Embedded Systems

CS 397

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Ethernet (IEEE 802.3): Theory of Operation

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Ethernet

Introduction

- Ethernet is an asynchronous Carrier Sense Multiple Access with Collision Detect (CSMA/CD) protocol/interface, with a payload size of 46-1500 bytes.
- With data rates of tens to hundreds of megabits/second, it is generally not well suited for low-power microcontroller applications.
- However, with ubiquitous (present everywhere) deployment, internet connectivity, high data rates and limitless range expansibility, Ethernet can accommodate nearly all wired communications requirements.
- Potential applications of microcontroller-based or embedded Ethernet include:
    - Remote sensing and monitoring
    - Remote command, control and firmware updating
    - Bulk data transfer
    - Live streaming audio, video and media
    - Public data acquisition (date/time, stock quotes, news releases, etc.)

CSMA/CD: https://en.wikipedia.org/wiki/Carrier-sense_multiple_access_with_collision_detection

Ethernet Glossary

Ethernet technology contains acronyms and terms defined as follows:

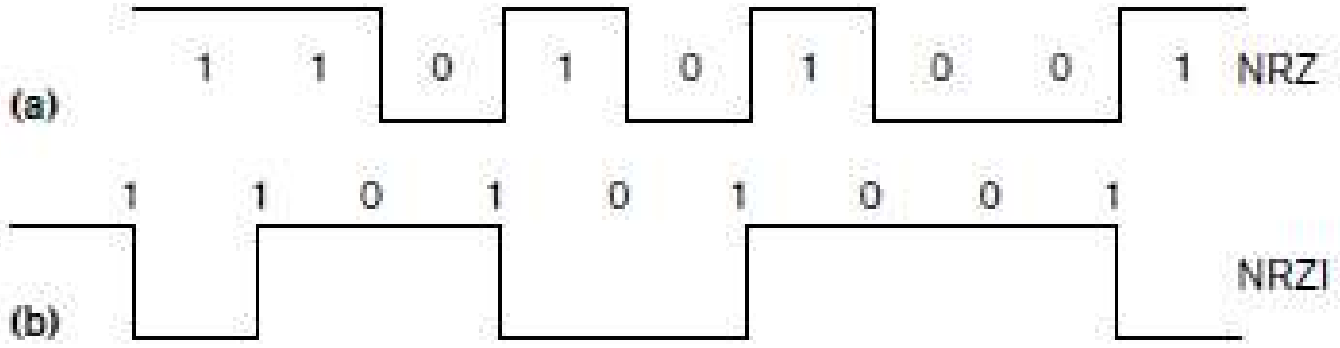
Term	Definition
CRC	Cyclic Redundancy Check: Type of checksum algorithm used when computing the FCS for all Ethernet frames and the key for hash table filtering of receive packets.
DA	Destination Address: The 6-byte destination address (MAC address) field of an Ethernet frame.
DMA	Direct Memory Access
FCS	Frame Check Sequence: The 4-byte field at the end of an Ethernet frame that holds the error detection checksum for that frame.
IP	Internet Protocol: Refers either to IPv4 or IPv6
LAN	Local Area Network or Large Area Network
MAC	Media Access Control
MAC Address	A 6-byte number representing the physical address of the node(s) on an Ethernet network.

Ethernet

MDC	Management Data Clock
MDI	Management Data Input or Medium Dependent Interface
MDO	Management Data Output.
MDIO	Management Data Input/Output.
MII	Media Independent Interface: Standard 4-bit interface between the MAC and the PHY for communicating TX and RX frame data. In 10 Mb/s mode, the MII runs at 2.5 MHz; in 100 Mb/s mode, it runs at 25.0 MHz.
MIIM	MII Management: Set of MII sideband signals used for accessing the PHY registers.
MMC	MAC Management Counters
OUI	Organizationally Unique Identifier: The upper three bytes of a MAC address are referred to as the OUI, and typically are assigned to an organization or company. Microchip's OUI is 00-04-A3-xx-xx-xxh, and STMicroelectronics is 00-80-E1-xx-xx-xxh.
Octet	In Ethernet terms, one 8-bit byte.
PHY	Ethernet physical layer
PMT	Power Management
PTP	Precision Time Protocol
RAM	Random Access Memory (normally volatile memory).

Ethernet

RX / TX	Receive / Transmit
SA	Source Address: The 6-octet source address field of an Ethernet frame.
SFD	Start Frame Delimiter: The single octet field of an Ethernet frame that marks the start of a frame.
Station Address	The Station Address is the MAC address of the Ethernet node. It is typically compared against the destination address in a received Ethernet frame to determine if the frame should be received or not. On the transmit side, it is typically transmitted as the source address of an Ethernet frame.
RMII	Reduced Media Independent Interface: A 2-bit version of the MII.
SMII	Serial Media Independent Interface: A 1-bit version of the MII.
NRZI	Non-Return-to-Zero Inverted: A binary code in which a logical one is represented by a signal transition and a logical zero is represented by the lack of a transition.



Ethernet

General Features

- Ethernet is a data link and physical layer protocol defined by the IEEE 802.3 specification.
- It comes in many flavors, defined by maximum bit rate, mode of transmission, and physical transmission medium.

  . Maximum Bit Rate (Mbits/s): 10, 100, 1000, etc.

  . Mode of Transmission: Broadband, Baseband

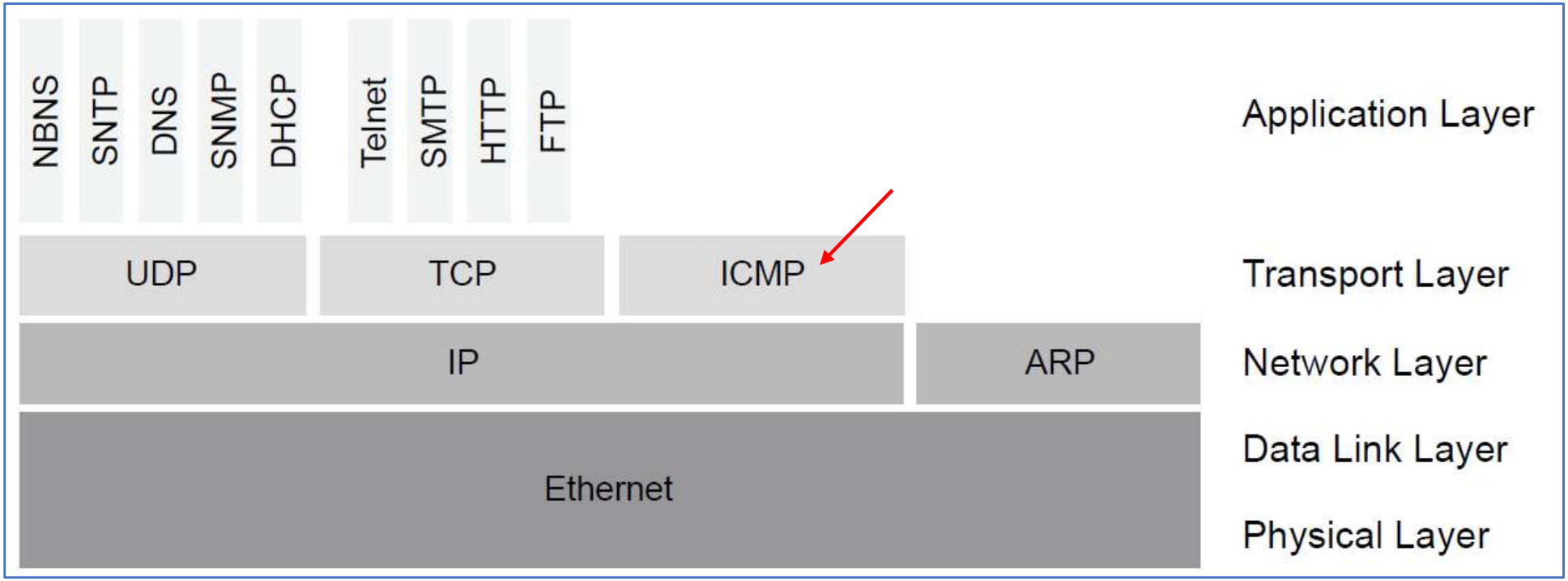
  . Physical Transmission Medium: Coax, UTP (unshielded twisted pair), Fiber, etc.

Protocol

- A protocol is a standard set of rules that allow electronic devices to communicate with each other. These rules include what type of data may be transmitted, what commands are used to send and receive data, and how data transfers are confirmed.
- For more details: https://techterms.com/definition/protocol

Protocol Stack

- The protocol stack describes a set of protocols in a layered approach.

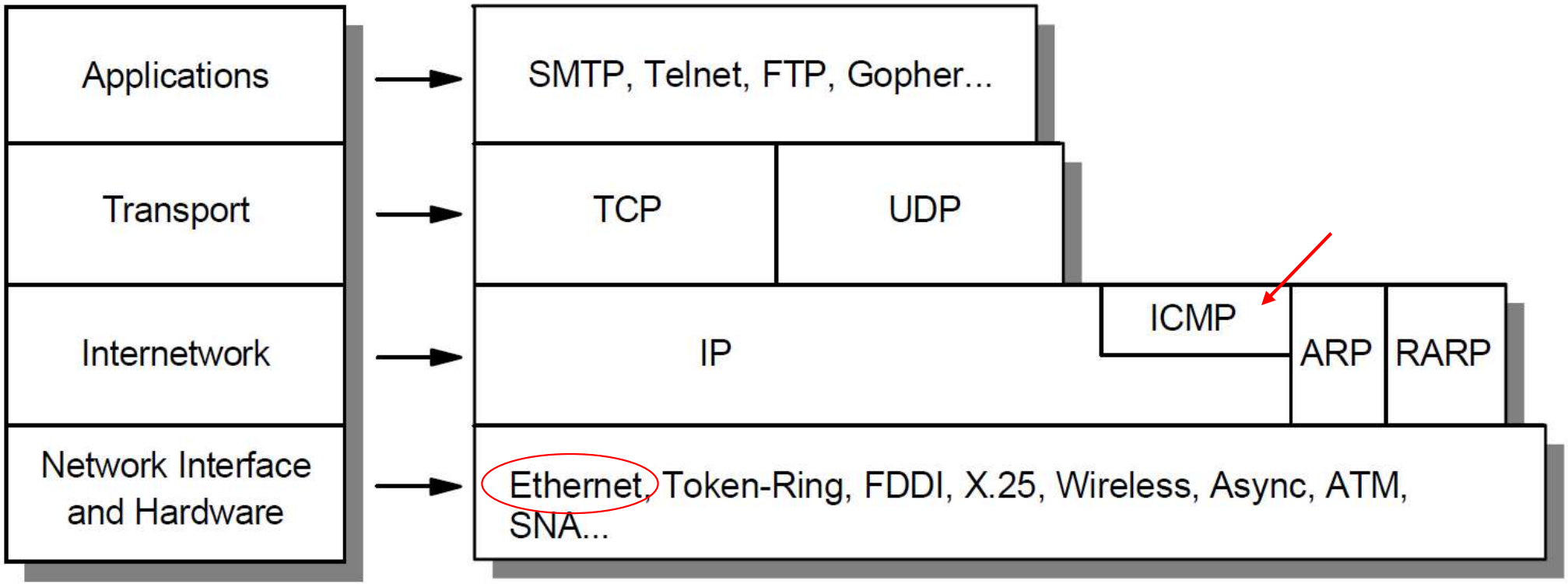


Internet Protocol Stack

- To understand how Ethernet works
  - need to understand the concept of packet encapsulation, and
  - study how the protocol stack fits into this concept.

ICMP (Internet Control Message Protocol) for network maintenance and debugging

Internet Protocol Stack

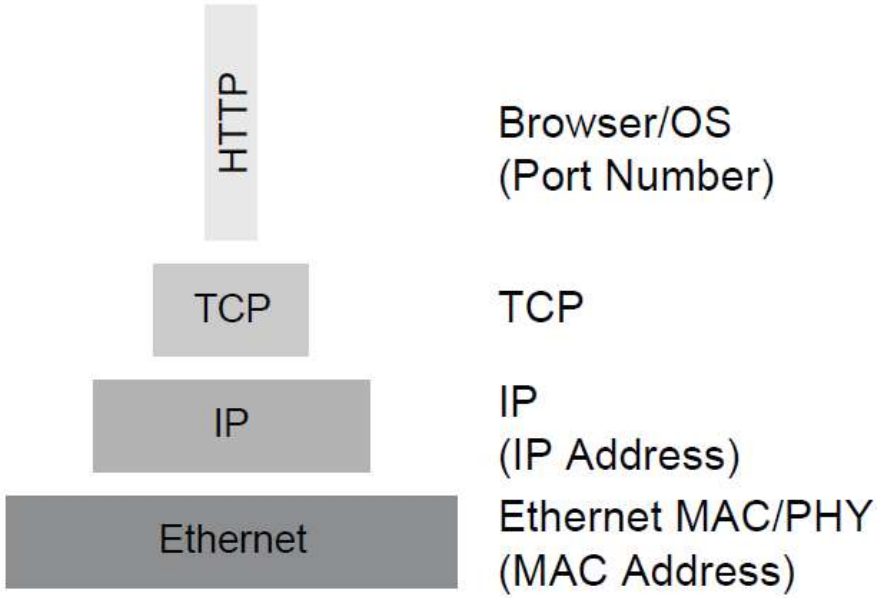


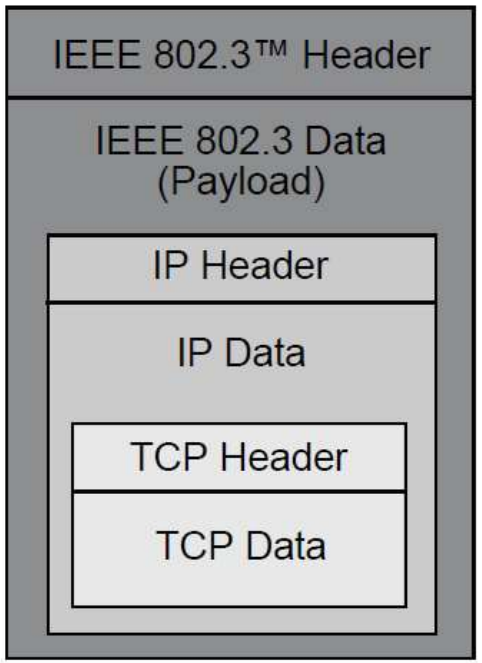
A layering model presented by the TCP/IP Tutorial and Technical Overview by IBM

ARP (Address Resolution Protocol)
RARP (Reverse ARP)

Frame/Packet Encapsulation

- Each layer of the internet protocol stack is responsible for a particular level of functionality.
- For example, the physical layer is concerned with the actual electrical transmission of bits across a medium.
- Each higher layer in the model utilizes the underlying layers in a somewhat independent fashion (meaning little or no overlap in functions between the layers).
- Below example shows how each layer associated with a web browser session maps to the protocol stack model.





Data Encapsulation Example

Data Encapsulation Example

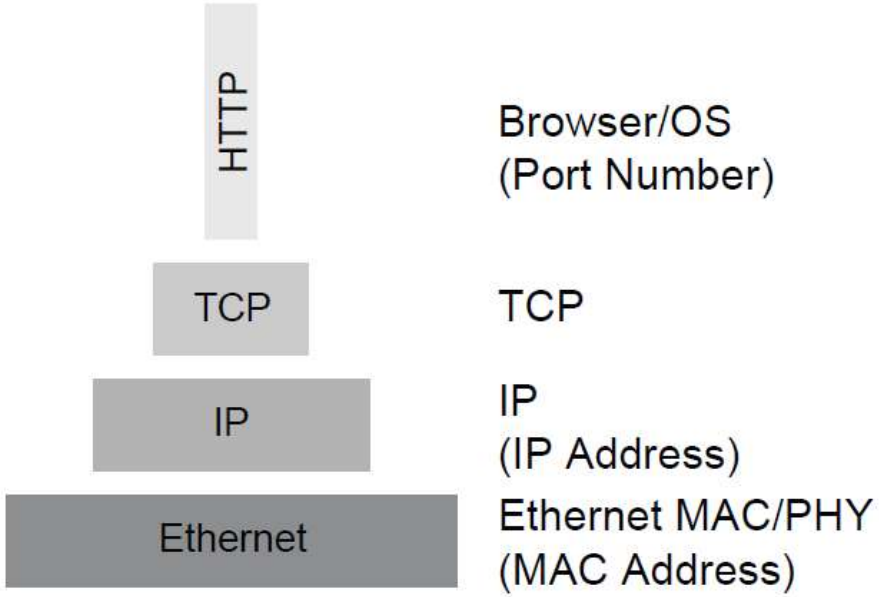
- Starting at the application layer, the web browser would generate an HTTP request using an application-specific command.
- This request would then be passed down to the TCP layer, which would construct a TCP packet consisting of a TCP header and TCP data.
- The TCP header contains information particular to the TCP protocol, such as packet sequencing information, checksum information and the source and destination port number (**HTTP typically has a port number of 80**).
- At the IP protocol level, an IP datagram is constructed to hold the TCP packet. Similar to the TCP packet, the IP datagram consists of an IP header and IP data.
- The IP header contains information such as the type of service, checksum information, protocol type (**06h for TCP**), and the source and destination IP addresses.
- The data field of the IP datagram contains the complete TCP packet to be transmitted.

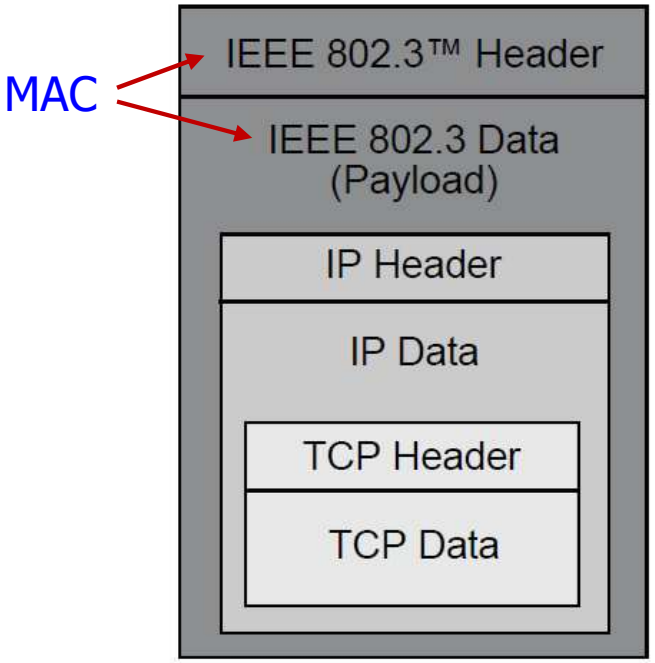
Note: The terms "packet", "frame" and "datagram" are often used interchangeably. These terms apply to specific protocols, such as an IEEE 802.3 frame, a TCP packet or an IP datagram.

Ethernet

- At the data link/physical layer, the IP datagram is transported across the network using the IEEE 802.3 protocol.
- A MAC (IEEE 802.3) frame consists of a MAC header and a MAC payload (data).
- The MAC header contains information about the MAC frame, such as the source MAC address, the destination MAC address and the length of the frame.
- The MAC payload field contains the complete IP datagram to be transported.

Note: The terms "MAC frame", "Ethernet frame" and "IEEE 802.3 frame" are used interchangeably.





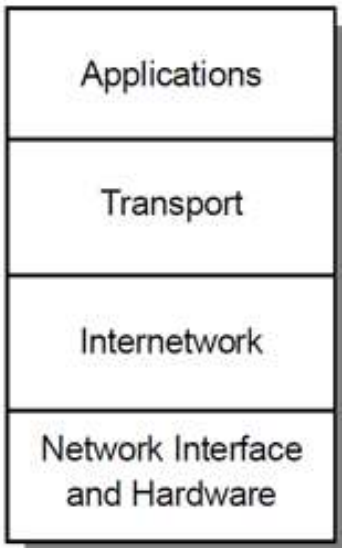
Data Encapsulation Example

Remark

- The various addresses encapsulated within each protocol are different, and typically, have no fixed relationship to one another.
- In the example, the TCP packet uses a port number, which is typically assigned based on the application layer protocol (i.e., port 80 for HTTP).
- The IP datagram uses an IP address, which is statically or dynamically assigned out of a pool of available internet addresses, and
- The MAC frame uses MAC addresses, which are assigned to the particular piece of hardware.

Application Layer Protocols

- The application layer provides the user interface.
- When used on top of some lower layer protocols (UDP or TCP), application layer protocols are usually assigned a port number.
- For example, **HTTP servers are typically associated with port 80.**
- The following are common application layer protocols associated with the Internet:
  - **Hyper Text Transfer Protocol (HTTP):**
    Use primarily to transfer data associated with browsing of the World Wide Web.
  - **Simple Mail Transfer Protocol (SMTP):**
    Use to transport e-mails across the internet.
  - **File Transfer Protocol (FTP):**
    Use to transfer files or other pieces of data over the internet.



Application Layer Protocols

- **Domain Name System (DNS):**

  Use to translate domain names, such as "abc.com", into IP addresses.

- **Dynamic Host Configuration Protocol (DHCP):**

  Use to dynamically assign IP addresses to a particular node from a pool of available IP addresses.

- **Telnet:**

  Use to establish an interactive TCP connection to a node.

- **Simple Network Time Protocol (SNTP):**

  Use to allow nodes to synchronize their clocks to a reference clock.

- **Simple Network Management Protocol (SNMP):**

  Use to monitor network attached devices for conditions that require intervention, such as faults, etc.

Email: SMTP (Simple Mail Transfer Protocol)

IMAP (Internet Message Access Protocol)

Transport Layer Protocols

- The transport layer hides network dependent details from the layers above, including transport address to network address translation, sequencing, error detection/recovery, etc.

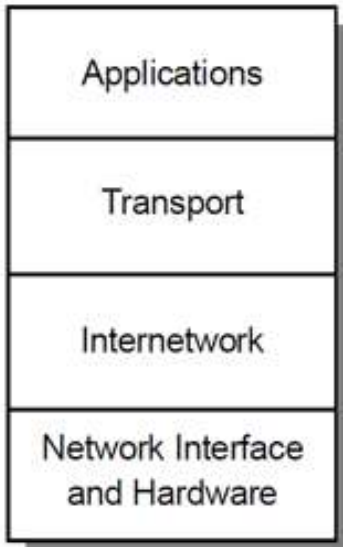
- When used on top of the IP protocol, **transport layer protocols are typically assigned an IP protocol number.**

- The following are common transport layer protocols associated with the internet:

  - **Transmission Control Protocol (TCP):**
    Provide reliable communication to applications.

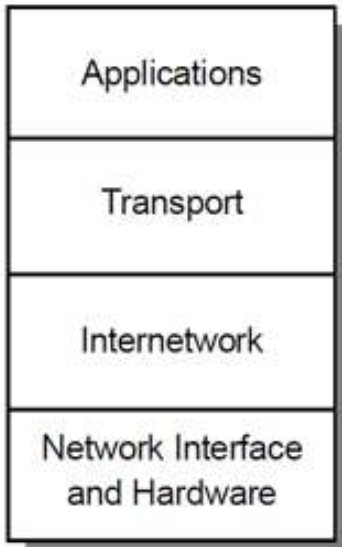
  - **User Datagram Protocol (UDP):**
    Provide high performance, but unreliable communication to applications.

  - **Internet Control Message Protocol (ICMP):**
    Use to send network and/or node error or status messages.



Network Layer Protocols

- The network layer determines how messages are routed into a network, including QoS (Quality of Service) services, provision of network addresses for the transport layer, etc.
- When used on top of Ethernet, **network layer protocols are typically assigned an "EtherType"**, which is discussed in more detail in the "Ethernet Frame Format" section.
- The following are common network layer protocols associated with the internet:
  - **Address Resolution Protocol (ARP):**
    Use to translate protocol addresses to hardware interface addresses, such as an IP address to a MAC address.
  - **Reverse Address Resolution Protocol (RARP):**
    Use to translate hardware interface addresses to protocol addresses, such as a MAC address to an IP address.
  - **Internet Protocol (IP):**
    Connectionless network layer protocol used by TCP, UDP, etc.



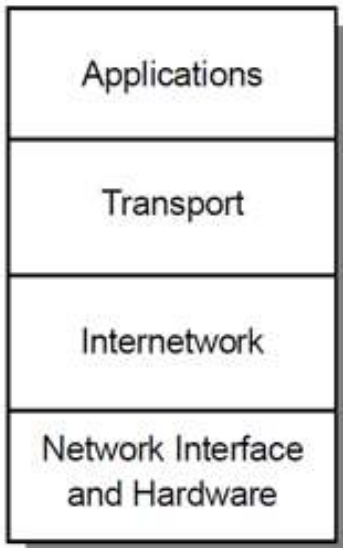
https://en.wikipedia.org/wiki/Internet_Protocol

Physical/Data Link Layer Protocols

- The physical layer provides for the transmission of bit streams across physical connections, including encoding, multiplexing, synchronization, clock recovery, serialization, etc.

- The data link layer is concerned with the transmission of frames (blocks) in an error-free manner, including frame sequencing, frame flow control, etc.

- Ethernet is one of the most common physical/data link layer protocols, and the subject of the remainder of these lecture notes.



Physical Medium Overview

Ethernet is defined in part by the physical medium over which frames are transmitted. The following is a summary of the more common mediums:

- 1 Mb/s
  - 1Base5: 2 twisted telephone wire pairs, <= 500 meters long
- 10 Mb/s
  - 10Broad36: 1 broadband cable
  - 10Base2: RG 58 coax cable, <= 185 meters long
  - 10Base5: 1 coax cable
  - 10Base-F: 1 optical fiber
  - 10Base-T: 2 pairs UTP CAT3 or better, full-duplex, (common: 4 pairs UTP CAT5 RJ-45)
- 100 Mb/s
  - 100Base-FX: 2 optical fibers, full-duplex, Fast Ethernet over fiber
  - 100Base-T2: 2 pairs UTP CAT3 or better, full-duplex (No longer in use)
  - 100Base-T4: 4 pairs UTP CAT3 or better, half-duplex (No longer in use)
  - 100Base-TX: 2 pairs UTP CAT5 or better, full-duplex, Fast Ethernet

Ethernet

- 1 Gb/s
  - 1000Base-CX: Copper jumper cable
  - 1000Base-LX: Long wavelength multi/single mode fiber
  - 1000Base-SX: Short wavelength multi mode fiber
  - 1000Base-T: 4 CAT5e, CAT6 or better pairs

Note:

1: T at the end of 10Base-T or 100Base-TX or 1000Base-T stands for twisted-pair.

2: UTP – Unshielded Twisted Pair wire

3: CAT3 wires and copper telephone wires are essentially interchangeable.

4: Ethernet Standards and Protocols Explained:

https://www.computernetworkingnotes.com/networking-tutorials/ethernet-standards-and-protocols-explained.html

https://en.wikipedia.org/wiki/Fast_Ethernet

https://en.wikipedia.org/wiki/Category_5_cable

https://en.wikipedia.org/wiki/Category_6_cable

(Please find out the specifications of the provided Ethernet cable)

Ethernet Specification (IEEE 802.3)

- The **IEEE 802.3** specification has evolved over the last number of years to address higher transmission rates and new functionality.

- The list below are part of the specification supplements.

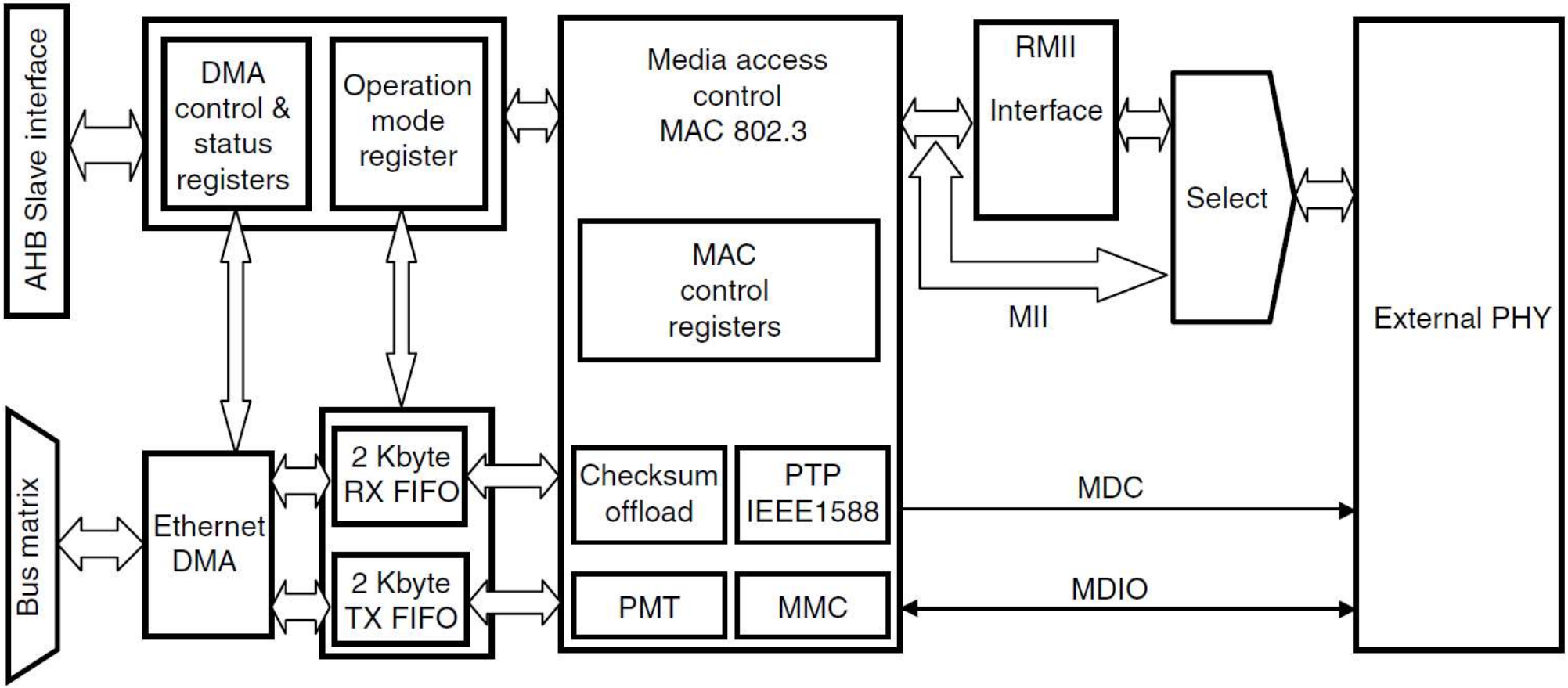
The Ethernet of STM32F7xx is compliant with IEEE 802.3-2002 standard.

Supplement	Year	Description
IEEE 802.3a	1985	10Base-2 Thin Ethernet
IEEE 802.3c	1985	10 Mb/s Repeater Specification
IEEE 802.3d	1987	Fiber Optic Inter-Repeater Link
IEEE 802.3i	1990	10Base-T Twisted Pair
IEEE 802.3j	1993	10Base-F Fiber Optic
IEEE 802.3u	1995	100Base-T Fast Ethernet and Auto-Negotiation
IEEE 802.3x	1997	Full-Duplex Standard
IEEE 802.3z	1998	1000Base-X Gigabit Ethernet (SX, LX, CX)
IEEE 802.3ab	1999	1000Base-T Gigabit Ethernet over Twisted Pair
IEEE 802.3ac	1998	Frame Size Extension to 1522 Octets for VLAN Tagging
IEEE 802.3ad	2000	Link Aggregation for Parallel Links
IEEE 802.3-2002	**2002**	**(802.3ag) A revision of base standard**
IEEE 802.3af	2003	Power Over Ethernet (PoE)
IEEE 802.3-2018	2018	802.3cj – maintenance, merge recent amendments

https://en.wikipedia.org/wiki/IEEE_802.3

https://standards.ieee.org/standard/802_3ag-2002.html

Ethernet Functional Description: MAC 802.3 (STM32F7)



The STM32F7 Ethernet (ETH) Block Diagram

PTP = Precision Time Protocol

PMT = Power Management

MMC = MAC Management Counters

RMII = Reduced Media Independent Interface

MDC = Management Data Clock

Ethernet Functional Description: MAC 802.3 (STM32F7)

- The IEEE 802.3 International Standard for **local area networks (LANs)** employs the **CSMA/CD (carrier sense multiple access with collision detection)** as the access method.
- The Ethernet peripheral consists of a **MAC 802.3 (media access control)** controller with **media independent interface (MII)** and a dedicated **DMA** controller.
- **Reduced media independent interface (RMII)** is also supported.
- The MAC block implements the LAN CSMA/CD sublayer for the following families of systems:
  - 10 Mbit/s and 100 Mbit/s of data rates for baseband and broadband systems.
  - Half- and full-duplex operation modes are supported.
  - The collision detection access method is applied only to the half-duplex operation mode.
  - The MAC control frame sublayer is supported.

Ethernet Functional Description: MAC 802.3 (STM32F7)

- The MAC sublayer performs the following functions associated with a data link control procedure:
  - Data encapsulation (transmit and receive)
    - Framing (frame boundary delimitation, frame synchronization)
    - Addressing (handling of source and destination addresses)
    - Error detection
  - Media access management
    - Medium allocation (collision avoidance)
    - Contention resolution (collision handling)

Ethernet Functional Description: MAC 802.3 (STM32F7)

- Basically, there are two operating modes of the MAC sublayer:
  - Half-duplex mode:
    The stations contend for the use of the physical medium, using the CSMA/CD algorithms.
  - Full duplex mode:
    Simultaneous transmission and reception without contention resolution (CSMA/CD algorithm are unnecessary) when all the following conditions are met:
    - physical medium capability to support simultaneous transmission and reception
    - exactly 2 stations connected to the LAN
    - both stations configured for full-duplex operation

Ethernet (MAC 802.3) Frame Format

- The MAC block implements the MAC sublayer and the optional MAC control sublayer (10/100 Mbit/s) as specified by the IEEE 802.3-2002 standard.
- Two frame formats are specified for data communication systems using the CSMA/CD MAC:
  - Basic MAC / Ethernet / IEEE 802.3 / MAC 802.3 frame format
  - Tagged MAC / Ethernet / IEEE 802.3 / MAC 802.3 frame format (extension of the basic MAC frame format)

Tagged MAC / Ethernet / IEEE 802.3 / MAC 802.3 frame format

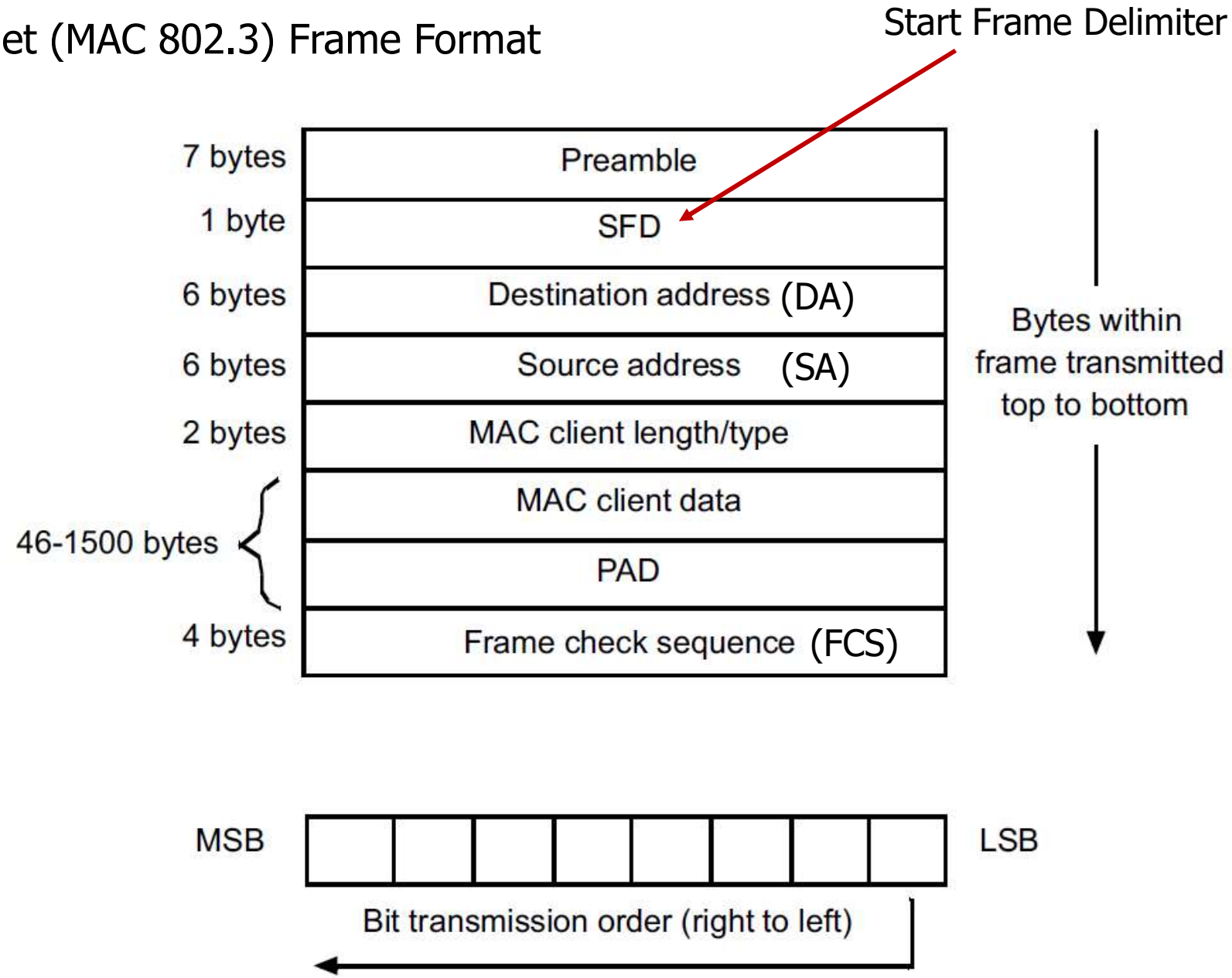
802.1Q Distributed VLANs

802.1Q is a standard for **distributing virtual LAN (VLAN)** information across multiple switches. It enables you to have users in the same VLAN distributed among different switches but still being treated as if they were connected to the same switch.

To set this up, you need to add a 4-byte tag that contains the necessary VLAN information to transmitted Ethernet frames. In a typical configuration, switches are set up with trunk ports between them and these ports are configured to tag the frames as they're transmitted. That way, tagged frames only pass between 802.1Q-compliant switches and don't travel anywhere else on the network.

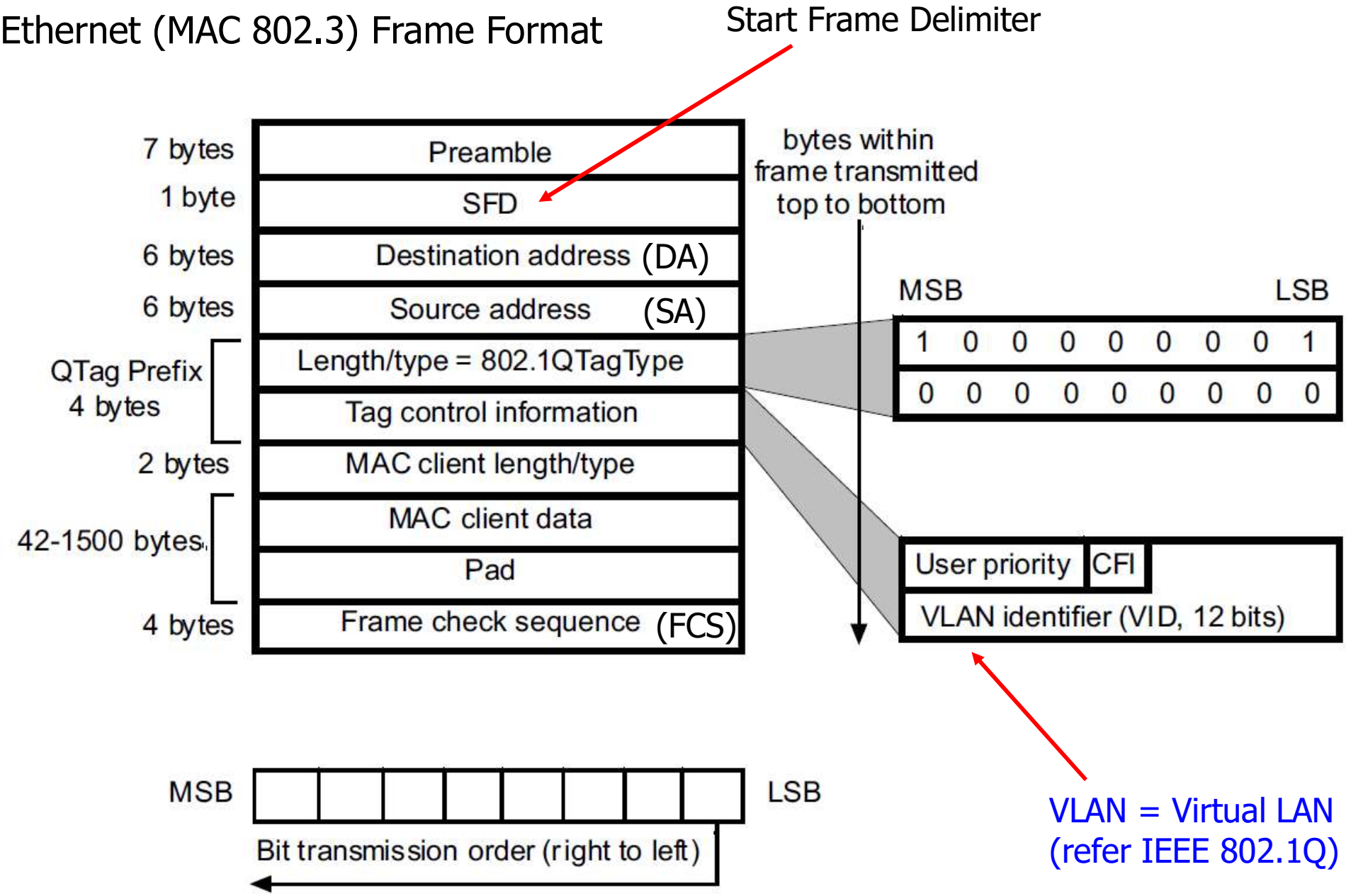
https://www.black-box.com.tw/en-tw/page/38854/Resources/Technical-Resources/Black-Box-Explains/wireless/ethernet-frame-tagging

Ethernet (MAC 802.3) Frame Format



The basic MAC / Ethernet / IEEE 802.3 / MAC 802.3 frame format

Ethernet (MAC 802.3) Frame Format

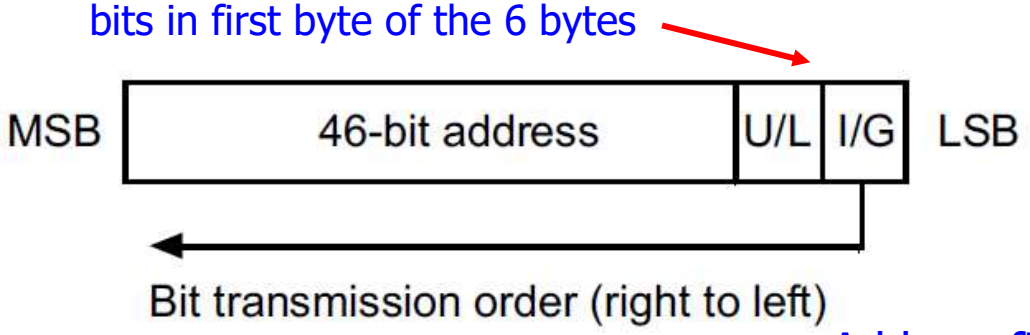


The tagged MAC / Ethernet / IEEE 802.3 / MAC 802.3 frame format

Ethernet (MAC 802.3) Frame Format

- The Ethernet frame structure (basic MAC and tagged MAC) that includes the following fields:

  - **Preamble**: 7-byte field used for synchronization purposes
    Hexadecimal value: 55-55-55-55-55-55-55 (right-to-left bit transmission)
    Bit pattern: 01010101 01010101 01010101 01010101 01010101 01010101 01010101
  - **Start frame delimiter (SFD):** 1-byte field used to indicate the start of a frame.
    Hexadecimal value: D5
    Bit pattern: 11010101 (right-to-left bit transmission)
  - **Destination and Source Address fields**: 6-byte (48 bits) fields to indicate the destination and source station MAC addresses as follows:



I/G = 0 Individual address
I/G = 1 Group address
U/L = 0 Globally administered address
U/L = 1 Locally administered address

Address field format

Ethernet (MAC 802.3) Frame Format

- **Destination and Source Address fields**:
  - Each address is 48 bits in length
  - The first LSB bit (I/G) in the destination address field is used to indicate an individual (I/G = 0) or a group address (I/G = 1). A group address could identify none, one or more, or all the stations connected to the LAN. In the source address the first bit is reserved and reset to 0.
  - The second bit (U/L) distinguishes between locally (U/L = 1) or globally (U/L = 0) administered addresses. For broadcast addresses this bit is also 1.
  - Each byte of each address field must be transmitted least significant bit first.

Enter Ethernet MAC Address: 02 : 80 : E1 : 00 : 00 : XX

Ethernet (MAC 802.3) Frame Format

- **Destination and Source Address fields**:

  The address designation is based on the following types:

  - Individual address:

    This is the physical address associated with a particular station on the network.

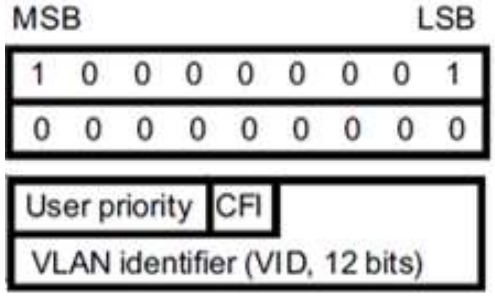
  - Group address:

    A multi-destination address associated with one or more stations on a given network. There are two kinds of multicast address:

    – Multicast-group address: an address associated with a group of logically related stations.

    – Broadcast address: a distinguished, predefined multicast address (all 1's in the destination address field) that always denotes all the stations on a given LAN.

Ethernet (MAC 802.3) Frame Format



Only for the tagged MAC frame

- **QTag Prefix:** 4-byte field inserted between the Source address field and the MAC Client Length/Type field.

  - This field is an extension of the basic MAC frame to obtain the tagged MAC frame. The basic MAC frames do not include this field.

  - The extensions for tagging are as follows:

    – 2-byte constant Length/Type field value consistent with the Type interpretation (greater than 0x0600) equal to the value of the **802.1Q Tag Protocol Type (0x8100)**. This constant field is used to distinguish tagged and basic MAC frames.

    – 2-byte field containing the Tag control information field subdivided as follows: a 3-bit user priority, a canonical format indicator (CFI) bit and a 12-bit VLAN Identifier.

    – The length of the tagged MAC frame is extended by 4 bytes by the QTag Prefix.

- **MAC client length/type**: 2-byte field with different meaning (mutually exclusive), depending on its value:
  - If the value is less than or equal to **maxValidFrame** (0d1500 decimal, 0x05DC) then this field indicates the number of MAC client data bytes contained in the subsequent data field of the 802.3 frame (length interpretation).
  - If the value is greater than or equal to **MinTypeValue** (0d1536 decimal, 0x0600) then this field indicates the nature of the MAC client protocol (Type interpretation) related to the Ethernet frame.

  Regardless of the interpretation of the length/type field, if the length of the data field is less than the minimum required for proper operation of the protocol, a PAD field is added after the data field but prior to the FCS (frame check sequence) field. The length/type field is transmitted and received with the higher-order byte first.

  For length/type field values in the range between **maxValidLength** and **minTypeValue** (boundaries excluded), the behavior of the MAC sublayer is not specified: they may or may not be passed by the MAC sublayer.

Ethernet (MAC 802.3) Frame Format

- **Data and PAD fields:** n-byte data field. Full data transparency is provided, it means that any arbitrary sequence of byte values may appear in the data field. The size of the PAD, if any, is determined by the size of the data field. Max and min length of the data and PAD field are:
  - Maximum length = 1500 bytes
  - Minimum length for basic MAC frames = 46 bytes
  - Minimum length for tagged MAC frames = 42 bytes

  When the data field length is less than the minimum required, the PAD field is added to match the minimum length (42 bytes for tagged frames, 46 bytes for untagged frames).

- **Frame check sequence (FCS):** 4-byte field that contains the cyclic redundancy check (CRC) value. The CRC computation is based on the following fields:
  - m(x) = [destination address, source address, QTag prefix, length/type, data and PAD] (i.e., all fields except the preamble, SFD, and FCS). The generating polynomial is:

$$G(x) = x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1$$

The CRC value of a frame is computed as follows:

- The first 32 bits of the frame, m(x), are complemented
- The n bits of the frame are the coefficients of a polynomial M(x) of degree (n – 1). The first bit of the destination address corresponds to the x^{n-1} term and the last bit of the data field corresponds to the x^0 term

  $M(x) = a_{(n-1)} x^{n-1} + a_{(n-2)} x^{n-2} + \ldots + a_1 x^1 + a_0 x^0$
- M(x) is multiplied by x^{32} and divided by G(x), producing a remainder R(x) of degree ≤ 31
- The coefficients of R(x) are considered as a 32-bit sequence
- The bit sequence is complemented and the result is the CRC
- The 32-bits of the CRC value are placed in the frame check sequence. The x^{31} term is first transmitted, and the x^0 term is last transmitted

https://www.xilinx.com/support/documentation/application_notes/xapp209.pdf

Ethernet (MAC 802.3) Frame Format

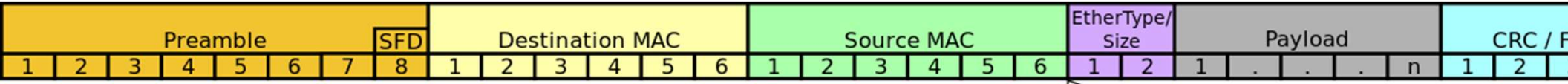
- Each byte of the MAC frame, except the FCS field, is transmitted low-order bit first.
- An invalid MAC frame is defined by one of the following conditions:
  - The frame length is inconsistent with the expected value as specified by the length/type field. If the length/type field contains a type value, then the frame length is assumed to be consistent with this field (no invalid frame)
  - The frame length is not an integer number of bytes (extra bits)
  - The CRC value computed on the incoming frame does not match the included FCS

https://www.xilinx.com/support/documentation/application_notes/xapp209.pdf

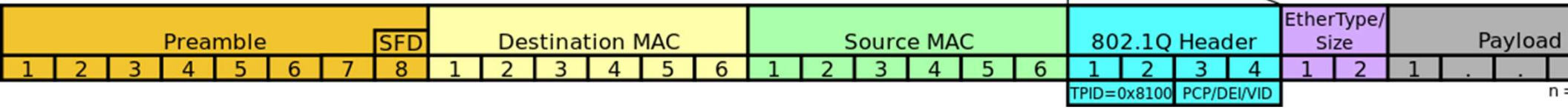
Ethernet (MAC 802.3) Frame Format

https://en.wikipedia.org/wiki/Ethernet_frame

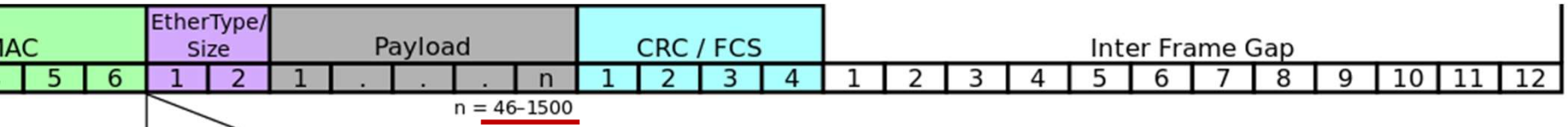
The basic MAC frame format (begin)



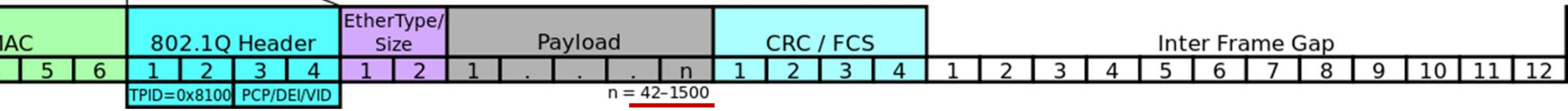
The tagged MAC frame format (begin)



The basic MAC frame format (end)



The tagged MAC frame format (end)



802.1Q tag format

16 bits	3 bits	1 bit	12 bits
TPID	TCI		
	PCP	DEI	VID

https://en.wikipedia.org/wiki/IEEE_802.1Q

TPID = Tag protocol identifier

TCI = Tag control information

PCP = Priority code point

DEI = Drop eligible indicator

VID = VLAN identifier

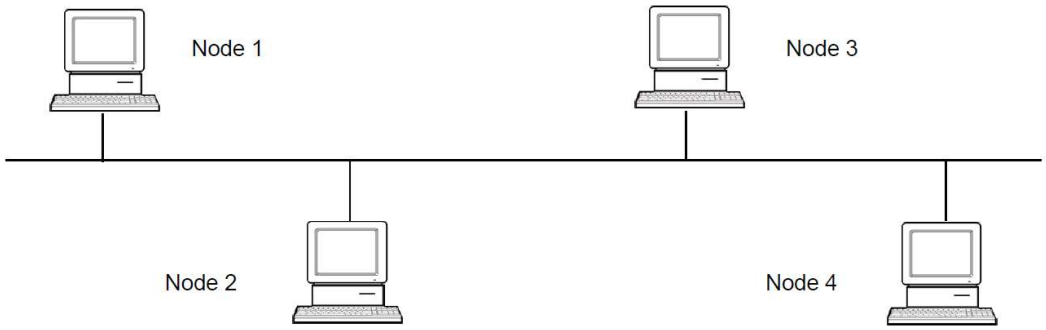
Carrier Sense Multiple Access / Collision Detection (CSMA/CD):

- A set of rules determining how network devices respond when two devices attempt to use a data channel simultaneously.
- Standard Ethernet networks use CSMA/CD to physically monitor the traffic on the line at participating stations.
- If no transmission is taking place at the time, the particular station can transmit.
- If two stations attempt to transmit simultaneously, this causes a collision, which is detected by all participating stations. On detection of a collision, the stations stop transmitting. https://www.webopedia.com/TERM/C/CSMA_CD.html
- After a random time interval, the stations that collided attempt to transmit again.
- If another collision occurs, the time intervals from which the random waiting time is selected are increased step by step.
- This is known as exponential back off.
- CSMA/CD is a type of contention protocol.
- Networks using the CSMA/CD procedure are simple to implement but do not have deterministic transmission characteristics.
- The CSMA/CD method is internationally standardized in IEEE 802.3 and ISO 8802.3.

Ethernet

Full-Duplex Operation

- Early Ethernet networks were implemented with a shared medium using shared bus topology, and required CSMA/CD.



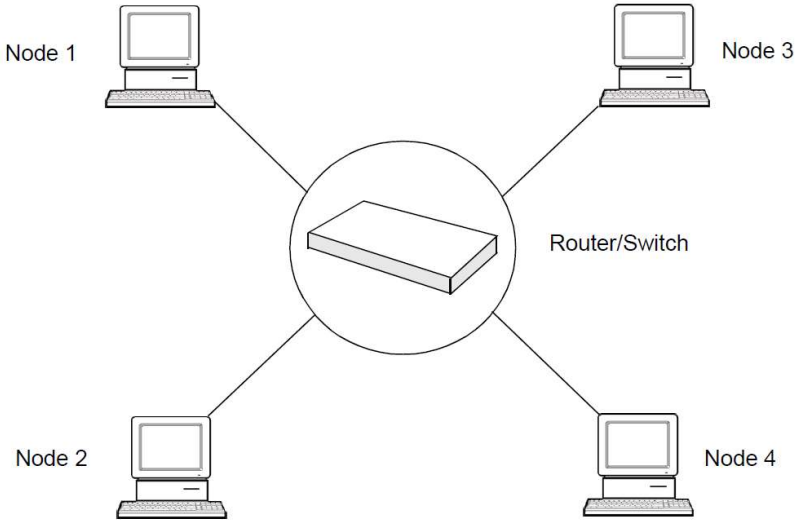
Shared Bus Topology

- Most modern Ethernet networks are configured in a point-to-point or a star topology, which can be viewed as a collection of point-to-point connections.

Point-To-Point Topology

- In point-to-point or star configuration, as each node is connected to a maximum of one other node, and each node may operate in Full-Duplex mode.

- With a point-to-point/full-duplex configuration, collisions are not possible, and CSMA/CD is therefore not used.



Star Topology