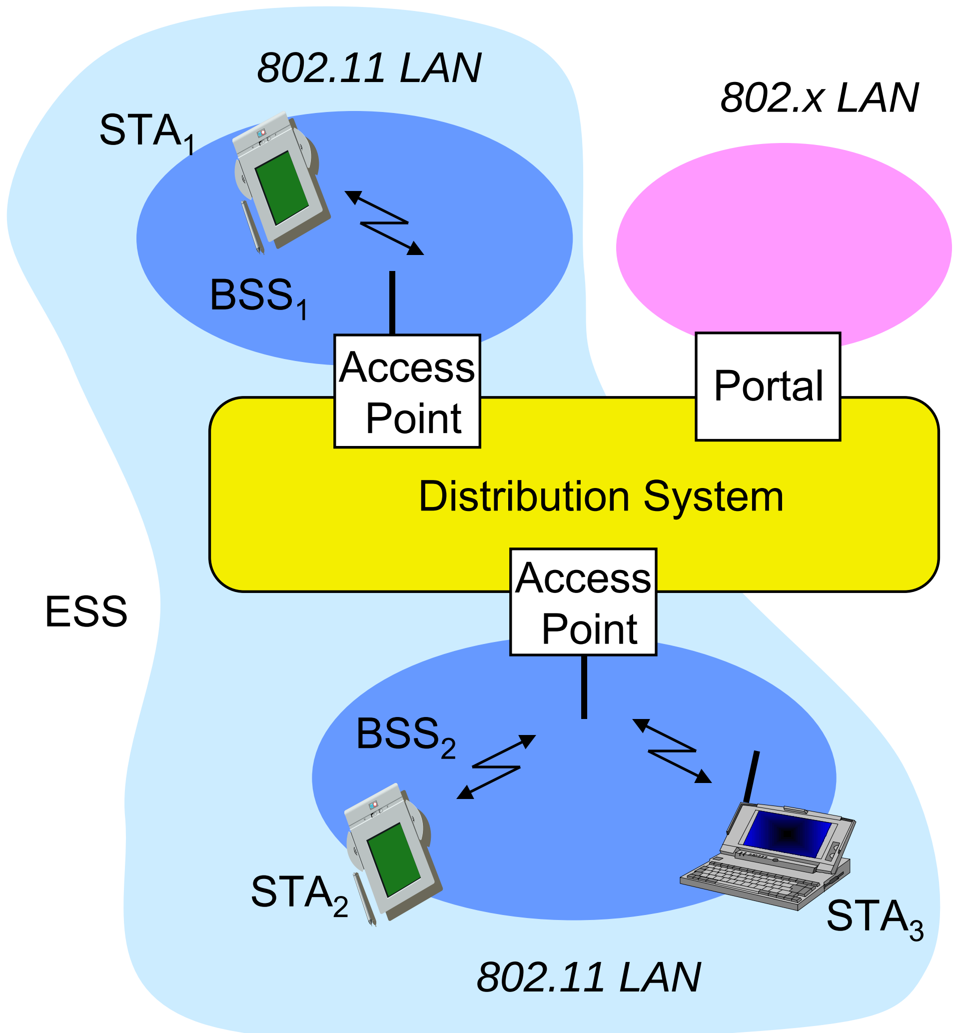
Infrastructure network



Ad-hoc network

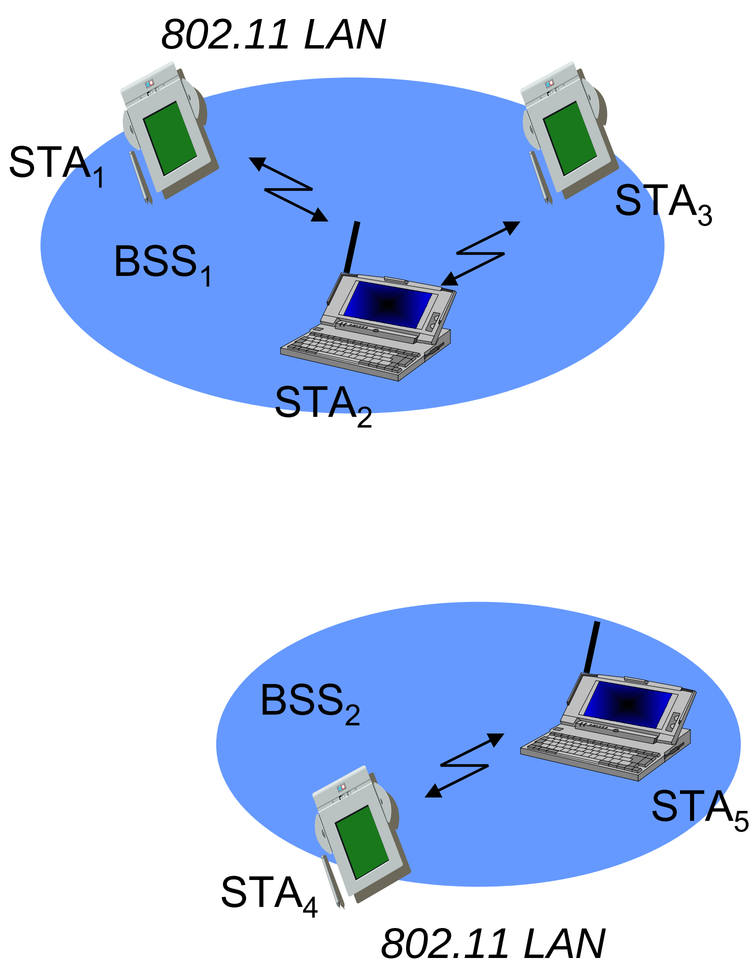


802.11 – Architecture of an infrastructure network



- Station (STA)
  - terminal with access mechanisms to the wireless medium and radio contact to the access point
- Basic Service Set (BSS)
  - group of stations using the same radio frequency
- Access Point
  - station integrated into the wireless LAN and the distribution system
- Portal
  - bridge to other (wired) networks
- Distribution System
  - interconnection network to form one logical network (ESS: Extended Service Set) based on several BSS

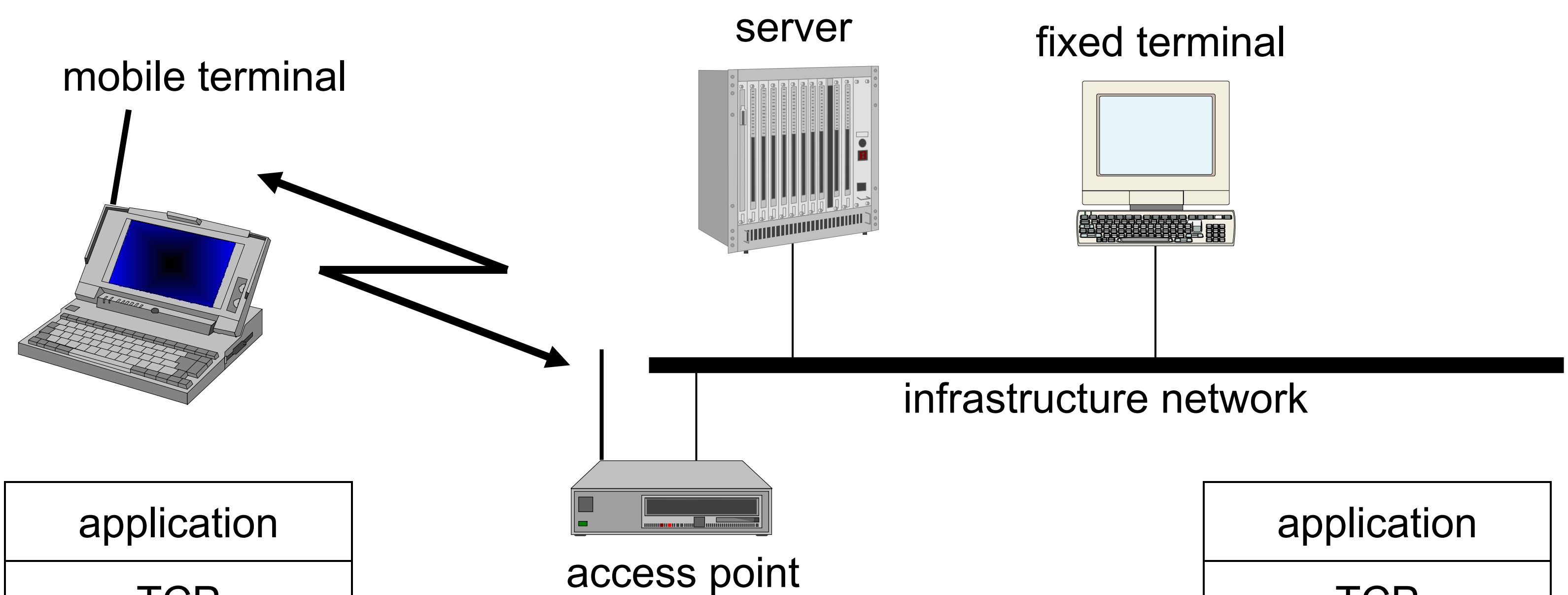
802.11 – Architecture of an ad-hoc network



- Direct communication within a limited range
  - Station (STA):
    terminal with access mechanisms to the wireless medium
  - [Independent] Basic Service Set ([I]BSS):
    group of stations using the same radio frequency

- You may use SDM or FDM to establish several BSS.

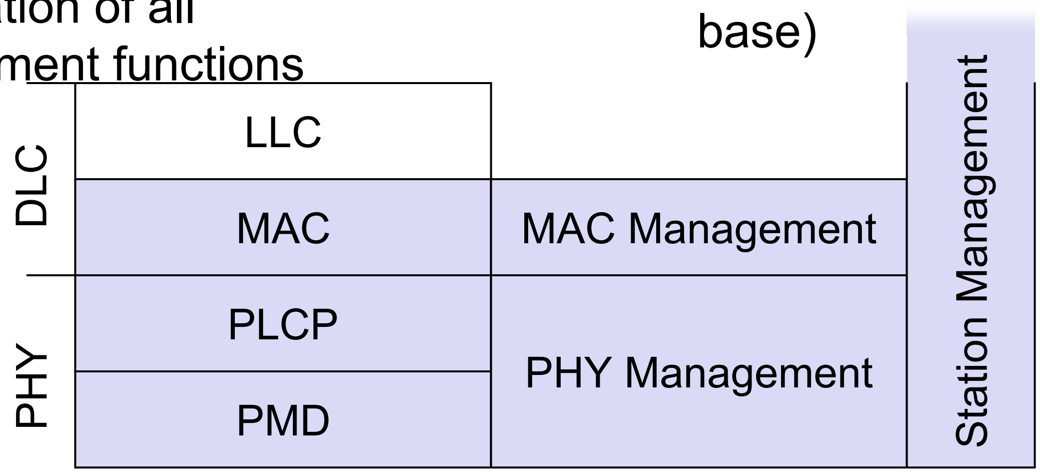
802.11 – Protocol architecture



mobile terminal	access point		fixed terminal
application			application
TCP			TCP
IP			IP
LLC	LLC		LLC
802.11 MAC	802.11 MAC	802.3 MAC	802.3 MAC
802.11 PHY	802.11 PHY	802.3 PHY	802.3 PHY

802.11 – The lower layers in detail

- PMD (Physical Medium Dependent)
  - modulation, coding
- PLCP (Physical Layer Convergence Protocol)
  - clear channel assessment signal (carrier sense)
- PHY Management
  - channel selection, PHY-MIB
- Station Management
  - coordination of all management functions
- MAC
  - access mechanisms
  - fragmentation
  - encryption
- MAC Management
  - Synchronization
  - roaming
  - power management
  - MIB (management information base)



Infrared vs. Radio transmission

Infrared

- uses IR diodes, diffuse light, multiple reflections (walls, furniture etc.)
- \+ simple, cheap, available in many mobile devices
- \+ no licenses needed
- \+ simple shielding possible
- – interference by sunlight, heat sources etc.
- – many things shield or absorb IR light
- – low bandwidth
- Example: IrDA (Infrared Data Association) interface available everywhere

Radio

- typically using the license free ISM band at 2.4 GHz
- \+ experience from wireless WAN and mobile phones can be used
- \+ coverage of larger areas possible (radio can penetrate walls, furniture etc.)
- – very limited license free frequency bands
- – shielding more difficult, interference with other electrical devices
- Examples: HIPERLAN, Bluetooth

802.11 - Physical layer (802.11legacy)

- 3 versions: 2 radio (2.4 GHz), 1 IR (outdated):

- FHSS (Frequency Hopping Spread Spectrum)
  - spreading, despreading, signal strength, 1 Mbit/s
  - at least 2.5 frequency hops/s, two-level GFSK modulation
- DSSS (Direct Sequence Spread Spectrum)
  - DBPSK modulation for 1 Mbit/s (Differential Binary Phase Shift Keying), DQPSK for 2 Mbit/s (Differential Quadrature PSK)
  - preamble and header of a frame is always transmitted with 1 Mbit/s, rest of transmission 2 (or optionally 1) Mbit/s
  - chipping sequence: Barker code (+ – + + – + + + – – –)
  - max. radiated power 1 W (USA), 100 mW (EU), min. 1mW
- Infrared
  - 850-950 nm, diffuse light,10 m range
  - carrier detection, energy detection, synchronization

DSSS PHY packet format

- Synchronization
  - synch., gain setting, energy detection, frequency offset compensation
- SFD (Start Frame Delimiter)
  - 1111001110100000
- Signal
  - data rate of the payload (0x0A: 1 Mbit/s DBPSK; 0x14: 2 Mbit/s DQPSK)
- Service (future use, 00: 802.11 compliant)
- Length (length of the payload)
- HEC (Header Error Check)
  - protection of signal, service and length, $x^{16}+x^{12}+x^5+1$

128	16	8	8	16	16	variable	bits
synchronization	SFD	signal	service	length	HEC	payload	

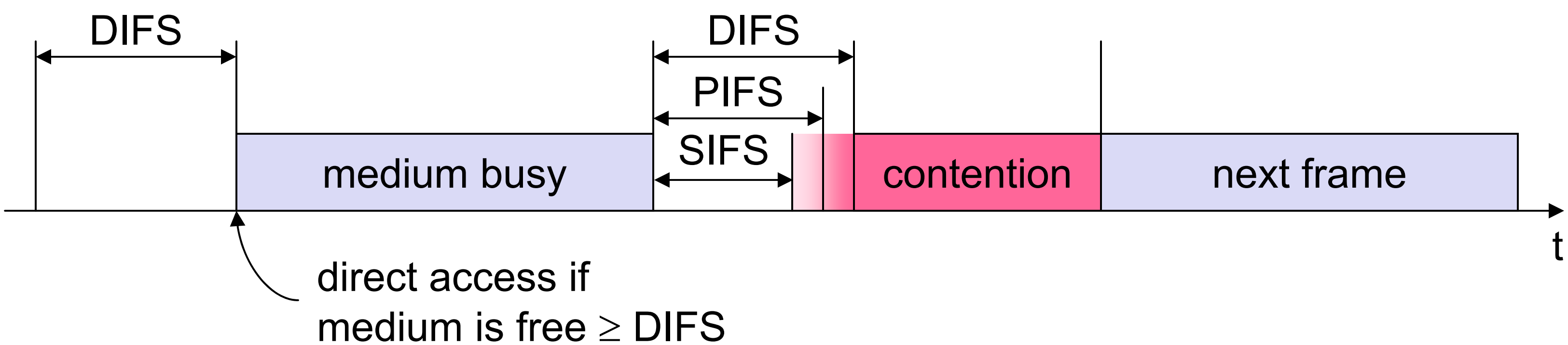
PLCP preamble (synchronization, SFD) — PLCP header (signal, service, length, HEC)

MAC layer: DFWMAC

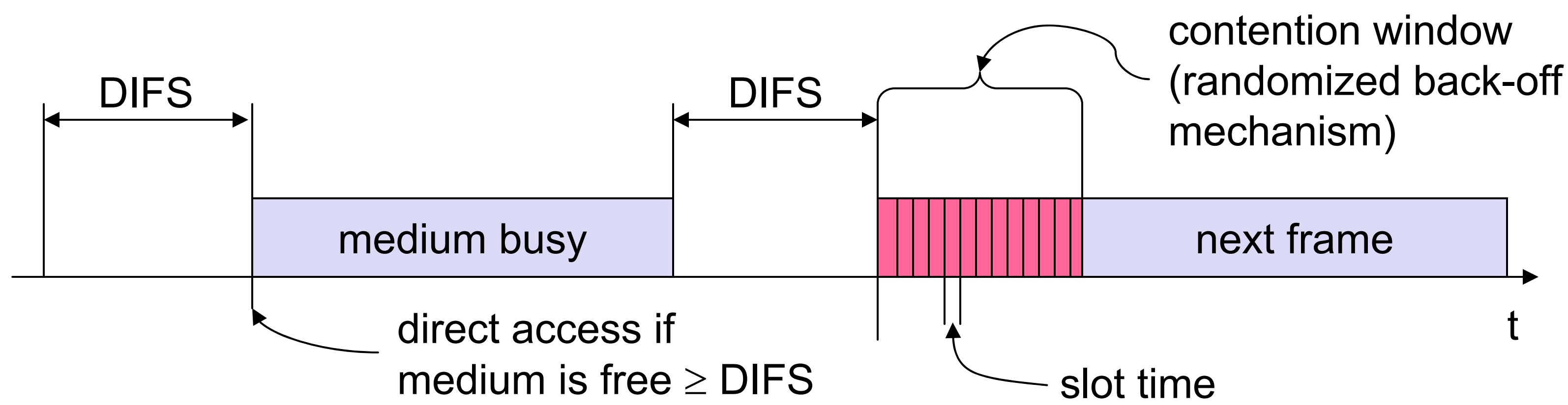
- Traffic services
  - Asynchronous Data Service (mandatory)
    - exchange of data packets based on “best-effort”
    - support of broadcast and multicast
  - Time-Bounded Service (optional)
    - implemented using PCF (Point Coordination Function)
- Access methods
  - DFWMAC-DCF CSMA/CA (mandatory)
    - collision avoidance via binary exponential back-off mechanism
    - minimum distance between consecutive packets
    - ACK packet for acknowledgements (not used for broadcasts)
  - DFWMAC-DCF w/ RTS/CTS (optional)
    - avoids hidden terminal problem
  - DFWMAC-PCF (optional)
    - access point polls terminals according to a list

MAC layer

- defined through different inter frame spaces
- no guaranteed, hard priorities
- SIFS (Short Inter Frame Spacing)
  – highest priority, for ACK, CTS, polling response
- PIFS (PCF IFS)
  – medium priority, for time-bounded service using PCF
- DIFS (DCF, Distributed Coordination Function IFS)
  – lowest priority, for asynchronous data service

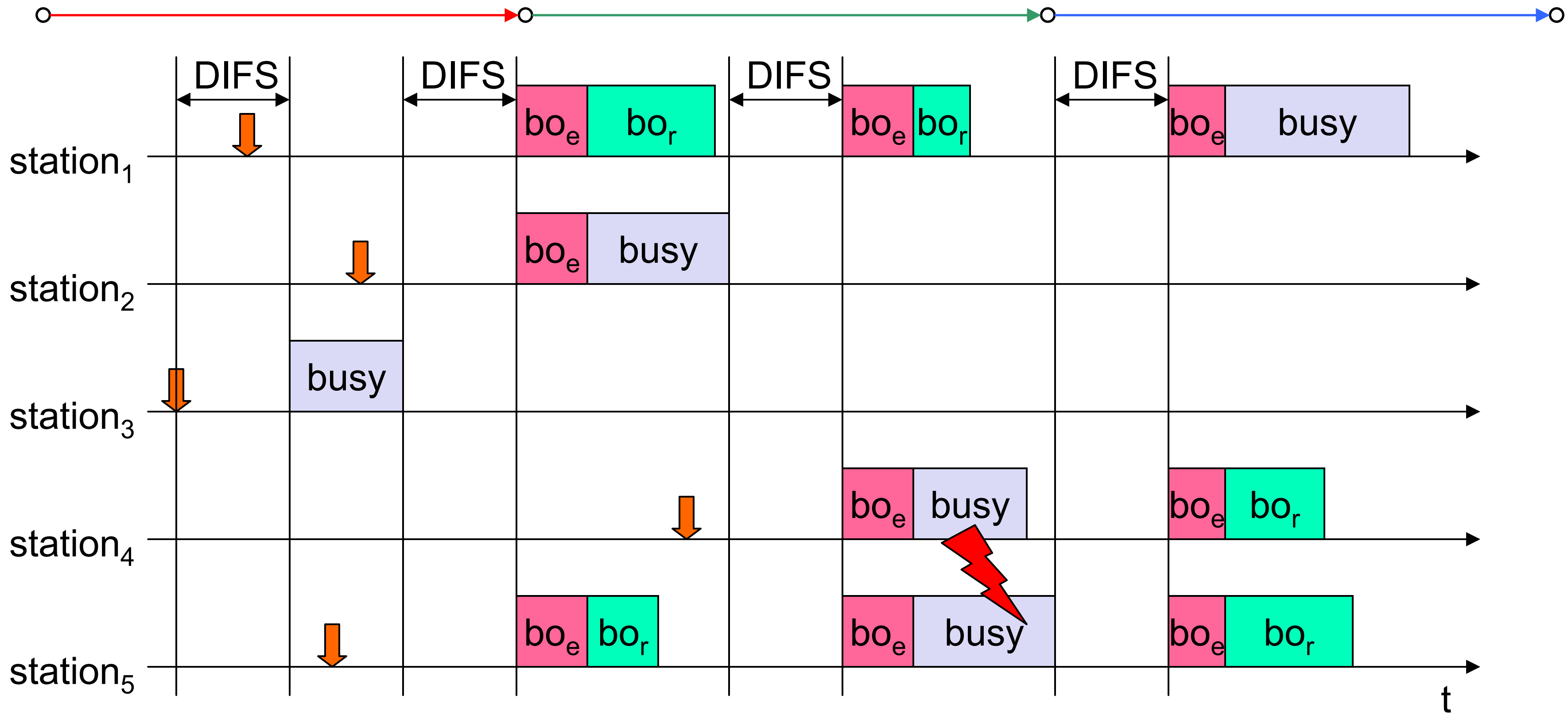


CSMA/CA



- station ready to send starts sensing the medium (Carrier Sense based on CCA, Clear Channel Assessment)
- if the medium is free for the duration of an Inter-Frame Space (IFS), the station can start sending (IFS depends on service type)
- if the medium is busy, the station has to wait for a free IFS, then the station must additionally wait a random back-off time (collision avoidance, multiple of slot-time)
- if another station occupies the medium during the back-off time of the station, the back-off timer stops (fairness)

Competing stations - simple example



busy medium not idle (frame, ack etc.)

packet arrival at MAC

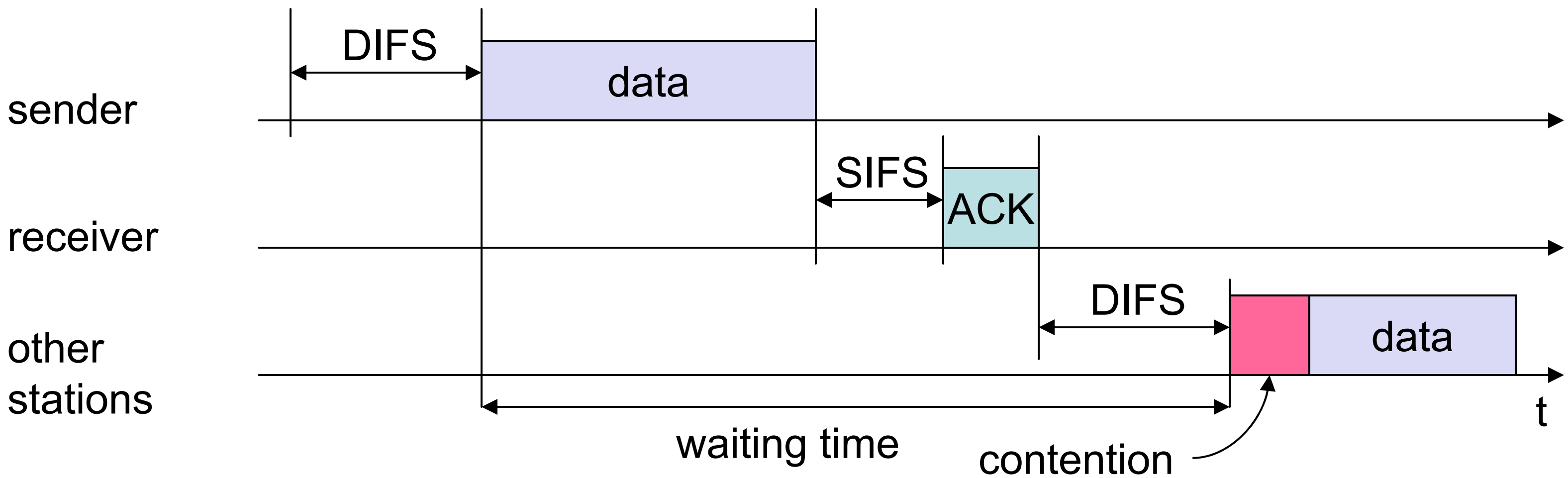
bo$_e$ elapsed backoff time

bo$_r$ residual backoff time

bo

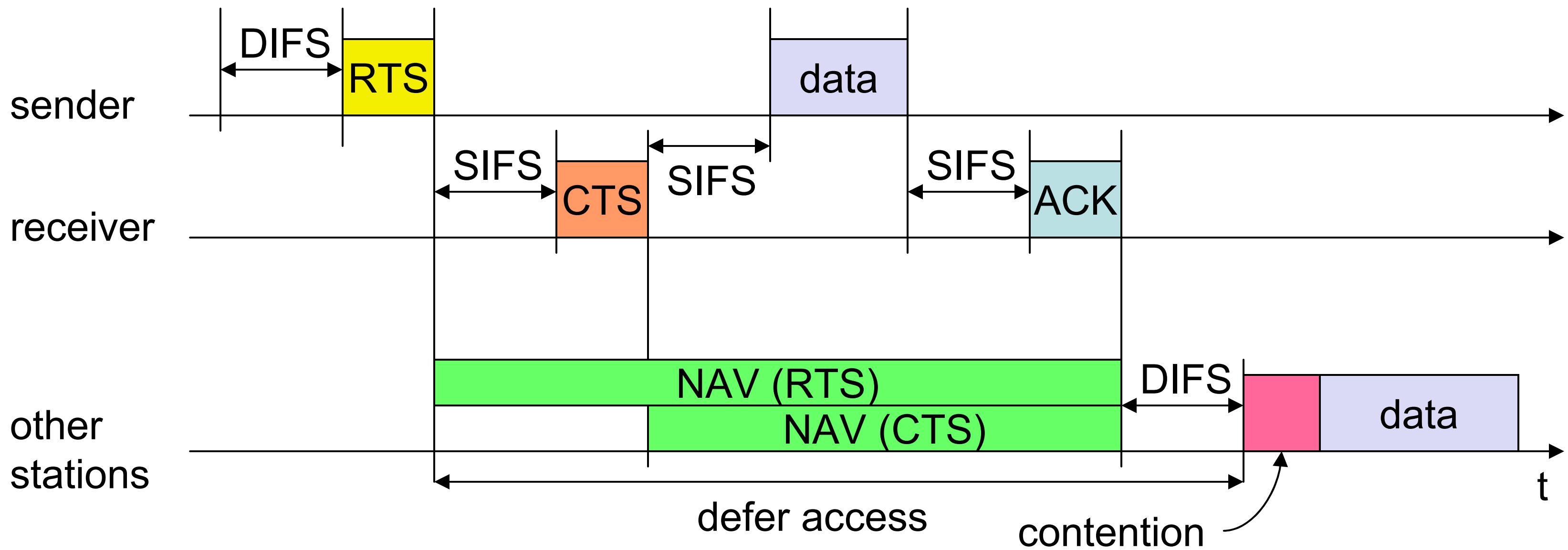
CSMA/CA 2

- Sending unicast packets
  - station has to wait for DIFS before sending data
  - receivers acknowledge at once (after waiting for SIFS) if the packet was received correctly (CRC)
  - automatic retransmission of data packets in case of transmission errors



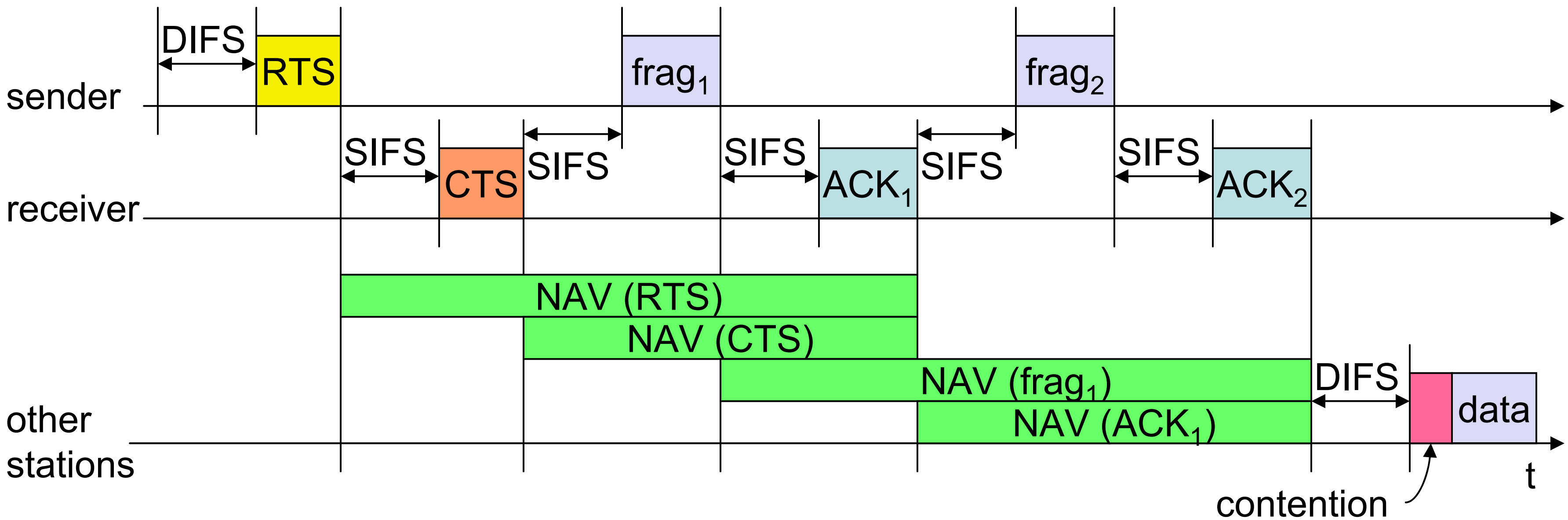
DFWMAC

- station can send RTS with reservation parameter after waiting for DIFS (reservation determines amount of time the data packet needs the medium)
- acknowledgement via CTS after SIFS by receiver (if ready to receive)
- sender can now send data at once, acknowledgement via ACK
- other stations store medium reservations distributed via RTS and CTS



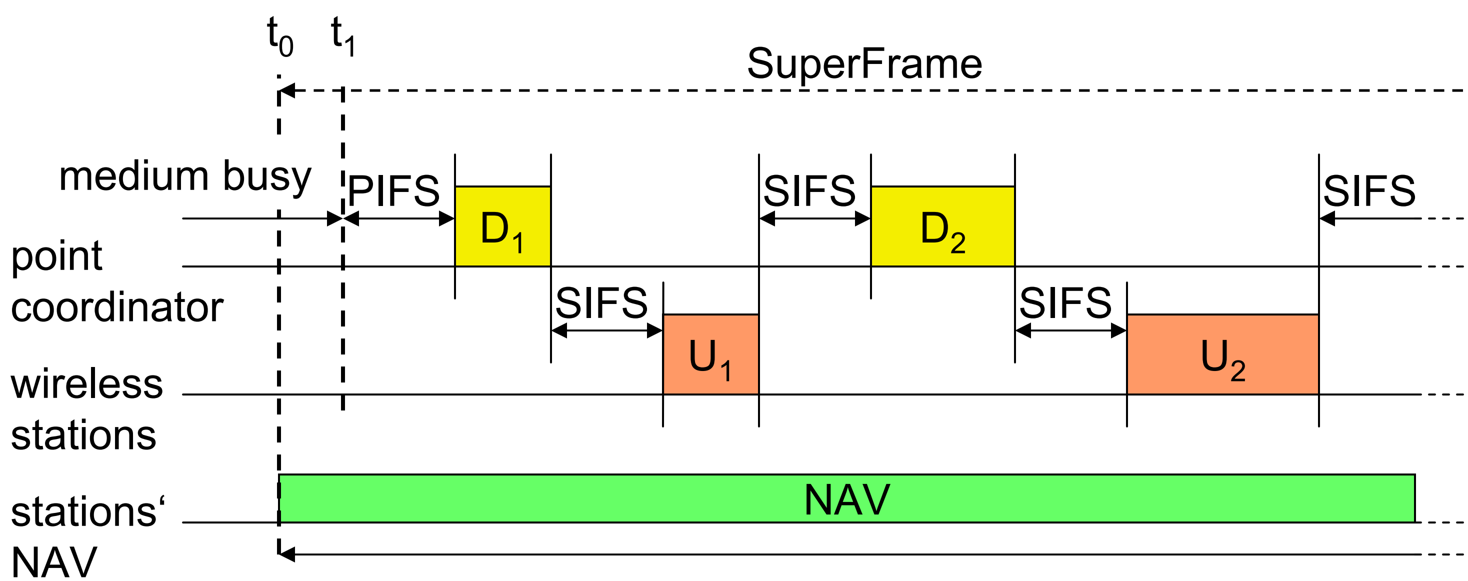
Fragmentation

- If packet gets too long transmission error probability grows
- A simple back of the envelope calculation determines the optimal fragment size

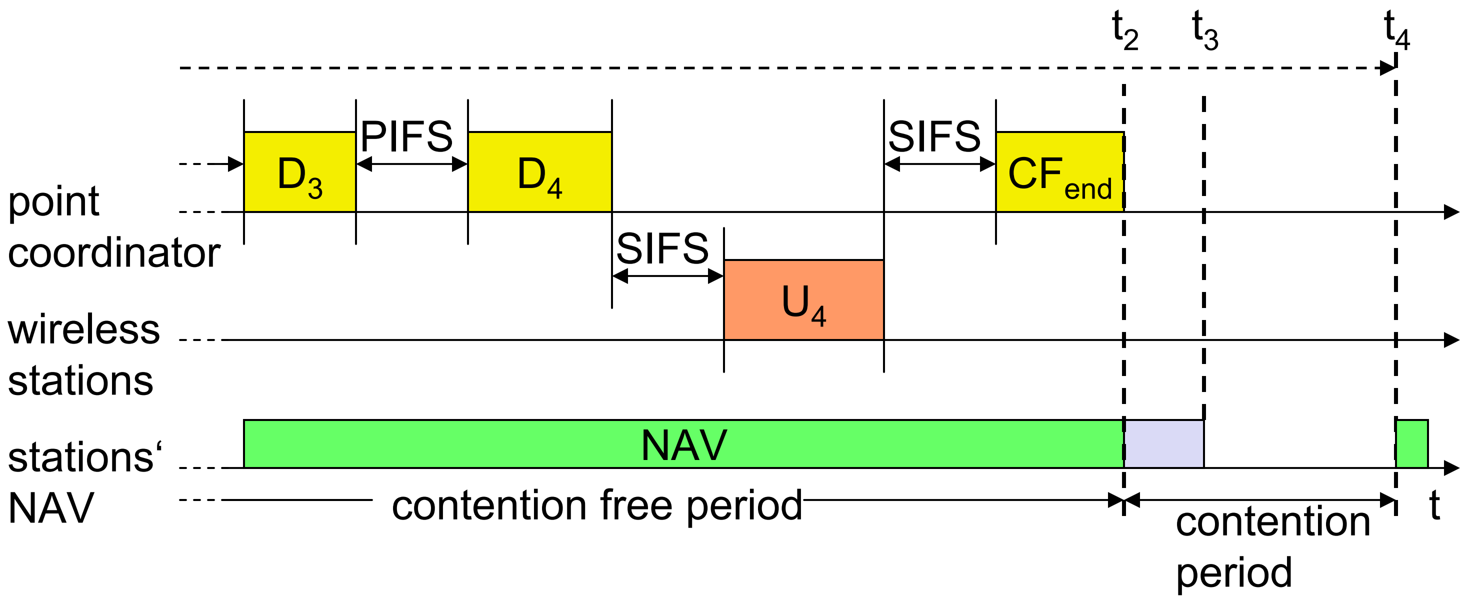


DFWMAC-PCF

- An access point can poll stations



DFWMAC-PCF 2



t2
t3
t4
D3
PIFS
D4
SIFS
CFend
point
coordinator
SIFS
U4
wireless
stations
stations‘
NAV
NAV
contention free period
contention
period
t

Frame format

2	2	6	6	6	2	6	0-2312	4 bytes
Frame Control	Duration ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Data	CRC

Byte 1: version, type, subtype
Byte 2: two DS-bits, fragm., retry, power man., more data, WEP, order

- Type
  - control frame, management frame, data frame
- Sequence control
  - important against duplicated frames due to lost ACKs
- Addresses
  - receiver, transmitter (physical), BSS identifier, sender (logical)
- Miscellaneous
  - sending time, checksum, frame control, data

MAC address format

scenario	to DS	from DS	address 1	address 2	address 3	address 4
ad-hoc network	0	0	DA	SA	BSSID	-
infrastructure network, from AP	0	1	DA	BSSID	SA	-
infrastructure network, to AP	1	0	BSSID	SA	DA	-
infrastructure network, within DS	1	1	RA	TA	DA	SA

DS: Distribution System
AP: Access Point
DA: Destination Address
SA: Source Address
BSSID: Basic Service Set Identifier
RA: Receiver Address
TA: Transmitter Address

Special Frames: ACK, RTS, CTS

- Acknowledgement

	bytes	2	2	6	4
ACK		Frame Control	Duration	Receiver Address	CRC

- Request To Send

	bytes	2	2	6	6	4
RTS		Frame Control	Duration	Receiver Address	Transmitter Address	CRC

- Clear To Send

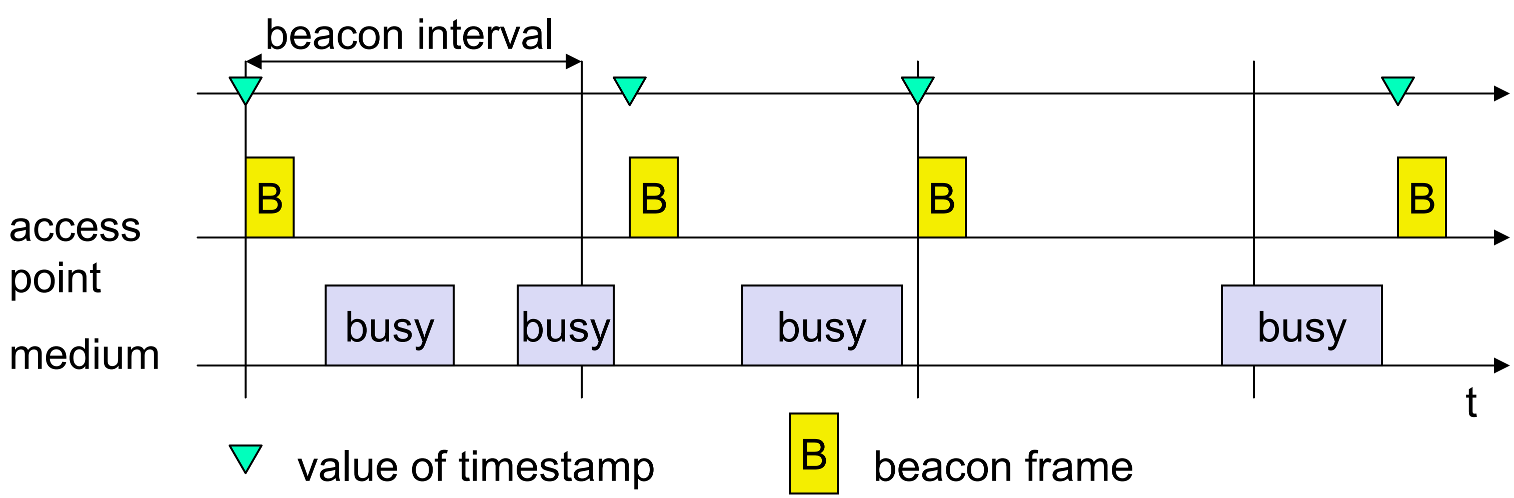
	bytes	2	2	6	4
CTS		Frame Control	Duration	Receiver Address	CRC

MAC management

- Synchronization
  - try to find a LAN, try to stay within a LAN
  - timer etc.
- Power management
  - sleep-mode without missing a message
  - periodic sleep, frame buffering, traffic measurements
- Association/Reassociation
  - integration into a LAN
  - roaming, i.e. change networks by changing access points
  - scanning, i.e. active search for a network
- MIB - Management Information Base
  - managing, read, write

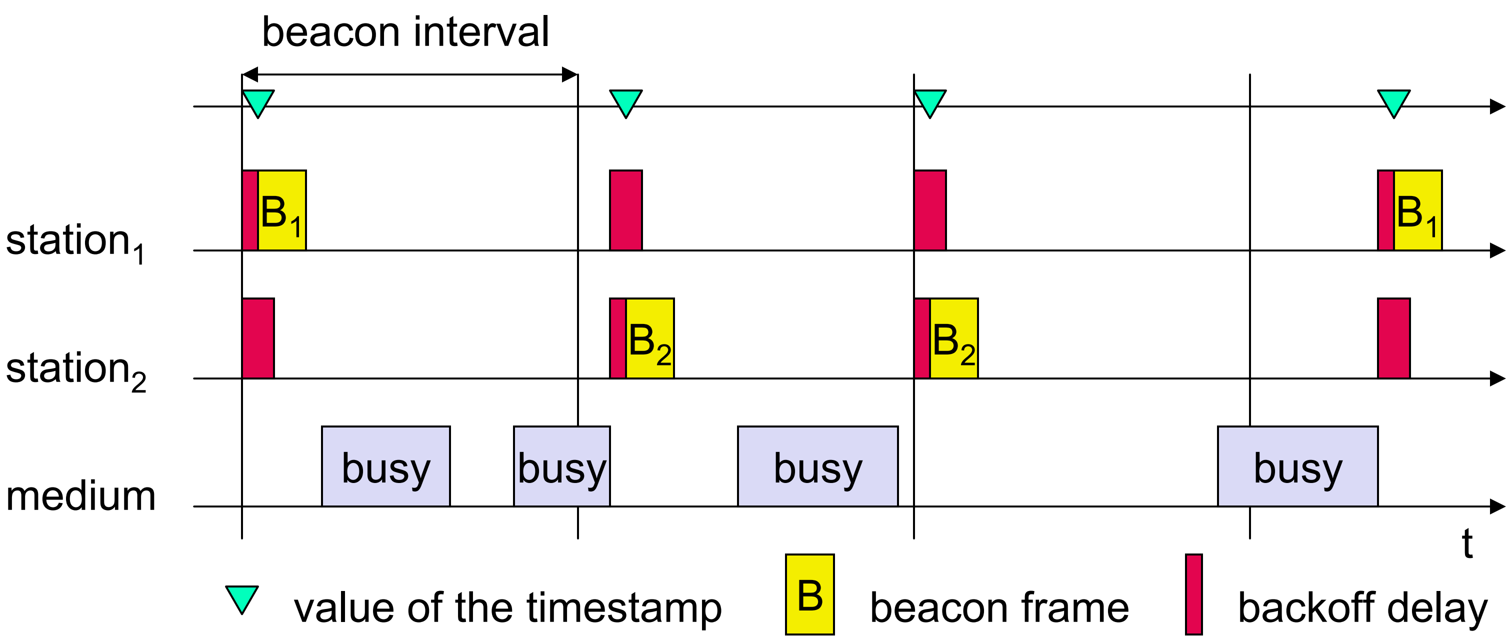
Synchronization

- In an infrastructure network, the access point can send a beacon



Synchronization

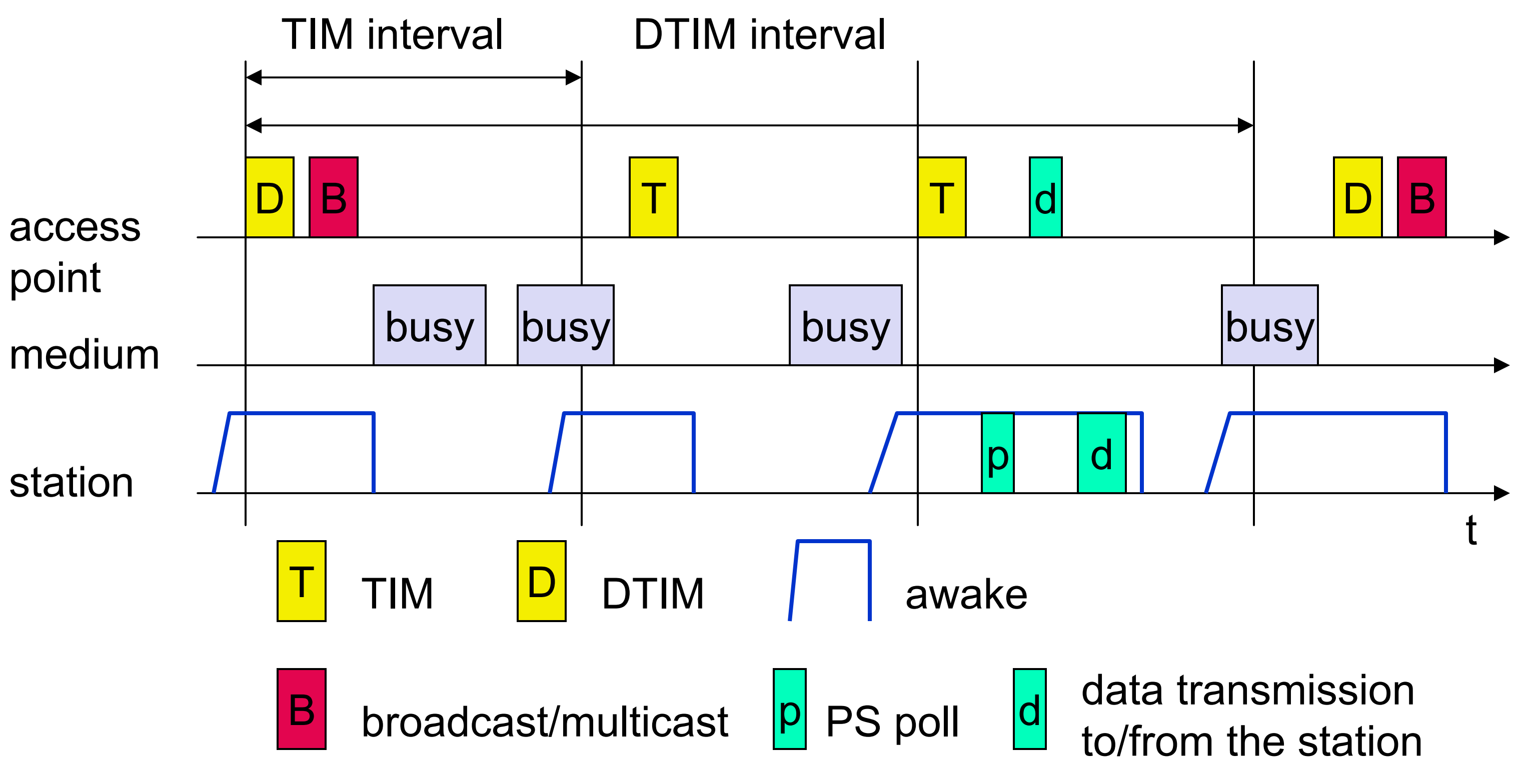
- In an ad-hoc network, the beacon has to be sent by any station



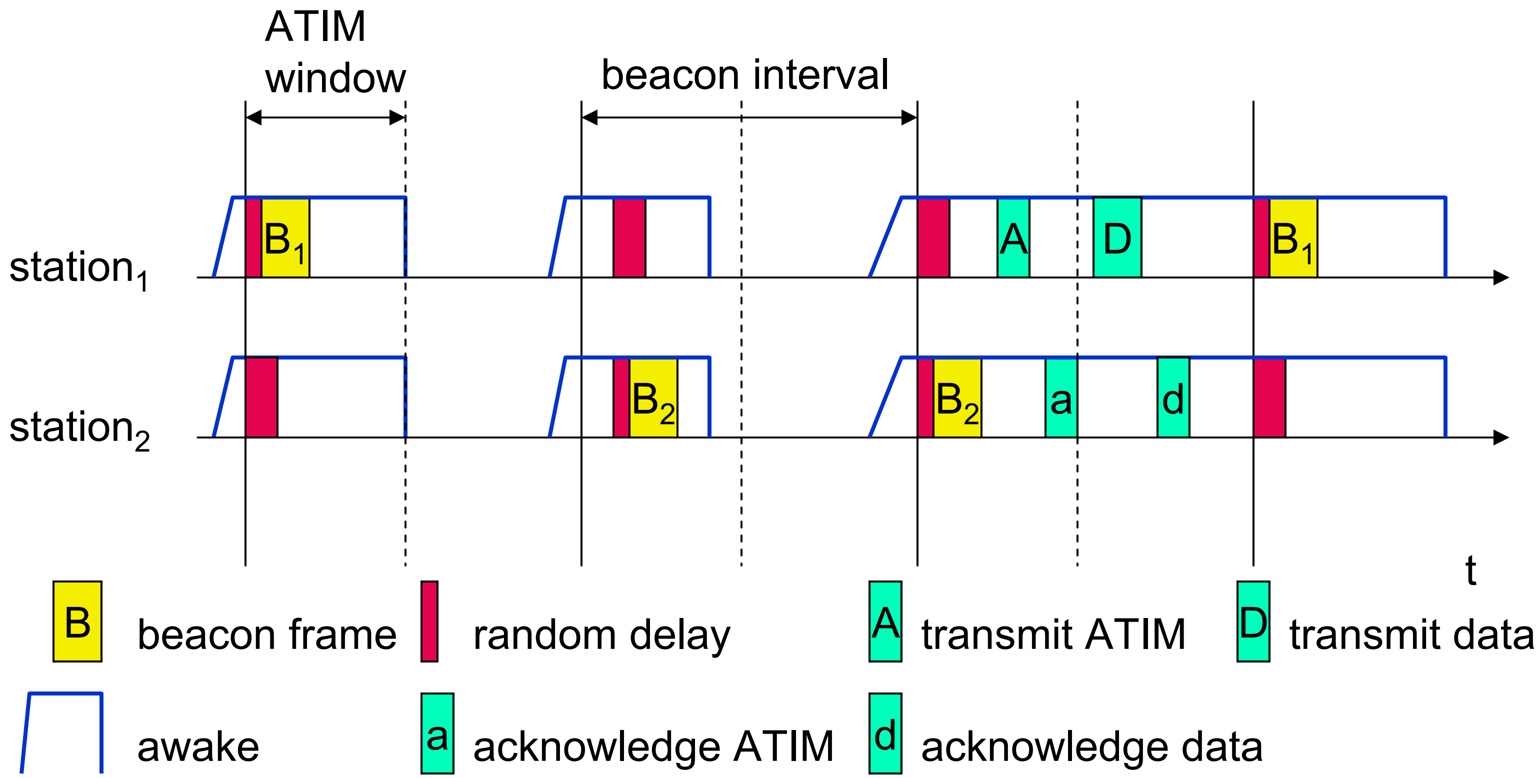
Power management

- Idea: if not needed turn off the transceiver
- States of a station: sleep and awake
- Timing Synchronization Function (TSF)
  - stations wake up at the same time
- Infrastructure
  - Traffic Indication Map (TIM)
    - list of unicast receivers transmitted by AP
  - Delivery Traffic Indication Map (DTIM)
    - list of broadcast/multicast receivers transmitted by AP
- Ad-hoc
  - Ad-hoc Traffic Indication Map (ATIM)
    - announcement of receivers by stations buffering frames
    - more complicated - no central AP
    - collision of ATIMs possible (scalability?)

Power saving with wake-up patterns (infrastructure)



Power saving with wake-up patterns (ad-hoc)



Roaming

- No or bad connection? Then perform:
- Scanning
  - scan the environment, i.e., listen into the medium for beacon signals or send probes into the medium and wait for an answer
- Reassociation Request
  - station sends a request to one or several AP(s)
- Reassociation Response
  - success: AP has answered, station can now participate
  - failure: continue scanning
- AP accepts reassociation request
  - signal the new station to the distribution system
  - the distribution system updates its data base (i.e., location information)
  - typically, the distribution system now informs the old AP so it can release resources

Mobile Communication Technology according to IEEE

Local wireless networks
WLAN 802.11

WiFi

- 802.11a → 802.11h
- 802.11b → 802.11g
- 802.11i/e/…/w

Personal wireless nw
WPAN 802.15

ZigBee

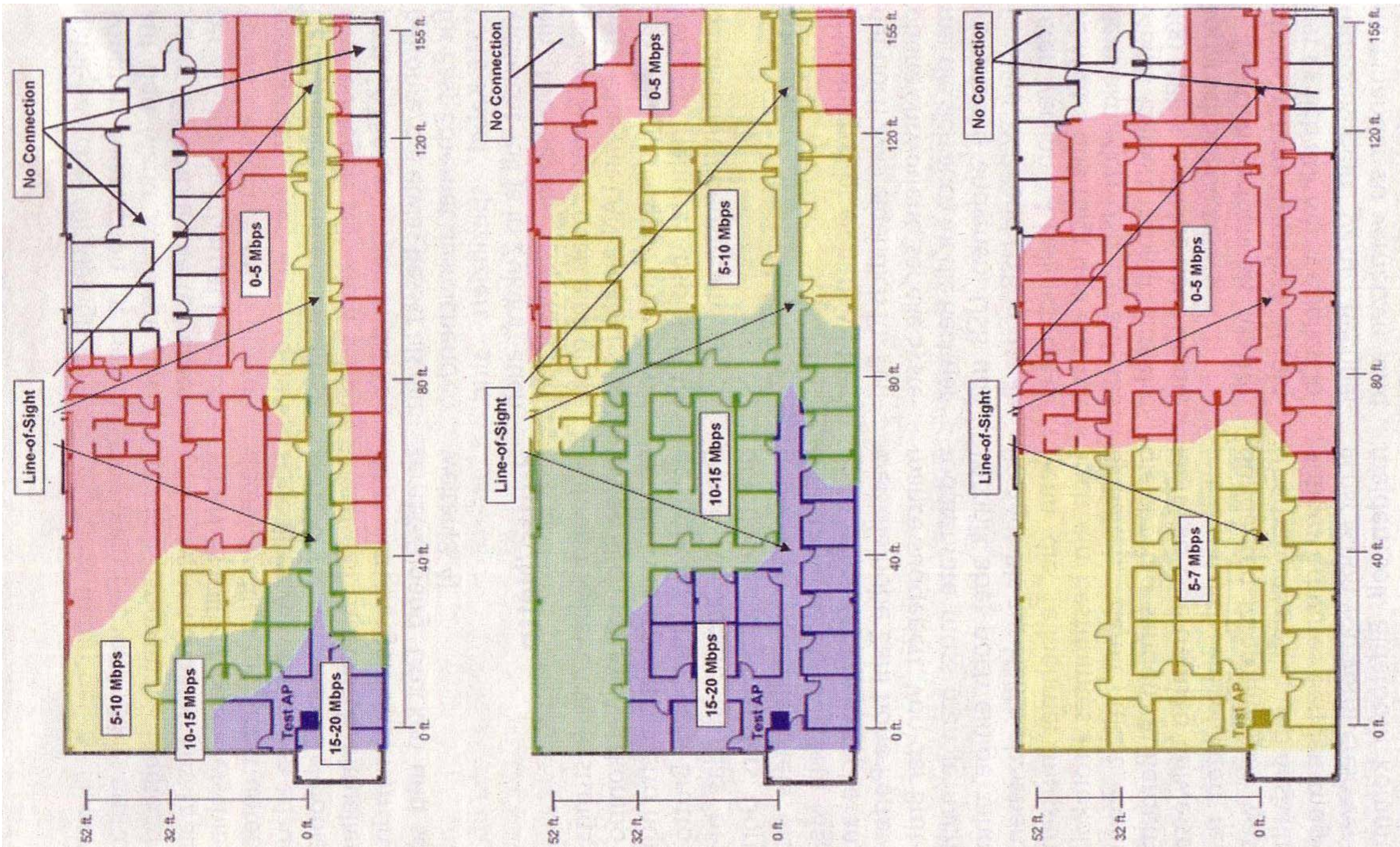
- 802.15.4 → 802.15.4a/b
- 802.15.5
- 802.15.3 → 802.15.3a/b
- 802.15.2
- 802.15.1 **Bluetooth**

Wireless distribution networks
WMAN 802.16 (Broadband Wireless Access) **WiMAX**

+ Mobility

→ 802.20 (Mobile Broadband Wireless Access)

Quiz: Which 802.11 standard?



WLAN: IEEE 802.11 – future developments (03/2005)

- 802.11c: Bridge Support
  - Definition of MAC procedures to support bridges as extension to 802.1D
- 802.11d: Regulatory Domain Update
  - Support of additional regulations related to channel selection, hopping sequences
- 802.11e: MAC Enhancements – QoS
  - Enhance the current 802.11 MAC to expand support for applications with Quality of Service requirements, and in the capabilities and efficiency of the protocol
  - Definition of a data flow (“connection”) with parameters like rate, burst, period…
  - Additional energy saving mechanisms and more efficient retransmission
- 802.11f: Inter-Access Point Protocol
  - Establish an Inter-Access Point Protocol for data exchange via the distribution system
  - Currently unclear to which extend manufacturers will follow this suggestion
- 802.11g: Data Rates > 20 Mbit/s at 2.4 GHz; 54 Mbit/s, OFDM
  - Successful successor of 802.11b, performance loss during mixed operation with 11b
- 802.11h: Spectrum Managed 802.11a
  - Extension for operation of 802.11a in Europe by mechanisms like channel measurement for dynamic channel selection (DFS, Dynamic Frequency Selection) and power control (TPC, Transmit Power Control)

WLAN: IEEE 802.11– future developments (03/2005)

- 802.11i: Enhanced Security Mechanisms
  - Enhance the current 802.11 MAC to provide improvements in security.
  - TKIP enhances the insecure WEP, but remains compatible to older WEP systems
  - AES provides a secure encryption method and is based on new hardware
- 802.11j: Extensions for operations in Japan
  - Changes of 802.11a for operation at 5GHz in Japan using only half the channel width at larger range
- 802.11k: Methods for channel measurements
  - Devices and access points should be able to estimate channel quality in order to be able to choose a better access point of channel
- 802.11m: Updates of the 802.11 standards
- 802.11n: Higher data rates above 100Mbit/s
  - Changes of PHY and MAC with the goal of 100Mbit/s at MAC SAP
  - MIMO antennas (Multiple Input Multiple Output), up to 600Mbit/s are currently feasible
  - However, still a large overhead due to protocol headers and inefficient mechanisms
- 802.11p: Inter car communications
  - Communication between cars/road side and cars/cars
  - Planned for relative speeds of min. 200km/h and ranges over 1000m
  - Usage of 5.850-5.925GHz band in North America

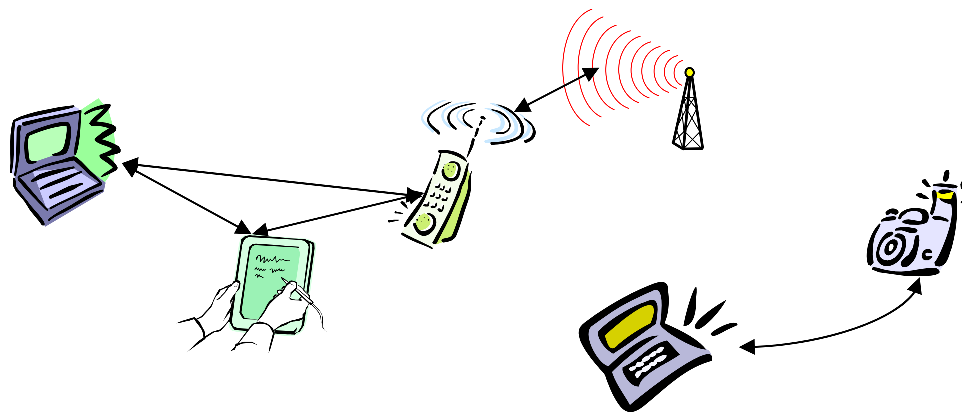
WLAN: IEEE 802.11– future developments (03/2005)

- 802.11r: Faster Handover between BSS
  - Secure, fast handover of a station from one AP to another within an ESS
  - Current mechanisms (even newer standards like 802.11i) plus incompatible devices from different vendors are massive problems for the use of, e.g., VoIP in WLANs
  - Handover should be feasible within 50ms in order to support multimedia applications efficiently
- 802.11s: Mesh Networking
  - Design of a self-configuring Wireless Distribution System (WDS) based on 802.11
  - Support of point-to-point and broadcast communication across several hops
- 802.11t: Performance evaluation of 802.11 networks
  - Standardization of performance measurement schemes
- 802.11u: Interworking with additional external networks
- 802.11v: Network management
  - Extensions of current management functions, channel measurements
  - Definition of a unified interface
- 802.11w: Securing of network control
  - Classical standards like 802.11, but also 802.11i protect only data frames, not the control frames. Thus, this standard should extend 802.11i in a way that, e.g., no control frames can be forged.

Bluetooth

- Idea
  - Universal radio interface for ad-hoc wireless connectivity
  - Interconnecting computer and peripherals, handheld devices, PDAs, cell phones – replacement of IrDA
  - Embedded in other devices, goal: 5€/device (2005: 40€/USB bluetooth)
  - Short range (10 m), low power consumption, license-free 2.45 GHz ISM
  - Voice and data transmission, approx. 1 Mbit/s gross data rate

One of the first modules (Ericsson).



Bluetooth

- History
  - 1994: Ericsson (Mattison/Haartsen), “MC-link” project
  - Renaming of the project: Bluetooth according to Harald “Blåtand” Gormsen [son of Gorm], King of Denmark in the 10th century
  - 1998: foundation of Bluetooth SIG, www.bluetooth.org
  - 1999: erection of a rune stone at Ercisson/Lund ;-)
  - 2001: first consumer products for mass market, spec. version 1.1 released

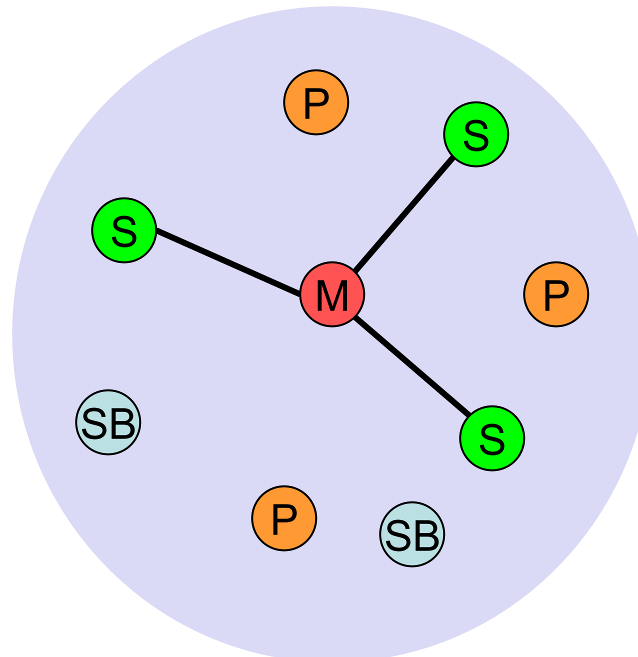
- Special Interest Group
  - Original founding members: Ericsson, Intel, IBM, Nokia, Toshiba
  - Added promoters: 3Com, Agere (was: Lucent), Microsoft, Motorola
  - > 2500 members
  - Common specification and certification of products

Characteristics

- 2.4 GHz ISM band, 79 RF channels, 1 MHz carrier spacing
  - Channel 0: 2402 MHz … channel 78: 2480 MHz
  - G-FSK modulation, 1-100 mW transmit power
- FHSS and TDD
  - Frequency hopping with 1600 hops/s
  - Hopping sequence in a pseudo random fashion, determined by a master
  - Time division duplex for send/receive separation
- Voice link – SCO (Synchronous Connection Oriented)
  - FEC (forward error correction), no retransmission, 64 kbit/s duplex, point-to-point, circuit switched
- Data link – ACL (Asynchronous ConnectionLess)
  - Asynchronous, fast acknowledge, point-to-multipoint, up to 433.9 kbit/s symmetric or 723.2/57.6 kbit/s asymmetric, packet switched
- Topology
  - Overlapping piconets (stars) forming a scatternet

Piconet

- Collection of devices connected in an ad hoc fashion
- One unit acts as master and the others as slaves for the lifetime of the piconet
- Master determines hopping pattern, slaves have to synchronize
- Each piconet has a unique hopping pattern
- Participation in a piconet = synchronization to hopping sequence
- Each piconet has one master and up to 7 simultaneous slaves (> 200 could be parked)

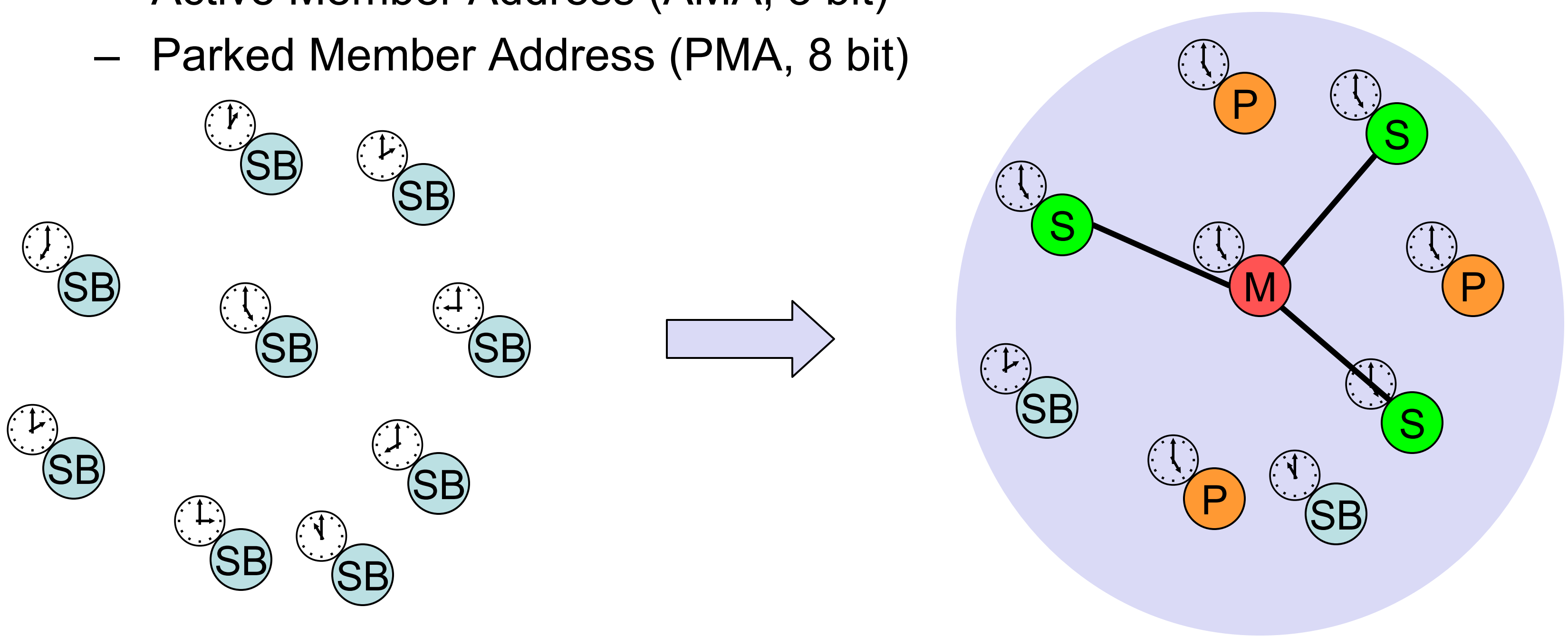


M=Master
S=Slave

P=Parked
SB=Standby

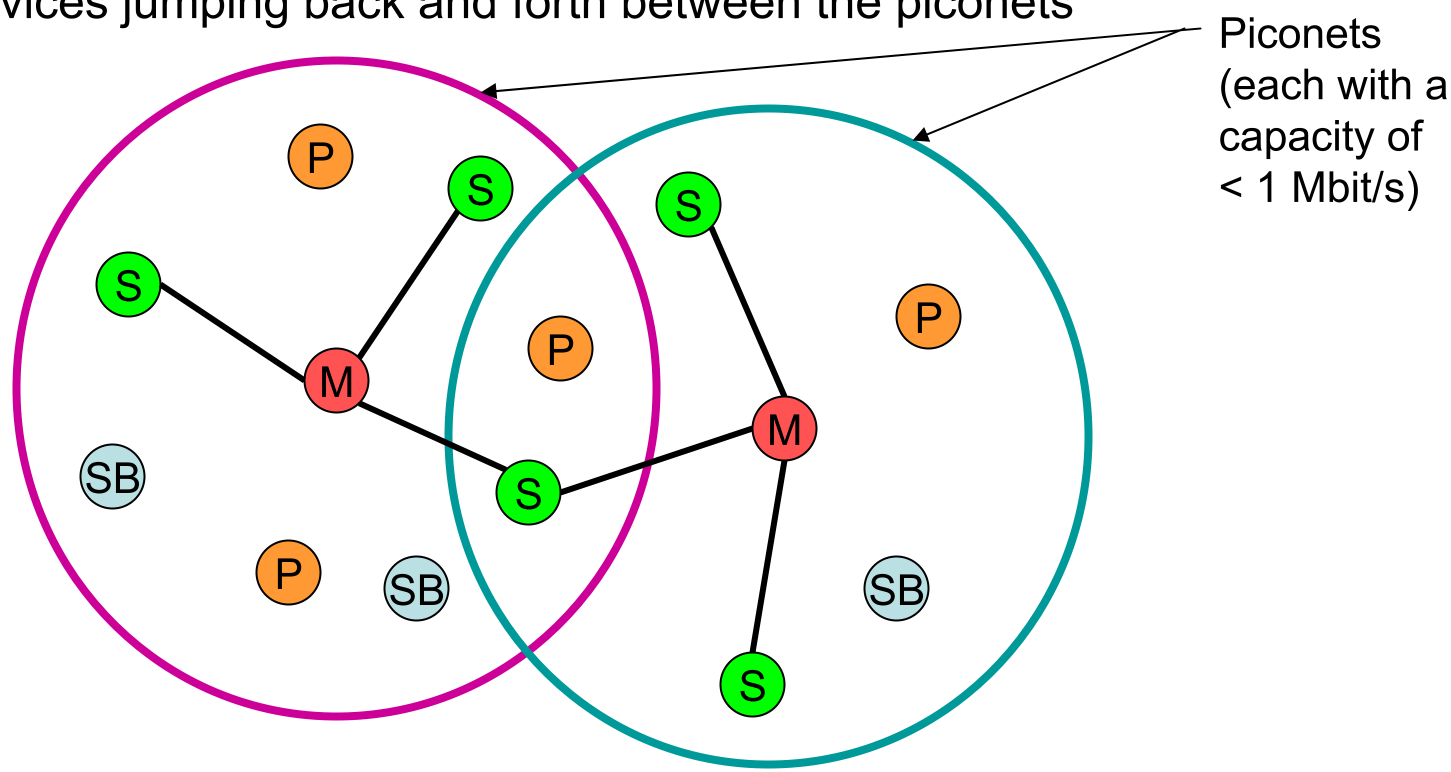
Forming a piconet

- All devices in a piconet hop together
  - Master gives slaves its clock and device ID
    - Hopping pattern: determined by device ID (48 bit, unique worldwide)
    - Phase in hopping pattern determined by clock
- Addressing
  - Active Member Address (AMA, 3 bit)
  - Parked Member Address (PMA, 8 bit)



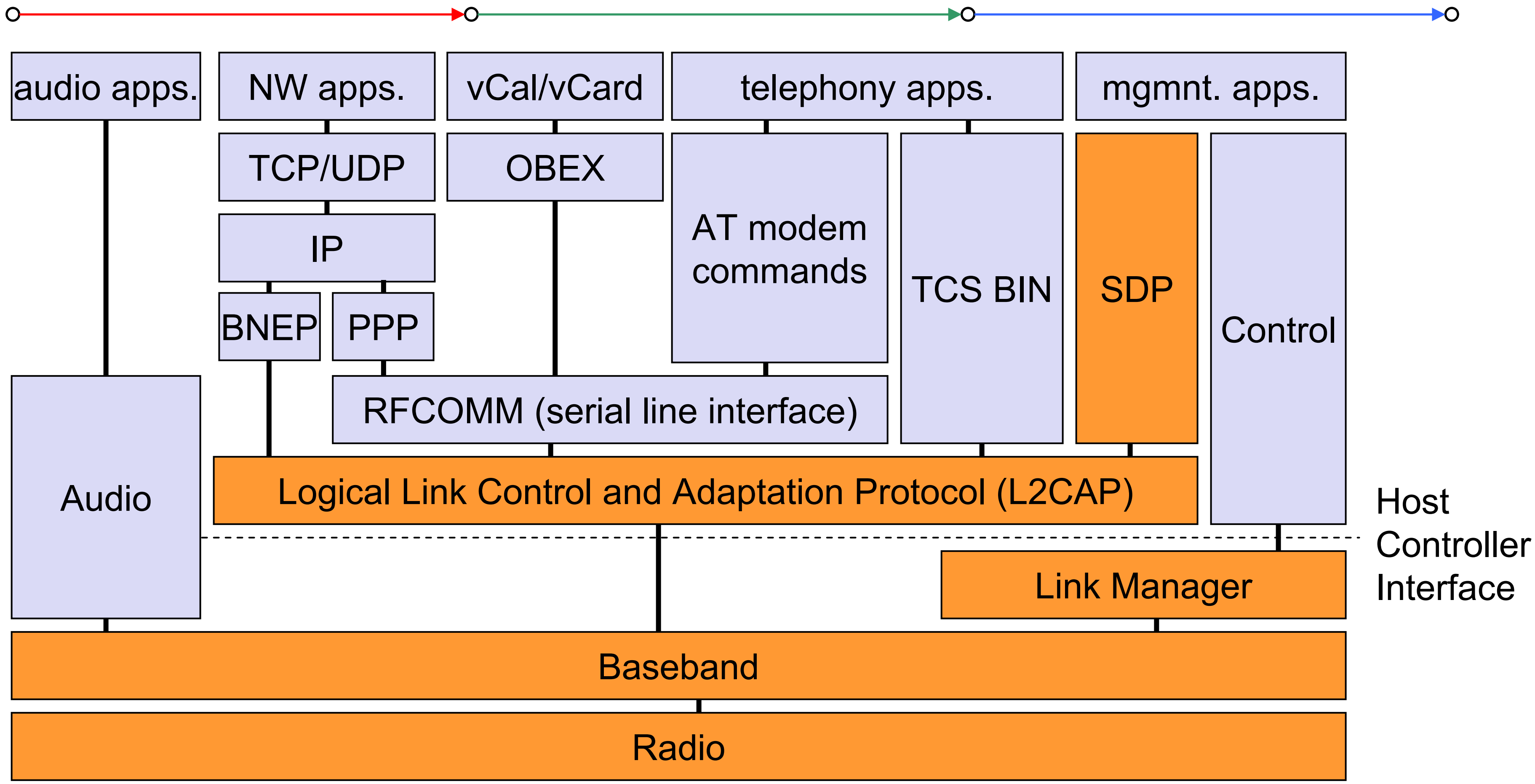
Scatternet

- Linking of multiple co-located piconets through the sharing of common master or slave devices
  - Devices can be slave in one piconet and master of another
- Communication between piconets
  - Devices jumping back and forth between the piconets



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

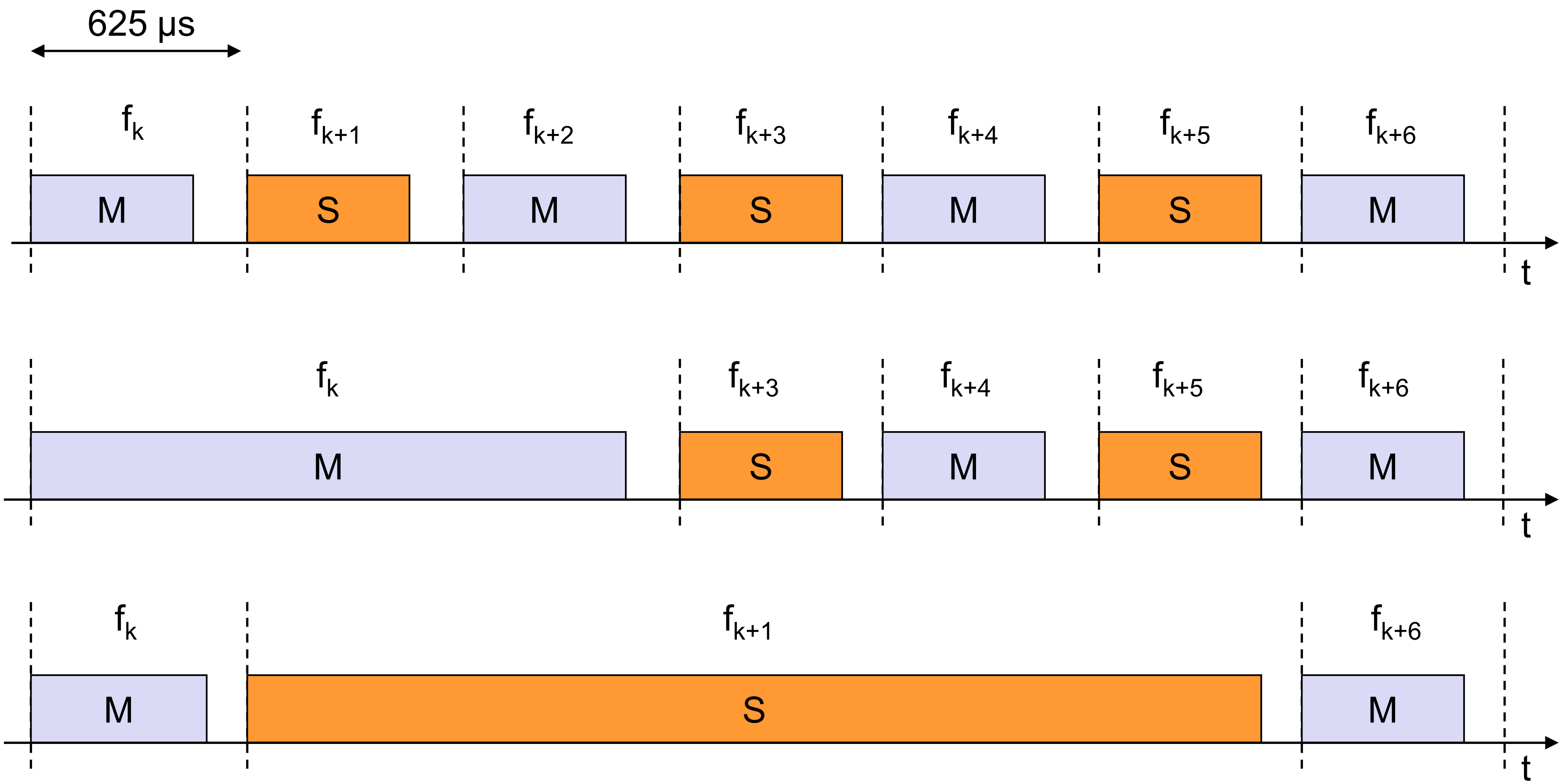
Bluetooth protocol stack



AT: attention sequence
OBEX: object exchange
TCS BIN: telephony control protocol specification – binary
BNEP: Bluetooth network encapsulation protocol

SDP: service discovery protocol
RFCOMM: radio frequency comm.

Frequency selection during data transmission



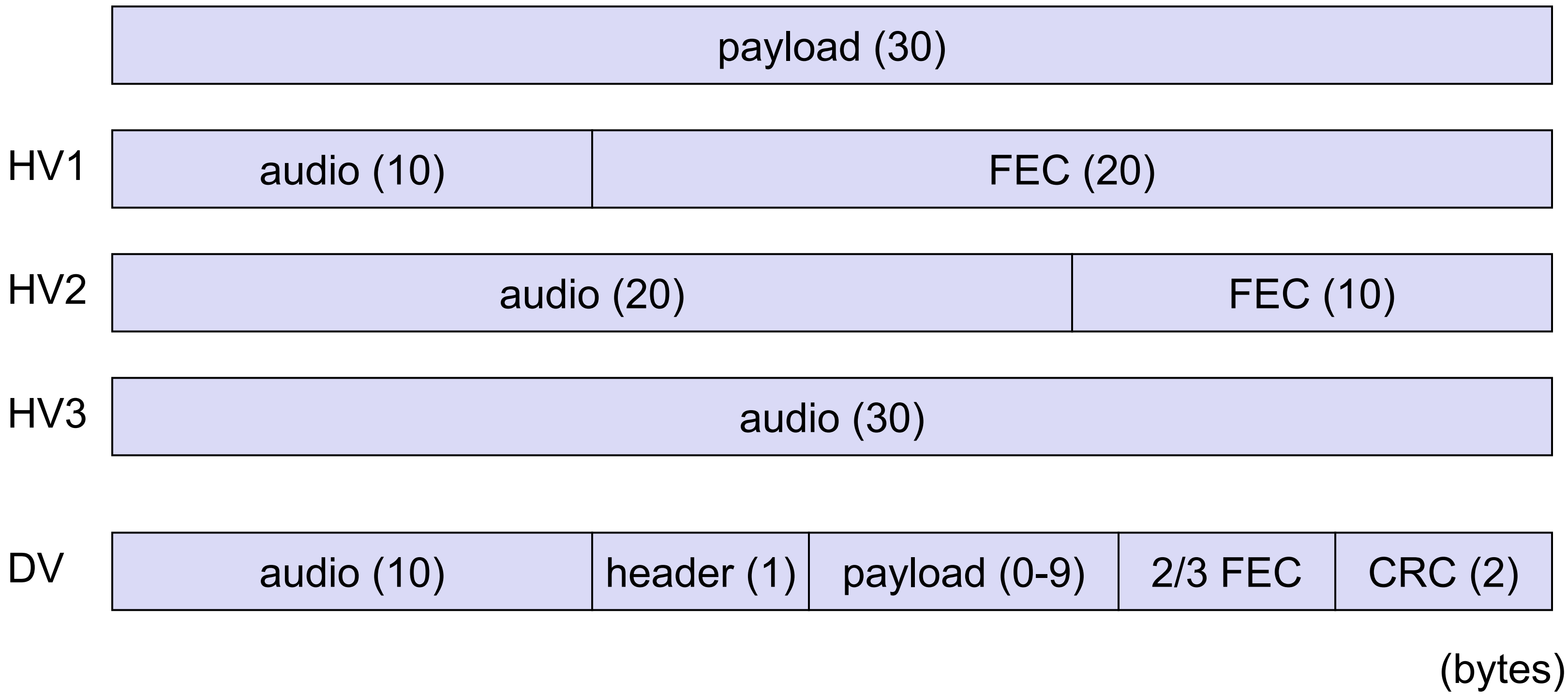
Baseband

- Piconet/channel definition
- Low-level packet definition
  - Access code
    - Channel, device access, e.g., derived from master
  - Packet header
    - 1/3-FEC, active member address (broadcast + 7 slaves), link type, alternating bit ARQ/SEQ, checksum

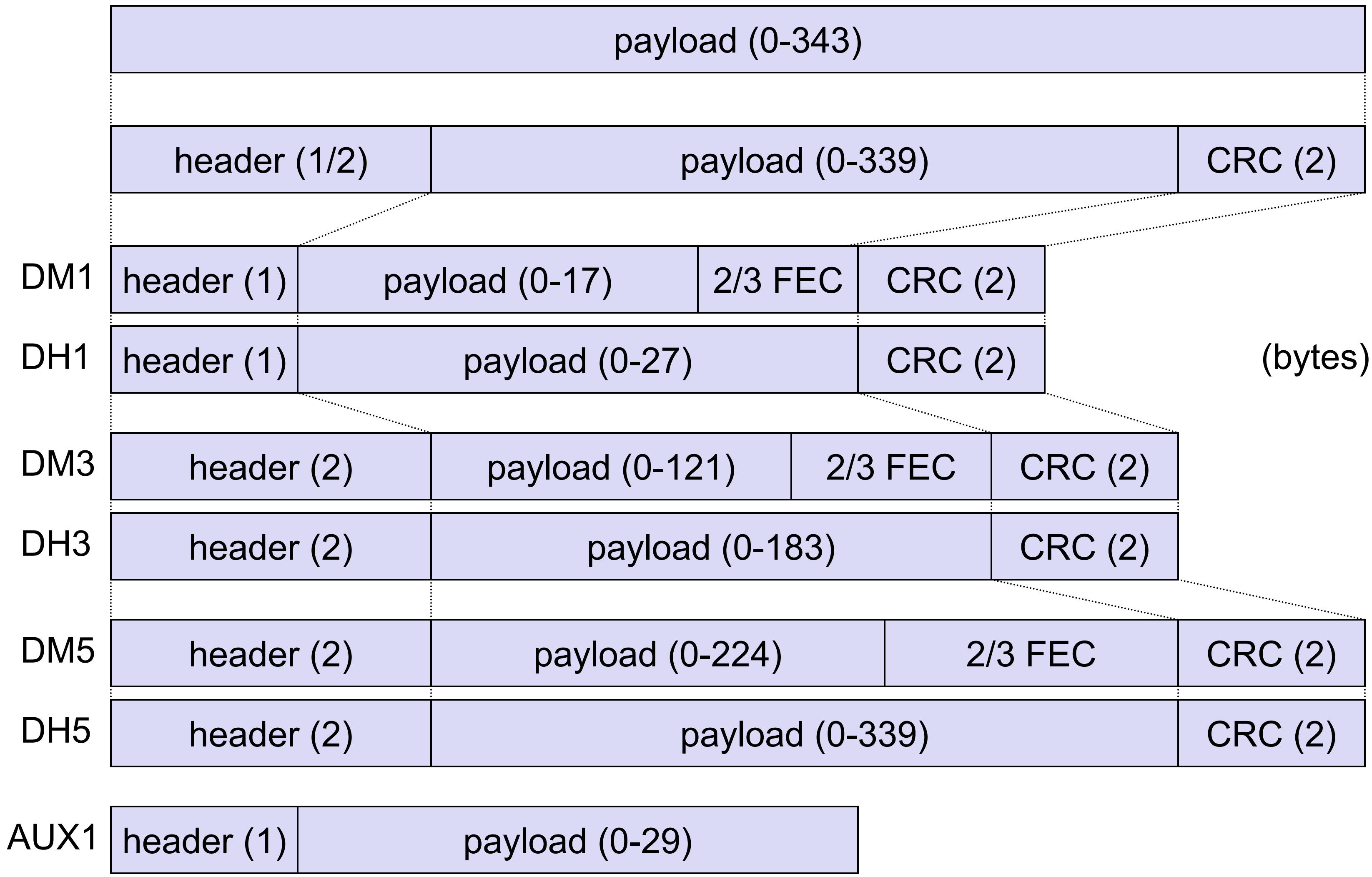
68(72)	54	0-2745	bits
access code	packet header	payload	

4	64	(4)	3	4	1	1	1	8	bits
preamble	sync.	(trailer)	AM address	type	flow	ARQN	SEQN	HEC	

SCO payload types



ACL Payload types



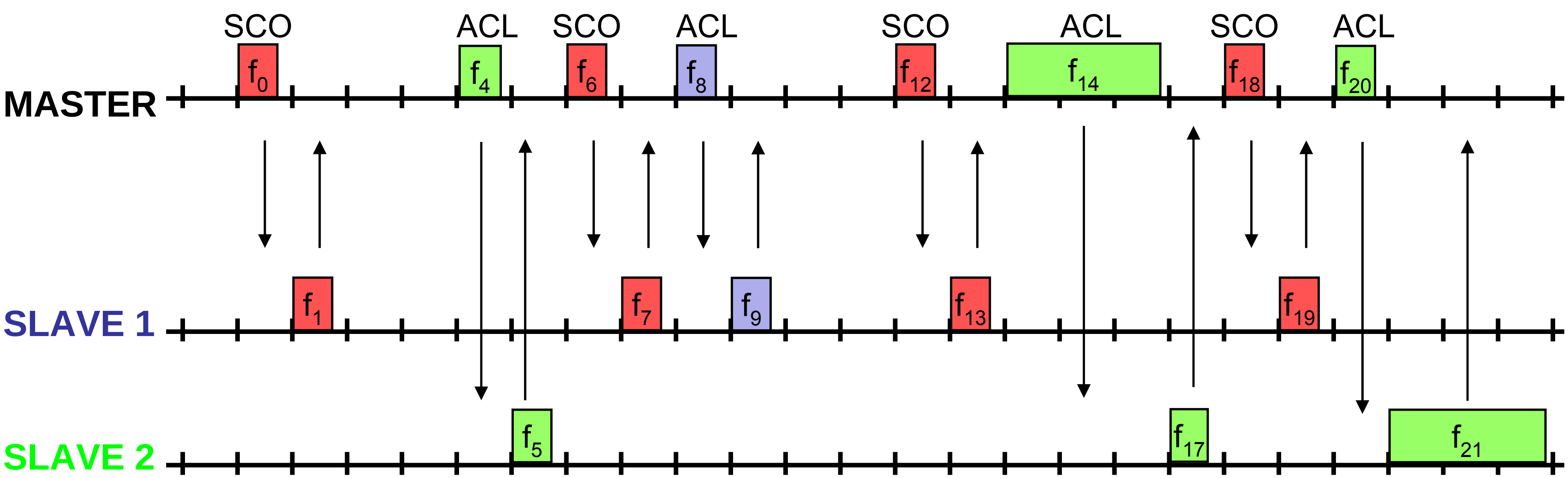
Baseband data rates

	Type	Payload Header [byte]	User Payload [byte]	FEC	CRC	Symmetric max. Rate [kbit/s]	Asymmetric max. Rate [kbit/s] Forward	Reverse
ACL								
1 slot	DM1	1	0-17	2/3	yes	108.8	108.8	108.8
	DH1	1	0-27	no	yes	172.8	172.8	172.8
3 slot	DM3	2	0-121	2/3	yes	258.1	387.2	54.4
	DH3	2	0-183	no	yes	390.4	585.6	86.4
5 slot	DM5	2	0-224	2/3	yes	286.7	477.8	36.3
	DH5	2	0-339	no	yes	**433.9**	**723.2**	57.6
	AUX1	1	0-29	no	no	185.6	185.6	185.6
SCO	HV1	na	10	1/3	no	64.0		
	HV2	na	20	2/3	no	64.0		
	HV3	na	30	no	no	64.0		
	DV	1 D	10+(0-9) D	2/3 D	yes D	64.0+57.6 D		

Data Medium/*H*igh rate, *H*igh-quality *V*oice, *D*ata and *V*oice

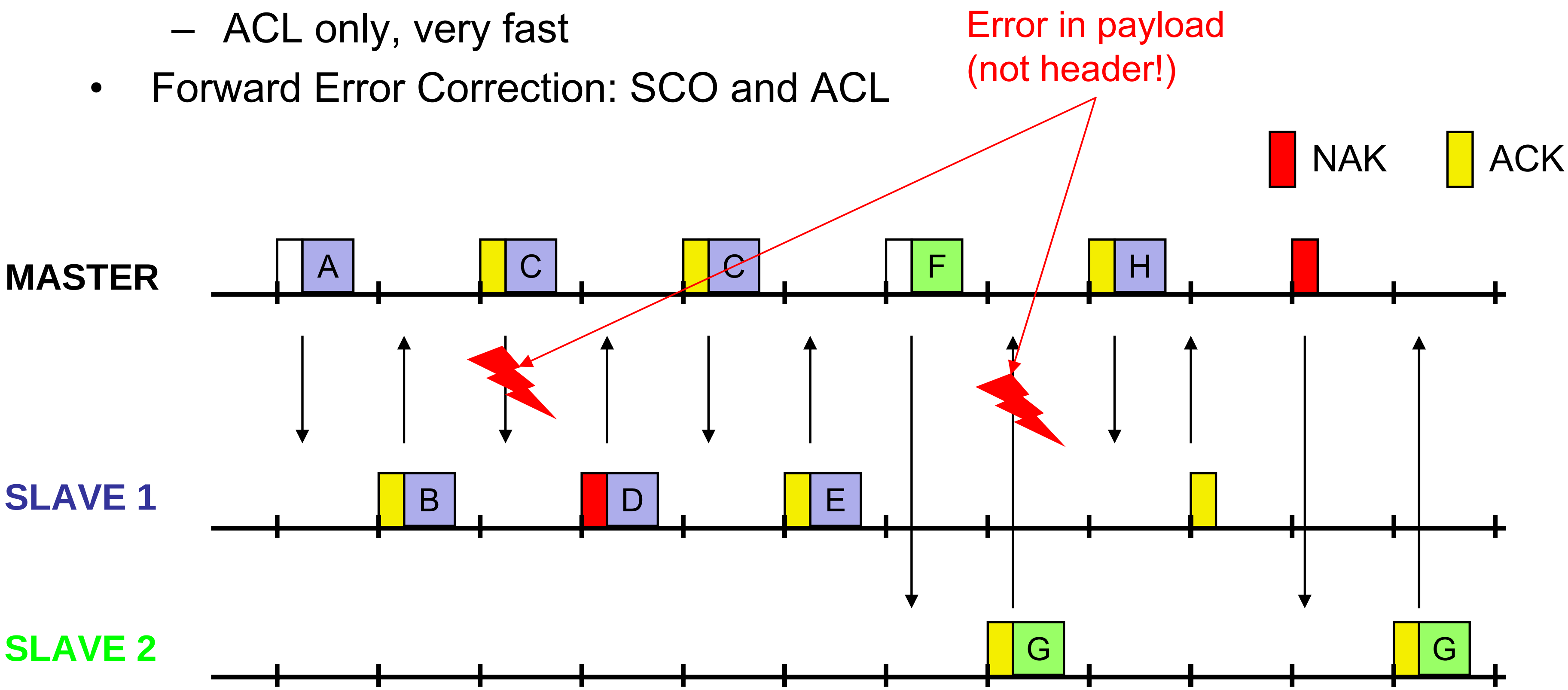
Baseband link types

- Polling-based TDD packet transmission
  - 625μs slots, master polls slaves
- SCO (Synchronous Connection Oriented) – Voice
  - Periodic single slot packet assignment, 64 kbit/s full-duplex, point-to-point
- ACL (Asynchronous ConnectionLess) – Data
  - Variable packet size (1,3,5 slots), asymmetric bandwidth, point-to-multipoint

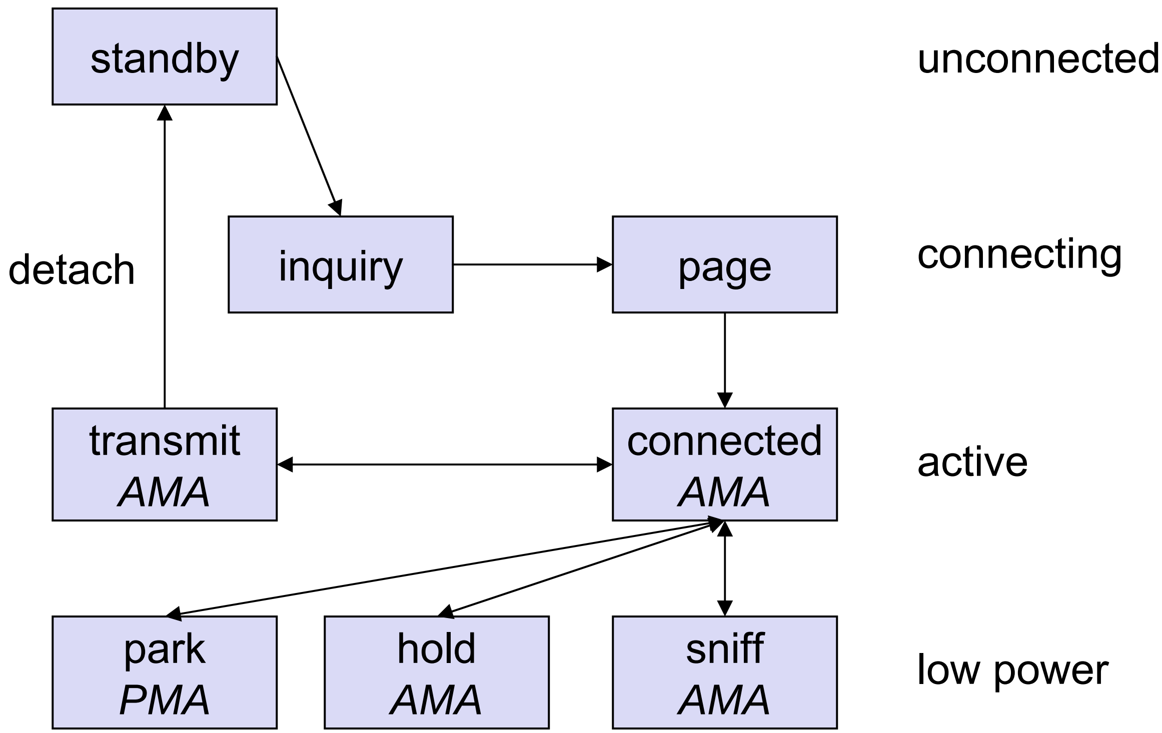


Robustness

- Slow frequency hopping with hopping patterns determined by a master
  - Protection from interference on certain frequencies
  - Separation from other piconets (FH-CDMA)
- Retransmission
  - ACL only, very fast
- Forward Error Correction: SCO and ACL



Baseband States of a Bluetooth Device



Standby: do nothing
Inquire: search for other devices
Page: connect to a specific device
Connected: participate in a piconet

Park: release AMA, get PMA
Sniff: listen periodically, not each slot
Hold: stop ACL, SCO still possible, possibly participate in another piconet

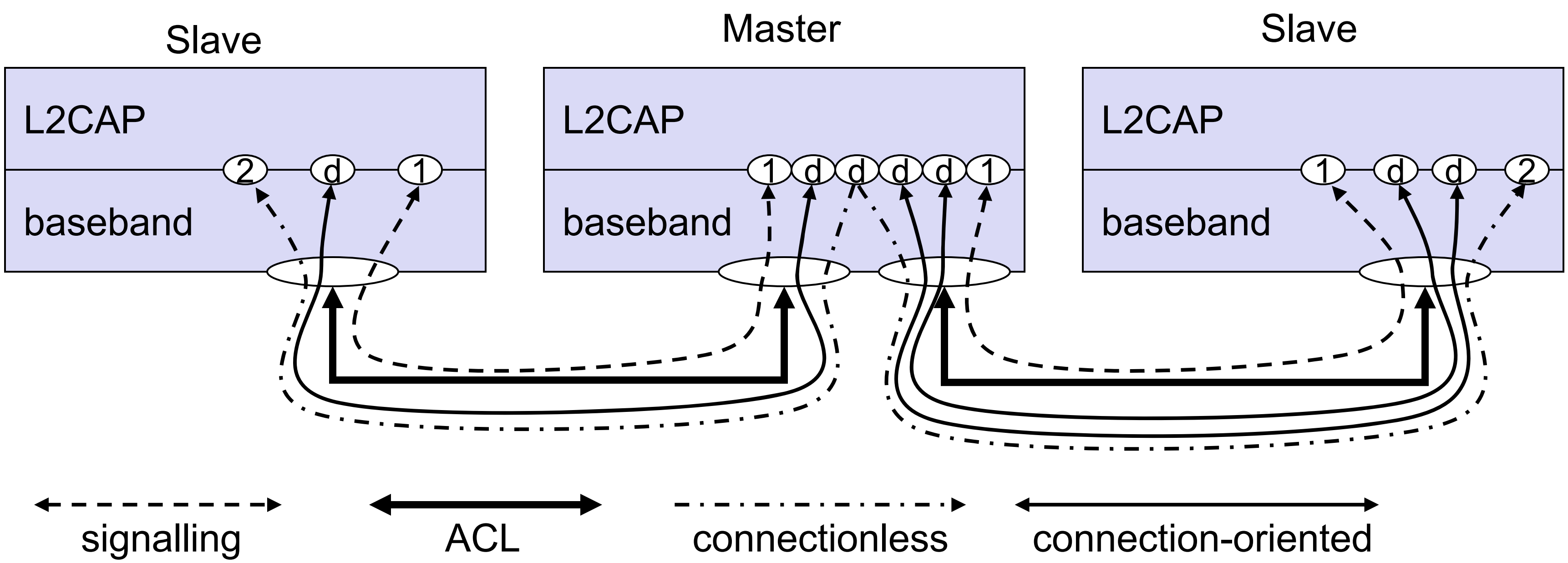
Example: Power consumption/CSR BlueCore2

- **Typical Average Current Consumption (1)**
- VDD=1.8V Temperature = 20°C
- **Mode**
- SCO connection HV3 (1s interval Sniff Mode) (Slave) 26.0 mA
- SCO connection HV3 (1s interval Sniff Mode) (Master) 26.0 mA
- SCO connection HV1 (Slave) 53.0 mA
- SCO connection HV1 (Master) 53.0 mA
- ACL data transfer 115.2kbps UART (Master) 15.5 mA
- ACL data transfer 720kbps USB (Slave) 53.0 mA
- ACL data transfer 720kbps USB (Master) 53.0 mA
- ACL connection, Sniff Mode 40ms interval, 38.4kbps UART 4.0 mA
- ACL connection, Sniff Mode 1.28s interval, 38.4kbps UART 0.5 mA
- Parked Slave, 1.28s beacon interval, 38.4kbps UART 0.6 mA
- Standby Mode (Connected to host, no RF activity) 47.0 µA
- Deep Sleep Mode(2) 20.0 µA
- **Notes:**
- (1) Current consumption is the sum of both BC212015A and the flash.
- (2) Current consumption is for the BC212015A device only.
- (More: www.csr.com)

L2CAP - Logical Link Control and Adaptation Protocol

- Simple data link protocol on top of baseband
- Connection oriented, connectionless, and signaling channels
- Protocol multiplexing
  - RFCOMM, SDP, telephony control
- Segmentation & reassembly
  - Up to 64kbyte user data, 16 bit CRC used from baseband
- QoS flow specification per channel
  - Follows RFC 1363, specifies delay, jitter, bursts, bandwidth
- Group abstraction
  - Create/close group, add/remove member

L2CAP logical channels



L2CAP packet formats

Connectionless PDU

2	2	≥2	0-65533	bytes
length	CID=2	PSM	payload	

Connection-oriented PDU

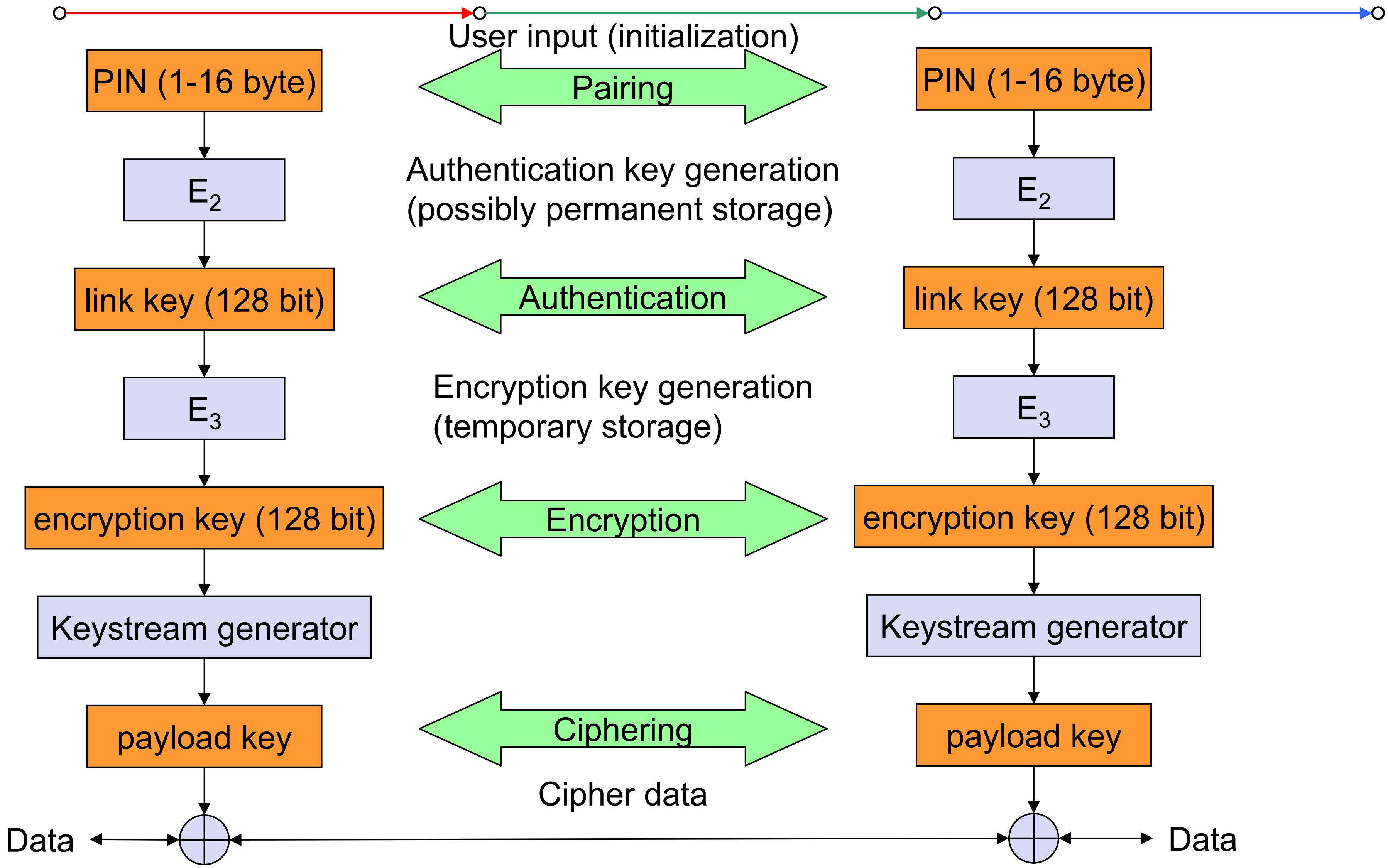
2	2	0-65535	bytes
length	CID	payload	

Signaling command PDU

2	2		bytes
length	CID=1	One or more commands	

1	1	2	≥0
code	ID	length	data

Security


User input (initialization)
PIN (1-16 byte)
Pairing
PIN (1-16 byte)
E2
Authentication key generation
(possibly permanent storage)
E2
link key (128 bit)
Authentication
link key (128 bit)
E3
Encryption key generation
(temporary storage)
E3
encryption key (128 bit)
Encryption
encryption key (128 bit)
Keystream generator
Keystream generator
payload key
Ciphering
payload key
Cipher data
Data
Data

SDP – Service Discovery Protocol

- Inquiry/response protocol for discovering services
  - Searching for and browsing services in radio proximity
  - Adapted to the highly dynamic environment
  - Can be complemented by others like SLP, Jini, Salutation, …
  - Defines discovery only, not the usage of services
  - Caching of discovered services
  - Gradual discovery

- Service record format
  - Information about services provided by attributes
  - Attributes are composed of an 16 bit ID (name) and a value
  - values may be derived from 128 bit Universally Unique Identifiers (UUID)

Additional protocols to support legacy protocols/apps

- RFCOMM
  - Emulation of a serial port (supports a large base of legacy applications)
  - Allows multiple ports over a single physical channel

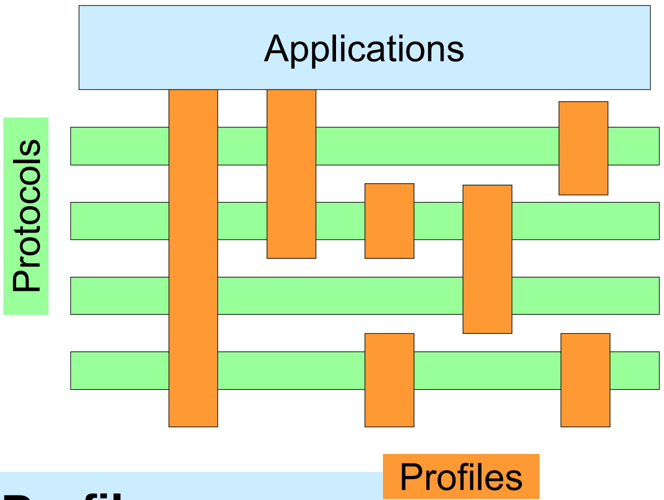
- Telephony Control Protocol Specification (TCS)
  - Call control (setup, release)
  - Group management

- OBEX
  - Exchange of objects, IrDA replacement

- WAP
  - Interacting with applications on cellular phones

Profiles

- Represent default solutions for usage models
  - Vertical slice through the protocol stack
  - Basis for interoperability
- Generic Access Profile
- Service Discovery Application Profile
- Cordless Telephony Profile
- Intercom Profile
- Serial Port Profile
- Headset Profile
- Dial-up Networking Profile
- Fax Profile
- LAN Access Profile
- Generic Object Exchange Profile
- Object Push Profile
- File Transfer Profile
- Synchronization Profile



Additional Profiles
Advanced Audio Distribution
PAN
Audio Video Remote Control
Basic Printing
Basic Imaging
Extended Service Discovery
Generic Audio Video Distribution
Hands Free
Hardcopy Cable Replacement

WPAN: IEEE 802.15-1 – Bluetooth

- Data rate
  - Synchronous, connection-oriented: 64 kbit/s
  - Asynchronous, connectionless
    - 433.9 kbit/s symmetric
    - 723.2 / 57.6 kbit/s asymmetric
- Transmission range
  - POS (Personal Operating Space) up to 10 m
  - with special transceivers up to 100 m
- Frequency
  - Free 2.4 GHz ISM-band
- Security
  - Challenge/response (SAFER+), hopping sequence
- Cost
  - 50€ adapter, drop to 5€ if integrated
- Availability
  - Integrated into some products, several vendors

WPAN: IEEE 802.15-1 – Bluetooth

- Connection set-up time
  - Depends on power-mode
  - Max. 2.56s, avg. 0.64s
- Quality of Service
  - Guarantees, ARQ/FEC
- Manageability
  - Public/private keys needed, key management not specified, simple system integration

\+ Advantages: already integrated into several products, available worldwide, free ISM-band, several vendors, simple system, simple ad-hoc networking, peer to peer, scatternets

– Disadvantages: interference on ISM-band, limited range, max. 8 devices/network&master, high set-up latency

WPAN: IEEE 802.15 – future developments

- 802.15-2: Coexistence
  - Coexistence of Wireless Personal Area Networks (802.15) and Wireless Local Area Networks (802.11), quantify the mutual interference
- 802.15-3: High-Rate
  - Standard for high-rate (20Mbit/s or greater) WPANs, while still low-power/low-cost
  - Data Rates: 11, 22, 33, 44, 55 Mbit/s
  - Quality of Service isochronous protocol
  - Ad-hoc peer-to-peer networking
  - Security
  - Low power consumption
  - Low cost
  - Designed to meet the demanding requirements of portable consumer imaging and multimedia applications

WPAN: IEEE 802.15 – future developments

- 802.15-4: Low-Rate, Very Low-Power
  - Low data rate solution with multi-month to multi-year battery life and very low complexity
  - Potential applications are sensors, interactive toys, smart badges, remote controls, and home automation
  - Data rates of 20-250 kbit/s, latency down to 15 ms
  - Master-Slave or Peer-to-Peer operation
  - Support for critical latency devices, such as joysticks
  - CSMA/CA channel access (data centric), slotted (beacon) or unslotted
  - Automatic network establishment by the PAN coordinator
  - Dynamic device addressing, flexible addressing format
  - Fully handshaked protocol for transfer reliability
  - Power management to ensure low power consumption
  - 16 channels in the 2.4 GHz ISM band, 10 channels in the 915 MHz US ISM band and one channel in the European 868 MHz band

RFID – Radio Frequency Identification

- Function
  - Standard: In response to a radio interrogation signal from a reader (base station) the RFID tags transmit their ID
  - Enhanced: additionally data can be sent to the tags, different media access schemes (collision avoidance)
- Features
  - No line-of sight required (compared to, e.g., laser scanners)
  - RFID tags withstand difficult environmental conditions (sunlight, cold, frost, dirt etc.)
  - Products available with read/write memory, smart-card capabilities
- Categories
  - Passive RFID: operating power comes from the reader over the air which is feasible up to distances of 3 m, low price (1€)
  - Active RFID: battery powered, distances up to 100 m

RFID – Radio Frequency Identification

- Data rate
  - Transmission of ID only (e.g., 48 bit, 64kbit, 1 Mbit)
  - 9.6 – 115 kbit/s
- Transmission range
  - Passive: up to 3 m
  - Active: up to 30-100 m
  - Simultaneous detection of up to, e.g., 256 tags, scanning of, e.g., 40 tags/s
- Frequency
  - 125 kHz, 13.56 MHz, 433 MHz, 2.4 GHz, 5.8 GHz and many others
- Security
  - Application dependent, typ. no crypt. on RFID device
- Cost
  - Very cheap tags, down to $1 (passive)
- Availability
  - Many products, many vendors
- Connection set-up time
  - Depends on product/medium access scheme (typ. 2 ms per device)
- Quality of Service
  - none
- Manageability
  - Very simple, same as serial interface

\+ Advantages: extremely low cost, large experience, high volume available, no power for passive RFIDs needed, large variety of products, relative speeds up to 300 km/h, broad temp. range

– Disadvantages: no QoS, simple denial of service, crowded ISM bands, typ. one-way (activation/ transmission of ID)

RFID – Radio Frequency Identification

- Applications
  - Total asset visibility: tracking of goods during manufacturing, localization of pallets, goods etc.
  - Loyalty cards: customers use RFID tags for payment at, e.g., gas stations, collection of buying patterns
  - Automated toll collection: RFIDs mounted in windshields allow commuters to drive through toll plazas without stopping
  - Others: access control, animal identification, tracking of hazardous material, inventory control, warehouse management, ...

- Local Positioning Systems
  - GPS useless indoors or underground, problematic in cities with high buildings
  - RFID tags transmit signals, receivers estimate the tag location by measuring the signal‘s time of flight

RFID – Radio Frequency Identification

- Example Product: Intermec RFID UHF OEM Reader
  - Read range up to 7m
  - Anticollision algorithm allows for scanning of 40 tags per second regardless of the number of tags within the reading zone
  - US: unlicensed 915 MHz, Frequency Hopping
  - Read: 8 byte < 32 ms
  - Write: 1 byte < 100ms

- Example Product: Wireless Mountain Spider
  - Proprietary sparse code anti-collision algorithm
  - Detection range 15 m indoor, 100 m line-of-sight
  - > 1 billion distinct codes
  - Read rate > 75 tags/s
  - Operates at 308 MHz

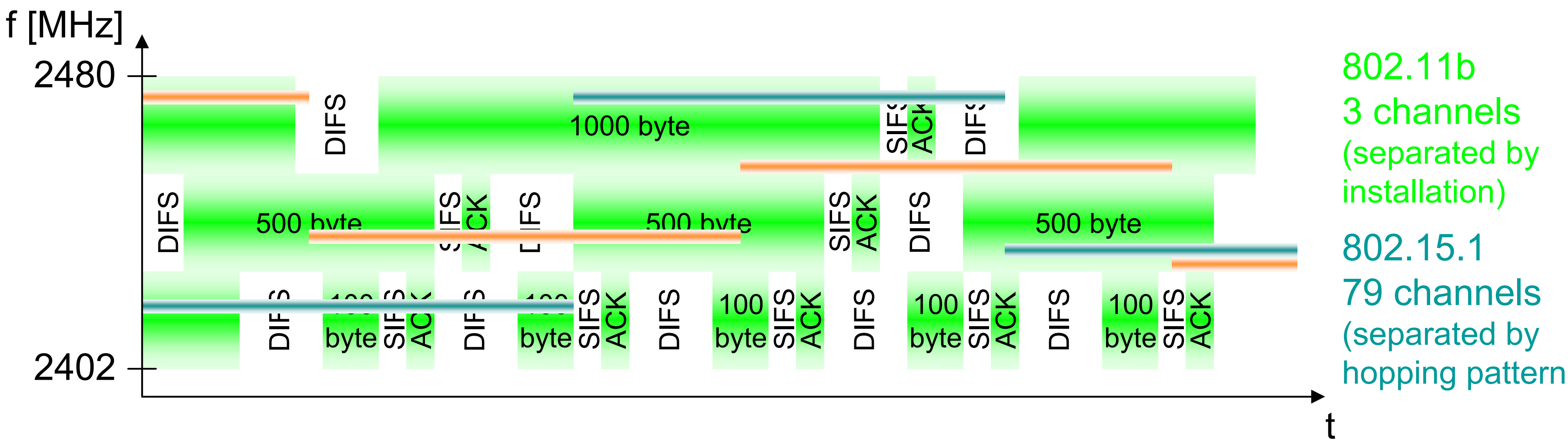
ISM band interference

- Many sources of interference
  - Microwave ovens, microwave lightning
  - 802.11, 802.11b, 802.11g, 802.15, Home RF
  - Even analog TV transmission, surveillance
  - Unlicensed metropolitan area networks
  - …

- Levels of interference
  - Physical layer: interference acts like noise
    - Spread spectrum tries to minimize this
    - FEC/interleaving tries to correct
  - MAC layer: algorithms not harmonized
    - E.g., Bluetooth might confuse 802.11

802.11 vs. Bluetooth

- Bluetooth may act like a rogue member of the 802.11 network
  - Does not know anything about gaps, inter frame spacing etc.



- IEEE 802.15-2 discusses these problems
  - Proposal: Adaptive Frequency Hopping
    - a non-collaborative Coexistence Mechanism
- Real effects? Many different opinions, publications, tests, formulae:
  - Results from complete breakdown to almost no effect
  - Bluetooth (FHSS) seems more robust than 802.11b (DSSS)