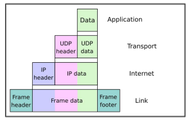


Physical Layer (PHY by convention **)**

Governs **analog** signals.

Usually implemented as an **integrated circuit**. Connects a **MAC** device to a **physical medium** such as copper or optical fibre - and is an **interface** between **digital** and **analog** layers.

Modulator-Demodulators (**Modems**) convert **between digital and analogue** signals.

802.11 refers to its Layer 2 frames as **MAC frames.**

Layer 1 (PHY : raw information transfer between 2 interfaces, unaware of software ports)

IEEE 802.3 | Ethernet **packet** and **frame** structure (**jumbo frames** are different); least-significant **bit** of the most-significant **byte** is transmitted first.

- 72--1530 **byte Ethernet Packet** (with **Jumbo Frames**, commonly 9030, up to 9224)
  - - **Layer 2** (Link : controlled transfer between 2 interfaces, unaware of software ports)
  - - - 7 **byte** Preamble
  - - - 1 **byte** Start Frame Delimiter (**SFD**)
  - - - 64--1522 **byte 802.3ac Ethernet Frame** (with **Jumbo Frames**, commonly 9022, up to 2216)
  - - - - 6 **byte MAC destination**
  - - - - 6 **byte MAC source**
  - - - - (optional 4 **byte 802.1Q VLAN tag**)
  - - - - 2 **byte Ethertype** (Ethernet II) or **length** (IEEE 802.3)
  - - - - 46-1500 **byte PAYLOAD** (Ethernet's Maximum Transmission Unit / **MTU**, with **Jumbo Frames** commonly 9000)
  - - - - 4 **byte** Frame Cyclic Redundancy Check (**CRC**)
- 12 **byte** Interpacket Gap (**IPG**), totalling 84-1542 **byte** on the wire (with **Jumbo Frames**, commonly 9042, up to 9236)

Layer 3 (Network : controlled transfer between >2 interfaces, unaware of software ports)

Internet Protocol packet structure

20--65536 **byte IPv4 Packet**, minimum MTU 576 **byte**
- 20--60 **byte IPv4 Packet Header**
  - - 0.5 **byte** Version
  - - 0.5 **byte** Internet Header Length (**IHL**)
  - - 0.75 **byte** Differentiated Services Code Point (**DSCP**)
  - - 0.25 **byte** Explicit Congestion Notification (**ECN**)
  - - 2 **byte** Total Length
  - - 2 **byte** Identification (of fragment in a datagram)
  - - 0.375 **byte** flags (Reserved, Don't Fragment / **DF**, More Fragments / **MF**)
  - - 1.625 **byte** Fragment Offset (of fragment in a datagram)
  - - 1 **byte** Time to Live (**TTL**)
  - - 1 **byte** Protocol
  - - 2 **byte** Header Checksum
  - - 4 **byte** Source Address
  - - 4 **byte** Destination Address
  - - 0--40 **byte** (padded to 4 **byte** chunks) Options
- 0--65516 **byte IPv4 Packet PAYLOAD**, 516 to fit **minimum MTU**, (1440--1480 to remain unfragmented within a 1500 MTU)

40-65,535 **IPv6 Packet**, minimum MTU 1280 **byte**
- 40 **byte IPv6 Packet Fixed Header** : no checksum, depends on Layer 2 for error detection; packets are never fragmented, and depend on Path MTU Discovery / **PMTUD**, but as an EXCEPTION : there is the Fragment extension header
  - - 0.5 **byte** Version
  - - 1 **byte** Traffic Class
  - - 0.75 **byte** Differentiated Services (**DS**)
  - - 0.25 **byte** Explicit Congestion Notification (**ECN**)
  - - 2.5 **byte** Flow Label
  - - 2 **byte** Payload Length
  - - 1 **byte** Next Header (maps to IPv4 Protocol field; also indicates the next Extension Header)
  - - 1 **byte** Hop Limit (maps to IPv4 Time to Live field)
  - - 16 **byte** Source Address
  - - 16 **byte** Destination Address
  - a chain of **IPv6 Extension Headers**
- 0-65,495 **IPv6 Packet PAYLOAD**, 1240 to fit **minimum MTU** without extension headers, (up to **4 gibibyte - 1 byte** with Jumbo Payload extension header, and a redesign of transport protocols)

Layer 4 (Transport : controlled transfer between >2 interfaces, aware of software ports)

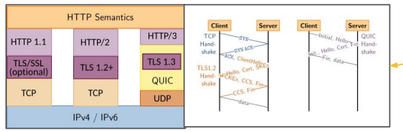
Transmission Control Protocol (**TCP**) - connection-oriented, **TLS** must tunnel over **TCP** with desynchronisation overheads; must be modified to fit IPv6 Jumbo Payloads

- 20-MSS **byte TCP Segment**, where Maximum Segment Size (**MSS**) can be set in header options
  - - 20-60 **byte TCP Segment Header**
  - - - 2 **byte** Source Port
  - - - 2 **byte** Destination Port
  - - - 4 **byte** Sequence Number : depends on SYN flag
  - - - 4 **byte** Acknowledgement Number : depends on ACK flag
  - - - 0.5 **byte** Data Offset (**DOffset**) size of the TCP header in **32-bit words** (5-15) allowing (0-10) words for options
  - - - 0.5 **byte** Reserved (**Rsrvd**)
  - - - 1 **byte** Flags (**CWR, ECE, URG, ACK, PSH, RST, SYN, FIN**)
  - - - 2 **byte** Window
  - - - 2 **byte** Checksum
  - - - 2 **byte** Urgent Pointer
  - - - 0-40 **byte** (in chunks of **32-bit words**), size(Options) == (DOffset - 5) * 32
  - - 0--(MSS-20) **byte TCP Segment DATA**

User Datagram Protocol (**UDP**) - connection-less; must be modified to fit IPv6 Jumbo Payloads

- 8--(65,535-8-(IPv4:20, IPv6:40)) **byte UDP Datagram**
  - - 2 **byte** Source Port
  - - 2 **byte** Destination Port
  - - 2 **byte** Length
  - - 2 **byte** Checksum
  - - **DATA**

QUIC (not at acronym) - connection-oriented, tunnels over **UDP**, integrates Transport Layer Security / **TLS** with less overhead; must be modified to fit IPv6 Jumbo Payloads



Layer 5 (Application : domain-specific transfer between >2 interfaces, aware of software ports)

HTTP/3

Secure Shell

IETF / Internet Engineering Task Force

6LoWPAN / IPv6 over Low-Power Wireless Personal Area Networks, using **IEEE 802.15.4** (Supports the **Matter** (standard) over **Thread** (protocol) framework.)

ITU / International Telecommunication Union

ITU-T Y.4400, **LoRa** / Long Range, radio frequency, 863-928 MHz, 10-330 km, 0.3-27 kbps

ITU-T G.9959, **Z-Wave** lower level protocol, 9.6-40 kbps, 1mW, mesh networking, gateways have **IP** so it may interoperate with **Matter**; **Z-wave LR** has longer range

ITU-T G.hn, Gigabit Home Networking

3GPP / Third Generation Partnership Project

LTE-M / LTE-MTC, Long-Term Evolution Machine Type Communication, cellular, 1.4-20 MHz, 1-7 mbps

IEEE / Institute of Electrical and Electronics Engineers

IEEE 802 family, for **LANs** / Local Area Networks, **PANs** / Personal Area Networks, **MANs** / Metropolitan Area Networks, restricted to **variable size packets**, excluding cell relay, and isochronous signal networks.

IEEE 802.2 Logical Link Control (**LLC**)

IEEE 802.3 Ethernet

IEEE 802.11 Wireless LAN (**WLAN**) & Mesh (**Wi-Fi**)

IEEE 802.11af White-Fi / Super Wi-Fi, 54-790 MHz, 8.67 mbps, 1 km, licensed bands (Contrasted with **IEEE 802.22** which applies cognitive radio sensing to use **white space** in (licensed) TV spectra.)

IEEE 802.11ah Wi-Fi **HaLow**, 700-900 MHz, 8.67 mbps, 1 km, unlicensed bands

IEEE 1901 Ethernet over Power Lines (**EoPL**)

IEEE 802.15 Wireless Specialty Networks (**WSN**) formerly Wireless Personal Area Networks (WPAN)

IEEE 802.15.1 Bluetooth (handed-over from IEEE to **Bluetooth Special Interest Group**); 0.7-2.1 mbps, 100 m, 2.4-2.4835 GHz Industrial, Medical, Scientific / ISM radio band, 1 W; Bluetooth **Low Energy** / BLE, non-compatible with Bluetooth, uses same spectrum, 0.01-0.5 W, 0.27-1.37 mbps, below 100m; supports **piconets** with up to 7 slaves/master, 0.2-2.1 kbps, which may be meshed into **scatternets**

IEEE 802.15.4e, Low-Rate Wireless Personal Area Networks (**LR-WPAN**), 10 m, 250 kbps line-of-sight, 780-2450 MHz, supports the **Zigbee**, and **6LoWPAN** frameworks among others;

Medium Access Control (**MAC**)

Governs datagrams, called **frames**, between **interfaces**, via **48-bit MAC addressing**, which is the **IEEE 802** name for **local** network addressing. MAC addresses are typically assigned to **hardware** at the time of manufacture.

MAC is defined differently for each higher-level protocol, such as **IEEE 802.3**, **IEEE 802.11**.

Hardware complexities are abstracted and hidden from the **LLC**.

A **channel access control mechanism** a.k.a. **multiple access method** allows multiple **hosts** to share a common **PHY medium** - the most common of which is Carrier-sense multiple access with collision detection (**CSMA/CD**)

HUBS & REPEATERS
Deprecated in as of 2011

Ethernet hubs a.k.a. **Multiport repeaters**, **active hubs**, **indiscriminately repeat** every incoming signal, to every **physical port** except the port from which the signal originated, transmitting a **jam signal** to every physical port upon detection of collision.

IEEE 802.2. Logical Link Control (**LLC**) is specific to all **IEEE 802** LANs such as **IEEE 802.3** (**Ethernet**) and **IEEE 802.11** (**WLAN** and **Wi-Fi**), and some **non-IEEE-802** networks also.

Provides **multiplexing** mechanisms that make it possible for higher-level **network** protocols to multiplely coexist on a shared **PHY** layer.

BRIDGES & SWITCHES

Ethernet switches a.k.a. **Switching hubs**, **bridging hubs**, **MAC bridges**, utilise **packet switching** to send incoming **Ethernet frames only to** the **physical port** corresponding to a particular **network address**.

A **bridge** connects **segments** of the same network which use the **same protocol**.

A **bridge** needs only two **ports**. A **switch** is basically a a multiport **bridge**.

When the network addressing uses **hardware / MAC addresses**, this is called a **layer-2 bridging**.

The mapping between MAC addresses and physical ports is often implemented in high-speed **content-addressable memory** (CAM), resulting in it sometimes being called a **CAM table**.

More generally, it is called a **MAC table**, **forwarding table**, or **forwarding information base**.

Segmentation, the splitting of **collision domains**, can be result in **collisionless full-duplex** connections between two hosts, if (each host is the **only host connected** to one of the switch's physical ports).

Small Form-factor Pluggable (SFP) modules are **transceivers** between a switch and a specific physical medium.

Switches may be packaged with additional hardware and software which provide **management features**.

Port mirroring means multiplying signals from one input port to more than one output port. This is often used for analysis.

Interconnects between switches may be regulated by spanning tree protocol (**STP**), shortest path bridging (**SPB**), or Transparent Interconnection of Lots of Links (**TRILL**) to **prevent** the emergence of **switching loops**, **enforcing** a **tree** shaped network.

Quality of Service (**QoS**), Power over Ethernet (**PoE**), **Link aggregation** a.k.a. **Ethernet bonding**, Simple Network Management Protocol (**SNMPv3**), VLAN tagging (**IEEE 802.1Q**), Network access control via **IEEE 802.1X**, Link Layer Discovery Protocol (**LLDP**), Network Time Protocol (**NTP**) synchronisation, Internet Group Management Protocol (**IGMP**) snooping, Remote Network Monitoring (**RMON**), Switch Monitoring (**SMON**), sampled flow (**sFlow**) etc.

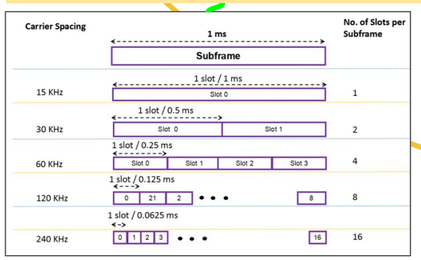
Gateways connects **separate networks** which **may** use **different** protocols. In either case, **each network** connected by a gateway will have its **own address space**, different from adjacent networks.

Wireless Access Points (**WAPs**) allow **wireless interfaces** to connect to a **fixed wire network**.

Routers maintain **routing tables** which may contain
- destination **IP address**
- destination net mask
- next hop / gateway address
- interface
- filtering criteria
- routing metric (score) compiled from various criteria like :

SNMP measured link utilisation, path speed, hop count, packet loss, network delay, path reliability, path bandwidth, throughput, load, MTU, etc.

5G NR uses Orthogonal Frequency-Division Multiplexing / **OFDM** on **spectra** from 400 MHz to 71 GHz, with **channel widths** of 5 Mhz to 400 MHz, and up to 3300 **subcarriers** per channel, with subchannel spacing / **SCS** of 15 kHz to 240 kHz, with **frame** length of 10 ms, **subframe** length of 1 ms, and 1 to 16 slots/subframe depending on SCS



Layer 2 : Link Layer Control / **LLC** is expanded somewhat ... in the (Access Stratum / **AS** of the **air interface** of the Radio Access Network / **RAN**) ... (**bearer services** or Radio Bearers / **RBs** are **logical pipelines**) between (User Equipment / **UE** and **access networks** a.k.a. Network Bearers / **NBs**).

Data Radio Bearers / **DRBs** carry User Plane data
Signal Radio Bearers / **SRBs** carry Control Plane Data and **NAS** messages

AS : Media Access Control / **MAC**, varying again based on the underlying Layer 1 : **PHY**

AS : Radio Link Control / **RLC**, fragmentation and reassembly, error correction.

AS : Packet Data Convergence Protocol / **PDCP**, compression of user plane, cyphering and integrity protection for user and control planes,

AS : Service Data Adaptation Protocol / **SDAP**, maps the Quality of Service / **QoS** flow (which is from **UE** to **RAN** to **CN** to **RAN** to **UE**) to each **RB**

Layer 3 : Transport

AS : Radio Resource Control / **RRC** managing the setup, maintenance, and release of radio connections, allocating radio resources, handling mobility and handoffs between cells, controlling power consumption, managing encryption keys, ensuring data integrity, by manipulation of the **SRB** to calibrate the **DRB**

NAS : Non Access Stratum is the transport protocol layer that mediates User Equipment / **UE** and the Core Network / **CN**, handling authentication, sessions, etc.

Internet Protocol