Chapter 4 WIRELESS LAN

Distributed Computing Group

Mobile Computing
Summer 2004

Overview

- Design goals
- Characteristics

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

- Bluetooth, RFID, etc.

Design goals

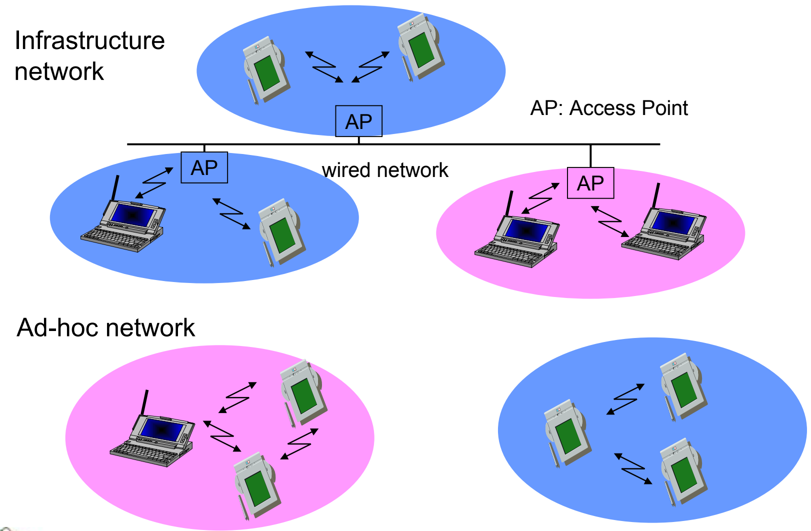
- Global, seamless operation
- Low power consumption for battery use
- No special permissions or licenses required
- Robust transmission technology
- Simplified spontaneous cooperation at meetings
- Easy to use for everyone, simple management
- Interoperable with wired networks
- Security (no one should 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

Characteristics

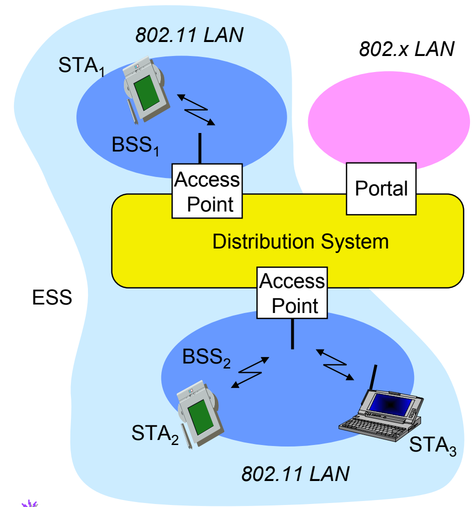
+ Very flexible (economical to scale)
+ Ad-hoc networks without planning possible
+ (Almost) no wiring difficulties (e.g. historic buildings, firewalls)
+ More robust against disasters or users pulling a plug

– 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

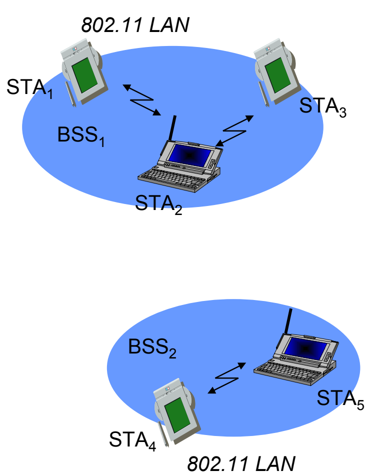


802.11 – Architecture of an infrastructure network



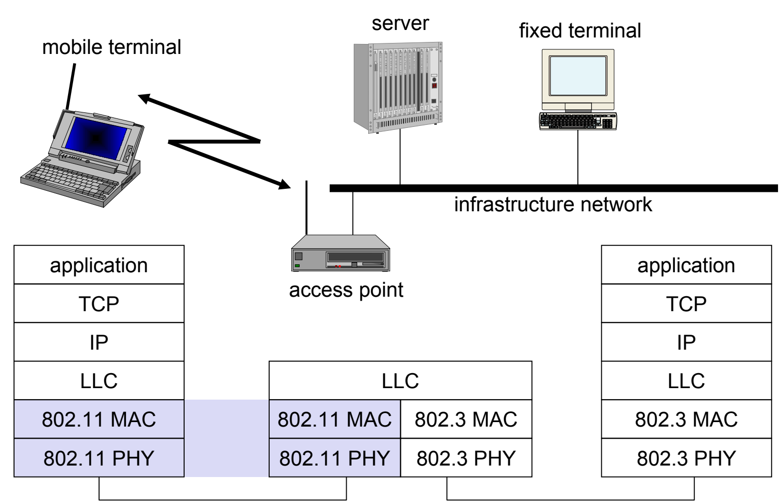
- Station (STA)
  - terminal with access mechanisms to the wireless medium and radio contact to the access point
- Basic Service Set (BSS)
  - group of stations using the same radio frequency
- Access Point
  - station integrated into the wireless LAN and the distribution system
- Portal
  - bridge to 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



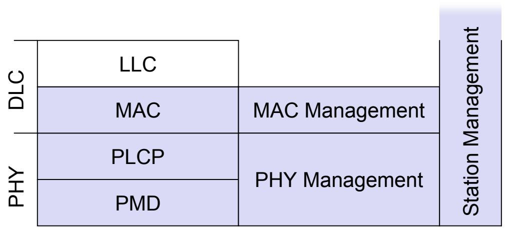
- Direct communication within a limited range
  - Station (STA):
    terminal with access mechanisms to the wireless medium
  - [Independent] Basic Service Set ([I]BSS):
    group of stations using the same radio frequency
- You may use SDM or FDM to establish several BSS.

802.11 – Protocol architecture



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

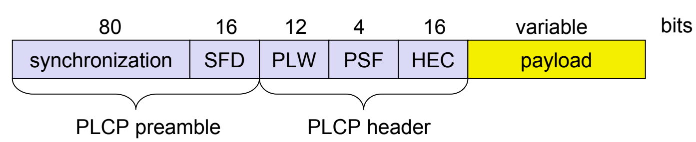
- Examples: HIPERLAN, Bluetooth

802.11 - Physical layer

- 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

FHSS PHY packet format

- Synchronization
  - synch with 010101... pattern
- SFD (Start Frame Delimiter)
  - 0000110010111101 start pattern
- PLW (PLCP_PDU Length Word)
  - length of payload incl. 32 bit CRC of payload, PLW < 4096
- PSF (PLCP Signaling Field)
  - data rate of payload (1 or 2 Mbit/s)
- HEC (Header Error Check)
  - CRC with $x^{16}+x^{12}+x^5+1$



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		PLCP header					

Cyclic Redundancy Code (CRC): Ring

- Polynomes with binary coefficients $b_k x^k + b_{k-1} x^{k-1} + \ldots + b_0 x^0$
- Order of polynome: max i with $b_i \neq 0$
- Binary coefficients b_i (0 or 1) form a field with operations "+" (XOR) and "·" (AND).
- The polynomes form a ring R with operations "+" and "·": (R,+) is an abelian group, (R, ·) is an associative set, and the distributive law does hold, that is, $a\cdot(b+c) = a\cdot b+a\cdot c$ respectively $(b+c)\cdot a = b\cdot a+c\cdot a$ with $a,b,c \in R$.
- Example:

$(x^3+1)\cdot(x^4+x+1)$	1001·10011
$= x^3\cdot(x^4+x+1) + 1\cdot(x^4+x+1)$	= 10011
$= (x^7+x^4+x^3) + (x^4+x+1)$	+ 10011000
$= x^7+x^3+x+1$	= 10001011

Cyclic Redundancy Code (CRC): Division

- Generator polynome $G(x) = x^{16}+x^{12}+x^5+1$
- Let the whole header be polynome T(x) (order < 48)
- Idea: fill HEC (CRC) field such that T(x) mod G(x) = 0.
- How to divide with polynomes? Example with $G(x) = x^2+1$ (=101)

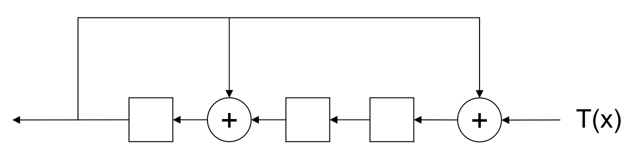
```
11101100 / 101 = 110110, Remainder 10
 100
  011
   111
    100
     010
```

- Idea: Fill CRC with remainder when dividing T(x) with HEC=00…0 by G(x). Then calculating and testing CRC is the same operation.

Cyclic Redundancy Code (CRC): Division in Hardware

- Use cyclic shift register r registers, where r is the order of G(x)
- Example

$G(x) = x^3 \quad + x^2 \quad + 1$



Finally the remainder of the division is in the registers

Cyclic Redundancy Code (CRC): How to chose G(x)?

- Generator polynome $G(x) = x^{16}+x^{12}+x^5+1$
- Why does G(x) have this complicated form?

- Let E(x) be the transmission errors, that is T(x) = M(x) + E(x)
- T(x) mod G(x) = (M(x) + E(x)) mod G(x)
  = M(x) mod G(x) + E(x) mod G(x)
- Since M(x) mod G(x) = 0 we can detect all transmission errors as long as E(x) is not divisible by G(x) without remainder

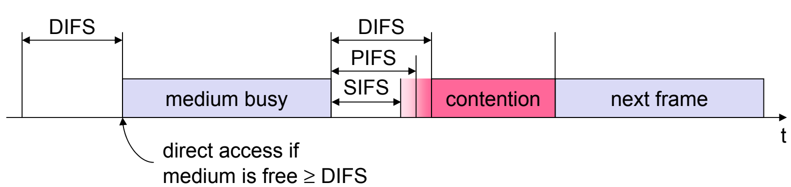
- One can show that G(x) of order r can detect
  - all single bit errors as long as G(x) has 2 or more coefficients
  - all bursty errors (burst of length k is k-bit long 1xxxx1 string) with $k \leq r$ (note: needs G(x) to include the term 1)
  - Any error with probability 2^{-r}

MAC layer: DFWMAC

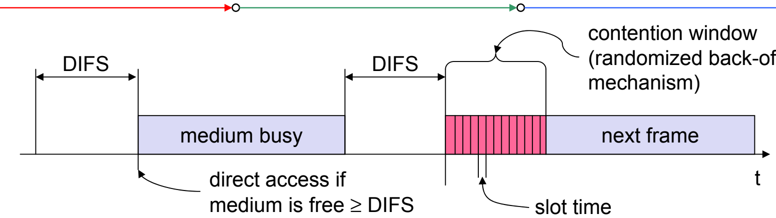
- Traffic services
  - Asynchronous Data Service (mandatory)
    - exchange of data packets based on "best-effort"
    - support of broadcast and multicast
  - Time-Bounded Service (optional)
    - implemented using PCF (Point Coordination Function)
- Access methods
  - DFWMAC-DCF CSMA/CA (mandatory)
    - 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

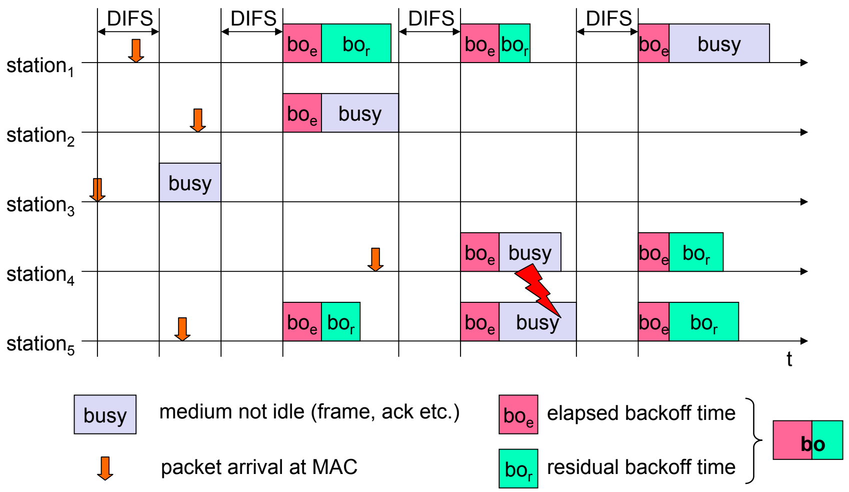


CSMA/CA



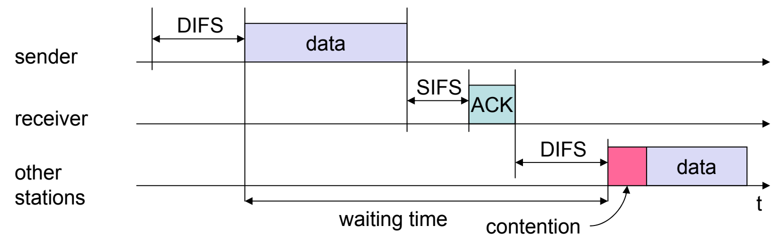
- station ready to send starts sensing the medium (Carrier Sense based on CCA, Clear Channel Assessment)
- if the medium is free for the duration of an Inter-Frame Space (IFS), the station can start sending (IFS depends on service type)
- if the medium is busy, the station has to wait for a free IFS, 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



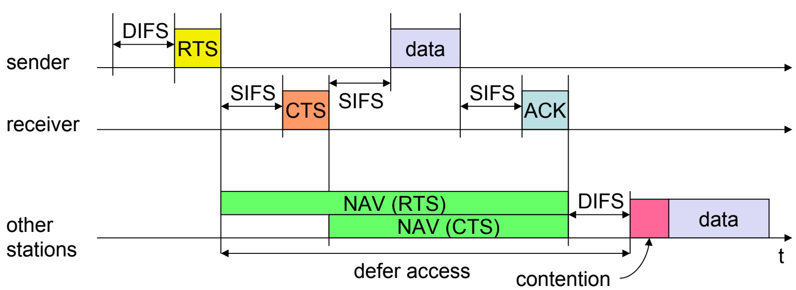
CSMA/CA 2

- 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



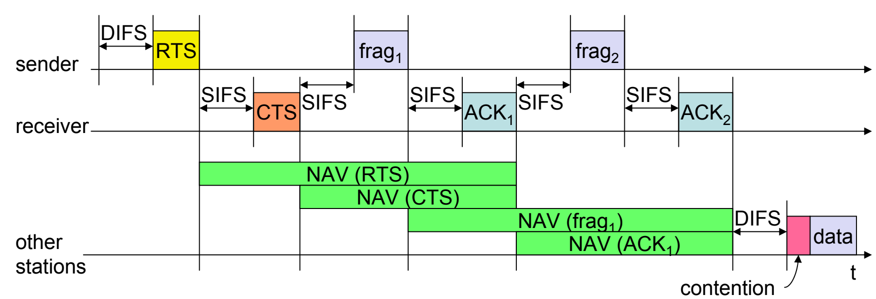
DFWMAC

- 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



Fragmentation: What fragment size is optimal?

- Total data size: D bits
- Overhead per packet (header): h bits
- Overhead between two packets (acknowledgement): a “bits”
- We want f fragments, then each fragment has $k = D/f + h$ data + header bits

- Channel has bit error probability $q = 1-p$
- Probability to transmit a packet of k bits correctly: $P := p^k$
- Expected number of transmissions until packet is success: $1/P$

- Expected total cost for all D bits: $f\cdot(k/P+a)$

- Goal: Find a $k > h$ that minimizes the expected cost

Fragmentation: What fragment size is optimal?

- For the sake of a simplified analysis we assume $a = O(h)$

- If we further assume that a header can be transmitted with constant probability c, that is, $p^h = c$.

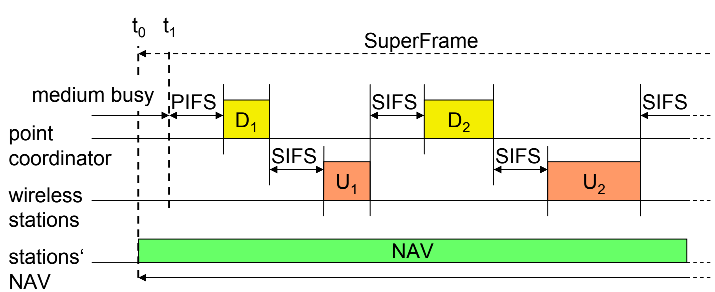
- We choose $k = 2h$; Then clearly $D = f\cdot h$, and therefore expected cost

$$f\cdot\left(\frac{k}{P}+a\right) = \frac{D}{h}\left(\frac{2h}{p^{2h}}+O(h)\right) = O\left(\frac{D}{p^{h^2}}\right) = O\left(\frac{D}{c^2}\right) = O(D).$$

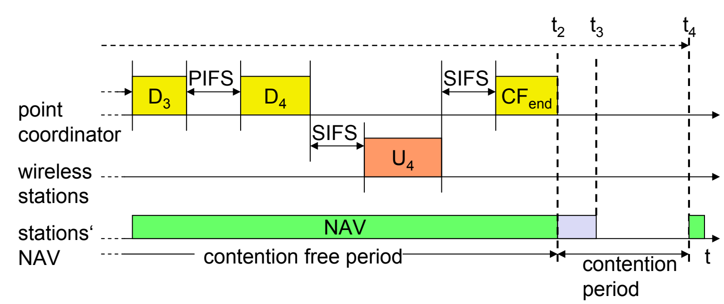
- If already a header cannot be transmitted with high enough probability, then you might keep the message very small, for example $k = h + 1/q$

DFWMAC-PCF

- An access point can poll stations



DFWMAC-PCF 2



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

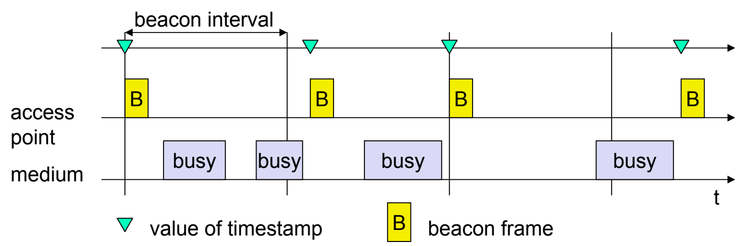
	bytes	2	2	6	4
CTS		Frame Control	Duration	Receiver Address	CRC

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

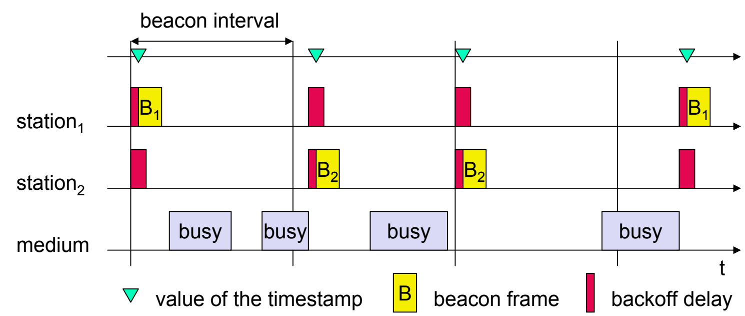
Synchronization

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



Synchronization

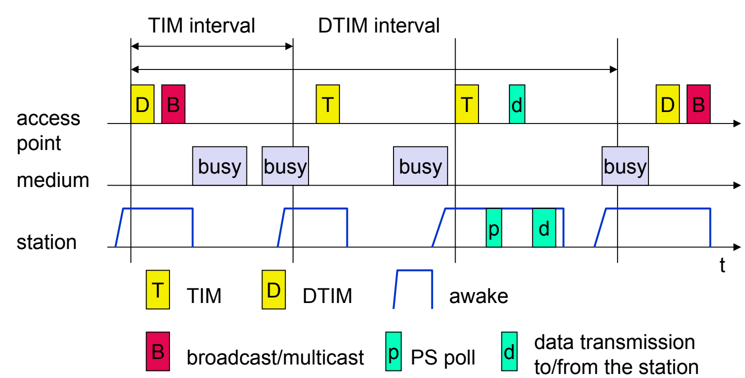
- In an ad-hoc network, the beacon has to be sent by any station



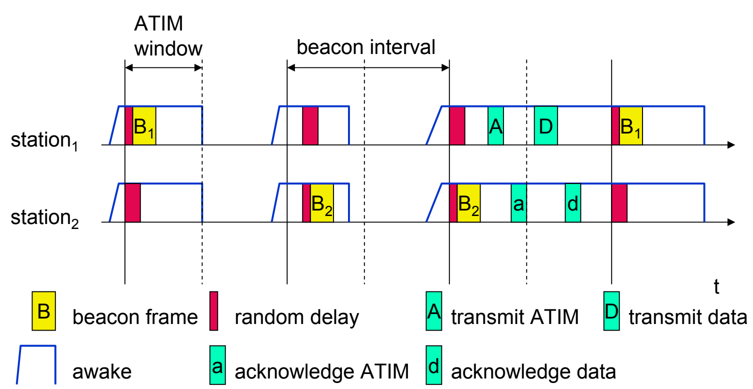
Power management

- 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

WLAN: IEEE 802.11b

- Data rate
  - 1, 2, 5.5, 11 Mbit/s, depending on SNR
  - User data rate max. approx. 6 Mbit/s
- Transmission range
  - 300m outdoor, 30m indoor
  - Max. data rate <10m indoor
- Frequency
  - Free 2.4 GHz ISM-band
- Security
  - Limited, WEP insecure, SSID
- Cost
  - $50 adapter, $150 base station, dropping
- Availability
  - Many products, many vendors

WLAN: IEEE 802.11b

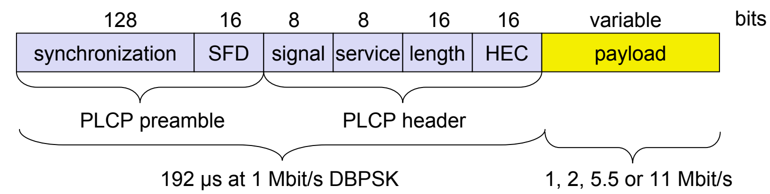
- Connection set-up time
  - Connectionless/always on
- Quality of Service
  - Typically best effort, no guarantees
  - unless polling is used, limited support in products
- Manageability
  - Limited (no automated key distribution, sym. encryption)

\+ Advantages: many installed systems, lot of experience, available worldwide, free ISM-band, many vendors, integrated in laptops, simple system

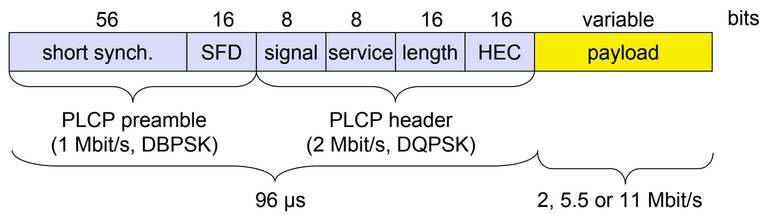
– Disadvantages: heavy interference on ISM-band, no service guarantees, slow relative speed only

IEEE 802.11b – PHY frame formats

Long PLCP PPDU format

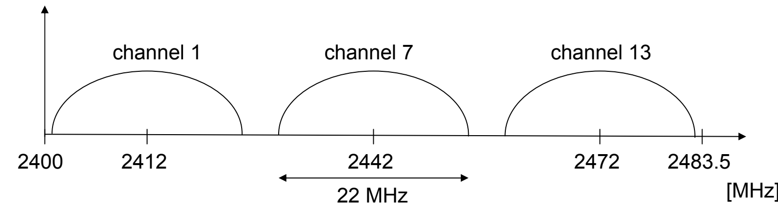


Short PLCP PPDU format (optional)

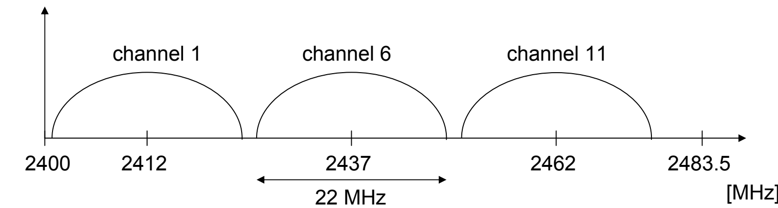


Channel selection (non-overlapping)

Europe (ETSI)



US (FCC)/Canada (IC)



WLAN: IEEE 802.11a

- Data rate
  - 6, 9, 12, 18, 24, 36, 48, 54 Mbit/s, depending on SNR
  - User throughput (1500 byte packets): 5.3 (6), 18 (24), 24 (36), 32 (54)
  - 6, 12, 24 Mbit/s mandatory
- Transmission range
  - 100m outdoor, 10m indoor: e.g., 54 Mbit/s up to 5 m, 48 up to 12 m, 36 up to 25 m, 24 up to 30m, 18 up to 40 m, 12 up to 60 m
- Frequency
  - Free 5.15-5.25, 5.25-5.35, 5.725-5.825 GHz ISM-band
- Security
  - Limited, WEP insecure, SSID
- Cost
  - $50 adapter, $100 base station, dropping
- Availability
  - Some products, some vendors

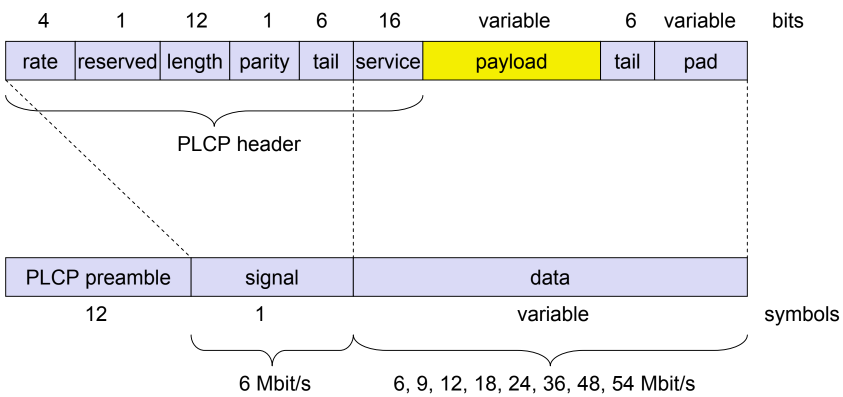
WLAN: IEEE 802.11a

- Connection set-up time
  - Connectionless/always on
- Quality of Service
  - Typically best effort, no guarantees (same as all 802.11 products)
- Manageability
  - Limited (no automated key distribution, sym. Encryption)

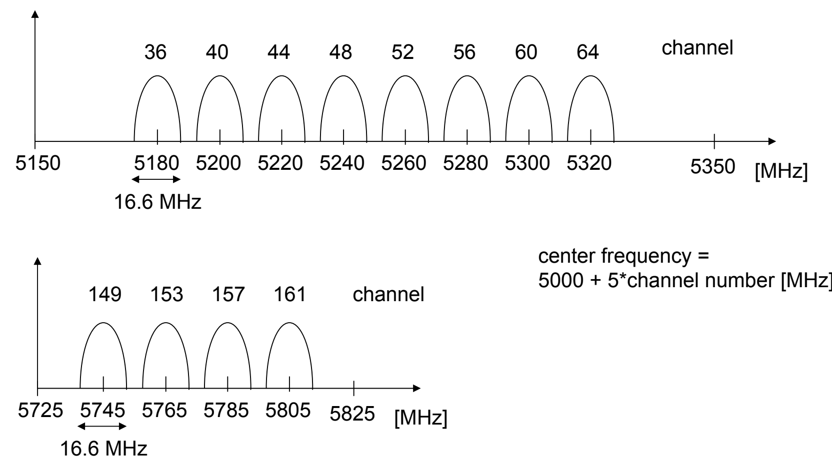
+ Advantages: fits into 802.x standards, free ISM-band, available, simple system, uses less crowded 5 GHz band

– Disadvantages: stronger shading due to higher frequency, no QoS

IEEE 802.11a – PHY frame format

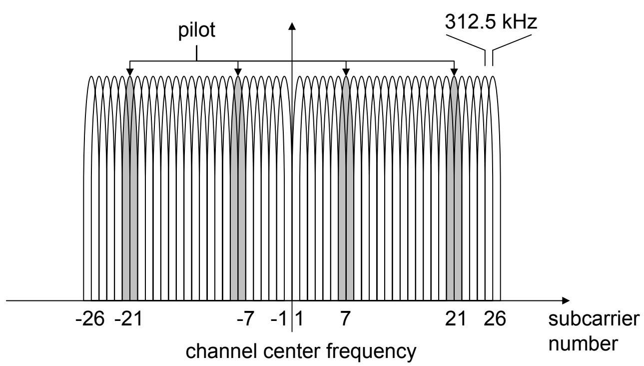


Operating channels for 802.11a / US U-NII



OFDM in IEEE 802.11a (and HiperLAN2)

- OFDM with 52 used subcarriers (64 in total)
- 48 data + 4 pilot (plus 12 virtual subcarriers)
- 312.5 kHz spacing



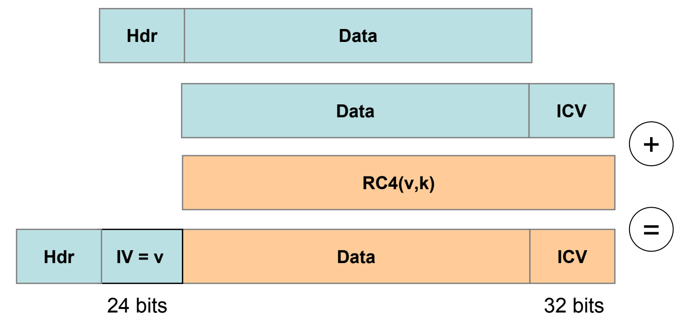
WLAN: IEEE 802.11 – future developments (Late 2002)

- 802.11d: Regulatory Domain Update – completed
- 802.11e: MAC Enhancements – QoS – ongoing
  - 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.
- 802.11f: Inter-Access Point Protocol – ongoing
  - Establish an Inter-Access Point Protocol for data exchange via the distribution system.
- 802.11g: Data Rates > 20 Mbit/s at 2.4 GHz; 54 Mbit/s, OFDM – ongoing
- 802.11h: Spectrum Managed 802.11a (DCS, TPC) – ongoing
- 802.11i: Enhanced Security Mechanisms – ongoing
  - Enhance the current 802.11 MAC to provide improvements in security.
- Study Groups
  - 5 GHz (harmonization ETSI/IEEE) – closed
  - Radio Resource Measurements – started
  - High Throughput – started

802.11 Security Today

- Existing security consists of two subsystems:
  - Wired Equivalent Privacy (WEP): A data encapsulation technique.
  - Shared Key Authentication: An authentication algorithm
- Goals:
  - Create the privacy achieved by a wired network
  - Simulate physical access control by denying access to unauthenticated stations

WEP Encapsulation

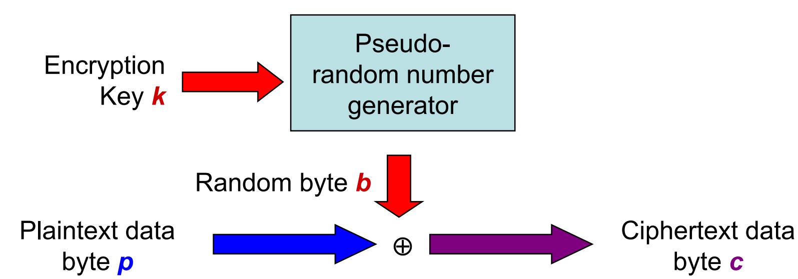


WEP protocol

- The sender and receiver share a secret key k
- Sender, in order to transmit a message:
  - Compute a CRC-32 checksum ICV, and attach it to the message
  - Pick a per-packet key IV v, and generate a keystream RC4(v,k)
  - Attention: WEP Allows v to be re-used with any packet
  - Encrypt data and attached ICV by XORing it with RC4(v,k)
  - Transmit header, IV v, and encrypted data/ICV
- Receiver:
  - Use received IV v and shared k to calculate keystream RC4(v,k)
  - Decrypt data and ICV by XORing it with RC4(v,k)
  - Check whether ICV is a valid CRC-32 checksum

Vernam Ciphers

The WEP encryption algorithm RC4 is a Vernam Cipher:



Decryption works the same way: $p = c \oplus b$

Properties of Vernam Ciphers

Thought experiment: what happens when p_1 and p_2 are encrypted under the same “random” byte b?

$c_1 = p_1 \oplus b$ $\qquad\qquad$ $c_2 = p_2 \oplus b$

Then: $\quad c_1 \oplus c_2 = (p_1 \oplus b) \oplus (p_2 \oplus b) = p_1 \oplus p_2$

Conclusion: it is a bad idea to encrypt any two bytes of data using the same byte output by a Vernam Cipher PRNG.

How to read WEP encrypted traffic

Hdr	IV = v	Data	ICV
	24 bits		32 bits

- By the Birthday Paradox, probability P_n two packets will share same IV after n packets is $P_2 = 1/2^{24}$ after two frames and $P_n = P_{n-1} + (n-1)(1-P_{n-1})/2^{24}$ for n > 2.
- 50% chance of a collision exists already after 4823 packets.

- Pattern recognition can disentangle the XOR’d recovered plaintext.
- Recovered ICV can tell you when you’ve disentangled plaintext correctly (or help to recover the plaintext in the first place).
- Once you know a single RC4, you can inject your own packets

How to read WEP encrypted traffic

- Ways to accelerate the process:

- Send spam into the network, then you already know the plaintext.
- Get the victim to send e-mail to you, the AP creates the plaintext, just for you.
- For a given AP, everybody uses the same secret key k

- Very bad: Many 802.11 cards reset their IV (=v) counter to 0 every time they are activated, and simply increment it for each packet they transmit. In this case a spy knows the RC(v,k) for low v values in short time.

- Naturally a spy would use a decryption dictionary to store the already found RC4(v,k)… needs at most $2^{24} \cdot 1500$ bytes = 24GBytes

Traffic Modification

Thought experiment: how hard is it to change a genuine packet’s data, so ICV won’t detect the change?

Represent an n-bit plaintext as an n-th degree binomial polynomial:

$$p = b_n x^n + b_{n-1} x^{n-1} + \ldots + b_0 x^0$$

Then the plaintext with ICV can be represented as :

$$px^{32} + \mathrm{ICV}(p) = b_n x^{n+32} + b_{n-1} x^{n+31} + \ldots + b_0 x^{32} + \mathrm{ICV}(p)$$

If the n+32 bit RC4 key stream used to encrypt the body is represented by the n+32nd degree polynomial r, then the encrypted message body is

$$px^{32} + \mathrm{ICV}(p) + r$$

Traffic Modification 2

But the ICV is linear, meaning for any polynomials p and q

$$ICV(p+q) = ICV(p) + ICV(q)$$

This means that if q is an arbitrary nth degree polynomial, i.e., an arbitrary change in the underlying message data:

$$(p+q)x^{32} + ICV(p+q) + r = px^{32} + qx^{32} + ICV(p) + ICV(q) + r$$

$$= ((px^{32} + ICV(p)) + r) + (qx^{32} + ICV(q))$$

Conclusion: Anyone can alter an WEP encapsulated packet in arbitrary ways without detection, and without knowing RC4(v,k)

WEP Authentication

- Goal is that client joining the network really knows the shared key k
- Protocol:
  - Access point sends a challenge string to client
  - Client WEP-encrypts challenge, and sends result back to AP
  - If the challenge is encrypted correctly, AP accepts the client
- Client can spoof protocol the same way as injecting a message.
- All a client needs is a valid RC4(v,k), for some v.

WEP message decryption revisited

- How can a client decrypt a specific packet with IV v for which the client does not have the RC4(v,k). (The first packet that uses v.)
- Idea: Use the access point (who knows k)
- Spoofing protocol (one of many possibilities):
  - Join the network (authentication spoofing)
  - Send a handcrafted message “encrypted” with key v to a destination you control, for example a node outside the wireless LAN.
  - The AP will “decrypt” the message for you, and forward it to your destination. When you XOR the “encrypted” with the “decrypted” message, you get the RC(v,k) for the v you wanted.
- There are some tedious details – but there are also other protocols

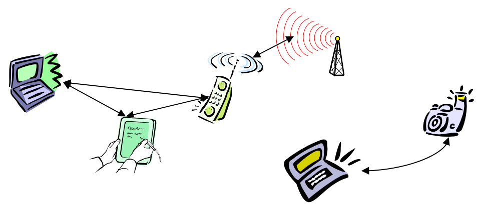
WEP lessons

- What could one do to improve WEP:
  - Use long IV’s that are used only once in the lifetime of a shared key k
  - Use a strong message authentication code (instead of a CRC code), that does depend on the key and the IV.
- What you should do:
- Don’t trust WEP. Don’t trust it more than sending plain messages over an Ethernet. However, WEP is usually seen as a good first deterrent against so-called “war drivers.”
- Put the wireless network outside your firewall
- There are new proprietary security solutions such as LEAP.
- Use other security mechanisms such as VPN, IPSec, ssh

Bluetooth 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 (2002: 50€/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

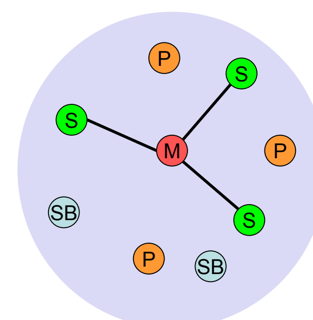
- History
  - 1994: Ericsson (Mattison/Haartsen), "MC-link" project
  - Renaming of the project: Bluetooth according to Harald "Blåtand" Gormsen [son of Gorm], King of Denmark in the 10th century
  - 1998: foundation of Bluetooth SIG, www.bluetooth.org
  - 1999: erection of a rune stone at Ercisson/Lund ;-)
  - 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

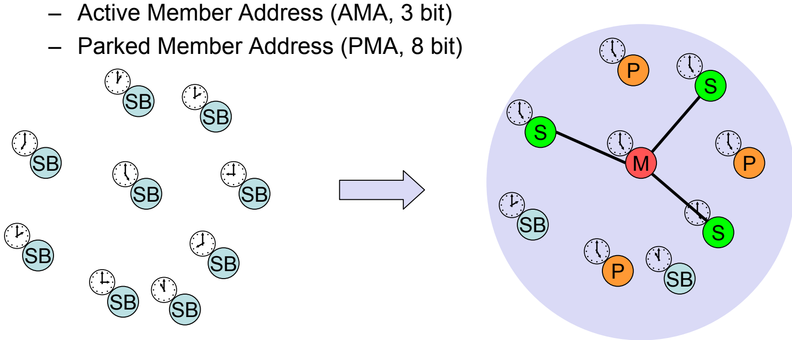
- Collection of devices connected in an ad hoc fashion
- One unit acts as master and the others as slaves for the lifetime of the piconet
- Master determines hopping pattern, slaves have to synchronize
- Each piconet has a unique hopping pattern
- Participation in a piconet = synchronization to hopping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



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

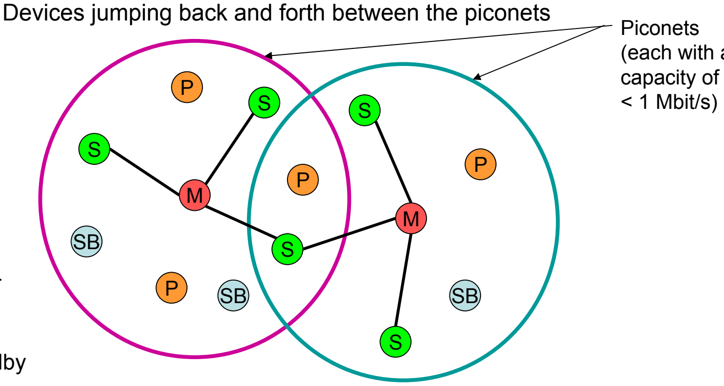
Forming a piconet

- 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)



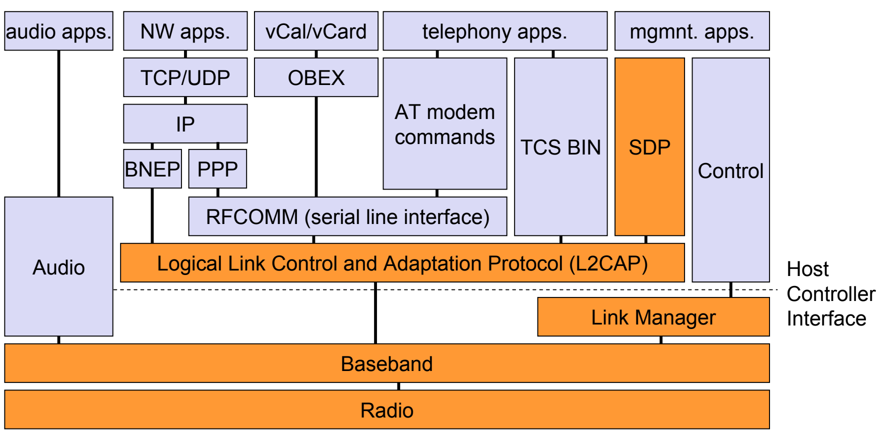
Scatternet

- 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

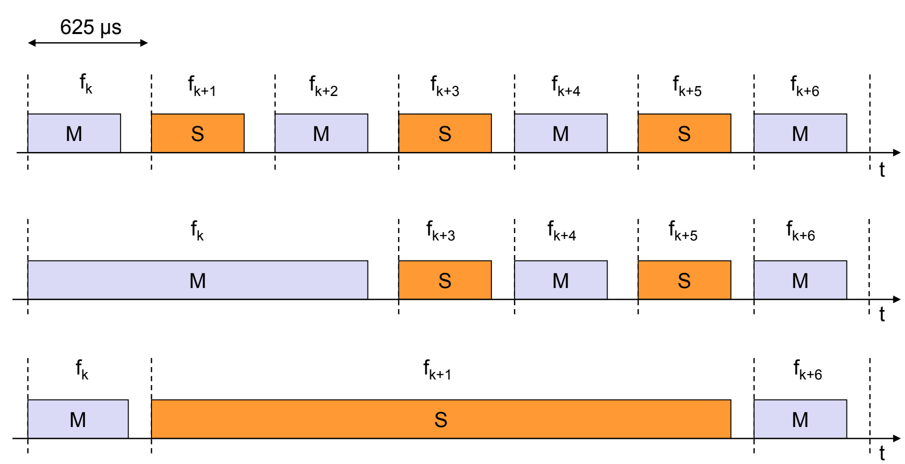
Bluetooth protocol stack



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

	payload (30)				
HV1	audio (10)	FEC (20)			
HV2	audio (20)	FEC (10)			
HV3	audio (30)				
DV	audio (10)	header (1)	payload (0-9)	2/3 FEC	CRC (2)

(bytes)

ACL Payload types

	payload (0-343)			
	header (1/2)	payload (0-339)	CRC (2)	
DM1	header (1)	payload (0-17)	2/3 FEC	CRC (2)
DH1	header (1)	payload (0-27)	CRC (2)	
DM3	header (2)	payload (0-121)	2/3 FEC	CRC (2)
DH3	header (2)	payload (0-183)	CRC (2)	
DM5	header (2)	payload (0-224)	2/3 FEC	CRC (2)
DH5	header (2)	payload (0-339)	CRC (2)	
AUX1	header (1)	payload (0-29)		

(bytes)

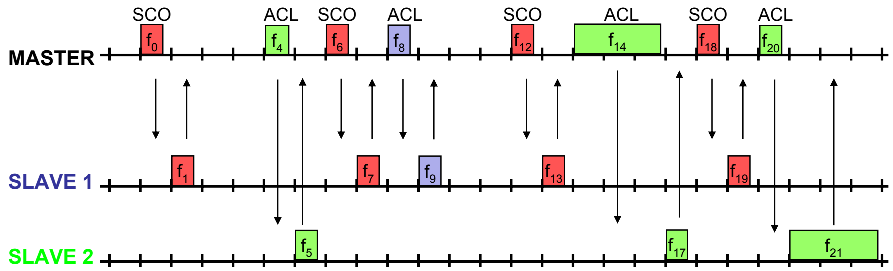
Baseband data rates

		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		

*D*ata *M*edium/*H*igh rate, *H*igh-quality *V*oice, *D*ata and *V*oice

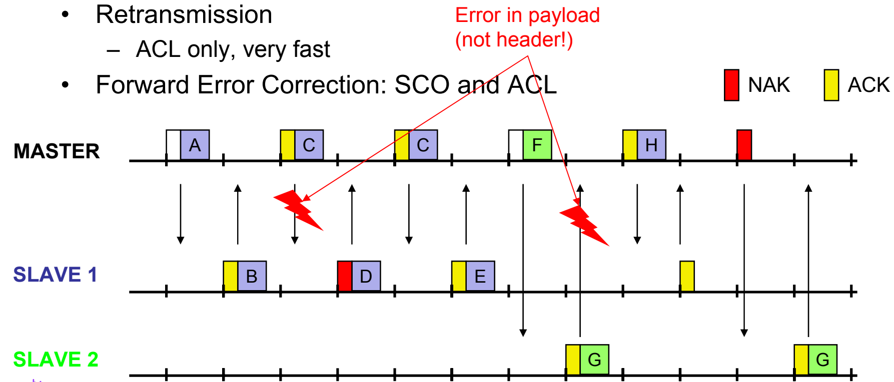
Baseband link types

- 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

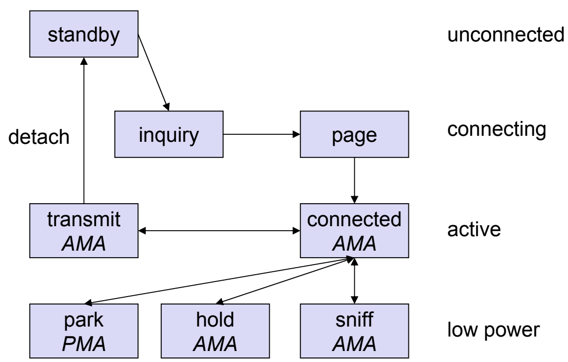


Robustness

- 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

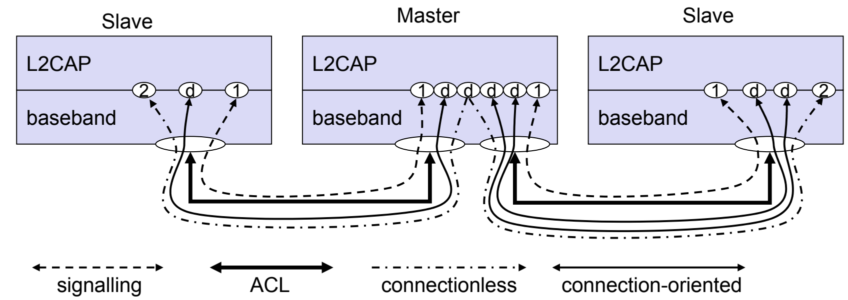
Example: Power consumption/CSR BlueCore2

- **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

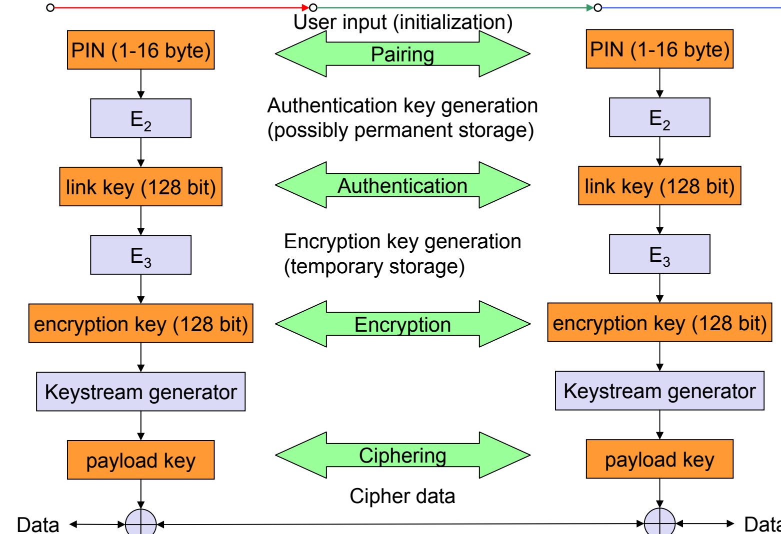
2	2	0-65535	bytes
length	CID	payload	

Signaling command PDU

2	2		bytes
length	CID=1	One or more commands	

1	1	2	≥0
code	ID	length	data

Security



SDP – Service Discovery Protocol

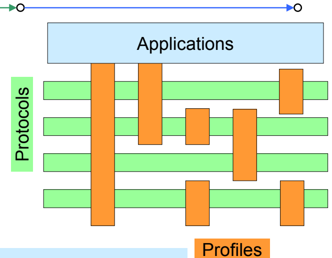
- Inquiry/response protocol for discovering services
  - Searching for and browsing services in radio proximity
  - Adapted to the highly dynamic environment
  - Can be complemented by others like SLP, Jini, Salutation, …
  - Defines discovery only, not the usage of services
  - Caching of discovered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

WLAN: Home RF

- Data rate
  - 0.8, 1.6, 5, 10 Mbit/s
- Transmission range
  - 300m outdoor, 30m indoor
- Frequency
  - 2.4 GHz ISM
- Security
  - Strong encryption, no open access
- Cost
  - Adapter $50, base station $100
- Availability
  - Several products from different vendors
- Connection set-up time
  - 10 ms bounded latency
- Quality of Service
  - Up to 8 streams A/V, up to 8 voice streams, priorities, best-effort
- Manageability
  - Like DECT & 802-LANs

+ Advantages: extended QoS support, host/client and peer/peer, power saving, security

– Disadvantages: future uncertain due to DECT-only devices plus 802.11a/b for data

RF Controllers – ISM bands

- Data rate
  - Typ. up to 115 kbit/s (serial interface)
- Transmission range
  - 5-100 m, depending on power (typ. 10-500 mW)
- Frequency
  - Typ. 27 (EU, US), 315 (US), 418 (EU), 426 (Japan), 433 (EU), 868 (EU), 915 (US) MHz (depending on regulations)
- Security
  - Some products with added processors
- Cost
  - Cheap: $10-$50
- Availability
  - Many products, many vendors
- Connection set-up time
  - N/A
- Quality of Service
  - none
- Manageability
  - Very simple, same as serial interface
- Advantages: very low cost, large experience, high volume available

– Disadvantages: no QoS, crowded ISM bands (particularly 27 and 433 MHz), typ. no Medium Access Control, 418 MHz experiences interference with TETRA

Broadband network types

- Common characteristics
  - ATM QoS (CBR, VBR, UBR, ABR)
- HIPERLAN/2
  - short range (< 200 m), indoor/campus, 25 Mbit/s user data rate
  - access to telecommunication systems, multimedia applications, mobility (<10 m/s)
- HIPERACCESS
  - wider range (< 5 km), outdoor, 25 Mbit/s user data rate
  - fixed radio links to customers (“last mile”), alternative to xDSL or cable modem, quick installation
  - Several (proprietary) products exist with 155 Mbit/s plus QoS
- HIPERLINK – currently no activities
  - intermediate link, 155 Mbit/s
  - connection of HIPERLAN access points or connection between HIPERACCESS nodes

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

- Security
  - Denial-of-Service attacks are always possible
    - Interference of the wireless transmission, shielding of transceivers
  - IDs via manufacturing or one time programming
  - Key exchange via, e.g., RSA possible, encryption via, e.g., AES

- Future Trends
  - RTLS: Real-Time Locating System – big efforts to make total asset visibility come true
  - Integration of RFID technology into the manufacturing, distribution and logistics chain
  - Creation of „electronic manifests" at item or package level (embedded inexpensive passive RFID tags)
  - 3D tracking of children, patients

RFID – Radio Frequency Identification

- Devices and Companies
  - AXCESS Inc., www.axcessinc.com
  - Checkpoint Systems Group, www.checkpointsystems.com
  - GEMPLUS, www.gemplus.com/app/smart_tracking
  - Intermec/Intellitag, www.intermec.com
  - I-Ray Technologies, www.i-ray.com
  - RF Code, www.rfcode.com
  - Texas Instruments, www.ti-rfid.com/id
  - WhereNet, www.wherenet.com
  - Wireless Mountain, www.wirelessmountain.com
  - XCI, www.xci-inc.com

- Only a very small selection…

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

RFID – Radio Frequency Identification

- Relevant Standards
  - American National Standards Institute
    - ANSI, www.ansi.org, www.aimglobal.org/standards/rfidstds/ANSIT6.html
  - Automatic Identification and Data Capture Techniques
    - JTC 1/SC 31, www.uc-council.com/sc31/home.htm, www.aimglobal.org/standards/rfidstds/sc31.htm
  - European Radiocommunications Office
    - ERO, www.ero.dk, www.aimglobal.org/standards/rfidstds/ERO.htm
  - European Telecommunications Standards Institute
    - ETSI, www.etsi.org, www.aimglobal.org/standards/rfidstds/ETSI.htm
  - Identification Cards and related devices
    - JTC 1/SC 17, www.sc17.com, www.aimglobal.org/standards/rfidstds/sc17.htm,
  - Identification and communication
    - ISO TC 104 / SC 4, www.autoid.org/tc104_sc4_wg2.htm, www.aimglobal.org/standards/rfidstds/TC104.htm
  - Road Transport and Traffic Telematics
    - CEN TC 278, www.nni.nl, www.aimglobal.org/standards/rfidstds/CENTC278.htm
  - Transport Information and Control Systems
    - ISO/TC204, www.sae.org/technicalcommittees/gits.htm, www.aimglobal.org/standards/rfidstds/ISOTC204.htm

RFID – Radio Frequency Identification

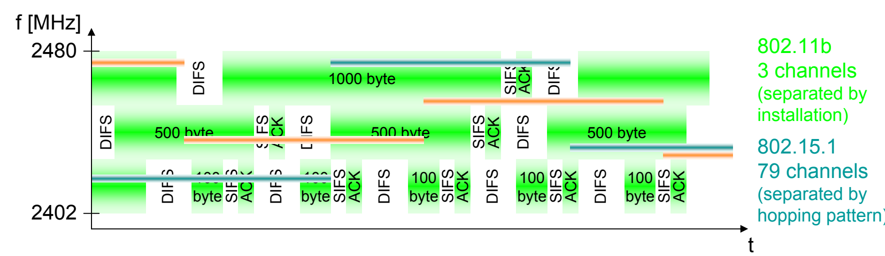
- ISO Standards
  - ISO 15418
    - MH10.8.2 Data Identifiers
    - EAN.UCC Application Identifiers
  - ISO 15434 - Syntax for High Capacity ADC Media
  - ISO 15962 - Transfer Syntax
  - ISO 18000
    - Part 2, 125-135 kHz
    - Part 3, 13.56 MHz
    - Part 4, 2.45 GHz
    - Part 5, 5.8 GHz
    - Part 6, UHF (860-930 MHz, 433 MHz)
  - ISO 18047 - RFID Device Conformance Test Methods
  - ISO 18046 - RF Tag and Interrogator Performance Test Methods

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)