Computer Networks
The Media Access Control Sublayer: Practical Implementations

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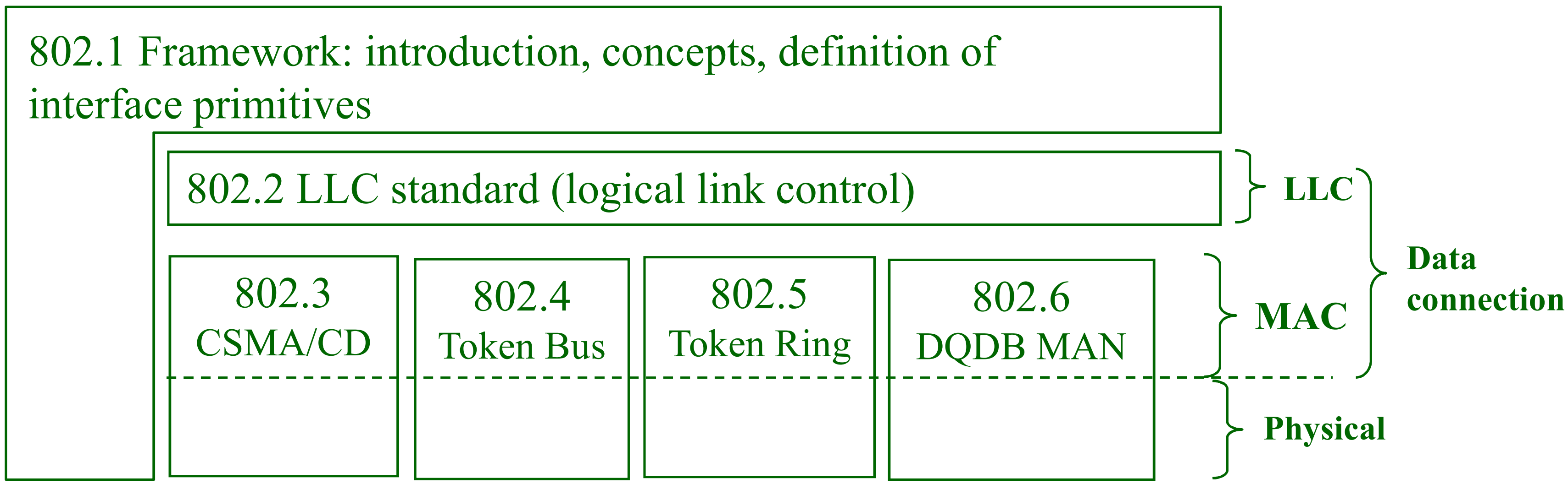
What will it be about?

- **Media Access Control Sublayer in practice**
  - **Ethernet,** or
  - **IEEE 802 standards suite**
    - **This includes CSMA/CD,**
    - **Token Bus,**
    - **Token Ring** and
    - **Wireless LAN (CSMA/CA) implementations,** as well as the
  - **FDDI** and the
  - **ATM.**

The IEEE 802

- IEEE: Institute of Electrical and Electronics Engineers
- Summary of IEEE 802 LAN standards
- It was also adopted by ISO as ISO 8802 (international standard)
- Also accepted by ANSI (US government)
- IEEE 802 consists of several parts
  - E.g. IEEE 802.3 adoption of Ethernet (1985)
    - Ethernet was developed by Xerox, DEC, and Intel.
      - Ethernet 1 specification (1980)
      - Ethernet 2 (1984) → IEEE 802.3

Structure of IEEE 802



- **802.3 CSMA/CD,** from the Ethernet 2 specifications (IEEE, 1985)
- **802.4 Token Bus;** developed by General Motors and manufacturing automation companies (IEEE, 1985)
  (bus, max. delay limited, priorities)
- **802.5 Token Ring;** IBM's Token Ring (IEEE,1985)
- **802.6 Distributed Queue Dual Bus,** MAN standard, dual bus, distributed queuing

Parts of IEEE 802

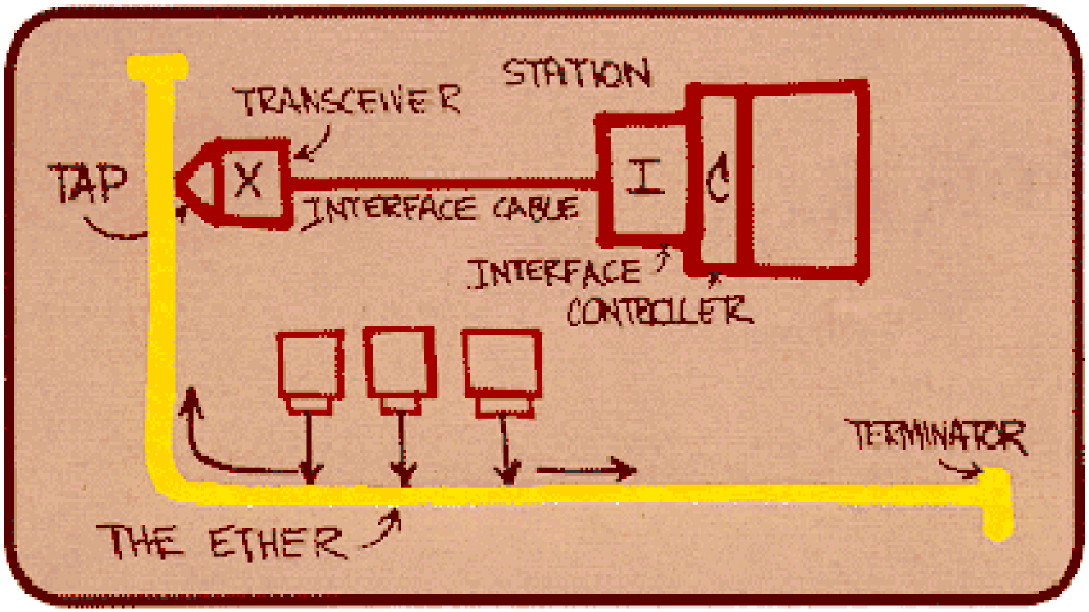
- **802.7 Broadband technology**
- **802.8 FDDI**
- **802.9 Integrated voice & data**
- **802.10 Network security**
- **802.11 Wireless networks, WLAN**
- **802.12 100VG_AnyLAN**
  - **Star topology; on-demand priority scheme;**
  - **CAT3,4 or 5 UTP & STP; Fiber**
  - **Cable lengths**
    - **CAT3,4: 100m, CAT4: 150m; Fibre: 2000 m**
- **802.16 Wireless MAN**
  - **Provides high-bandwidth duplex connectivity for buildings**
  - **802.16a 2-11GHz, 802.16b 5GHz ; 50-100-150Mbps**
  - **Developed since 1999, the standard was adopted in 2002**

Ethernet II versus 802.3

- **The origin of the name: luminiferous ether -** a substance filling space, which was imagined as a medium for transmitting electromagnetic radiation.
- **DIX Ethernet** (Dec Intel Xerox)
- **Comparing the two:**
  - **802.3 also defines more extensive physical media and speeds;**
  - **different frame format**
  - **but are identical in the media access method**

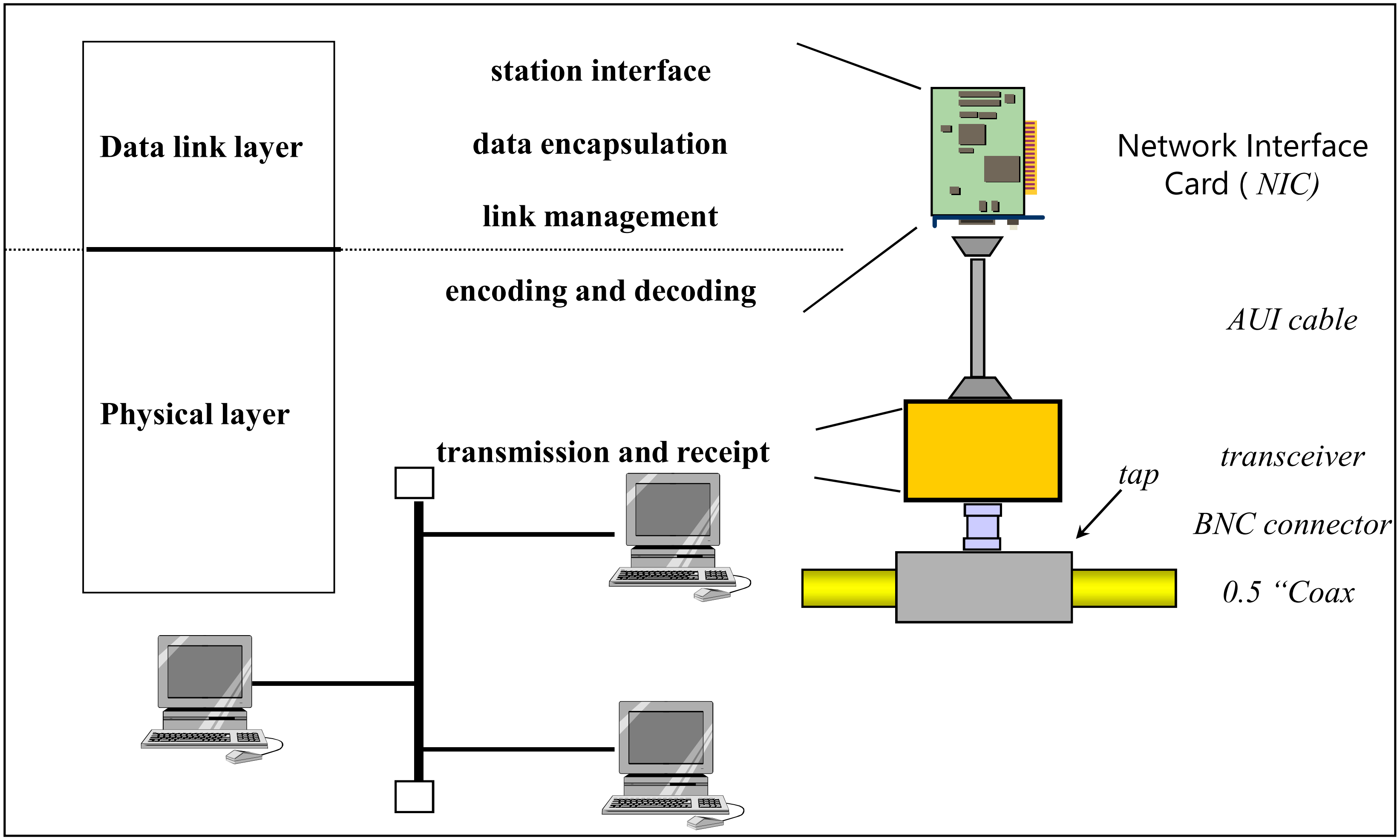
Ethernet II

- *``The diagram ... was drawn by Dr. Robert M. Metcalfe in 1976 to present Ethernet ... to the National Computer Conference in June of that year. On the drawing are the original terms for describing Ethernet. Since then other terms have come into usage among Ethernet enthusiasts."* ***The Ethernet Sourcebook*** , ed. Robyn E. Shotwell (New York: North-Holland, 1985), title page.



802.3

Ethernet (10Base5)



Ethernet standards

- **Thick Ethernet (yellow cable or thick E)**
  - **0.5" diameter, 50 Ω, yellow coaxial cable, max segment length 500m**
  - **at least every 2.5 meters on a "vampire" connector (tap) transceiver, including a 15-pin AUI (Attachment Unit Interface) cable to the machine;**
  - **with repeaters, up to 5 cables can be connected, with a total length of 2.5 km** (max. propagation delay limit, 51.2μs, 512bit (64byte) min. frame size);

Ethernet standards

- **Thin Ethernet**
  - **50 Ω coaxial cable, max. length 185 m;**
  - **BNC plugs, T connectors, connection directly to the machine's built-in transformers;**
  - **max. 30-32 connectors (less depending on the quality of the construction), from this comes the max. number of machines that can be connected to one segment: (30) 14-18, or less;**
  - **There can be up to four repeaters between two stations:**
    from this comes the max total "logical segment" length (depending on repeater, cabling quality, station, it may be less);
  - **multiport repeaters too:**
    to connect thick and thin segments.

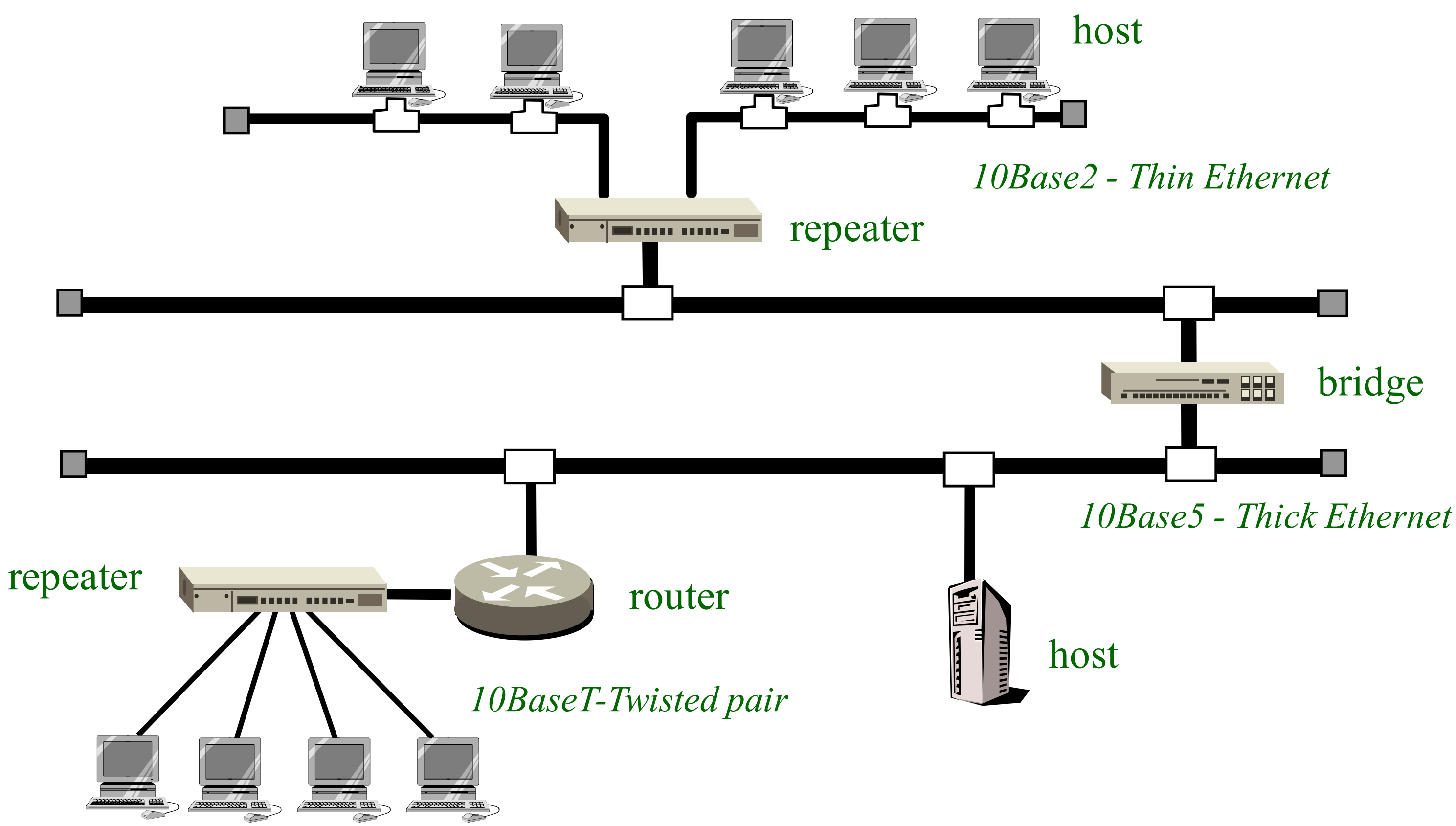
Ethernet standards

- **In both systems, the modulation is:**
  - **baseband, the voltage values are:**
    - **idle: 0 Volts;**
    - **high: +0.85V;**
    - **low: - 0.85 V,**
  - **Manchester encoding.**
- **In the 802.3 notation system**

10 Base 5

- 10 → Transfer speed Mbps
- Base → Indications: baseband, or broadband
- 5 → max segment length (in 100m), or medium indication

Multi-segment Ethernet LAN

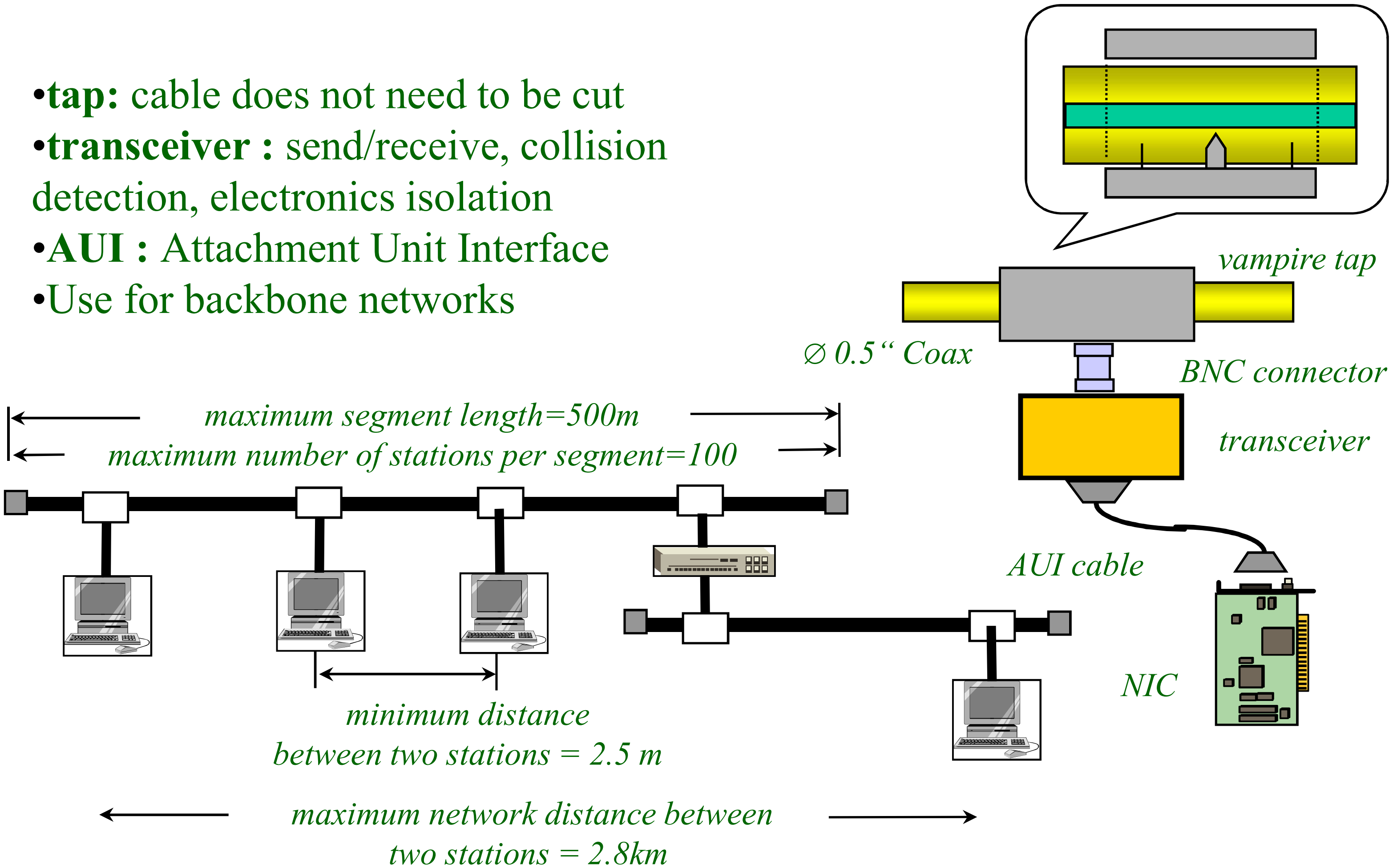


IEEE 802.3 specifications, markings

- **The marking system in 802.3**
  - **10Base5 -- thickwire coaxial, 500m**
  - **10Base2 -- thinwire coaxial or cheapernet, 185m**
  - **10BaseT -- twisted pair: UTP/STP, point-to-point, 100 m (now widely used today)**
  - **10BaseF -- fiber optics, point-to-point, multimode: 2 Km ; singlemode: 3-10 Km**
  - **10Broad36 -- broadband (only 802.3 standard 1/2" coax, 1800m)**
- **Fast Ethernet (802.3u)**
  - **100BaseTX (CAT5), 100BaseT4 (CAT3), 100BaseFX**
- **Gigabit Ethernet 1000 Mbps**
  - **1000BaseSX, 1000BaseLX, 1000BaseCX (802.3z)**
  - **1000BaseT (802.3ab)**
- **10 Gigabit Ethernet 10000 Mbps** (802.3ae)
  - **10GBase-S (850nm, 50 μ multi – 65m),**
    10GBase-LX4 (1310nm, 62.5μ multi – 300m, 9.0μ mono – 10km),
    10GBase-L (1310nm, 9.0μ mono – 10km),
    10GBase-E (1550nm, 9.0μ mono – 40km)

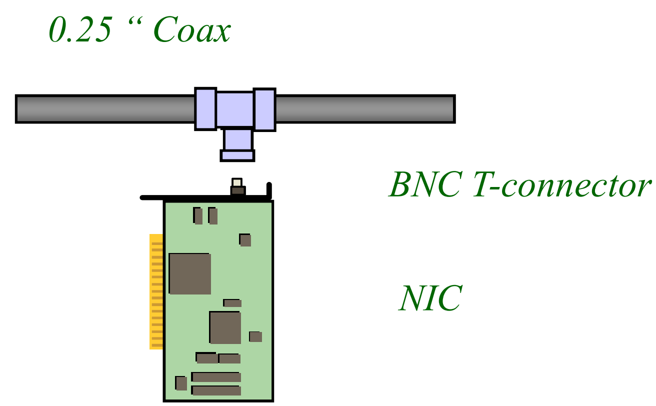
10Base5

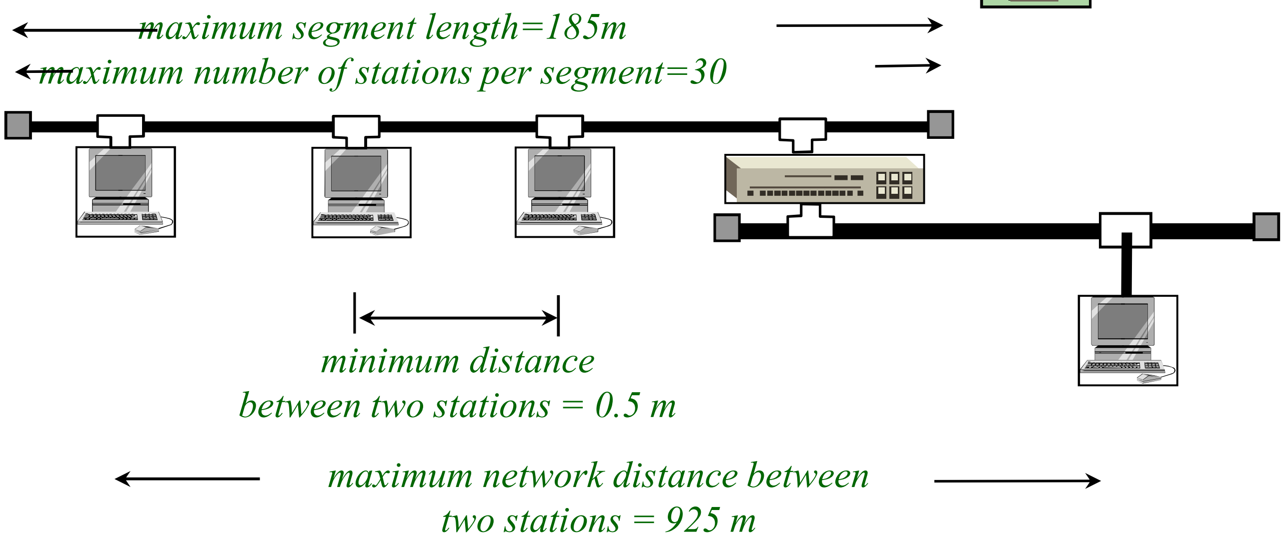
- **tap:** cable does not need to be cut
- **transceiver :** send/receive, collision detection, electronics isolation
- **AUI :** Attachment Unit Interface
- Use for backbone networks



10Base2

- **BNC connector**
- **No drop cable**
- **use for office LAN**

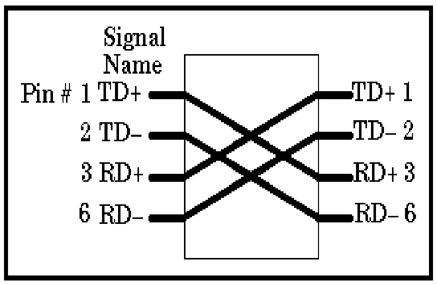


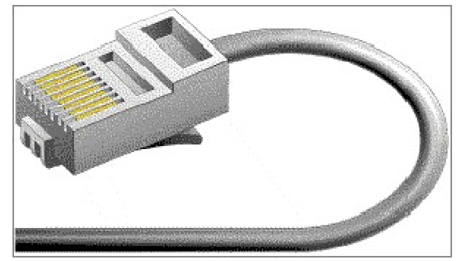


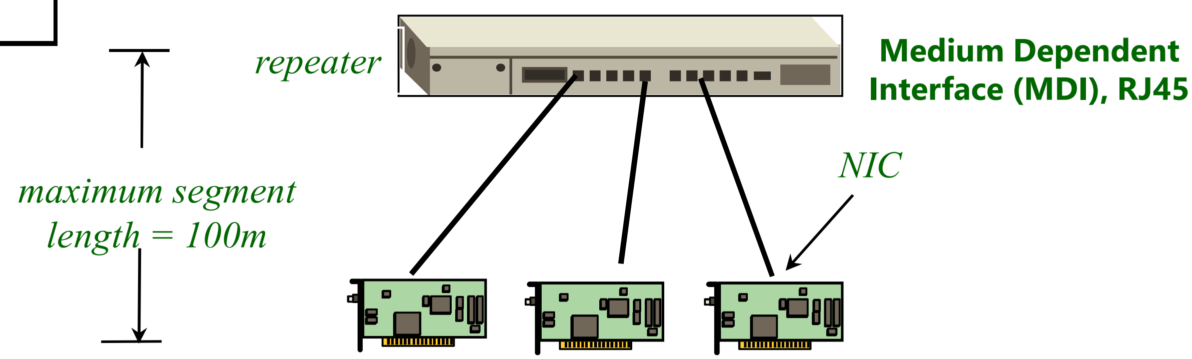
10BaseT

- **Broadcasting on point-to-point connections: repeater ("hub")**
- **UTP category 5 uses 2 pairs of wires terminated by an 8-pin (RJ-45 style) connector. This means that 4 pins of the 8-pin are used.**

Pin	1	2	3	4	5	6	7	8
Sig	TD+	TD-	RD+	U	U	RD-	U	U





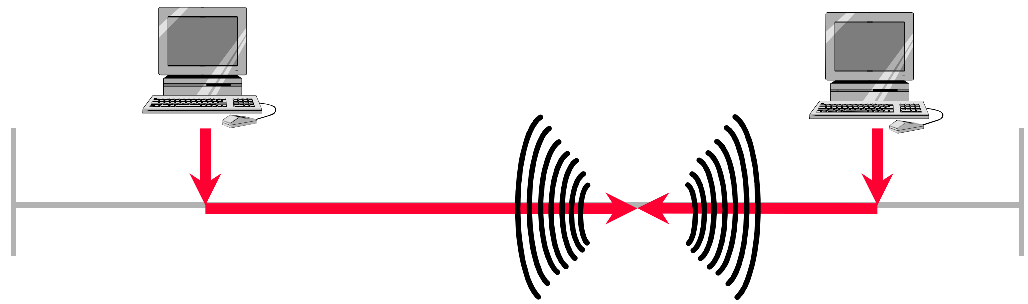


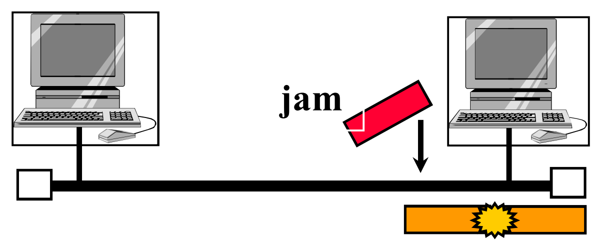
802.3

The 802.3 MAC technique

- **Carrier Sense Multiple Access/Collision Detection: CSMA/CD**
  - **Before transmitting, the station monitors the channel (CS) and determines whether**
    - **that the channel is idle, no transmission (idle): then it starts transmitting.**
    - **or the channel is busy, there is a transmission (busy). Then it continues to monitor until the channel becomes idle: at which point it starts transmitting.**
  - **The topology ensures multiple access (for channel monitoring) (MA)**
  - **CD: is capable of detecting collisions while transmitting (listen while you talk). Collisions occur when multiple stations transmit simultaneously.**

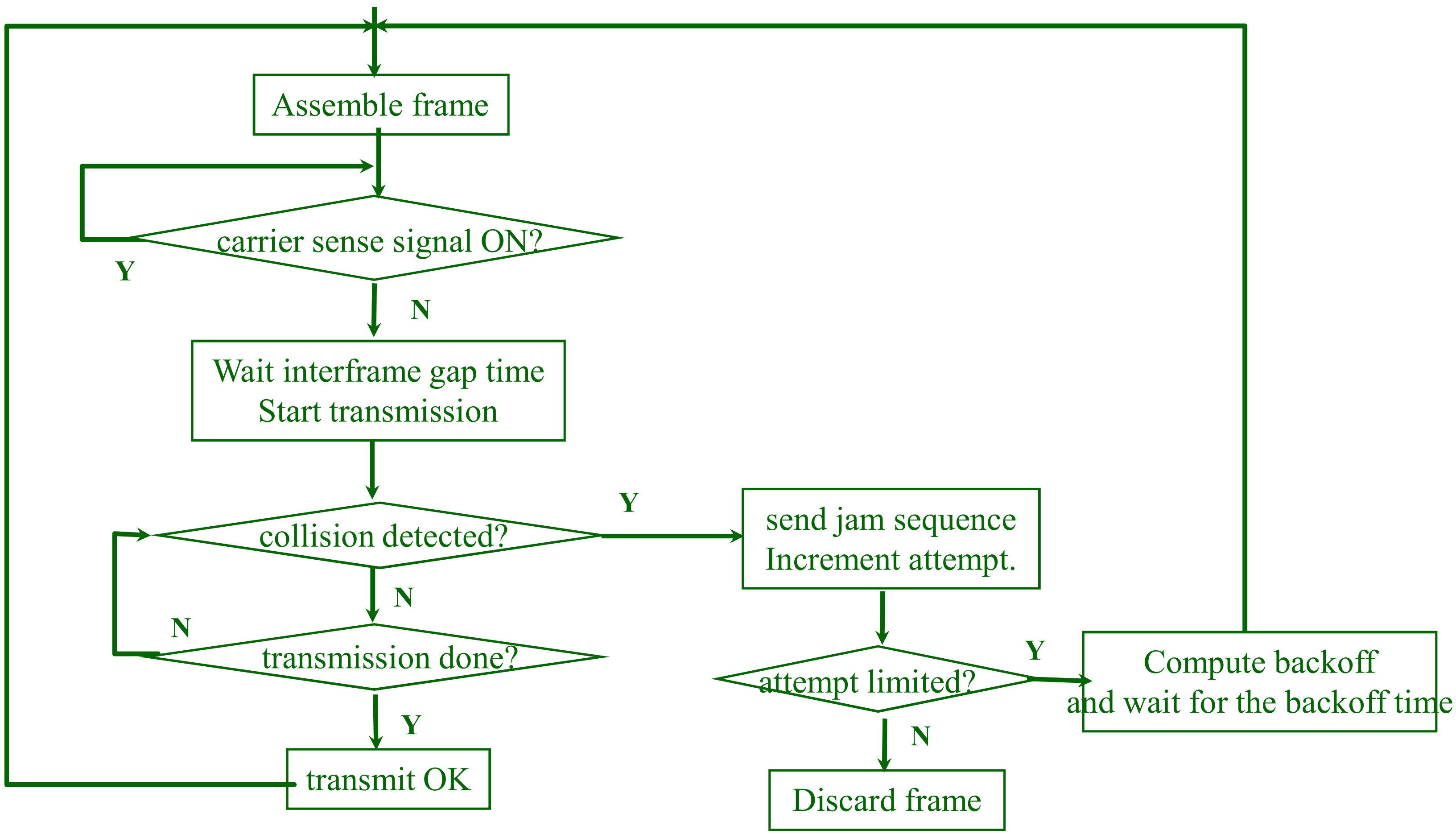
The 802.3 MAC technique



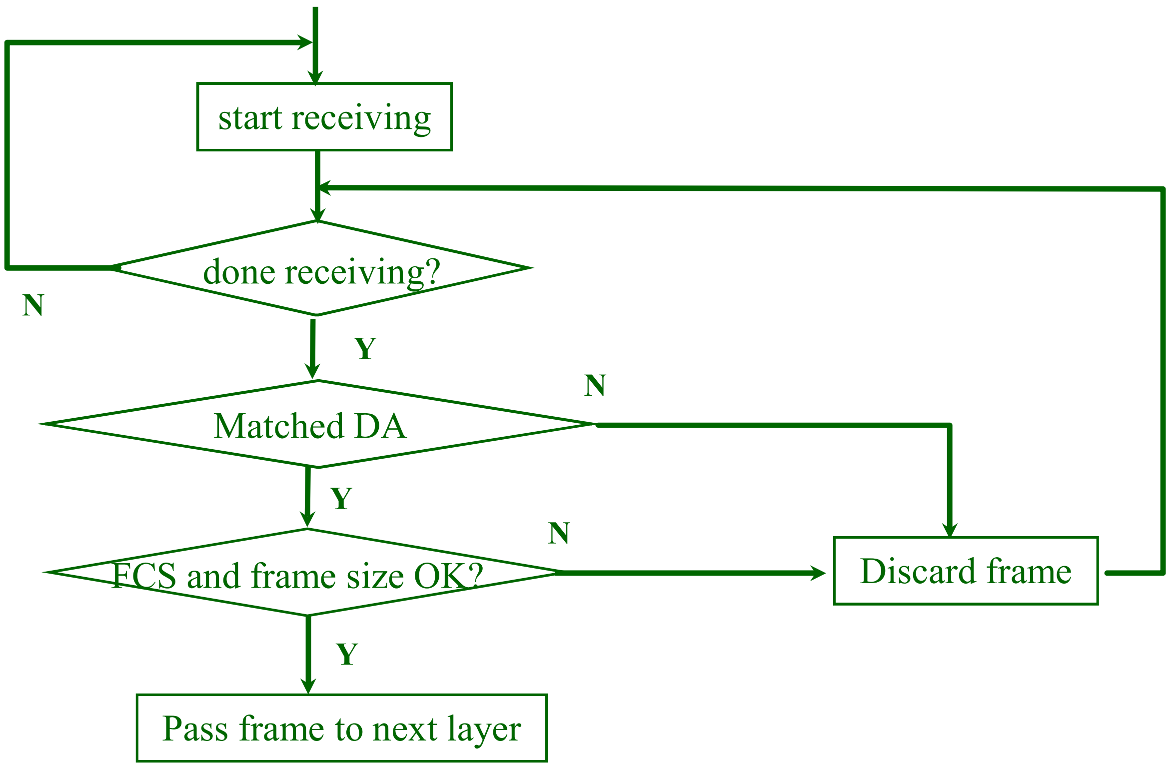


- **If a collision is detected (during transmission),**
  - **Decision is based on the received voltage level**
- **Any station that detects a collision stops transmitting and instead sends a meaningless signal** (jamming signal) **to ensure that everyone notices the collision.**
- **It then waits for a random amount of time (binary exponention backoff) and then tries again.**

Frame transmission



Frame reception



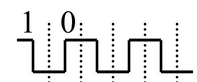
802.3/Ethernet frame structure

7	1	6	6	2	46-1500		4	
PA	SFD	DA	SA	LEN	LLC PDU	Pad	FCS	**IEEE 802.3**

calculation of the FCS (DA … Pad)

64-1518 bytes (DA … FCS)

7	1	6	6	2	46-1500		4	
PA	SFD	DA	SA	Type	Data	Pad	FCS	**Ethernet**

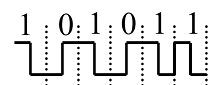


: PA

PA: Preamble - 7 times the bit sequence 10101010, for synchronization;

7 * 8 = 56 bits; 10Mbps ⇒ 5.6 μsec long ⇒ 5 MHz signal (Manchester encoding) ⇒ to synchronize the receiver clock!

SFD : Start of Frame delimiter -- 10101011 to indicate the start of a frame



: SFD

DA: Destination Address -- MAC address (6 bytes – 48 bits)

SA: Source Address -- MAC address

LEN: Data field length (Length) -- length measured in bytes

Type: identify the higher-level protocol (e.g. IP, ARP, RARP)

LLC PDU+Pad: Data+fill -- minimum 46 bytes, maximum 1500

FCS : Frame Check Sequence -- CRC-32

Pad role: the min frame size - from the destination address to the end of the frame - 64 bytes 512bit 51.2μs (excluding PA and SFD).

If the data field is shorter than 46 bytes, it is padded up to 46 bytes! (Min. frame length)

MAC addresses

- **According to the standard, DA and SA addresses can be 2 or 6 bytes, but for 10 Mbps they are only 6 bytes. (in practice, only 6-byte (48-bit) ones are used)**
- **All 1: address for all stations (Broadcast Address)**
- **If the highest (47th) bit = 1: group address (Multicast Address)**
  - **the remaining bits define the group;**
  - **the frame is taken by all members of the group.**
- **If the highest (47th) bit = 0: ordinary address**
- **The 46th bit has a special role: to distinguish between local (1) and global (0) addresses**
  - **Local address: configured by the network manager (e.g. DECNet)**
  - **Global address: assigned by IEEE** (Organizationally Unique Identifier (OUI)) **unique in the world (every machine "automatically" has a unique MAC address**
    – e.g. burned into ROM on the card).

MAC addresses

E.g.

Organizationally Unique Identifier (OUI) - IEEE ↔ Part administered locally by the assignee (24 bit)

```
Octets 0 1 2 3 4 5
Binary 0011 0101 0111 1011 0001 0010 0000 0000 0000 0000 0000 0001
Hex CAED 8 4 0 0 0 0 0 8
```

Y/G U/L

- (The least significant bit of the first word is the very first bit)
- **I/G bit: Individual /unicast address (0) or Group /multicast address (1)**
- **U/L bit: Universally (0) or Locally (1) Administered**
- **E.g.: OUI**
  CISCO: 00 : 07 : 0d
  3COM: 00 : 50 : 99
- **Eg: if U/L=0**

	Unicast (I/G=0):	Multicast (I/G=1):
	`0x0 (0000)`	`0x1 (0001)`
	`0x4 (0100)`	`0x5 (0101)`
	`0x8 (1000)`	`0x9 (1001)`
	`0xC (1100)`	`0xD (1101)`

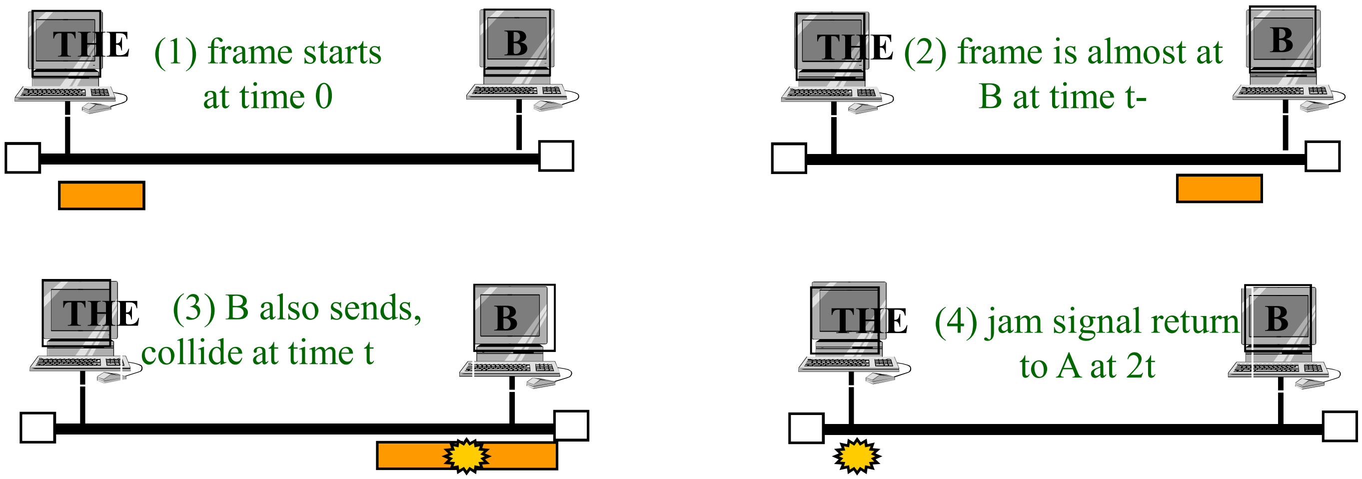
- **E.g. CISCO Multicast: 0 1 : 07 : 0d : x : y : z**

The minimum frame size

- It is related to the maximum delay allowed on the channel (τ)
  - the frame must be long enough to detect the collision even with the worst-case round-trip delay ($2*\tau$)!
  - 64 bytes = 512 bits; 10Mbps $\Rightarrow 2\tau = 51.2\ \mu$sec: this is the max. allowed round trip delay!
  - And from this comes the 2.5 Km length (5 segments connected by 4 repeaters.
  - Fast Ethernet (802.u) 100Mbps $\Rightarrow 2\tau = 5.12\ \mu$sec (max 2*100m segments)

The late collision

A and B are at the two ends of the cable (t is the time required between the two machines)



- **A collision that occurs after the first 64 bytes have been sent.**
  - **The reason is long cable, many repeaters; short frame.**
- **Result: the sender incorrectly concludes that his frame went through properly.**
  (it does not detect a collision while sending its frame)

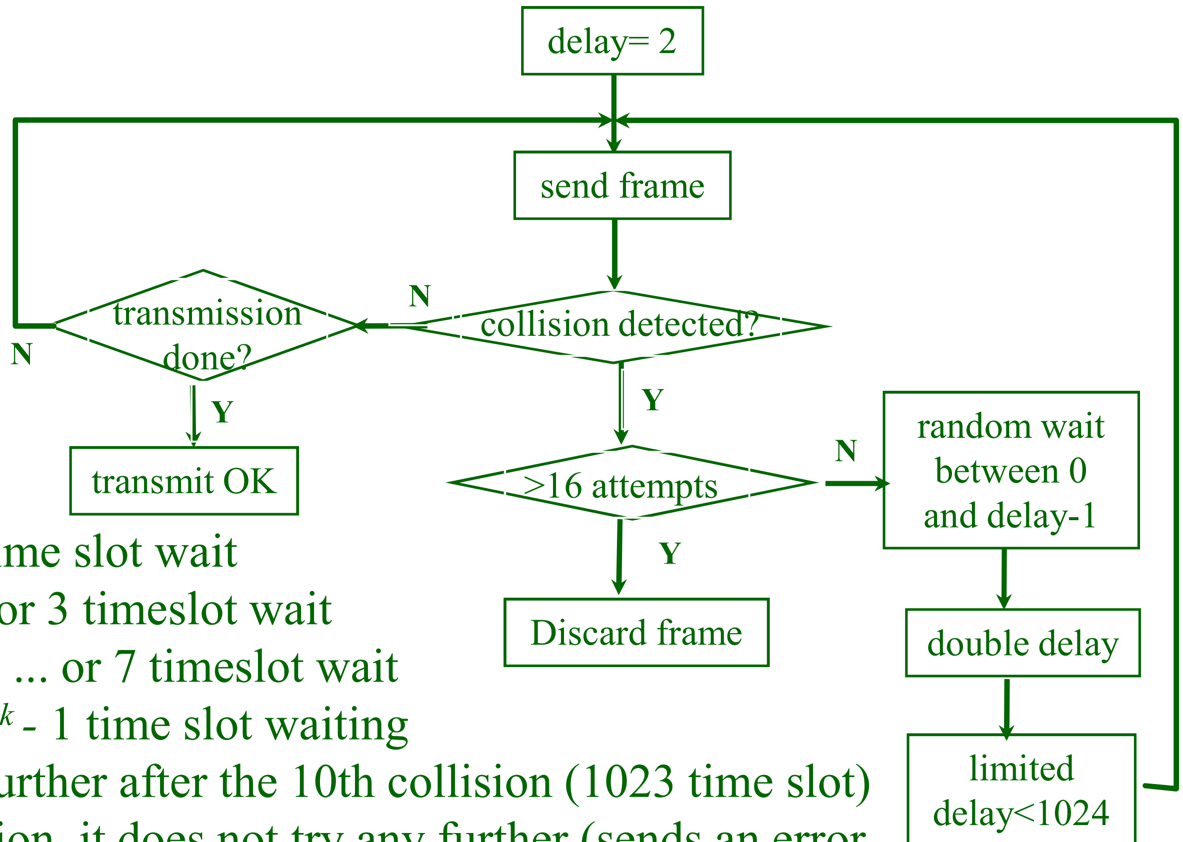
Binary Exponential Backoff

- **Binary Exponential Backoff Algorithm for collision handling**
- **If a collision is detected, it sends a “jam”, then stops transmitting and waits:**
  - **Divides time into slots** (durations), **slot time = 51.2 μsec (max. round trip delay)**
  - **After the first collision, the station waits (randomly) 0 or 1 timeslot before trying again...**
    - **If two stations collide again, it's because they accidentally generated the same random number...**
  - **After the i^{th} collision, a random number of waiting timeslots between 0 and $2^{i} - 1$ are inserted.**

Binary Exponential Backoff

- Continuation of the algorithm:
  - If i ≥ 10, then between 0 - 1023 they generate a random number and wait for a time slot (10 is the so-called backoff limit).
  - If i = 16, the station will not try any further (16 is the so-called attempt limit),
    - It reports an error to the upper layer.
- The algorithm dynamically adapts to the number of stations intending to transmit!
  - Exponentially increasing the random number generation interval results in short waiting times with few collisions;
  - and reasonable values when there are many collisions.

Binary Exponential Backoff Algorithm

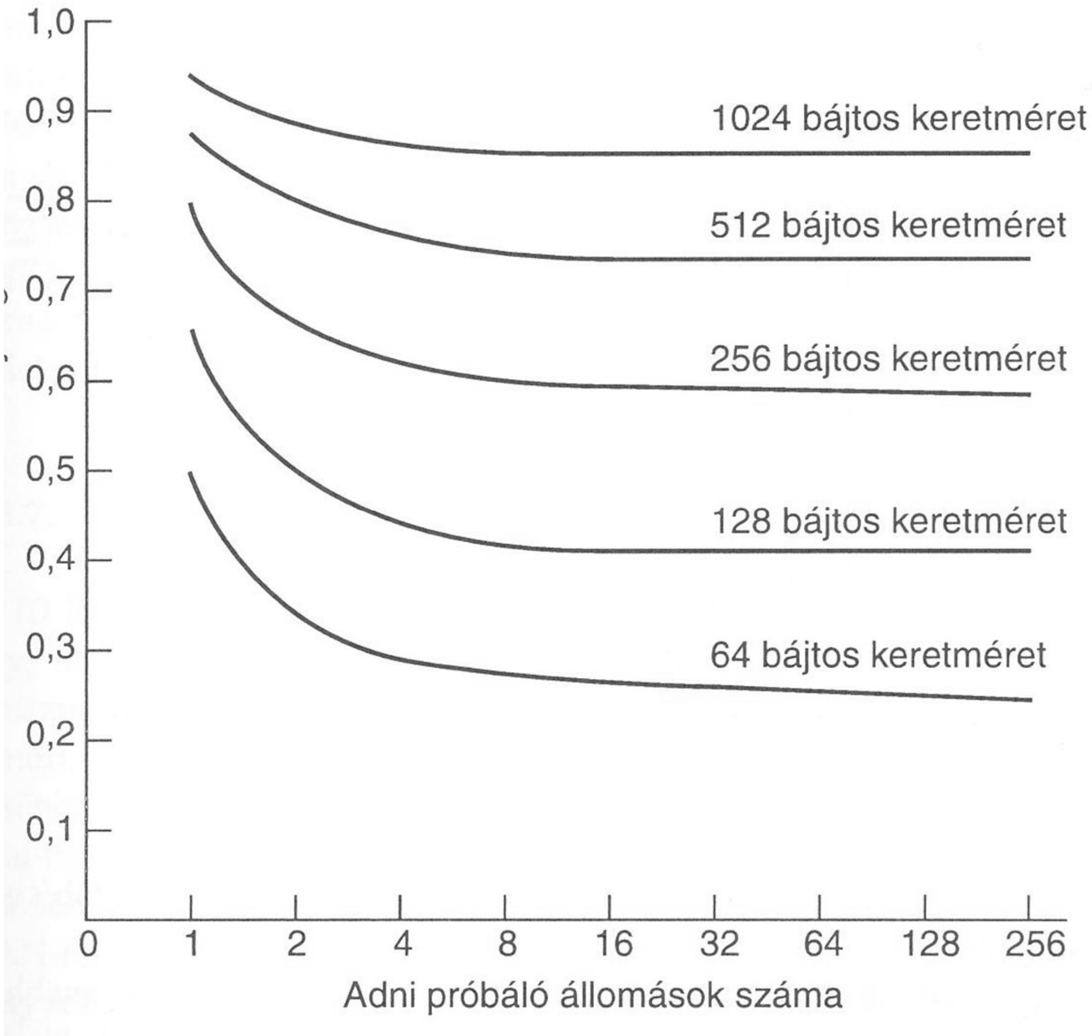


Slot=Window size= 2t

1st collision: 0 or 1 time slot wait
2nd collision: 0, 1, 2 or 3 timeslot wait
3rd collision: 0 , 1, 2, ... or 7 timeslot wait
kth collision: 0. . . 2^{k} - 1 time slot waiting
– does not increase further after the 10th collision (1023 time slot)
– after the 16th collision, it does not try any further (sends an error message to the upper layer)

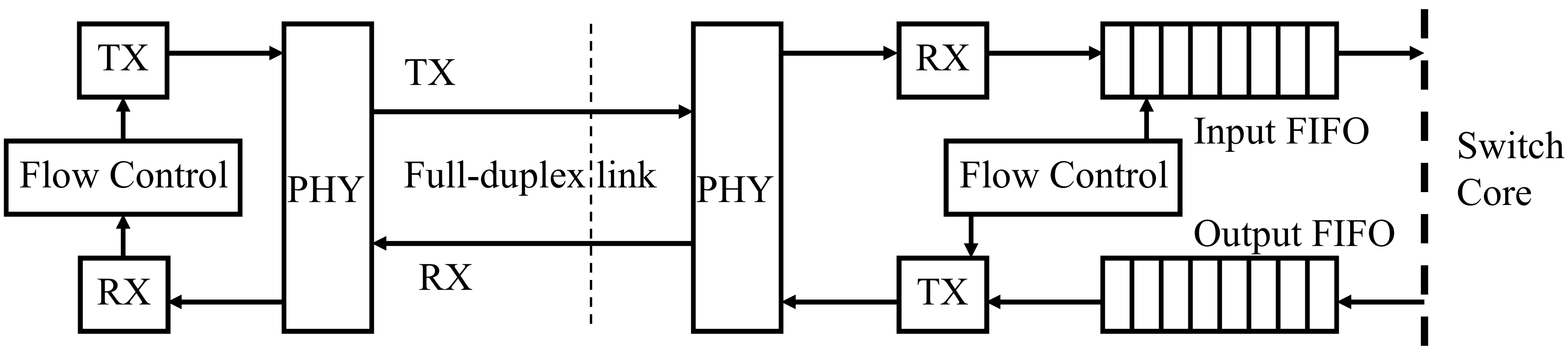
max delay is limited at 1023*51.2μs = 52.4ms

Ethernet efficiency
(at 10Mbps, 512 bit slot)



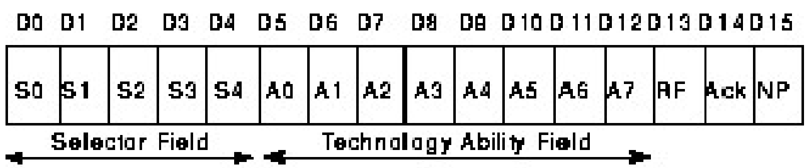
10BaseT - 100BaseTx

- **10BaseT - 10Mbps**
  - **min. frame 64 bytes = 512 bits; $\Rightarrow 2\tau = 51.2\ \mu sec$**
  - **Manchester encoding**
- **100BaseT Fast Ethernet (802.u) - 100Mbps**
  - **min. frame 64 bytes = 512 bits; $\Rightarrow 2\tau = 5.12\ \mu sec$**
  - **4B/5B + MLT-3 encoding**
- **Point-to-point connections**
  - **Half-Duplex – CSMA/CD**
  - **Full-Duplex - flow control 802.3x "pause frame"**
    - **When receiving a "pause frame", it temporarily stops transmission**

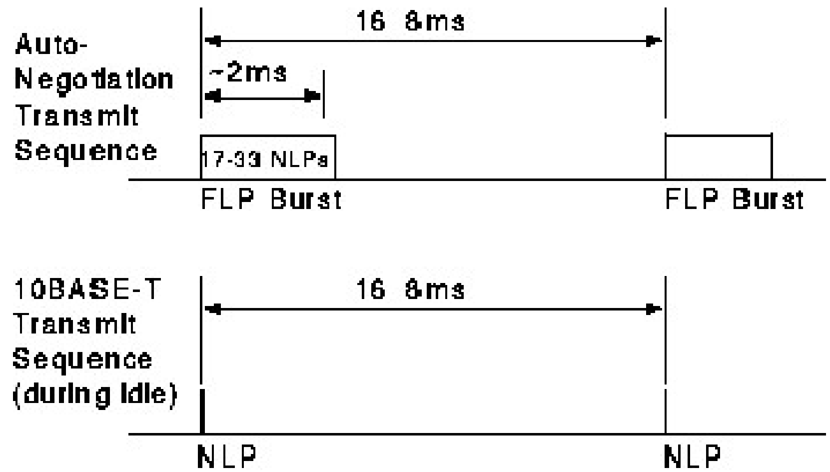


10BaseT - 100BaseTx

- **Auto-Negotiation**
  - **10BaseT – Normal Link Pulse (NLP)**
  - **100BaseT – Fast Link Pulse (FLP)**
- **FLP**
  - **16 bit Link Code Word**



Base Link Code Word Encoding



FLP Burst Timing

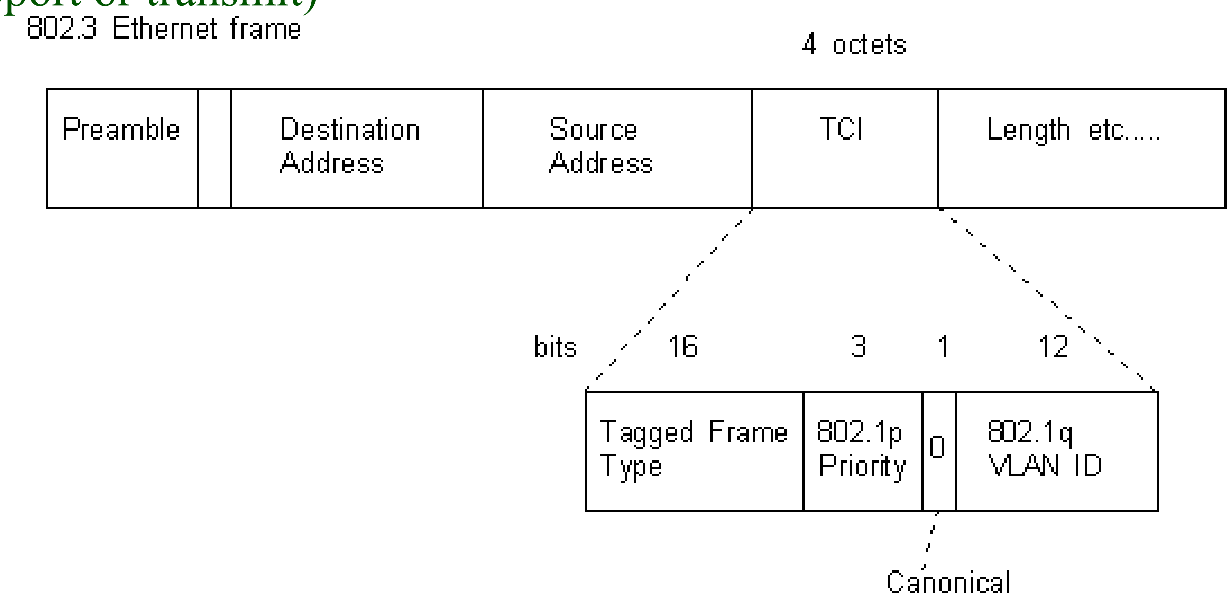
- **The Selector Field, S[4:0], allows for the differentiation of 32 Technology Ability Fields e.g. S[4:0]=< 00001 > represents IEEE 802.3**
- **The meaning of the Technology Ability Field A[7:0] depends on the value of the Selector Field.**
  - **For example, in the case of IEEE 802.3 :**

1. 100BASE-TX Full Duplex
2. 100BASE-T4
3. 100BASE-TX
4. 10BASE-T Full Duplex
5. 10BASE-T

10BaseT - 100BaseTx

- **Class of Service and VLANs (802.1p, 802.1q)**
- **Tag Control Info (TCI)**
  - Additional 4 bytes ⇒ maximum frame size 1518 → 1522 (not all devices support or transmit)

Cisco: Inter Switch Link (ISL)
frame encapsulation (completely different)



- **Tagged Frame Type** – Tag type , currently for Ethernet frames always **0x8100** .
- **802.1p Priority** – from low priority binary 000 (0) to high priority binary 111 (7) (Usually only 2 priority classes are implemented)
- **Canonical** - always **0** .
- **802.1q VLAN ID** - the VLAN ID on VLAN trunks.

Gigabit Ethernet

- Since 1970, Ethernet has been the most common network technology (Ethernet - Fast Ethernet - Gigabit Ethernet)
- Gigabit Ethernet - 802.3z - draft issued in 1997
- Compatible with older Ethernet systems
- CSMA/CD with full and half duplex support
- Copper, single- and multimode fiber optic cable support
- Its physical signaling system is based on Fibre Channel technology
- Backbone and high bandwidth applications

Gigabit Ethernet physical layer

- A mix of the original Ethernet and the ANSI X3T11 Fibre Channel specification
- Fibre Channel based Physical Layer: **1000Base-X** (802.3z)
- – **1000Base-SX** 850nm laser
- – **1000Base-LX** 1300nm laser
- – **1000Base-CX** Short haul copper “twinax” STP cable
  - – 8B/10B encoding
- Ethernet based Physical Layer: **1000Base-T (802.3ab)**
- – **1000Base-T** Long haul copper UTP (Unshielded Twisted Pair) 100m over 4 pairs of Category 5 UTP.

Physical layer, max. cable lengths (1000Base)

- Single-mode Fiber (9 micron)
  - **3000m – 1000Base-LX** 1300nm laser
- Multi-mode Fiber (62.5 micron)
  - **300m – 1000Base-SX** 850nm laser
  - **550m – 1000Base-LX** 1300nm laser
- Multi-mode Fiber (50 micron)
  - **550m – 1000Base-SX** 850nm laser
  - **550m – 1000Base-LX** 1300nm laser
- Short haul copper "twinax" STP cable
  - **25m – 1000Base-CX**
- UTP
  - **100 m – 1000Base-T**

Gigabit Ethernet
Media Access Control Layer

- **Carrier Extension**
- **Packet Bursting**

Carrier Extension

SFD : Start of Frame Delimiter
DA : Destination Address
SA: Source Address
FCS: Frame Check Sequence

Preamble	SFD	DA	SA	Type/ Length	Data	FCS	Carrier Extension *RRRRRRRRRRR*

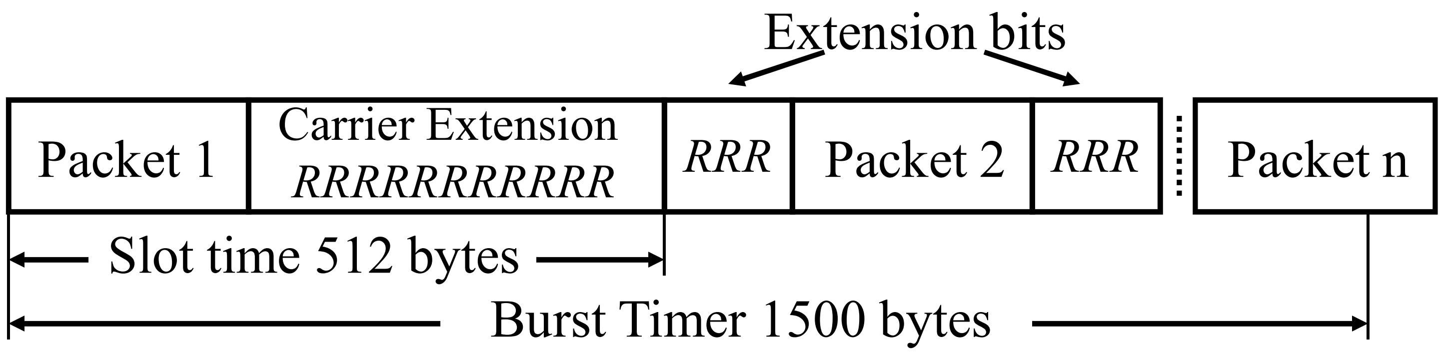
64 bytes min

512 bytes min

Duration of Carrier Event

- 10Mbps on 2.5km - Slot time: 64 bytes
- 1Gbps on 200m - Slot time: 512 bytes
- Fills the minimum frame size with control (non-data) characters (carrier extension)
- These control characters are discarded by the destination station.
- For **small frames ,** its throughput is **barely better than 100Mbps Ethernet.**

Packet Bursting

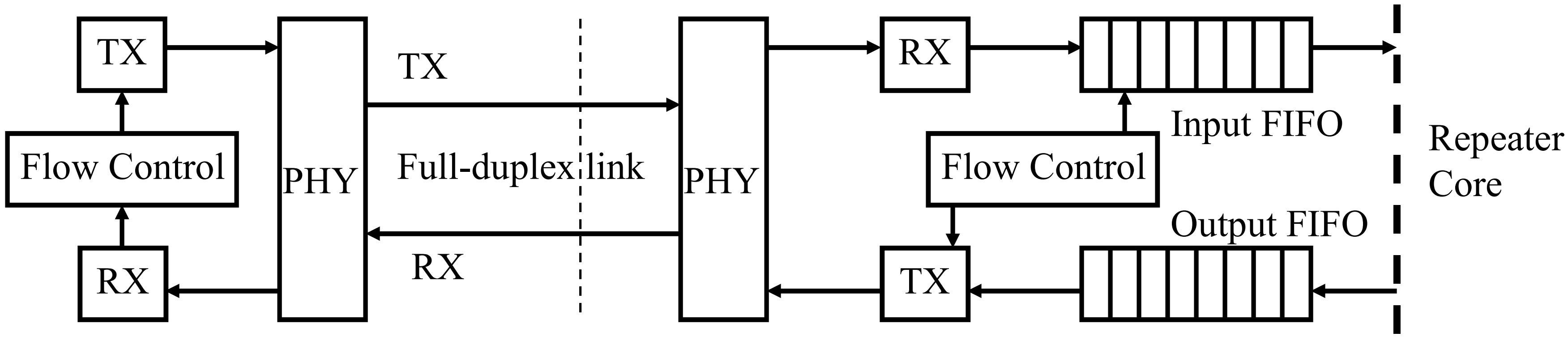


- Supplement to the Carrier Extension technique (for loss reduction).
- **It does not release the channel after sending each frame.**
- After filling the first slot time (the length of the first frame is extended to the slot time (if necessary)), it continues transmitting with further frames (with the minimum Inter-packet gap (IPG) spacing) until the Burst Timer expires (max. 1500 bytes).
- Inter-frame gaps are filled with extension bits.
- Releases the channel after the Burst Timer expires.

Buffered Distributor (obslate)

- **Reapeater functions on full duplex links (also known as *Buffered Distributor*, *Full Duplex Repeater*, or *Buffered Repeater*)**
- Basic idea **: CSMA/CD controls *network access and not* access to the *link*** (permanent full duplex connection)

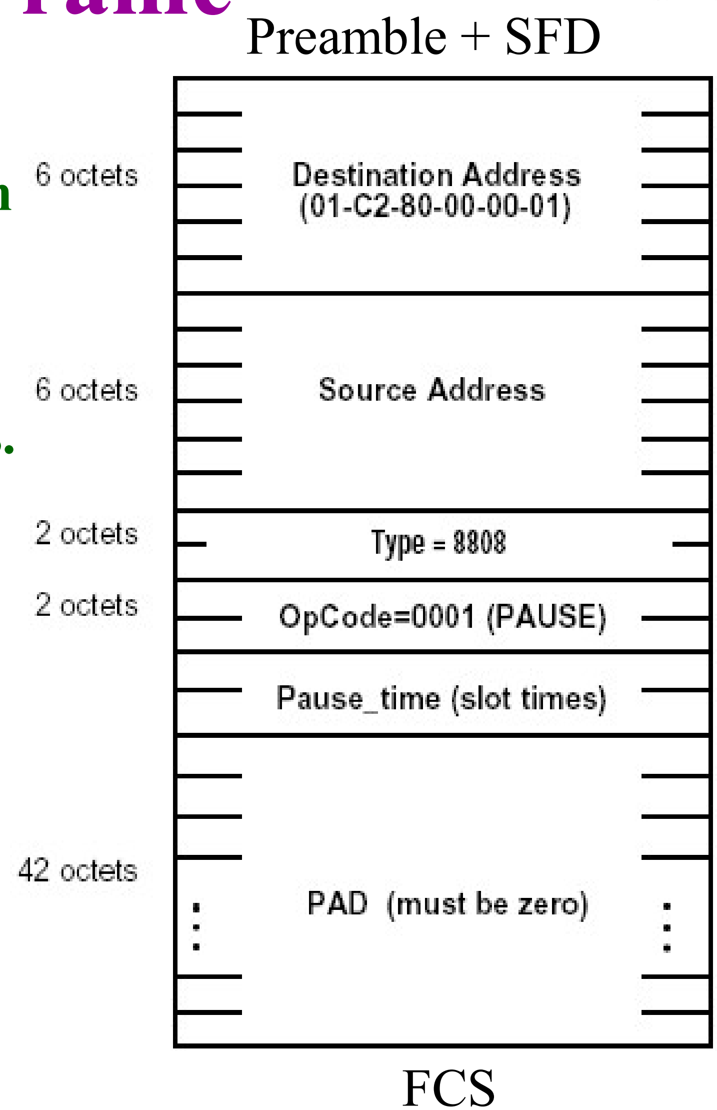
Full Duplex link – Buffered Distributor



- Both 10/100/1000 Ethernet
- Each port has an Input and Output FIFO queue
- A frame arriving on the Input queue is forwarded to all Output queues (except the one on which it arrived)
- CSMA/CD arbitration (scheduling) takes place within the Buffered Distributor, resulting in frames being placed in the Output queues.
- Since there are no collisions on the links, the maximum length limit of the links depends only on the physical medium (there is no round trip time limit).
- Since the sender can easily flood the FIFO, frame-level flow control (802.3x – pause frame) is used between the port and the sending station.
- It was a cheap device (compared to a switch) that can handle full duplex traffic on links.

802.3x – Pause Frame

- **Devices that want to "stop" the data stream send a Pause Frame.**
- **The Pause Frame contains the time, counted in "slot times", during which the transmitter should suspend its transmission.**
- **This duration can be modified (deleted, extended) by sending additional Pause Frames. (Additional Pause frames will overwrite the current pause process.)**
- **DA:** 01-80-C2-00-00-01
  globally-assigned multicast address –
  IEEE 802.1D bridges do not forward it
- **SA:** MAC address of the station sending the frame
- **Length/Type:** 8808.
  "MAC Control of CSMA/CD LANs"
- **Opcode:** 0001 - Pause
- **Parameters:** Pause_time. 0-65535 unsigned int.
  Calculated in 512 bit times



e.g. in case of 1000 it is 512,000 bit time, which for Gigabit Ethernet is 512 µsec (max. 65535 * 512 = 33,553,920 bit time, which is 33.554ms for Gigabit Ethernet).

10GBASE Ethernet (802.3ae)

- 10-Gbps Ethernet (IEEE 802.3ae) was **standardized in June 2002** – Only for optics!
- **1 bit: 0.1 nanosecond**
- **Only supports Duplex mode**
- **Repeater is not defined**
- **The frame format does not change (min. 64byte (512 bit), max . 1518 bytes, interframe space : 96 bits)**
- **Bit encoding: complex serial bit stream,**
  Wide Wavelength Division Multiplex (WWDM) for 10GBASE-LX4

10GBASE Ethernet (802.3ae)

Interfaces:

- **10GBASE-SR** – short distances over already-installed multimode fiber, supports a range between 26 m to 82 m
- **10GBASE-LX4** –wavelength division multiplexing (WDM), supports 240 m to 300 m over already-installed multimode fiber and 10 km over single-mode fiber
- **10GBASE-LR and 10GBASE-ER** – Support 10 km and 40 km over single-mode fiber
- **10GBASE-SW, 10GBASE-LW, and 10GBASE-EW** – Known collectively as 10GBASE-W, intended to work with OC-192 synchronous transport module SONET/SDH WAN equipment

10GBASE Ethernet (802.3ae 802.3an)

10GBASE-LX4	1310 nm	62.5μm MMF	500 MHz/km	2 - 300 m
10GBASE-LX4	1310 nm	50μm MMF	400 MHz/km	2 - 240 m
10GBASE-LX4	1310 nm	50μm MMF	500 MHz/km	2 - 300 m
10GBASE-LX4	1310 nm	10μm MMF	N/A	2 - 10 km
10GBASE-S	850 nm	62.5μm MMF	160 MHz/km	2 - 26 m
10GBASE-S	850 nm	62.5μm MMF	200 MHz/km	2 - 33 m
10GBASE-S	850 nm	50μm MMF	400 MHz/km	2 - 66 m
10GBASE-S	850 nm	50μm MMF	500 MHz/km	2 - 82 m
10GBASE-S	850 nm	50μm MMF	2000 MHz/km	2 - 300 m
10GBASE-L	1310 nm	10μm SMF	N/A	2 - 10 km
10GBASE-E	1550 nm	10μm SMF	N/A	2 - 30 km

10GBASE-SR SFP+ transceiver

10GBASE-T 802.3an-2006 (64B65B PAM-16 128-DSQ)

100m Cat 6A, 55m Cat 5e , Cat 6

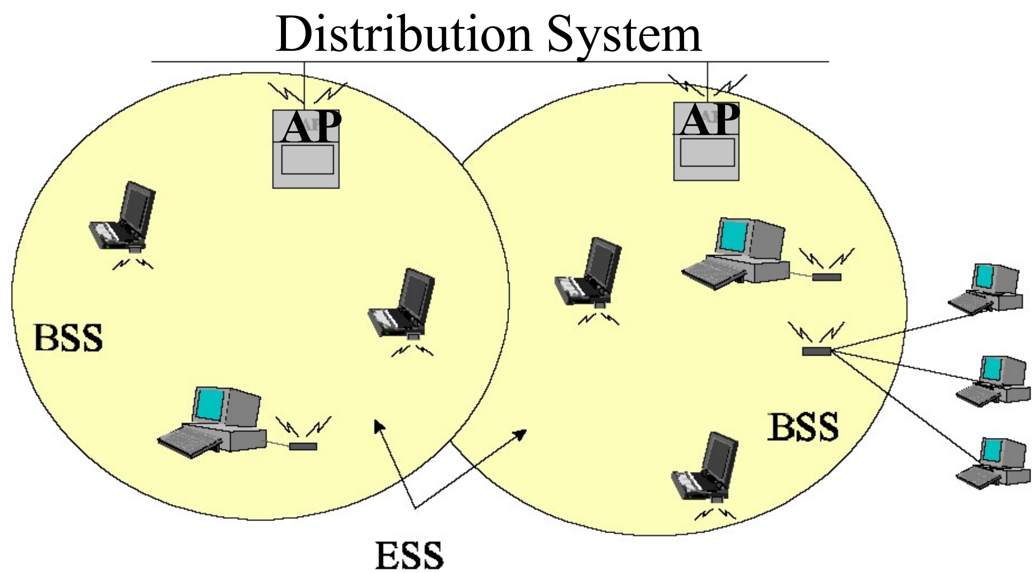
2.5GBASE-T , **5GBASE-T IEEE 802.3bz-2016** , NBASE-T, MGBASE-T

100m Cat 5e, Cat 6

The IEEE 802.11 standard is a wireless LAN (Wireless LAN)

- Originally a 1997 IEEE standard (WLAN), revised in 1999 (802.11b).
- The IEEE 802.11 standard defines the MAC sublayer, the MAC management protocol, services, and three possible physical media.
- Physical media:
  - IR at baseband with 1-2 Mbps,
  - FHSS at 2.4GHz with 1-2 Mbps,
  - DSSS at 2.4GHz with 1-2 Mbps.
- Changes:
  - IEEE 802.11b (1999):
PHY Layer - DSSS at 2.4 GHz with 11Mbps
  - IEEE 802.11a (1999):
PHY Layer – OFDM at 5 GHz with 54 Mbps
  - IEEE 802.11g (2003):
PHY Layer – OFDM at 2.4 GHz with 54 Mbps

IEEE 802.11 – terminology

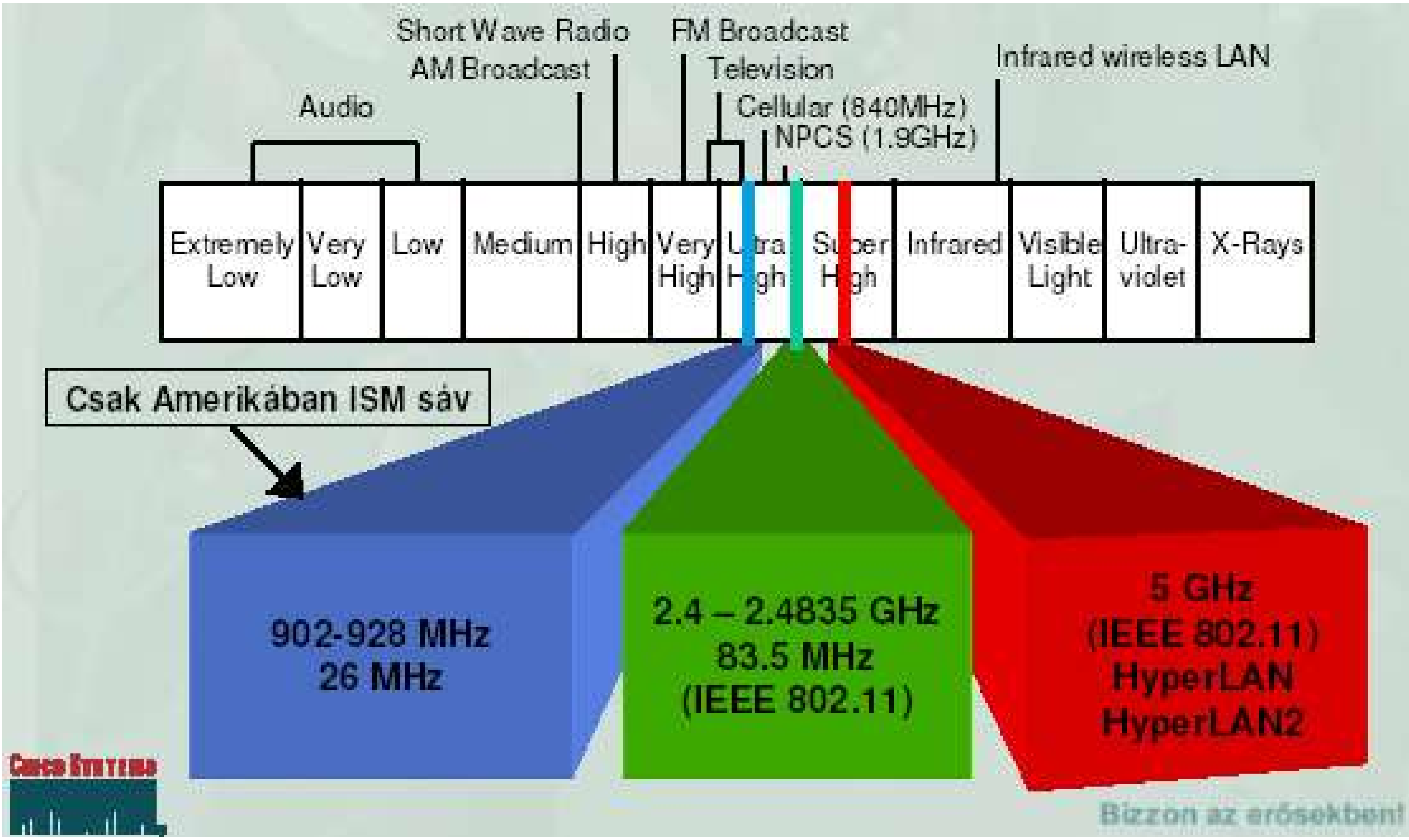


- **Cell -based structure**
- **BSS (Basic Service Set) – a cell**
- **AP (Access Point) – the base stations that control each cell**
- **DS (Distribution System) – the network connecting the cells**
  (it can also be wireless “WDS”)
- **ESS (Extended Service Set) – the entire network**
  (several connected cells together – you can also roam between them)

IEEE 802.11 PHY

- **Speed: 1, 2, 5.5, 11Mbps (IEEE 802.11b)**
- **Frequency 2400-2483.5 MHz**
- **Power: 100mW**
- **Range 1Mbps (typical):**
  - 460m in open terrain,
  - 300m for manual equipment,
  - 90m office
- **Range 11Mbps (typical):**
  - 120m in open terrain,
  - 90m for manual equipment,
  - 30m office
- **Spread spectrum radio channel**
  - **Direct Sequence Spread Spectrum (DSSS), or**
  - **Frequency Hopped Spread Spectrum (FHSS), or**
  - **Orthogonal Frequency Division Multiplexing (OFDM)**
- **Not need for frequency usage license**

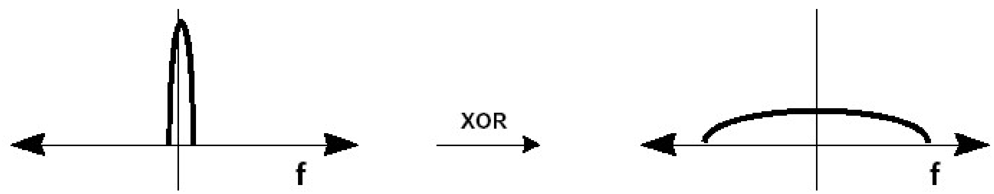
IEEE 802.11 PHY



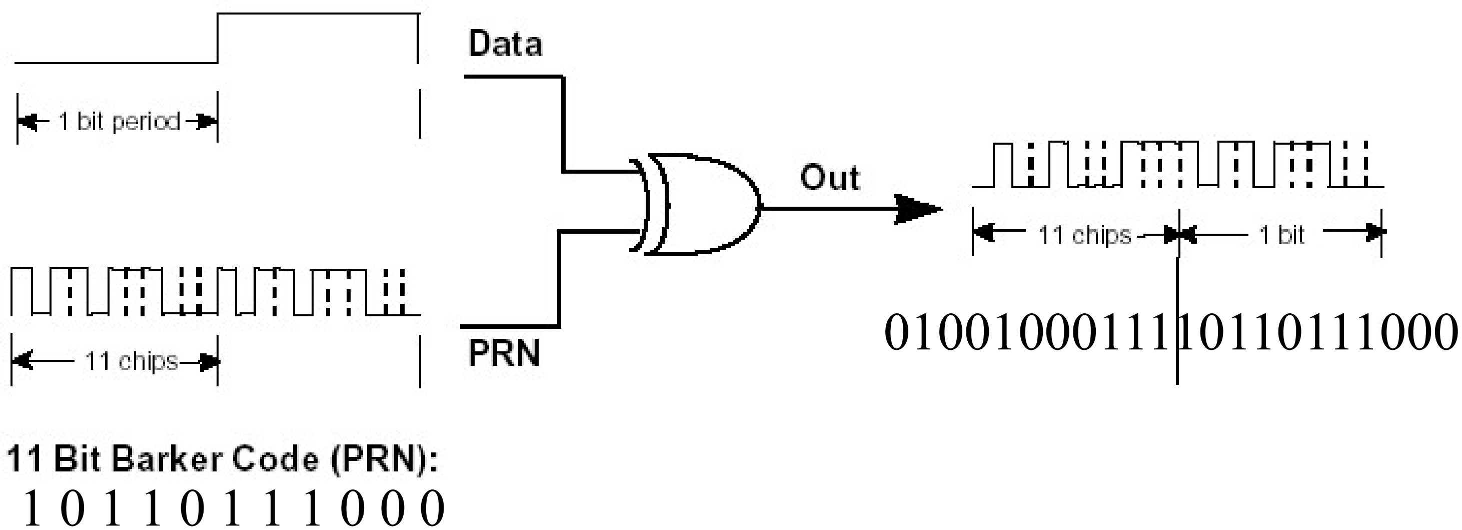
ISM: industrial, scientific and medical

IEEE 802.11 PHY DSSS

- **Spread spectrum radio channel**
  - **Higher bandwidth:**
    reduced transmitter power,
    unchanged signal power

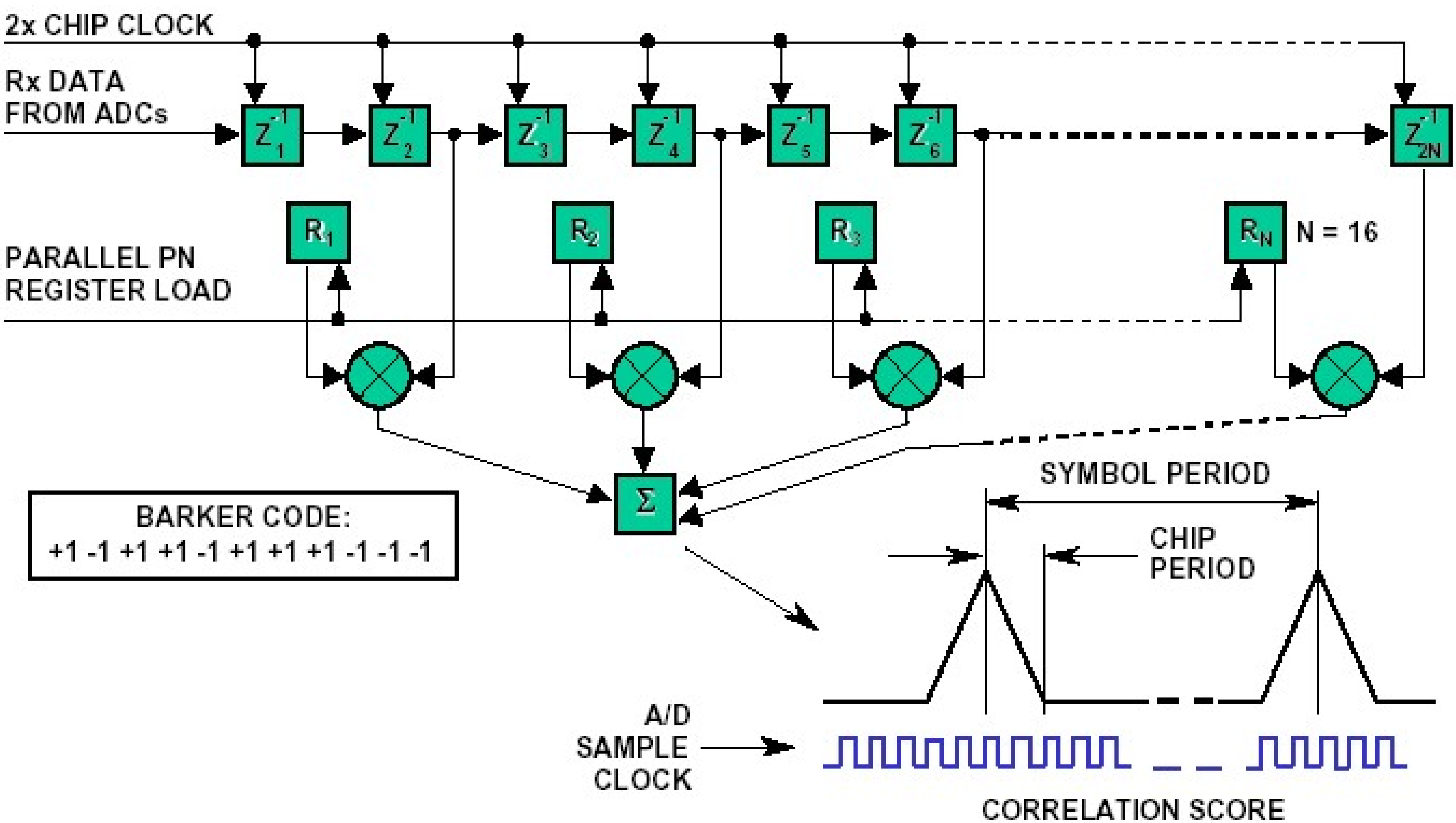


- **Direct Sequence Spread Spectrum (DSSS)**



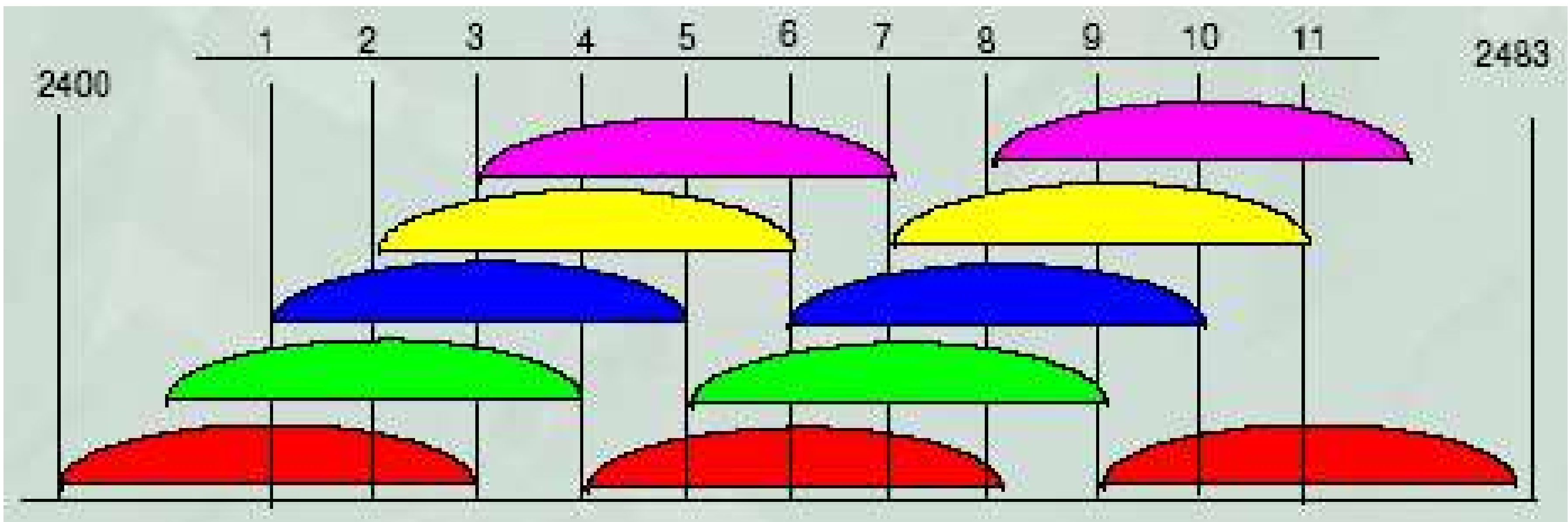
  - **Demodulation with a correlator (removal of the Barker code)**

IEEE 802.11 PHY DSSS : Matched Filter Correlator



IEEE 802.11 PHY DSSS

- **Direct Sequence Spread Spectrum (DSSS) spread spectral radio channels**
  - 13 x 22 MHz wide overlapping channels
  - Of which, max. three non-overlapping (disjoint) channels (stable in time)
  - **1, 6, 11, or 2, 7, 12, or 3, 9, 13**
  - Max. three devices in a given area



IEEE 802.11 PHY DSSS

- **2.4 GHz DSSS channels**

Channel Identifier	Center Frequency	Regulatory Domain			
		Americas	Europe, Middle East and Asia	Japan	Israel
1	2412 MHz	X	X	X	
2	2417 MHz	X	X	X	
3	2422 MHz	X	X	X	X
4	2427 MHz	X	X	X	X
5	2432 MHz	X	X	X	X
6	2437 MHz	X	X	X	X
7	2442 MHz	X	X	X	X
8	2447 MHz	X	X	X	X
9	2452 MHz	X	X	X	X
10	2457 MHz	X	X	X	
11	2462 MHz	X	X	X	
12	2467 MHz		X	X	
13	2472 MHz		X	X	
14	2484 MHz			X	

IEEE 802.11 PHY DSSS

- **2.4 GHz DSSS (802.11b) modulations**
  - Binary Phase Shift Keyed (BPSK)
  - Quadrature Phase Shift Keying (QPSK)
  - Complementary Code Keying (CCK)

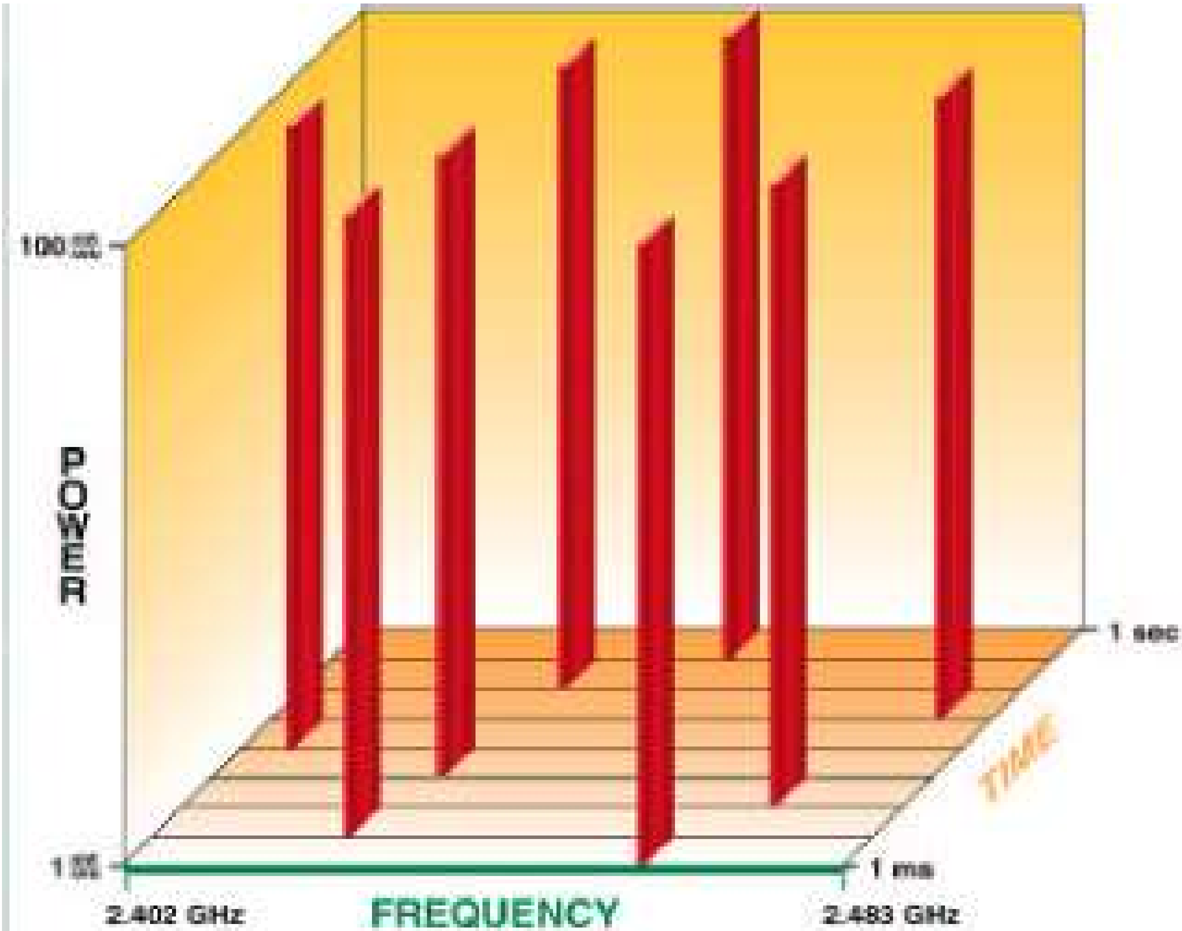
csatorna moduláció	sebesség (Mbps)
BPSK	1
QPSK	2
CCK	5,5
CCK	11

IEEE 802.11 PHY FHSS

- **Frequency Hopped Spread Spectrum (FHSS)**
  - **Rapidly changing the transmitter frequencies according to some predefined function** (frequency hopping sequence) **– which the receiver follows** (802.11: 79 channels 1MHz apart)
    – effective against narrowband noise

IEEE 802.11 PHY FHSS

- **Frequency Hopped Spread Spectrum (FHSS)**
  - One hop 400 ms
  - 79 channels in the 2.4-2.483 GHz band



IEEE 802.11 PHY OFDM

- **Orthogonal Frequency Division Multiplexing (OFDM) - (IEEE 802.11a 5GHz)**
  - **the high-speed bit stream into several lower-speed bits** (52 bits - 802.11a) **and modulates them into several parallel smaller bandwidth channels.**

IEEE 802.11 PHY OFDM

- **OFDM - (IEEE 802.11a 5GHz) modulations**

csatorna moduláció	sebesség (Mbps)
BPSK	6
BPSK	9
QPSK	12
QPSK	18
16QAM	24
16QAM	36
64QAM	48
64QAM	54

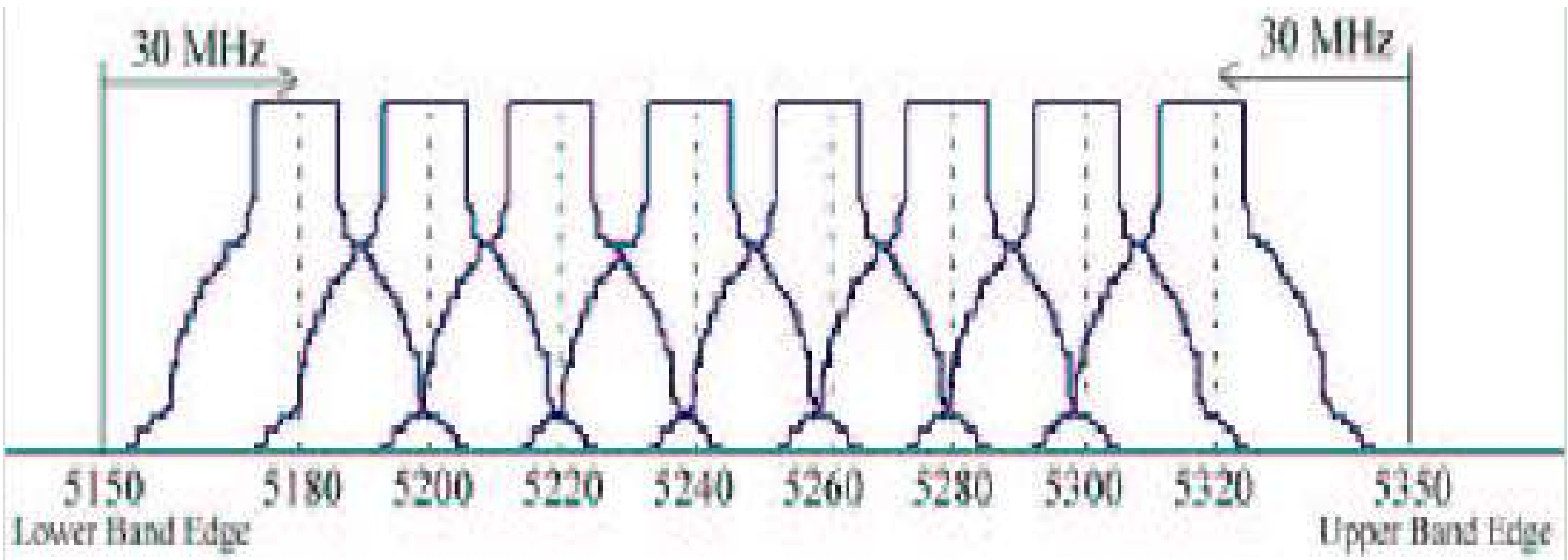
IEEE 802.11 PHY OFDM

- **OFDM - (IEEE 802.11a 5GHz) bands**

Channel ID	Frequency (MHz)	Channel Set: Americas (-A)	Channel Set: Japan (-J)	Channel Set: Singapore (-S)	Channel Set: Taiwan (-T)
34	5170		x		
36	5180	x		x	
38	5190		x		
40	5200	x		x	
42	5210		x		
44	5220	x		x	
46	5230		x		
48	5240	x		x	
52	5260	x			x
56	5280	x			x
60	5300	x			x
64	5320	x			x
Cisco Maximum Peak Power (mW)*		40	40	20	40

IEEE 802.11 PHY OFDM

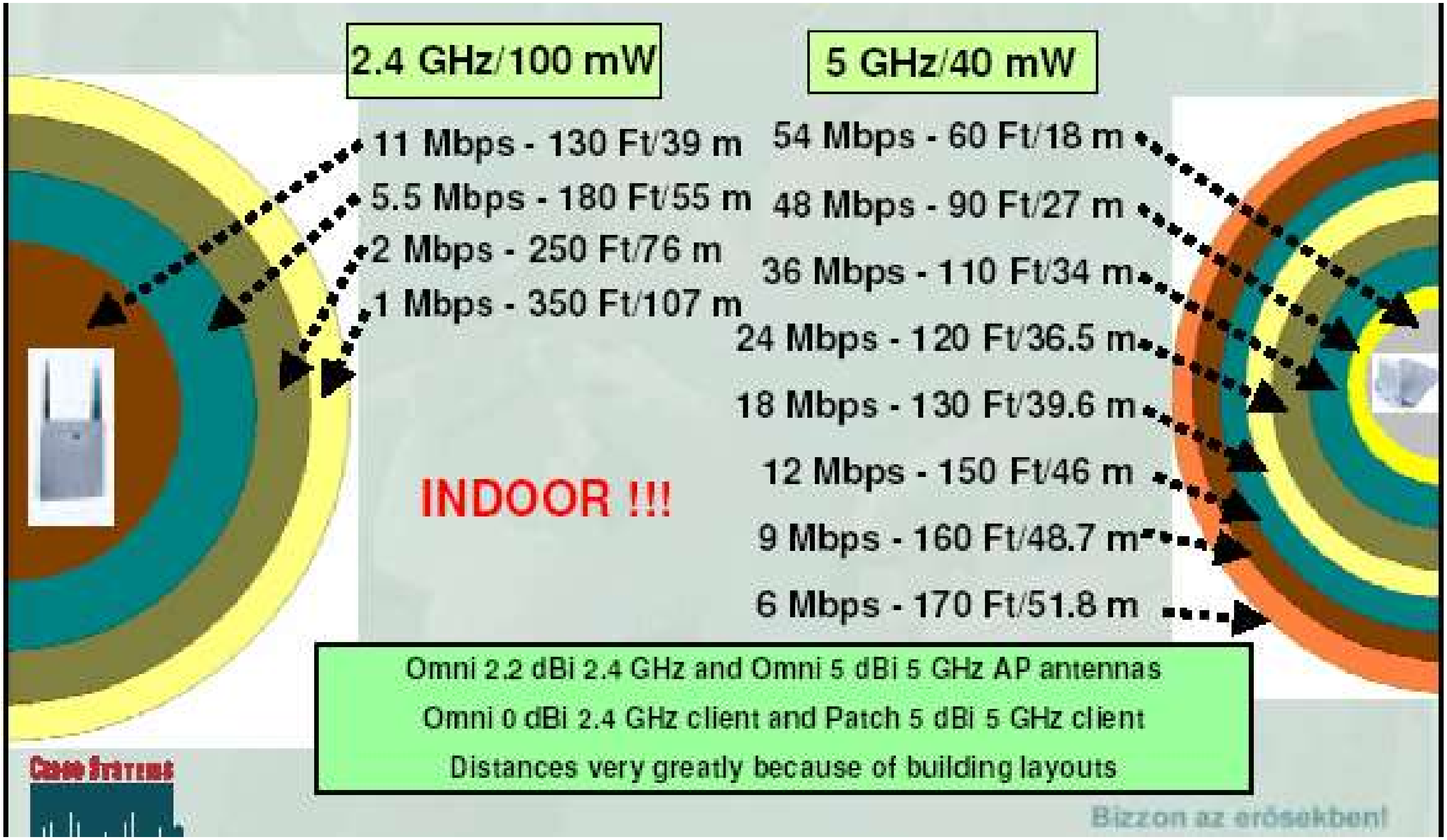
- **OFDM - (IEEE 802.11a 5GHz) 20 MHz bands e.g. USA**



IEEE 802.11 PHY DSSS - FHSS - OFDM

- **Frequency Hopped Spread Spectrum (FHSS)**
  – immune to multipath
- **Direct Sequence Spread Spectrum (DSSS)**
  – higher data transfer speed
  – better range
- **Orthogonal Frequency Division Multiplexing (OFDM)**
  – better signal-to-noise ratio (not disturbed by nearby reflections)
  – even higher data transfer speed
  – better range

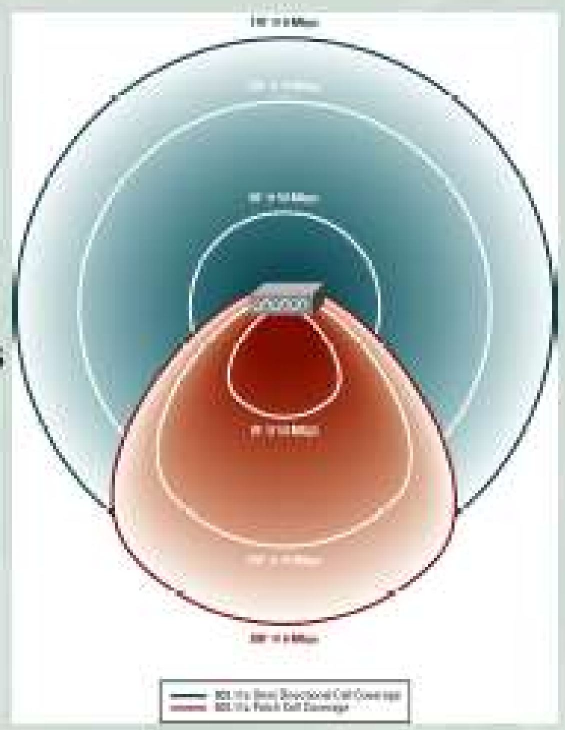
IEEE 802.11 PHY ranges



IEEE 802.11 PHY (802.11a) ranges

802.11a Omni-directional Antenna:

- Indoor:
  - 60 ft (18 m) @ 54 Mbps
  - 130 ft (40 m) @ 18 Mbps
  - 170 ft (52 m)@ 6 Mbps
- Outdoor:
  - 100 ft (30 m) @ 54 Mbps
  - 600 ft (183 m) @ 18 Mbps
  - 1000 ft (304 m) @ 6 Mbps



802.11a Patch Antenna:

- Indoor:
  - 70 ft (21 m) @ 54 Mbps
  - 150 ft (45 m) @ 18 Mbps
  - 200 ft (61 m) @ 6 Mbps
- Outdoor:
  - 120 ft (36 m) @ 54 Mbps
  - 700 ft (213 m) @ 18 Mbps
  - 1200 ft (355 m) @ 6 Mbps

Bizzon az erősekben!

IEEE 802.11 PHY (802.11 b) omni-directional ant.

IEEE 802.11 PHY Summary

	802.11b	802.11a	802.11g
Frekvencia sáv	2.4 GHz	5 GHz	2.4 GHz
Használhatóság	Világszerte	US/AP	Világszerte
Maximális sebesség	11 Mbps	54 Mbps	54 Mbps
Egyéb szolgáltatások (Interferenciák)	Vezeték nélküli telefon Mikrohullámú sütő Bluetooth	HyperLAN	Vezeték nélküli telefon Mikrohullámú sütő Bluetooth
	DSSS	OFDM	OFDM

- **Higher data transfer rate → shorter range**
- **Higher output power → range increases but battery life decreases (if mobile)**
- **Higher radio frequency → higher data transfer rate, but longer range**

IEEE 802.11n-2009 WiFi 4

- Multiple-input multiple-output OFDM (MIMO-OFDM)
  - Spatial Division Multiplexing (SDM): multiple antennas simultaneously transmit different TX (spatial data streams) on the same channel to multiple antennas of the same receiver (RX)
  - Use of multiple antennas for both transmit and receive (TXxRX:spatial data streams, max 4x4:4)
  - (multi-user MIMO – multiple receivers 802.11ac)
  - Beamforming: phase-shifted summation of antenna signals during reception, adjustment during transmission
- Frame aggregation in the MAC layer
  - Sends multiple frames one after the other and acknowledges them simultaneously (Block acknowledgement – BA frame 64*16 bit (fragment number)) sender-receiver negotiates in advance
- 40 MHz channel bandwidth for 5GHz, or optionally for 2.4GHz (20 MHz or 40MHz)

IEEE 802.11n

Modulation and coding schemes

MCS index	Spatial streams	Modulation type	Coding rate (m/n)	Data rate (in Mbit/s) [a] 20 MHz channel		40 MHz channel	
				800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	1	BPSK	1/2	6.5	7.2	13.5	15
1	1	QPSK	1/2	13	14.4	27	30
2	1	QPSK	3/4	19.5	21.7	40.5	45
3	1	16-QAM	1/2	26	28.9	54	60
4	1	16-QAM	3/4	39	43.3	81	90
5	1	64-QAM	2/3	52	57.8	108	120
6	1	64-QAM	3/4	58.5	65	121.5	135
7	1	64-QAM	5/6	65	72.2	135	150
8	2	BPSK	1/2	13	14.4	27	30
9	2	QPSK	1/2	26	28.9	54	60
10	2	QPSK	3/4	39	43.3	81	90
11	2	16-QAM	1/2	52	57.8	108	120
12	2	16-QAM	3/4	78	86.7	162	180
13	2	64-QAM	2/3	104	115.6	216	240
14	2	64-QAM	3/4	117	130	243	270
15	2	64-QAM	5/6	130	144.4	270	300
16	3	BPSK	1/2	19.5	21.7	40.5	45
17	3	QPSK	1/2	39	43.3	81	90
18	3	QPSK	3/4	58.5	65	121.5	135
19	3	16-QAM	1/2	78	86.7	162	180
20	3	16-QAM	3/4	117	130	243	270
21	3	64-QAM	2/3	156	173.3	324	360
22	3	64-QAM	3/4	175.5	195	364.5	405
23	3	64-QAM	5/6	195	216.7	405	450
24	4	BPSK	1/2	26	28.8	54	60
25	4	QPSK	1/2	52	57.6	108	120
26	4	QPSK	3/4	78	86.8	162	180
27	4	16-QAM	1/2	104	115.6	216	240
28	4	16-QAM	3/4	156	173.2	324	360
29	4	64-QAM	2/3	208	231.2	432	480
30	4	64-QAM	3/4	234	260	486	540
31	4	64-QAM	5/6	260	288.8	540	600

GI : Guard Interval
MCS : Modulation and Coding Scheme (standard)

https://en.wikipedia.org/wiki/IEEE_802.11n-2009

IEEE 802.11n

2.4 GHz channel usage for 40 MHz channels

Primary channel	20MHz	40 MHz above			40 MHz below		
	Blocks	2nd chapter.	Center	Blocks	2nd chapter.	Center	Blocks
1	1–3	5	3	1–7	N/A		
2	1–4	6	4	1–8	N/A		
3	1–5	7	5	1–9	N/A		
4	2–6	8	6	2–10	N/A		
5	3–7	9	7	3–11	1	3	1–7
6	4–8	10	8	4–12	2	4	1–8
7	5–9	11	9	5–13	3	5	1–9
8	6–10	12	10	6–13	4	6	2–10
9	7–11	13	11	7–13	5	7	3–11
10	8–12	N/A			6	8	4–12
11	9–13	N/A			7	9	5–13
12	10–13	N/A			8	10	6–13
13	11–13	N/A			9	11	7–13

https://en.wikipedia.org/wiki/IEEE_802.11n-2009

IEEE 802.11ac WiFi 5 (2013, 2016)

- **80MHz channel bandwidth, optionally 160MHz**
- **8 MIMO spatial streams (SDM)**
- **Downlink multi-user MIMO (MU-MIMO)**
  - **4 independent downlink channels in parallel for 4 users**
  - **Beamforming**
- **IEEE 802.11ac Wave 1 (2013) 1.3 Gbit/s**
- **IEEE 802.11ac Wave 2 (2016) 2.34 Gbit/s**

IEEE 802.11ac

Modulation and coding schemes
1 spatial stream
(max 4 streams)

index [a]	Spatial Streams	Modulation type	Coding rate	Data rate (in Mbit/s) [16][b] 20 MHz channels 800 ns GI	20 MHz channels 400 ns GI	40 MHz channels 800 ns GI	40 MHz channels 400 ns GI	80 MHz channels 800 ns GI	80 MHz channels 400 ns GI	160 MHz channels 800 ns GI	160 MHz channels 400 ns GI
0	1	BPSK	1/2	6.5	7.2	13.5	15	29.3	32.5	58.5	65
1	1	QPSK	1/2	13	14.4	27	30	58.5	65	117	130
2	1	QPSK	3/4	19.5	21.7	40.5	45	87.8	97.5	175.5	195
3	1	16-QAM	1/2	26	28.9	54	60	117	130	234	260
4	1	16-QAM	3/4	39	43.3	81	90	175.5	195	351	390
5	1	64-QAM	2/3	52	57.8	108	120	234	260	468	520
6	1	64-QAM	3/4	58.5	65	121.5	135	263.3	292.5	526.5	585
7	1	64-QAM	5/6	65	72.2	135	150	292.5	325	585	650
8	1	256-QAM	3/4	78	86.7	162	180	351	390	702	780
9	1	256-QAM	5/6	N/A	N/A	180	200	390	433.3	780	866.7

https://en.wikipedia.org/wiki/IEEE_802.11ac

IEEE 802.11ac WiFi 5

Advertised speeds : highest link rates in Mbit/s of all the simultaneously-usable radios in the device added up

Type	2.4GHz band [e] Mbit /s	2.4 GHz band configuration [all 40 MHz]	5 GHz band Mbit/s	5 GHz band config [all 80 MHz]
AC450 [17]	-	-	433	1 stream @ MCS 9
AC600	150	1 stream @ MCS 7	433	1 stream @ MCS 9
AC750	300	2 streams @ MCS 7	433	1 stream @ MCS 9
AC1000	300	2 streams @ MCS 7	650	2 streams @ MCS 7
AC1200	300	2 streams @ MCS 7	867	2 streams @ MCS 9
AC1300	400	2 streams @ 256-QAM	867	2 streams @ MCS 9
AC1300 [18]	-	-	1,300	3 streams @ MCS 9
AC1350 [19]	450	3 streams @ MCS 7	867	2 streams @ MCS 9
AC1450	450	3 streams @ MCS 7	975	3 streams @ MCS 7
AC1600	300	2 streams @ MCS 7	1,300	3 streams @ MCS 9
AC1700	800	4 streams @ 256-QAM	867	2 streams @ MCS 9
AC1750	450	3 streams @ MCS 7	1,300	3 streams @ MCS 9
AC1900	600 [d]	3 streams @ 256-QAM	1,300	3 streams @ MCS 9
AC2100	800	4 streams @ 256-QAM	1,300	3 streams @ MCS 9
AC2200	450	3 streams @ MCS 7	1,733	4 streams @ MCS 9
AC2300	600	4 streams @ MCS 7	1,625	3 streams @ 1024-QAM
AC2400	600	4 streams @ MCS 7	1,733	4 streams @ MCS 9
AC2600	800 [d]	4 streams @ 256-QAM	1,733	4 streams @ MCS 9
AC2900	750 [e]	3 streams @ 1024-QAM	2,167	4 streams @ 1024-QAM
AC3000	450	3 streams @ MCS 7	1,300 + 1,300	3 streams @ MCS 9 x 2
AC3150	1000 [e]	4 streams @ 1024-QAM	2,167	4 streams @ 1024-QAM
AC3200	600 [d]	3 streams @ 256-QAM	1,300 + 1,300 [f]	3 streams @ MCS 9 x 2
AC5000	600	4 streams @ MCS 7	2.167 + 2.167	4 streams @ 1024-QAM x 2
AC5300 [22]	1000 [e]	4 streams @ 1024-QAM	2.167 + 2.167	4 streams @ 1024- QAM x 2

https://en.wikipedia.org/wiki/IEEE_802.11ac

IEEE 802.11ax WiFi 6 (2020 draft)

- OFDMA Resource Units (RU)
  - The AP can allocate the OFDMA component channels (RU) to users
- Multi-user MIMO in both downlink and uplink directions
  - The AP allocates the RUs to the stations.
- Multiple RUs can be used in parallel for contention
  - (random access, if a station is not assigned to an RU)
- "Spatial" frequency reuse ”
- They can add to the broadcasts of stations from foreign cells
  - (detection of transmissions from foreign cells, adaptive threshold , received signal level, transmission level)
- Dynamic fragmentation (variable size fragmentation)
  - Utilizing available RUs

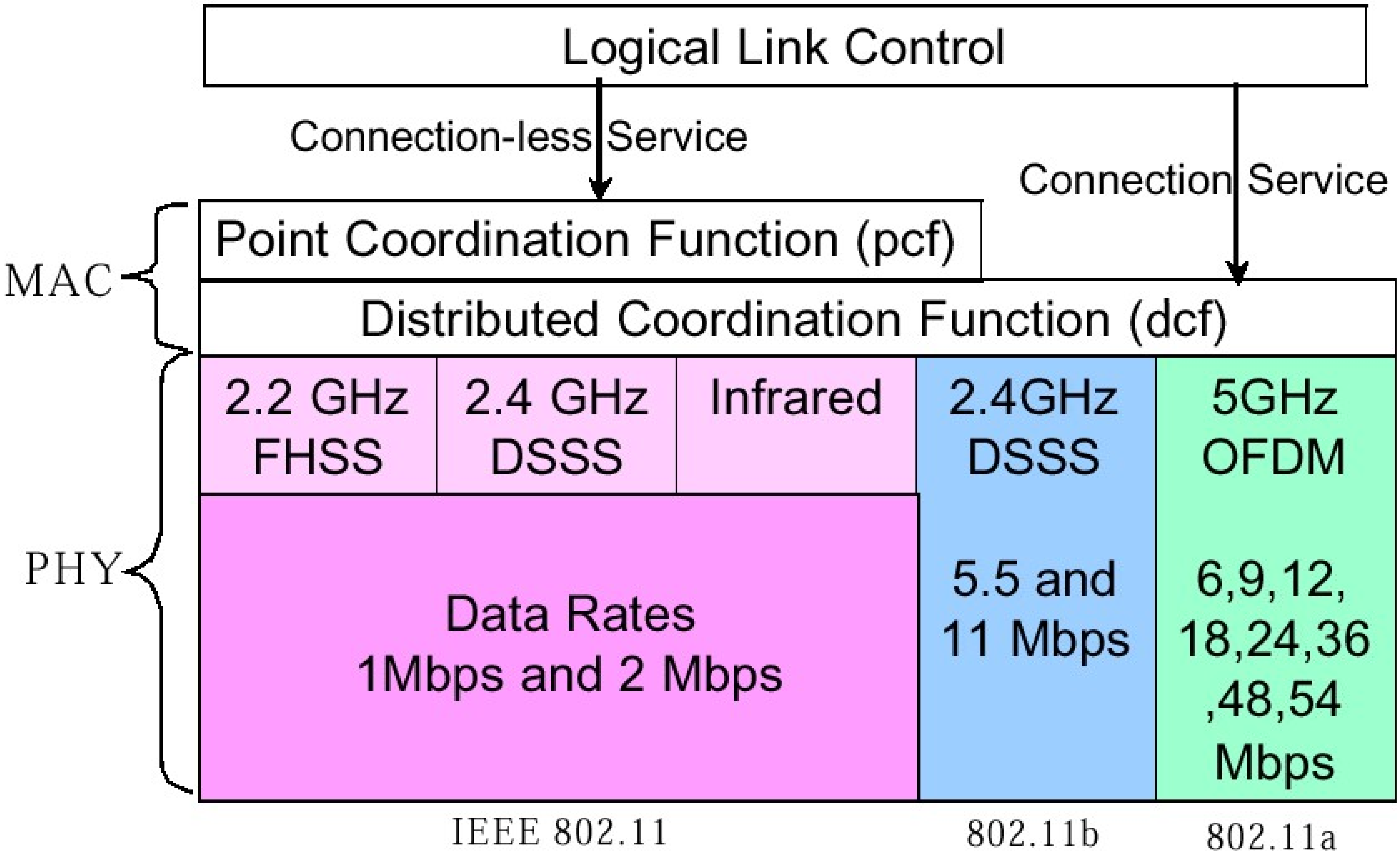
IEEE 802.11ax

Modulation and coding schemes
1 spatial stream
(max 4 streams)

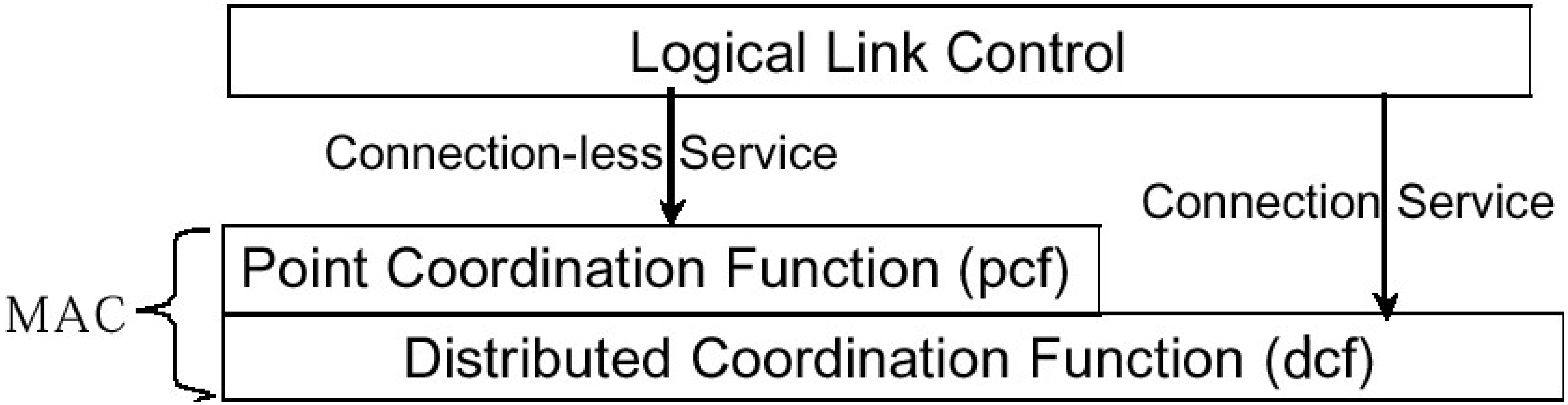
MCS index [a]	Modulation type	Coding rate	Data rate (in Mbit/s) [b]							
			20 MHz channels		40 MHz channels		80 MHz channels		160 MHz channels	
			1600 ns GI [c]	800 ns GI	1600 ns GI	800 ns GI	1600 ns GI	800 ns GI	1600 ns GI	800 ns GI
0	BPSK	1/2	8	8.6	16	17.2	34	36.0	68	72
1	QPSK	1/2	16	17.2	33	34.4	68	72.1	136	144
2	QPSK	3/4	24	25.8	49	51.6	102	108.1	204	216
3	16-QAM	1/2	33	34.4	65	68.8	136	144.1	272	282
4	16-QAM	3/4	49	51.6	98	103.2	204	216.2	408	432
5	64-QAM	2/3	65	68.8	130	137.6	272	288.2	544	576
6	64-QAM	3/4	73	77.4	146	154.9	306	324.4	613	649
7	64-QAM	5/6	81	86.0	163	172.1	340	360.3	681	721
8	256-QAM	3/4	98	103.2	195	206.5	408	432.4	817	865
9	256-QAM	5/6	108	114.7	217	229.4	453	480.4	907	961
10	1024-QAM	3/4	122	129.0	244	258.1	510	540.4	1021	1081
11	1024-QAM	5/6	135	143.4	271	286.8	567	600.5	1134	1201

https://en.wikipedia.org/wiki/IEEE_802.11ax

IEEE 802.11 PHY



IEEE 802.11 MAC

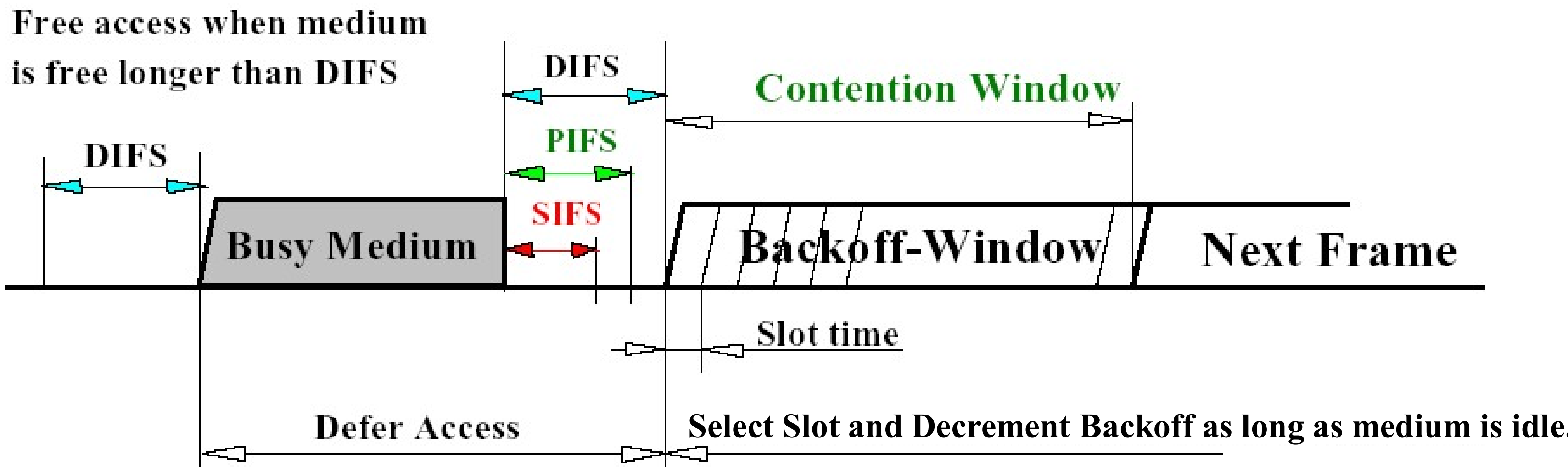


Two different MAC access method:

- **Distributed Coordination Function (DCF) - competitive CSMA/CA.**
- **Point Coordination Function (PCF) – centralized, collision-free**

DCF: CSMA/CA

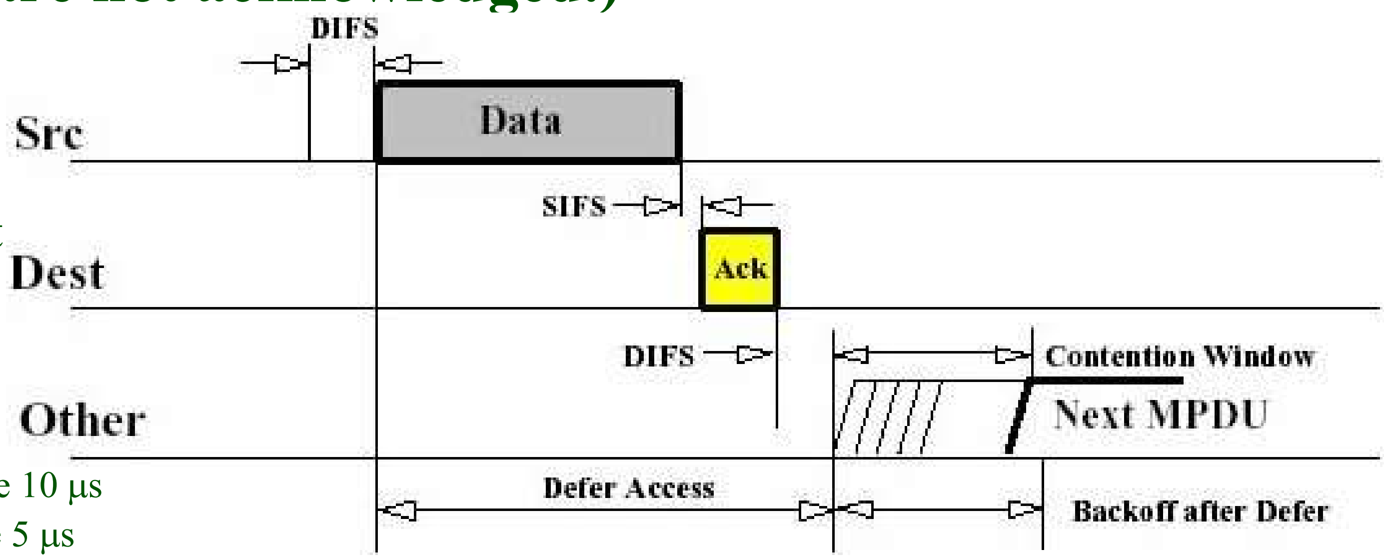
- The station listens to the channel before it starts transmitting (CSMA)
- If it is empty for a Distributed Interframe Space (DIFS) period, it starts transmitting.
- If it is busy, it waits until it is free and then waits for a random amount of time (Binary Exponential Backoff – like in 802.3), then tries again.
- In case of an error (collision (or other noise)), a new Backoff time is drawn.



DCF: CSMA/CA – MAC level ACK

- **Error (collision) detection – missing positive acknowledgement**
- **If a station receives an error-free message addressed to it, it sends a positive acknowledgement to the sender after a Short Interframe Space (SIFS).** (SIFS+Slot = PIFS, PIFS+Slot = DIFS)
- **The sender knows from the receipt that the sending was successful**
- (Multicasts **are not acknowledged.)**

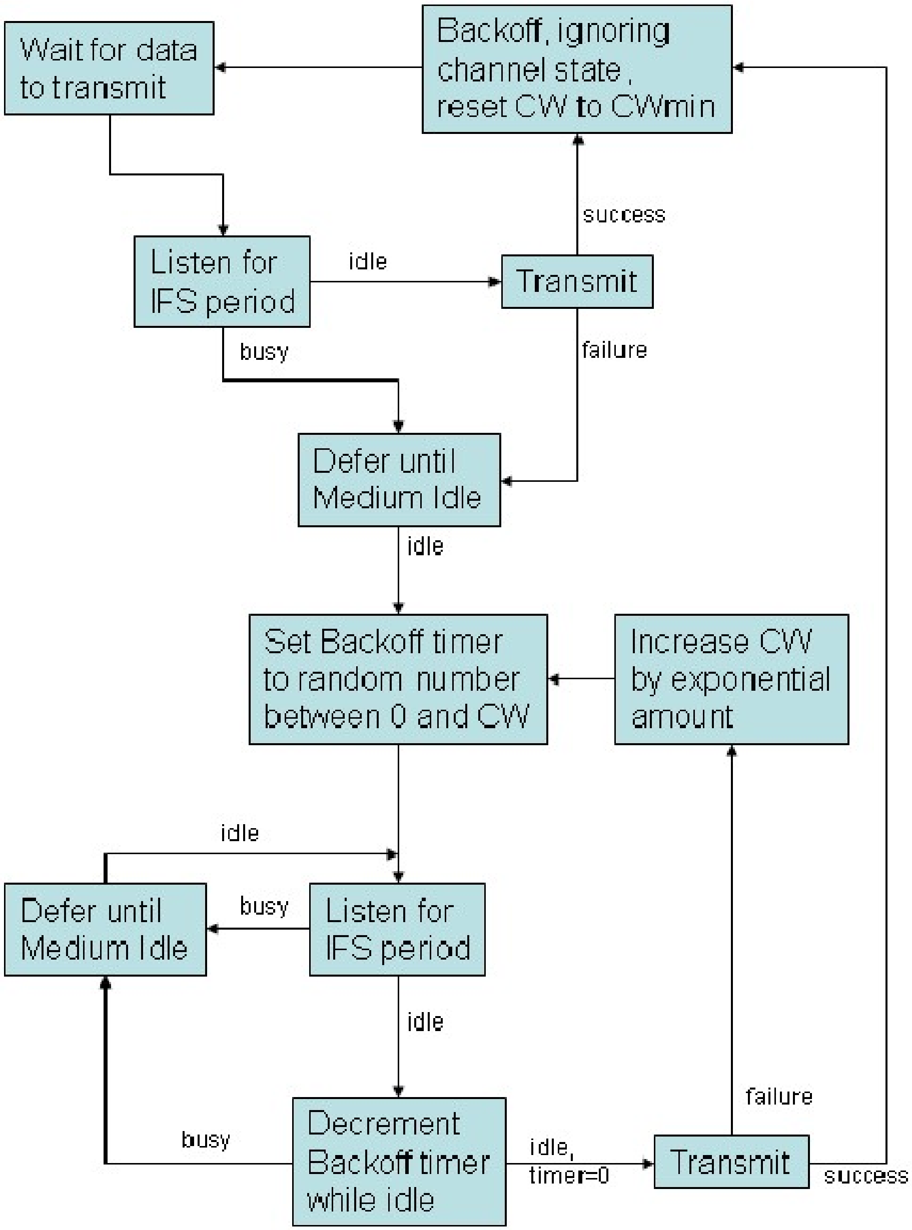
Slot Time : maximum time required from the start of transmission until it is detected



E.g. DSSS

- Slot time 20 μ s
- TX to Rx turnaround time 10 μs
- Rx to Tx turnaround time 5 μs

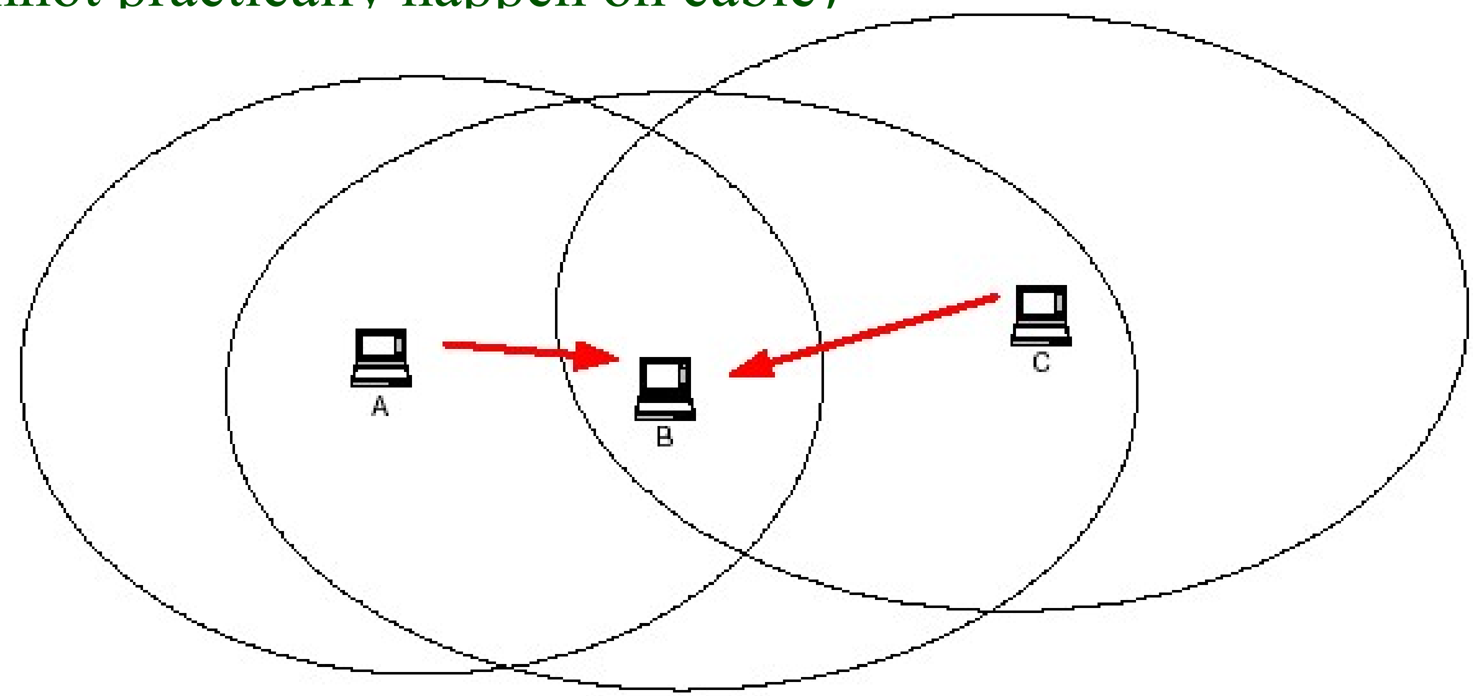
DCF: CSMA/CA - Exponential Backoff



- **CW: Contention Window** (within this, a slot number is drawn)
- **In case of successful transmission:** $CW = CW_{min}$
- **The reduction of the "Bacokff" duration is interrupted by the medium occupancy (+ IFS) time** (does not start over)
- Channel occupancy: CS+NAV
- **Exponential Backoff:** $CW_{new}=\min(2*(CW_{old}+1)-1, CW_{max})$ i.e. as in 802.3 $CW_i = 2^i-1$, more precisely $CW_i = \min(2^i-1, CW_{max})$

Radio networks – additional problems

- **A fundamental problem is that in a radio network, not all stations can hear each other:**
- **Hidden Node Problem**
- B hears A, C ; A does not hear C
  (this cannot practically happen on cable)



“Hidden node” problem

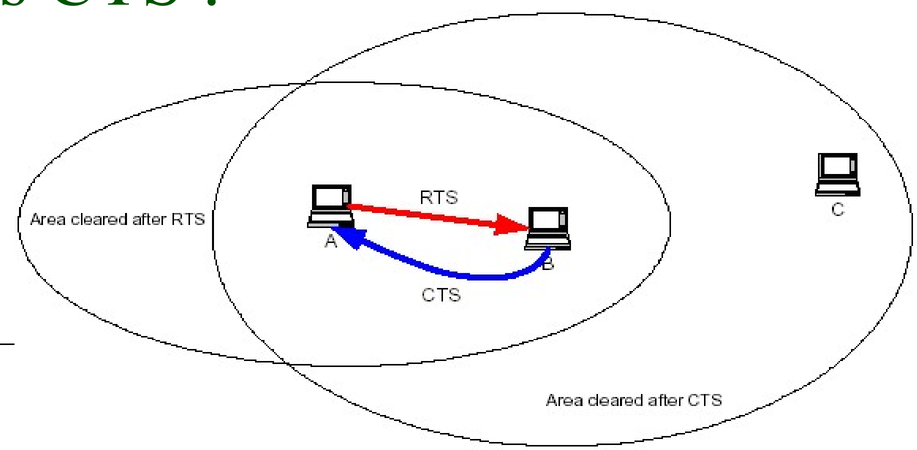
Solution: “Virtual” carrier sense

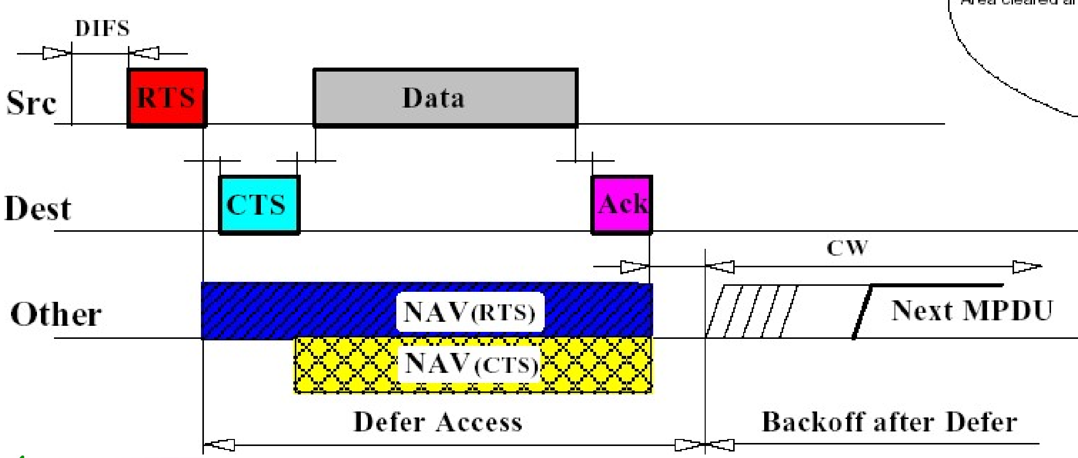
- **The station wishing to transmit indicates its intention to transmit with a short** (Request To Send - **RTS**) **frame in which it specifies the duration of the frame to be sent (Duration field).**
- **The receiver acknowledges this with a short** (Clear To Send - **CTS**) frame which repeats the (recalculated) **duration indicated in the RTS.**
- Each station has a **Network Allocation Vector (NAV)** .
- **NAV always indicates the time remaining until the channel is freed**
  – during this time, stations consider the channel busy even if they do not physically detect a transmission.
  ⇒ “Virtual” carrier sense
- **Stations that receive either RTS or CTS update their NAV based on the time period contained therein.**

IEEE 802.11 “Virtual” Carrier Sense

802.11: Virtual + real carrier sensing

- **If the transmitting station is not heard (RTS),**
  - no real carrier sensing
- **The NAV (Network Allocation Vector) can also be set based on** the receiver 's CTS .
  - virtual carrier sensing

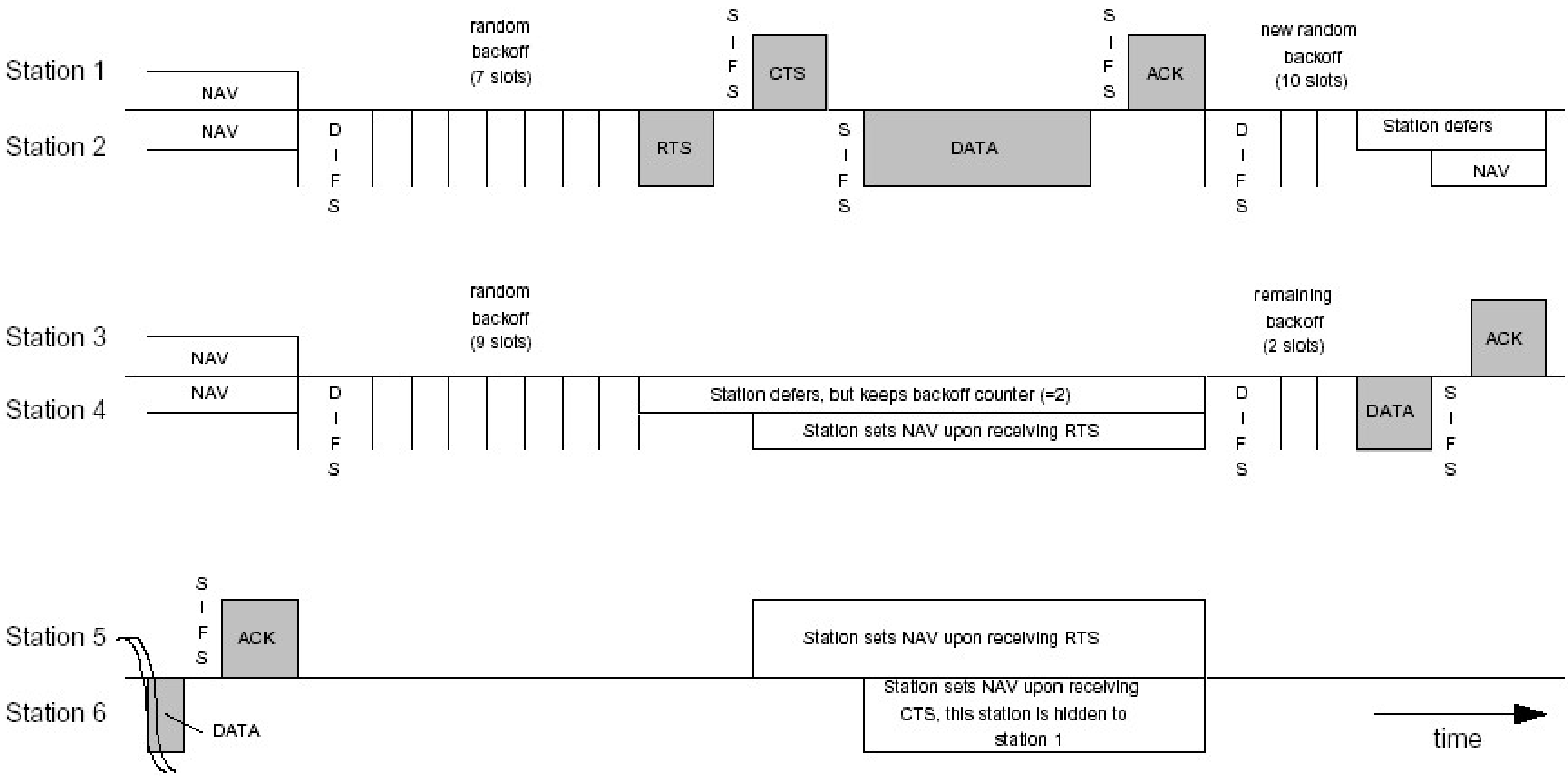




IEEE 802.11 “Virtual” Carrier Sense

- **If a station receives a meaningless frame, it waits for a longer period of time Extended IFS (EIFS)**
  - so that possible reception errors do not spoil the virtual carrier sensing (it does not know for sure from the erroneous frame how long it should wait)
- **The RTS/CTS mechanism** (being short frames) **also reduces collision losses.**
- **The RTS/CTS mechanism can be disabled.**
- **It is possible to define the minimum frame size below which the RTS/CTS mechanism is not needed**
  (unnecessary overhead in the case of short frames)
- **It is also not needed if:**
  - **There is little bandwidth requirement and there is not much competition for the channel** (low traffic or few stations – low collision probability) and
  - **in a place where every station can hear everyone.**

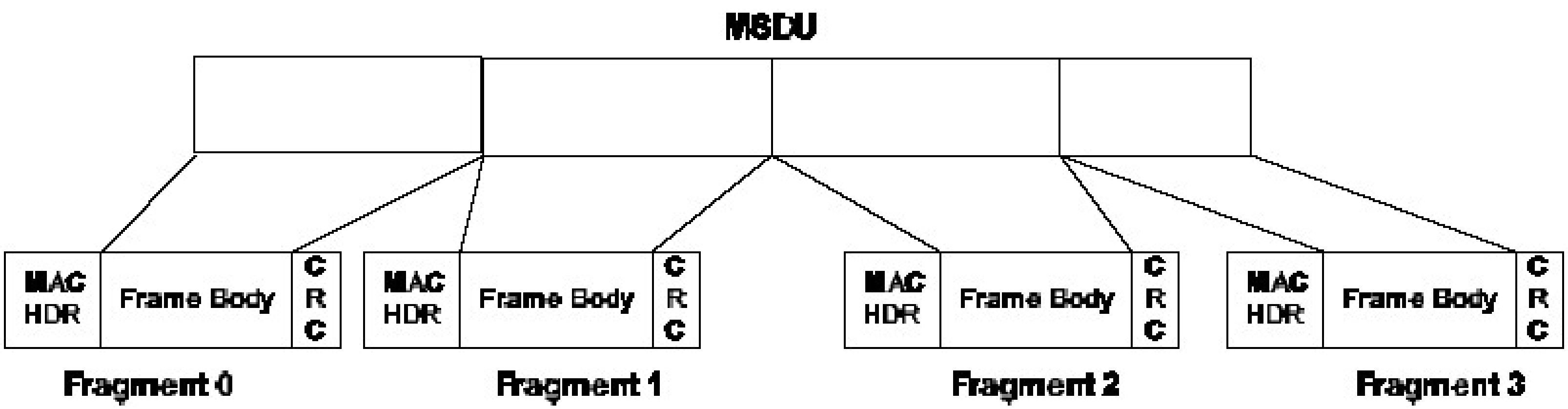
IEEE 802.11 “Virtual” Carrier Sense



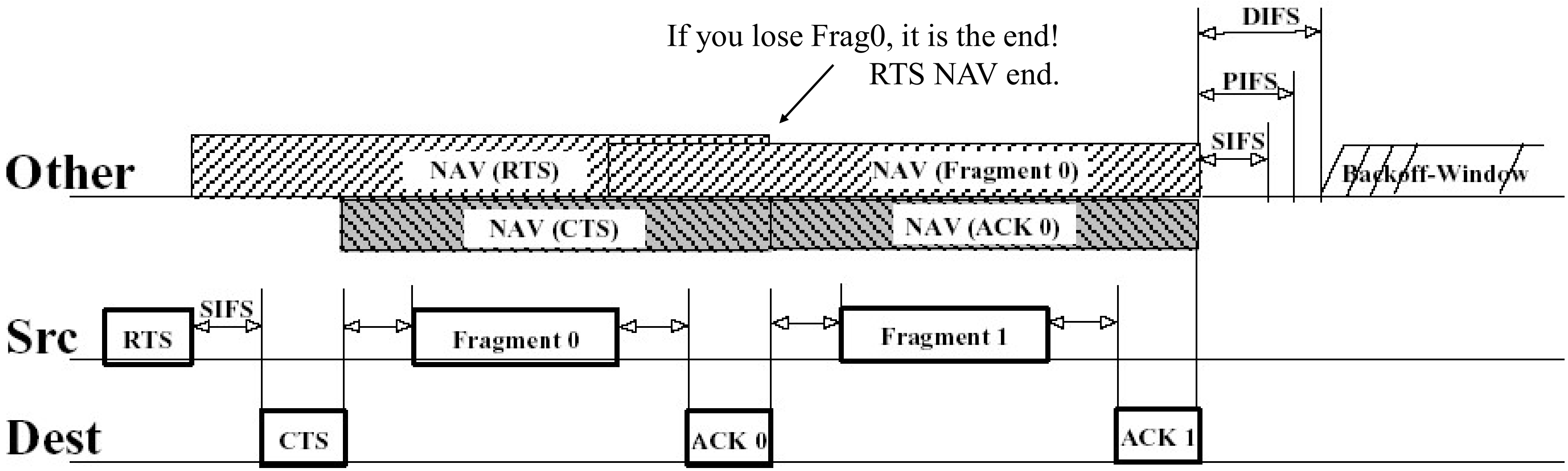
- **Station** 6 does not hear **RTS from station 2** , only CTS **from station 1** .

Frame Fragmentation and Reassembly

- Because of the higher bit error rate, in radio networks, it is advisable to use shorter frame sizes to reduce losses (802.3 - 1518byte max)
- Simple fragmentation – sender create fragments + header + CRC
- The receiver acknowledges each piece, collects it, and then assembles the frame. If it takes too long to receive any piece, the whole thing is discarded.
- If the sender cannot send a piece for too long, it also discards the entire frame.



Frame Fragmentation and Reassembly

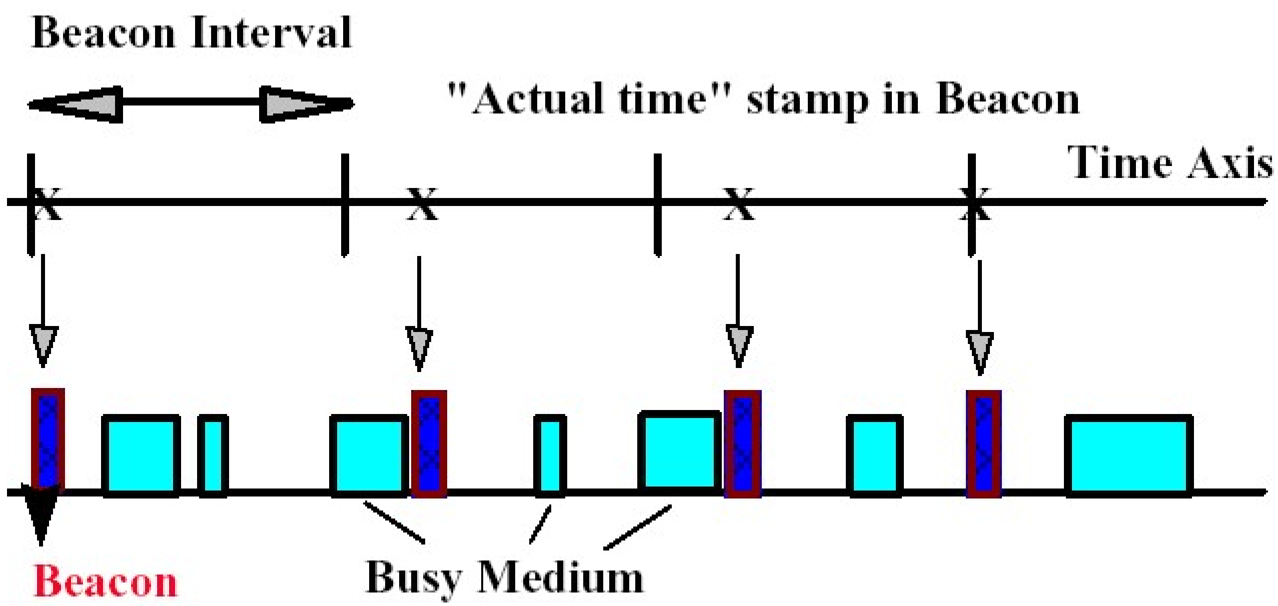


- **Each piece is acknowledged one by one by the recipient → Only usable for Unicast frames.**
- **If the transmitter does not receive an acknowledgement, it waits for a random amount of time and retransmits.**
- **Stations update their NAV based on the Data and Ack Duration field of the frames,** (maintaining channel occupancy – virtual carrier sensing)

New station joining to the BSS

- **It need to synchronize itself with the Access Point (AP) of the BSS (Basic Service Set)**
- **Passive Scanning**
  - waits until it hears the AP's **Beacon Frame** (sent periodically and contains synchronous information, e.g. the AP clock value (stations update their clocks based on this)).
- **Active Scanning**
  - Sends a **Request Frame** and waits for the mandatory **Probe Response** from the AP.
- The station that wants to join then identifies itself to the AP and connects (**Authentication, Association Process**) (it must know the shared secret key (WEP))

Synchronization



- **The AP sends Beacon frames periodically** (Beacon Interval)
- **This may change due to CSMA** (it does not measure the next one against the previous one, but against the ideal one – so for example, in the case of power saving, the station can sleep via multiple Beacons)
- **The Beacon timestamp shows the time of posting.**

802.11 frame format

Preamble	PLCP Header	MAC Data	CRC

- **Preamble** (always at 1Mbps):
  - **Sync: 128 bit 0101... – receiver synchronization** (**56 bit short sync** - option e.g.video)
  - **SFD: 16 bit Start Frame Delimiter** 0000 1100 1011 1101,
- **PLCP Header** (always at 1Mbps):
  - **PLCP Signaling Field**: bit rate of the remaining part of the frame
  - **PLCP_MPDU Length Word**: the number of bytes of MAC data
  - **Header Error Check Field:** 16 Bit CRC (CCITT CRC-16)
- **MAC Data**

Octets: 2	2	6	6	6	2	6	0 - 2312	4
Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Frame Body	CRC

MAC Header

PHY: Physical Layer Convergence Protocol + Physical Medium Dependent sublayer.
(PLCP - wireless encoding) **(PMD -** common interface for MAC sublayer)

802.11 frame format – Frame Control

B0–B1	B2–B3	B4–B7	B8	B9	B10	B11	B12	B13	B14	B15
Protocol Version	Type	Subtype	To DS	From DS	More Frag	Retry	Pwr Mgt	More Data	WEP	Order
Bits: 2	2	4	1	1	1	1	1	1	1	1

- **Protocol version:** currently 00
- **ToDS:** 1 if sent to AP to forward to **Distribution System** or repeat (same BSS, but can't hear each other) – otherwise 0
- **FromDS:** 1 if the AP is re-sending from the **Distribution System** – otherwise 0
- **More Fragments** : 1 if there are still more fragments left in the frame
- **Retry** : This bit indicates that this is a retransmitted chunk (indicating possible duplication to the receiver if the ACK was lost)
- **Power Management** : After sending, the station changes state Power Save ↔ Active
- **More Data** : In the case of Power Management, this indicates that there are still additional frames stored in the AP after the Poll (another Poll, possibly Active state required)
- **WEP**: This bit indicates if the frame body is WEP encrypted (Wired Equivalent Privacy, an encryption based on RSA RC4 , 64-128-152 bit single shared key encryption)
- **Order**: If the order of Unicast and Multicast frames cannot be swapped. (E.g. in case of DEC LAT)

802.11 frame format – Type, Subtype

Type Value b3 b2	Type Description	Subtype Value b7 b6 b5 b4	Subtype Description	
00	Management	0000	Association Request	
00	Management	0001	Association Response	
00	Management	0010	Association Request	
00	Management	0011	Reassociation Response	
00	Management	0100	Probe Request	
00	Management	0101	Probe Response	
00	Management	0110-0111	Reserved	
00	Management	1000	Beacon	
00	Management	1001	ATIM	
00	Management	1010	Disassociation	
00	Management	1011	Authentication	
00	Management	1100	Deauthentication	
00	Management	1101-1111	Reserved	
01	Control	0000-0001	Reserved	
01	Control	1010	PS-Poll	Power Save - poll
01	Control	1011	RTS	
01	Control	1100	CTS	
01	Control	1101	ACK	
01	Control	1110	CF End	
01	Control	1111	CF End + CF-ACK	
10	Data	0000	Data	
10	Data	0001	Data + CF-Ack	
10	Data	0010	Data + CF-Poll	
10	Data	0011	Data + CF-ACK + CF-Poll	
10	Data	0100	Null Function (no data)	
10	Data	0101	CF-Ack (no data)	
10	Data	0110	CF-Poll (no data)	Contentio-Free-poll
10	Data	0111	CF-Ack + CF-Poll (no data)	
10	Data	1000-1111	Reserved	
10	Data	0000-1111	Reserved	

802.11 Frame Format – MAC Data

Octets: 2	2	6	6	6	2	6	0 - 2312	4
Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Frame Body	CRC

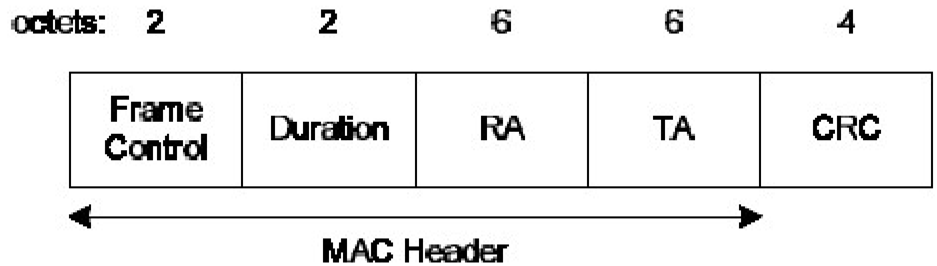
MAC Header

- **Duration/ID:**
  - In case of Power-Save Poll, the station ID (Station ID)
  - In other cases, the duration required to calculate NAV (duration value)
- **Sequence Control:** Indicates the parts belonging to the same frame. Their sequence number consists of two fields: Fragment Number (which frame, 12bit) and Sequence Number (which part, 4b)
- **CRC:** 32-bit Cyclic Redundancy Check (CCITT CRC-32)
- **Address-1:** the address of the receiver in BSS, or in the case of ToDS the address of the AP (**Receiver**)
- **Address-2:** the address of the sender in BSS, or in the case of FromDS the address of the AP (**Target**)
- **Address-3:** In the case of FromDS, the original **Source Address** , in the case of ToDS, the original **Destination Address** .
- **Address-4:** Used in Wireless Distribution System when sending the frame between two APs

To DS	From DS	Address 1	Address 2	Address 3	Address 4
0	0	DA	SA	BSSID	N/A
0	1	DA	BSSID	SA	N/A
1	0	BSSID	SA	DA	N/A
1	**1**	**RA**	**TA**	**DA**	**SA**

BSSID : the **AP** MAC address

802.11 frame format – common frames

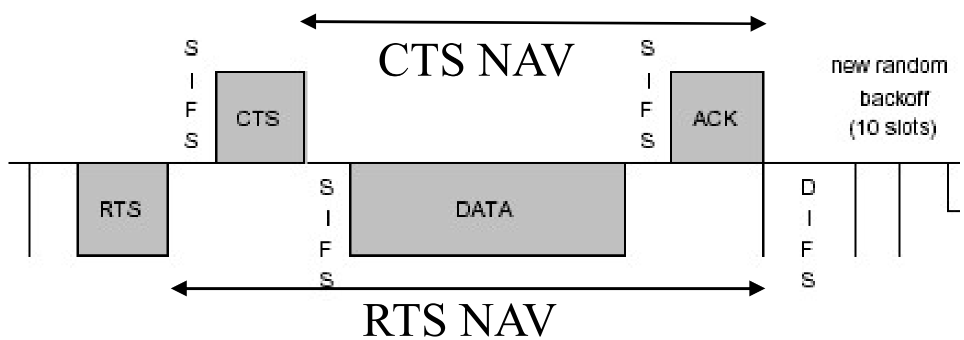


RTS frame :

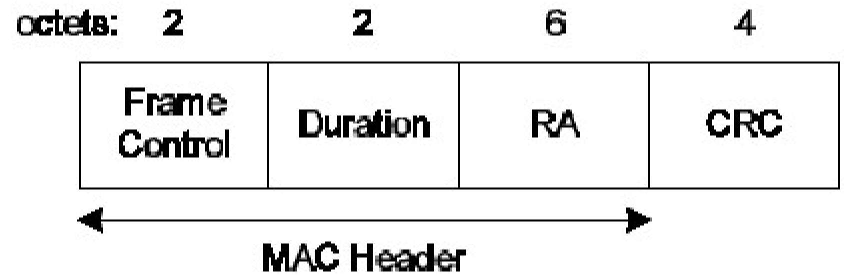
- **RA**: address of the destination station (expects CTS from it)
- **TA**: address of the station sending the RTS frame
- **Duration**: time in µsec to wait before sending the next Data or Management frame + 1 CTS + 1 ACK + 3 SIFS time

CTS frame:

- **RA**: the TA (Transmitter Address) of the previous RTS frame
- **TA**: address of the station sending the CTS frame
- **Duration**: Duration of the previous RTS frame – 1 CTS – 1 SIFS time (µsec) .

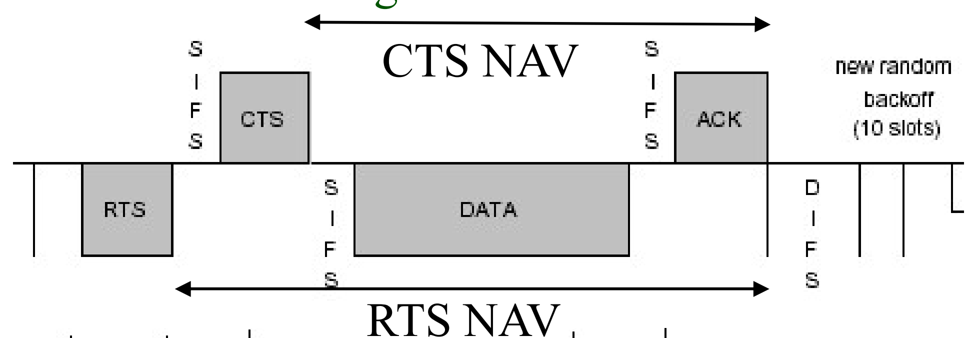


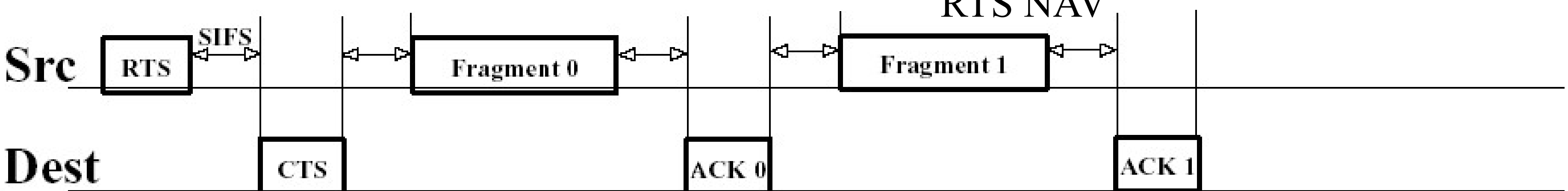
802.11 frame format – common frames



ACK frame (Frame Control: Retry bit indicates if it is a repeated acknowledgement (no sequence number)):

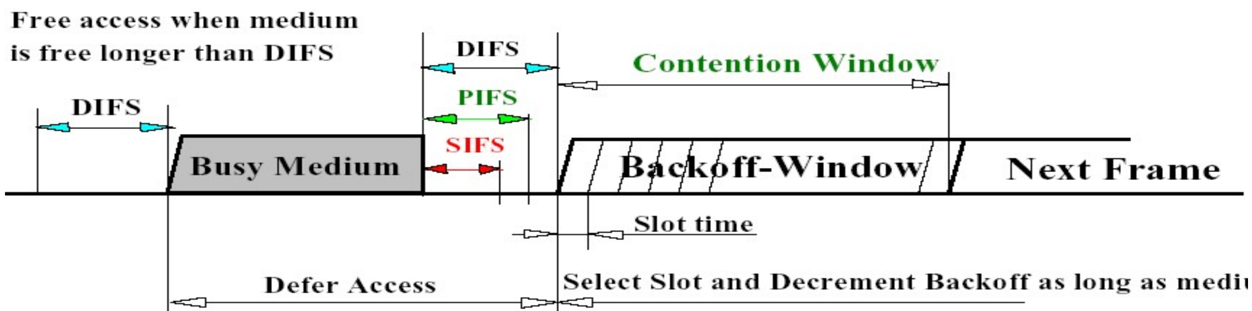
- **RA**: Address-2 field of the acknowledged (preemptive) frame (TA (Transmitter Address))
- **Duration**:
  - If the More Fragment bit of the acknowledged frame is 0, it is 0 (this is the end)
  - In case of 1, the Duration value of the acknowledged frame is – 1 ACK – 1 SIFS time (µsec) .



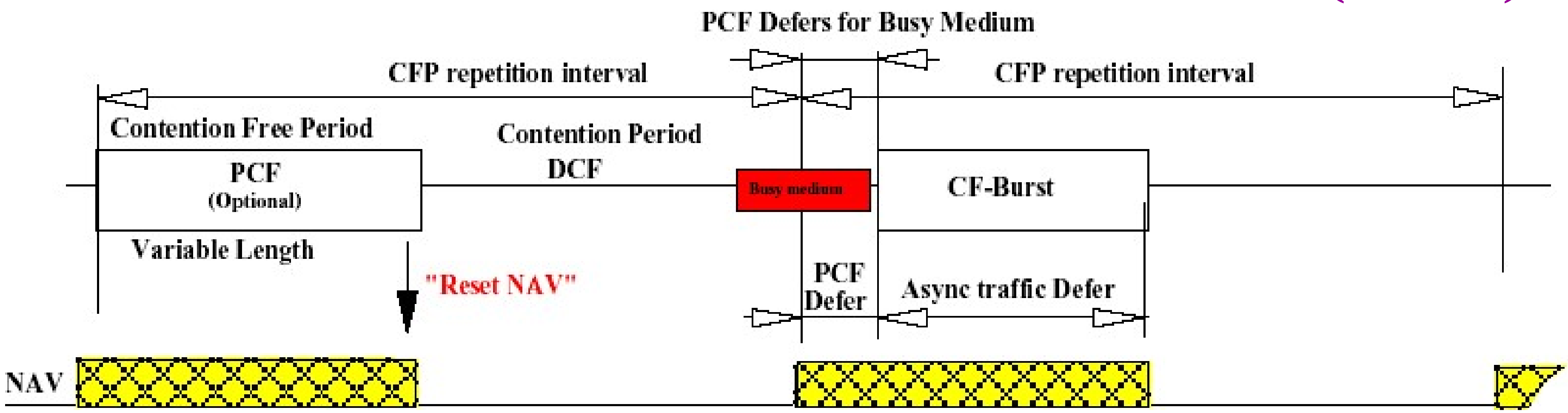


802.11 Point Coordination Function (PCF)

- **Centralized collision-free media access control**
- Can be used for time-limited traffic such as voice, video, etc.
- **The PCF is controlled by the Point Coordinator (PC)** (located on the AP)
- **Stations can request to be added to the PC Polling List.**
- **At regular intervals, the PC (Access Point) is given higher priority during DCF contention – using PIFS (Point Coordination IFS) which is shorter than DIFS**
  (it seizes the channel before other stations - the others wait for a DIFS before starting to compete)
- **After acquiring the channel, the Access Point station sends Polling Requests frames to the selected stations to send their data** (centralized, **contention- free period** (CFP))

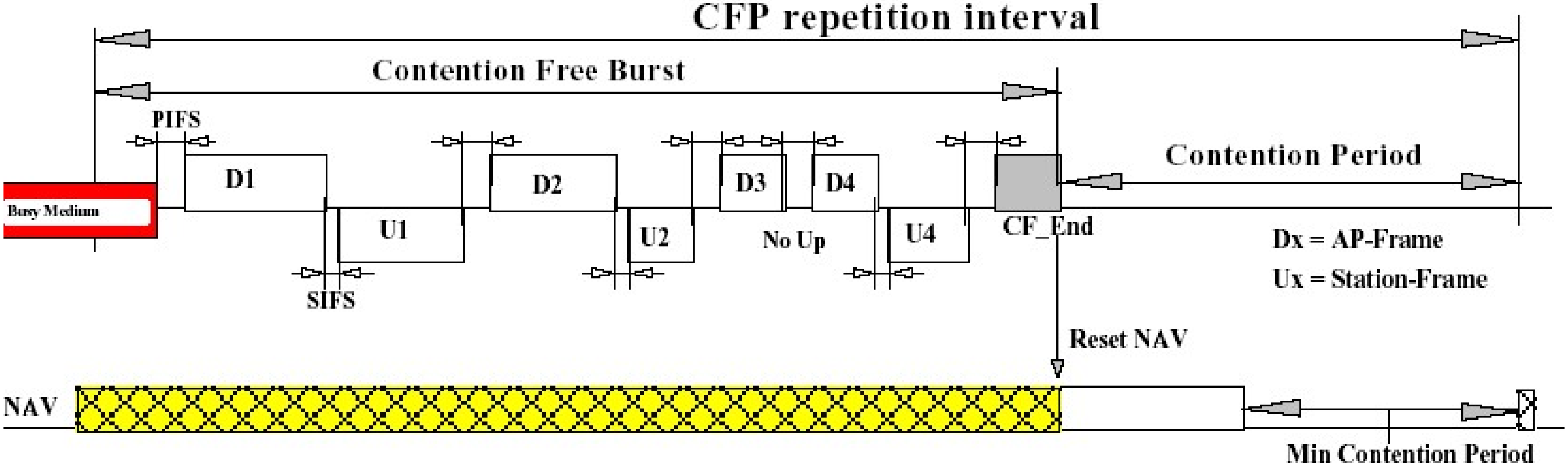


802.11 Point Coordination Function (PCF)



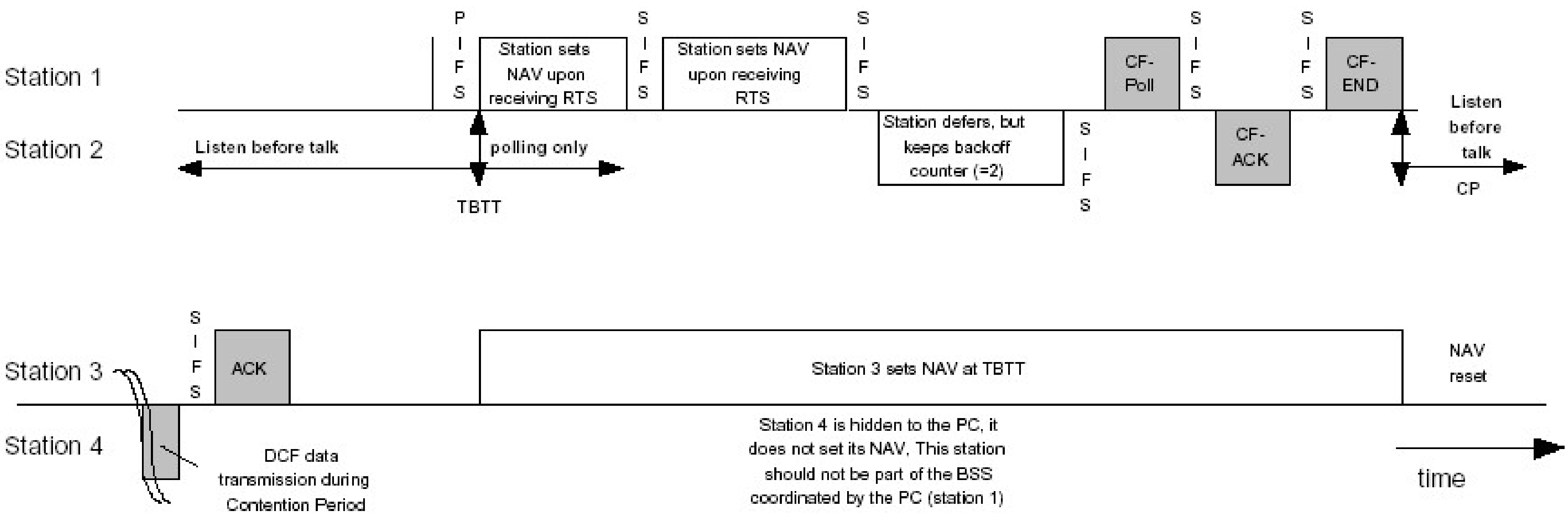
- **Contention-free and contention-free periods alternate.**
- **The PC uses the Duration field of the Beacon frame** (NAV setting on the stations) **to stop the DCF** (contention) **period.**
- **The length of the Contention Free periods can vary - both the PCF and DCF busy periods can delay the other.**
  (Neither can start until the channel is freed)
- **In order to keep the competing Distributed Coordination Function (DCF) traffic alive, the Point Coordinator (PC) must allow time for DCF between regularly recurring** (near-isochronous service) **PCFs.**
  (Mandatory minimum: one max. frame size time including its acknowledgement)

802.11 PCF – CF-Burst



- **CF-Burst: active Polling bit** (CF_Poll) in **CF-Down** (Dx) **frame** (**PC** starts by sending **Beacon** frame – **NAV to other stations**) – in order to those stations that requested CF service from PC.
- **The polled station responds immediately** (Ux) – **data and acknowledgement** ("ACK Previous Frame" bit).
- **Responses (queries) can be of variable length**
- **The last frame of the PC (CF_End) clears the NAV – end of CFP.**

802.11 Point Coordination Function (PCF)



- Station1: PC polling station, station2 and station3 set their NAV based on the Beacon frame for the entire CFP duration – but if station4 does not hear station1, it remains in DCF.
- **The PC uses PIFS so it is not interfered with by DCF stations using DIFS**

802.11 Power Saving

- In the case of mobile stations, reducing energy consumption may be important
- 802.11 allows stations to sleep **without data loss**

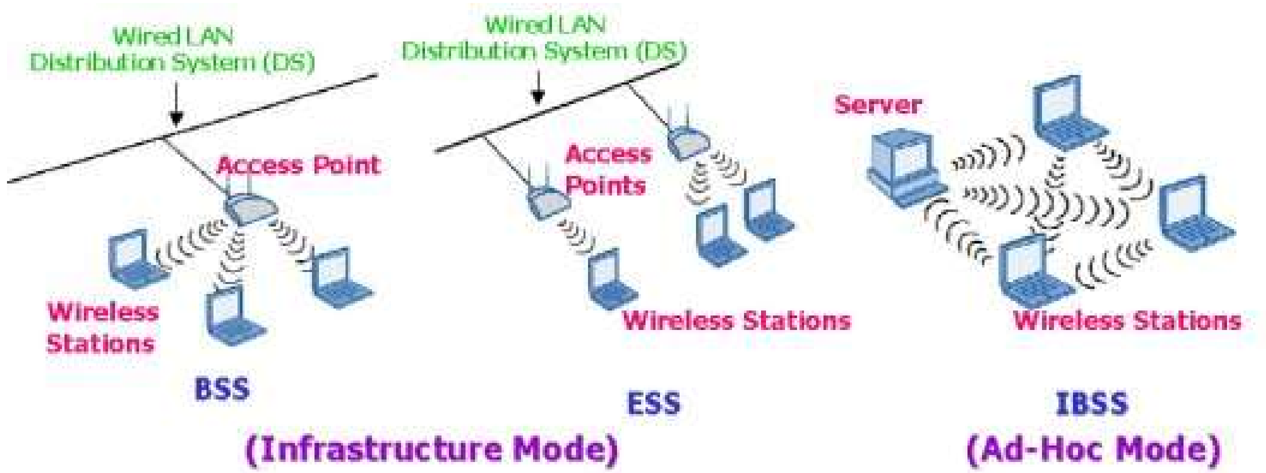
Basic idea:

The AP keeps track of which stations are currently in Power Saving mode and stores traffic addressed to them until they do not request it (Power Save (PS) **Poll), or they become active.**

- **In addition, in Beacon Frames, the AP periodically advertises which stations it stores frames for** (bits in the Traffic Indication Map) **.**
- **This way, these stations can wake up when the AP sends the Beacon frame.**
- **Then, if there are messages waiting for them, they can request them from the AP with a polling request** (PS Poll) message.
- **Multicasts and Broadcasts frames are also stored by the AP and retransmitted at a time known in advance** (by the sleeping stations) (it advertises in the Beacon frame how many Beacons are left before sending them) **– so they can wake up at this time** (if they need such frames) **.**
- during the **PS**, the station can also search for other BSSs (**Active** , or **Passive Scanning**)

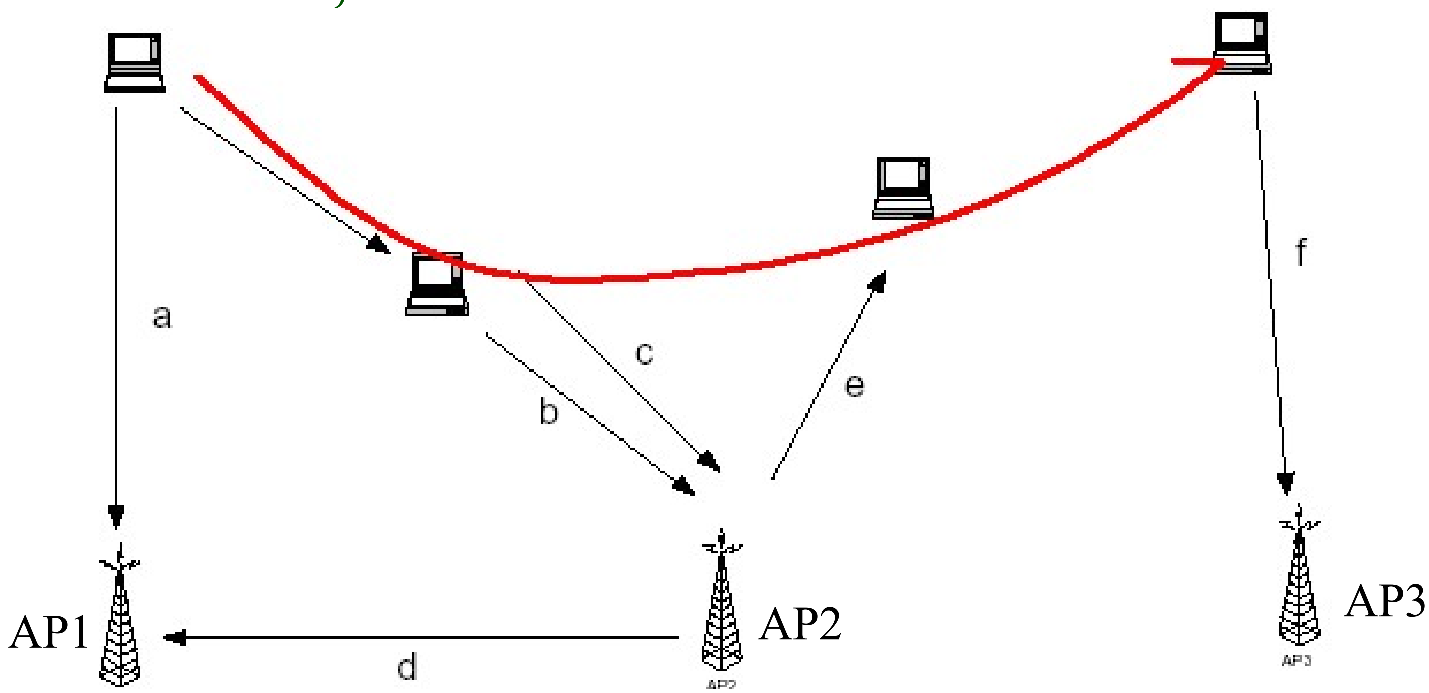
802.11 Ad Hoc Networks

- **An Access Point station is not necessarily required to operate an 802.11 network, in which case one of the stations takes over some of its functions** ("ad-hoc" mode)**, e.g. Beacon Generation, synchronization, etc.**
- relaying **between two stations, or the Power Saving mode of the stations, are not possible.**



802.11 Roaming

- **In case of ESS, the mobile station can roam between BSSs**



(a) ---- The station finds AP1, it will authenticate and associate.

(b) ---- As the station moves, it may pre-authenticate with AP2.

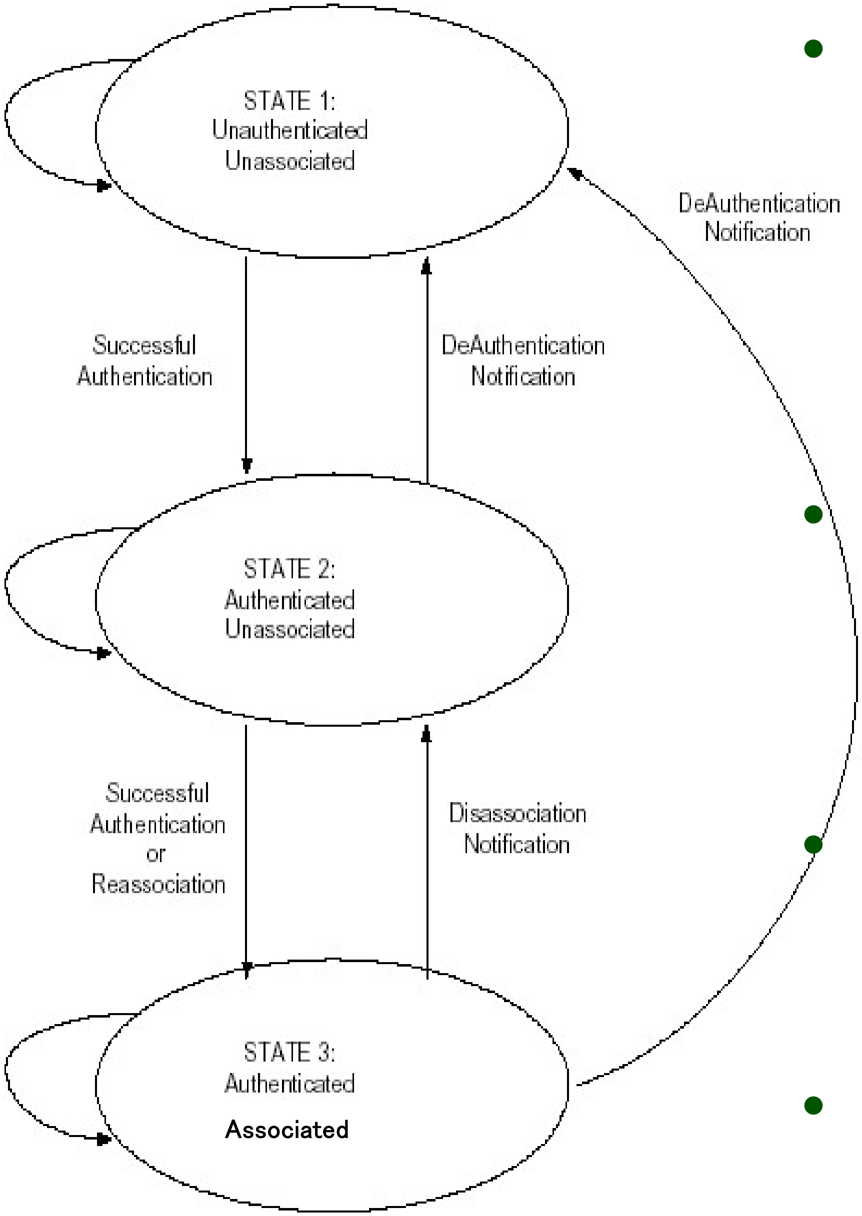
(c) ---- When the association with AP1 is no longer desirable, it may reassociate with AP2.

(d) ---- AP2 notify AP1 of the new location of the station, terminates the previous association with AP1.

(e) ---- At some point, AP2 may be taken out of service. AP2 would disassociate the associated stations.

(f) ---- The station find another access point and authenticate and associate.

802.11 Authentication - Association



- **A station can be authenticated in multiple BSSs** (Preauthentication - Roaming), **but can be "Associated" only in one.**
- **Authentication:**
  - **a mobile station identifies itself to the AP** (but it can also be between any two stations)
- **Association:**
  - **Login,** each Assigned station receives an AID identifier
- **Reassociation:**
  - **Transfer,** new AP speaks to old one

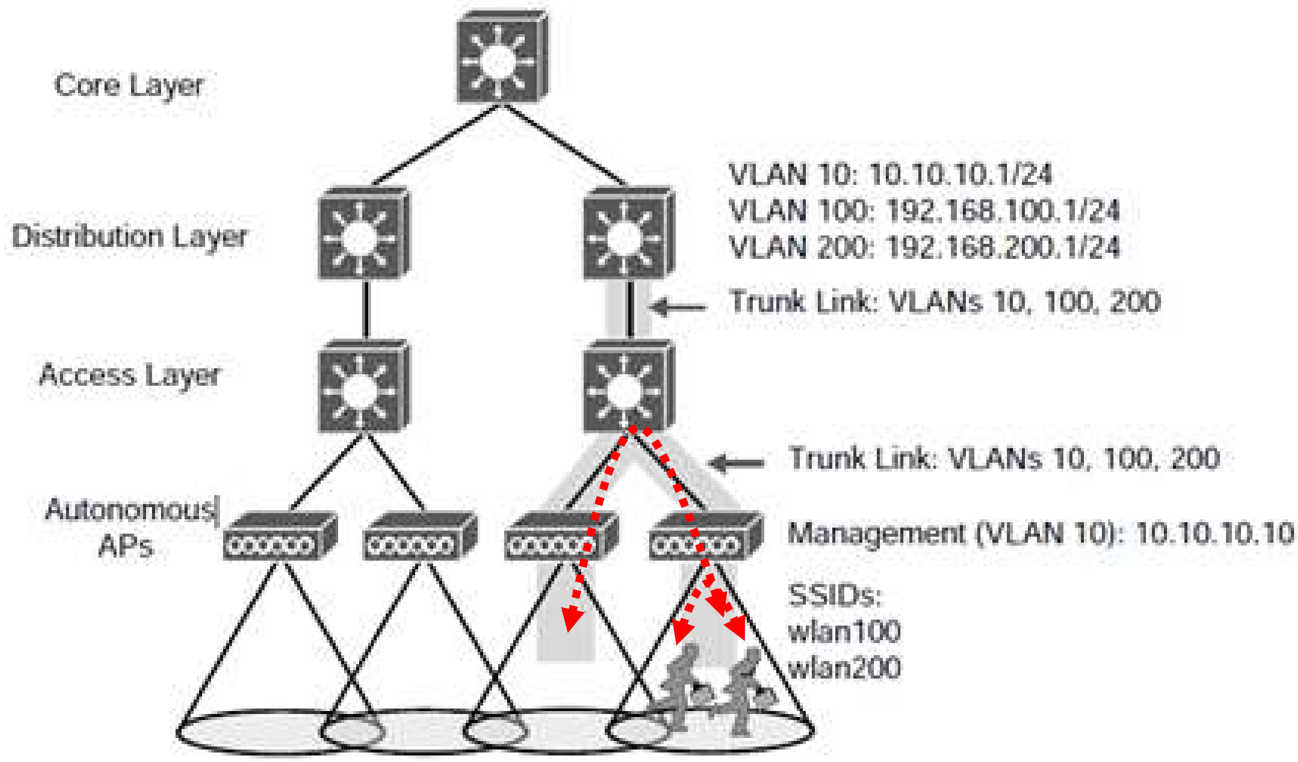
802.11 Authentication

- A station **authenticates its identity** to another station (e.g. AP)
- **Two methods:**
  - **"Open system authentication"** – "introduction" without verification (always successful)
  - **"Shared key authentication algorithm"** – based on single-key encryption.
- **Shared key authentication:**
  - **Both stations have the secret WEP key (single key)**
  - **At the beginning of authentication, station A (e.g. mobile) sends its identifier to station B (e.g. AP).**
  - **In response, B also sends its ID and a "challenge text"**
  - **Station A sends it back as a response, encrypted with the secret WEP key.**
  - **Station B decrypts it with the same secret key. If the decryption is successful, station B authenticates A (if not, it sends an error message).**
- **A station can authenticate itself to more than one other station.**
- **The mobile station always authenticates itself (the AP checks).**
- *Vulnerabilities:* E.g. a rogue station (knowing the SSID (AP MAC address)) can send beacon frames and load (query - they respond) the stations (Denial of Service Attack).

802.11 Association

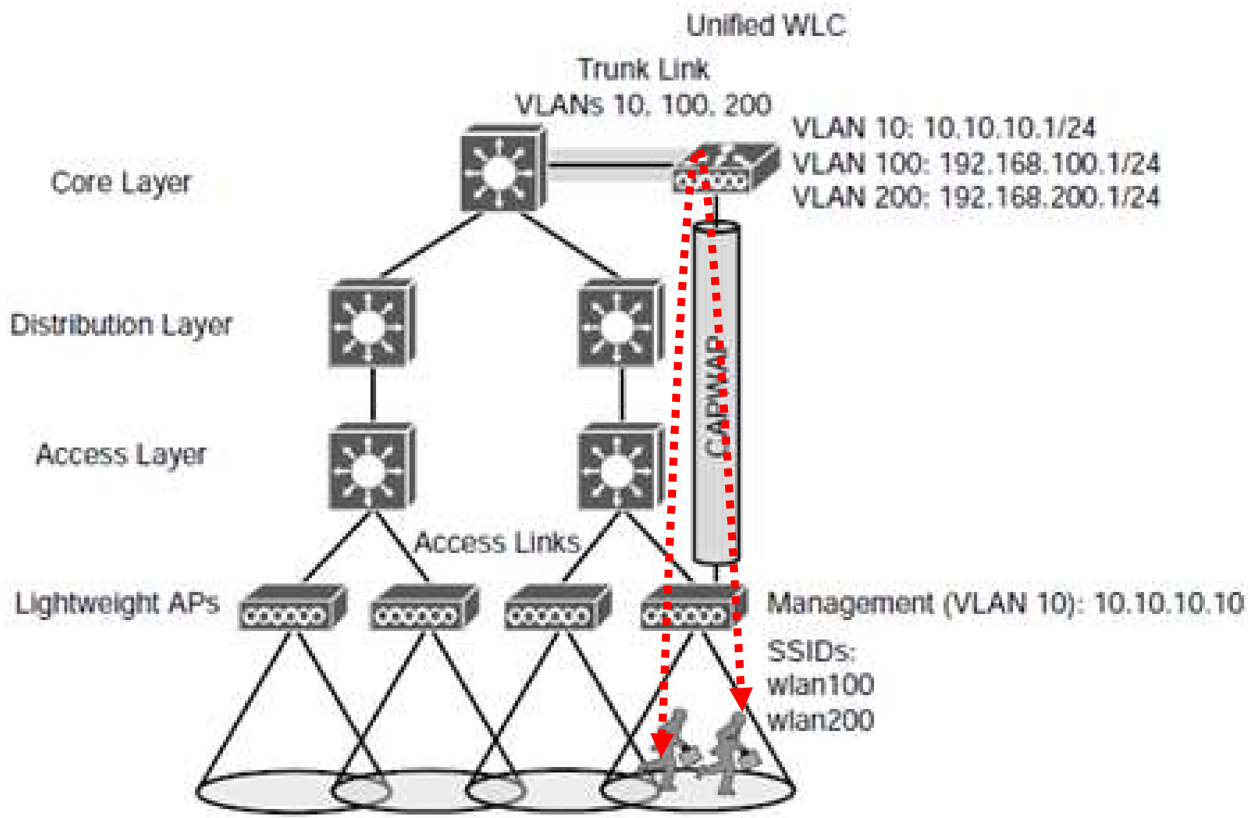
- **Only possible after successful authentication.**
- **The mobile station requests the AP** (association request) to **connect to the WLAN.**
- **The connection request contains the station's capabilities** , such as data rate, PHY options, CF services, WEP support, and the max. Power Saving time that the station requires (with the AP buffer).
- The **AP's response** (association response) contains the result of the request (**success/failure** – in case of rejection, the reason for it).
- After successful association, the AP is responsible for forwarding the station's traffic (either within the BSS or to the DS)
- If a **station loses contact with a BSS** (its **AP**) – **new association with the AP of another BSS** .
- Then **Reassociation Request** to the new AP (in which it specifies the address of the old AP) **- the new AP notifies the old AP of the transfer of the mobile station** (the association is deleted there) the DS (Distribution System) then reaches the station through the new AP

Wireless LAN - Autonomous Topology



- Standalone APs
- Each must be configured separately
- One or more BSS, ESS

Wireless LAN -Lightweight AP Topology



WLC : Wireless LAN Controller – shared management, bridge, AP realtime 802.11

CAPWAP tunnel : Control And Provisioning of Wireless AP

- Layer 3 connection of VLANs is provided by the WLC
- The CAPWAP is tunnel access link, not trunk, even in case of multiple VLANs or WLANs
- Traffic from clients within a cell also passes through the WLC

The IEEE 802.4 standard Token Bus.

- **Developed by General Motors and manufacturing automation companies**
- **The characteristics:**
  - **75 Ω coax; analog modulation; 1.5 or 10 Mbps**
  - **bus topology, but the stations are arranged in a logical ring: each station knows its previous (left) and next (right) neighbors.**
  - **A token - a special control frame - “circulates” on the logical ring .**
  - **The person who owns the signal can always give.**
  - **When it has finished transmitting, it forwards the beacon to its logical neighbor (if it has nothing to send, it forwards it immediately)**

IEEE 802.4

- The maximum delay is limited!
  - A station can only hold the token for a specific period of time (token-holding time) (T_{TH}).
    - Once this has expired, you must continue to give the signal even if you still have something to give.
  - For n number of stations, $n*T_{TH}$ time must be waited to send a frame.
- There are priorities for the frameworks:
  - 4 priority classes: 0, 2, 4, 6;
  - each has its own row.
  - Within the pilot hold time, there are 4 timings for the maximum transmission time of each line (first 6, then 4, ...)

802.4 frame structure

≥ 1	1	1	2 or 6	2 or 6	0 – 8182	4	1	
PA	FD	FC	DA	SA	Data	FCS	FD	IEEE 802.4

PA: Preamble - synchronization

FD : Frame delimiter - start and end marker (analog encoding violation, different from normal 0 and 1 encoding)

FC: Frame Control - distinguishes between data and control frames

- **in the case of a data frame, indicates the priority of the frame**
- **in the case of control, the definition of the various control functions**

  (E.g. 00001000 - token when transferring)

DA: Destination Address -- MAC address as in 802.3

SA: Source Address -- MAC address

Data: the data field can be much longer than in 802.3, it does not hold up the system as much as CSMA/CD)

FCS : Checksum (Frame Check Sequence)

Ring maintenance

- **Add a new station**
  - **The station that owns the beacon periodically sends a Solicit-successor frame control frame, which contains the address of its own station and the station that succeeds it,**
  - **then waits for a response window.**
    - **during this time, stations with addresses between the two addresses can register (if more than one register, a separate mechanism is used to resolve conflicts)**
  - **The station that applies will be the logical next station (will be wedged in).**

Ring maintenance

- Exiting a station (e.g. exiting X from the P → X → S line)
  - Station X sends a Set-successor frame control frame to station P, which contains the address of S, and then exits.
  - Then P passes the token to S.
- Ring departure
  - If a station detects that there has been no traffic for a while, it sends a Claim-token frame control frame.
  - If there is no response, he generates a token and creates a ring with only him in it: then Solicit-successor: invites others to join.

Ring maintenance

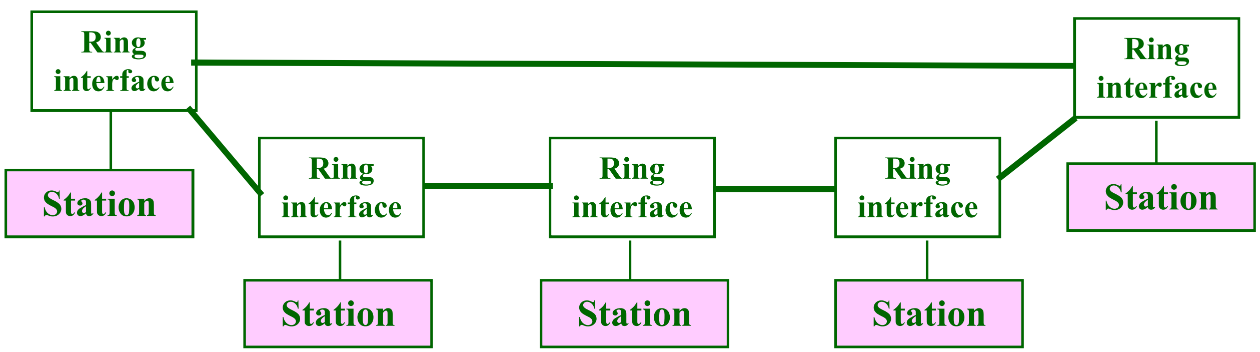
- **Loss of token (follower station breaks down)**
  - **When a station sends a token to its neighbor, it listens,**
    - **whether it sends a frame or a token.**
    - **If it doesn't send, it sends another token to it (just in case the previous frame was corrupted).**
    - **If it doesn't respond to this either (e.g. it's turned off):**
  - **Sends Who-follows control frame to the (neighboring) follower address (addressed to the "bad" neighbor).**
    - **If someone senses that the address preceding it is the same, they send back a Set-successor frame, marking themselves as the new neighbor.**
    - **This removes the faulty station from the ring.**
  - **If there is no response to Who-follows either, it rebuilds the ring.**

Ring maintenance

- **In case of failure of the signal holder: the ring restarts.**
- **Multiple control signal:**
  - **If a station that owns the beacon detects a token, it discards its own .
    So, sooner or later, only one token remains.**

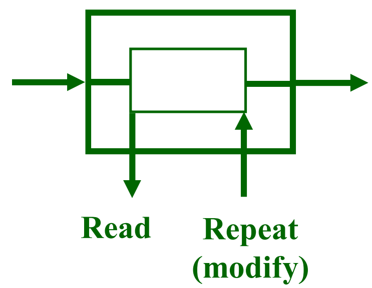
The IEEE 802.5 standard Token Ring.

- Developed by IBM, compatible with IBM Token Ring
- True point-to-point ring topology (unidirectional ring)
- Provides predictable upper bound channel access (max . latency is also limited here)



IEEE 802.5

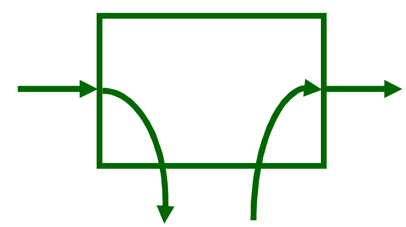
- The physical medium
  - Shielded twisted pair (2-2 wires, one for each cable)
  - Differential Manchester encoding
    - high-low voltage level: ± (3.0 - 4.5 V)
  - 1, 4, 16 Mbps speeds
    (IBM Token Ring: 4 and 16 only)



- The ring interface
  - In receive mode
    - takes a bit, transmits it to the station
      (can modify it if necessary)
    - and passes it to the interface with a one-bit delay,
    - which forwards it to the next station
      (repeat, possibly changing some bits of the passing frame)

IEEE 803.5

- **The ring interface**
  - **In transmission mode**
    - **"breaks" the ring,**
    - **and transmits the bits received from the station (its own frame) (transmitting its own data).**
  - **THE receive/transmit switching takes place in 1 bit time**
    (the frame to be sent must be buffered in advance)



The media access protocol

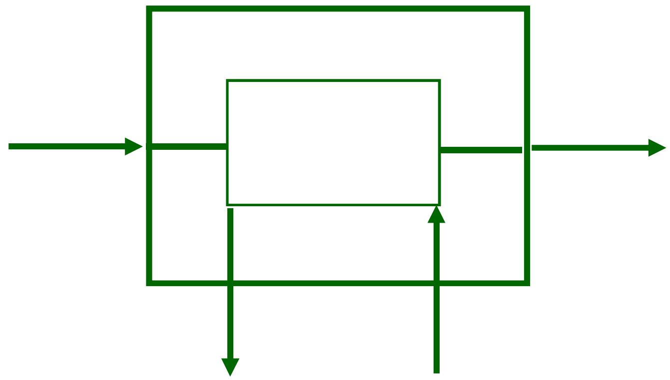
- A control signal circulates on the idle ring
- If the station wants to broadcast,
  - waits for the token and takes it off the ring;
  - he splits the ring and begins to give;
  - it removes its own frames;
  - If it has nothing more to send or the token holding time expires, it transmits the beacon.
- Problem: the entire token must fit on the ring! We need to calculate the "storage capacity" of the ring!

Ring storage capacity

- The two components of “storage capacity”
  - the delay of the signal on the medium (the signal is "stored" on the medium while it travels at the speed of signal propagation - this is the storage capacity of the connections) plus
  - signal delay at stations (each interface delays 1 bit: stores 1 bit).
- Storage capacity of connections:
  1 bit "physical" length
  - At a speed of S bps, 1 bit is transmitted onto the medium every 1/S sec;
  - If the signal propagation speed is R, then it requires 1 bit R/S length on the ring.
  - Eg: S=1Mbps, R=200m/ μ sec $\Rightarrow$ 1bit 200m
    (a ring with a circumference of 1000m stores 5 bits)
  - This is due to the storage capacity of the ring interfaces.
    - If this is less than the size of the beacon, some station must add an additional delay.

The ring interface:

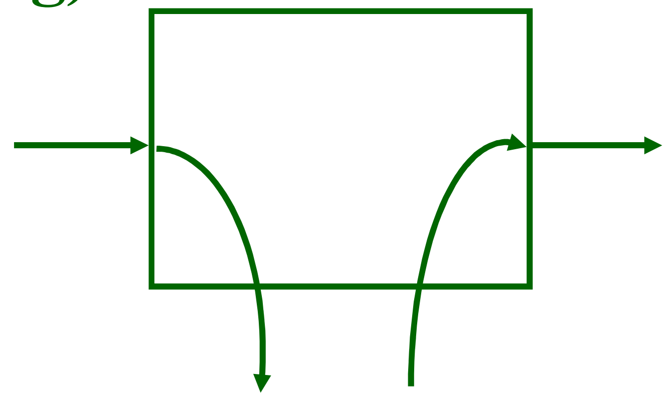
Receive (1 bit delay)



Read

Repeat (maybe modify)

Transmission (breaking the ring)



Since the ring is interrupted when transmitted, a frame can be much longer than the ring's storage capacity!

The frame formats

Token Frame

1	1	1
SD	AC	ED

total of 3 bytes, this goes around on a traffic-free ring

SD : Frame marker (Start delimiter)
AC: Access control byte, here: control frame start (can be immediately converted to data start sequence by modifying 1 bit)
ED: End delimiter

Data frame

1	1	1	2 v. 6	2 v. 6	≥ 0, no limit	4	1	1
SD	AC	FC	DA	SA	Data	FCS	ED	FS

AC: Access control byte, here: start of data frame:
(can be converted into start of control sequence by modifying 1 bit)
FC: Frame control
FCS: Frame Check Sequence
ED: End delimiter
FS: Frame status

The MAC protocol

- The station that wants to transmit (waits for the token, waits and receives the bits, transmits them. The bits can be: data frame bits, control frame bits, and start of frame (SD):
  - Detects SD bits (SD and ED are invalid differential Manchester code to distinguish them from data bits: HH v. LL)
  - By taking (and repeating) the bits of the AC, it recognizes that it has received a token.
  - It converts 1 bit into a data frame (it also receives the other bits, but does not send them further)
  - sends the contents of its own data frame after the AC, the FC, DA, SA, Data, FCS, ED and FS bits.
  - This can be much longer than the ring's storage capacity, so it hasn't even sent its entire frame, while the beginning of it may already be arriving back, so it can start removing its own frame from the ring while it's still sending.

The MAC protocol

- The station can hold the token for a maximum of the token holding time, during which it can send multiple frames, but if the time expires, it must pass on the token (it must send SD+AC+ED bytes, with the appropriate bit set in AC).
  - The default token holding time is 10msec, but a different time can be configured.
- In order to distinguish the frame from the SD and ED data bits, they contain an invalid differential Manchester code pattern
(HH or LL).

Fields of the data frame

1	1	1	2 v. 6	2 v. 6	≥ 0, no limit	4	1	1
SD	AC	FC	DA	SA	Data	FCS	ED	FS

- **AC: Contains access byte**
  - the token bit,
  - the watch bit (may indicate that the frame has gone through a round),
  - the priority bits,
  - the reservation bits.
- **FC: frame control byte to distinguish between data and control frames**
- **DA, SA: Destination and source address, etc., like 802.3, 802.4**
- **FCS: Checksum, CRC, Cyclic Redundancy Code, Error Reporting (like 802.3, 802.4)**
- **ED: End indicator, indicates the end of the frame and also contains the E bit.**
  - The E bit can be set to 1 by any interface if it detects an error (e.g. invalid format)

Fields of the data frame

1	1	1	2 v. 6	2 v. 6	≥ 0, no limit	4	1	1
SD	AC	FC	DA	SA	Data	FCS	ED	FS

- **FS : Frame status, contains A and C bits**
  - **A bit : when a frame arrives at the destination, it is set to 1 by the interface during its transit;**
  - **C bit : sets to 1 if it can copy it into memory;**
  - **From this, if A and C:**
    - **0 0 : destination does not exist (e.g. not turned on);**
    - **1 0: exists, but could not receive the frame;**
    - **1 1: exists and has copied the frame.**
  - **Bits A and C are outside the scope of the checksum, so they are transferred doubled!**
- **The CRC, the E bit in ED, and the FS may indicate an error.**

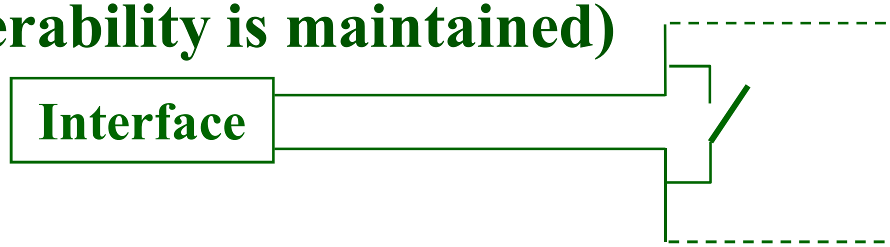
Priority management

1	1	1	2 v. 6	2 v. 6	≥ 0, no limit	4	1	1
SD	AC	FC	DA	SA	Data	FCS	ED	FS

- The AC (access field) contains both priority and reservation bits.
- If a station wants to send frames with priority n, it does not enough to have token, it has to wait until a token with a lower or equal priority arrives... (if a higher one arrives: it can eagerly forward it, but not its own frame...)
- However, you can set the reservation bits of the passing frame to the desired level if they were previously at a lower level.
- Finally, the sender, having finished transmitting, sets the priority of the token to be forwarded according to the reservation bits (highest demand).
  - if this is high, the priority of the request will be high: good for the requester …
  - if low: good for many, for everyone...
- Note that there is a chance of "starvation", the signal priority is increasing
- The signal bus has bandwidth sharing with timings, there is no such problem there

Dealing with physical defects in the ring

- If a cable breaks, an interface/station goes down: the physical ring is broken, and the entire network becomes inoperable.
- We can protect ourselves by installing a wire center
  - in the wire center relay (active interface keeps it open, faulty, switched off closes it) can short circuit (excluding the faulty network part)
  - By short-circuiting, the ring becomes continuous (operability is maintained)



Ring maintenance

- In contrast to the decentralized signal rail, maintenance is centralized here
- Each ring has exactly one monitor station: it is responsible for maintenance
- Any station can be a supervisor
  - Selected based on competition protocol at ring start (or supervisor failure)
  - The first station to notice that there is no supervisor
    - Sends a Claim-token Frame Control (FC) control frame, and
    - if it arrives back to him without receiving a Claim-token frame sent by someone else, he will become the supervisor.

Supervisor's duties

- **Control signal loss monitoring (checked with timing)**
  - if there is no signal for more than station-number times signal-retention time: clears the ring and generates a new signal.
- **Remove bad frames (invalid format, bad CRC)**
  - ring cleaning and new signal.
- **Removing orphan frames (orphans that are not removed by the sender)**
  - Set the **AC monitor bit** in every frame that passes through,
  - if it is already set: it has already gone one round, it will remove the orphan frame.

Supervisor's duties

- Setting ring storage capacity (to accommodate 24-bit token)
  - If the capacity is less than this, additional delay (storage) is introduced.
- Identifying the location of a ring rupture
  - If a station detects one of its neighbors as inoperable, it sends special “beacon” controlled frames to the address of the supposedly faulty station.
  - Based on this, the monitor can eliminate faulty stations with the help of the wire center.

- Centralized maintenance may be less reliable than signal bus. E.g. monitor fails, but continues to send Active-monitor-present frames: the whole thing stops...

FDDI

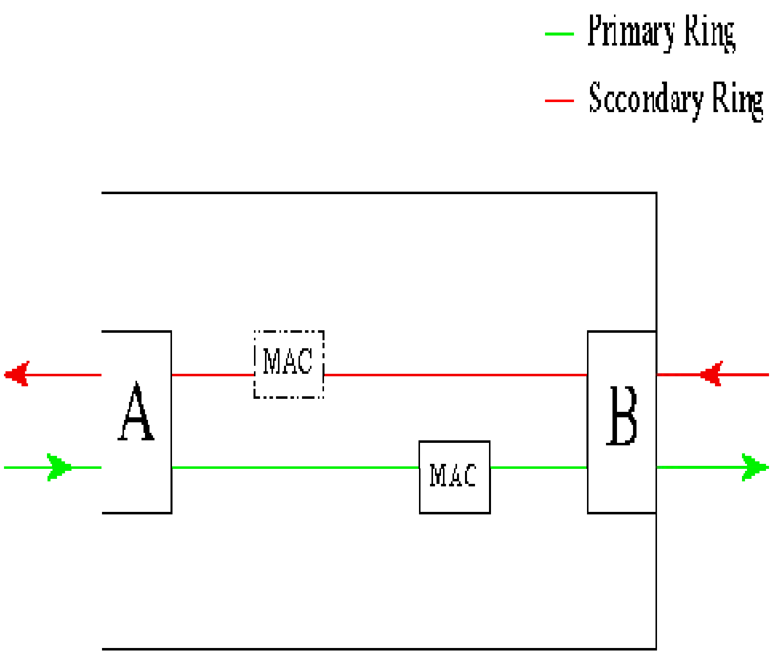
- **Fiber Distributed Data Interface: optical fiber distributed data interface**
- **The FDDI protocol model is based on the 802.5 protocol.**
- **High-performance fiber optic signal ring**
  - **There is also twisted pair (CDDI): Copper DDI**
- **LAN-MAN network**
  - **bridging max 200 Km;**
  - **max 1000 stations;**
  - **100Mbps**

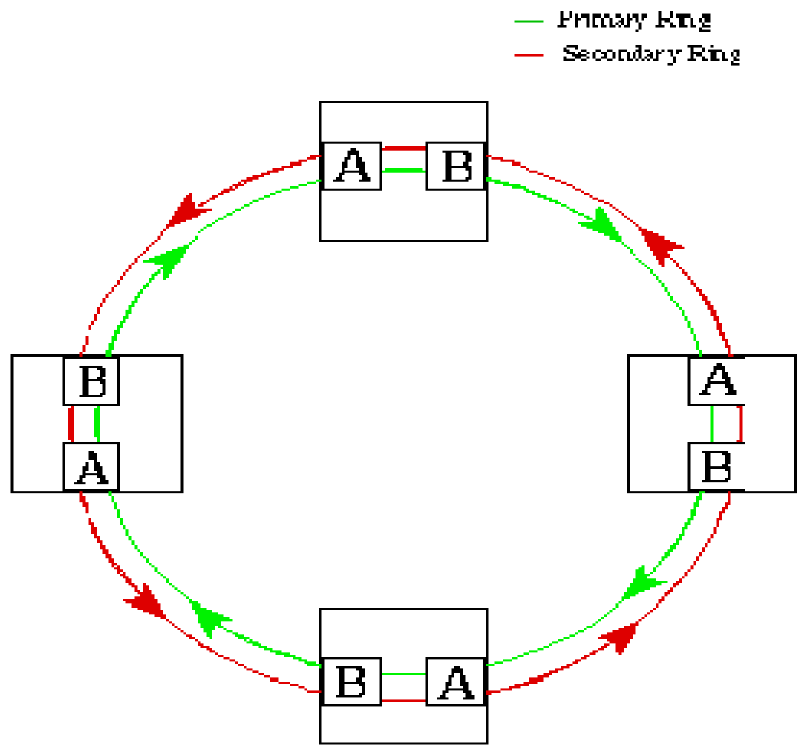
FDDI

- **Very widespread – it was (e.g. ME backbone network was like this before 2000)**
- **Nowadays, it is increasingly supplanting**
  - **For LANs, Fast and Gigabit Ethernet (100BaseFX/TX, 1000BaseX/T) are preferred because they are much cheaper and faster;**
  - **In the case of MANs, ATM (also WAN connection (telecommunications standard))**
- **There is also a version that can handle synchronous data (e.g. line-switched PCM signals): FDDI-II.**

FDDI physical layer

- Multi- or single-mode optical fiber
- Double (two opposite directions) ring
  - There is traffic only on the primary ring , the other is only a backup (cable break, station failure)





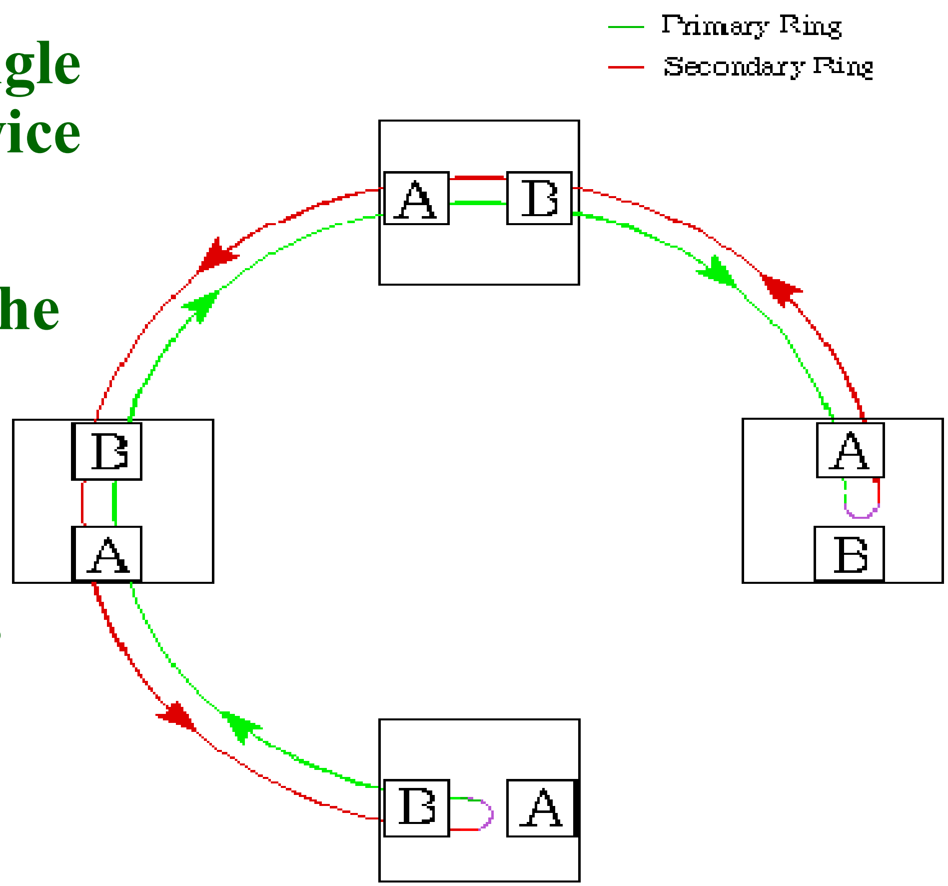
FDDI physical error repair

In the event of a cable break, it can be transformed into a single ring approximately twice as long.

(Stations adjacent to the fault will loop back)

Bypass switch: the inactive station mechanically excludes itself from the ring.

There could also be a wire center here



FDDI station types

- **Two types of stations**
  - **DAS (Dual Attached Station): connected to both rings;**
  - **SAS (Single AS): connected to only one ring.**
- **In case of mixed network, FDDI concentrator is used**
  - **Connect the single ring of SAS stations to the active ring of the dual ring.**

FDDI encoding

- **Also known as 4 out of 5 (4B/5B) encoding**
  - **4 distinctive signs**
  - **5-bit groups are encoded**
- **Not Manchester encoding,**
  - **because 100 Mbps would require 200 baud!**

There are 32 possible combinations
16 for the data;
3 delimiters;
2 controls;
3 HW indication
8 unused

- **The advantage is bandwidth savings,**
- **The disadvantage is that the code is not self-synchronizing.**
  - **Therefore, at the beginning of each frame there is a long prefix for receiver synchronization,**
  - **the clocks are accurate to at least 0.005%;**
  - **A frame can be up to 4500 bytes long.**
    (Do not lose bit synchronization during the frame time.)

FDDI MAC protocol

- A token ring, like 802.5.
- A station can transmit only when it receives a token.
- The frames are removed from the ring by the sending station (each one has its own frame).
- Once it has finished transmitting, it immediately retransmits its token (as opposed to 802.5, which has to wait until the sent frame has returned. Here, due to the max. 1000 stations and 200 Km length, you would have to wait too long).
- From this: multiple signals and frames can circulate on the ring!

FDDI MAC protocol

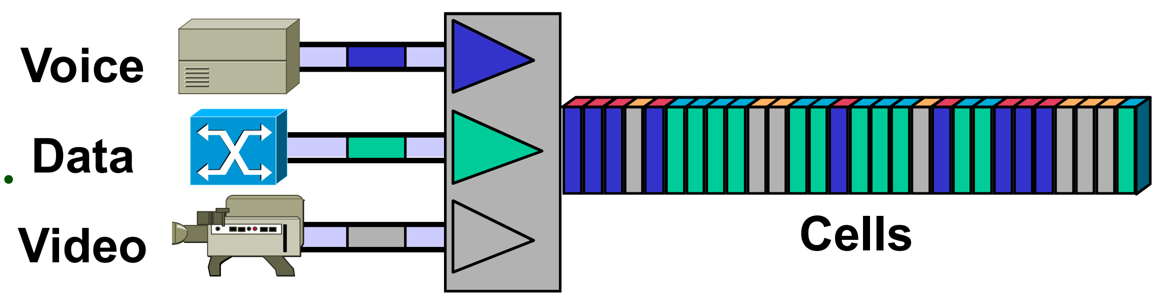
- **Data frames are similar to 802.5**
  - e.g. there are acknowledgement bits in the frame status byte)
- **Priorities are similar to 802.4 (token bus)**
  - each station has a signal round trip clock, which
  - measures the time since the last token was detected,
  - Different priorities may apply in each signal round.

FDDI II.

- In case of synchronous traffic (FDDI II.)
  - a master station generates sync frames every 125 μsec (PCM: 8000 samples/sec)
  - the synchronized garden:
    - head part;
    - 16 bytes of data;
    - 96 bytes of line-switched data (max 96 PCM channels, 96 → 4 T1(4*24), or 3 E1 (3*32)
  - 1 sync frame every 125 μsec: 6.144 Mbps;
  - max 16 sync frames: 1536 PCM channels→ 98.3 Mbps
  - If a station acquires one or more time slots in a sync frame, they are its own until it releases them.

The ATM

- Asynchronous Transfer Mode
  - high-speed, connection-oriented;
  - Both for LANs and WANs;
  - its development was part of the broadband ISDN development;
  - Performance between 100 Mbps and Gbps;
  - requires complex equipment and SW
    - fiber optic media, switches;
  - in small, fixed-size frames (cell)
    - voice,
    - data and
    - video transmission.



- Transfer mode

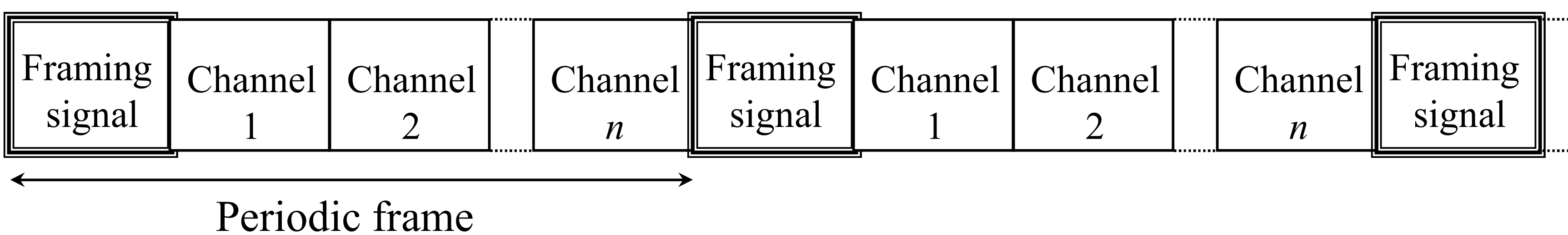
  →**a specific way of transmitting and switching information in a network**

- **Synchronous transfer mode (STM)**

  →a data unit associated with a given channel is identified by its position (TDM)

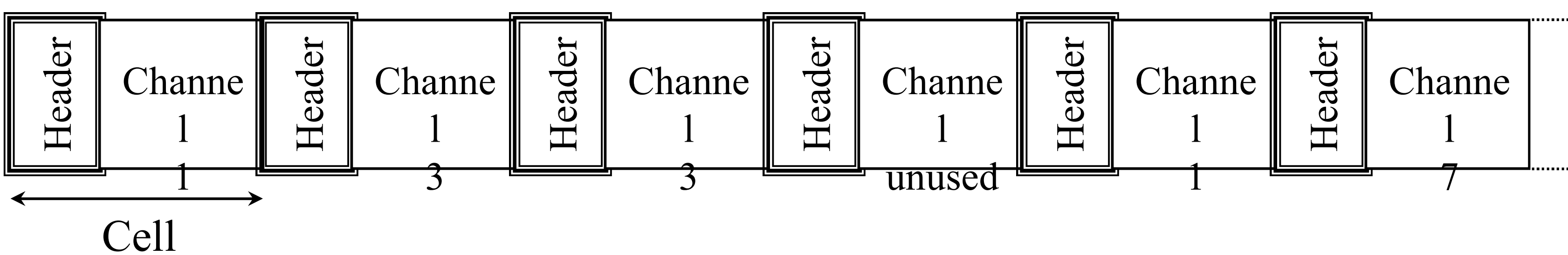
  →predefined channel bit rates (n*64kbs, E1: 2.048Mbps)

  →end to end synchronous circuit



- **Asynchronous Transfer Mode (ATM)**
  - →a data unit associated with a specific virtual channel may occur in any position
  - →flexibility of bit bit rate allocation ! (eg bandwidth allocation on demand)
  - →some problems:
    - →impacts of possible cell loss
    - →cell transfer delay
    - →cell delay variation

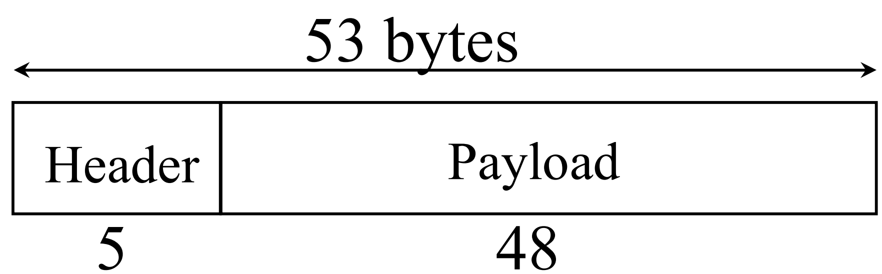
Quality of Service



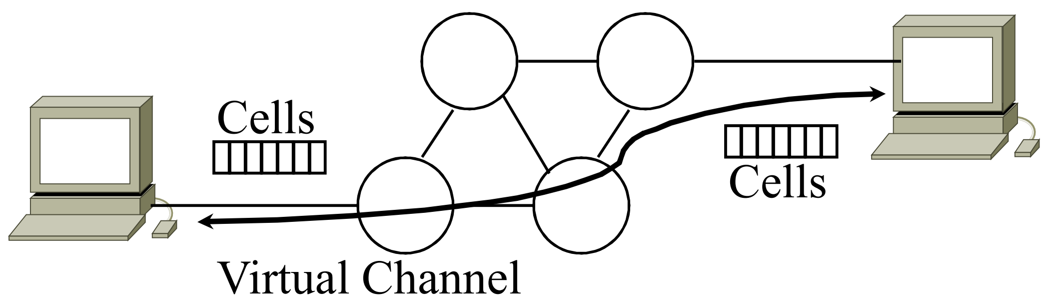
ATM - fundamentals

- **Small fixed-size cells (5+48 bytes, header+payload)**
  - **too long → higher delays**
  - **too short → too many overheads**

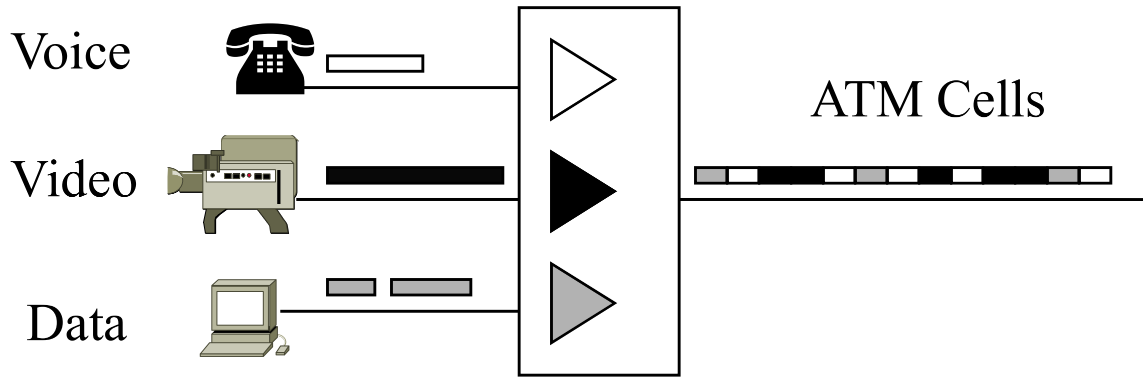
ATM Cell Format :



- Connection oriented - cell switching
  - low overhead → low processing time and delay

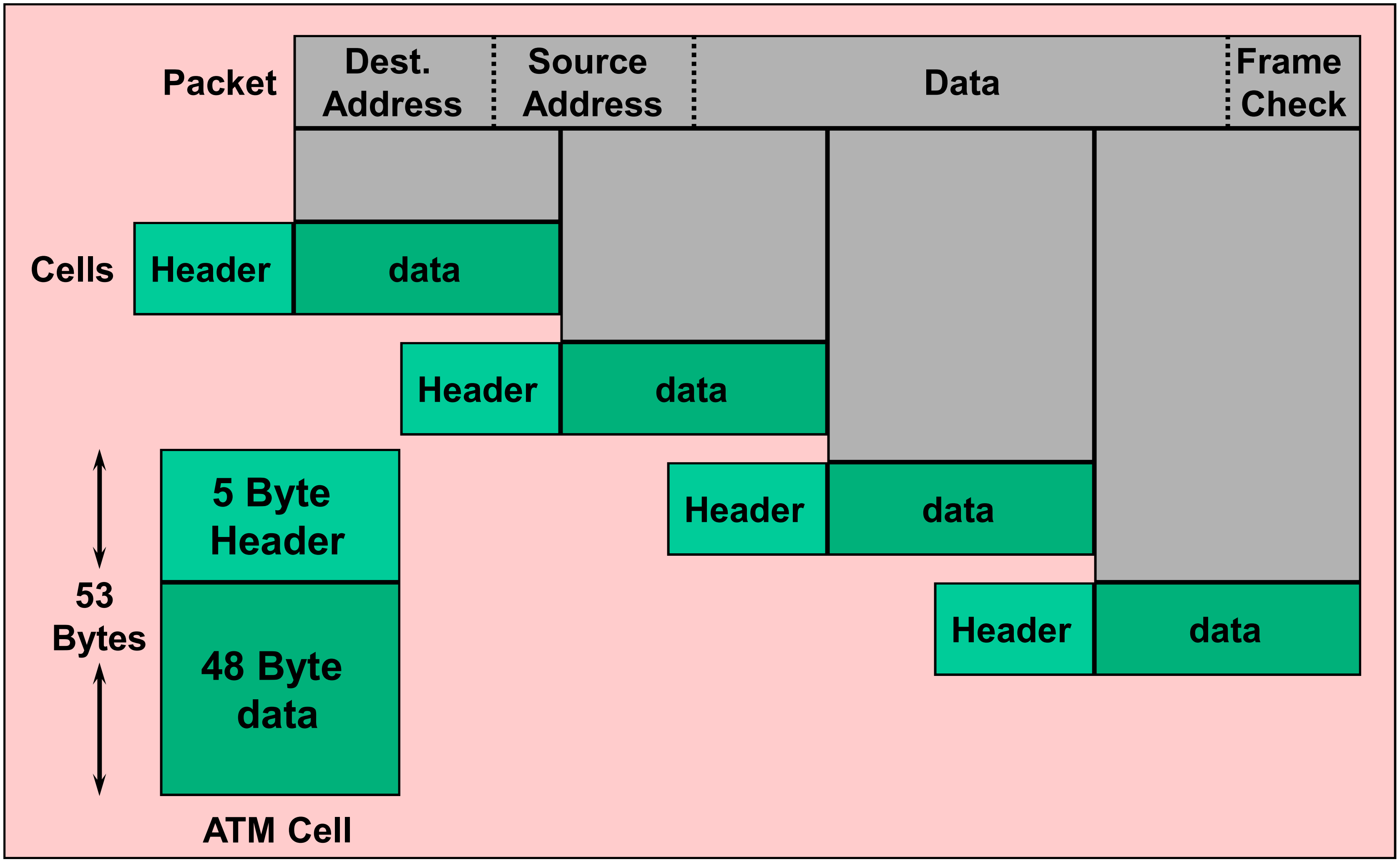


- **Flexible, application independent (conversion of application data units to/from cells), it can handle**
  - **low or high bit rate connection or**
  - **dynamic bandwidth allocation**

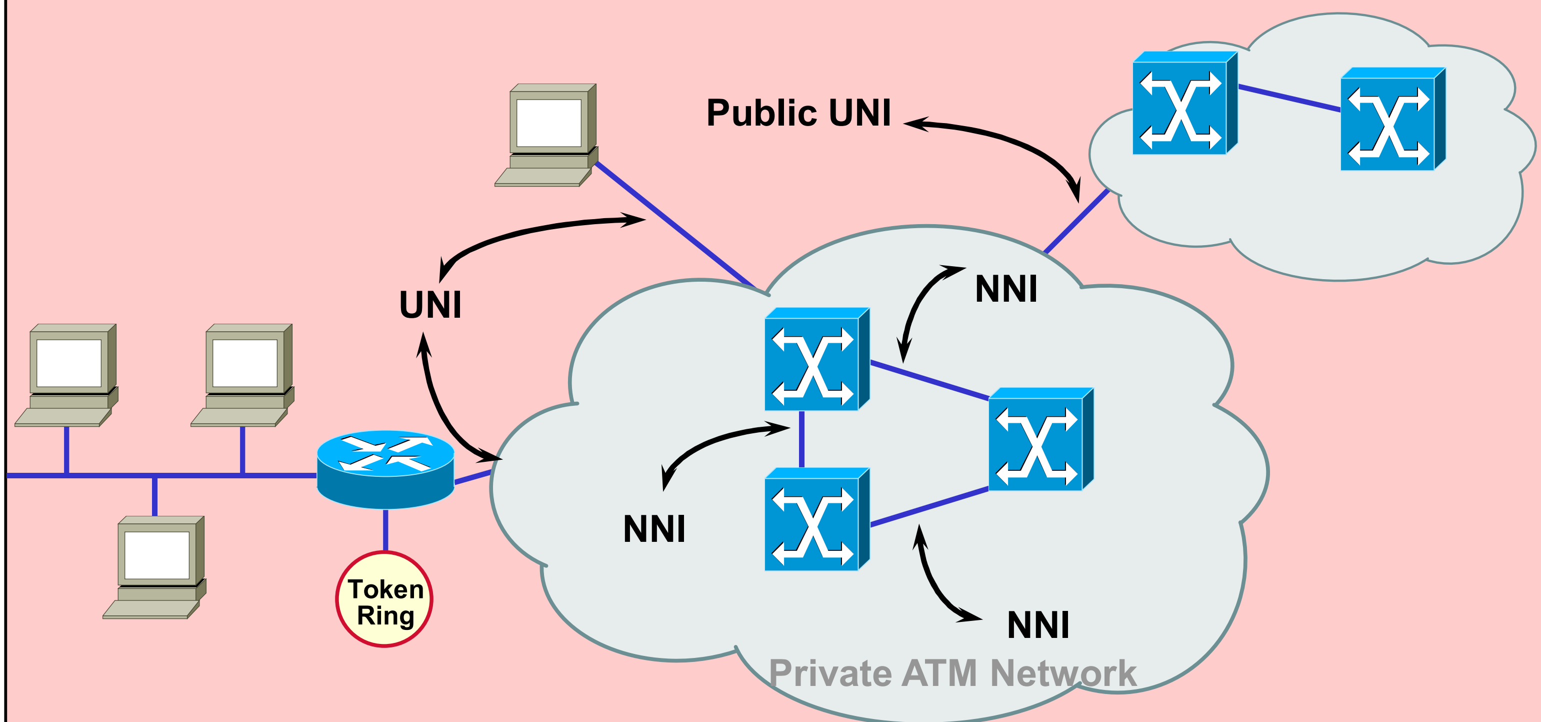


- Both LAN and WAN technology
  - 20 bytes structured hierarchical address format

ATM cells from frames

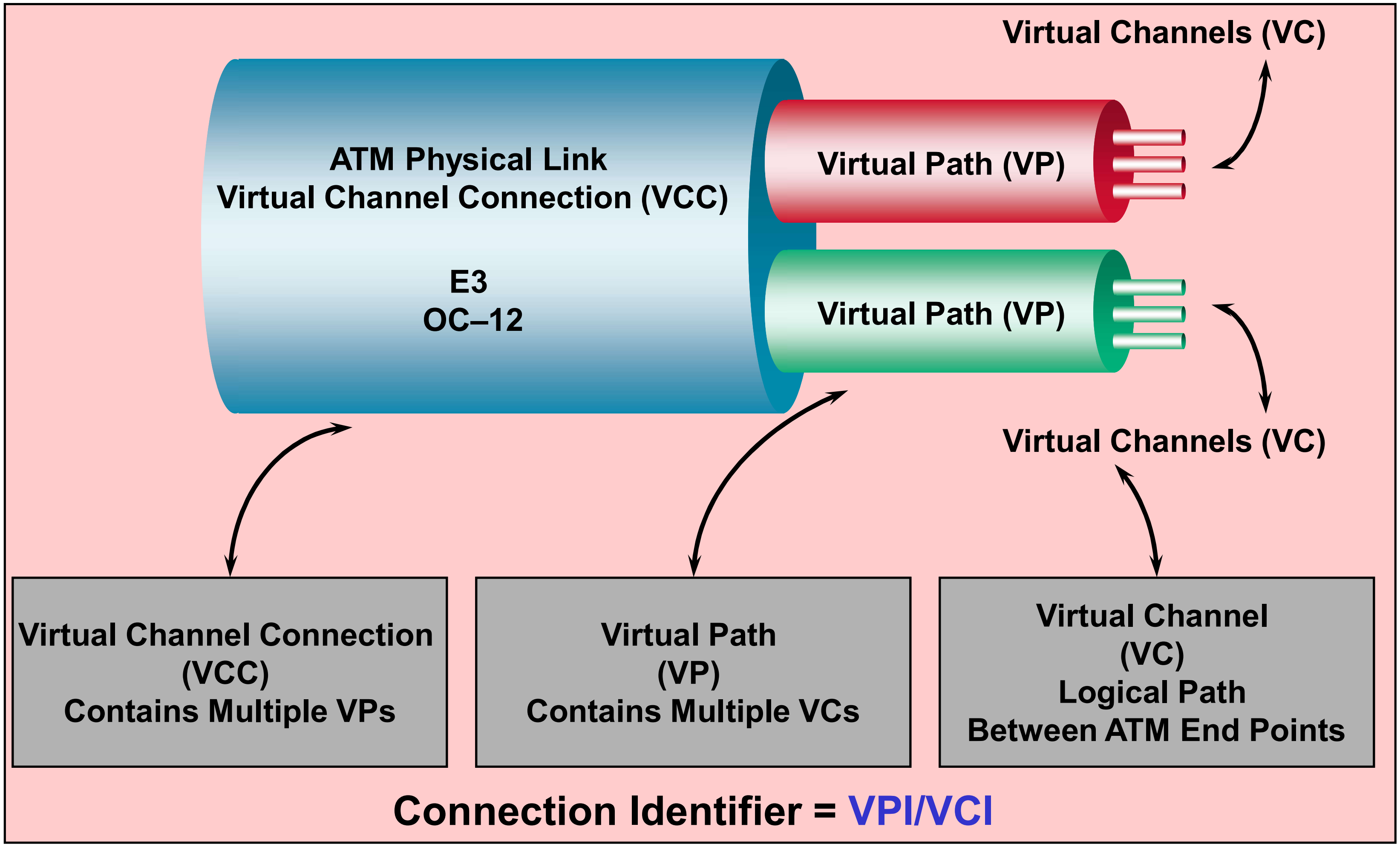


ATM Signaling

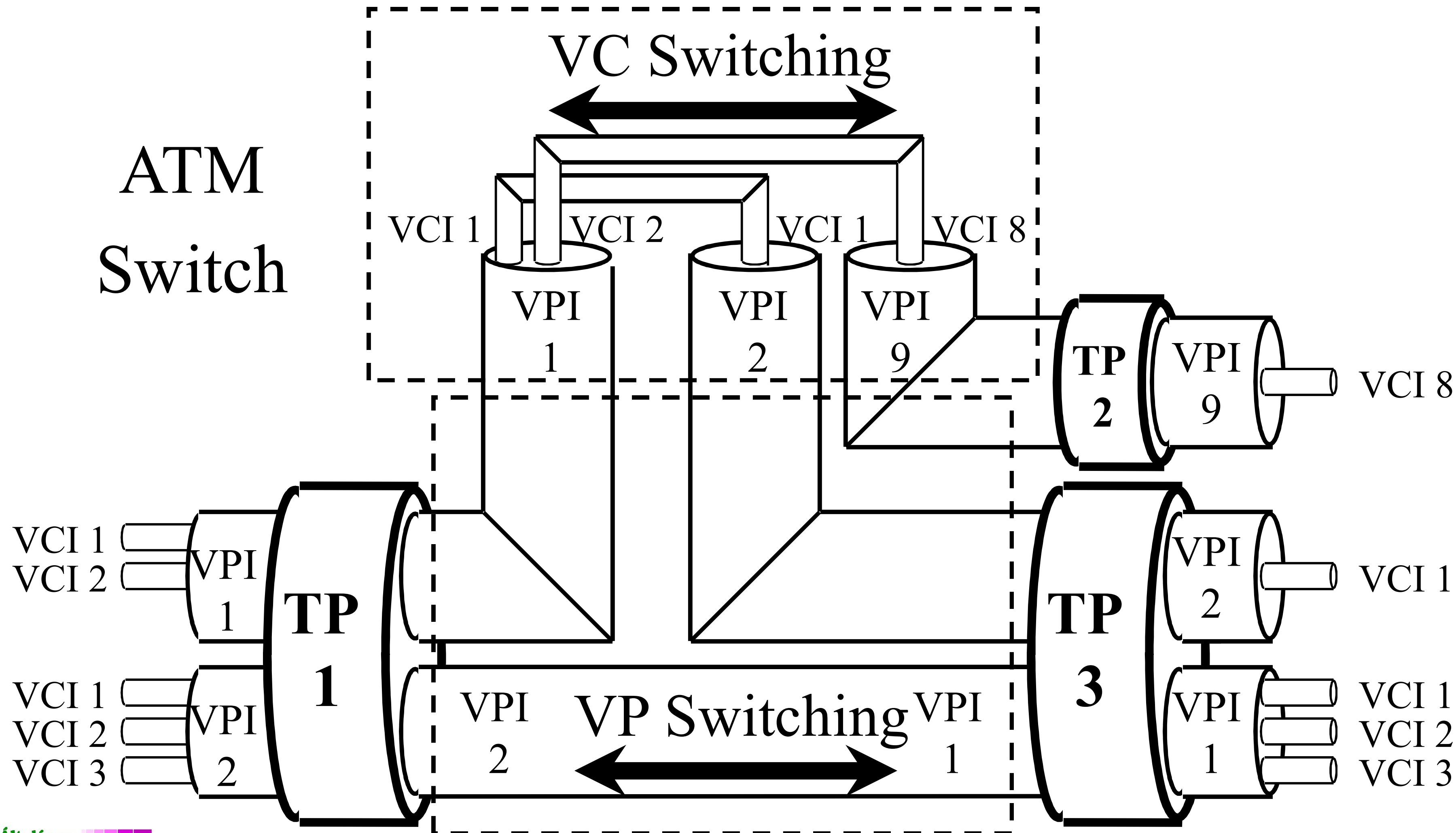


- UNI = User-to-Network Interface
- NNI = Network-to-Network Interface
- Cell header content varies depending on who's talking to whom

Virtual Path and Virtual Channel

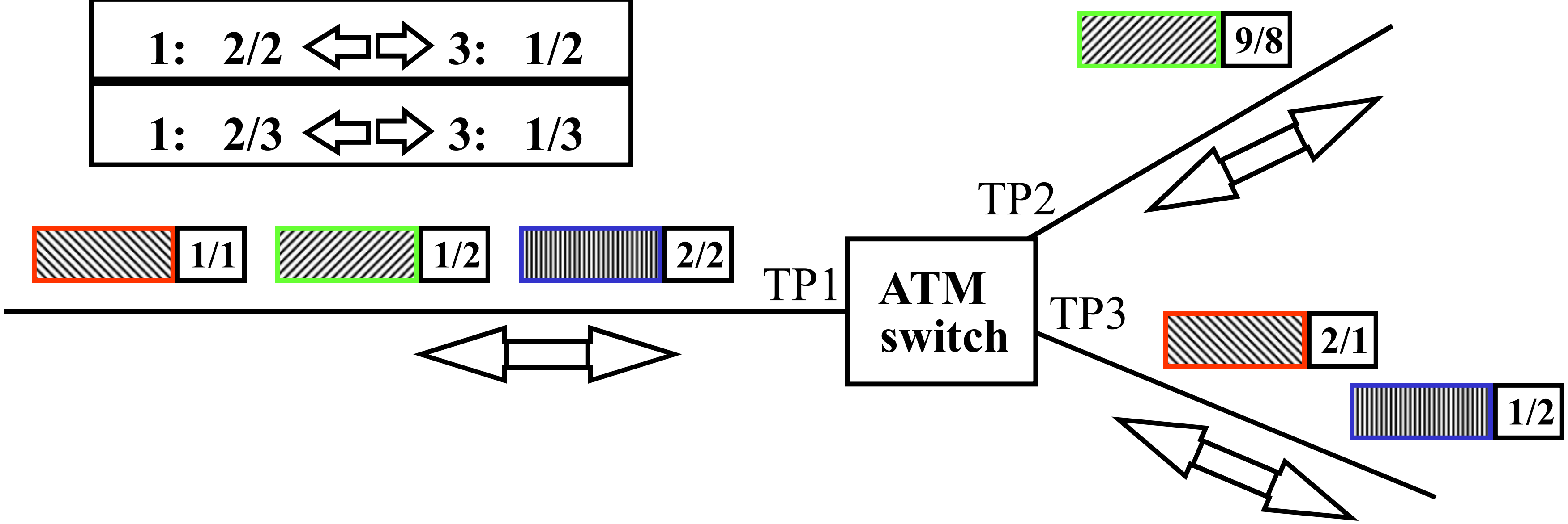


- A connection can have different VPI/VCI identifiers on



ATM Switching Table

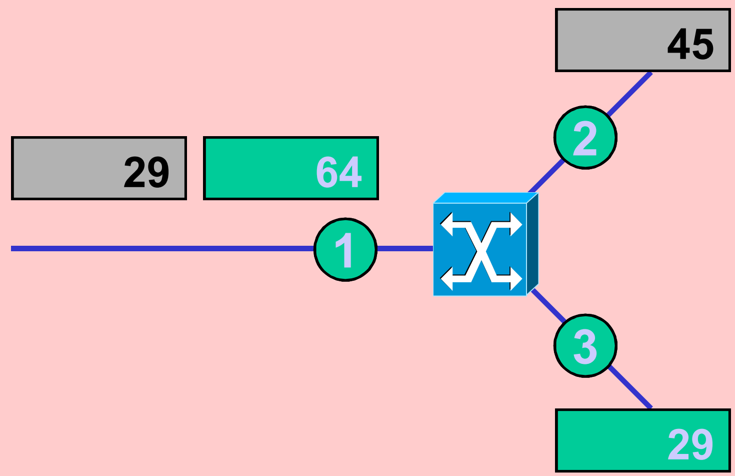
Port TP	VPI/VCI		Port TP	VPI/VCI
1:	1/1	⇔	3:	2/1
1:	1/2	⇔	2:	9/8
1:	2/1	⇔	3:	1/1
1:	2/2	⇔	3:	1/2
1:	2/3	⇔	3:	1/3



ATM Switches

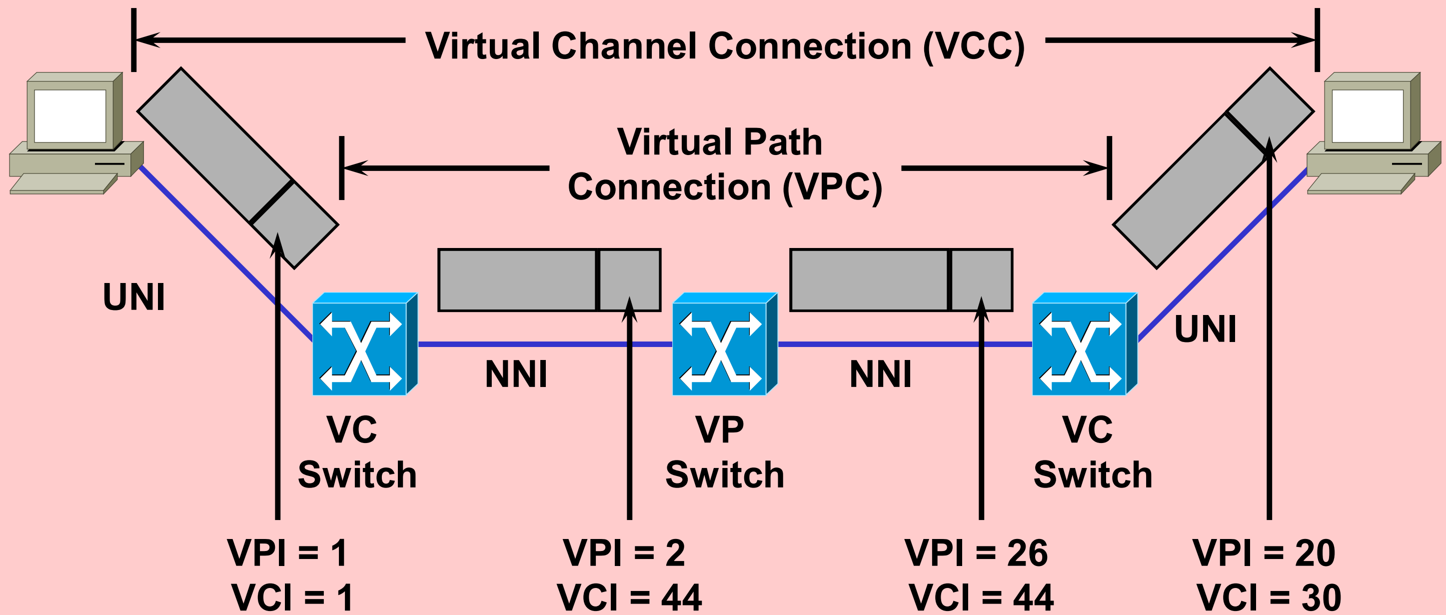
- ATM switches translate VPI/VCI values
- VPI/VCI value unique only per interface
  eg: locally significant and may be re-used elsewhere in network

Input		Output	
Port	VPI/VCI	Port	VPI/VCI
1	29	2	45
2	45	1	29
1	64	3	29
3	29	1	64

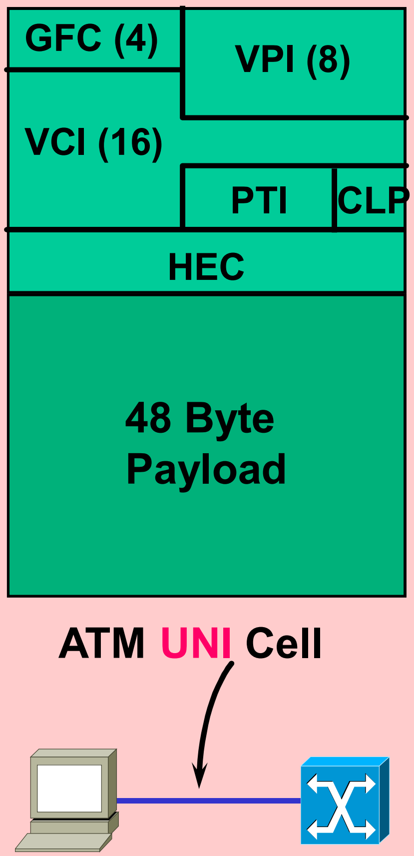


Virtual Channels and Virtual Paths

- **This hop-by-hop forwarding is known as cell relay/switching**



ATM Cell Header Details



GFC Generic Flow Control
UNI Cells Only!

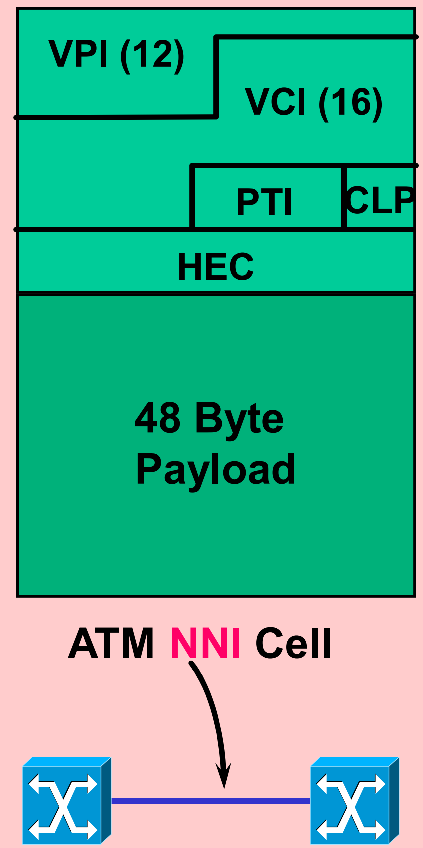
V PI/VCI Identifies Virtual
Paths and Channels

PT I Payload Type Identifier
3 Bits:

1 . User/Control Data
2. Congestion
3. Last Cell

CLP Cell Loss Priority Bit

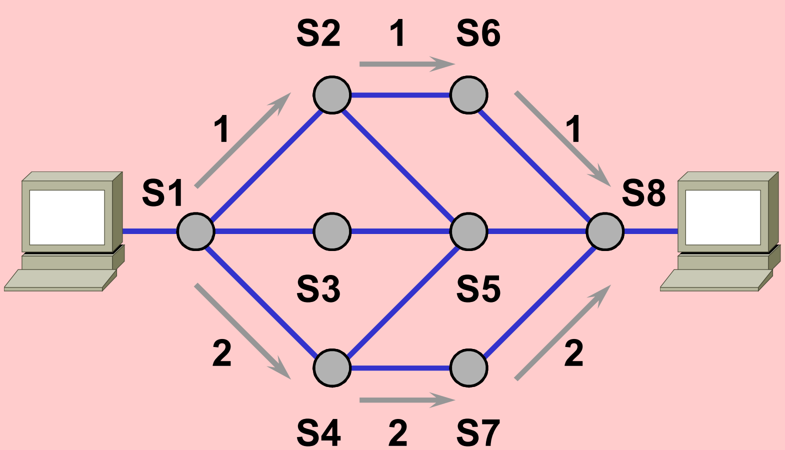
HEC Header E rror Check
8 Bit CRC



Connection Types

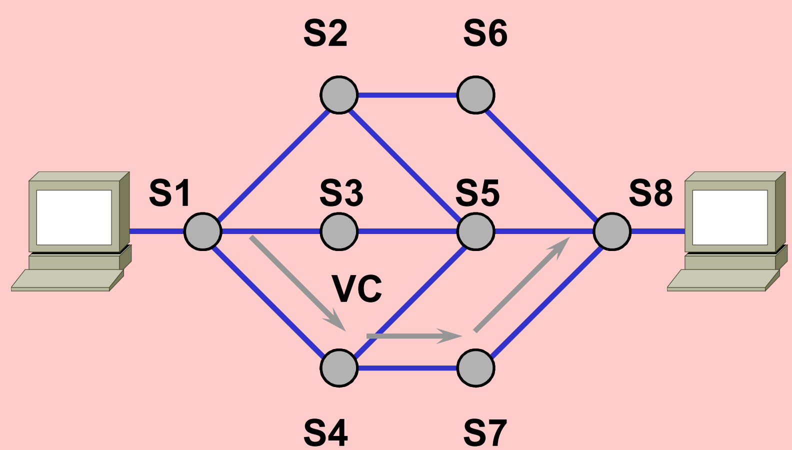
Connectionless: Packet Routing

- Path 1 = S1, S2, S6, S8
- Path 2 = S1, S4, S7, S8
- Data can take different paths and can arrive out of order

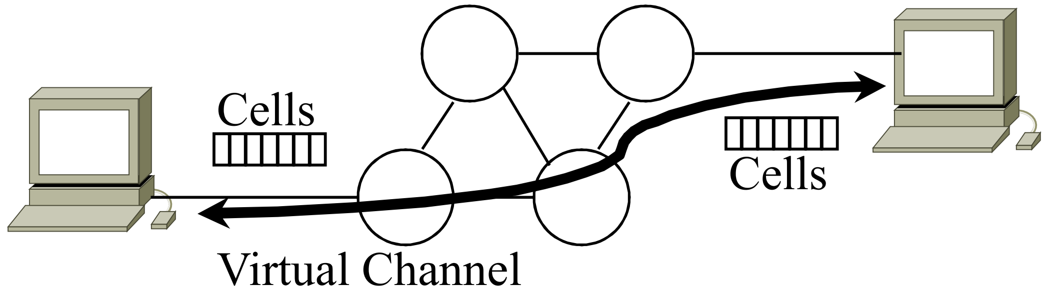


Connection Oriented: Cell Switching

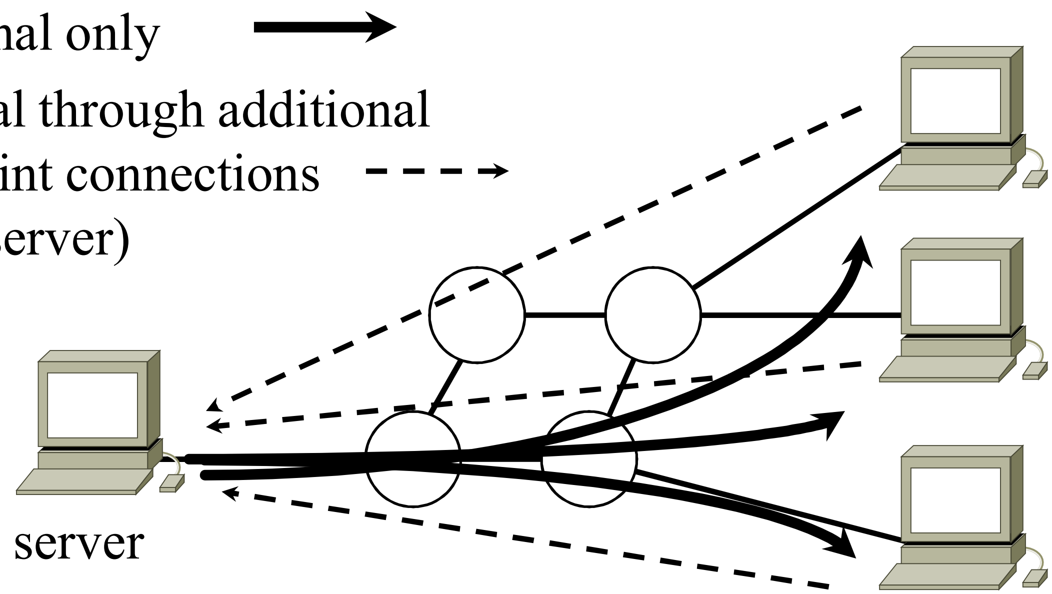
- VC = S1, S4, S7, S8
- Data takes the same path and arrives in sequence



- **Point-to-point** connection types
  - unidirectional or bidirectional



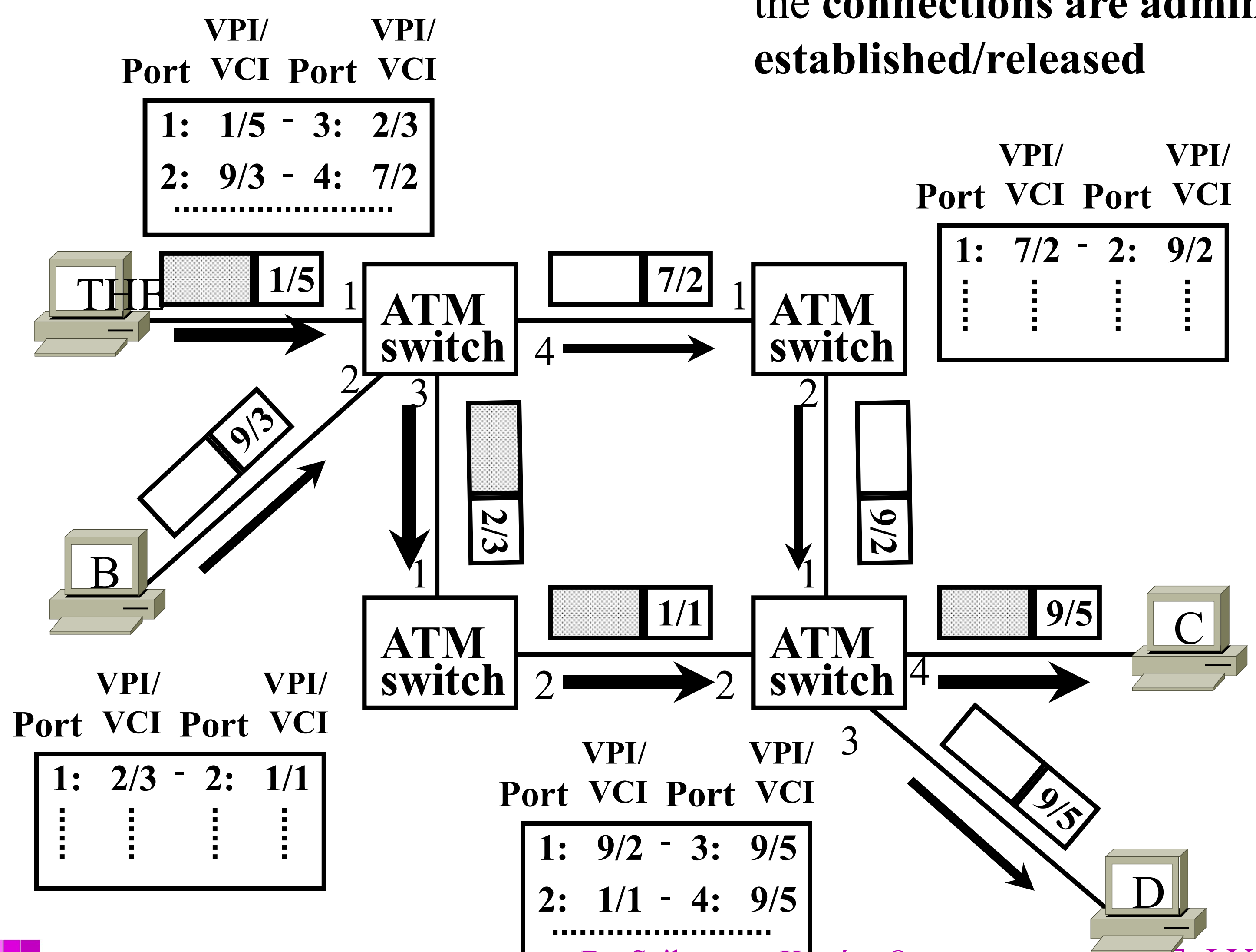
- **Point-to-multipoint** connection types
  - unidirectional only
  - bidirectional through additional point-to-point connections (multicast server)



Connection Services

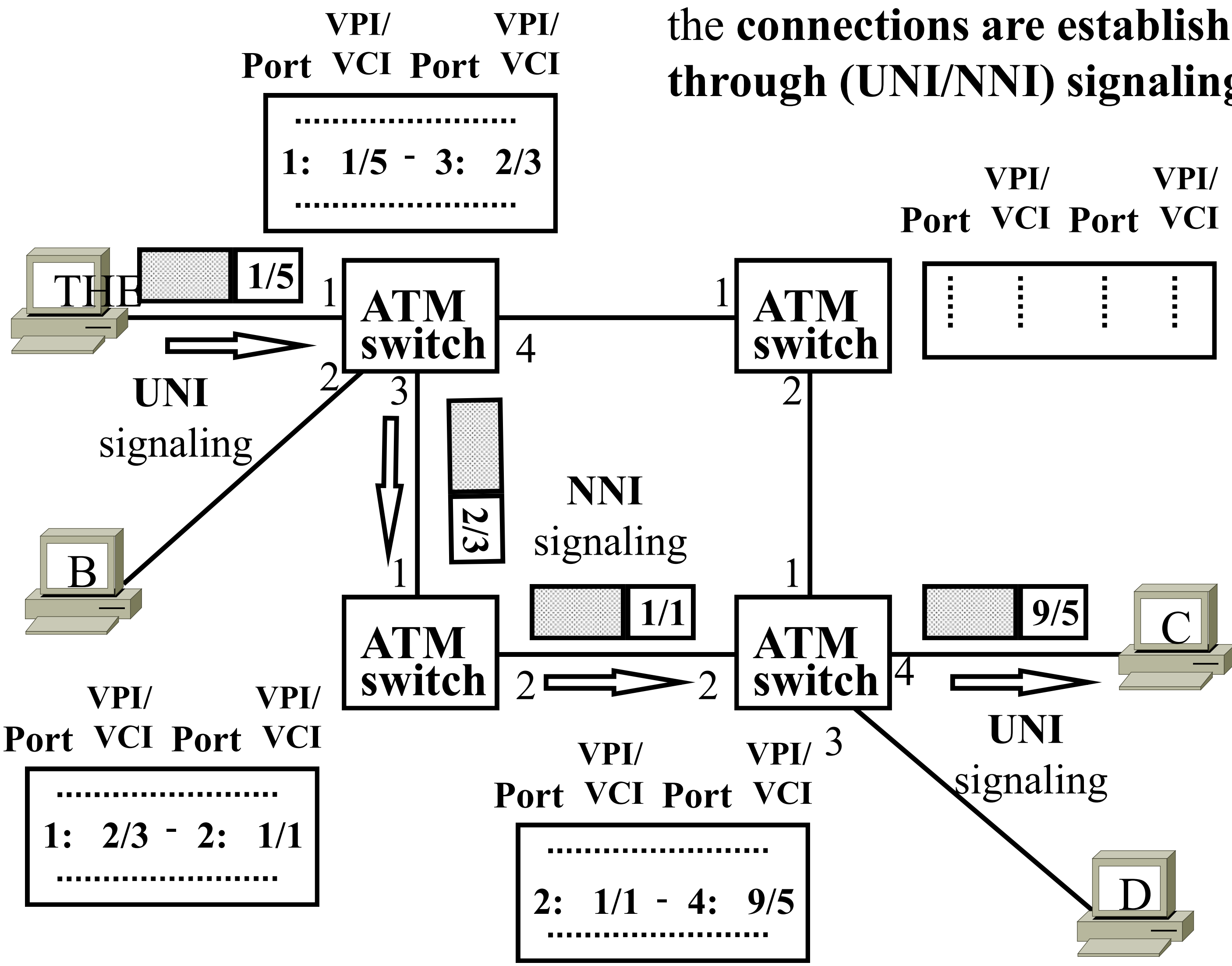
- **Permanent Virtual Circuit (PVC)**

VPI/VCI tables are handled manually, the **connections are administratively established/released**

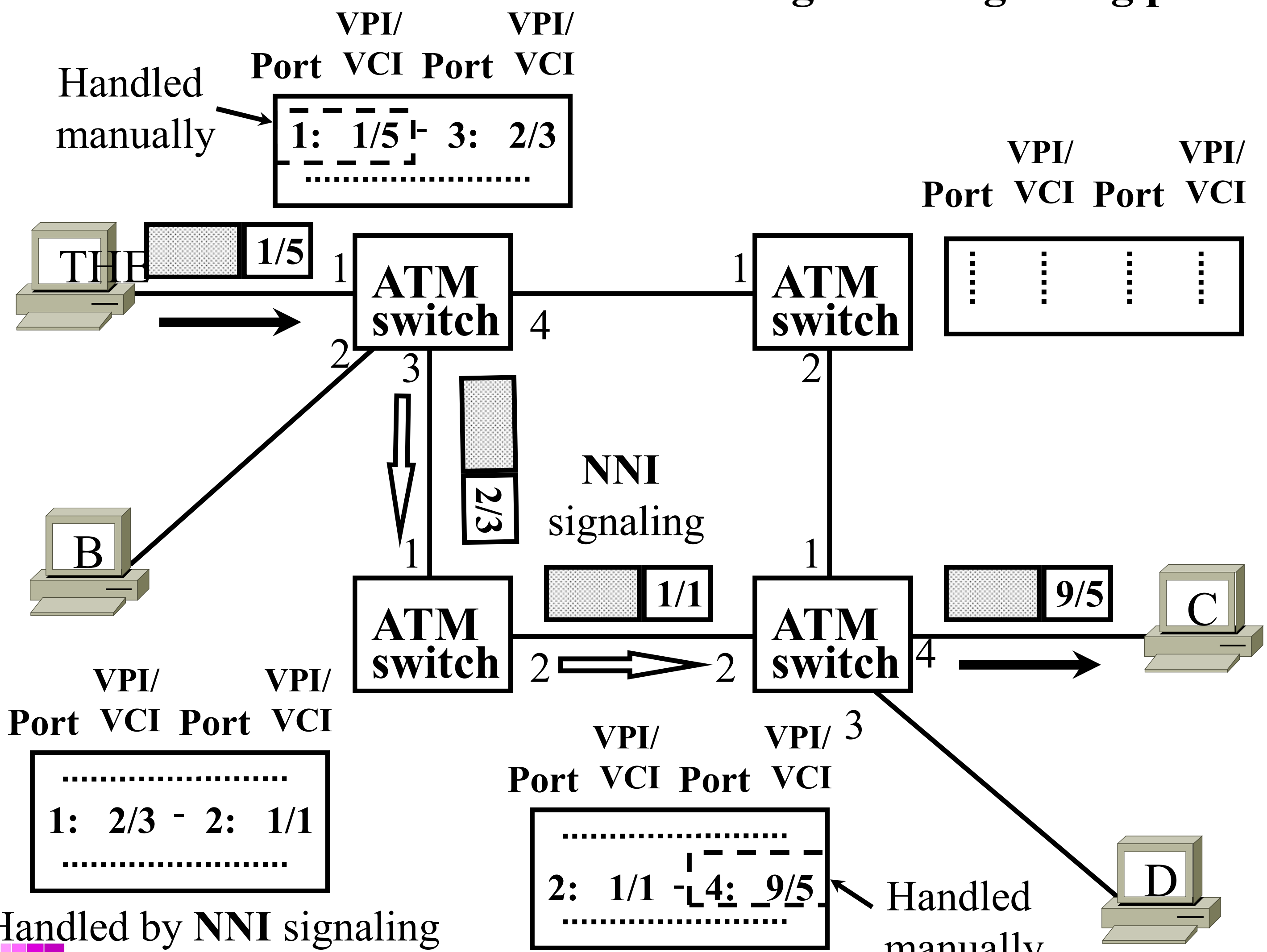


- **Switched Virtual Circuit (SVC)**

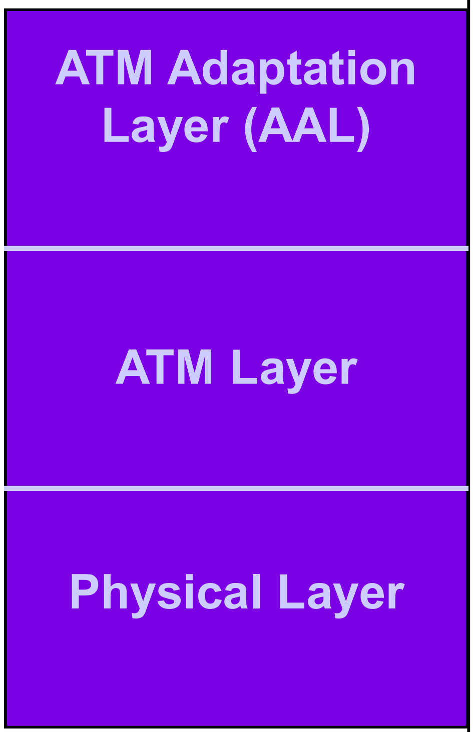
VPI/VCI tables are automatically handled, the **connections are established/released through (UNI/NNI) signaling procedure**



- **Soft Permanent Virtual Circuit (Soft PVC)**
  - **User - network connections are established/released administratively**
  - **Network - network connections through NNI signaling procedure**

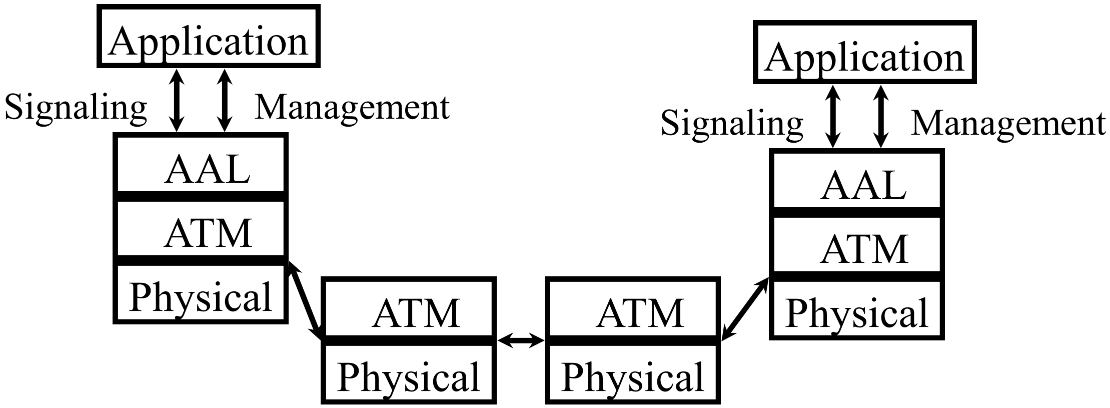


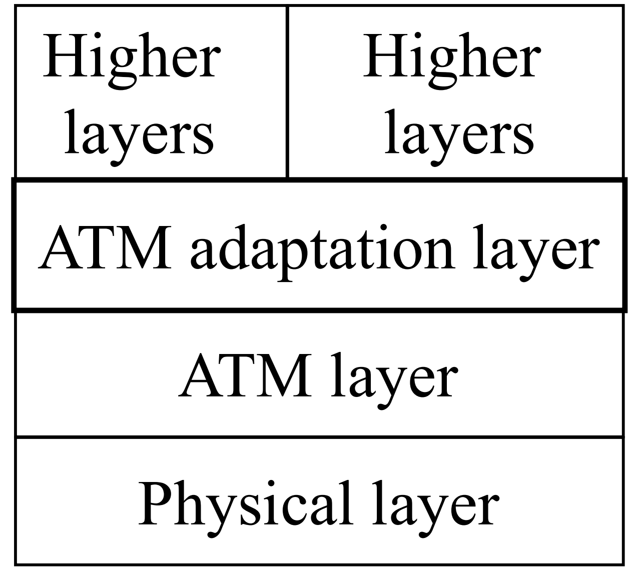
ATM Reference Model



- **Physical Layer:**
  - **Transmission Convergence (TC)**
  - **Physical Media Dependent (PMD)**
- **ATM Layer: Cell header insertion or removal, Cell Relay, Multiplexes or demultiplexes cells of different connections. Provides VPI/VCI values in the header and ensures that cells stay in the correct order.**
- **ATM Adaption Layer (AAL):**
  - **Convergence Sublayer (CS)**
  - **Segmentation and Reassembly (SAR)**

The ATM Reference Model



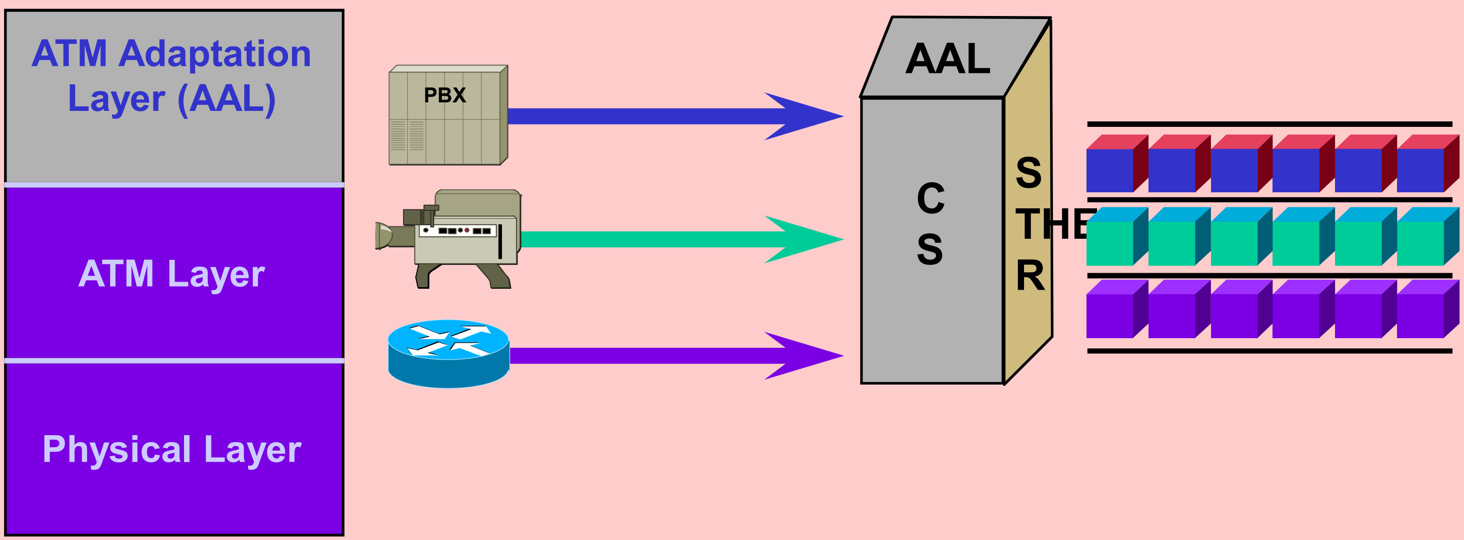


- **ATM adaptation layer (AAL)**
  - →**adaptation of services provided by the ATM layer to the requirements of the higher layer**
    - →**set-up/terminate end-end virtual channel**
    - →**segmentation/reassembly of messages to/from cells**
    - →**control Quality of Service delivery**
    - →**flow control**

ATM Adaptation Layer—AAL

AAL = QoS + SAR

- **CS—assigns different AAL's/QoS for different traffic types**
- **SAR—cell ⇔ packet**



ATM Adaptation Layer (cont)

ATM Adaptation Layer (AAL)

ATM Layer

Physical Layer

Class	Service Categories	Bit Rate	Connection Mode	Timing Concern	Application Examples
THE	AAL1	CBR (Constant)	Connection-Oriented	Yes	• Bandwidth and throughput guaranteed • Good for voice and video
B	AAL2	VBR (Variable) VBR-AT and VBR-NRT	Connection-Oriented	Yes	• Best effort bandwidth and throughput • Good for live video, multimedia, LAN-to-LAN
C	AAL5	ABR (Available)	Connection-Oriented	Woman	• Best effort with congestion feedback • Reliable delivery of bursty traffic if latency is okay
D	AAL3/4	UBR (Unspecified)	Connectionless	Woman	• No guarantee • For SMDS/LAN

ATM Service Classes and the Quality of Service

(According to the ATM Forum)

	Constant Bit Rate	Variable Bit Rate Real Time	Variable Bit Rate Non RT	Available Bit Rate	Unspecified Bit Rate
Cell Loss Ratio	*Specified*	*Specified*	*Specified*	*Specified*	*Unspecified*
Cell Transfer Delay Cell Delay Variation	*Specified*	*Specified*	*Mean CTD only*	*Unspecified*	*Unspecified*
Peak Cell Rate	*Specified*	*Specified*	*Specified*	*Specified*	*Specified*
Sustainable Cell Rate Burst Tolerance	*n/a*	*Specified*	*Specified*	*n/a*	*n/a*
Minimum Cell Rate	*n/a*	*n/a*	*n/a*	*Specified*	*n/a*

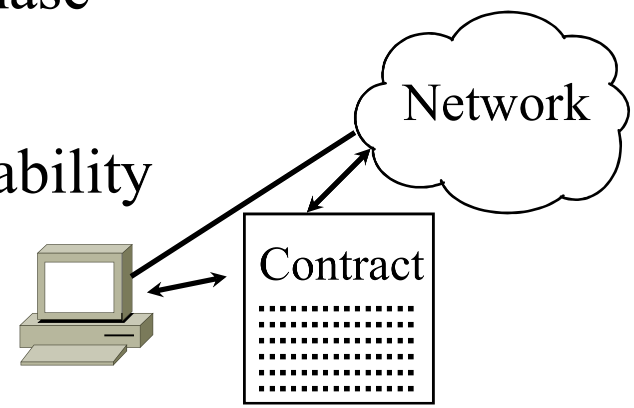
n/a : Not applicable

Mechanisms to achieve a specified QoS

- **Connection Admission Control (CAC)**
  - **negotiation** of the **traffic contract** is between the user and the network in the call establishment phase
- **Usage and Network Parameter Control (UPC, NPC)**
  - **'Traffic Policing'** - a set of actions taken by the network to **monitor** and **control** the **traffic contract is respected** in terms of traffic offered and validity of the ATM connection, at the user access and the network access respectively
- **Traffic Shaping**
  - **altering the traffic characteristics** on the user side to **ensure conformance to the traffic contract** , eg reducing the peak cell rate by buffering

Connection Admission Control (CAC)

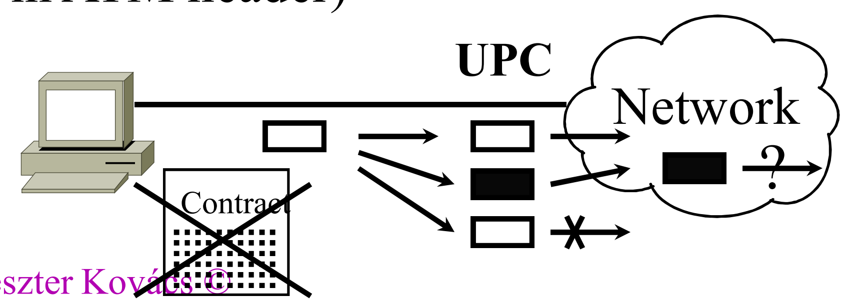
- **negotiation** of the **traffic contract** is between the user and the network in the call establishment phase
- CAC is provided with:
  - the required ATM layer transfer capability
  - the source traffic descriptors
  - the required QoS class



- a connection can only be accepted if sufficient network resources are available to establish the connection end-to-end with is required quality of service
  - eg for a required CBR service class the available link capacity needs to be checked; for a required UBR service class the available buffer space could be the primary factor to be considered

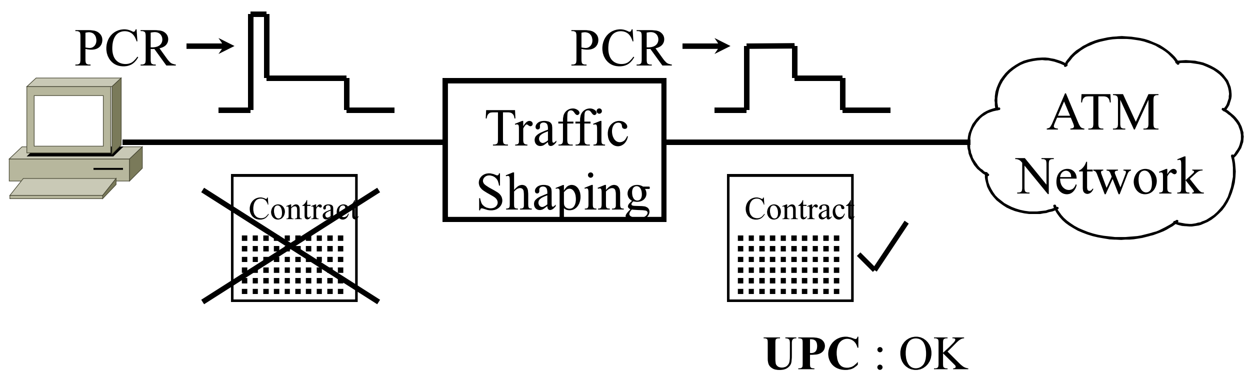
Usage and Network Parameter Control (UPC, NPC)

- **'Traffic Policing'** - a set of actions taken by the network to **monitor** and **control** the **traffic contract also respected**
- Checking the validity of VPI/VCI values
- Monitoring the traffic volume entering the network from all active VP and VC connections to ensure that the agreed parameters are not violated
- **In case of traffic contract violation** UPC/NPC can
  - **discarding cells** that violate the negotiated parameters
  - the 'guilty' connection may be released
  - **tagging of violating cells** and discard later if necessary (CLP - congestion loss priority bit in ATM header)
  - do nothing (**forwarding**)

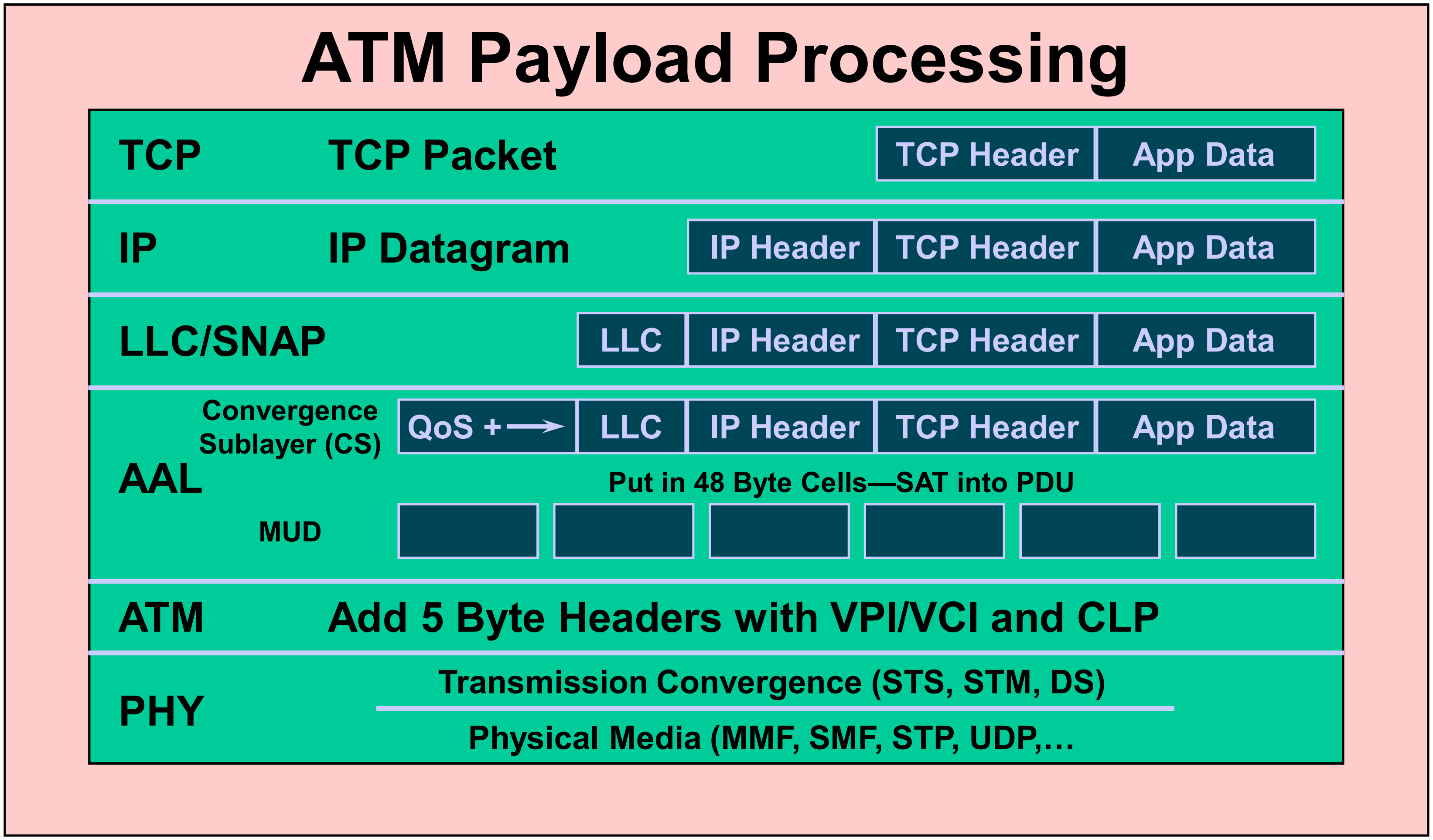


Traffic Shaping

- **altering the traffic characteristics on the user side** to **ensure conformance to the traffic contract** , eg reducing the peak cell rate by buffering - better network utilization, but increased cell transfer delay



A Day in the Life of a Cell



Exercise

- **Task 1: Probability of Ethernet collisions**
  - **Two persistent CSMA/CD** stations attempt to send long (multi-frame) packets. After one of them has sent a frame, they compete again for the channel using **a binary exponential holdback algorithm .**
  - **Question :**
    What is the probability that the competitive situation will be resolved after n rounds?

Exercise

- **Solution to task 1:**
  - **Let's say** they **start "at the same time"** - neither of them have collided before - and **one of them gets the channel**
  - **1 persistent CSMA/CD:**
    If it wants to transmit – waits until the channel is empty and starts transmitting **immediately** If it collides, waits for a random amount of time (bin. exp. hold)
  - **Binary exponential holdback:**
    after the ith collision, the station draws a number between 0 and 2 i $^{-1}$ and waits for that many timeslots. If 10 ≤ i<16, 0 - Draws between 1023, if i=16, gives up. **(Those starting** this time will collide again if they draw the same number)
  - **What is the 1, 2 , ... n. collision probability e?**
  - The probability of the **first collision** is : $P_{1ü} = 1$; since it is a persistent CSMA/CD!
  - Probability of collision 2 (both draw the same):
  - ...
  - **The probability of the nth collision is:**

0	**0**	**1/4**
0	1	1/4
1	0	1/4
1	**1**	**1/4**

$$P_{2ü} = \left(\frac{1}{2}\cdot\frac{1}{2}\right)\cdot 2 = \frac{1}{2}$$

$$P_{nü} = \left(\frac{1}{2^{n-1}}\cdot\frac{1}{2^{n-1}}\right)\cdot 2^{n-1} = \frac{1}{2^{n-1}}$$

Exercise

- **Solution to task 1 :**
  - **The probability of exactly 1 collision** is:
    (it crashes once, but passes the second time)

$$P_1 = P_{1ü} \cdot (1 - P_{2ü}) = 1 \cdot \left(1 - \frac{1}{2}\right) = \frac{1}{2}$$

  - **The probability of exactly n. collisions:**

$$P_n = 1 \cdot \frac{1}{2} \cdot \frac{1}{4} \cdot \ldots \cdot \frac{1}{2^{n-1}} \cdot \left(1 - \frac{1}{2^n}\right) = \frac{1}{2^{n \cdot \frac{n-1}{2}}} \cdot \left(1 - \frac{1}{2^n}\right) = \frac{2^n - 1}{2^{\frac{n^2+n}{2}}}$$

$$\sum_{i=0}^{n-1} i = n \cdot \frac{n-1}{2}$$

$$P_n = \frac{2^n - 1}{2^{\frac{n^2+n}{2}}}$$

Exercise

- **Solution to task 1 :**
  - **What is the average value of the competition rounds?**

$$\overline{n} = \sum_{n=1}^{\infty} n \cdot P_n$$

(can be very well estimated with its first 5 members)

$$\overline{n} \cong 1 \cdot 0.5 \cdot 2 \cdot 0.375 \cdot 3 \cdot 0.109 \cdot 4 \cdot 0.0146 \cdot 5 \cdot 0.00095$$

$$\overline{n} \cong 1.641$$

$$n = 1 \qquad P_1 = \frac{1}{2} = 0.5$$

$$n = 2 \qquad P_2 = \frac{3}{2^3} = \frac{3}{8} = 0.375$$

$$n = 3 \qquad P_3 = \frac{7}{2^{\frac{12}{2}}} = \frac{7}{64} = 0.109$$

$$n = 4 \qquad P_4 = \frac{15}{2^{\frac{20}{2}}} = \frac{15}{2^{10}} = 0.0146$$

$$n = 5 \qquad P_5 = \frac{31}{2^{\frac{30}{2}}} = \frac{31}{2^{15}} = 0.00095$$

$$n = 6 \qquad P_6 = \frac{63}{2^{21}} = 3 \cdot 10^{-5}$$

$$n = 7 \qquad P_7 = \frac{127}{2^{28}} = 4.7 \cdot 10^{-7}$$

$$n = 8 \qquad P_8 = \frac{255}{2^{36}} = 4 \cdot 10^{-9}$$

$$n = 9 \qquad P_9 = \frac{511}{2^{45}} = 1.45 \cdot 10^{-11}$$

$$n = 10 - 15 \qquad P_{10\text{-}15} = \frac{1023}{2^{55}} = 2.84 \cdot 10^{-14}$$

What "fits" on the ring?

- **If :**
  - **S - the medium data rate [bps]**
  - **τ - the signal delay time [sec]**
  - **R - the signal propagation speed $R = L / \tau$ [m/sec]**
  - **L - the ring length [m]**
- **Then:**
  - **How many bits can fit on the medium? $B = S * \tau = S * L/R$ [bit]**
  - **How many meters does 1 bit require? mpb = R/S [m/bit]**
  - **How many bits does 1 meter carry? bpm = S/R [bits/m]**
  - **If the total storage capacity of the ring interfaces is: N [bit]**
    (N = number of stations [pcs] * storage capacity per interface [bit/ pcs])
  - **Total storage capacity of the ring : B + N [bits]**

Task 2: Control ring

- A 4 Mbps beacon ring has a beacon hold time of 10msec.
- What is the longest frame that can be transmitted on the ring?
- Solution
  - Max. frame length, if the max. v gives the signal hold time:

    $4 * 10^{6} - 10 * 10^{-3} = 4 * 10^{4}$ [bits]

Task 3: Token Bus

- We create 4 priority classes on a signal bus as follows:
  - When the beacon arrives at a station, the timer clock is reset. The station then starts sending priority 6 frames until the clock reaches T6; then it switches to sending priority 4 frames until T4; then to priority 2 and 0 frames until T2 and T0, respectively.
    When T0 is reached, it retransmits the beacon.
  - If the timing values of each station T6, T4, T2, and T0 correspond to 40, 80, 90, and 100 msec, respectively, what fraction of the total bandwidth is allocated to each priority class?

Task 3: Token Bus

- **Solution:**

Sending	How long	Duration	The traffic
Class 6 frames	$0 \rightarrow T6$:	40 msec	40/100 = 40%
Class 4 frames	$T6 \rightarrow T4$:	40 msec	40/100 = 40%
Class 2 frames	$T4 \rightarrow T2$:	10 msec	10/100 = 10%
Class 0 frames	$T2 \rightarrow T0$:	10 msec	10/100 = 10%

Task 4: Token Ring

- **How many meters of cable, with a transmission rate of 5 Mbps and a signal propagation speed of 200 m/μsec, cause the same 1-bit delay as the ring interface of the Token Ring?**
- **Solution**

  $S = 5.106 \text{ bps};$

  $R = 200.106 \text{ m/s};$

  $m\,pb = ?$

$$mpb = \frac{R}{S} = \frac{200 \cdot 10^6}{5 \cdot 10^6} = 40 \;\; [\text{m/bit}]$$

  - **1 bit is equivalent to 40 meters, or**
  - **1 bit carries 40 meters.**