Chapter 4
WIRELESS LAN

Distributed
Computing
Group

Mobile Computing

Summer 2003

Overview

- Design goals
- Characteristics

- IEEE 802.11
  - Architecture
  - Protocol
  - PHY
  - MAC
  - Roaming
  - Security
  - a, b, d, etc.

- Short intermezzo on Cyclic Redundancy codes

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

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

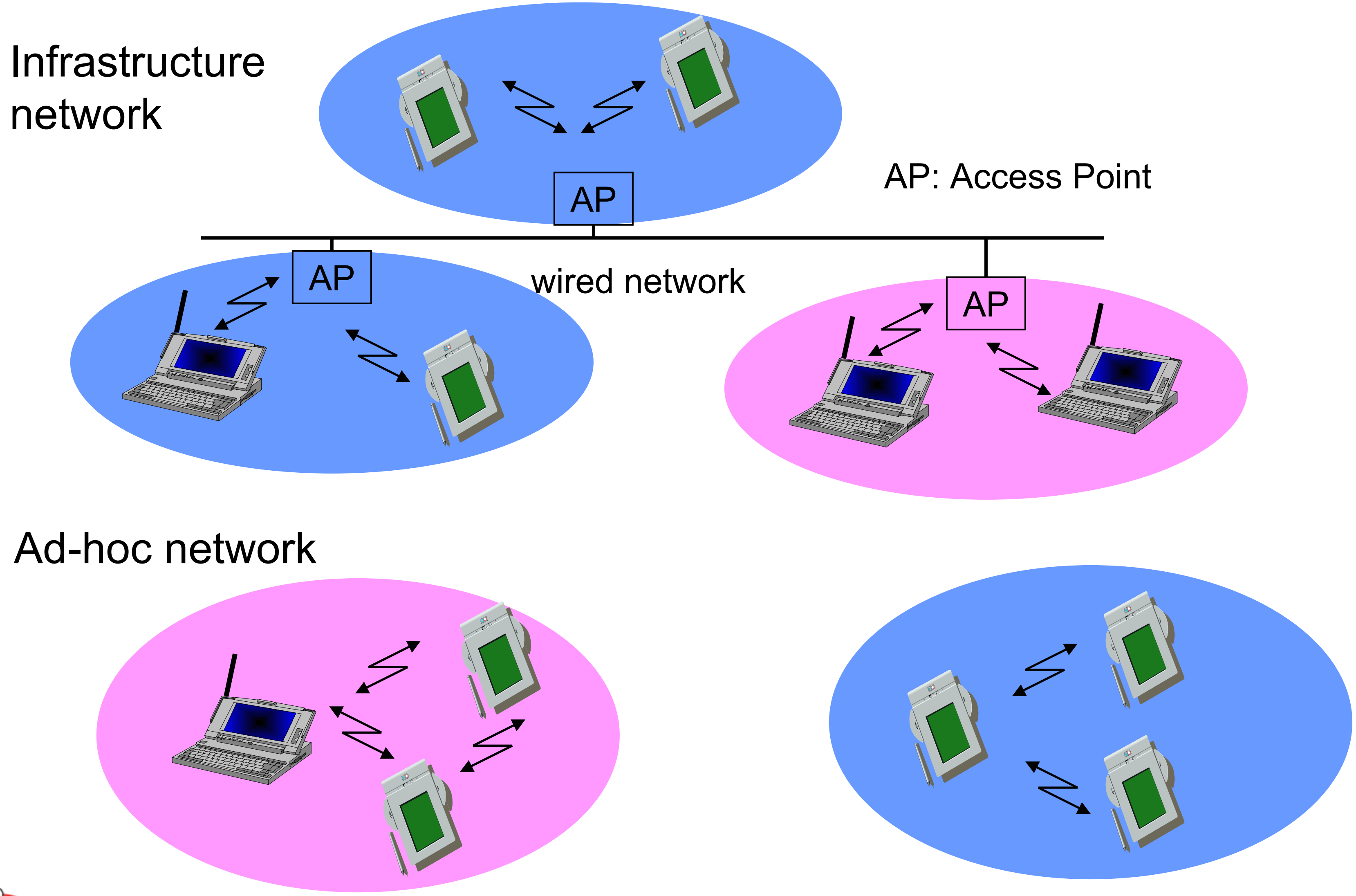
\+ coverage of larger areas possible (radio can penetrate walls, furniture etc.)

– very limited license free frequency bands

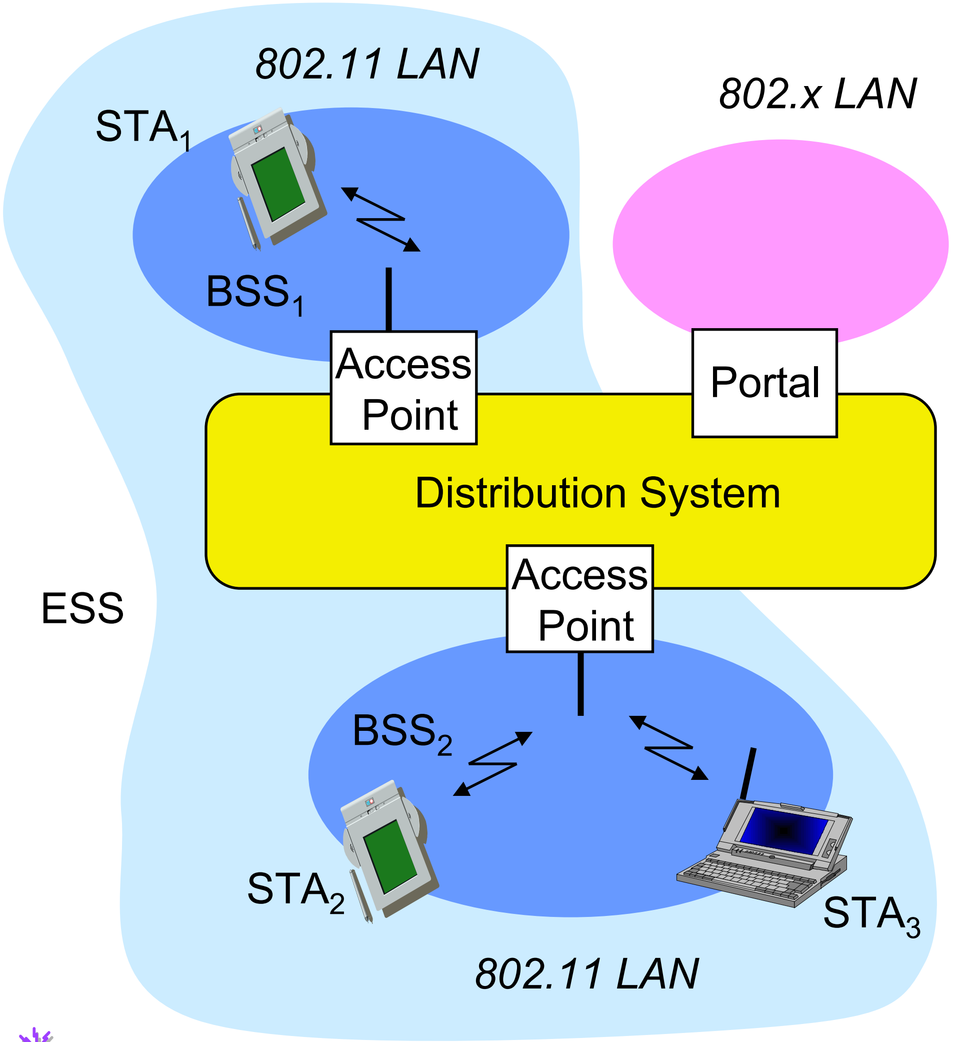
– shielding more difficult, interference with other electrical devices

- Examples: HIPERLAN, Bluetooth

Infrastructure vs. ad-hoc networks

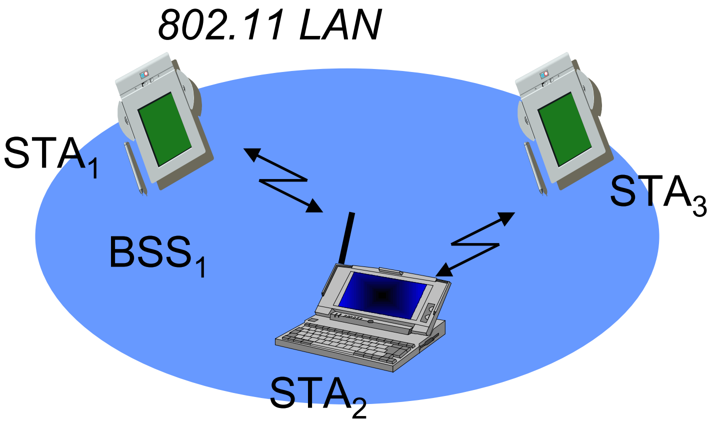


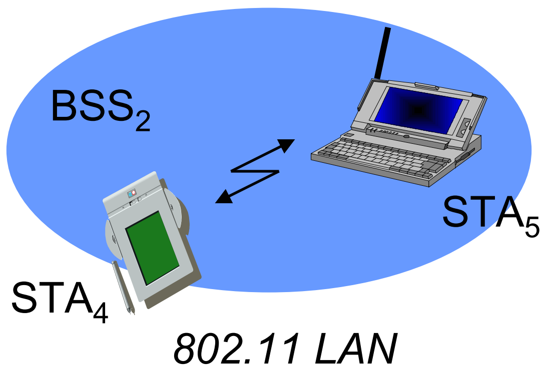
802.11 – Architecture of an infrastructure network



- 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 (EES: Extended Service Set) based on several BSS

802.11 – Architecture of an ad-hoc network

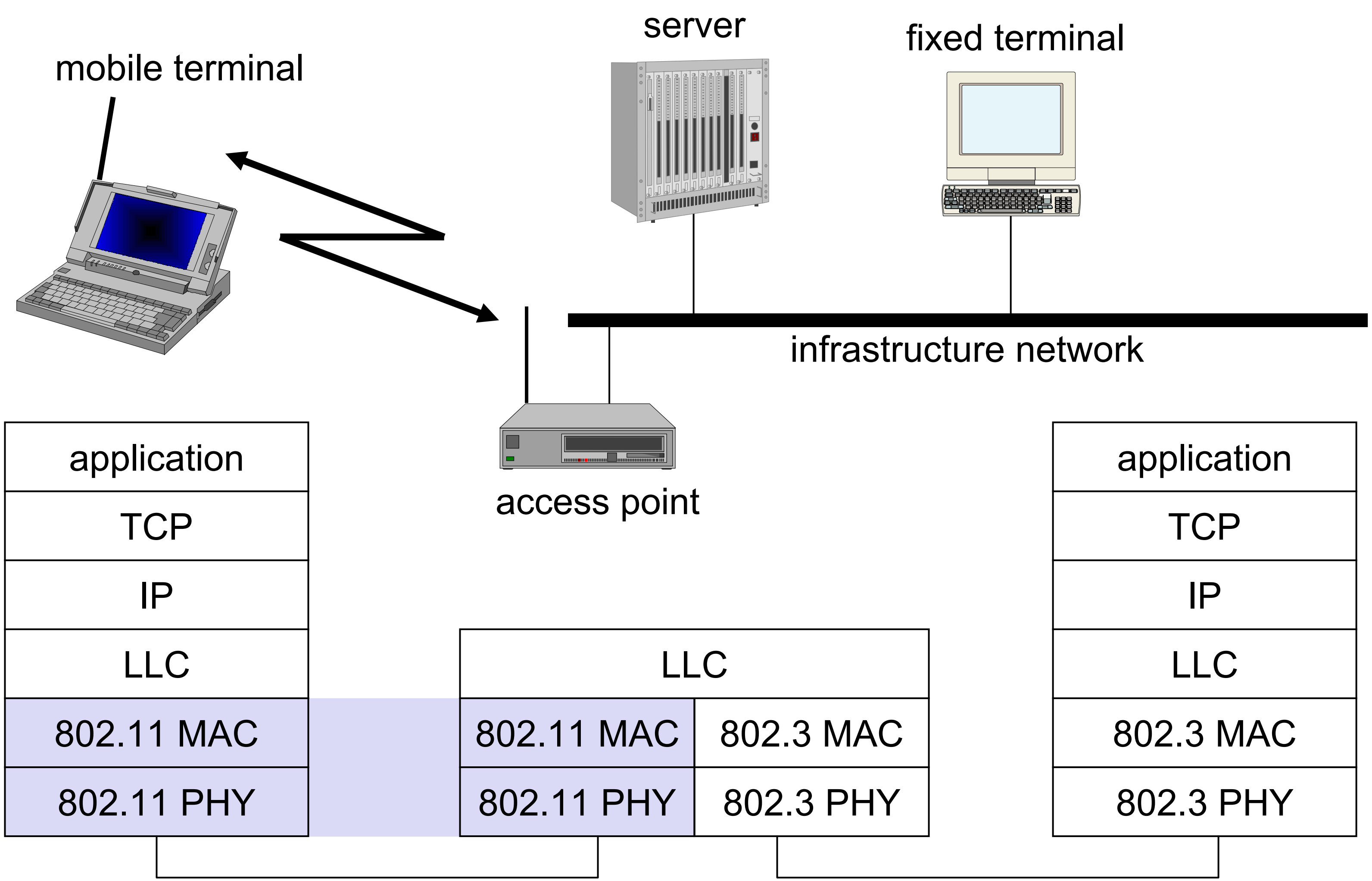




- Direct communication within a limited range
  - Station (STA):
    terminal with access mechanisms to the wireless medium
  - Basic Service Set (BSS):
    group of stations using the same radio frequency

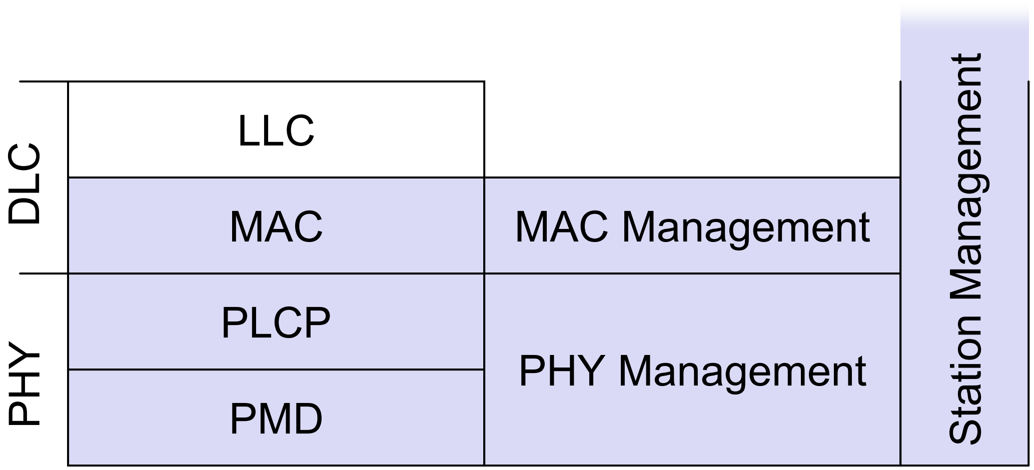
- You may use SDM or FDM to establish several BSS.

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)



802.11 - Physical layer

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

- 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

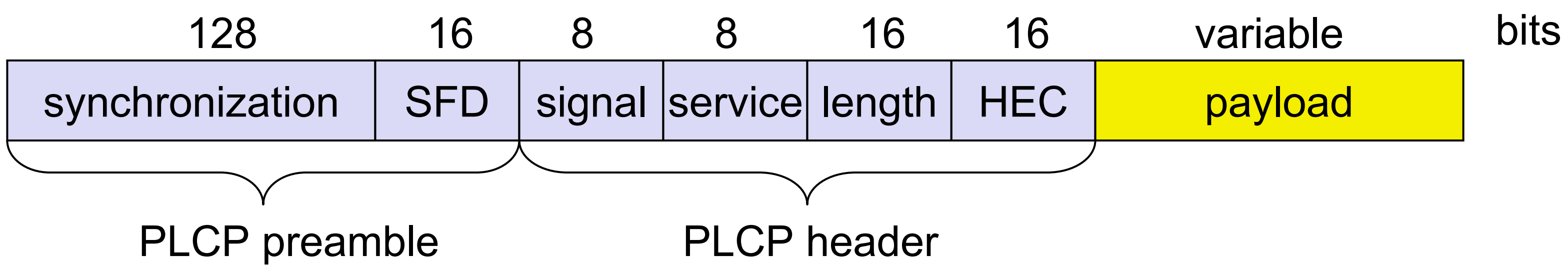
FHSS PHY packet format

- 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 $x^{16}+x^{12}+x^5+1$

80	16	12	4	16	variable	bits
synchronization	SFD	PLW	PSF	HEC	payload	
PLCP preamble		PLCP header				

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, $x^{16}+x^{12}+x^5+1$



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:

$$
\begin{aligned}
& (x^3+1)\cdot(x^4+x+1) & & 1001 \cdot 10011 \\
&= x^3\cdot(x^4+x+1) + 1\cdot(x^4+x+1) & &= \quad 10011 \\
&= (x^7+x^4+x^3) + (x^4+x+1) & &+ 10011000 \\
&= x^7+x^3+x+1 & &= 10001011
\end{aligned}
$$

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 $T(x) \bmod G(x) = 0$.
- How to divide with polynomes? Example with $G(x) = x^2+1$ (=101)

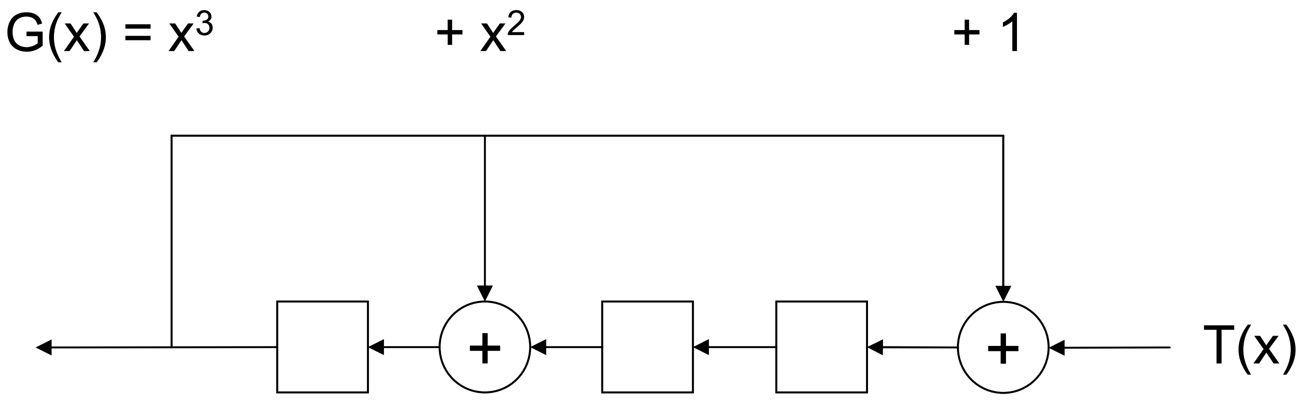
```
11101100 / 101 = 110110, Remainder 10
 100
  011
   111
    100
     010
```

- 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



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

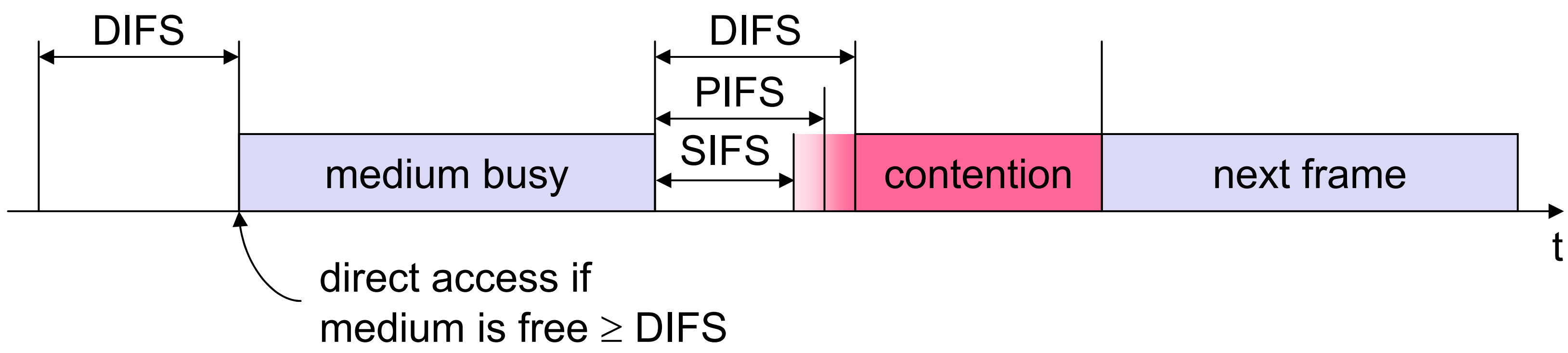
- One can show that G(x) of order r can detect
  – all single bit errors as long as G(x) has 2 or more coefficients
  – all bursty errors (burst of length k is k-bit long 1xxxx1 string) with $k \leq r$ (note: needs G(x) to include the term 1)
  – Any error with probability 2^{-r}

MAC layer: DFWMAC

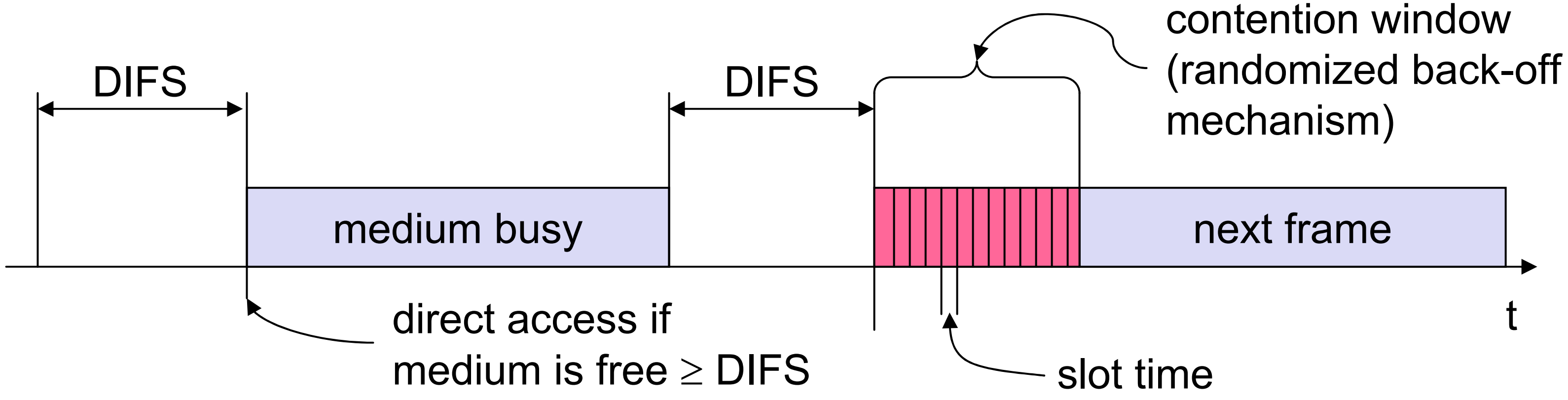
- Traffic services
  - Asynchronous Data Service (mandatory)
    - exchange of data packets based on "best-effort"
    - support of broadcast and multicast
  - Time-Bounded Service (optional)
    - implemented using PCF (Point Coordination Function)
- Access methods
  - DFWMAC-DCF CSMA/CA (mandatory)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

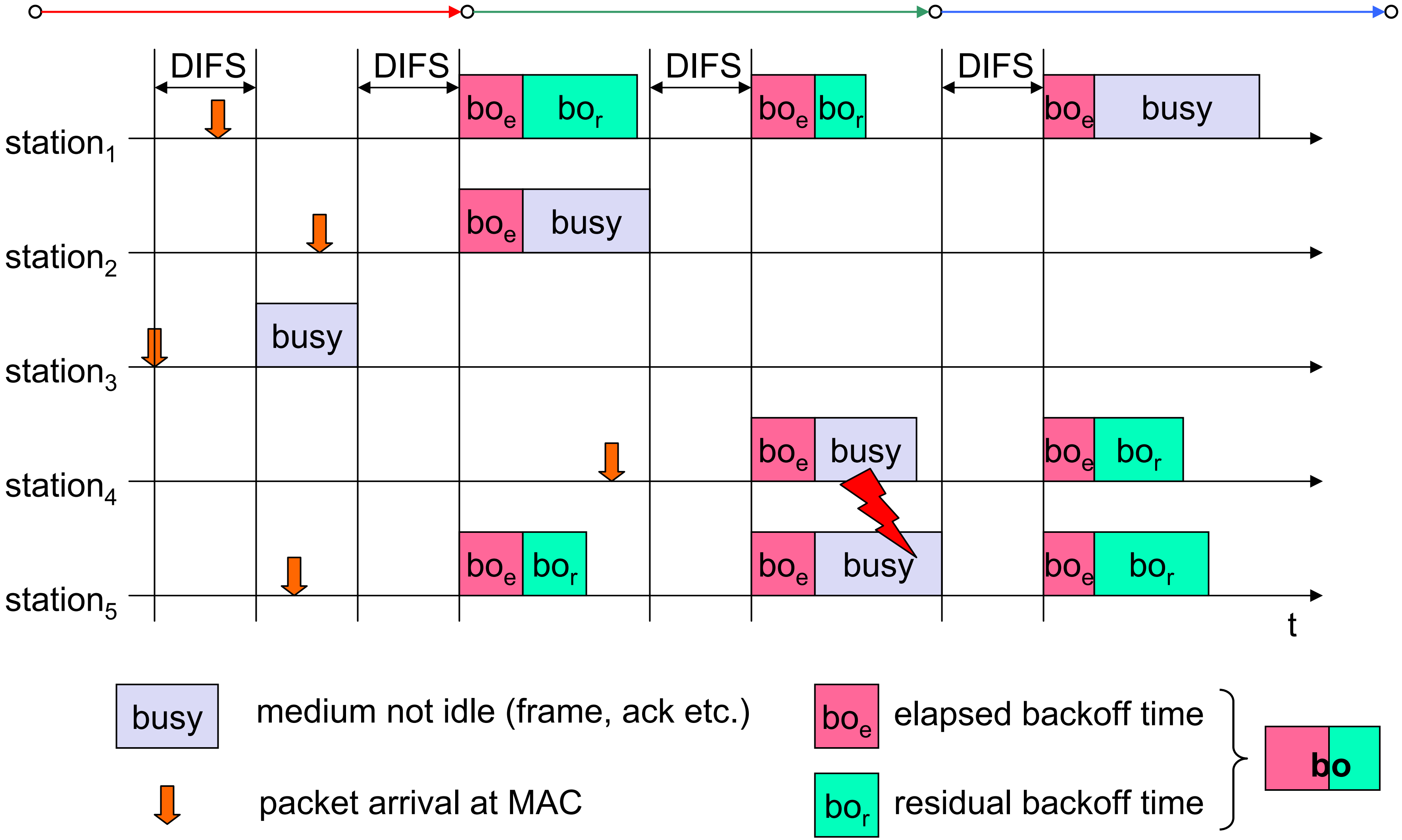


CSMA/CA



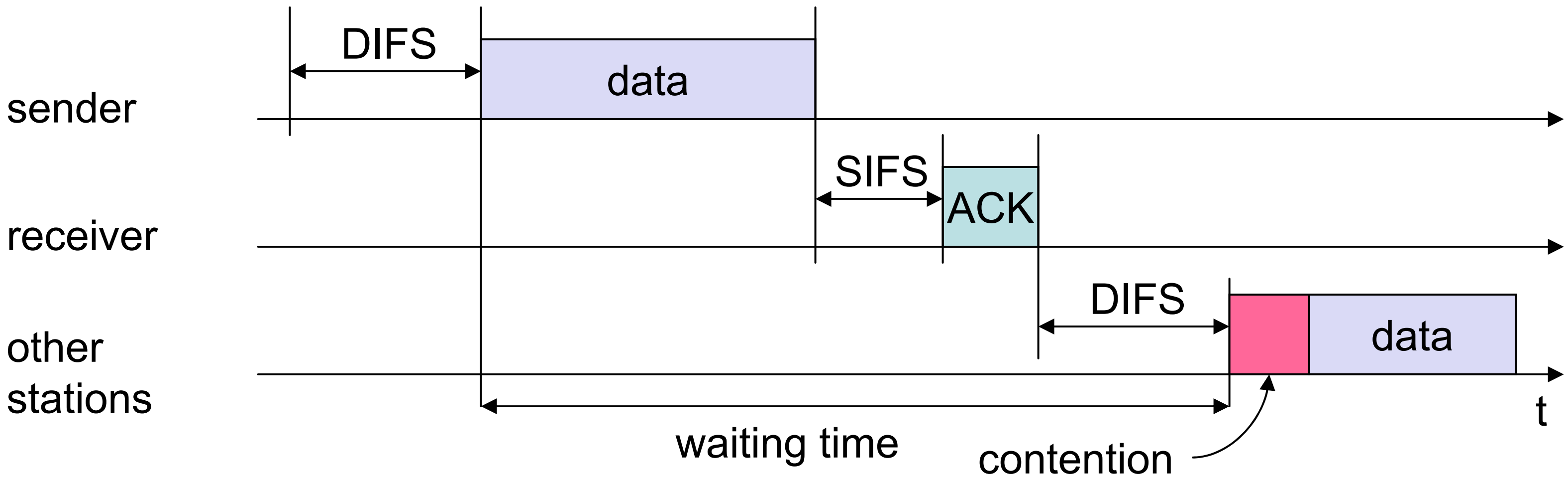
- station ready to send starts sensing the medium (Carrier Sense based on CCA, Clear Channel Assessment)
- if the medium is free for the duration of an Inter-Frame Space (IFS), the station can start sending (IFS depends on service type)
- if the medium is busy, the station has to wait for a free IFS,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



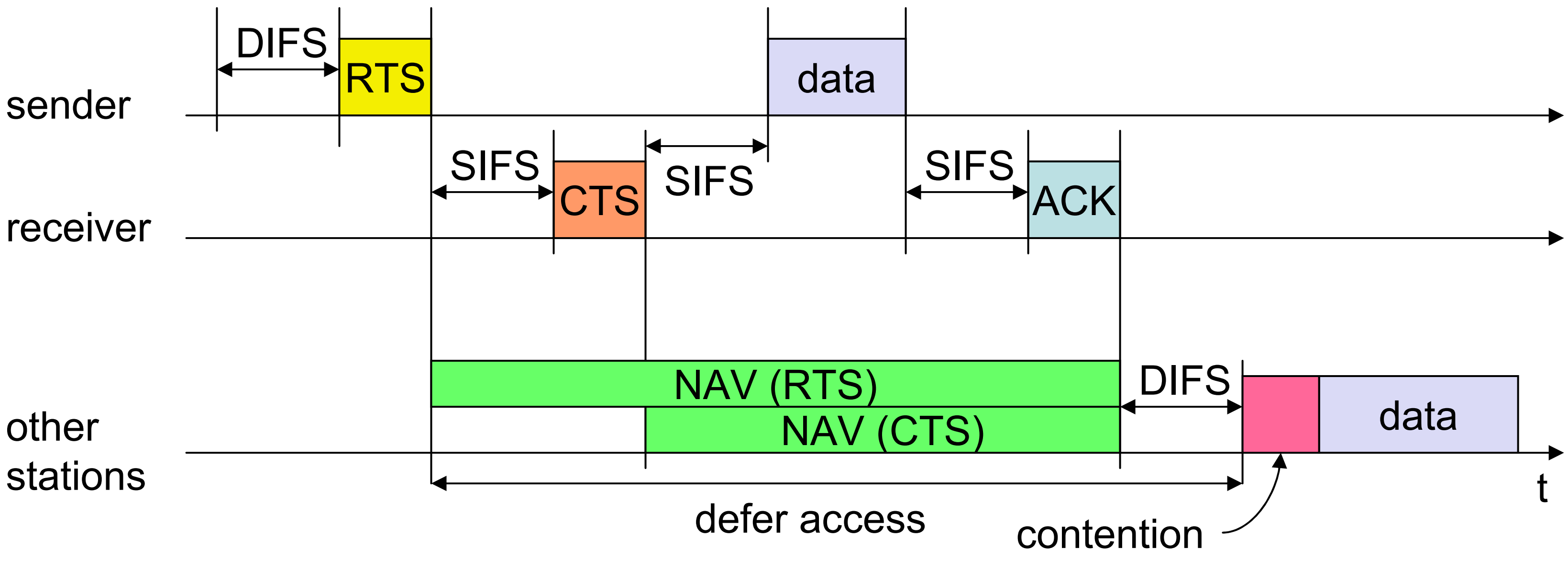
CSMA/CA 2

- 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



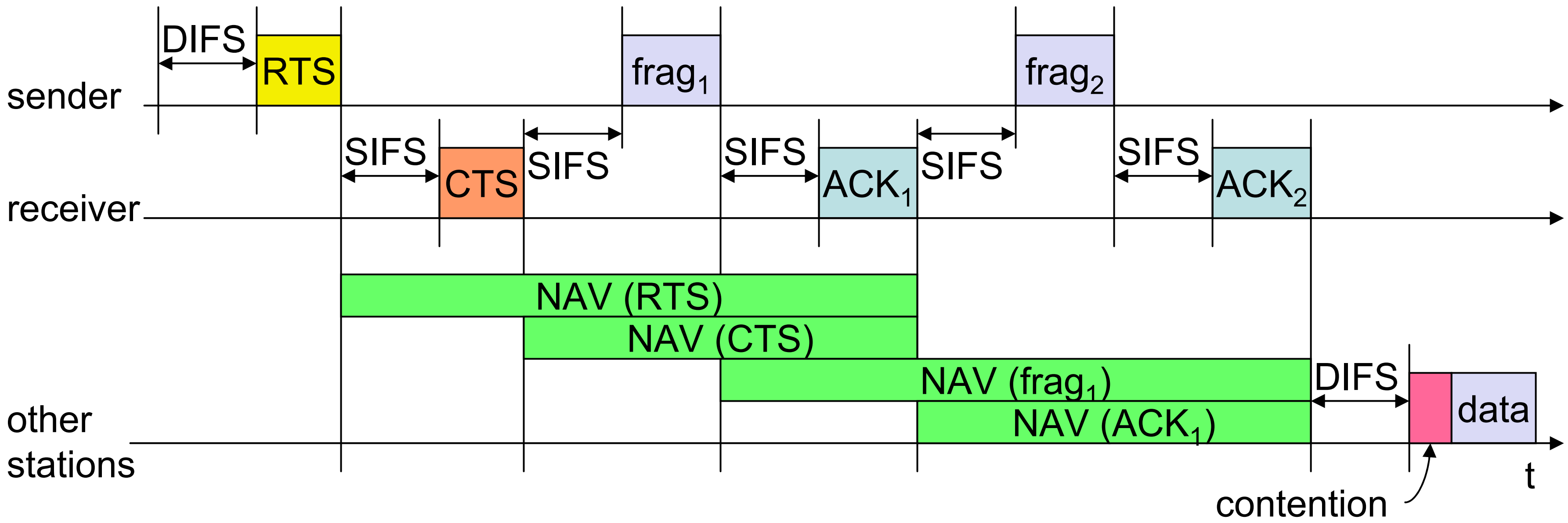
DFWMAC

- 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?

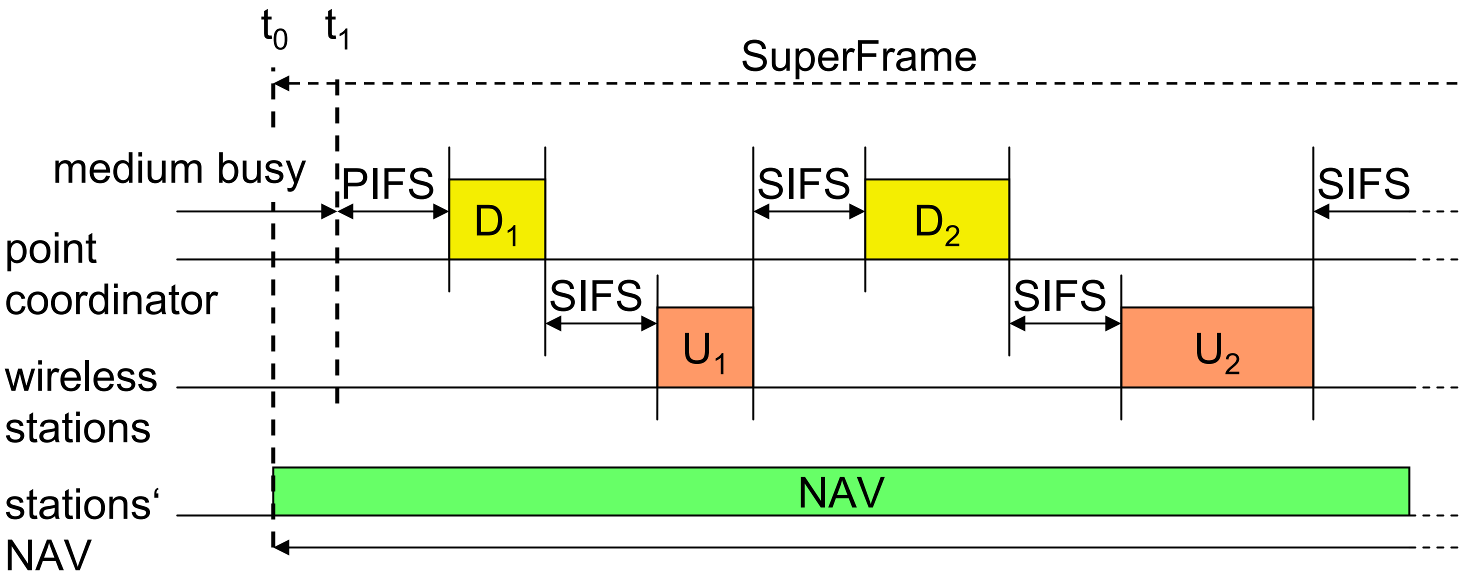
- For the sake of a simplified analysis we assume a = O(h)
- If we further assume that a header can be transmitted with constant probability c, that is, $p^h = c$.
- We choose k = 2h; Then clearly D = f·h, and therefore expected cost

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

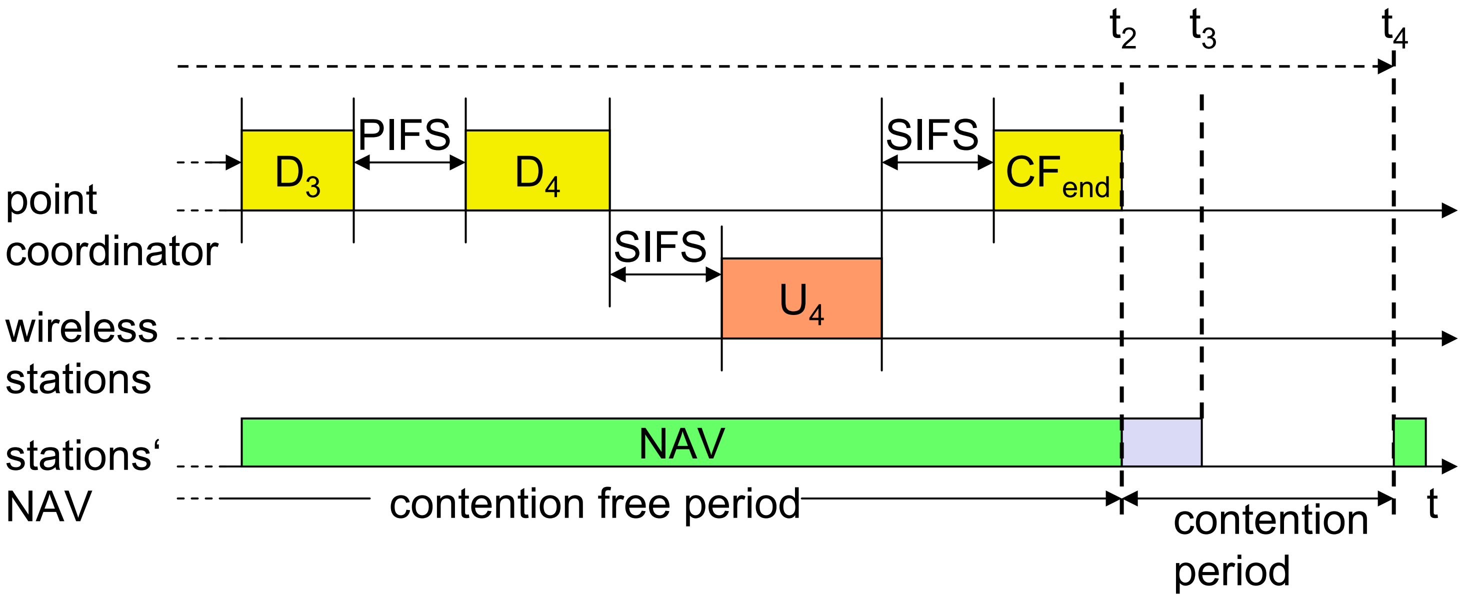
- If already a header cannot be transmitted with high enough probability, then you might keep the message very small, for example k = h + 1/q

DFWMAC-PCF

- An access point can poll stations



DFWMAC-PCF 2



t2
t3
t4
point coordinator
D3
PIFS
D4
SIFS
CFend
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

version, type, fragmentation, security, two DS-bits, ...

- 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

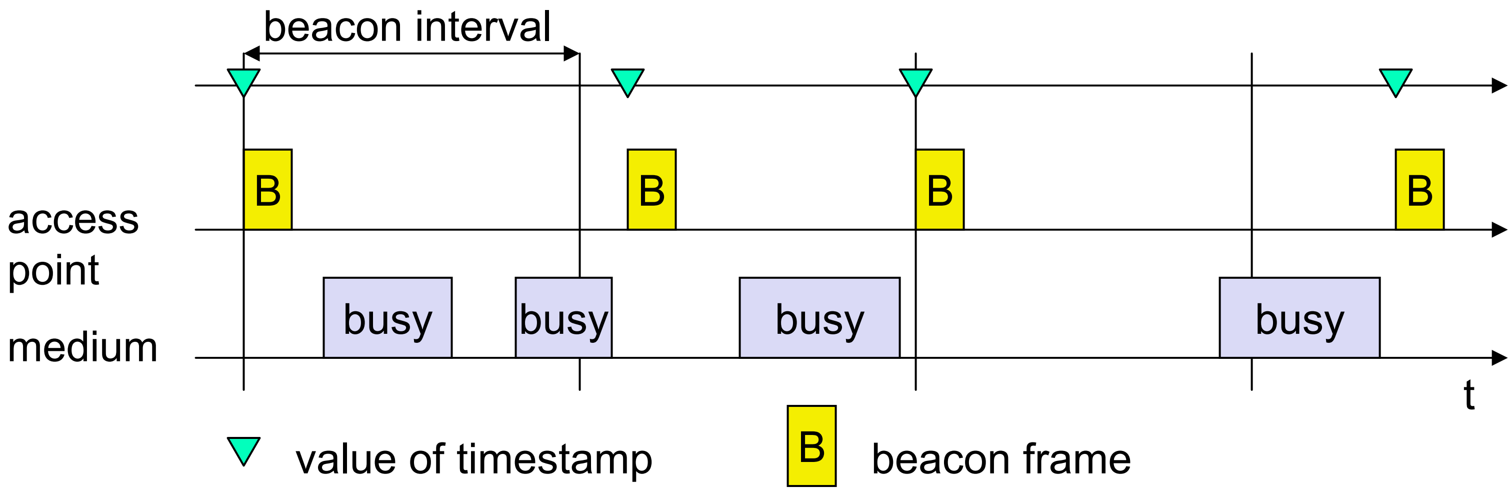
DS: Distribution System
AP: Access Point
DA: Destination Address
SA: Source Address
BSSID: Basic Service Set Identifier
RA: Receiver Address
TA: Transmitter Address

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

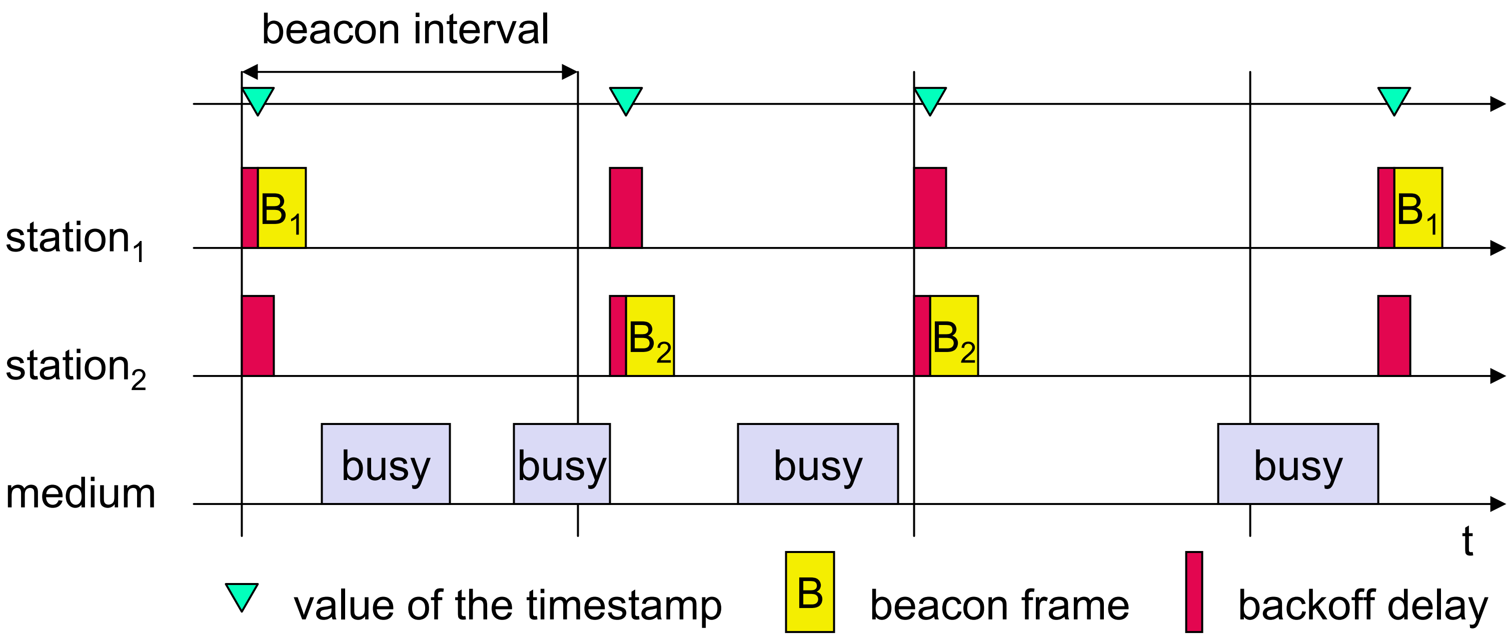
Synchronization

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



Synchronization

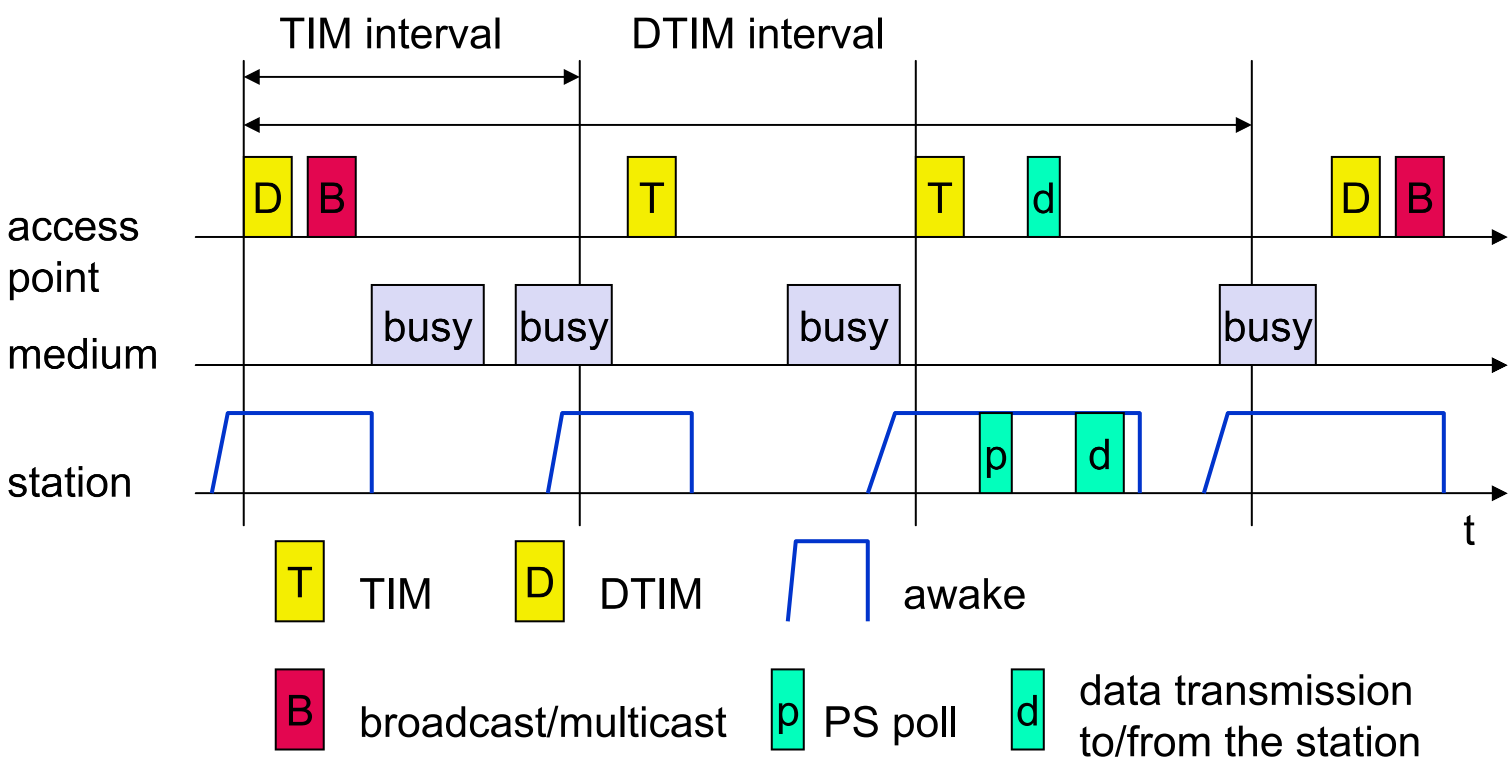
- In an ad-hoc network, the beacon has to be sent by any station



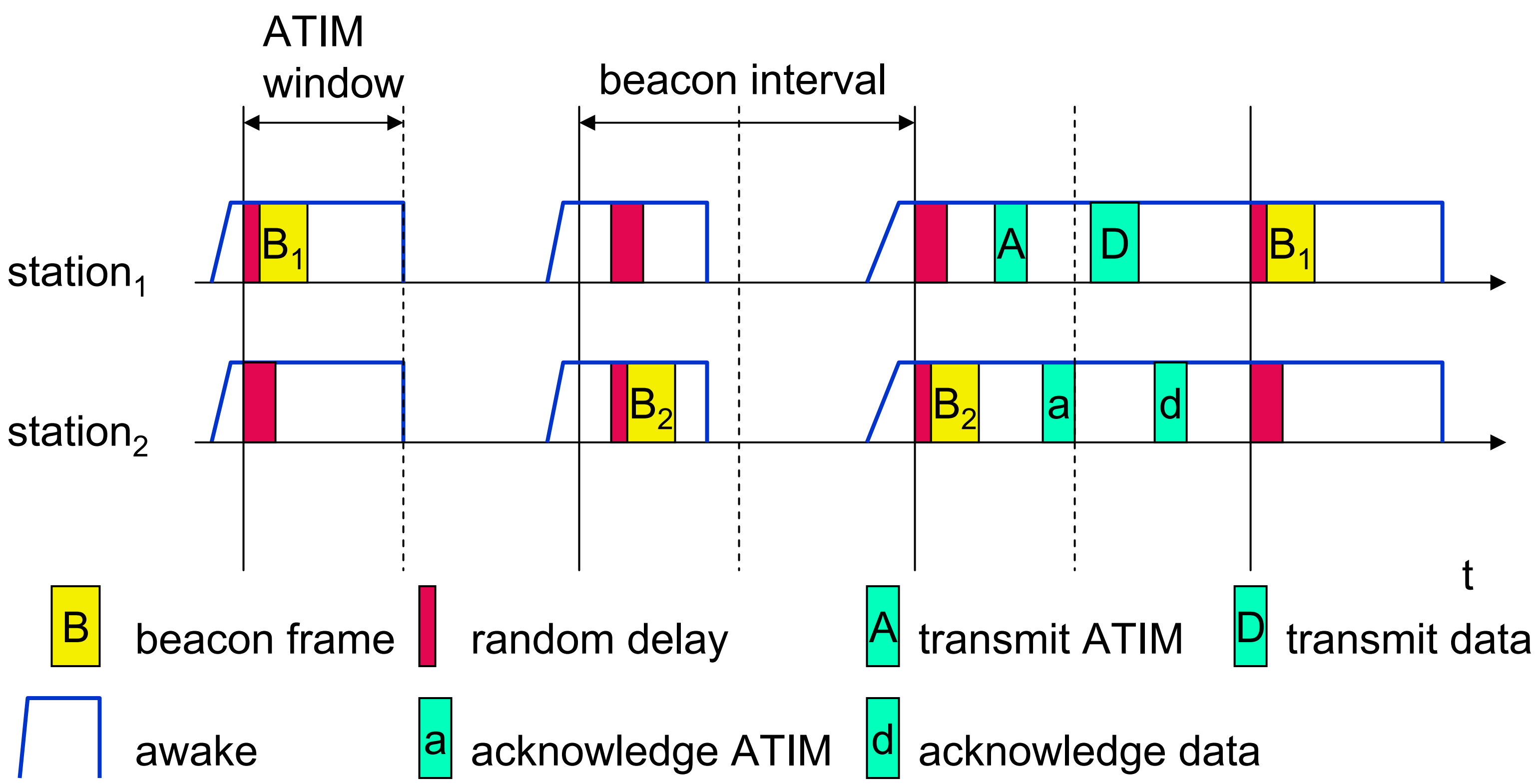
Power management

- 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

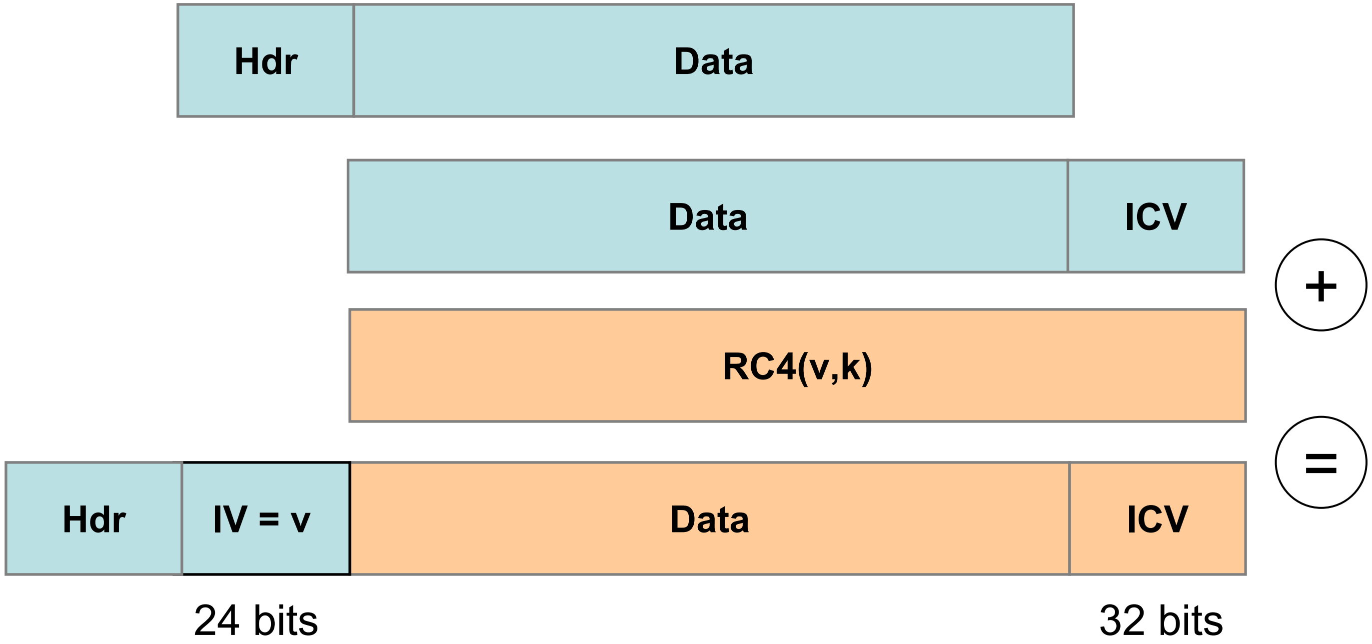
- No or bad connection? Then perform:
- Scanning
  - scan the environment, i.e., listen into the medium for beacon signals or send probes into the medium and wait for an answer
- Association Request
  - station sends a request to one or several AP(s)
- Association Response
  - success: AP has answered, station can now participate
  - failure: continue scanning
- AP accepts association 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

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

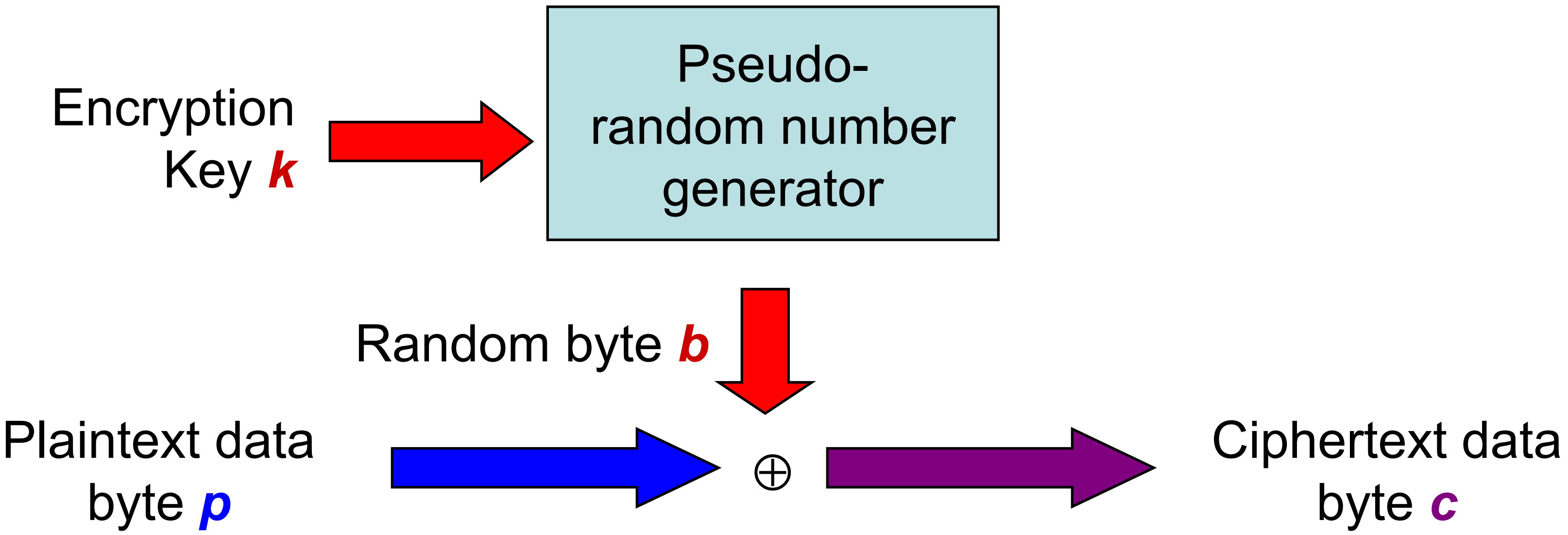


WEP protocol

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

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

- 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.

WEB 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

Future developments

- IEEE 802.11a
  - compatible MAC, but now 5 GHz band
  - transmission rates up to 20 Mbit/s
  - close cooperation with BRAN (ETSI Broadband Radio Access Network)
- IEEE 802.11b
  - higher data rates at 2.4 GHz
  - proprietary solutions offer 11 Mbit/s
- IEEE WPAN (Wireless Personal Area Networks)
  - market potential
  - compatibility
  - low cost/power, small form factor
  - technical/economic feasibility
  - Example: Bluetooth