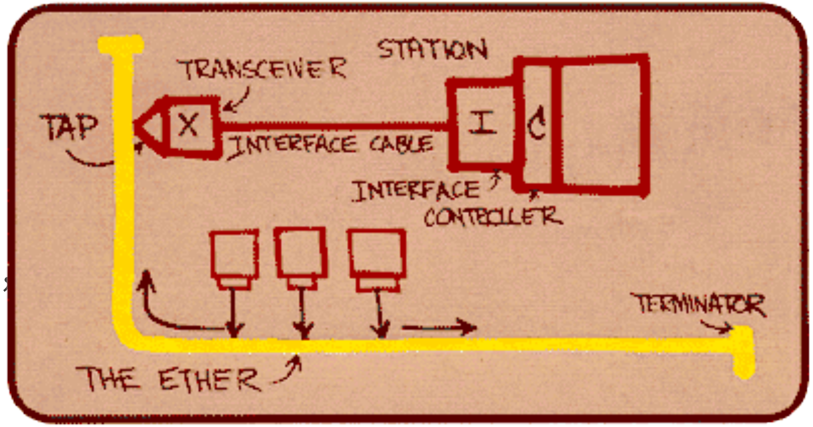
Ethernet - IEEE 802.3

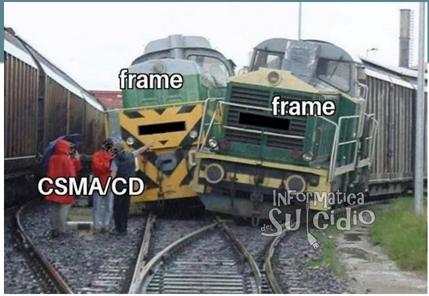
- Most successful local area networking technology of last 45 years.
- Developed in the mid-1970s by Bob Metcalfe and others at the Xerox Palo Alto Research Centers (PARC)
- DEC and Intel joined Xerox to define a 10-Mbps Ethernet standard in 1978. This yielded the IEEE standard 802.3 (1985)
- The standard defines both
  - physical layer (level 1):
    mezzo fisico ← medium, signals, encodings…
  - datalink layer (level 2):
    frame format, error handling, media access control…



Metcalfe's original Ethernet Sketch

Ethernet

→ non ci sono meccanismi di turni, quando uno vuole trasmettere prova a trasmettere. se già uno sta trasmettendo c'è collisione → quando succede si fermano entrambe e si riprova



- Ethernet uses CSMA/CD protocol for media access
  - Carrier Sense Multiple Access with Collision Detection.
  - A set of nodes send and receive frames over a shared link.
  - *Carrier sense* means that all nodes can distinguish between an idle and a busy link.
  - *Multiple Access* means that any node can access the link concurrently (i.e., no time division, no turns)
  - *Collision detection* means that a node listens as it transmits and can therefore detect when a frame it is transmitting has collided with a frame transmitted by another node.

↱ aveva turni fissi con satellite

- Derived from ALOHA (packet radio network) protocol developed in the '70s at the University of Hawaii to support communication across the Hawaiian Islands

Ethernet - 10Base5

- Let us study first the original version - 10Base5

come il cavo dell'antenna

- An Ethernet segment is implemented on a coaxial cable (no electro-magnetic interferences) of up to 500 m.
  - This cable is similar to that used for TV antenna
- Up to 100 hosts can connect to an Ethernet segment by *tapping* into it.

prende segnale analogico, lo decodifica e riconosce i frame

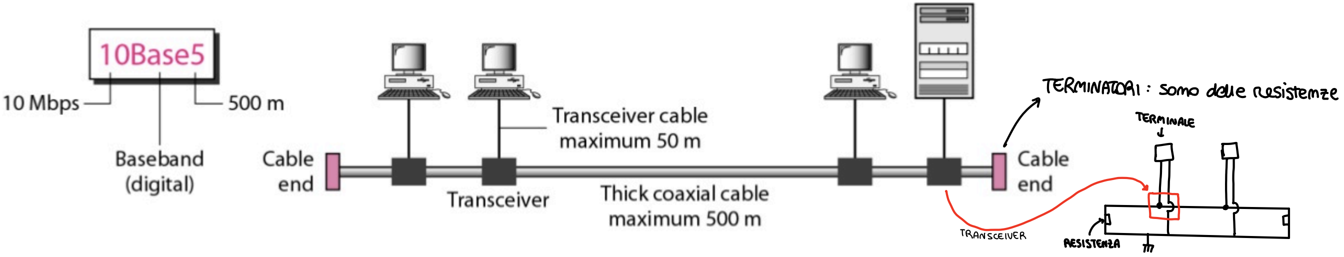
- A transceiver (a small device directly attached to the tap) detects when the line is idle and drives signal when the host is transmitting.

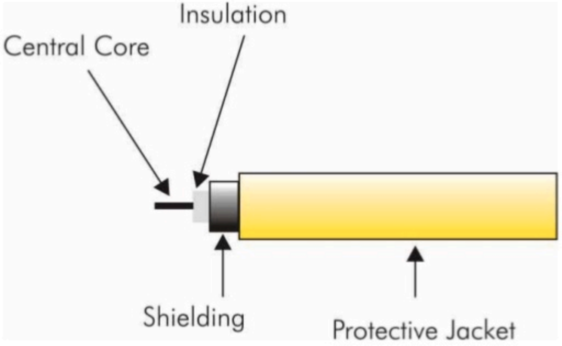
deve sia trasmettere il segnale che ascoltare la linea stessa

- The transceiver also receives incoming signal.
- The transceiver is connected to an Ethernet adaptor which is plugged into the host.
- The CSMA/CD protocol is implemented on the adaptor.

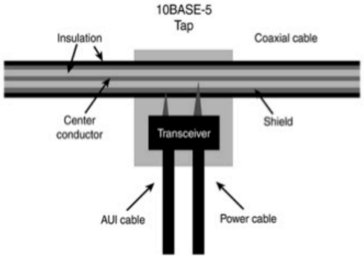
10 megabit
500m

10Base5



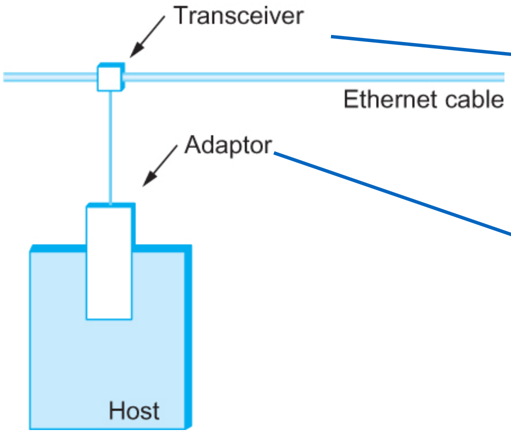


Source: http://www.openxtra.co.uk/articles/ethernet-network-cabling

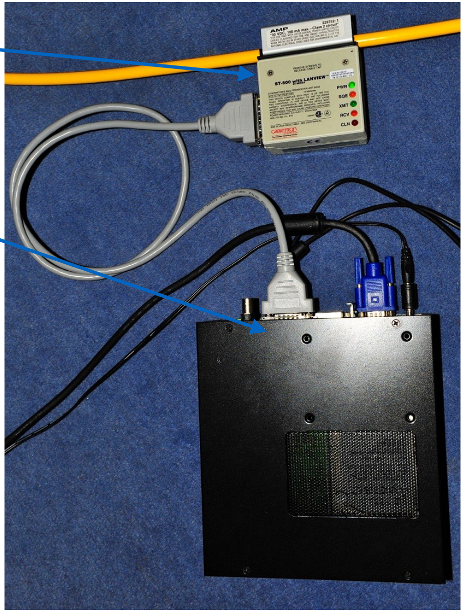


Source: http://flylib.com/books/en/1.408.1.35/1/

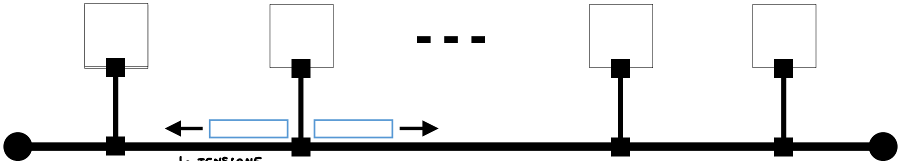
Ethernet - 10Base5

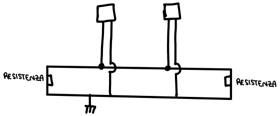


Ethernet transceiver and adaptor



Ethernet - 10Base5





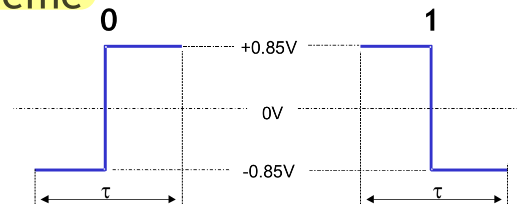
la TENSIONE

assorbono l'energia

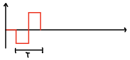
è un cavo e se inizio a modulare il segnale, questo si propaga e se agli estremi non ci fossero le resistenze ritornerebbe indietro

- Any signal placed on the Ethernet by a host is broadcast over the entire network (Signal propagates in both directions, at speed 2c/3)
- Terminators attached to the end of each segment absorb the signal (impedance adaptation), to avoid signals to bounce back
- 10base5 Ethernet uses Manchester encoding scheme
  - 0V when not transmitting
  - ±0.85V when transmitting
- End of transmission is recognised by lack of carrier (no need of an explicit sentinel)

↳ quando torna a 0V, visto che durante la trasmissione passa di continuo da +0,85V a -0,85V



es. 0 :



es. $T = 0{,}1 \cdot 10^{-6}$ s

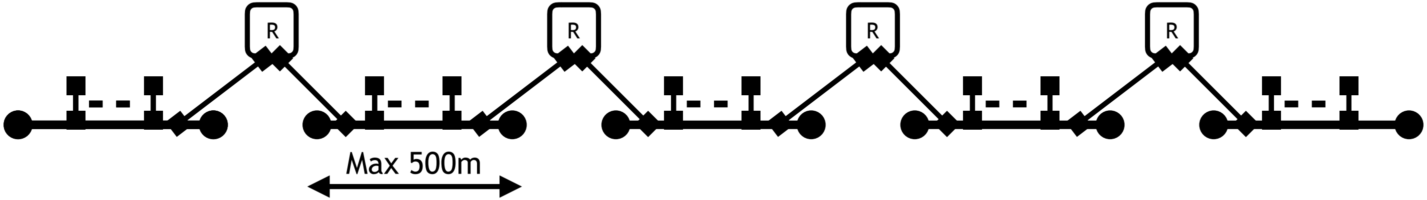
$f = \frac{1}{T} = \frac{1}{0{,}6 \cdot 10^{-6}} = 10 \cdot 10^6$ Hz $= 10$ MHz

baudrate = 10 Mbaud   bitrate = 10 Mbps

1 simbolo → 1 bit (2 liv)

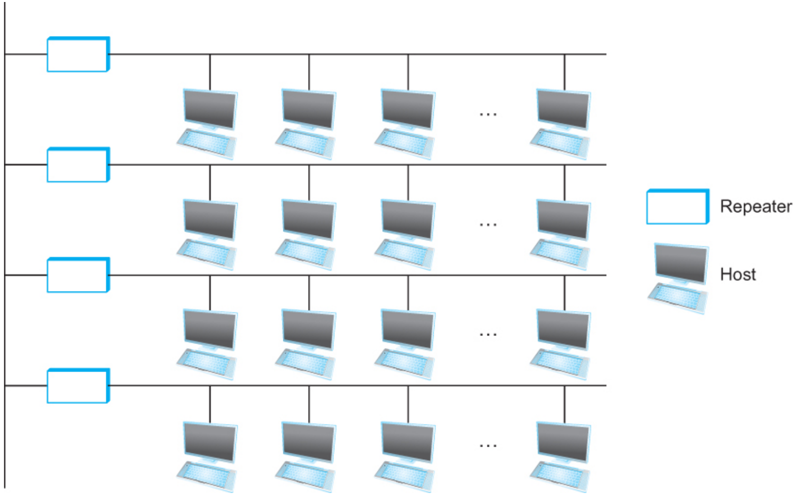
Ethernet - 10Base5

- Multiple Ethernet segments can be joined together by *repeaters*.
  ↳ di livello 1, prende i bit codifica e decodifica. NON SA COSE' IL FRAME
- A repeater is a device that decodes and re-encodes digital signals on both directions, bit-by-bit
  - no concept of frame, no CRC checks
- No more than four repeaters may be positioned between any pair of hosts; thus a 10base5 Ethernet has a total reach of ~2500 m.
  ↳ al max. posso usare 4 repeaters



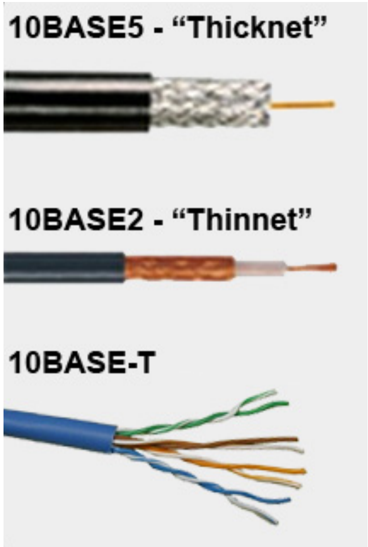
Ethernet - 10Base5

- Segments can be connected in any way, as long as there are no loops and there are no more than 4 repeaters between two hosts
- A typical arrangement was a segment connecting the repeaters only (and possibly some monitoring device), called the **backbone**, and all stations are on each segments



Ethernet - 10Base2, 10BaseT

- An Ethernet can be constructed also from a thinner (and cheaper) coax cable known as 10Base2 → meno isolato portata minore → 200 m
  - 10 means the network operates at 10 Mbps
  - Base means the cable is used in a baseband system
  - 2 means that a given segment can be no longer than 200 m
  - Encoding, voltages, speed, etc, are the same
- Another widespread cable technology is 10BaseT usato oggi
  - T stands for *twisted pair*
  - Limited to 100 m in length
  - Uses 4B/5B encoding and MLT-3 instead of Manchester



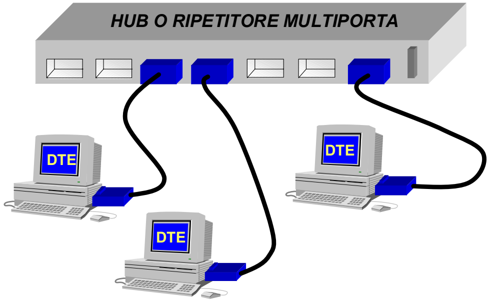
Minimum velocity factors for network cables

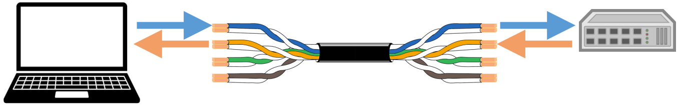
- Velocity factor = speed of light in medium / speed of light in void
- The velocity factors different quite a lot in different media
  - (It depends of the dielectric capacity of the insulators)
- The lower the VF, the slower the signal propagates, the greater the delay introduced by signal propagation

VF (%)	Cable	Ethernet physical layer
74-79	Cat-7 twisted pair	
77	RG-8/U	Minimum for 10BASE5
67	Optical fiber	Minimum for 10BASE-FL, 100BASE-FX, ...
65	RG-58A/U	Minimum for 10BASE2
65	Cat-6A twisted pair	10GBASE-T
64	Cat-5e twisted pair	100BASE-TX, 1000BASE-T
58.5	Cat-3 twisted pair	Minimum for 10BASE-T

Ethernet - 10baseT

- With 10BaseT, the common configuration is to have several point to point segments (“star topology”) coming out of a multiway repeater, called *Hub*
  - A hub is similar to a repeater: when it receives a frame on a port, it forwards it to all other ports.
  - Not to be confused with switches (which are more clever)
- So, each twisted pair can be seen as a single Ethernet segment with exactly one transmitting host and one receiving host
  - One pair from hub to DTE
  - One pair from DTE to hub



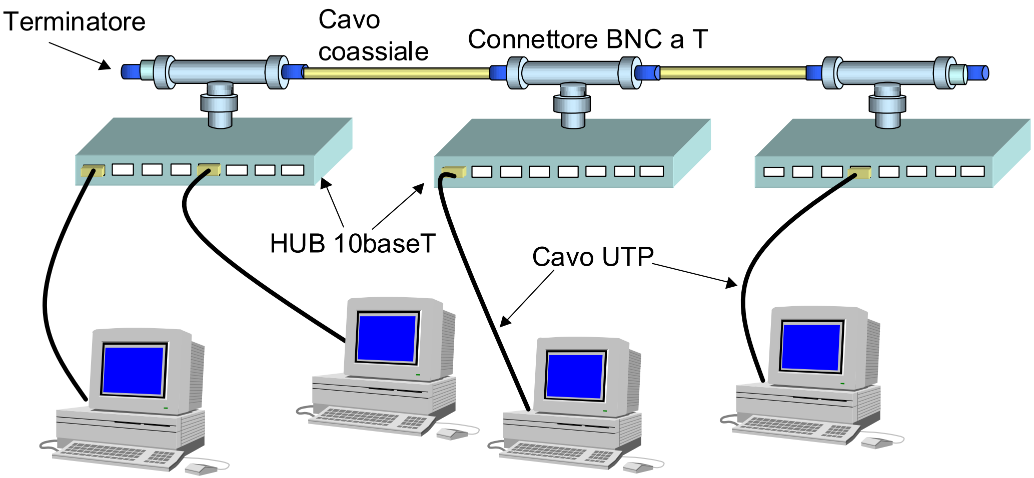


The other two pairs are unused in 10baseT, but are used in 100baseT and 1000baseT

HUB: prende un frame da un ramo e lo inoltra su tutti gli altri rami → TOPOLOGIA a STELLA
↳ porte
↳ non indirizza a liv. MAC, quello lo fa lo switch

Ethernet - mixed networks

- *Mixed network*: hosts are connected to hubs, which are connected each other by a 10base-5 or -2 cable (the *backbone*)
  - Still, the whole networks must be intended as a single one: A frame sent by any host is forwarded to all segments and to all hosts

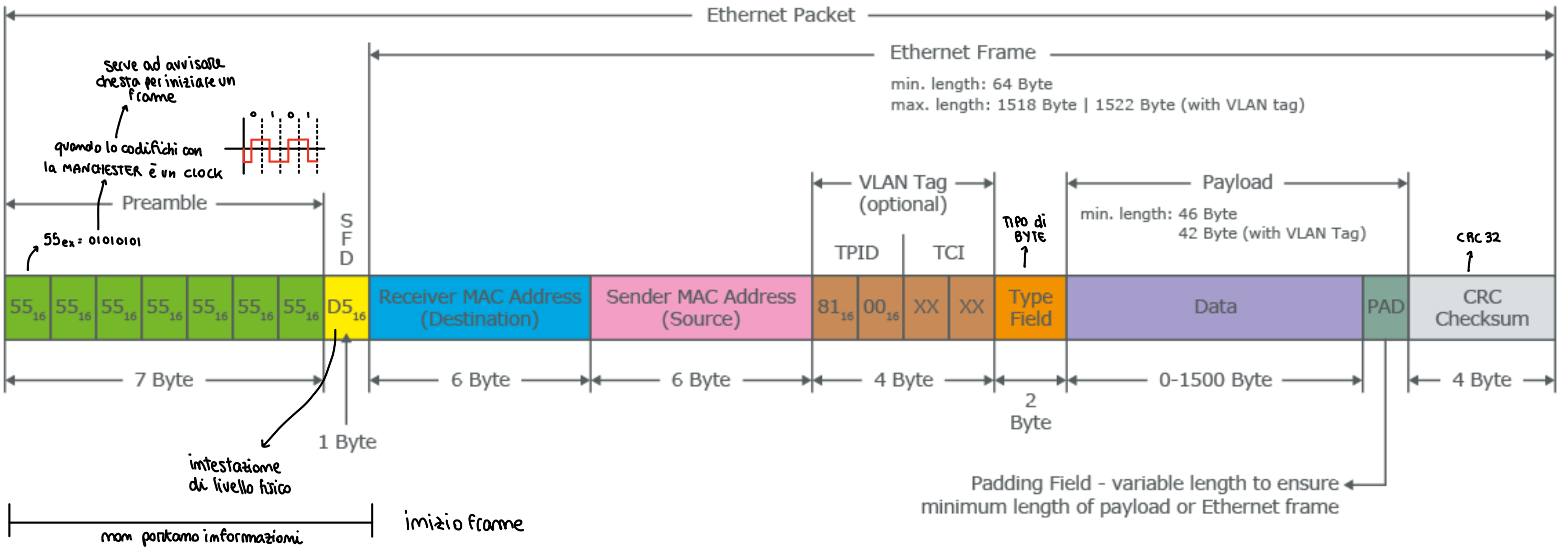


Ethernet - other variants

- More recently 802.3 has been extended to include
  - **100BASE-TX (*Fast Ethernet*)**: 100-Mbps version on twisted pairs (not available on coax cable)
  - **100BASE-FX**: same, on fiber
  - **1000BASE-T *(Gigabit Ethernet)***: 1000-Mbps on twisted pairs
  - Other variants up to 1 Tb/s are in development
- Physical layer and access protocol may vary, but frame is always the same (so it can be moved across different segments)
- The success of Ethernet has paved the way for the definition of a similar standard for wireless communications: 802.11, aka Wi-Fi
  - (on the other hand, 802.15 (Bluetooth) is not quite similar to 802.3)

Ethernet frame format

pacchetto Ethernet ≠ pacchetto frame



Ethernet frame format

- Preamble (7 bytes 10101010): on 10Base-5 and 10Base-2 generates a 10MHz square wave which allows the receiver to synchronise with the signal
- *Start of Frame* Delimiter (8 bit 10101011): sentinel to indicate the beginning of frame
- Host and Destination Address (48 bit each)

"segmento una LAN in più sottolan (di liv. 2), analogo al SUBNETTING (di liv. 3)
soltanto che non creo gerarchie

- VLAN tag (optional, 4 bytes): to indicate to which Virtual LAN this frame belongs to
- Packet type (16 bit): acts as demux key to identify the higher level protocol.
- Data (minimum 64, maximum 1500 bytes)
    - Possibly padded in order to have a frame of 64 byte, to detect collision
- CRC (32bit): CRC-32

quando la tensione torna a 0

- (end of frame is implicit in the loss of carrier, no need of sentinel)
- Overall: a 14(+4)-bytes header and a 4-bytes trailer (preamble is not part of the frame)

Ethernet addresses

- Each host on an Ethernet (in fact, every Ethernet card in the world) has a unique **Ethernet Address**, composed by 48 bits → unico al mondo, come un seriale
  - Theoretical limit of $2^{48} = 2{,}8 \cdot 10^{14}$ network cards, but some are reserved
    ↳ circa 5k dispositivi a testa per ogni umano
- The address belongs to the adaptor, not the host
  - Used to be burnt into ROM, now in flash memory of the adapter
    → i primi 3BYTE identificano il produttore
  - Each manufacturer of Ethernet devices is allocated one or more different prefixes (first three bytes) of the address on every adaptor they build
- Ethernet addresses are typically printed in a human readable format as a sequence of six numbers separated by colons.
  - Each number corresponds to 1 byte of the 6 byte address and is given by a pair of hex digits, one for each of the 4-bit nibbles; leading 0s are dropped
  - For example, 8:0:2b:e4:b1:2 is
    00001000 00000000 00101011 11100100 10110001 00000010
    (and 8:0:2b was assigned to Digital Equipment Corporation (DEC))

Ethernet Receiver Algorithm

lato RICEVITORE

- Each frame transmitted on an Ethernet is received by every adaptor connected to that Ethernet.
- Each adaptor recognises those frames addressed to its address, checks the CRC, and passes only those frames on to the host. Other unicast frames are ignored.
- destinati ad uno solo
- In addition to unicast address, an Ethernet address consisting of all 1s (that is, FF:FF:FF:FF:FF:FF) is treated as a *broadcast* address
  - All adaptors pass frames addressed to the broadcast address up to the host.

Ethernet Receiver Algorithm

- Similarly, an address that has the first bit set to 1 but is not the broadcast address is called a *multicast* address.
  - A given host can program its adaptor to accept some (not very large) set of multicast addresses (32-64 possible entries)
  - Not to be confused with IP multicast (we will see)
- To summarize, an adaptor receives *all* frames and accepts
  - Frames addressed to its own address
  - Frames addressed to the broadcast address
  - Frames addressed to a multicast addressed if it has been instructed

Ethernet Transmitter Algorithm

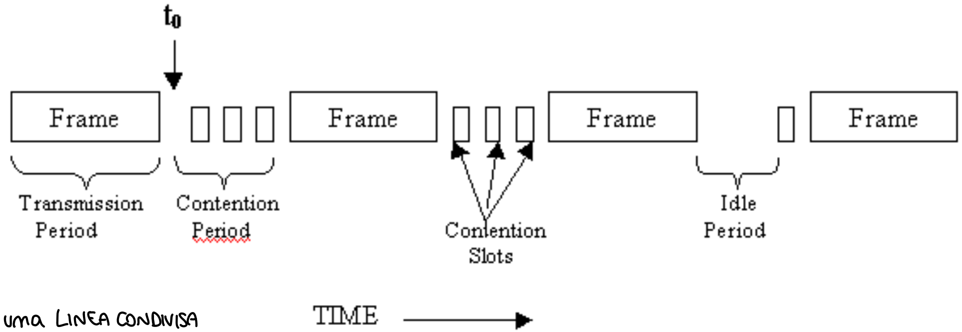
- The algorithm is commonly called Ethernet's **Media Access Control (MAC)**.
- It is implemented in hardware on the network adaptor.
- When the adaptor has a frame to send, it listens the line → come funziona CSMA-CD
  - If the line is idle (i.e., no signal), it transmits the frame immediately.
    - The upper bound of 1500 bytes in the message means that the adaptor can occupy the line for a fixed length of time. → altrimenti rischierei la STARVATION
  - If the line is busy, it waits for the line to go idle (for a minimum amount of time, called *Inter Packet gap*, ITP) and then transmits immediately

→ perchè se trova la linea occupata dopo trasmette sicuramente

- Ethernet is said to be **1-persistent CSMA/CD** protocol because an adaptor with a frame to send transmits with probability 1 whenever a busy line goes idle.

→ la COLLISIONE può avvenire soltanto se due host provano a trasmettere CONTEMPORANEAMENTE su una linea idle. se fossero sfasati non ci sarebbe una collisione in quanto il secondo ASCOLTA la linea (prima di spedire) e la TROVA OCCUPATA, perciò non spedisce, aspetta un tempo random e riprova

Ethernet Transmitter Algorithm



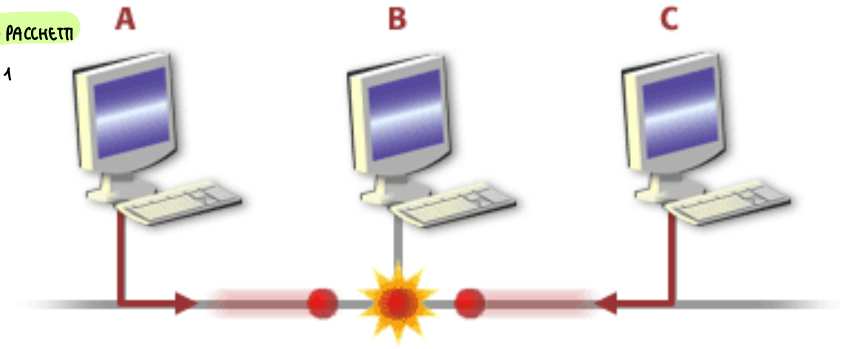
→ c'è una LINEA CONDIVISA

- In CSMA/CD protocol, there are three states:
  - **Idle**: no station has frames to transmit → 0 V
  - **Contention**: some stations want to transmit, and have to wait the line to be free - which means no signal on the line for ITP time → si decide a chi tocca parlare (the equivalent of 8 bytes=96 bit; 9.6 µs in 10Base-5 and 2)
  - **Transmission**: one (or more) stations transmit → sta trasmettendo

Ethernet Transmitter Algorithm

- Since there is no centralized control it is possible for two (or more) adaptors to begin transmitting at the same time,
  - Either because both found the line to be idle,
  - Or, both had been waiting for a busy line to become idle.
- When this happens, the two (or more) frames are said to *collide* on the network
- During collision, signals are overlapped and hence they cannot be decoded correctly

SONO ONDE, NON PACCHETTI
è di LIV. 1



Ethernet Transmitter Algorithm

serve per risolvere il problema delle collisioni

- Ethernet supports *collision detection*: each sender is able to determine that a collision is in progress

appena rileva una collisione, ferma tutto

  - The electronics compares what it transmits and what receives; if the difference is not 0, there is a collision
- At the moment an adaptor detects that its frame is colliding with another, it first makes sure to transmit a 32-bit *jamming sequence* and then stops transmission.

per avvisare tutti le schede connesse che è avvenuta una collisione

il peggio è quando ha praticamente inviato quasi tutto il frame e c'è una collisione → BUTTA VIA TUTTO

così

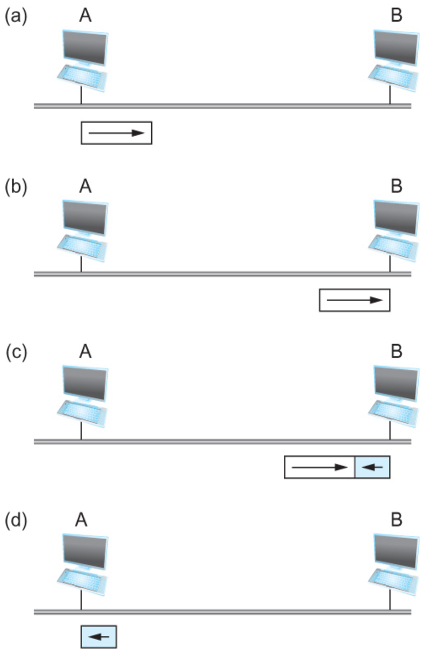
- Thus, a transmitter will minimally send 96 bits in the case of collision: 64-bit preamble + 32-bit jamming sequence
- One way that an adaptor will send only 96 bit (called a *runt frame*) is if the two hosts are close to each other.
  - Had they been farther apart, they would have had to transmit longer, and thus send more bits, before detecting the collision.

Ethernet Transmitter Algorithm

- The worst case scenario happens when the two hosts are at opposite ends of the Ethernet. → per vedere se c'è collisione mentre trasmetto ascolto se c'è qualcun altro che trasmette
- To know for sure that the frame its just sent did not collide with another frame, the transmitter may need to send as many as 512 bits.
  - Every Ethernet frame must be at least 512 bits (64 bytes) long
  - 14 bytes of header + 46 bytes of data + 4 bytes of CRC
- Why 512 bits?
- Why is its length limited to 2500 m?
  - The farther apart two nodes are, the longer it takes for a frame sent by one to reach the other, and the network is vulnerable to collision during this time

Ethernet Transmitter Algorithm

- Worst-case scenario: Let t_{prop} denotes the one link latency (*propagation time*)
  - (a) A begins transmitting a frame at time t
  - (b) The first bit of A's frame arrives at B at time t + t_{prop}
  - (c) An instant before host A's frame arrives, host B begins to transmit its own frame. B's frame will immediately collide with A's frame and this collision will be detected by host B Host B will send the 32-bit jamming sequence
  - (d) Host A will not know that the collision occurred until B's frame reaches it, which will happen at t + 2*t_{prop}
- Therefore, *host A must continue to transmit until this time in order to detect the collision*
- Host A must transmit at least for 2*t_{prop} to be sure that it detects all possible collisions!



Ethernet Transmitter Algorithm

- Overall, the maximum round trip delay $2t_{prop}$ has been determined to be 51.2 µs ($t_{prop} \leq 25.6$ µs)

  $\underbrace{10 \cdot \cancel{10^6}}_{10\text{ Mbps}} \cdot \underbrace{51{,}2 \cdot \cancel{10^{-6}}}_{51{,}2\,\mu s} = 10 \cdot 51{,}2 = 512$ bit
  $[\text{bit}/s]\ [s]$

  - Which on 10 Mbps Ethernet corresponds to 512 bits = 64 bytes, which is the minimum frame length → se fosse meno finirei di trasmettere il frame prima di accorgermi di che c'è una collisione → se vuoi ricevere le collisioni devi spedire frame di almeno 512 bit
- Propagation time through a maximally configured 10Base-5 Ethernet is about 11 µs (2500m / $2.3 \cdot 10^8$ m/s), plus the delays introduced by (up-to 4) repeaters.

  ↳ ogni repeater per ritrasmettere ci impiega del tempo, non è istantaneo

  - thus the delay of a repeater can be up to 3.7 µs
- Other way to look at this situation:
  - For the access algorithm to work, we need to limit the Ethernet's maximum latency to a fairly small value, hence **the maximum length for the Ethernet is ~2500m and the repeaters are limited to 4 and their delay is limited to 3.7 µs**

Ethernet Transmitter Algorithm

- Once an adaptor has detected a collision, and stopped its transmission, it waits a certain amount of time and tries again.
- Each time the adaptor tries to transmit but fails due to a collision, it doubles the possible amount of time it waits before trying again.
- This strategy of doubling the possible delay interval between each retransmission attempt is known as *Exponential Backoff*.

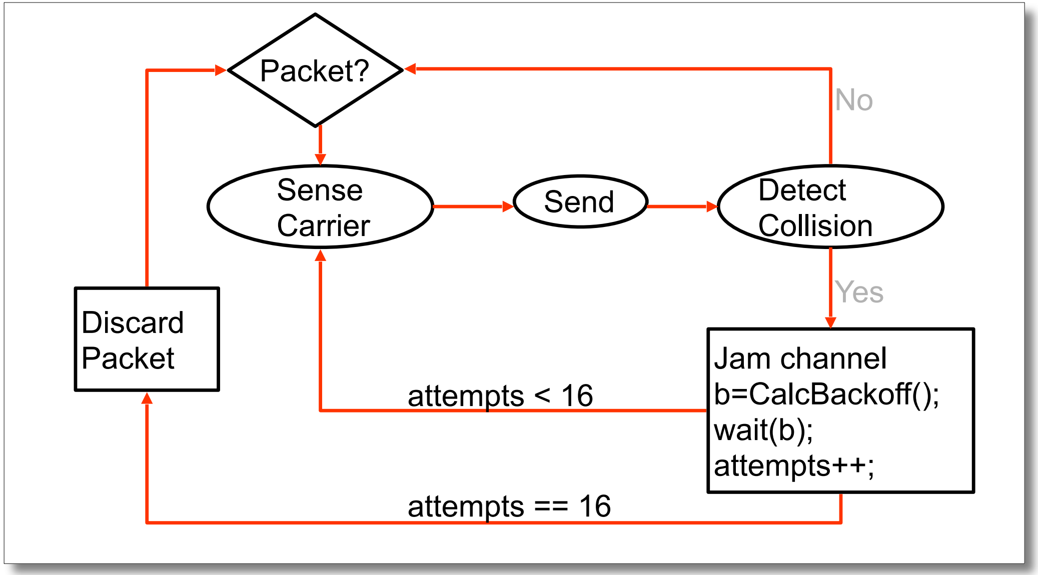
  ↳ tempo RANDOM im um range che raddoppia ad ogni tentativo di trasmissione
- As a consequence, *the time taken to transmit a frame is not deterministic*: it depends on how many collisions it takes, that is, how many adaptors are trying to transmit, that is, on the overall load of the network

Ethernet Transmitter Algorithm - Exponential Backoff

è possibile che uno che ha già molti tentativi provi a trasmettere insieme ad uno che prova a trasmettere la prima volta → ha la precedenza quello nuovo
↳ NON È EQUO

- Let us call SlotTime=51.2 μs.
- At first attempt, the adaptor tries immediately after waiting ITP. If no collision is detected in SlotTime, ok.
- Otherwise, the adaptor sends runt frame, waits ITP, and retries but first delays either 0 or SlotTime, selected at random.
- If this effort fails (i.e., a collision is detected again), it tries again but this time waiting k * SlotTime for k = 0...3 random (i.e., 0, 51.2, 102.4, 153.6 μs)
- If this gives another collision, it waits k*SlotTime for k = 0...2^3 - 1. Etc.
- In general, after n collisions, the algorithm randomly selects k in 0...2^n - 1
    - if 10<n<16, the exponent is fixed at 10
- n is limited to 15; after 16 consecutive collisions, the packet is discarded and an error is raised.
    - EXTREMELY RARE situation - in practice it happens only if the cable has some hardware problems (e.g. missing terminator)

Ethernet Transmitter Algorithm



Ethernet Efficiency

↳ non da garanzie di consegna

- Efficiency = long-run fraction of successful transmissions = long-run fraction of channel used for data
- Efficiency is given by the ratio between transmission time and actual time needed to transmit frame
- The CSMA/CD protocol is not easy to analyze, due to the the non deterministic nature, and the fact that not all stations behave in the similar way
- We consider here some simplified situations:
  - When only one station transmits
  - When all stations behave in the same way

Ethernet Efficiency - one transmitting station only

e gli altri ricevono
quindi NO COLLISIONI

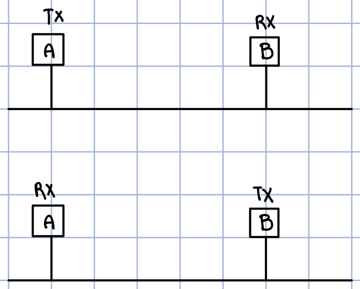
previous frame	ITP	Slot1 - with whole frame	ITP	Slot1 - with whole frame	---------

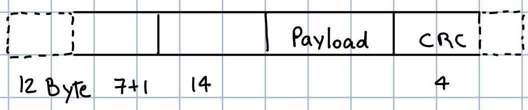
- Very simple case: 1 single station transmitting on the channel, and all the others only receiving
  - This is the situation of a hub or switch-based network LAN
- In this situation, no collisions at all: a frame is successfully sent immediately after ITP
  - ITP = 9.6 μs = 96 bit = 12 byte

    tempo per vedere se la linea è libera
  - Preamble + SFD = 8 bytes (7 + 1)
  - P = length of payload (up to 1500 byte)
  - Header + CRC = 18 bytes
- Theoretical efficiency: $P / (12 + 8 + P + 18) = 1/(1+38/P)$

CASO 1 TRASMETTITORE:

dentro un cavo ho due canali





efficienza $E(P) = \frac{P}{38 + \max(P, 46)}$

se $P = 1 \Rightarrow E(1) = \frac{1}{86} \simeq 1{,}2\%$ → vuoe dire che ie 99% del contenuto mandato sono solo intestazioni

⇒ puoi avere anche connessione 10Gbps ma e'efficienza è sempre la stessa se mando via pacchettini

pacchetti grandi

se $p = 1500$ Byte $E(1500) = \frac{1500}{1538} \simeq 97\%$ → caso fortunato anche se spreco un 3%

es. se sto andando a 100 Mbps in realtà i dati utili sono 97Mbps

e

Ethernet Efficiency - one transmitting station only

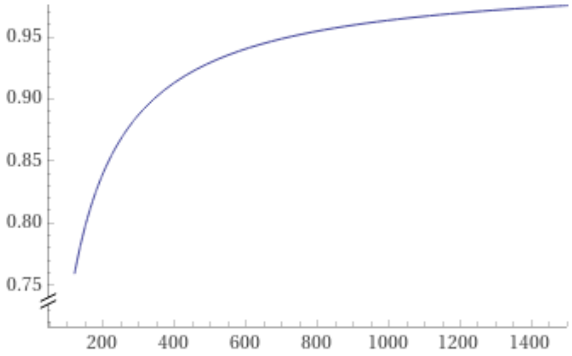
previous frame	ITP	Slot1 - with whole frame	ITP	Slot1 - with whole frame	....

efficienza $E(P) = \dfrac{P}{38 + \max(P, 46)}$

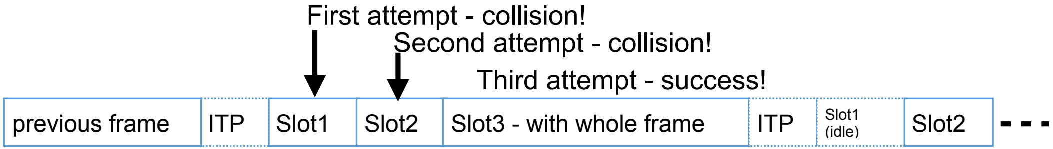
- Theoretical efficiency: 1/(1+38/P)
- The larger the P, the more efficient is the protocol

  PAYLOAD

  - Worst case with padding: P=1, but actual P=46 => efficiency = 1/(12+8+18+46)=1.2%
  - Worst case without padding: P=46 => efficiency = 54%
  - Best case: P=1500 => efficiency = 97%



Ethernet Efficiency - N equal stations competing



- N equal stations are competing on a shared media (cable, hub, …)
- At each slot, each station wants to transmit a frame (either new, or a retransmission after collision) with probability *p* $p=\frac{1}{2}$ la metà prova a trasmettere
  ↳ se $p=1$ tutti provano a trasmettere
    - N*p is the average number of stations willing to transmit at each slot
    - In other words, Np is the *global load* of the network ↱ deve essere il più vicino a 1, sotto è 1
- Transmission is successful if for the whole slot one station detects no collision (and hence all the other stations have not tried to transmit). In this case, the whole frame is transmitted
- If failure (idle or collision), try next slot (1-persistence)
- (continues on next slide)

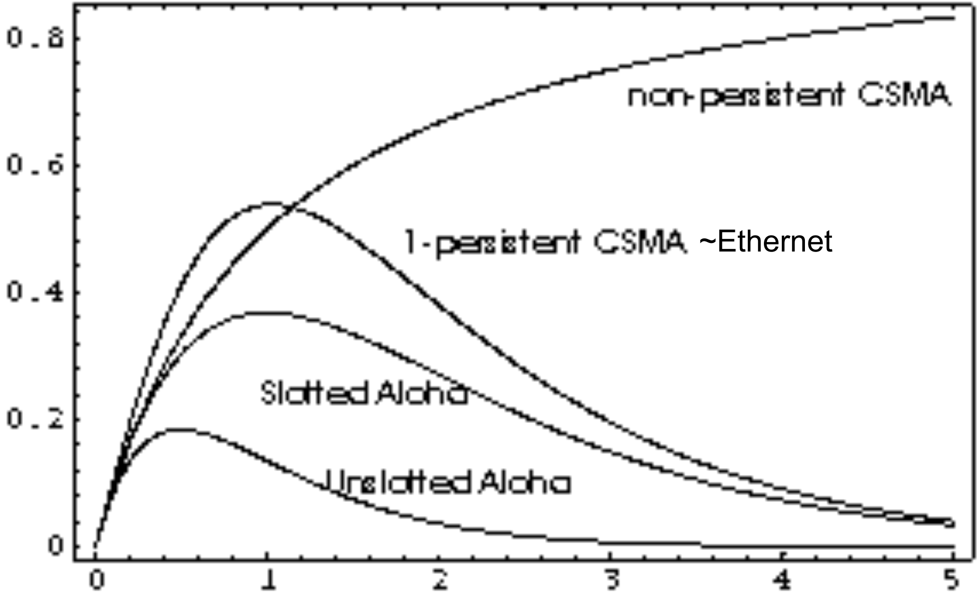
Ethernet Efficiency - N equal stations competing

- tempo che ti viene assegnato per trasmettere
  Slot time = $2t_{prop}$ where t_{prop} = propagation time
- At each slot after the ITP:
  P(the slot is successfully taken for a transmission) = P(exactly 1 out of N transmits) = $Np(1 - p)^{N-1}$
  per tutti gli N — 1 trasmette — N-1 non trasmettono
- lo studi con la derivata
  Maximum probability is when p = 1/N, that is, Np = 1
  sono invers. prop. → più aumenti N più diminuisce P e viceversa
  - Thus, in order to avoid collisions and optimise global throughput, the more the hosts, the less likely they should transmit
- In this case: P(success) = $(1 - 1/N)^{N-1} \overset{N\to+\infty}{\approx} 1/e = 0.37$ (for N large)
  - At most, 37% of slots are used by successful transmissions
- Average number of attempts for sending a frame: 1/(1/e) = e = 2.7
- (continues on next slide)

probabilità del 37% di ~~prendere il mezzo~~ riuscire a trasmettere correttamente, il resto sono collisioni

Ethernet Efficiency - N equal stations competing

Packets successfully transmitted per slot



Load = Np = average number of attempts per slot, including retransmissions

Ethernet Efficiency - N equal stations competing

tempo per codificare il payload

- Let t_{trans} = time to transmit payload = payload / bitrate
  slot time = $2t_{prop}$
  t_{oh} = frame overhead = preamble + header + CRC = 26 byte / bitrate
  tempo per codificare le intestazioni e il CRC
- Average transmission time (maximizing throughput, i.e. N*p* = 1):
  $$ITP + e^{*}2t_{prop} + t_{trans} + t_{oh}$$
  # turni medio per spedire
  - Because we have to try *e* times, in average
- Hence

  è diverso da quello con 1 trasmettitore perché qui trasmettono N

  $$\text{Efficiency} = \frac{t_{trans}}{t_{trans} + ITP + t_{oh} + 2et_{prop}} = \frac{1}{1 + (ITP + t_{oh} + 2et_{prop})/t_{trans}}$$

  sempre compresa tra [0,1]
- To increase efficiency
  - t_{prop} tending to 0: if the propagation delay is zero, colliding nodes will abort immediately without wasting the channel
  - t_{trans} very large: when a station grabs the channel, it will hold it for a very long time; thus the channel will be doing productive work most of the time

Ethernet Efficiency - N equal stations competing

- In the case of 10base-5 Ethernet (10Mbps), measuring times in bytes:
  ITP = 9,6μs = 96 bit = 12 byte; $10Mbs \cdot 9{,}6 \cdot 10^{-6}$
  t_{prop} = 25,6 μs = 256 bit = 32 byte;
  t_{oh} = 8+14+4 = 26 byte;
  P = payload (in bytes)

$$\text{Efficiency} = \frac{1}{1 + (38 + 64e)/P} \approx \frac{1}{1 + 212/P}$$

- If P=1500 byte: efficiency = 87.6%
  - A 10 Mbps classical Ethernet network accessed by many equivalent stations actually provides no more than 8.7 Mbps
- If P=46 byte: efficiency = 17.8%

Ethernet Efficiency - N equal stations competing

- Efficiency goes to 1 as t_{prop} goes to 0, or P goes to infinity
  - Better small networks and/or large frames
  - This is one of the reasons more recent Ethernet standards allow for shorter maximum distances (latest standards are ≤ 35m) and larger frames ("Jumbo frame", up to 8KB)
- Ethernets work best under lightly loaded conditions.
  - Under heavy loads, too much of the network's capacity is wasted by collisions.
- Most Ethernets are used in a conservative way.
  - Have fewer than 200 hosts connected to them which is far fewer than the maximum of 1024.
- Most Ethernets are far shorter than 2500m with a round-trip delay of ~5 µs, far lower than the limit 51.2 µs.

Experience with Ethernet

- (Classic) Ethernets are easy to administer and maintain
    - There are no switches that can fail and no routing and configuration tables that have to be kept up-to-date
        - (Not true anymore in switched Ethernets…)
- It is easy to add a new host to the network
- It is inexpensive: cable is cheap, and only other cost is the network adaptor on each host, which we need anyway
    - (Not true anymore in switched Ethernets…)
- For these reasons, Ethernet has been tremendously successful and competitors (IEEE 802.4 (Token Bus), 802.5 (Token Ring), etc) have disappeared
- Many variants have been developed → modificato l'algoritmo CSMA/CD, che hanno tempi di consegna garantiti
    - Industrial, Avionic, Rail… (deterministic)

Wireless Links

mentre nei cavi riusciamo a "confinare" il segnale, con il wireless si diffonde in tutte le direzioni

- Wireless links transmit electromagnetic signals
  - Radio, microwave, infrared, …
- Wireless links all share the same "wire" (so to speak)
- The challenge is to share it efficiently without unduly interfering with each other
  - Most of this sharing is accomplished by dividing the "wire" along the dimensions of time, frequency and space
  - Exclusive use of a particular frequency in a particular geographic area may be allocated to an individual entity such as a corporation
- These allocations are determined by government agencies
  - The electromagnetic spectrum is a national-wide resource, like shores and air, and licensed at a cost.

Wireless Links

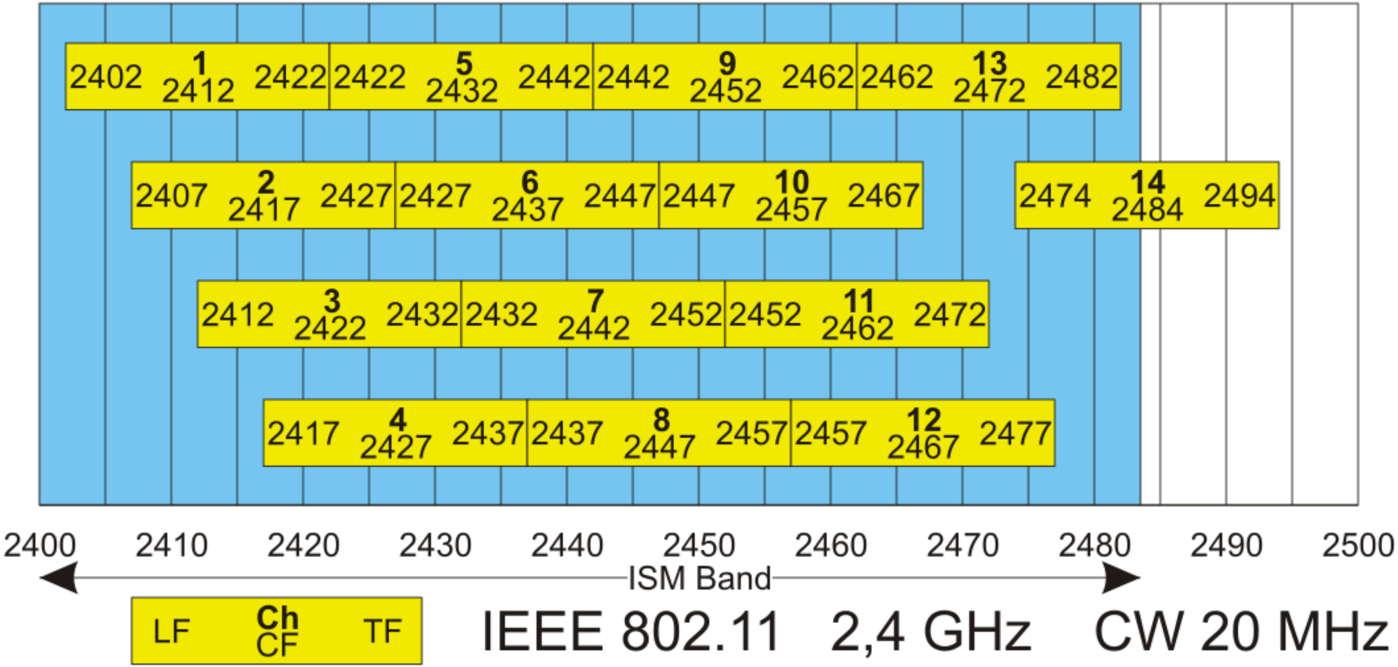
la TV cambierà frequenza perché verrà riassegnata per il 5G

- Specific bands (frequency) ranges are allocated to certain uses.
  - Some bands are reserved for government use
  - Other bands are reserved for uses such as AM radio, FM radio, televisions, satellite communications, and cell phones
- Specific frequencies within these bands are then allocated to individual organizations for use within certain geographical areas
  - e.g. point-to-point radio links
- Finally, there are several frequency bands set aside for "license exempt" usage → BANDE ISM, si possono utilizzare senza licenza (es. 433KHz per i telecomandi, 2.4 GHz, 5 GHz ...) ma hanno delle regole
  - Bands in which a license is not needed
  - ISM band: "Industrial, Scientific, Medical"

ISM 2.4 GHz band

(2400 - 2480) MHz

↳ suddivisa in 14 canali (da 20 MHz ciascuno)



Wireless Links

REGOLE

- Devices that use license-exempt frequencies are still subject to certain restrictions
- First: a limit on transmission power (e.g. 100mW on 2.4 GHz), to limit the range of signal, making it less likely to interfere with another signal
  - For example, a cordless phone might have a range of about 30-40 m.
- Second restriction: require the use of *Spread Spectrum* technique

  ↳ DISTRIBUISCO SU tutto il canale
  - Idea is to spread the signal over a wider frequency band, so as to minimize the impact of interference from other devices
  - Originally designed for military use
    - (Look for Hedy Lamarr's work)

↳ queste tecniche sono state inventate da questa attrice →
(FREQUENCY HOPPING), per non farsi beccare dai nazisti, al massimo loro beccavano un canale ma pochi secondi dopo c'era un salto di canale (banda) e loro (nazisti) non potevano sapere quale sarebbe stato il canale successivo visto che la sequenza di Hopping (ovvero l'ordine dei canali a cui passerò) è segreta.

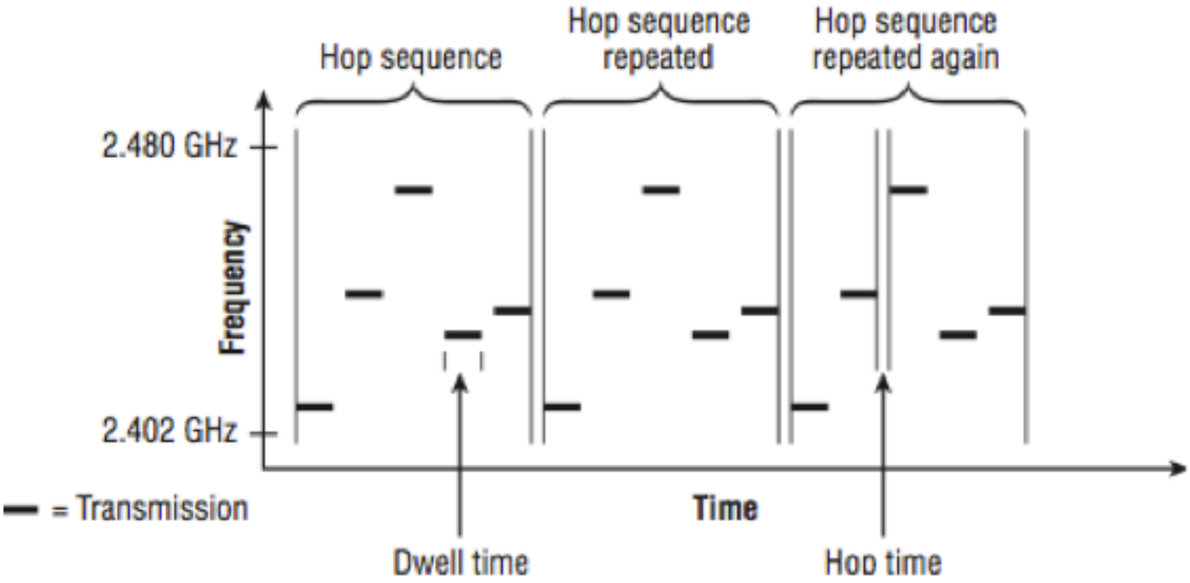
Wireless Links

→ durante la trasmissione SALTELLO da un canale all'altro in base ad una sequenza pseudocasuale → FREQUENCY HOPPING (succede anche per la radio)

→ usato nel BLUETHOOTH

- **Frequency hopping spread spectrum** → è poco efficiente
    - Transmitting signal over a "random" sequence of frequencies
    - First transmitting at one frequency, then a second, then a third…
    - The sequence of frequencies is not truly random, instead computed algorithmically by a pseudorandom number generator
    - The receiver uses the same algorithm as the sender, initialises it with the same seed, and is able to hop frequencies in sync with the transmitter to correctly receive the frame

Wireless Links



Wireless Links

usato nel WIFI

si trasmette lo XOR della mia sequenza con una sequenza random

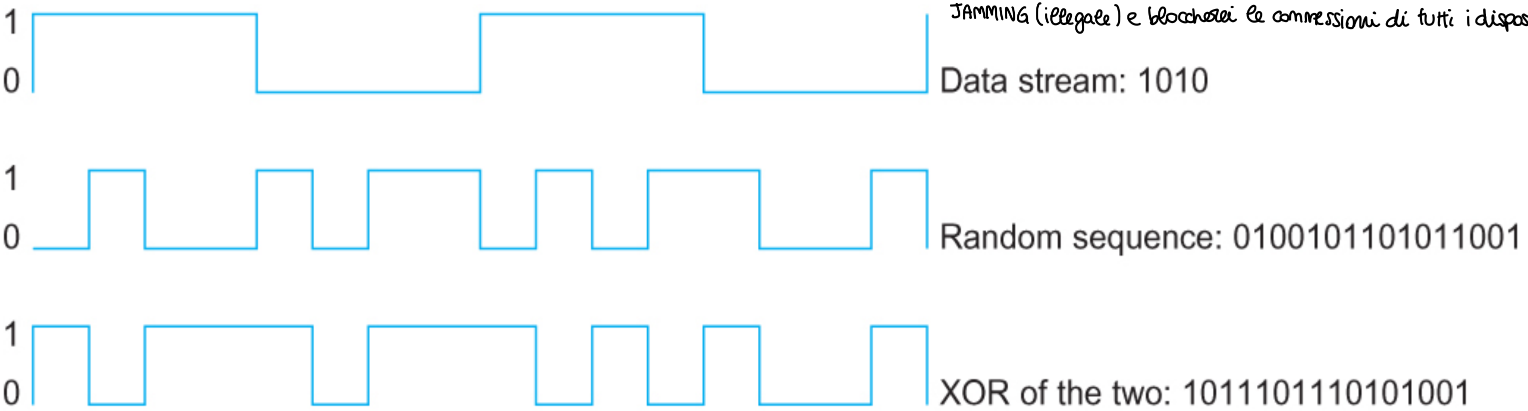
- Direct sequence spread spectrum
  - Represents each bit in the frame by multiple bits in the transmitted signal.
  - For each bit the sender wants to transmit, it actually sends the exclusive OR of that bit and n random bits, called **chipping sequence**
  - The sequence of random bits is generated by a pseudorandom number generator known to both the sender and the receiver; thus in order to recover the original data bits the receiver needs only to XOR the received sequence with the chipping sequence again
  - The transmitted values, known as an **n-bit chipping code**, spread the signal across a frequency band that is n times wider

più rendo "complessa" l'onda più frequenze sono necessarie per trasmetterla → così distribuisci su più frequenze

Wireless Links

Le tecniche HOPPING e DSS servono per redistribuire meglio il segnale piuttosto che garantire la segretezza.

→ se voglio "sparare" in tutte le frequenze a caso faccio del JAMMING (illegale) e bloccherei le connessioni di tutti i dispositivi



il RX fa poi la XOR tra quello che riceve e la sequenza random di trasmissione

es.

	DATI		CH. SEQ.	
TX :	1111	⊕	0100	= 1011
RX :	1011	⊕	0100	= 1111

Example 4-bit chipping sequence

Wireless Links

- Wireless technologies differ in a variety of dimensions
  - How much bandwidth they provide
  - How far apart the communication nodes can be
- Four prominent wireless technologies, with different characteristics and applications
  - Wi-Fi (more formally known as 802.11)
  - Bluetooth / ZigBee
  - WiMAX (802.16) → accesso satellitare con antenna
  - 3G/4G/5G cellular wireless

Wireless Links

	Bluetooth (802.15.1)	Wi-Fi (802.11)	Cellular
Typical link length	10 m	100 m	Tens of kilometers
Typical data rate ↳ velocità dei simboli che viaggiano sul canale, poi in realtà va meno	2 Mbps (shared) ↳ è LENTO ma ha RITARDO BASSISSIMO	54 Mbps (shared) ↳ valore "vecchio", ora sono più veloci	Hundreds of kbps (per connection)
Typical use	Link a peripheral to a computer	Link a computer to a wired base	Link a mobile phone to a wired tower
Wired technology analogy	USB	Ethernet	DSL

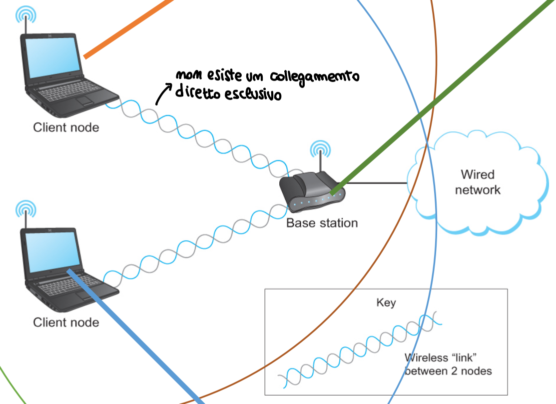
Overview of leading wireless technologies

Wireless Links

→ le Ethernet sono SWITCHATE (ai giorni nostri)
il WIFI è condiviso (non tutti i dispositivi si vedono, solo se sono nei RANGE)
Nelle vecchie Ethernet (coax) era un canale condiviso (e tutti i dispositivi si vedevano)

- Mostly widely used wireless links today are usually **asymmetric**
  - Two end-points are usually different kinds of nodes
  - One end-point usually has no mobility, but has wired connection to the Internet (known as **base station**)
  - The node at the other end of the link is often mobile

se esco dal RANGE VERDE non ricevo i pacchetti dall'Access Point



non esiste un collegamento diretto esclusivo

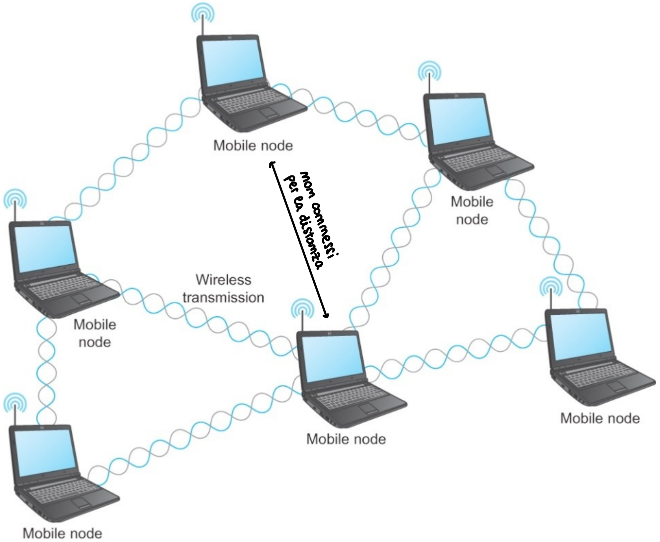
Wireless Links

→ a differenza delle reti cablate, con le reti wireless supporto la MOBILITÀ degli host
es. con cellulare se mi sposto mi si collega in automatico ad un'antenna più vicina

- Wireless communication supports point-to-multipoint communication
  - Communication between non-base (client) nodes can be direct (as in WiFi), or routed via the base station (as in cell phones and Bluetooth)
- Three levels of mobility for clients
  - No mobility: the receiver must be in a fix location to receive a directional transmission from the base station (initial version of WiMAX)
  - Mobility is within the range of a base (Bluetooth)
  - Mobility between bases (Cell phones and Wi-Fi)

Wireless Links

- Mesh or *ad-hoc* network
  - Nodes are peers
  - Messages may be forwarded via a chain of peer nodes
  - Useful when there is no fixed base station, like in IoT, o to reach areas not covered by the base station



A wireless ad-hoc or mesh network

IEEE 802.11

↳ 802 sono per le reti LOCALI

- Also known as **Wi-Fi**
- Like its Ethernet and token ring siblings, 802.11 is designed for local area networks, i.e. in a limited geographical area (homes, office buildings, campuses)
- Primary challenge is to mediate access to a shared communication medium – in this case, signals propagating through space
- 802.11 supports additional features
  - power management
  - security mechanisms

IEEE 802.11

- Original 802.11 standard defined two radio-based physical layer standard
  - One using the frequency hopping over 79 1-MHz-wide frequency bandwidths (used also by Bluetooth)
    → faccio l'HOPPING
    → divido in 79 canali da 1MHz ie 2.4GHz (2400-2480)
  - Second using direct sequence using 11-bit chipping sequence
  - Both standards run in the license-exempt 2.4-GHz band and provide up to 2 Mbps → vecchi
- Then physical layer standard **802.11b** was added
  - Using a variant of direct (DSS) sequence 802.11b provides up to 11 Mbps → ormai obsoleto

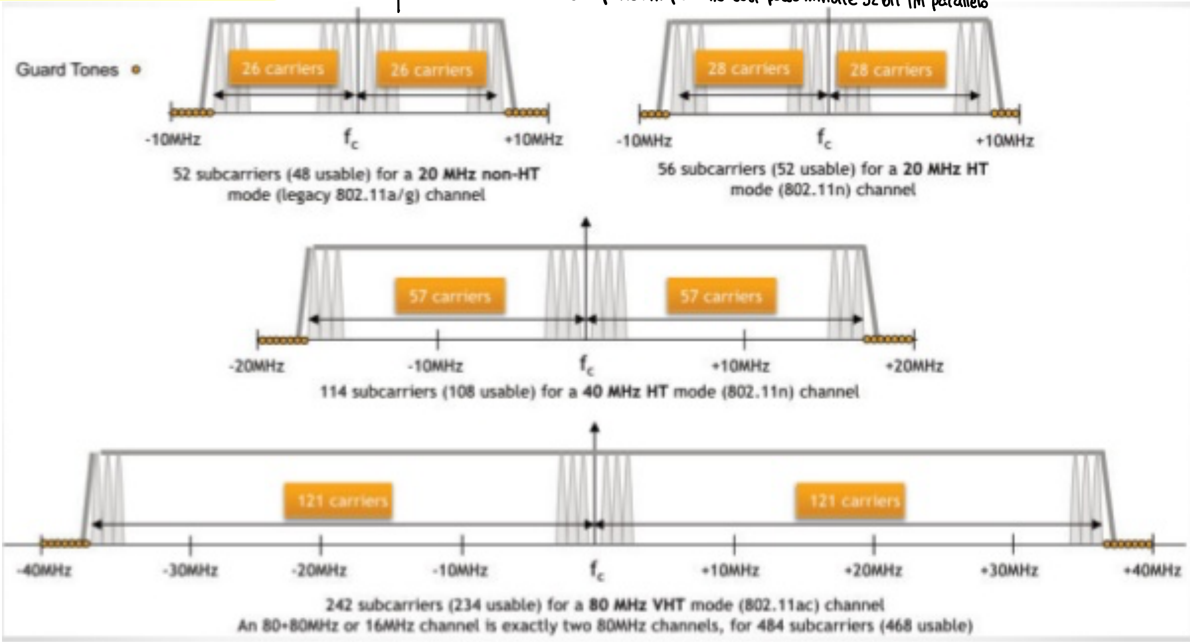
IEEE 802.11

- Then came 802.11a which delivers up to 54 Mbps using OFDM
    - 802.11a runs on license-exempt 5-GHz band
    - Actual speed available is about 20 Mbps
- Then, 802.11g which is backward compatible with 802.11b
    - Uses 2.4 GHz band, OFDM and delivers up to 54 Mbps
- Then, 802.11n
    - Uses 2.4 and 5,4 GHz bands, OFDM and delivers up to 300 Mbps
    - Allows for MIMO - multiple in, multiple out (several antennas in parallel)
- Then, 802.11ac
    - Uses 5,4 GHz band, delivers 1300 Mbps
    - Allows for MIMO - multiple in, multiple out antennas
- etc…
- Notice that actual bitrate can vary a lot; it depends on the signal quality (i.e., SNR), coding rate, channel width, etc.
    - E.g., 802.11n can range from 6.5 Mbps to 600 Mbps

IEEE 802.11 - OFDM

Orthogonal Frequency-Division Multiplexing is a frequency-division multiplexing (FDM) scheme, where a large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams or channels

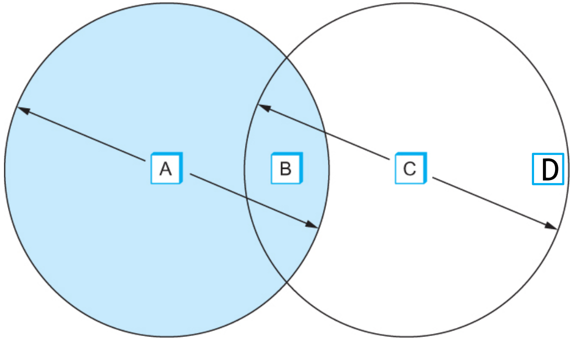
Suddivido in 26 sottoportanti per lato così posso inviare (48) 52 bit in parallelo



IEEE 802.11 - Collision Avoidance

- In wireless networks, Media Access is more problematic
- Consider the situation in the following figure where each of four nodes is able to send and receive signals that reach just the nodes to its immediate left and right
  - For example, B can exchange frames with A and C, but it cannot reach D
  - C can reach B and D but not A

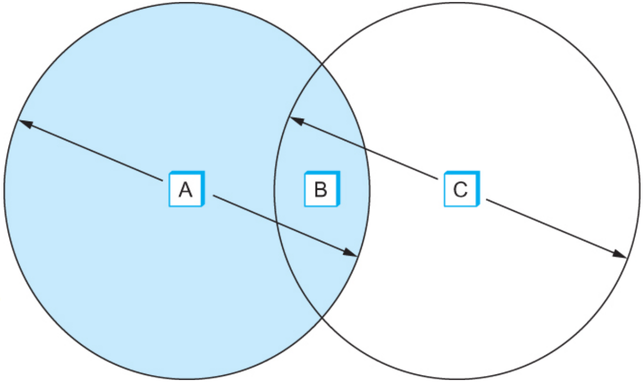
es. con
4 STAZIONI



Example of a wireless network

IEEE 802.11 - Collision Avoidance

- Suppose both A and C want to communicate with B and so they each send it a frame. → a differenza della Ethernet, non posso trasmettere e ascoltare se ci sono trasmissioni (perché fuori dalla mia portata)
  - A and C are unaware of each other since their signals do not carry that far
  - These two frames collide with each other at B
- But unlike an Ethernet, neither A nor C is aware of this collision
  - A and C are said to be **hidden nodes** (NODI NASCOSTI) with respect to each other

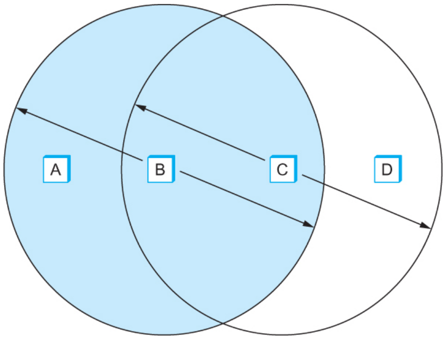


The "Hidden Node" Problem. Although A and C are hidden from each other, their signals can collide at B. (B's reach is not shown.)

→ non per forza avviene quando A e C iniziano a trasmettere contemporaneamente (come nell'Ethernet) magari uno dei due stava già trasmettendo ma è fuori dalla portata dell'altro

IEEE 802.11 - Collision Avoidance

- Another problem called **exposed node** occurs
  - Suppose B is sending to A. Node C is aware of this communication because it hears B's transmission.
  - It would be a mistake for C to conclude that it cannot transmit to anyone just because it can hear B's transmission.
  - Suppose C wants to transmit to node D.
  - This is not a problem since C's transmission to D will not interfere with A's ability to receive from B.



A e C non si vedono

Exposed Node Problem. Although B and C are exposed to each other's signals, there is no interference if B transmits to A while C transmits to D. (A and D's reaches are not shown.)

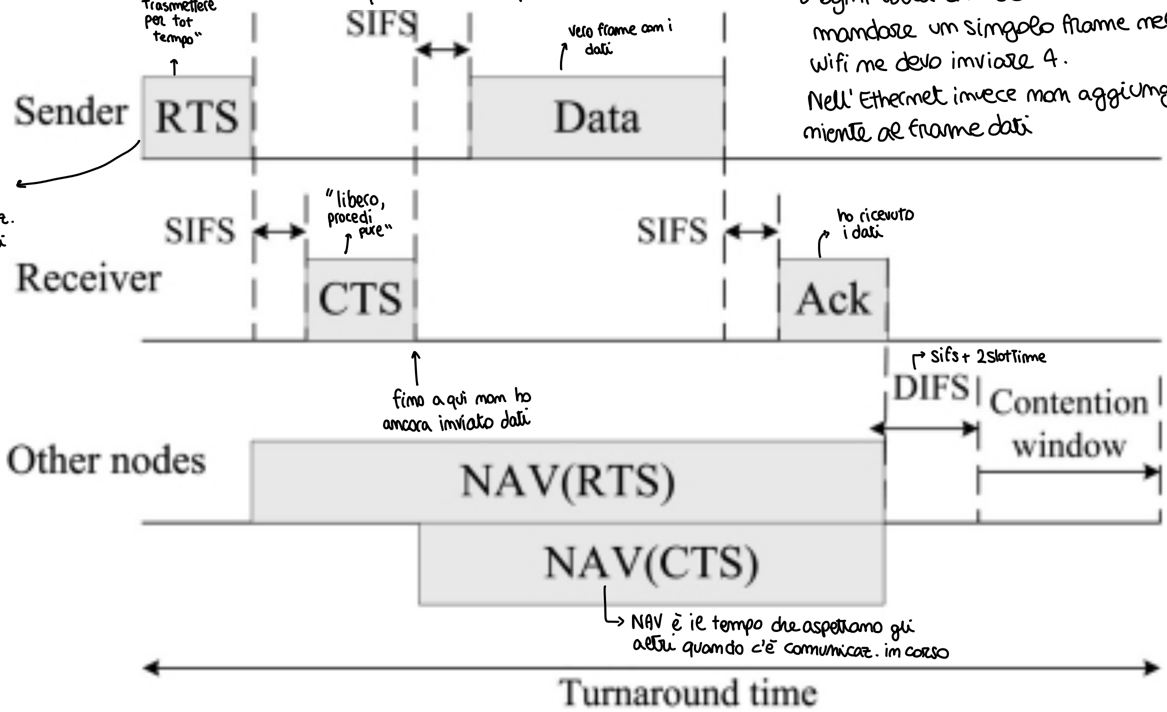
IEEE 802.11 - Collision Avoidance → per il WIFI, per il BLUETOOTH è a turni

- 802.11 addresses these problems with an algorithm called **Carrier Sense Multiple Access with Collision Avoidance** (CSMA/CA, or MACA).
  ↳ evita le collisioni
  ↳ riadattato da CSMA-CD, qui non abbiamo l'intera visibilità della rete
- Key Idea:
  - Sender and receiver exchange control frames with each other before the sender actually transmits any data. → verifico se posso trasmettere con FRAME che non contengono dati: RTS e CTS
  - This exchange informs all nearby nodes that a transmission is about to begin, so that they keep silent for the required time
  - Sender transmits a **Request to Send (RTS)** frame to the receiver.
    - The RTS frame includes a field, called DURATION, that indicates how long the sender wants to hold the medium
    - Time of the whole transmission, till the end of ACK
  - Receiver replies with a **Clear to Send (CTS)** frame
    - This frame echoes DURATION length field back to the sender

IEEE 802.11 - Collision Avoidance

ovviamente ogni frame (anche quelli di controllo) hanno ind. sorgente e destinatario

→ ogni volta che devo mandare un singolo frame nel wifi ne devo inviare 4.
Nell'Ethernet invece non aggiungo niente al frame dati



"voglio trasmettere per tot tempo"

short interframe space (per dare tempo all'elettronica)

vero frame con i dati

Contengono la durata di quanto durerà la comunicaz. Arriverà a tutti i nodi nel raggio

"libero, procedi pure"

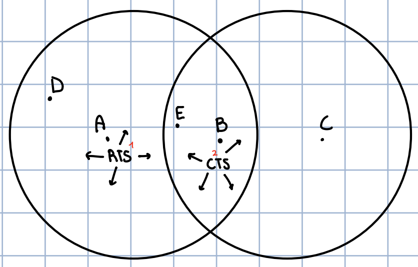
ho ricevuto i dati

sifs + 2slotTime

fino a qui non ho ancora inviato dati

NAV è il tempo che aspettano gli altri quando c'è comunicaz. in corso

CTS e RTS hanno indirizzo specifico ma tutti ascoltano il canale perché è condiviso



A vuole trasmettere a B

D non vede B

CASI: - A manda un RTS a B e D sente RTS ma non il CTS (visto che è fuori dalla portata di B)

=> D non deve mutarsi, E (che sente sia RTS che CTS) si muta anche lui, in generale si mutano i nodi che sentono CTS (non per loro)

- A manda un RTS a B e C riceve un CTS (ma non riceve il RTS di A perché fuori dalla sua portata)

=> C si muta e aspetta NAV secondi

- A e C (che non si vedono) inviano contemporaneamente un RTS a B e B che si vede arrivare due RTS capisce che c'è COLLISIONE perciò non risponde → Scadono i SIFS di A e C che riproveranno a trasmettere dopo ALG. BACKOFF.

=> NON POSSONO AVVENIRE COLLISIONI SUI DATI. SOLO SU RTS e CTS, perché una volta che si iniziano a trasmettere gli altri si mutano. Se per sfiga dovesse intromettere un nodo, non arriva l'ACK.

IEEE 802.11 - Collision Avoidance

- Any node that sees the CTS frame knows that it is close to the receiver, therefore cannot transmit for the period of time it takes to send a frame of the specified length
  - This time is called **Network Allocation Vector (NAV)**
  - This solve the hidden node problem → ovvero che io trasmettitore sono ignaro se altri fuori dalla mia portata stanno trasmettendo alla stazione
- Any node that sees the RTS frame but not the CTS frame is not close enough to the receiver to interfere with it, and so is free to transmit
  - This solves the exposed node problem

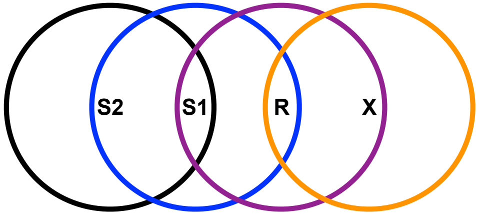
↳ se ricevi RTS e non CTS sei un nodo esposto (ovvero sei esposto alla loro comunicaz. senza vedere il ricevente)

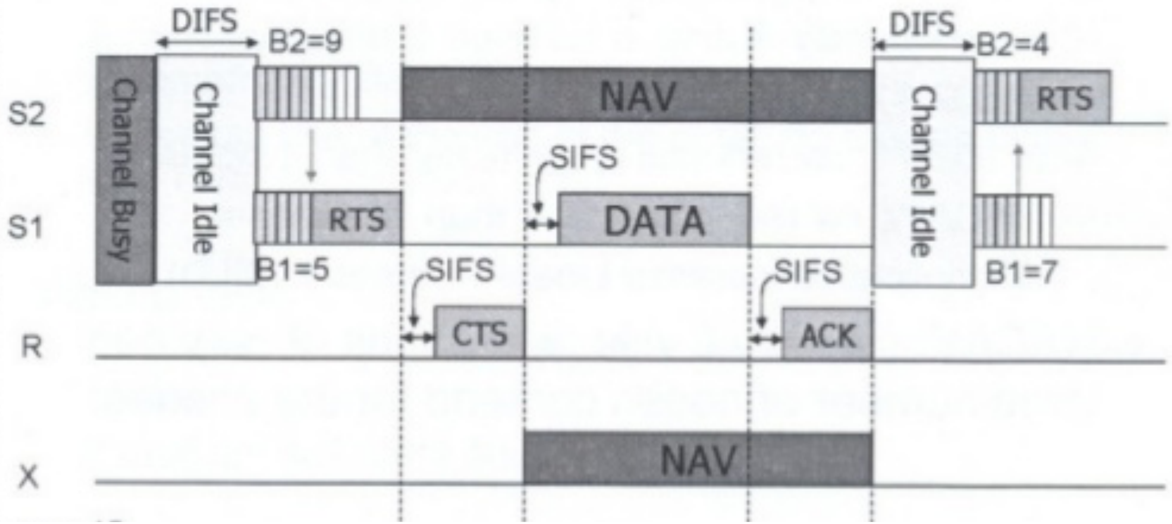
IEEE 802.11 - Collision Avoidance

- If two or more nodes detect an idle link and try to transmit an RTS frame at the same time, their RTS frame will collide with each other (hidden node)
  - But 802.11 does not support *collision detection*: the sender cannot sense the “line” during transmission, because a radio works either in transmission or in reception
- So the senders realize the collision has happened when they do not receive the CTS frame after a period of time
- In this case, they each wait a random amount of time before trying again.
- The amount of time a given node delays is defined by the same *exponential backoff algorithm* used on the Ethernet.
- Using ACK: Receiver sends an ACK to the sender after successfully receiving a frame
  - All nodes must wait for this ACK before trying to transmit

IEEE 802.11 - Collision Avoidance

Example of Distributed Coordination with 4 stations: S1, S2 try to transmit, R is the receiver of S1, X is another station close to R but not to S1 and S2

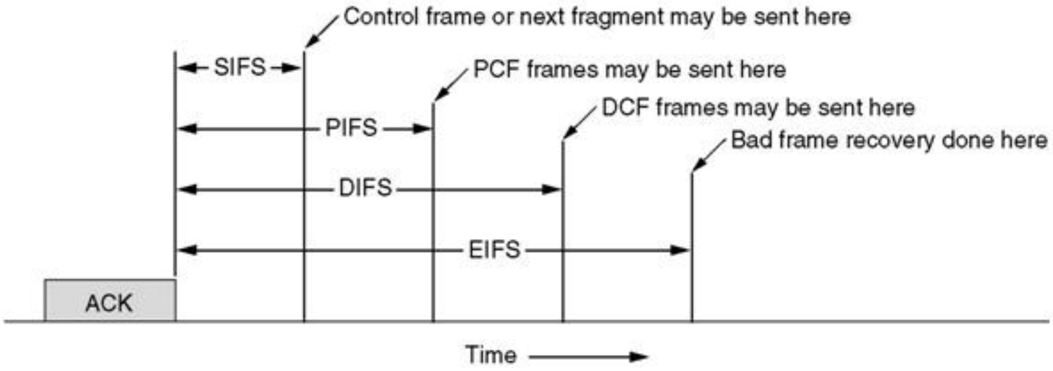




IEEE 802.11 - Collision Avoidance

- Intervals are defined in the various standards; it is always SIFS < PIFS < DIFS

FISSI
- **Slot time**: minimum interval; used in exponential backoff
- **SIFS: Short Inter Frame Space**: time used to process and answer a frame within the same transaction
- **PIFS: Point Control Function Interframe Space**: time that the Access Point has to wait (and sense the wireless medium) before sending a RTS. → SIFS + slotTime ⇒ gli access Point hanno la precedenza → PRIORITÀ MAGGIORE
- **DIFS: Distributed Control Function Interframe Space**: time that a station has to wait, and sense the wireless medium, before sending a RTS. → SIFS + 2 slotTime



SIFS < PIFS < DIFS
PIFS = SIFS + Slot time
DIFS = SIFS + 2*Slot time

IEEE 802.11 - Collision Avoidance

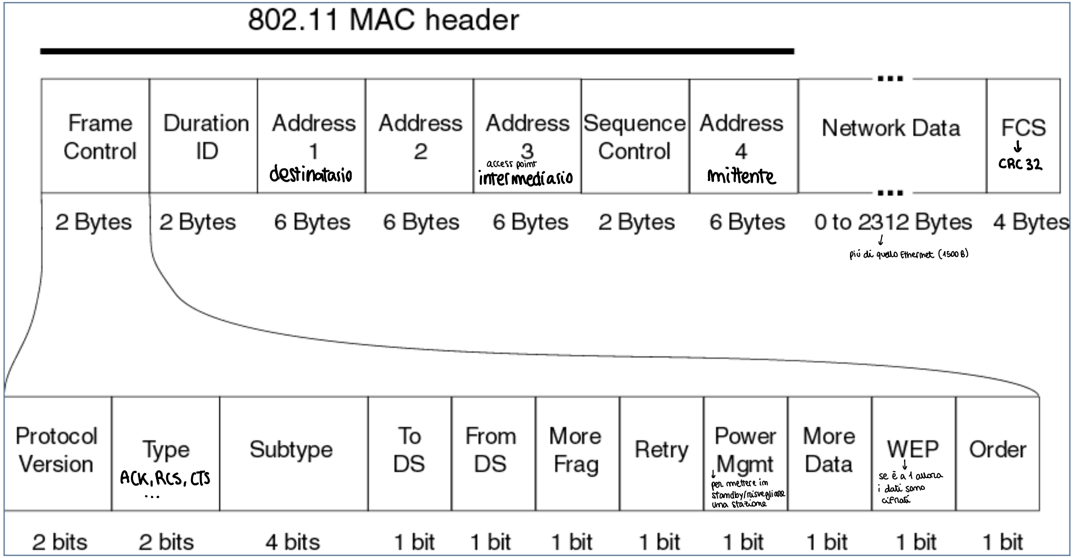
Standard	Slot time	SIFS	PIFS	DIFS
IEEE 802.11-1997 (FHSS)	50	28	78	128
IEEE 802.11-1997 (DSSS)	20	10	30	50
IEEE 802.11b	20	10	30	50
IEEE 802.11a	9	16	25	34
IEEE 802.11g	9 or 20	10	19 or 30	28 or 50
IEEE 802.11n (2.4 GHz)	9 or 20	10	19 or 30	28 or 50
IEEE 802.11n (5 GHz)	9	16	25	34
IEEE 802.11ac	9	16	25	34

All times are in μs

IEEE 802.11 - Frame Format

trasmesso dagli Access Point di continuo per rendere visibile il proprio SSID

- Many different frames: DATA, RTS, CTS, ACK or BEACON (used by the scanning algorithm) (in Ethernet there was just one)
- Can be identified by looking at their first two bytes (bits Type and Subtype of Frame Control)
- DATA frame:



IEEE 802.11 - Frame Format

- **Frame Control field:** 16 bits
  - Contains three subfields (of interest)
    - 6 bit *Type* field: indicates which kind of frame is
    - Two bits called *ToDS* and *FromDS*
- **Duration / ID:** contains either the remaining duration of the transaction (in μs) for the CSMA/CA algorithm (the NAV is set to this value), or the ID of the network (in *Beacon* frames)
- **Source and Destinations addresses:** usual 48 bit Ethernet addresses
  - Same structure and assignment policy
- Other addresses are used in the distribution system
- **Sequence control:** used in frag / defrag of large frames
- **Data:** up to 2312 bytes
- **FCS:** CRC-32. 32 bit

- So the header is 30 bytes, and the FCS is 4 bytes

IEEE 802.11 - Frame Format

- Other frames (ACK, RTS, CTS, …) have fixed size
- They are recognised by looking at the first two bytes
- Hence, transmission of a frame has always an overhead of 30+4+14+20+14 = 82 byte (plus the intervals)

ACK

bytes	2	2	6	4
	Frame Control	Duration	Receiver Address	CRC

=14 byte

RTS

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

=20 byte

CTS

bytes	2	2	6	4
	Frame Control	Duration	Receiver Address	CRC

=14 byte

IEEE 802.11 - Efficiency of transmission

- As for CSMA/CD, CSMA/CA is difficult to model precisely

velocità a cui vengono trasmessi i bit in codifica poi nella trasmissione reale consumo banda per mandare i frame in più

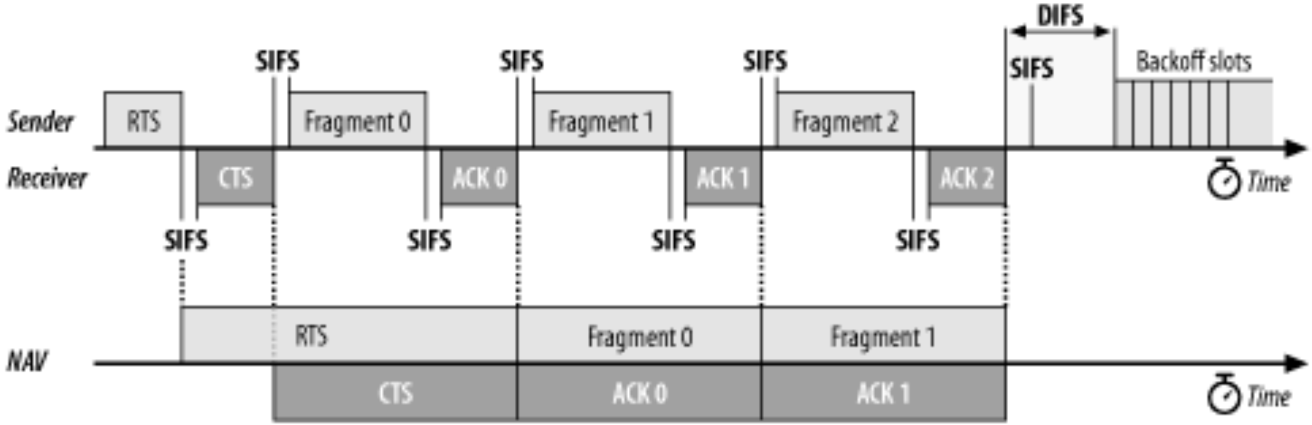
- we see only an example for one transmission in 802.11g, at 54 Mbps. In this situation, CSMA/CA adds (at least):
  - 1 DIFS+3 SIFS = 4 SIFS+2 Slot time = 4*10+ 2*9 = 58 µs, which are equivalent to 58µs * 54 Mbps = 3132 bit = 391,5 byte
  - Frame header, CRCs and other frames: 82 bytes
- In total the overhead is 473,5 byte, for each transaction.

per trasmettere 1500 byte di dati ne devo trasmettere 1973,5 a causa delle regole

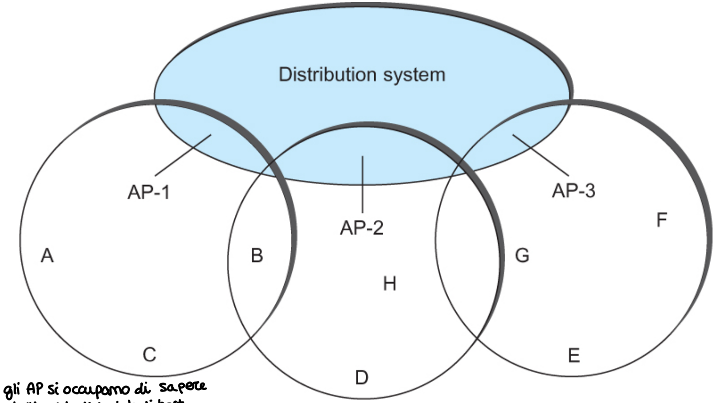
- If the payload is 1500 byte, the efficiency is no more than 1500/(1500+473,5) = 76%
  - the net bandwidth is ≤ 41Mbps, not 54Mbps
  - Compare with Ethernet, whose efficiency was up to 97%

IEEE 802.11 - Frame Fragmentation

- A data unit can be sent in more than one DATA segment, within the same transaction → se ho un frame di più di 2300 byte posso frammentare e inviare aspettando più ACK, max. 3-4 frammenti a comunicazione
  ↳ più PERICOLOSO, se un singolo frammento si rovina si perde tutto
  ↳ uno per ogni segmento
- Each segment is called *Fragment*. All fragments but the last one have the bit *MoreFrag* in the header set to 1. Each fragment is acknowledged on its own.
- The SIFS delay between an ACK and the successive fragment forbids the beginning of a new contention window, until the last fragment is sent (and acknowledged)



IEEE 802.11 - Distribution



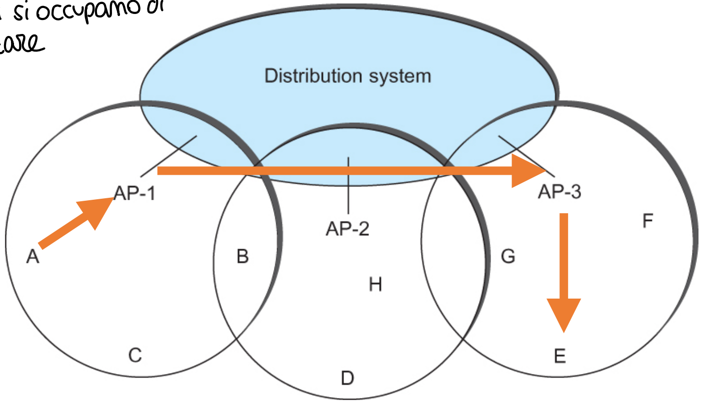
- DATA frame contains four addresses
- How these addresses are interpreted depends on the settings of the ToDS and FromDS bits in the frame's Control field
- This is to account for the possibility that the frame had to be forwarded across a *distribution system*, a background wired network infrastructure connecting the APs (typically an Ethernet LAN)

  gli AP si occupano di sapere tutti gli indirizzi degli host

  - This would mean that the original sender is not necessarily the same as the most recent transmitting node
  - Same is true for the destination address
- Simplest case: When one node is sending directly to another node
  - both the DS bits are 0, Addr1 identifies the target node (ex. C), and Addr2 identifies the source node (ex. A)

IEEE 802.11 - Distribution

→ invio sempre agli AP e loro poi si occupano di reindirizzare



- Most complex case: Both DS bits are set to 1
  - Indicates that the message went from a wireless node onto the distribution system and then from the distribution system to another wireless node
  - Addr1 identifies the ultimate destination
  - Addr2 identifies the immediate sender (the one that forwarded the frame from the distribution system to the ultimate destination)
  - Addr3 identifies the intermediate destination (the one that accepted the frame from a wireless node and forwarded across the distribution system)
  - Addr4 identifies the original source
- Example: Addr1: E, Addr2: AP-3, Addr3: AP-1, Addr4: A

Bluetooth - IEEE 802.15

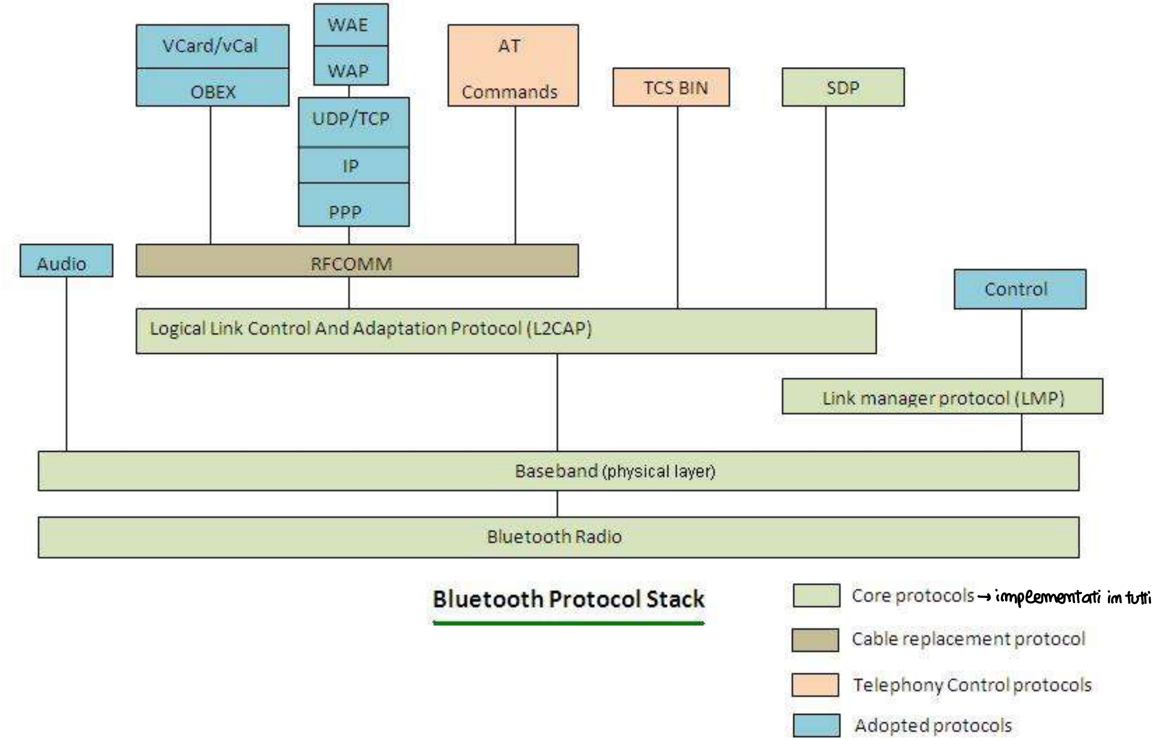
- Bluetooth is specified by an industry consortium called the *Bluetooth Special Interest Group*, mainly Ericsson
- Named after Harald "Blötand" Gormsson, viking king unifier of Denmark and Norway (958-986)
- Used for very short range communication between mobile phones, PDAs, notebook computers and other personal or peripheral devices
  - Operates in the license-exempt band at 2.45 GHz, with FHSS
    stessa banda del wifi
    suddivide in 74 canali e fa hopping
    Usa il TIME DIVISION (al posto di CSMA-CA)
  - Range of 10-50 m, with "low" power consumption (up to 1W)
    solo le prime versioni, ora consumano sui 100 mW
  - Communication devices typically belong to one individual or group
    - Sometimes categorized as *Personal Area Network* (PAN)
      copre una stanza
- Versions 1.1 and 1.2 had raw speed of 1Mbps, net speeds up to 723 kbps
  VELOCITÀ NETTA
- Version 2.0 provides raw speeds up to 3 Mbps (net speed up to 2.1 Mbps)

Bluetooth - IEEE 802.15

→ non è un protocollo, è una suite di protocolli.
Sono stati fatti più stack (profili) a seconda del contesto.

- It specifies an entire suite of protocols, going beyond the link layer to define application protocols, which it calls *profiles*, for a range of applications
  - There is a profile for synchronizing a PDA with personal computer
  - Another profile gives a mobile computer access to a network, via a simulated modem (RFCOMM)
  - Another for exchanging vCards …
- Types of connections:
  - Synchronous Connection-oriented (SCO): symmetrical, circuit switched, point to point. Used for real time data
  - Asynchronous Connectionless Link (ACL): packet switched, point-to-multipoint, master polls. Used for data transfers

Bluetooth - IEEE 802.15



Bluetooth Piconet

→ BANDA MINIMA e RITARDO MINIMO sono garantiti

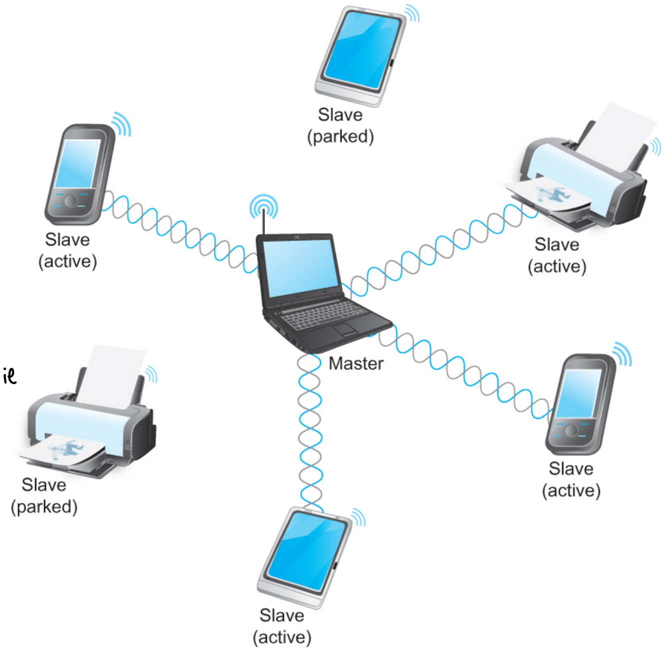
- The basic Bluetooth network configuration is called a **piconet**

  rete piccola che creo

  - Consists of a *master* device and up to seven *slave* devices
- Any communication is between the master and a slave, in a defined order (Time Division Multiplexing)

  ↳ non c'è CSMA-CA, c'è TIME DIVISION, uno può parlare solo quando è il suo turno. Il master decide l'ordine

- The slaves do not communicate directly with each other
- Up to other 8-slave can be parked: set to an inactive, low-power state



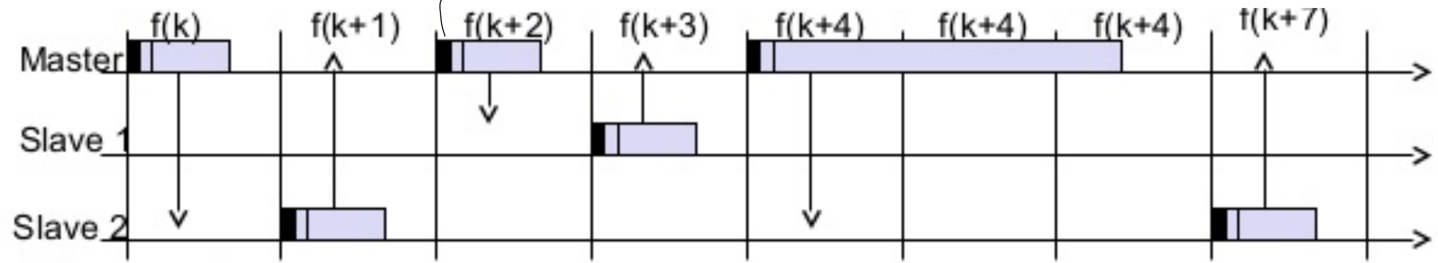
Bluetooth Piconet MAC

negli slot PARI parla un MASTER (trasmette)

negli slot DISPARI possono parlare gli SLAVE → si possono inviare o 1 o 3 o 5 frame consecutivi

- Each node has a Bluetooth Device Address (BD_ADDR)
- The master node determines the sequence of frequency hops

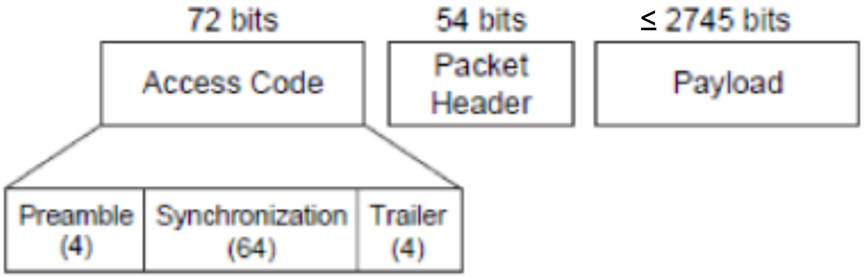
→ tempo dell'elettronica per cambiare canale



- Each slot takes 625 μs and contains a frame (see next slide)
- Bluetooth uses FHSS over all 1-MHz 79 channels of 2.4 GHz ISM band, with hopping time of 625μs, so that each slot is on a different frequency (and the radio needs some time to change channel)

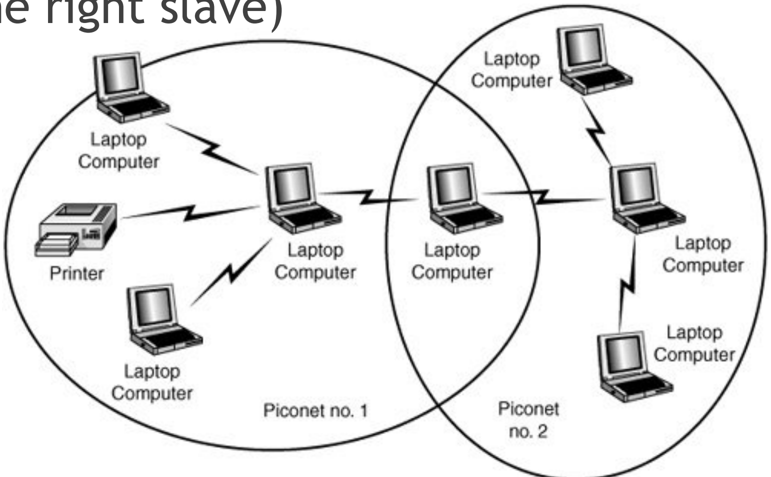
Bluetooth frame (called *packet*)

- Packet format:
  - Access code: synchronisation, derived from master when piconet active
  - Packet header (for ACL): 1/3-FEC, MAC address, link type, ARQ/SEQ, checksum (HEC)
  - Payload is up to 483 bit for one slot, up to 1124 bit for three slots, and up to 2745 bit for five slots



Bluetooth scatternets

- Several piconets can be joined to form a **scatternet**
  - Consists of two or more piconets sharing at least one node
  - Shared node can act as a bridge between the two nets: receives a frame from one master and sends to another (possibly to be forwarded to the right slave)
  - Masters of each piconet must keep track of node positions, to forward frames to the correct intermediating node
- Very useful for building ad hoc networks (e.g. in IoT)



Bluetooth Low Energy

- Integrated in Bluetooth 4.0 (2009)
- Intended to use reduced power w.r.t. “classic BT”: 0.01-0.5W, instead of 1W (with shorter range)
- PHY: same band of Classic BT (2.4 GHz) in FHSS, but with 40 channels of 2MHz each
- Raw speed: 2Mbps (effective: up to 1.37 Mbps)
- Much faster recover from non-connected state
- Many new applications (e.g. healthcare, sport, sensors, contact tracing, …)

Summary

- We introduced the many and varied type of links that are used to connect users to existing networks, and to construct large networks from scratch.
- We looked at the five key issues that must be addressed so that two or more nodes connected by some medium can exchange messages with each other
  - Encoding
  - Framing
  - Error Detecting
  - Reliability
  - Multiple Access Links
    - Ethernet
    - Wireless 802.11, Bluetooth