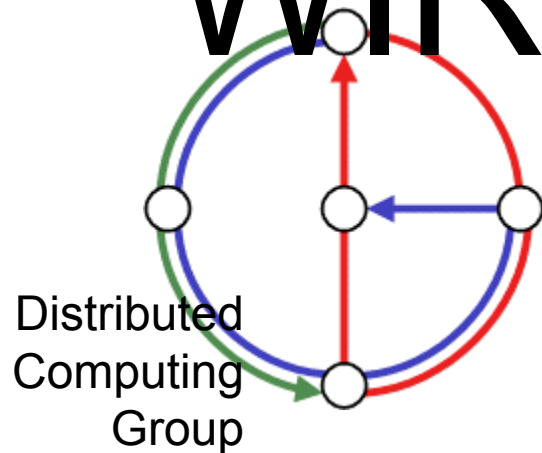


Chapter 4

WIRELESS LAN

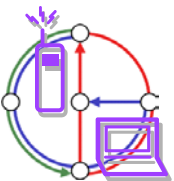


Mobile Computing
Summer 2002

Overview



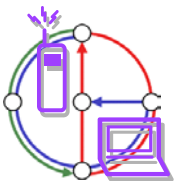
- Design goals
- Characteristics
- IEEE 802.11
 - Architecture
 - Protocol
 - PHY
 - MAC
 - Roaming
 - Security
 - a, b, d, etc.
- Short intermezzo on Cyclic Redundancy codes



Design goals



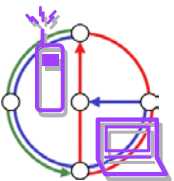
- Global, seamless operation
- Low power consumption for battery use
- No special permissions or licenses required
- Robust transmission technology
- Simplified spontaneous cooperation at meetings
- Easy to use for everyone, simple management
- Interoperable with wired networks
- Security (no one should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

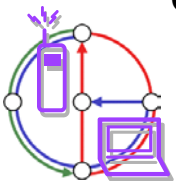


Infrared vs. Radio transmission



- 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

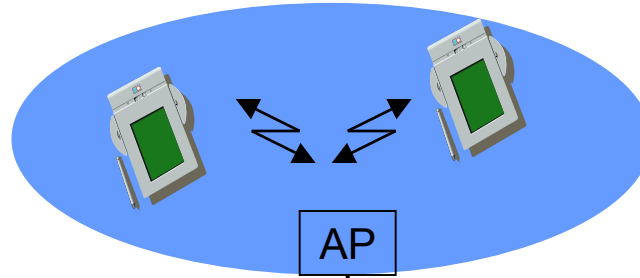
- Radio
- typically using the license free ISM band at 2.4 GHz
- + experience from wireless WAN and mobile phones can be used
- + coverage of larger areas possible (radio can penetrate walls, furniture etc.)
- very limited license free frequency bands
- shielding more difficult, interference with other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



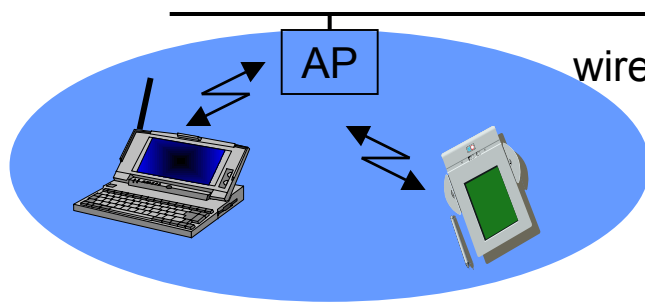
Infrastructure vs. ad-hoc networks



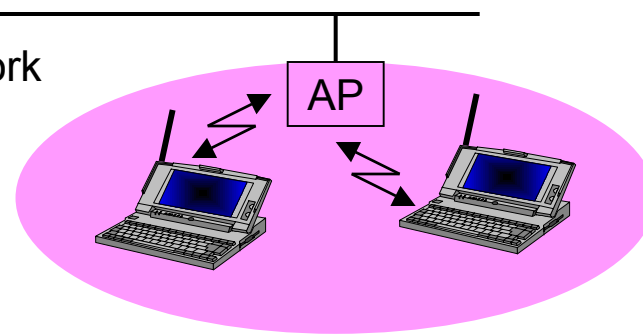
Infrastructure network



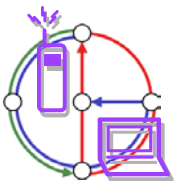
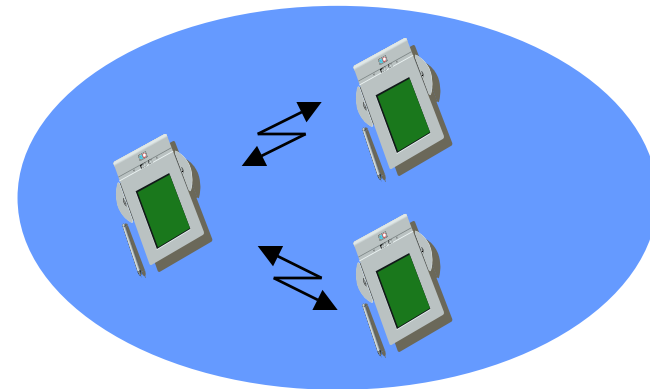
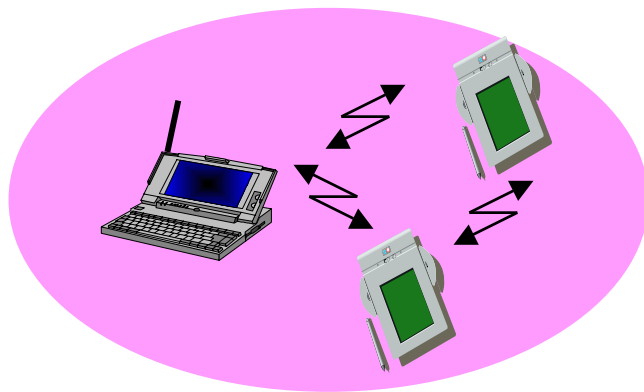
AP: Access Point



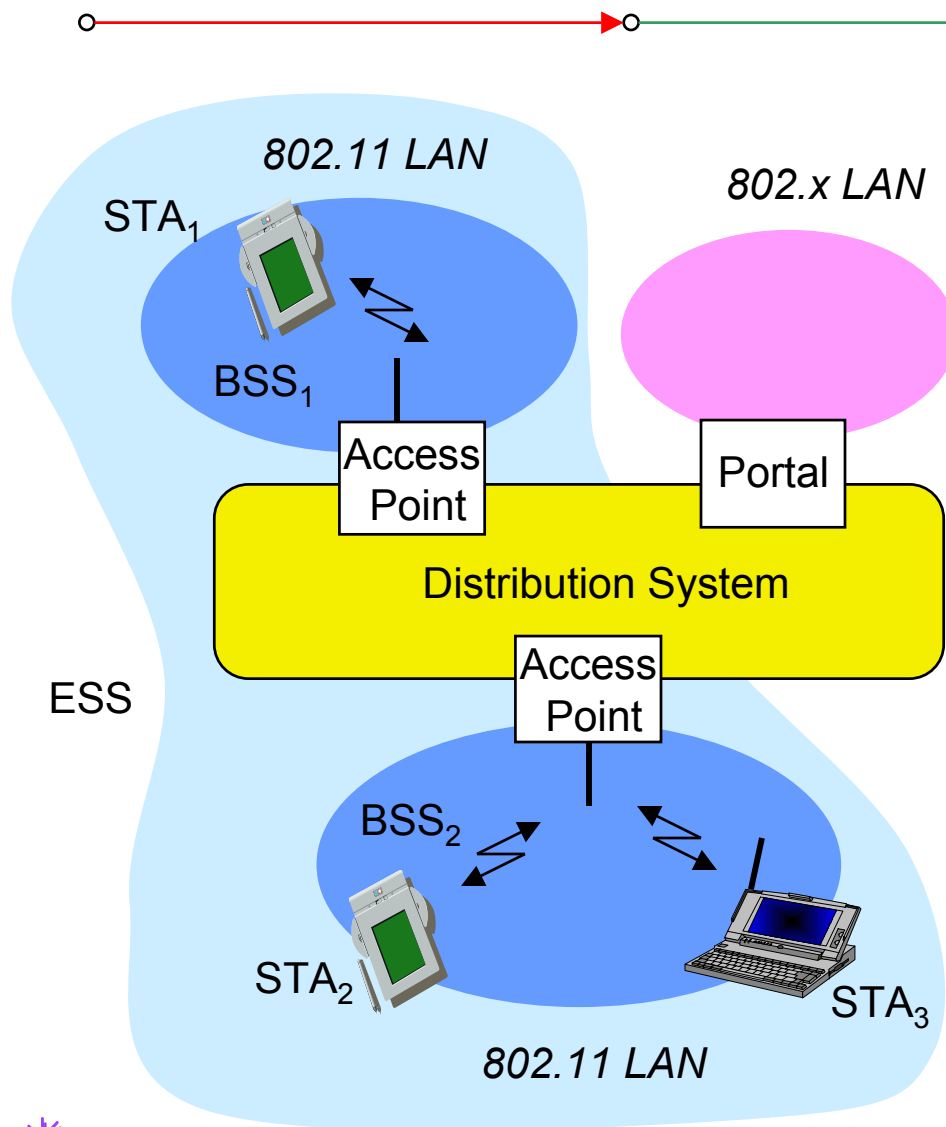
wired network



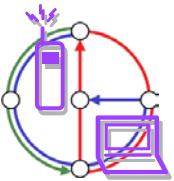
Ad-hoc network



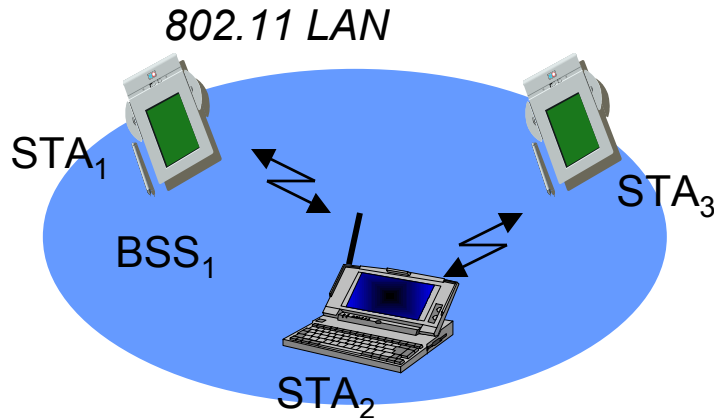
802.11 – Architecture of an infrastructure network



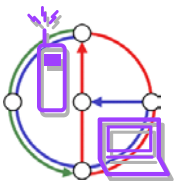
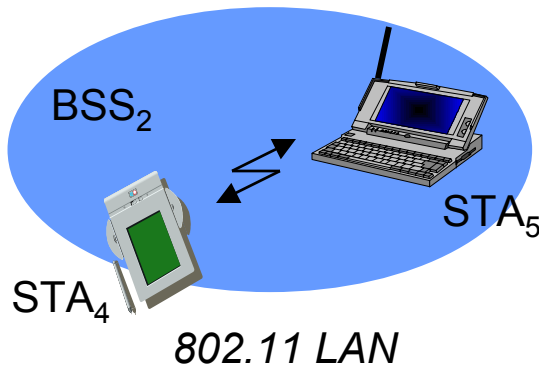
- **Station (STA)**
 - terminal with access mechanisms to the wireless medium and radio contact to the access point
- **Basic Service Set (BSS)**
 - group of stations using the same radio frequency
- **Access Point**
 - station integrated into the wireless LAN and the distribution system
- **Portal**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



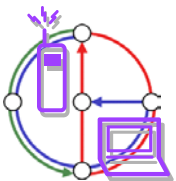
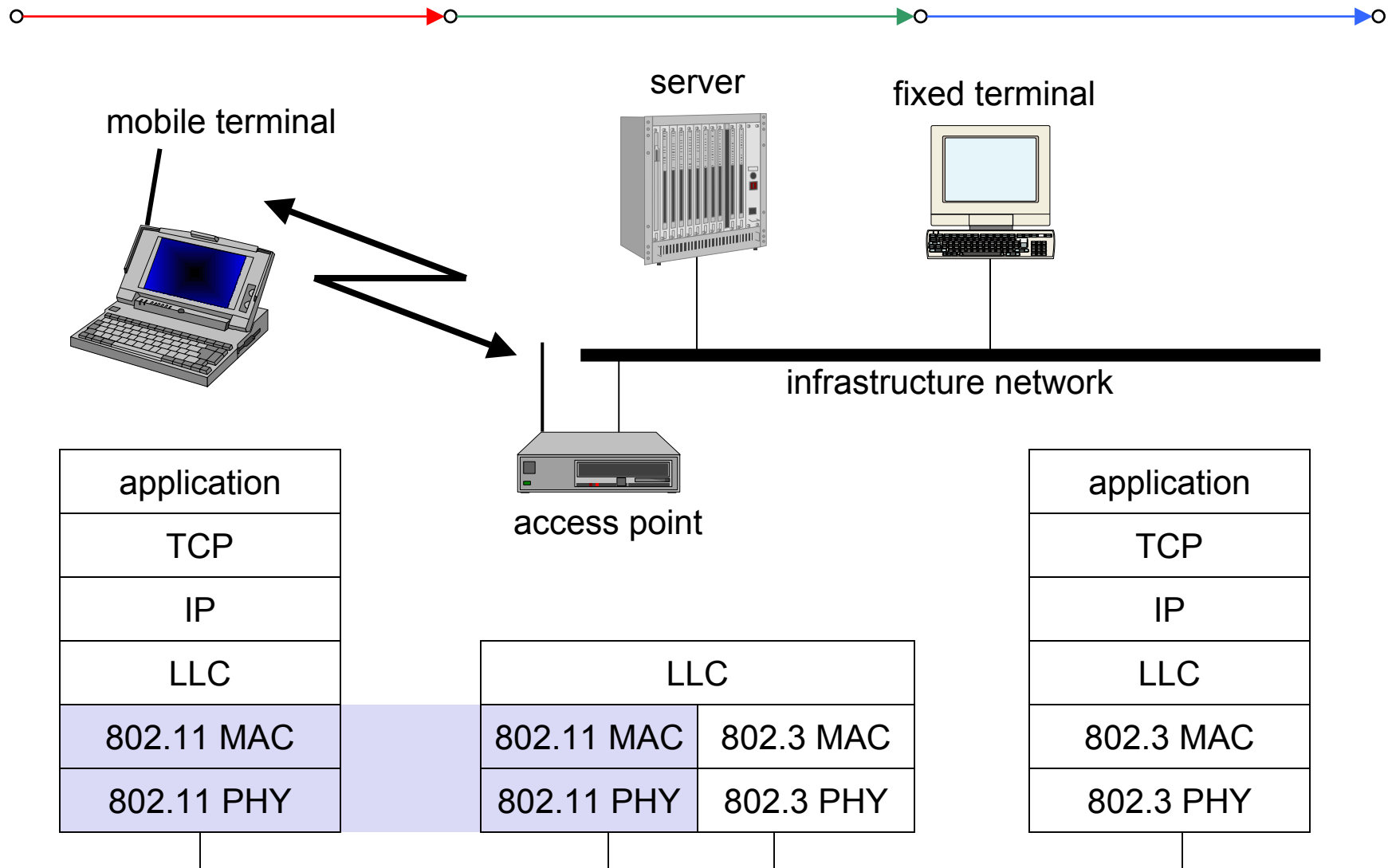
802.11 – Architecture of an ad-hoc network



- 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



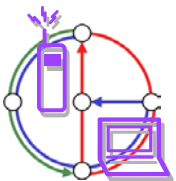
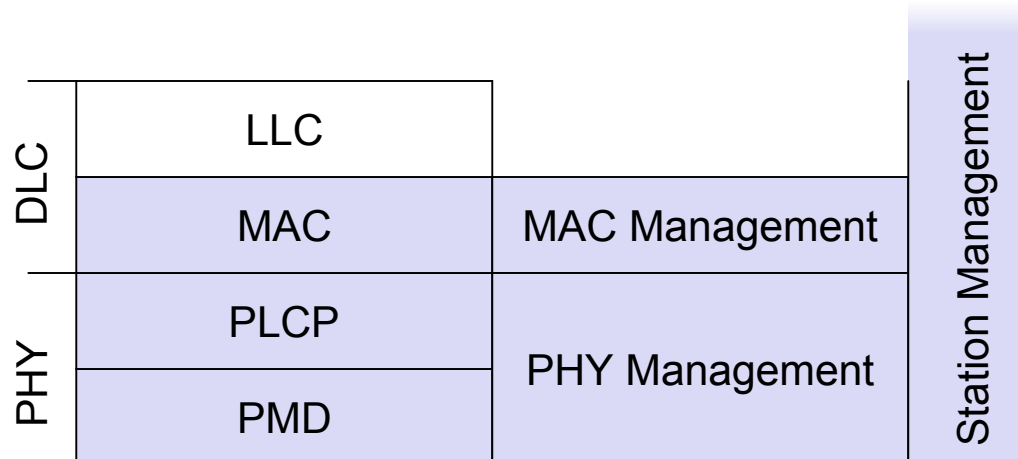
802.11 – Protocol architecture



802.11 – The lower layers in detail



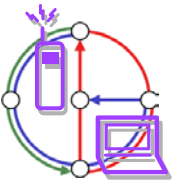
- PMD (Physical Medium Dependent)
 - modulation, coding
- PLCP (Physical Layer Convergence Protocol)
 - clear channel assessment signal (carrier sense)
- PHY Management
 - channel selection, PHY-MIB
- Station Management
 - coordination of all management functions
- MAC
 - access mechanisms
 - fragmentation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



802.11 - Physical layer



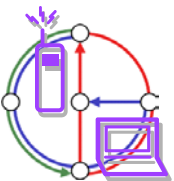
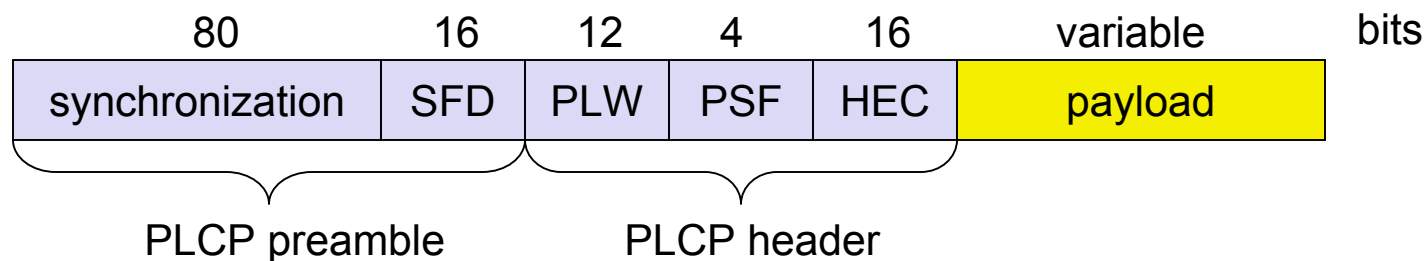
- 3 versions: 2 radio (2.4 GHz), 1 IR:
- FHSS (Frequency Hopping Spread Spectrum)
 - spreading, despreading, signal strength, 1 Mbit/s
 - at least 2.5 frequency hops/s, two-level GFSK modulation
- DSSS (Direct Sequence Spread Spectrum)
 - DBPSK modulation for 1 Mbit/s (Differential Binary Phase Shift 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



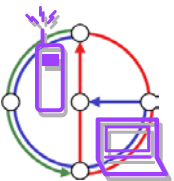
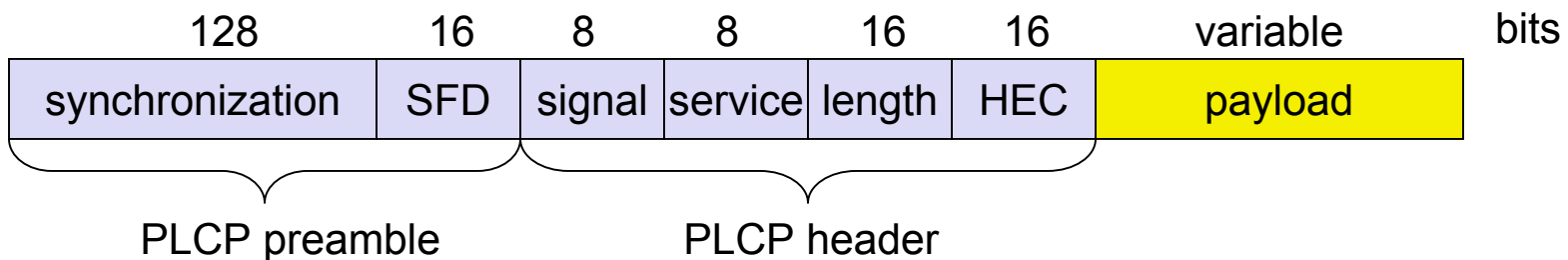
- Synchronization
 - synch with 010101... pattern
- SFD (Start Frame Delimiter)
 - 0000110010111101 start pattern
- PLW (PLCP_PDU Length Word)
 - length of payload incl. 32 bit CRC of payload, $PLW < 4096$
- PSF (PLCP Signaling Field)
 - data rate of payload (1 or 2 Mbit/s)
- HEC (Header Error Check)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



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

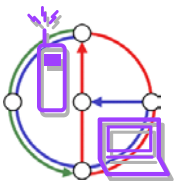


Cyclic Redundancy Code (CRC): Ring



- Polynomes with binary coefficients $b_k x^k + b_{k-1} x^{k-1} + \dots + b_0 x^0$
- 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, \cdot) 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:

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



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

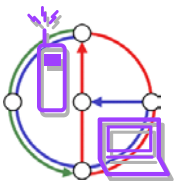
011

111

100

010

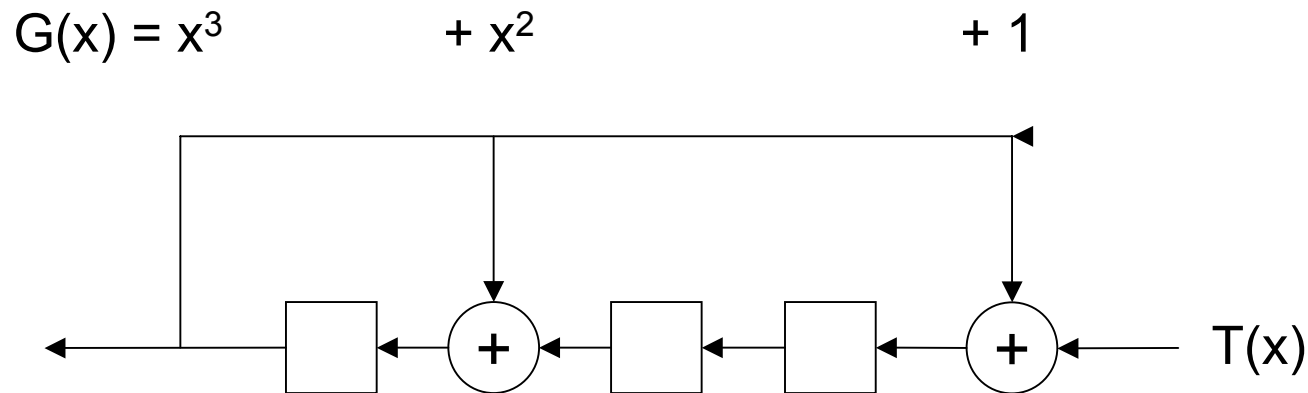
- Idea: Fill CRC with remainder when dividing $T(x)$ with HEC=00...0 by $G(x)$. Then calculating and testing CRC is the same operation.



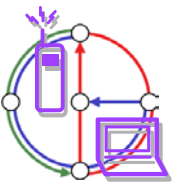
Cyclic Redundancy Code (CRC): Division in Hardware



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



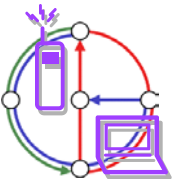
Finally the remainder of the division is in the registers



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



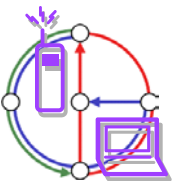
- Generator polynome $G(x) = x^{16} + x^{12} + x^5 + 1$
- Why does $G(x)$ have this complicated form?
- Let $E(x)$ be the transmission errors, that is $T(x) = M(x) + E(x)$
- $T(x) \bmod G(x) = (M(x) + E(x)) \bmod G(x)$
 $= M(x) \bmod G(x) + E(x) \bmod G(x)$
- Since $M(x) \bmod G(x) = 0$ we can detect 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



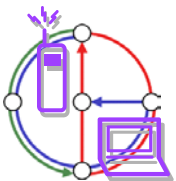
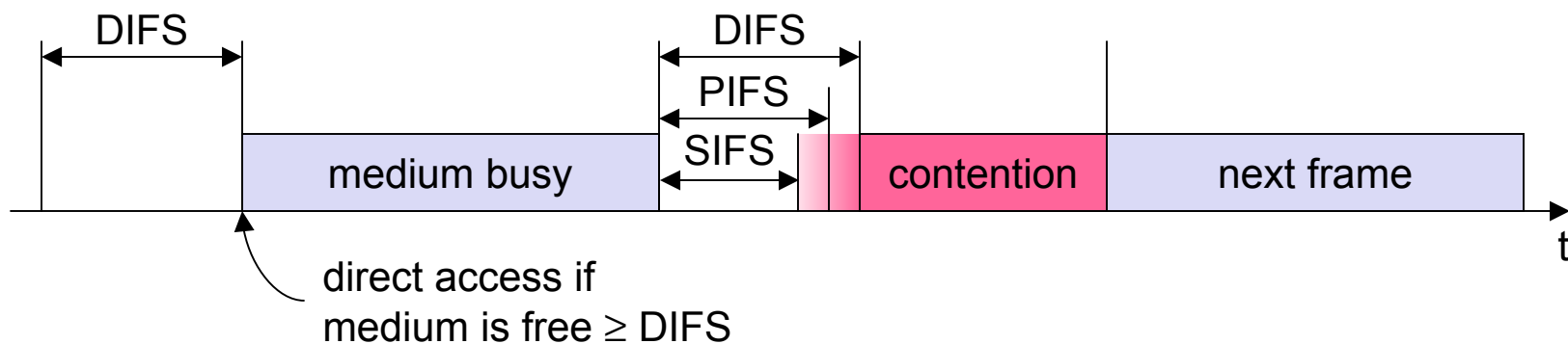
- Traffic services
 - Asynchronous Data Service (mandatory)
 - exchange of data packets based on “best-effort”
 - support of broadcast and multicast
 - Time-Bounded Service (optional)
 - implemented using PCF (Point Coordination Function)
- Access methods
 - DFWMAC-DCF CSMA/CA (mandatory)
 - collision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



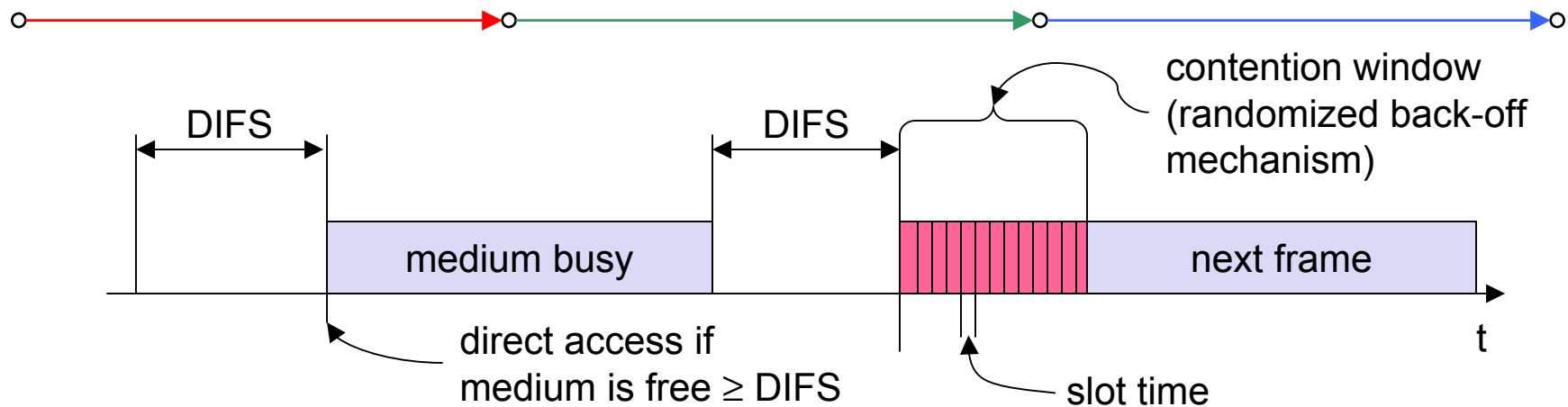
MAC layer



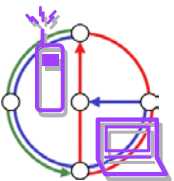
- defined through different inter frame spaces
- no guaranteed, hard priorities
- SIFS (Short Inter Frame Spacing)
 - highest priority, for ACK, CTS, polling response
- PIFS (PCF IFS)
 - medium priority, for time-bounded service using PCF
- DIFS (DCF, Distributed Coordination Function IFS)
 - lowest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



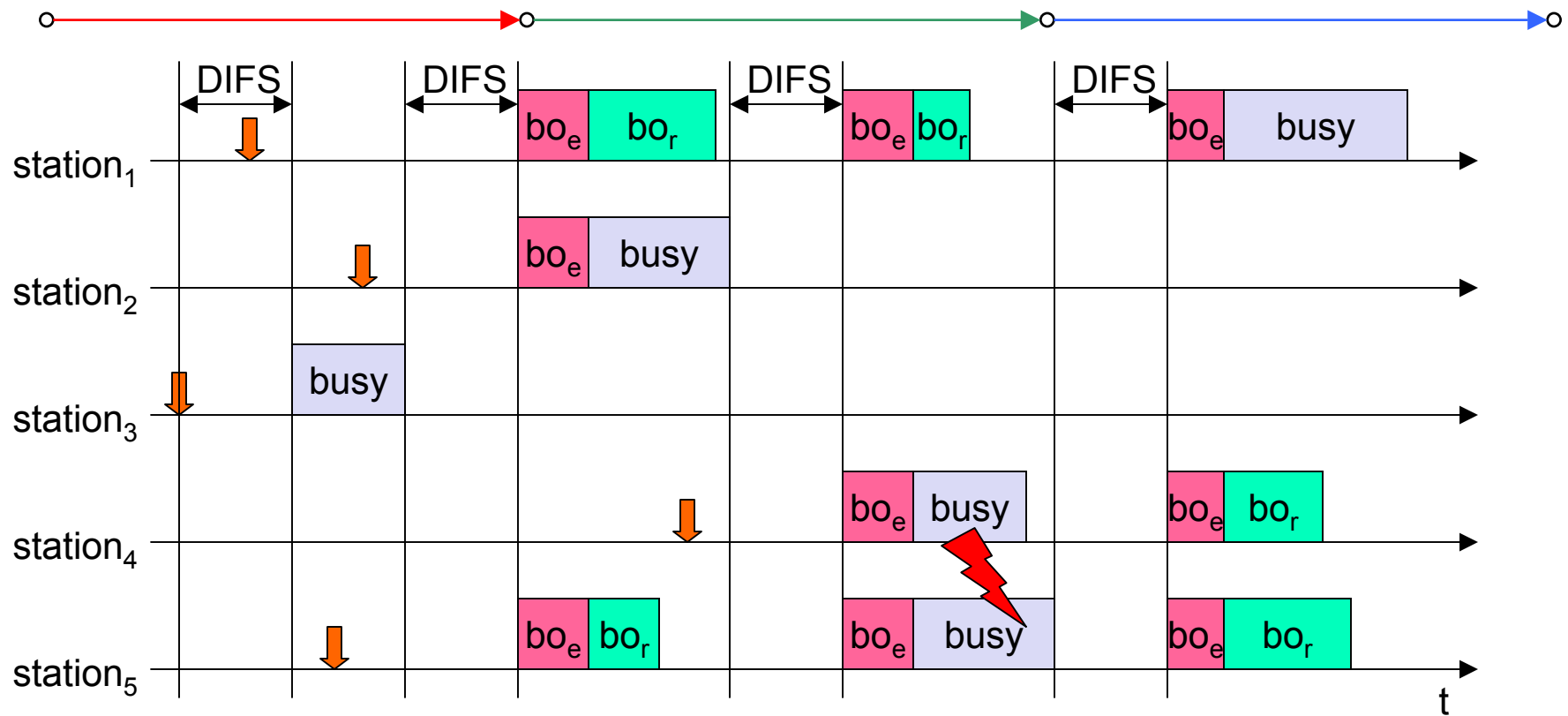
CSMA/CA



- 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



busy

medium not idle (frame, ack etc.)

bo_e

elapsed backoff time

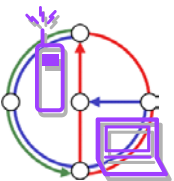


packet arrival at MAC

bo_r

residual backoff time

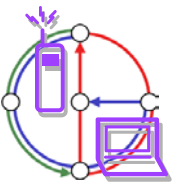
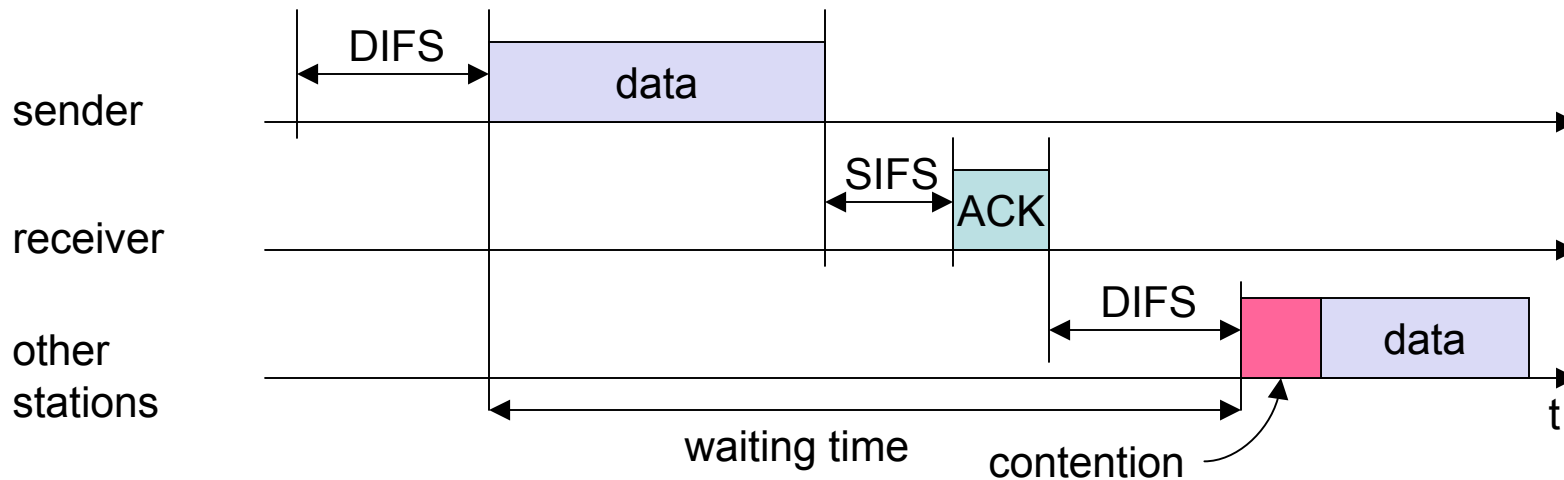
bo



CSMA/CA 2

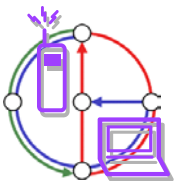
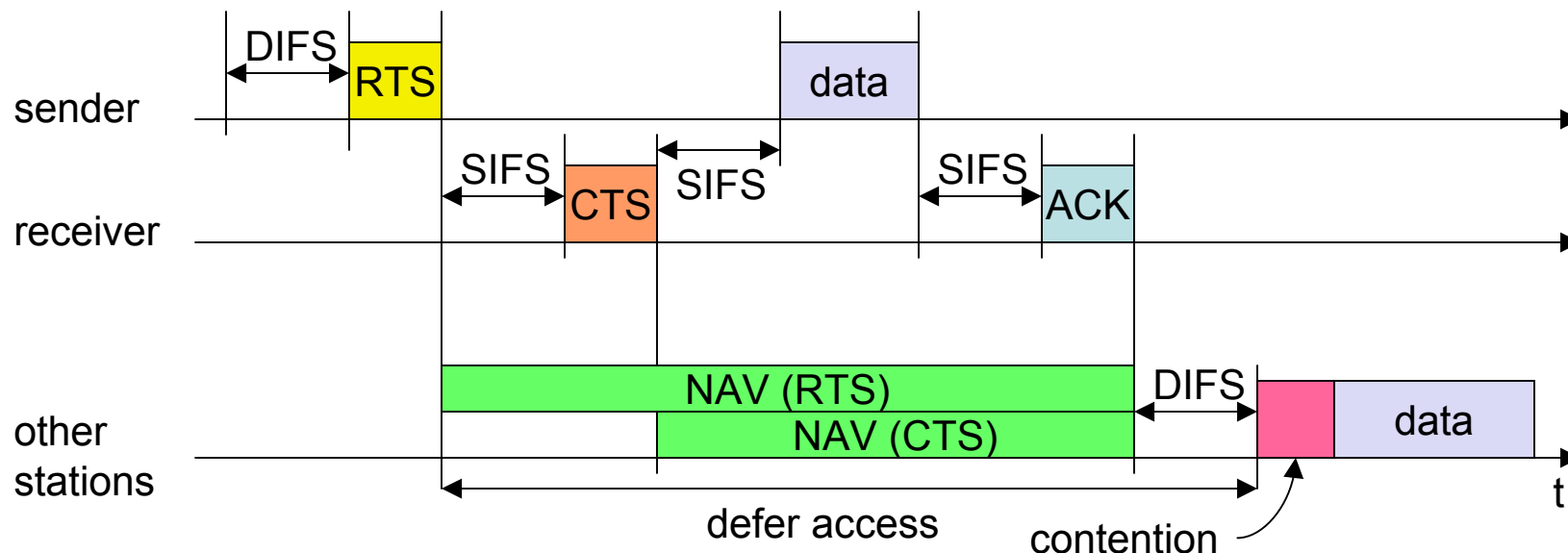


- Sending unicast packets
 - station has to wait for DIFS before sending data
 - receivers acknowledge at once (after waiting for SIFS) if the packet was received correctly (CRC)
 - automatic retransmission of data packets in case of transmission errors



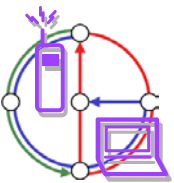
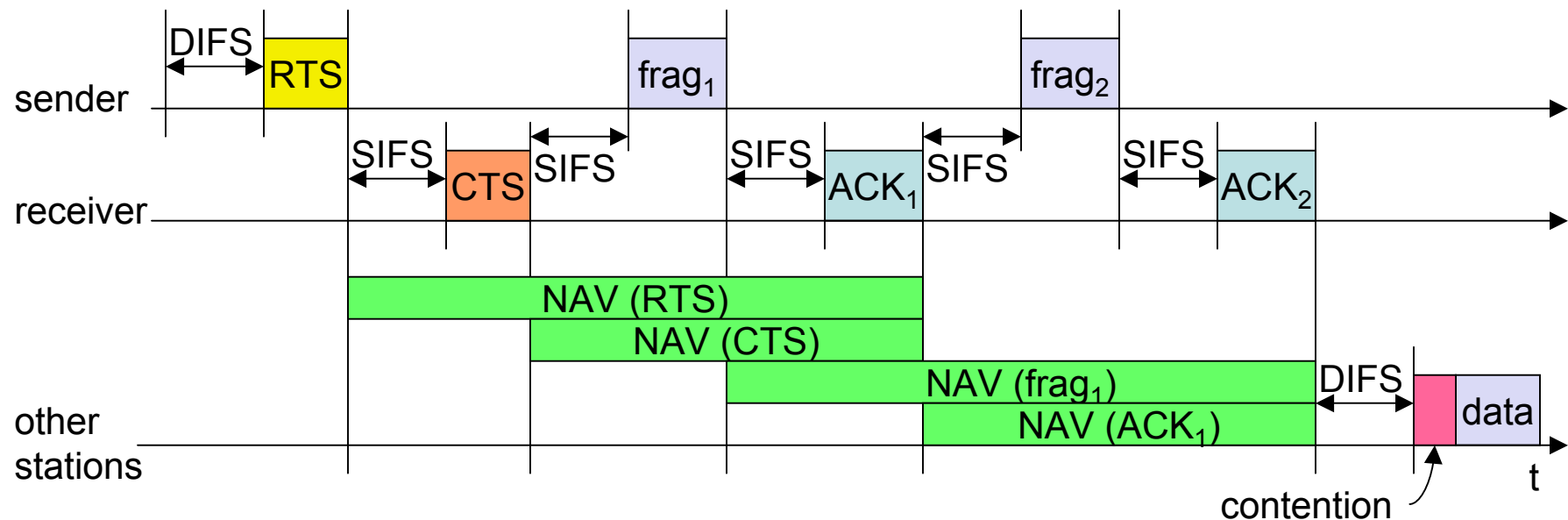
DFWMAC

- 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

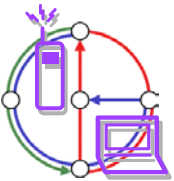
- If packet gets too long transmission error probability grows
- A simple back of the envelope calculation determines the optimal fragment size



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



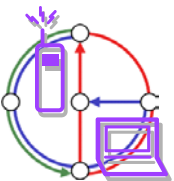
Fragmentation: What fragment size is optimal?



- 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

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

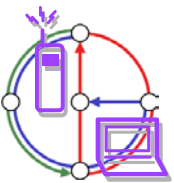
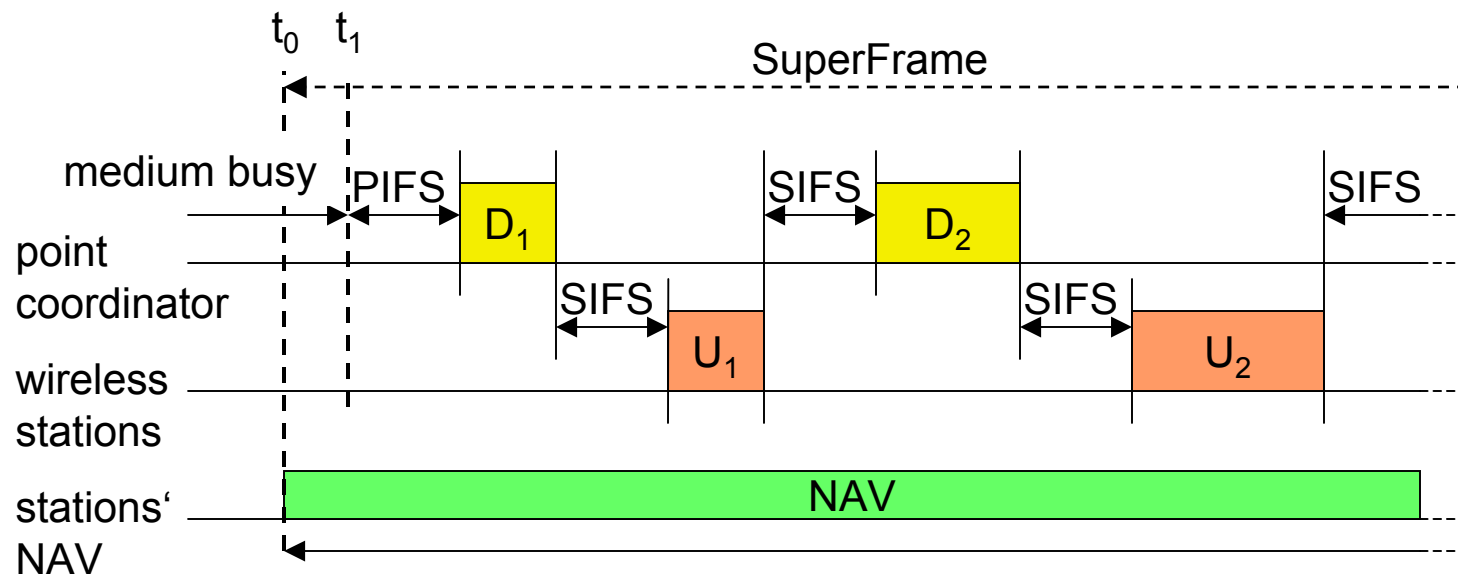
- If already a header cannot be transmitted with high enough probability, then you might keep the message very small, for example $k = h + 1/q$



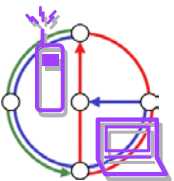
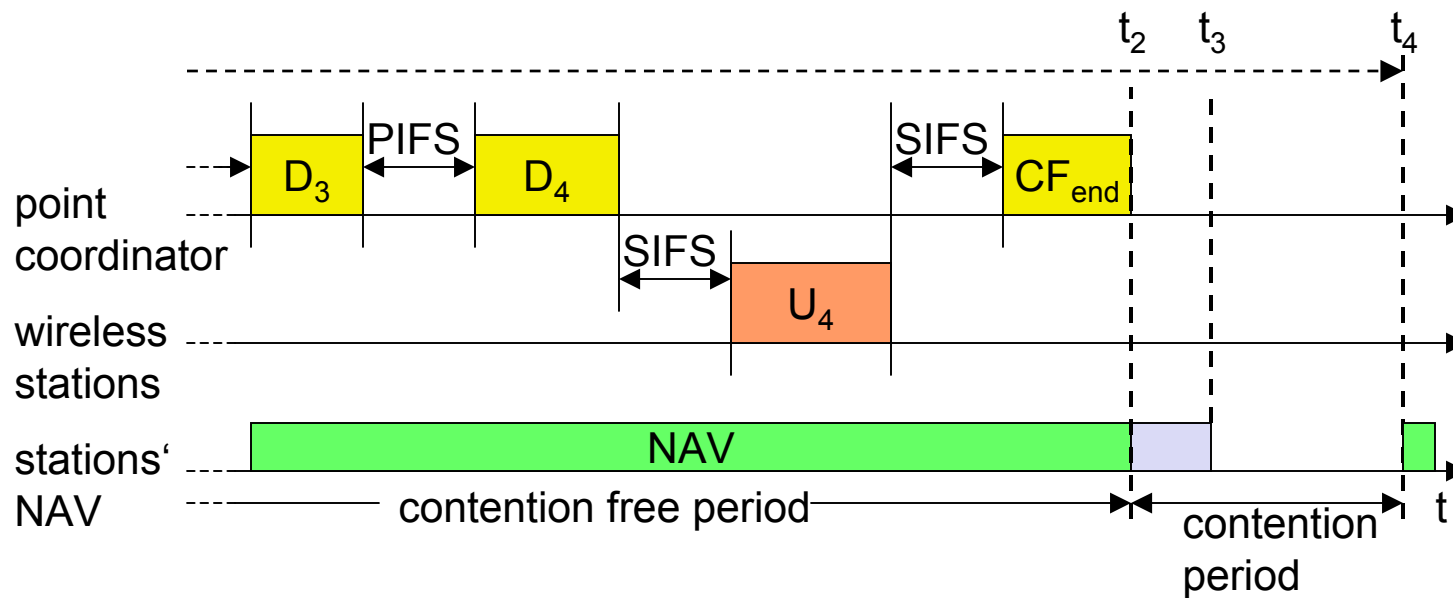
DFWMAC-PCF



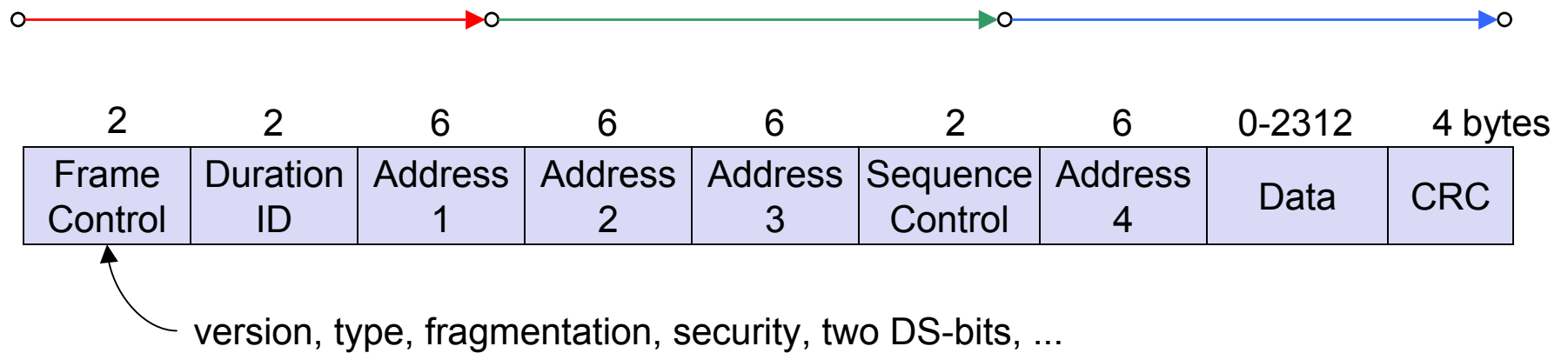
- An access point can poll stations



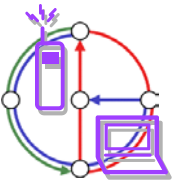
DFWMAC-PCF 2



Frame format



- 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

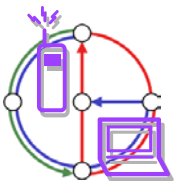
DA: Destination Address

SA: Source Address

BSSID: Basic Service Set Identifier

RA: Receiver Address

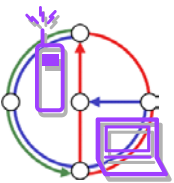
TA: Transmitter Address



MAC management



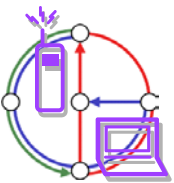
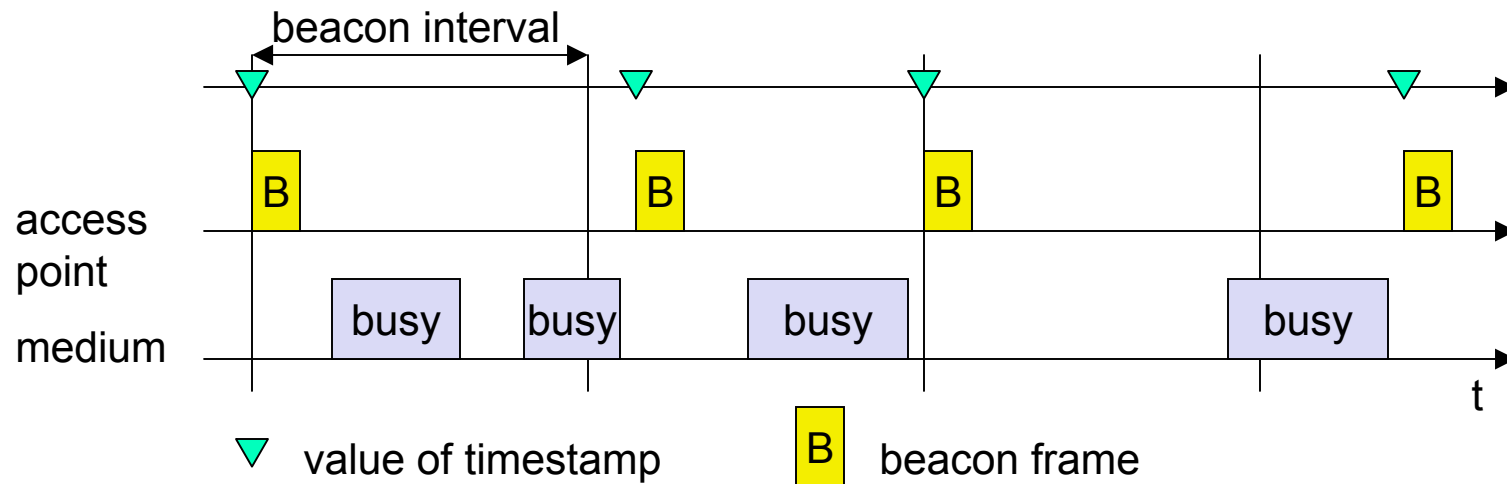
- Synchronization
 - try to find a LAN, try to stay within a LAN
 - timer etc.
- Power management
 - sleep-mode without missing a message
 - periodic sleep, frame buffering, traffic measurements
- Association/Reassociation
 - integration into a LAN
 - roaming, i.e. change networks by changing access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



Synchronization



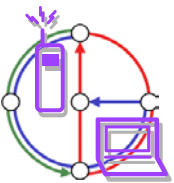
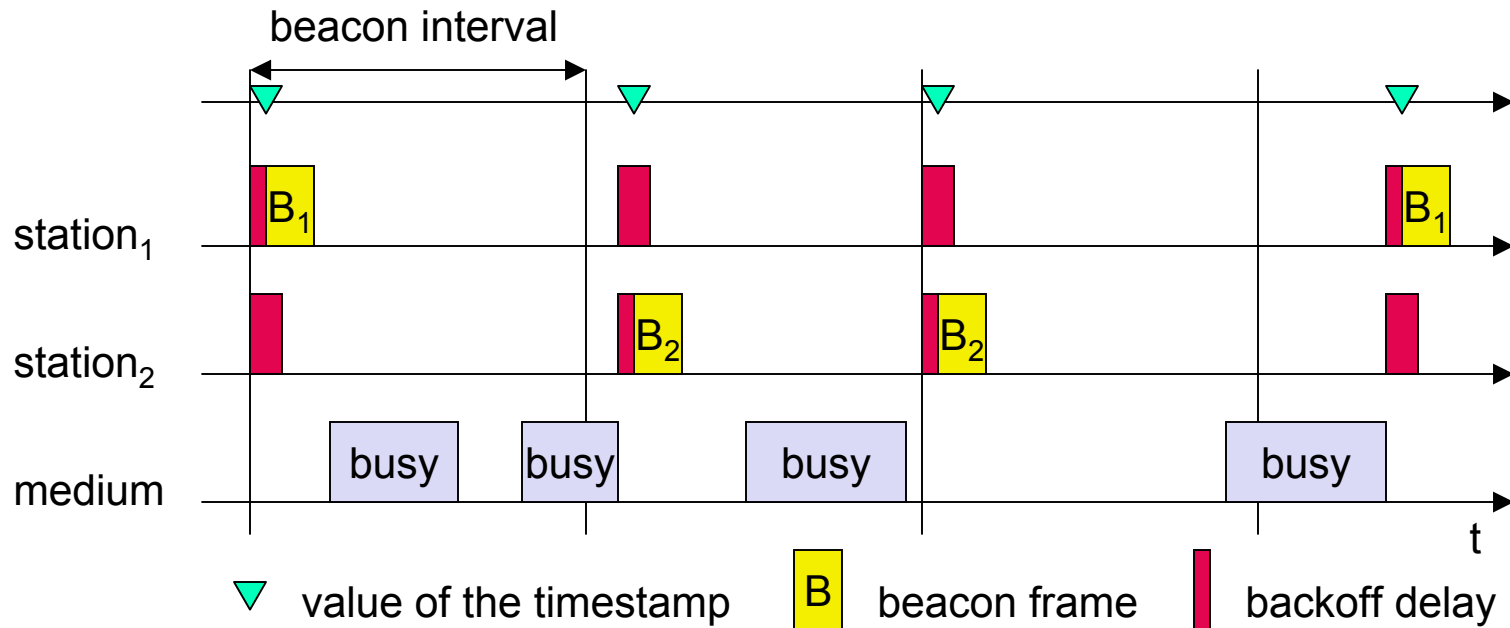
- In an infrastructure network, the access point can send a beacon



Synchronization



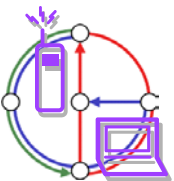
- In an ad-hoc network, the beacon has to be sent by any station



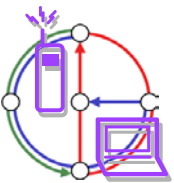
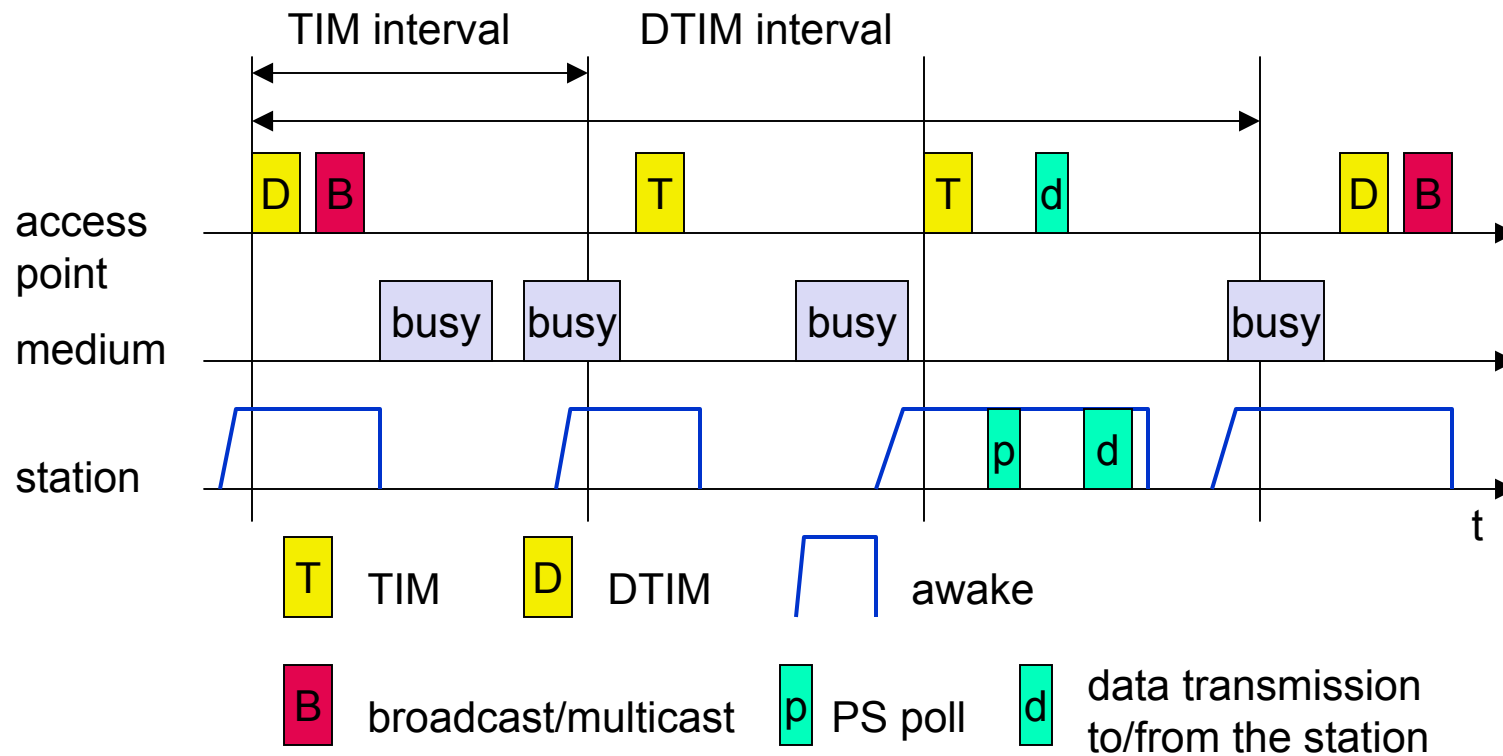
Power management



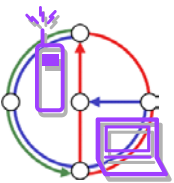
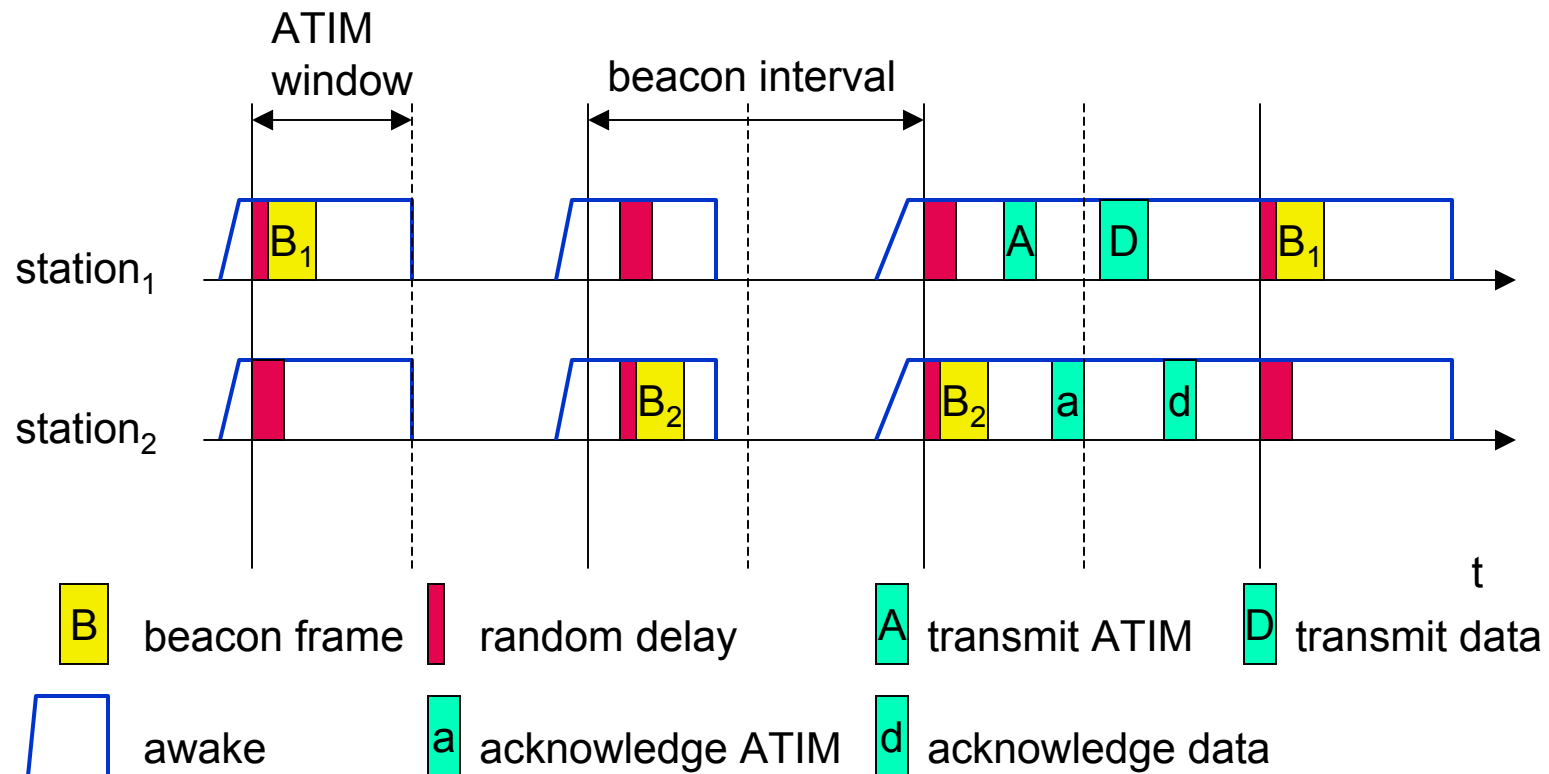
- Idea: if not needed turn off the transceiver
- States of a station: sleep and awake
- Timing Synchronization Function (TSF)
 - stations wake up at the same time
- Infrastructure
 - Traffic Indication Map (TIM)
 - list of unicast receivers transmitted by AP
 - Delivery Traffic Indication Map (DTIM)
 - 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)



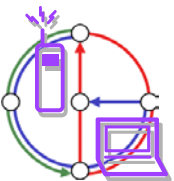
Power saving with wake-up patterns (ad-hoc)



Roaming



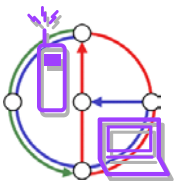
- No or bad connection? Then perform:
- Scanning
 - scan the environment, i.e., listen into the medium for beacon signals or send probes into the medium and wait for an answer
- Association Request
 - station sends a request to one or several AP(s)
- Association Response
 - success: AP has answered,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



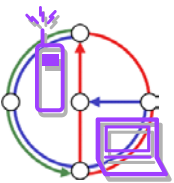
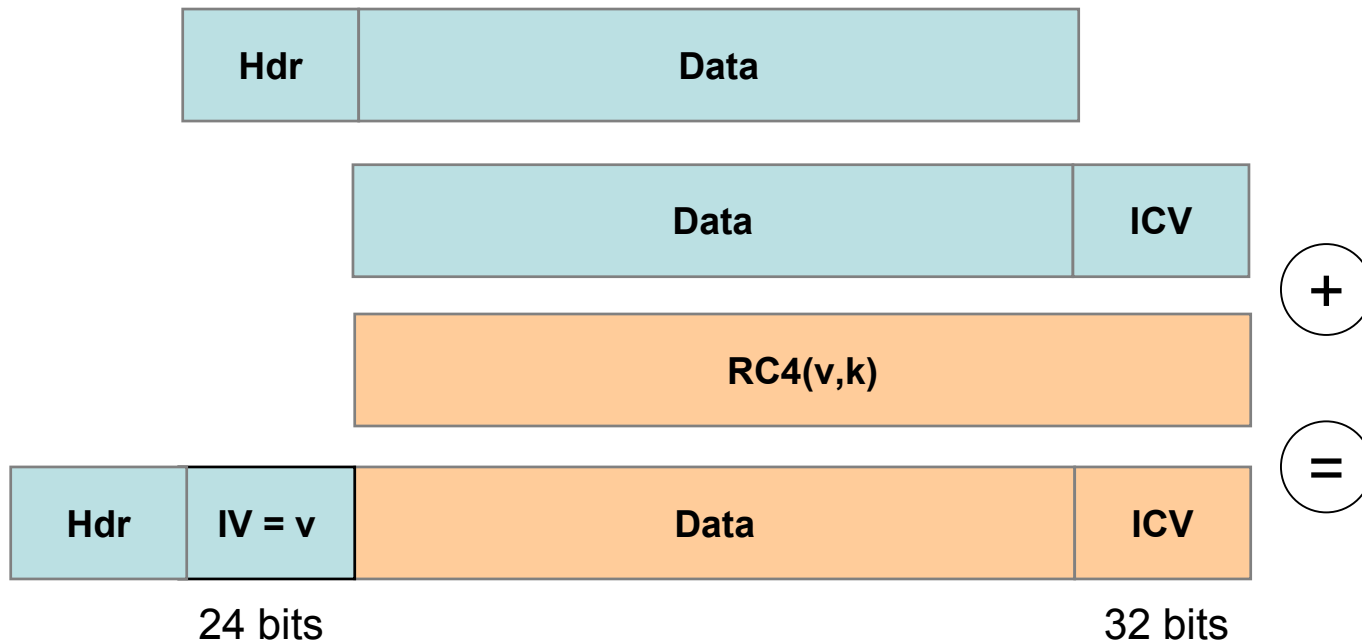
802.11 Security Today



- 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



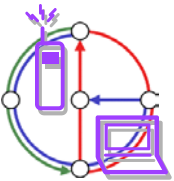
WEP Encapsulation



WEP protocol



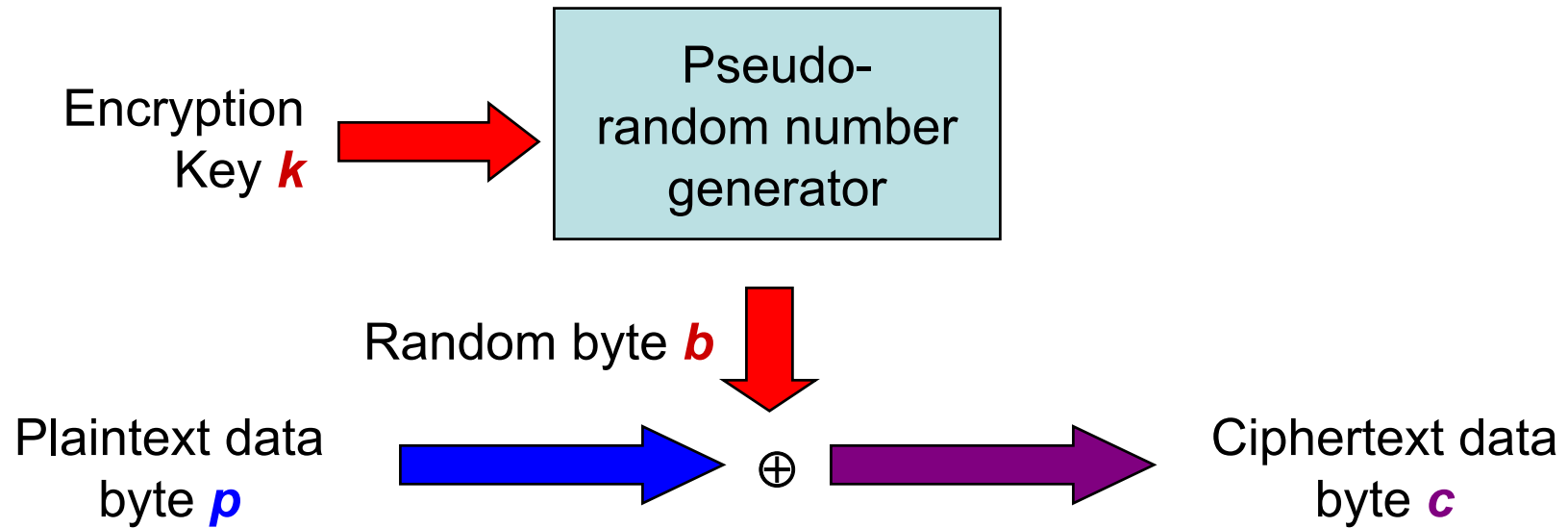
- The sender and receiver share a secret key k
- Sender, in order to transmit a message:
 - Compute a CRC-32 checksum ICV, and attach it to the message
 - Pick a per-packet key IV v , and generate a keystream $RC4(v, k)$
 - Attention: WEP Allows v to be re-used with any packet
 - Encrypt data and attached 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



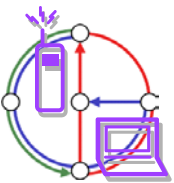
Vernam Ciphers



The WEP encryption algorithm RC4 is a Vernam Cipher:



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



Properties of Vernam Ciphers



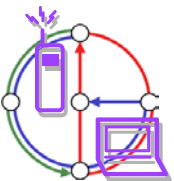
Thought experiment: what happens when p_1 and p_2 are encrypted under the same “random” byte b ?

$$c_1 = p_1 \oplus b$$

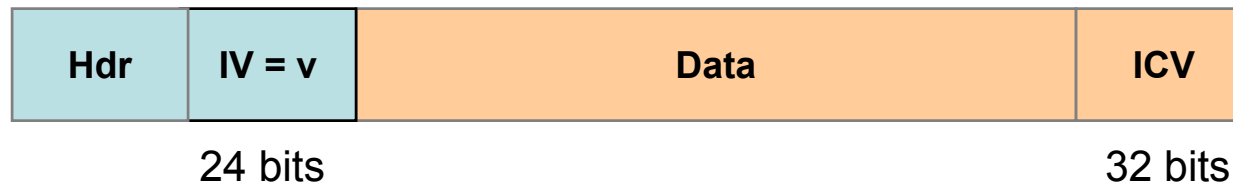
$$c_2 = p_2 \oplus b$$

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

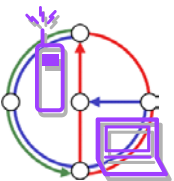
Conclusion: it is a bad idea to encrypt any two bytes of data using the same byte output by a Vernam Cipher PRNG.



How to read WEP encrypted traffic



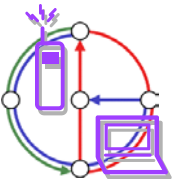
- By the Birthday Paradox, probability P_n two packets will share same IV after n packets is $P_2 = 1/2^{24}$ after two frames and $P_n = P_{n-1} + (n-1)(1-P_{n-1})/2^{24}$ for $n > 2$.
- 50% chance of a collision exists already after 4823 packets.
- Pattern recognition can disentangle the XOR'd recovered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

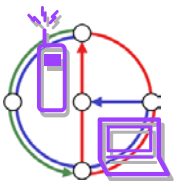
$$p = b_n x^n + b_{n-1} x^{n-1} + \dots + b_0 x^0$$

Then the plaintext with ICV can be represented as :

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

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

$$p x^{32} + \text{ICV}(p) + r$$



Traffic Modification 2



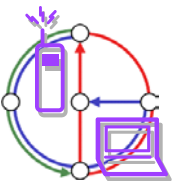
But the ICV is linear, meaning for any polynomials p and q

$$\text{ICV}(p+q) = \text{ICV}(p) + \text{ICV}(q)$$

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

$$\begin{aligned} (p+q)x^{32} + \text{ICV}(p+q) + r &= px^{32} + qx^{32} + \text{ICV}(p) + \text{ICV}(q) + r \\ &= ((px^{32} + \text{ICV}(p)) + r) + (qx^{32} + \text{ICV}(q)) \end{aligned}$$

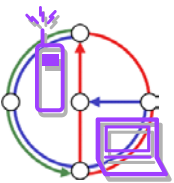
Conclusion: Anyone can alter an WEP encapsulated packet in arbitrary ways without detection, and without knowing $\text{RC4}(v,k)$



WEP Authentication



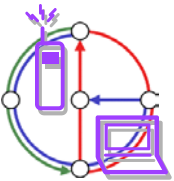
- Goal is that client joining the network really knows the shared key k
- Protocol:
 - Access point sends a challenge string to client
 - Client WEP-encrypts challenge, and sends result back to AP
 - If the challenge is encrypted correctly, AP accepts the client
- Client can spoof protocol the same way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



WEB Message decryption revisited



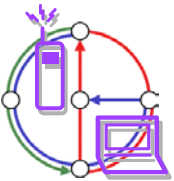
- How can a client decrypt a specific packet with IV v for which the client does not have the $RC4(v,k)$. (The first packet that uses v .)
- Idea: Use the access point (who knows k)
- Spoofing protocol (one of many possibilities):
 - Join the network (authentication spoofing)
 - Send a handcrafted message “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

