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Smart Grid Fundamentals

Communication Networks for Smart Grids

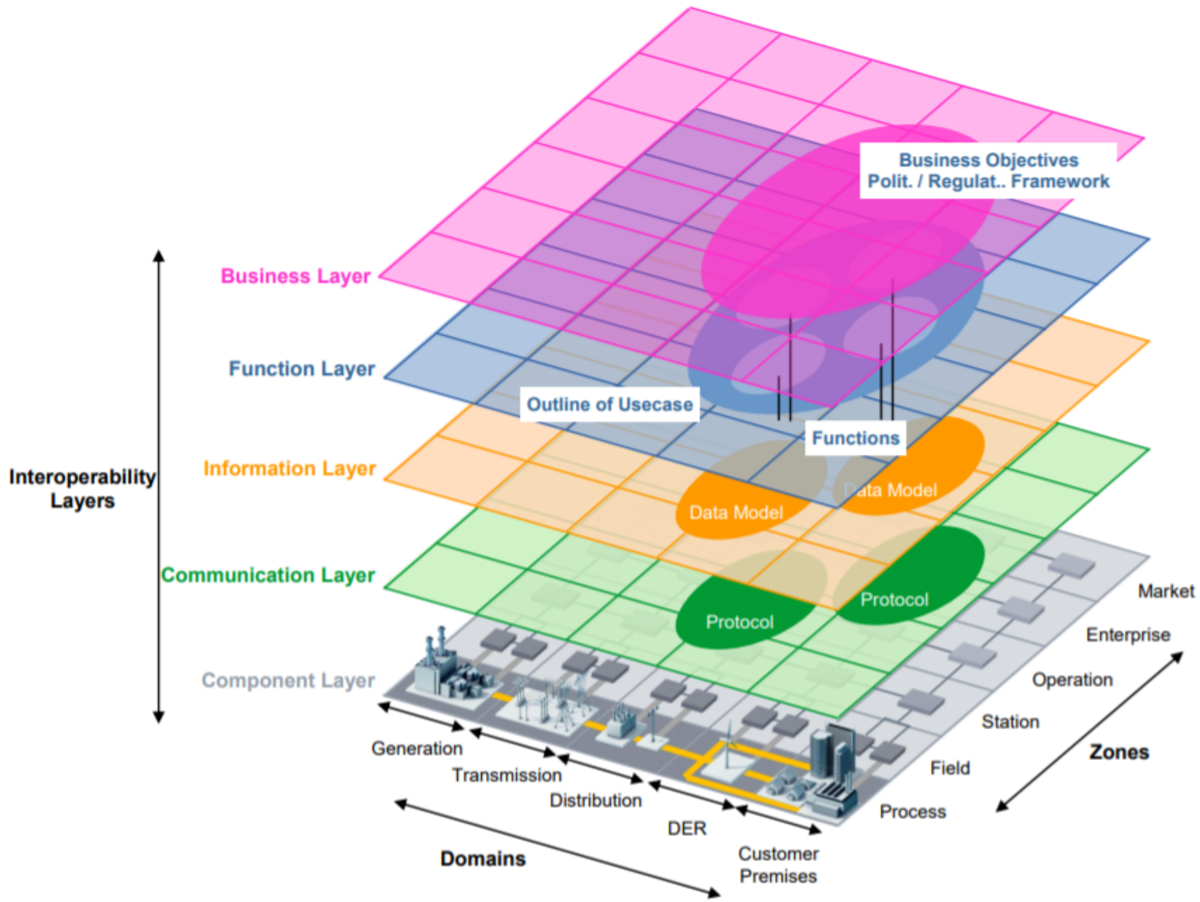
António Grilo

Smart Grid Architecture Model (SGAM)

- It is a three dimensional model that is merging the dimension of:
  - Five **interoperability layers** (Business, Function, Information, Communication and Component)
  - Two dimensions of the Smart Grid Plane, i.e.:
    - **Zones** (representing the hierarchical levels of power system management: Process, Field, Station, Operation, Enterprise and Market)
    - **Domains** (covering the complete electrical energy conversion chain: Bulk Generation, Transmission, Distribution, DER and Customers Premises).

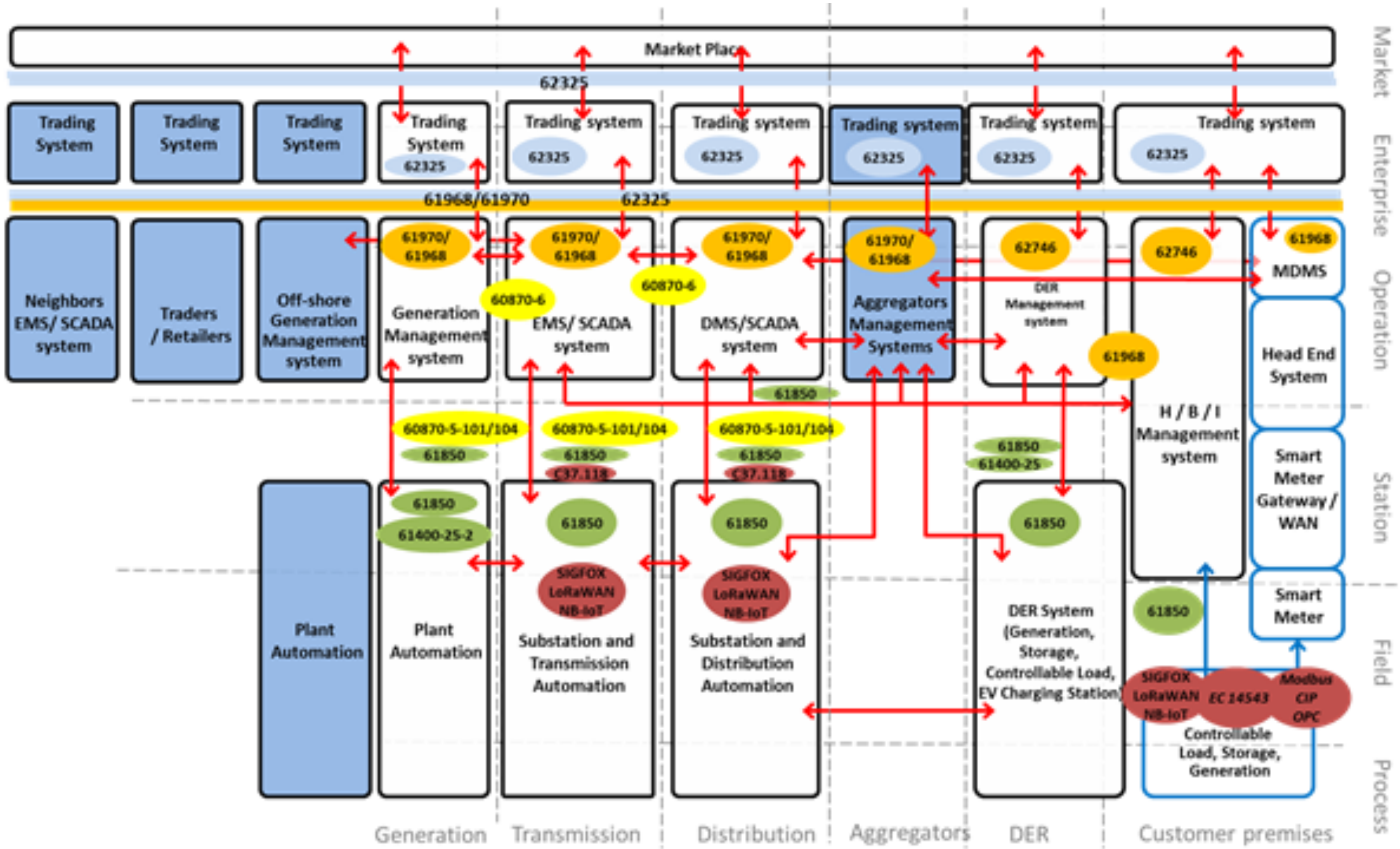
Smart Grid Architecture Model (SGAM)

- SGAM graphical representation:



Smart Grid Architecture Model (SGAM)

- Mapping of communication networks and protocols on SGAM communication layer:

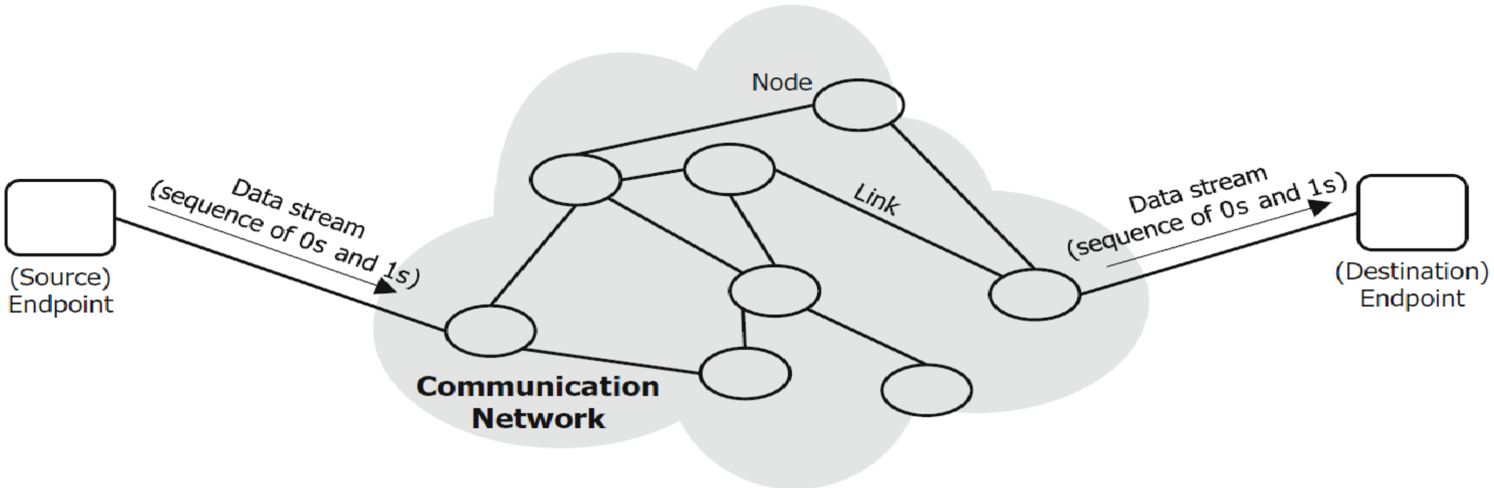


Communication Network

- A *communication network* (or simply *network*):
  - Used to transfer information from a network *endpoint* (also called a *host*) to another *endpoint*.
  - Transmission of digital data encoded in bits, e.g.:
    - Voltage measurement by SCADA IED (32 bits),
    - Status of a substation switch (open = '1', closed = '0'),
    - Text string of 8-byte characters,
    - Image (pixels, 1-byte per pixel),
    - Etc.

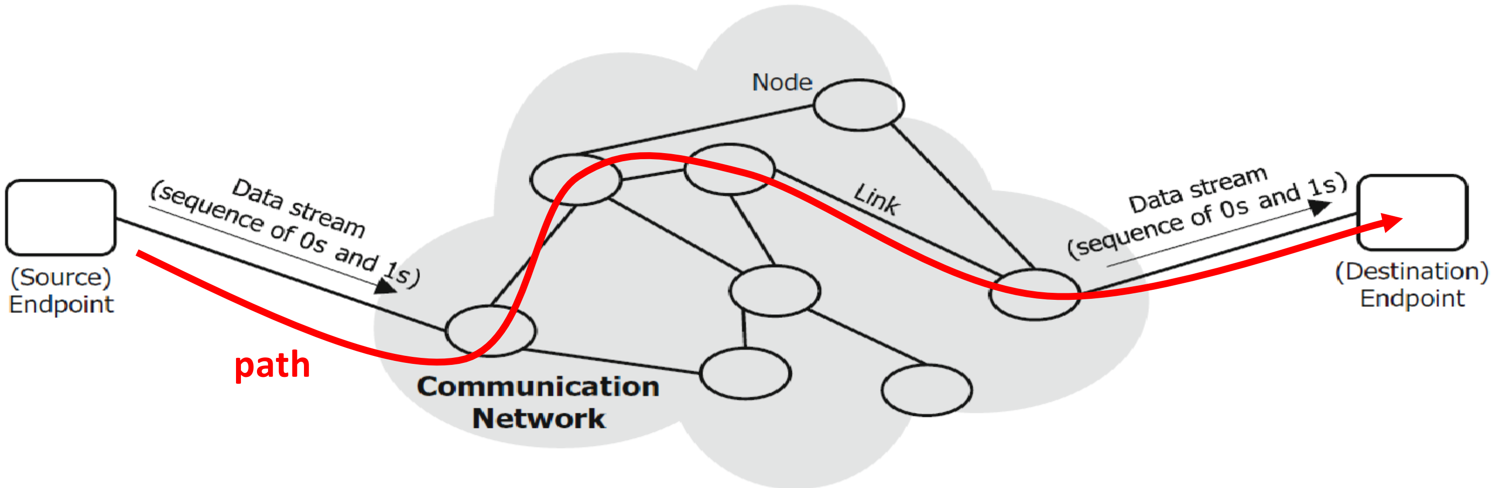
Nodes, Links and Paths

- A **communication network** (or simply **network**):
  - Collection of **relay nodes** (or simply **nodes** or **relays**) interconnected by **links.**
  - The **node** receives data from an endpoint or another node over a link and forwards it to another node or an endpoint over another link.



Nodes, Links and Paths

- **Links** can be wired (e.g., PLC, Optical Fiber) or wireless (e.g., radio waves).
  - Links can separate traffic through different **channels** defined in space, frequency, time and/or code.
  - Data are transferred from source to destination through a sequence of nodes called **path**: <source endpoint; node1; node2; : : : ; nodek;destination endpoint>



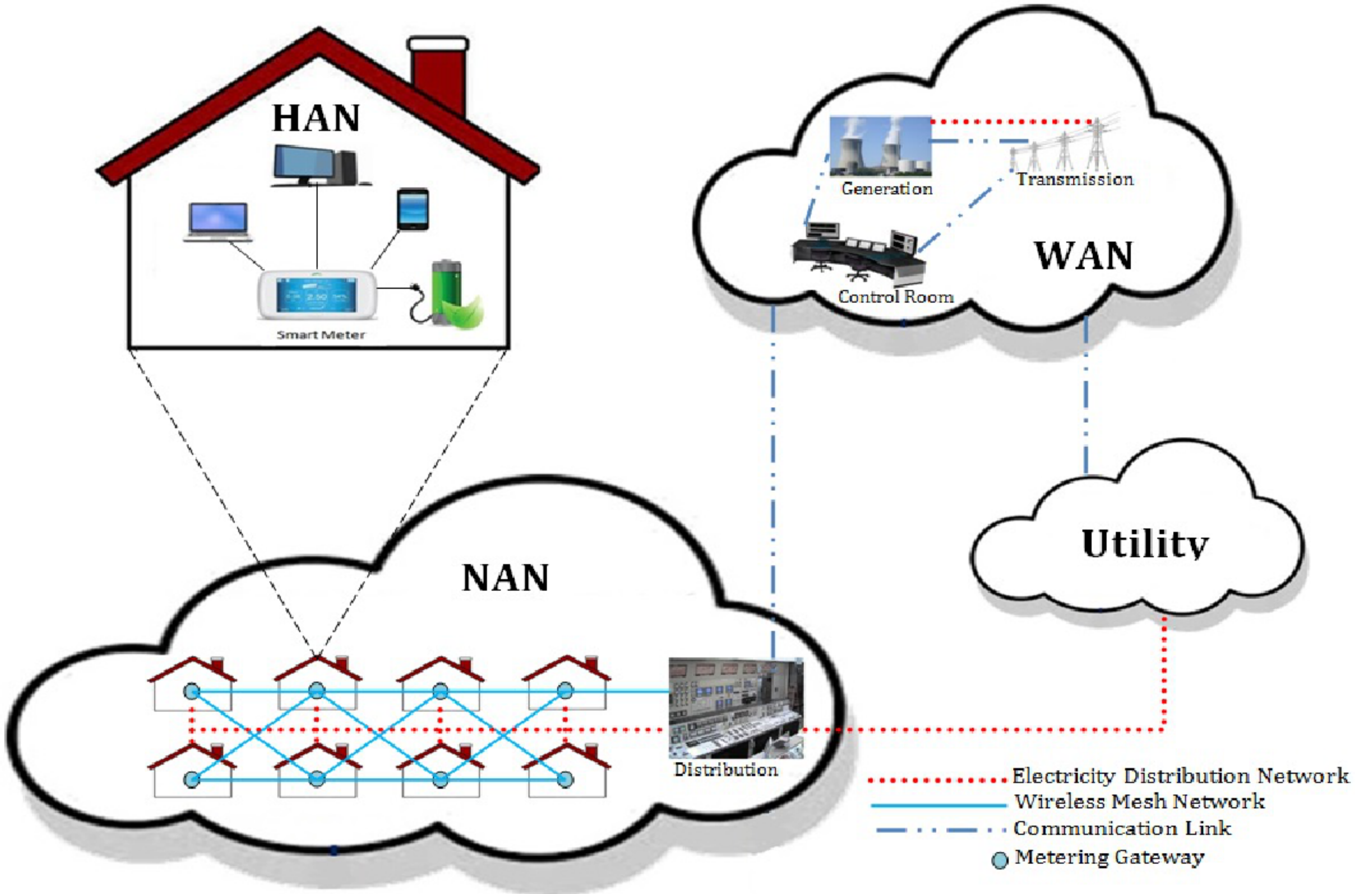
Classification of Networks

- A **network** may be generally classified as:
  - **Local Area Networks (LANs)**
    - Confined to a building or a complex of buildings
  - **Metropolitan Area Networks (MANs)**
    - Confined to a city or a metropolitan area
  - **Wide Area Networks (WANs)**
    - All others

Classification of Networks

- **Utility networks** may also be classified as:
  - **Wide Area Networks (WANs)**
    - Core network that connects main utility locations
  - **Field Area Networks (FANs)**
    - Networks connecting remote utility endpoints to the WAN
  - **Neighborhood Area Networks (NANs)**
    - networks that are limited to connecting utility endpoints within a small area (e.g., smart meters in a neighborhood)
  - **Home Area Networks (HANs), Building Area Networks (BANs), Industrial Area Networks (IANs)**
    - Connect devices within customer premises.

Classification of Networks



A. A. Khan, M. H. Rehmani, M. Reisslein, ” Cognitive Radio for Smart Grids: Survey of Architectures, Spectrum Sensing Mechanisms, and Networking Protocols”, IEEE Communications Surveys & Tutorials, 2016

A Communication Network Architecture for the Smart Grid

- Core-Edge Architecture:

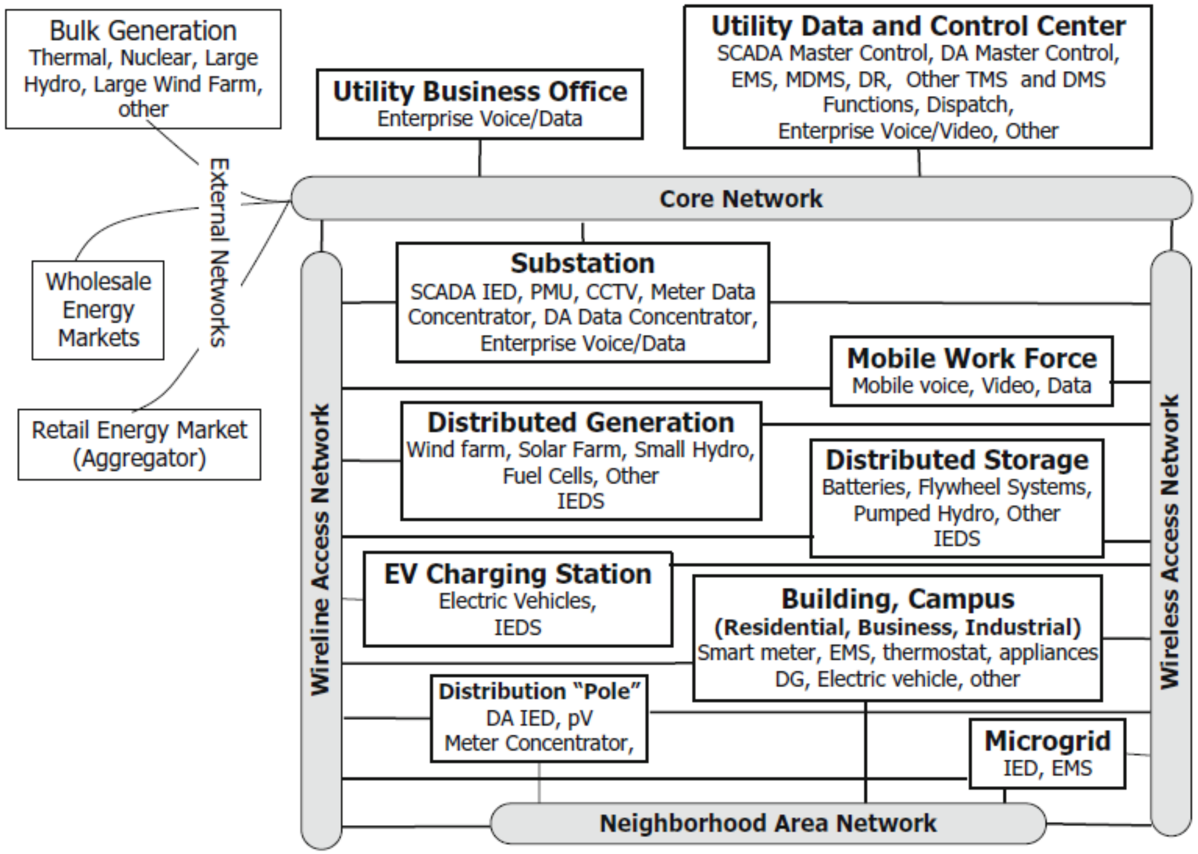


Fig. 6.1 Physical architecture framework for Smart Grid network

Communication Technologies by Network Segment

Table 1
Comparison of communication technologies for the smart grid.

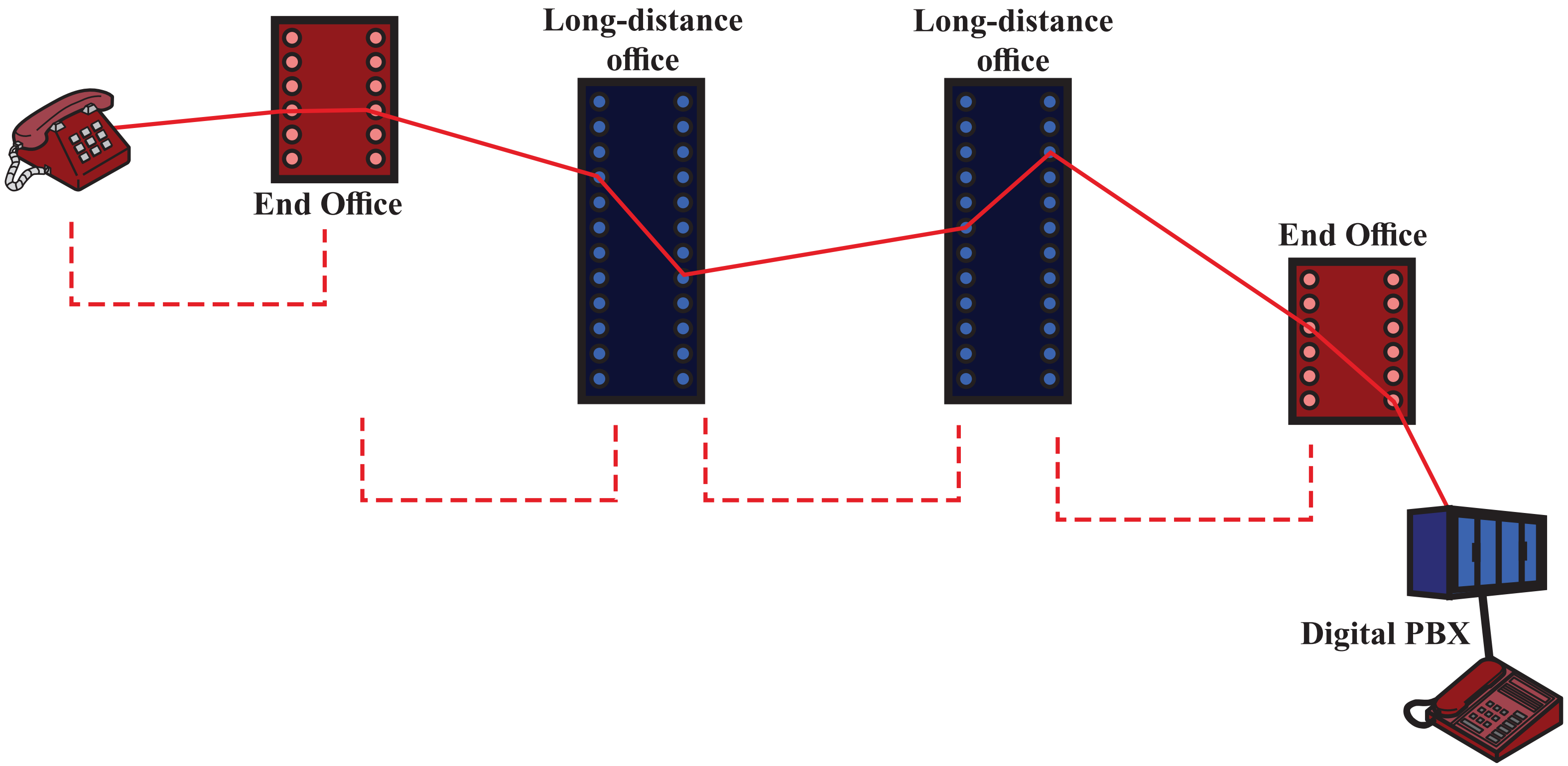
Technology	Standard/protocol	Max. theoretical data rate	Coverage range	Network		
				HAN/BAN/IAN	NAN/FAN	WAN
Wired communication technologies						
Fiber optic	PON	155 Mbps–2.5 Gbps	Up to 60 km			X
	WDM	40 Gbps	Up to 100 km			
	SONET/SDH	10 Gbps	Up to 100 km			
DSL	ADSL	1–8 Mbps	Up to 5 km		X	
	HDSL	2 Mbps	Up to 3.6 km			
	VDSL	15–100 Mbps	Up to 1.5 km			
Coaxial Cable	DOCSIS	172 Mbps	Up to 28 km		X	
PLC	HomePlug	14–200 Mbps	Up to 200 m	X		
	Narrowband	10–500 kbps	Up to 3 km		X	
Ethernet	802.3x	10 Mbps–10 Gbps	Up to 100 m	X	X	
Wireless communication technologies						
Z-Wave	Z-Wave	40 kbps	Up to 30 m	X		
Bluetooth	802.15.1	721 kbps	Up to 100 m	X		
ZigBee	ZigBee	250 kbps	Up to 100 m	X	X	
	ZigBee Pro	250 kbps	Up to 1600 m			
WiFi	802.11x	2–600 Mbps	Up to 100 m	X	X	
WiMAX	802.16	75 Mbps	Up to 50 km		X	X
Wireless Mesh	Various (e.g., RF mesh, 802.11, 802.15, 802.16)	Depending on selected protocols	Depending on deployment	X	X	
Cellular	2G	14.4 kbps	Up to 50 km		X	X
	2.5G	144 kbps				
	3G	2 Mbps				
	3.5G	14 Mbps				
	4G	100 Mbps				
Satellite	Satellite Internet	1 Mbps	100–6000 km			X

Murat Kuzlu, Manisa Pipattanasomporn, Saifur Rahman, Communication network requirements for major smart grid applications in HAN, NAN and WAN, Computer Networks, Volume 67, 2014, Pages 74-88, ISSN 1389-1286.

Circuit Switching

- Circuit establishment
  - An end to end circuit is established through relay nodes
- Information Transfer
  - Information transmitted through the network
  - Data may be voice, video, or other binary data
- Circuit disconnect
  - Circuit is terminated
  - Each node deallocates dedicated resources

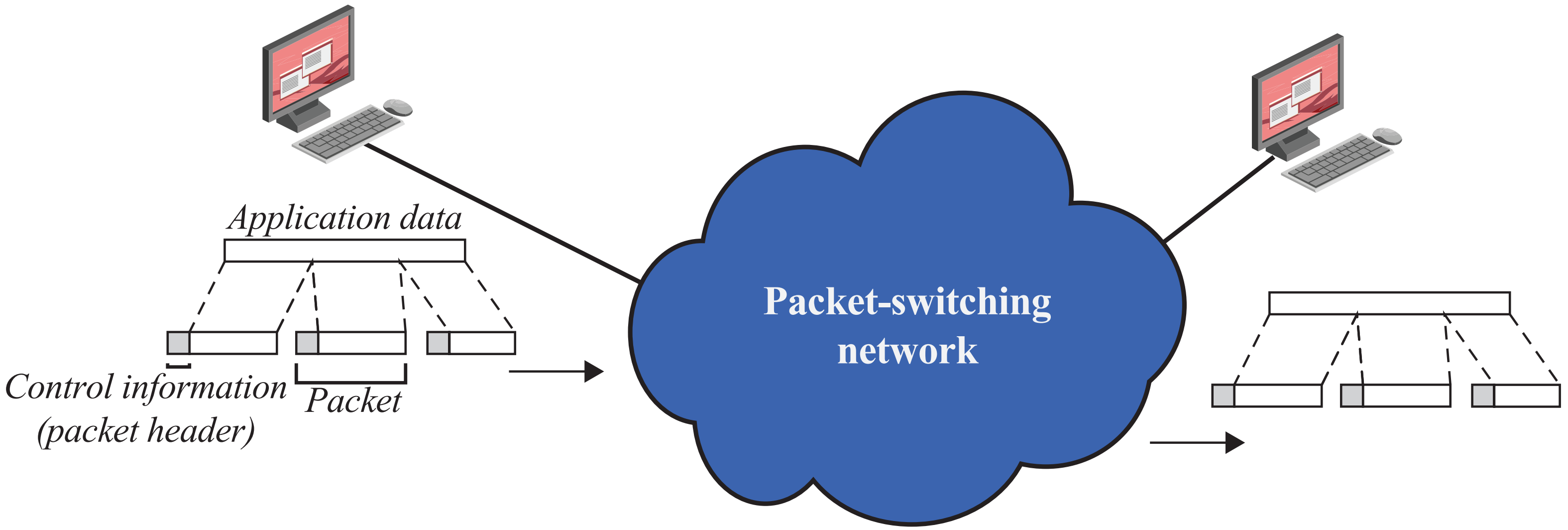
Circuit Switching



Data, Messages and Packets

- Data is transmitted in blocks, called **packets**
- Before sending, the **data message** is broken into a series of packets
  - Typical packet length depends on the data and link characteristics
  - Packets consists of a portion of data plus a packet header that includes control information
- At each node in the route, packet is received, stored briefly and passed to the next node
- Packet communication is used for connectionless networks as well as for connection-oriented networks

Packet Switching Networks



Packet Switching Advantages

- Line efficiency is greater
- Many packets over time can dynamically share the same node to node link
- Packet-switching networks can carry out data-rate conversion
  - Two stations with different data rates can exchange information
- Unlike circuit-switching networks that block calls when traffic is heavy, packet-switching still accepts packets, but with increased delivery delay
- Priorities can be used

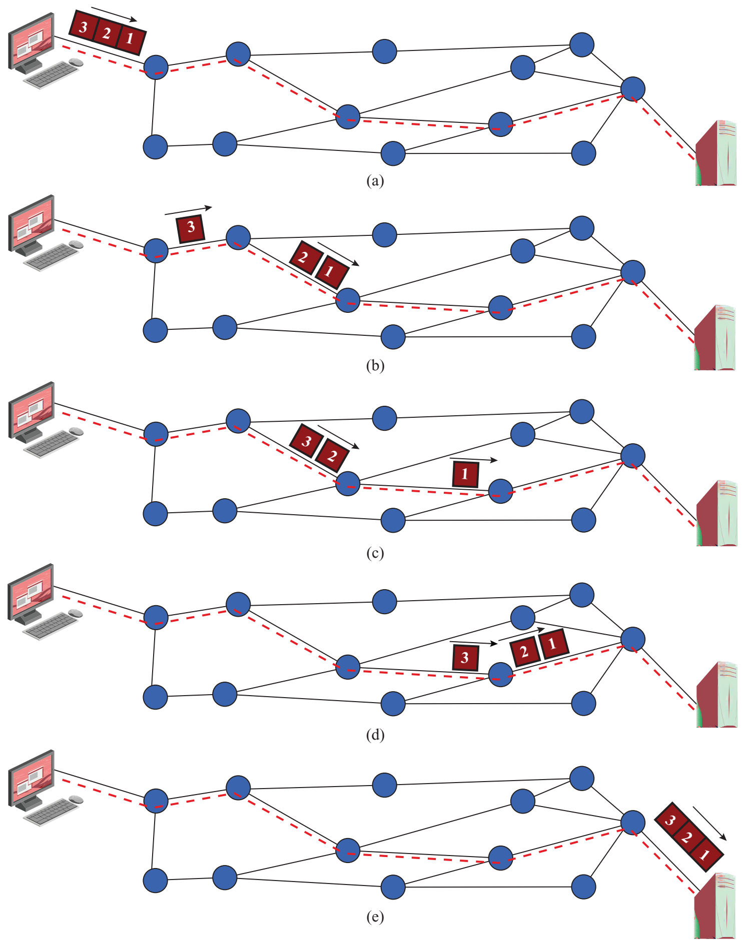
Packet Switching Disadvantages

- Each packet switching node introduces a delay
- Overall packet delay can vary substantially
  - This is referred to as jitter
  - Caused by differing packet sizes, routes taken and varying delay in the switches
- Each packet requires overhead information
  - Includes destination and sequencing information
  - Reduces communication capacity
- More processing required at each node

Packet Switching Networks – Virtual Circuit

- Preplanned route established before packets sent
- All packets between source and destination follow this route
- Routing decision not required by nodes for each packet
- Emulates a circuit in a circuit switching network but is not a dedicated path
- Packets still buffered at each node and queued for output over a line

Packet Switching Networks – Virtual Circuit



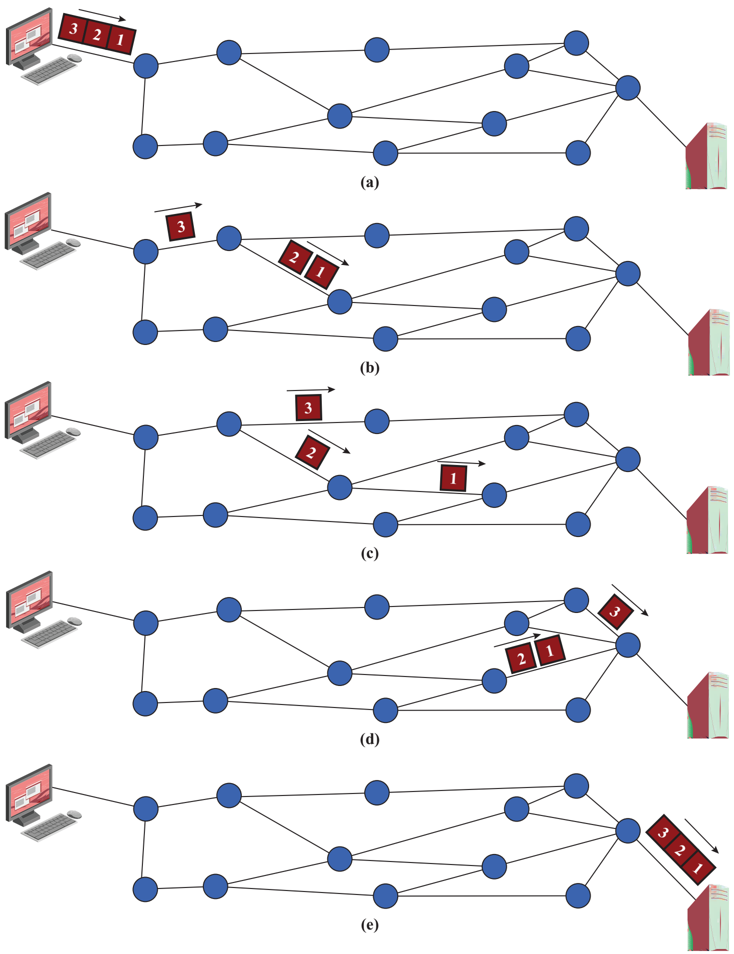
Packet Switching Networks – Virtual Circuit

- Advantages:
  - Packets arrive in original order
  - Packets arrive correctly
  - Packets transmitted more rapidly without routing decisions made at each node
  - Easier to perform resource reservation to provide QoS to packet flows

Packet Switching Networks - Datagrams

- Each packet treated independently, without reference to previous packets
- Each node chooses next node on packet’s path
- Packets don’t necessarily follow same route and may arrive out of sequence
- Exit node restores packets to original order
- Responsibility of exit node or destination to detect loss of packet and how to recover

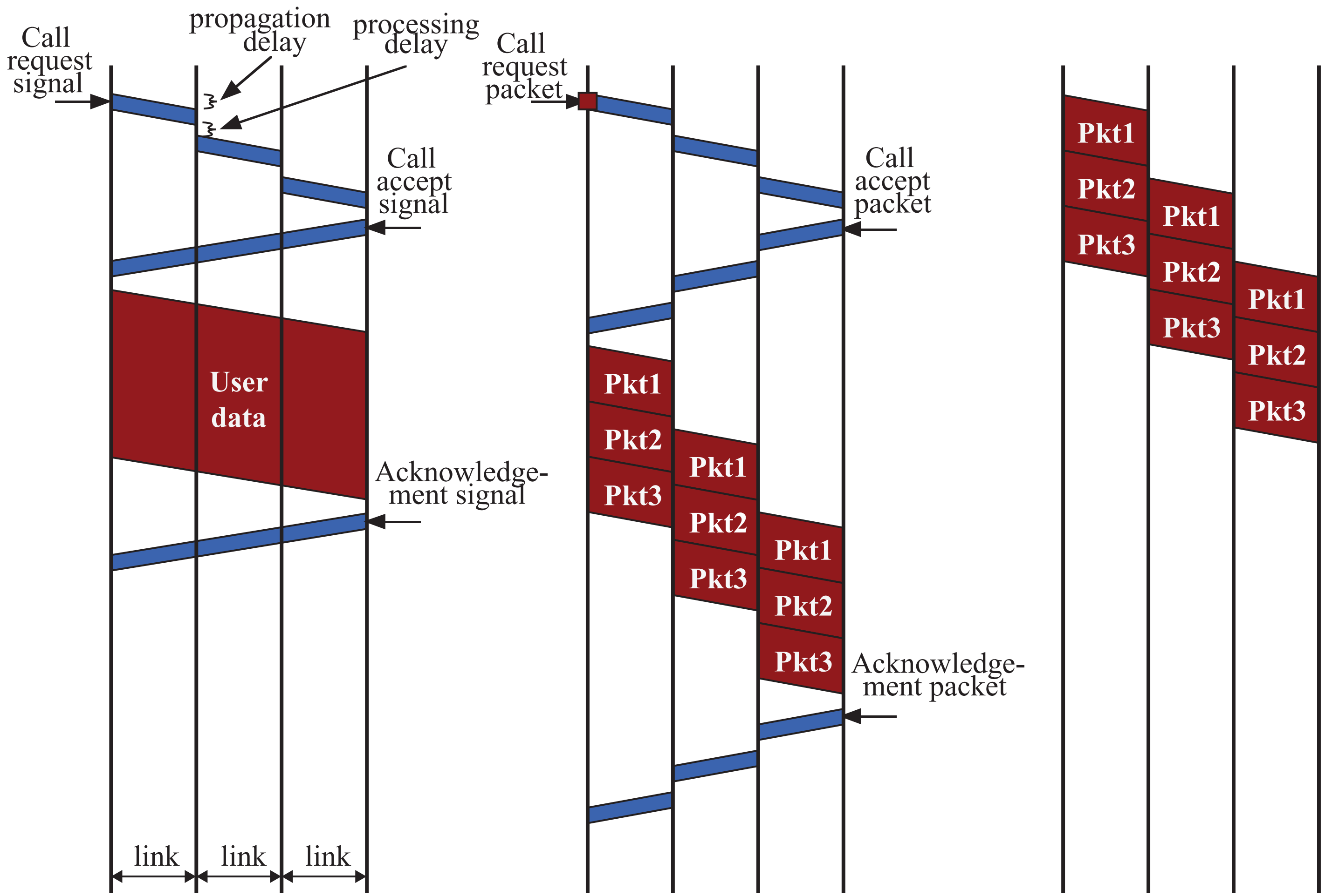
Packet Switching Networks - Datagrams



Packet Switching Networks - Datagrams

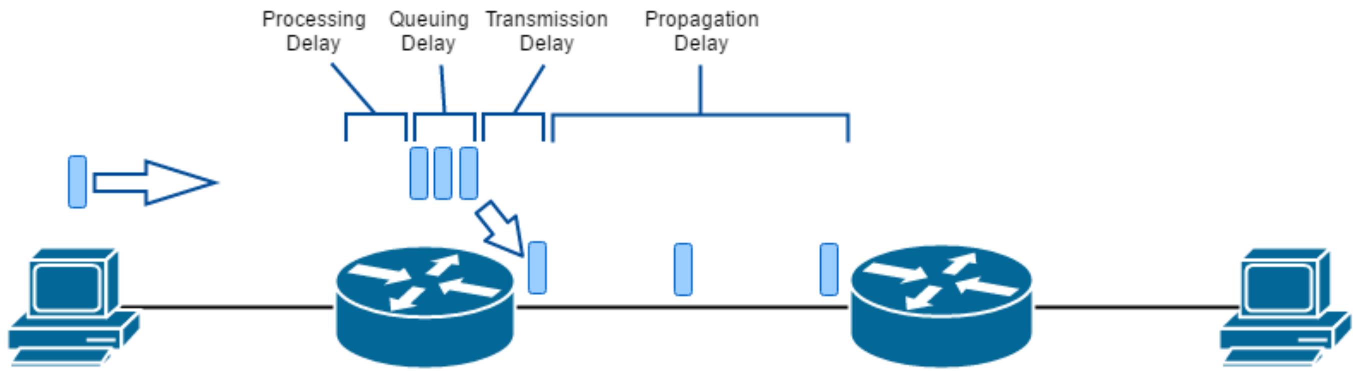
- Advantages:
  - Call setup phase is avoided
  - Because it's more primitive, it's more flexible
  - Datagram delivery is more reliable
  - Load balancing

Event timing for circuit switching and packet switching



End-to-End Delay

- End-to-end delay comprises:
  - Processing delay: protocol processing and finding outgoing interface.
  - Queuing delay: waiting in the output queue for packets that arrived first or have higher priority.
  - Transmission delay: time that elapses from the instant that the fist bit of the packet starts to be transmitted until the last bit is transmitted; depends on the link interface bitrate.
  - Propagation delay: time for propagation of the electrical or electromagnetic signal in the link up to the next node.



Jan Ho's Network World, https://www.jannet.hk/en/post/end-to-end-delay/

Effect of Packet Size on Transmission Delay

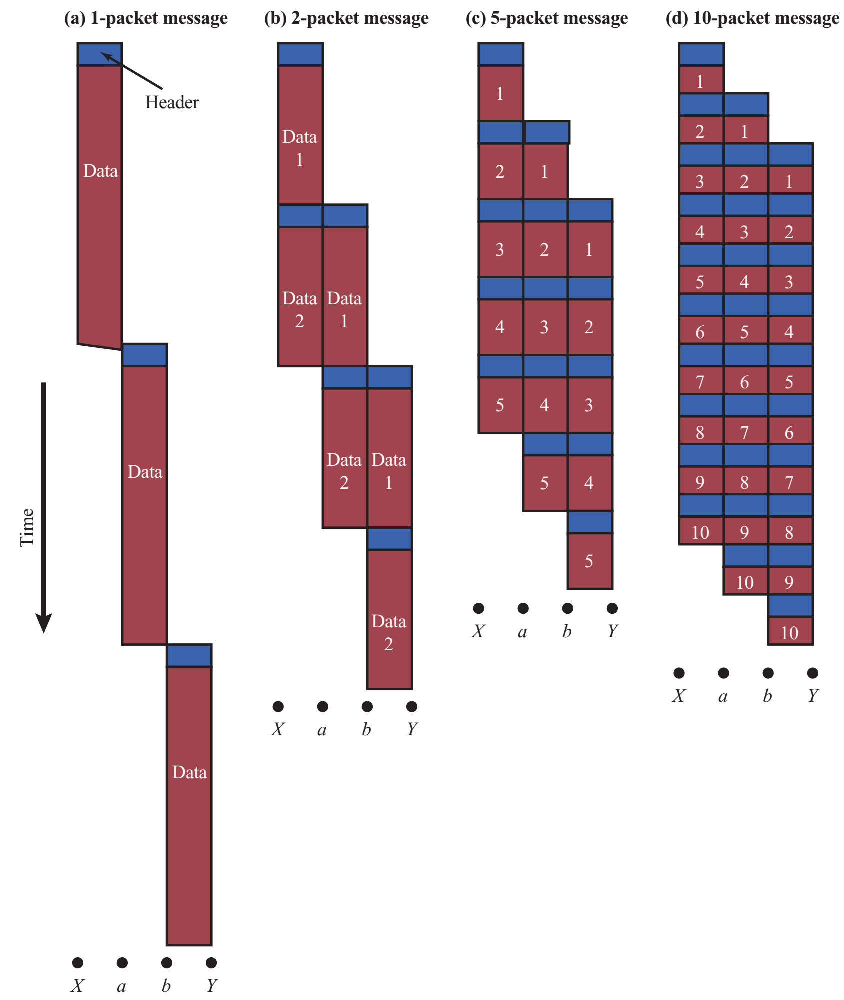
- Transmission delay of one packet in a single link:
    - Td = packet_size / data_rate
    - E.g., packet_size=1000 bytes, data_rate = 1 Mbit/s
        - Tt = 1000 x 8 / 1000000 = 8 ms

Effect of Packet Size on Transmission Delay

- Breaking up packets decreases transmission time because transmission is allowed to overlap.

- Example for 3 hops:
  - Entire message (40 octets) + header information (3 octets) sent at once
    - Transmission time: 129 octet-times
  - Message broken into 2 packets (20 octets) + header (3 octets)
    - Transmission time: 92 octet-times

Effect of Packet Size on Transmission Delay



Effect of Packet Size on Transmission Delay

- Message broken into 5 packets (8 octets) + header (3 octets)
  - Transmission time: 77 octet-times
- Each packet requires a fixed header; the more packets, the more headers
- Making the packets too small, transmission time starts to increase

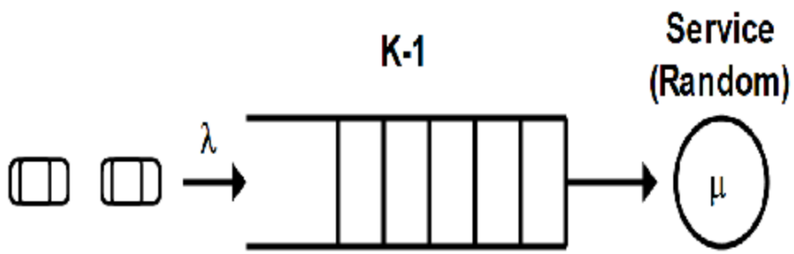
Queueing Delay

- Queueing delay
  - At each node, results from the relationship between the packet arrival process, the packet departure process, number of channels and queue size.

  - M/M/c/K queue is one of the simplest models:
    - Poisson arrival process calculates the probability of *n* arrivals within time interval of length *t* as (λ is the arrival rate):

$$\mathbb{P}\{N(t) = n\} = \frac{(\lambda t)^n}{n!} e^{-\lambda t}.$$

    - Exponential distribution of service times (transmission delay) with rate parameter μ.
    - Maximum of *K* packets in the system.
    - There are *c* parallel servers/channels (e.g., *c*=1).



M/M/1/K Queue

- Effective arrival rate (effective):
  - $\lambda_k = \begin{cases} \lambda, & k < K \\ 0, & otherwise\ (during\ blocking) \end{cases}$
- Traffic intensity or utilization of the queue:
  - $\rho = \frac{\lambda}{\mu}$
- Steady state probabilities on the number of customers (packets) in the system (queue+server):
  - $\pi_0 = \frac{1-\rho}{1-\rho^{K+1}}$
  - $\pi_k = \begin{cases} \pi_0 \cdot \rho^k, & k \leq K \\ 0, & otherwise \end{cases}$
- Server utilization:
  - $E[U] = 1 - \pi_0 = 1 - \frac{1-\rho}{1-\rho^{K+1}} = \frac{\rho(1-\rho^K)}{1-\rho^{K+1}}$
- Throughput:
  - $E[R] = \mu(1 - \pi_0) = \lambda \frac{(1-\rho^K)}{1-\rho^{K+1}} < \lambda$

M/M/1/K Queue

- Blocking (packet loss) Probability:
  - $P_B = \pi_K = \frac{(1-\rho)\rho^K}{1-\rho^{K+1}}$
- Average number in the system:
  - $L = \frac{\rho}{1-\rho} - \frac{(K+1)\rho^{K+1}}{1-\rho^{K+1}}$
- Average number in the queue:
  - $L_q = L - (1 - \pi_0)$
- Average waiting time in the system (including transmission delay):
  - $W = \frac{L}{\bar{\lambda}}$, where $\bar{\lambda} = \sum_{i=0}^{+\infty} \lambda_i \pi_i = E[R]$
- Average waiting time in the queue:
  - $W_q = \frac{L_q}{\bar{\lambda}}$
- Maximum waiting time in the system ($k < K$):
  - $W_{max} = \frac{K \cdot l_{max}}{R}$, where l_{max} is the maximum packet size and R is the bitrate.
- Maximum waiting time in the queue ($k < K$):
  - $W_{qmax} = \frac{(K-1) \cdot l_{max}}{R}$

Independent Priority Queues

- Priority queue are quite complex to model accurately, even if separate queues per priority are considered.
- We will use the following approximation:
  - Priority of a packet defined as $p \in [0, P_{max}]$.
  - Assume that lower values of p means higher priority.
  - Assume that each different priority p has its own queue of length K_p, packet arrival rate λ_p, and average message size l_p.
  - Each priority p corresponds to an independent M/M/1/K_p process.
  - For priority p, consider that bitrate R_p and service rate μ_p are calculated as follows:
    - $R_p = \max\left(0, R - \sum_{i=0}^{p-1} l_i \cdot \lambda_i\right)$
    - $\mu_p = \frac{R_p}{l_p}$

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Independend Priority Queues

- Maximum times can be **meaningfully** obtained **only** for the highest priority queue:
  - Maximum waiting time in the system:
    - $W^0_{max} = \frac{(K_0-1)\cdot l^0_{max}+l_{max}}{R}$, where l^p_{max} is the maximum packet size of priority p, l_max is the maximum packet size in the system, and R is the bitrate.
  - Maximum waiting time in the queue:
    - $W^0_{qmax} = \frac{(K_0-2)\cdot l^0_{max}+l_{max}}{R}$

Networks of Queues

- Problem:
  - We know from the special case of two tandem queues that even if the packet streams are Poisson with independent packet lengths at their point of entry into the network, this property is lost after the first transmission line.

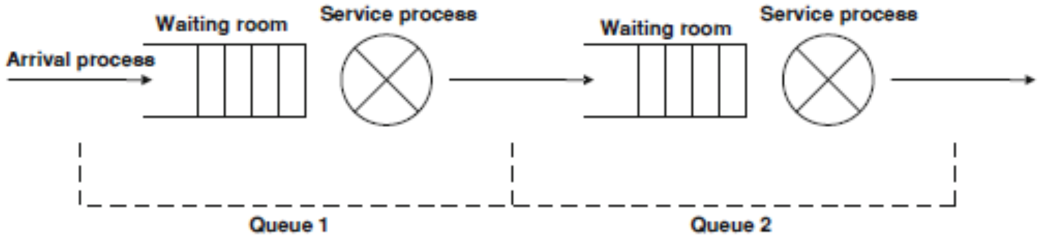
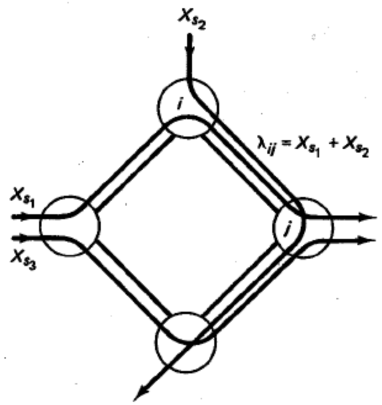


Fig. 9.3 The $M/M/1$ tandem queue

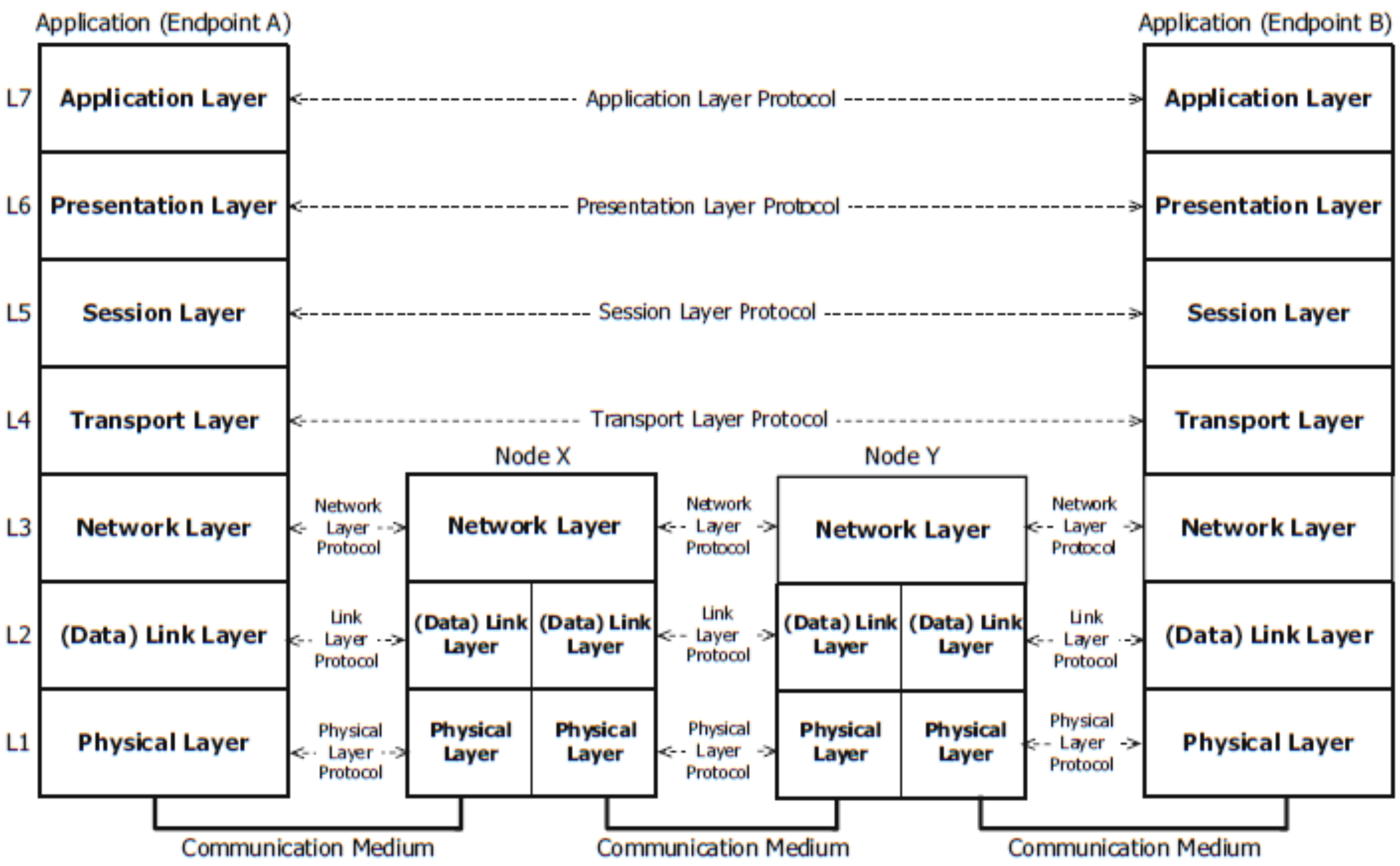
From the "Handbook of Healthcare System Scheduling"

Networks of Queues

- Kleinrock independence approximation for M/M/1 queues:
  - Merging several packet streams on a transmission line has an effect akin to restoring the independence of interarrival time and packet lengths.
  - It is often appropriate to adopt an M/M/1 queueing model for each communication link regardless of the interaction of traffic on this link with traffic on other links.
- In practice, even for models other than M/M/1, apply the independence approximation (though often optimistic):
  - Apply the queue model independently in each queue in the network.
  - Sum the delays in a path to obtain the end-to-end delay.



OSI Protocol Reference Model



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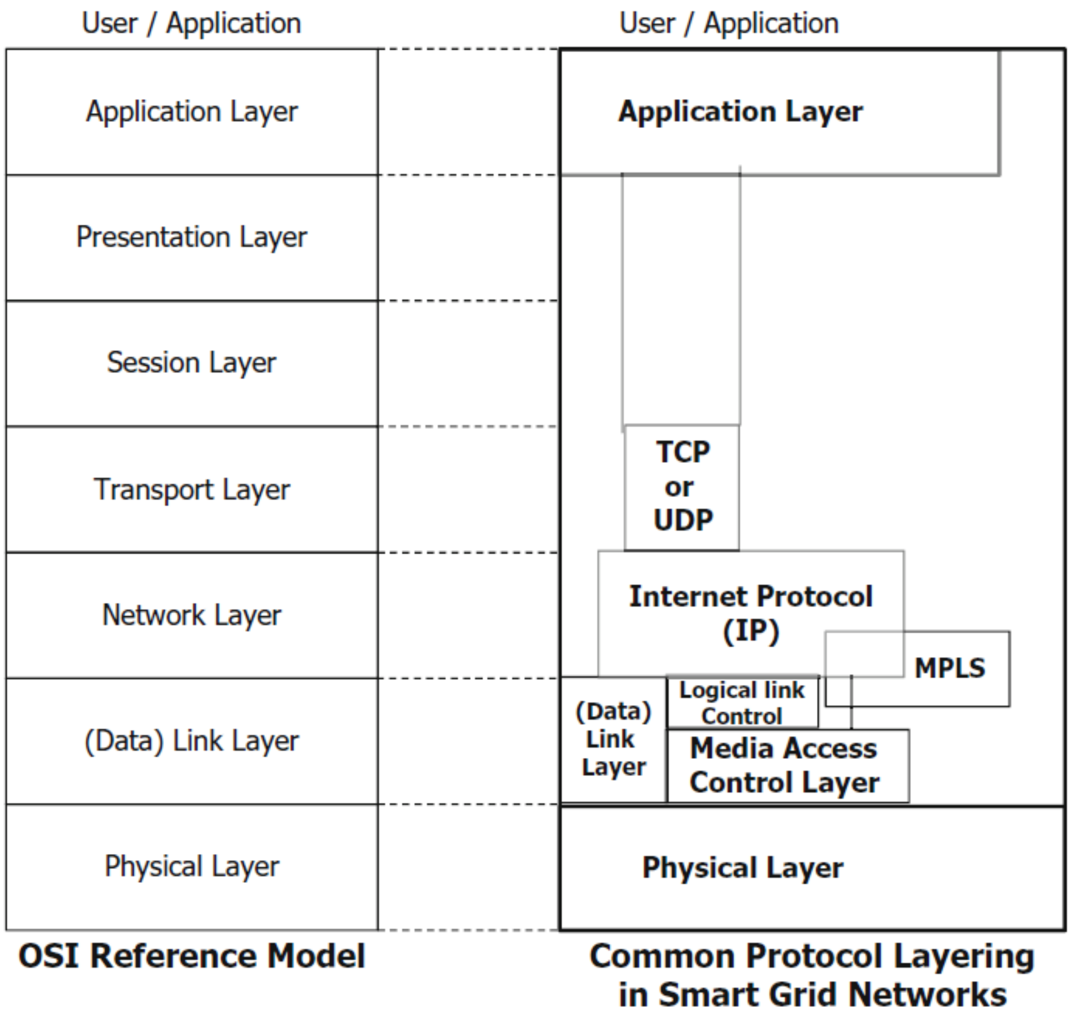
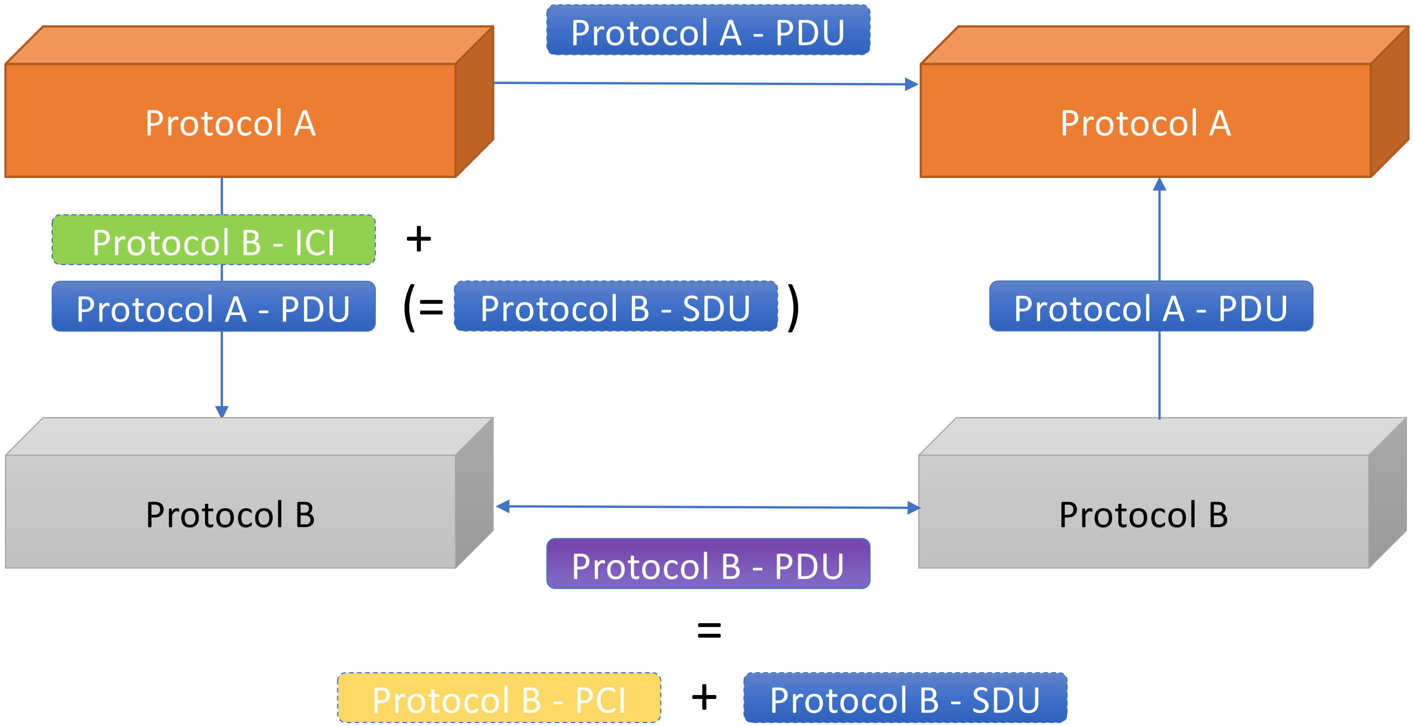
OSI Protocol Reference Model

Layer			Protocol data unit (PDU)	Function
Host layers	7	Application	Data	High-level APIs, including resource sharing, remote file access
	6	Presentation		Translation of data between a networking service and an application; including character encoding, data compression and encryption/decryption
	5	Session		Managing communication sessions, i.e., continuous exchange of information in the form of multiple back-and-forth transmissions between two nodes
	4	Transport	Segment, Datagram	Reliable transmission of data segments between points on a network, including segmentation, acknowledgement and multiplexing
Media layers	3	Network	Packet	Structuring and managing a multi-node network, including addressing, routing and traffic control
	2	Data link	Frame	Reliable transmission of data frames between two nodes connected by a physical layer
	1	Physical	Bit, Symbol	Transmission and reception of raw bit streams over a physical medium

Common Protocol Layers in Smart Grids



Protocol Nomenclature



PDU = Protocol Data Unit **SDU = Service Data Unit** **PCI = Protocol Control Information**

ICI = Interface Control Information IDU = Interface Data Unit = ICI + SDU

Protocol Encapsulation and Fragmentation

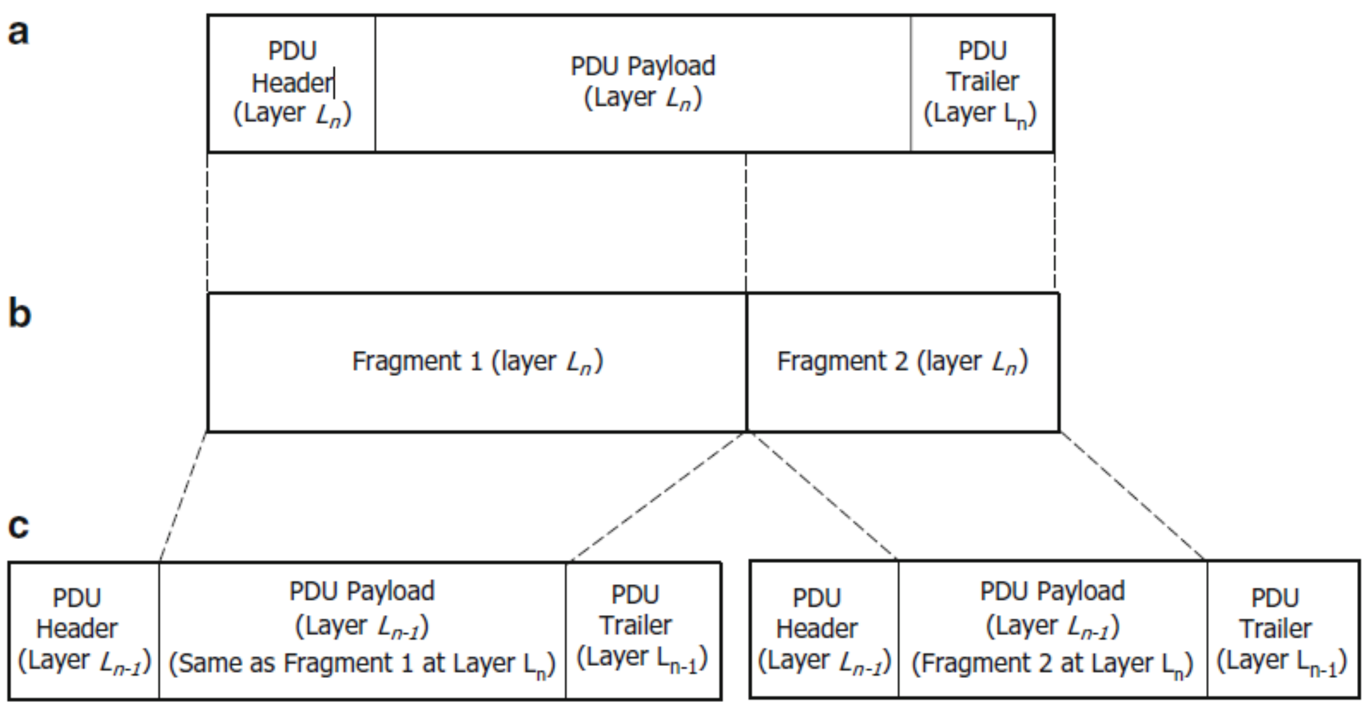
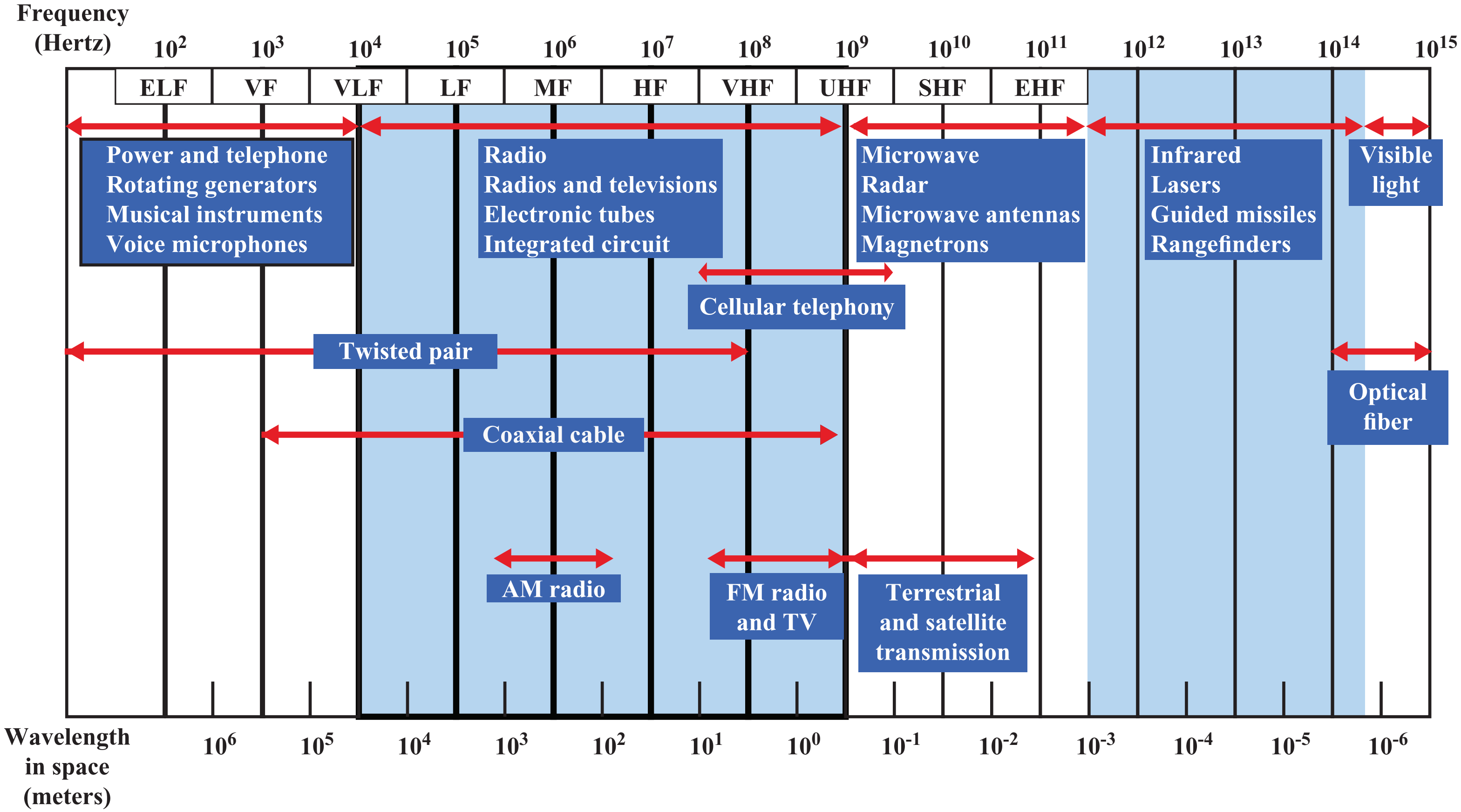


Fig. 3.5 Protocol data unit (PDU) format, fragmentation, and data payloads. (**a**) Header, PDU, and trailer. (**b**) Fragmenting. (**c**) Fragments as payloads in lower level PDUs

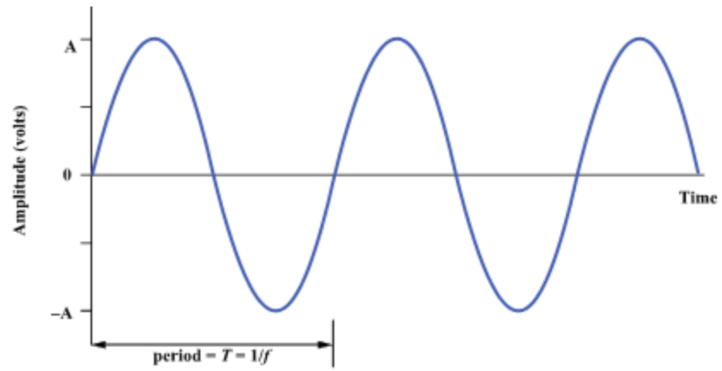
PHY Layer: Spectrum



ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

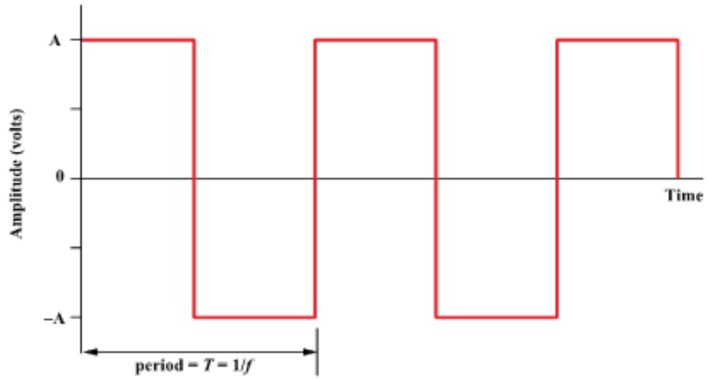
PHY Layer: Signals

- **Analog:** continuous time, continuous values



(a) Sine wave

- **Digital:** discrete time intervals, discrete values



(b) Square wave

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PHY Layer: Time Domain Concepts

- **Aperiodic signal** - analog or digital signal pattern that doesn't repeat over time
- **Periodic Signal** - analog or digital signal pattern that repeats over time
- **Peak amplitude (*A*)** - maximum value or strength of the signal over time; typically measured in volts
- **Frequency (*f*)**
  - Rate, in cycles per second, or Hertz (Hz) at which the signal repeats

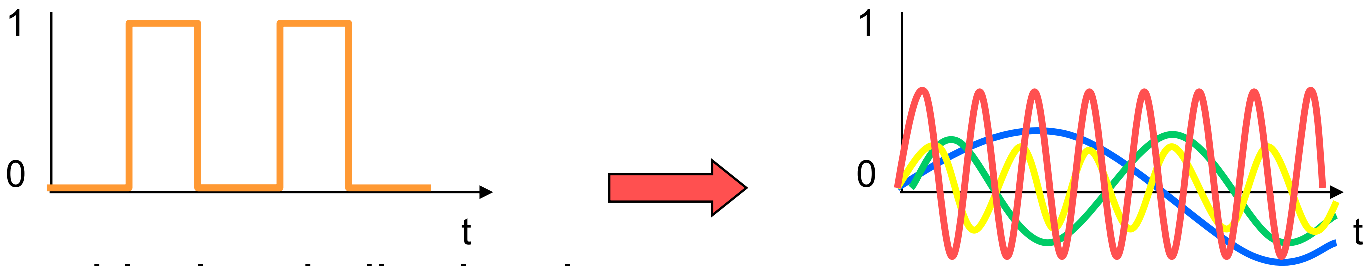
PHY Layer: Time Domain Concepts

- **Period (T)** - amount of time it takes for one repetition of the signal
  - $T = 1/f$
- **Phase (*ϕ*)** - measure of the relative position in time within a single period of a signal
- **Wavelength (*λ*)** - distance occupied by a single cycle of the signal
  - Or, the distance between two points of corresponding phase of two consecutive cycles
  - $\lambda = vT = v/f$
- At a particular instant of time, the intensity of the signal varies as a function of distance from the source

$$s(t,d) = A \sin(2\pi ft - \frac{2\pi d}{\lambda} + \phi)$$

PHY Layer: Composition of Periodic Signals

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n f t) + \sum_{n=1}^{\infty} b_n \cos(2\pi n f t)$$

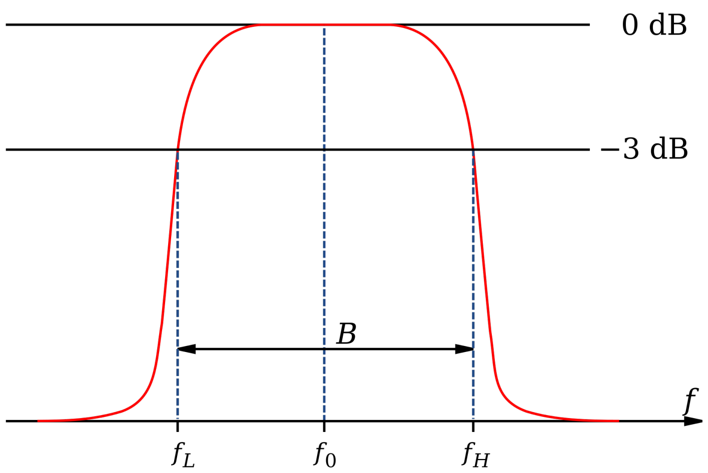


ideal periodic signal

real composition (based on harmonics)

PHY Layer: Frequency Domain Concepts

- **Fundamental frequency -** when all frequency components of a signal are integer multiples of one frequency, it's referred to as the fundamental frequency
- **Spectrum -** range of frequencies that a signal contains
- **Absolute bandwidth -** width of the spectrum of a signal
- **Effective bandwidth (or just bandwidth) -** narrow band of frequencies that most of the signal's energy is contained in



PHY Layer: Concepts Related to Channel Capacity

- **Data:** entities that convey meaning, or information – **bits or sequences of bits.**
- **Signals:** electric or electromagnetic representations of **data**
- **Symbol:** elementary signal element (each symbol represents a number of **data bits**)
- **Data rate (*Rb*):** number of **data bits** transmitted per unit time
  - Other conditions being the same: **data rate ∝ bandwidth**
- **Symbol rate or baud rate (*Rs*):** number of symbols transmitted per second
  - *Rb = C x Rs, where C is the number of **data bits** encoded in one **symbol***
- **Shannon-Heartley Theorem (Shannon Capacity Limit):**

$$C = B \log_2 (1 + \mathrm{SNR})$$

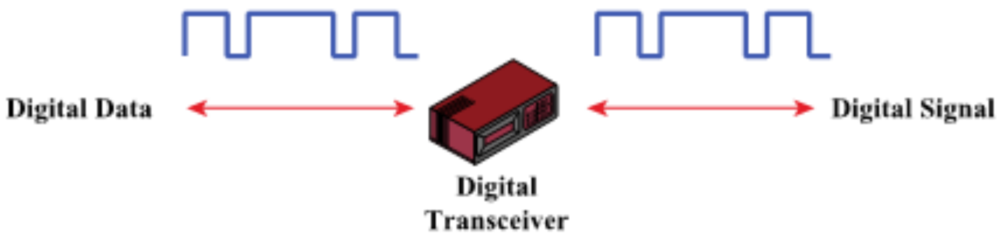
- **Signal-to-Noise Ratio (SNR):**
  - S/N, where S is signal power and N is noise power.

PHY Layer: Transmission Media

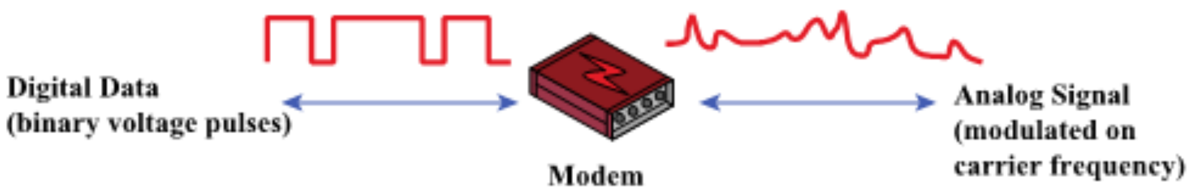
- Transmission Medium
  - Physical path between transmitter and receiver
- Guided Media
  - Waves are guided along a solid medium
  - E.g., copper twisted pair, copper coaxial cable, optical fiber
- Unguided Media
  - Provides means of transmission but does not guide electromagnetic signals
  - Usually referred to as wireless transmission
  - E.g., atmosphere, outer space

PHY Layer: Transmission of Digital Data

- By means of **digital signal**:



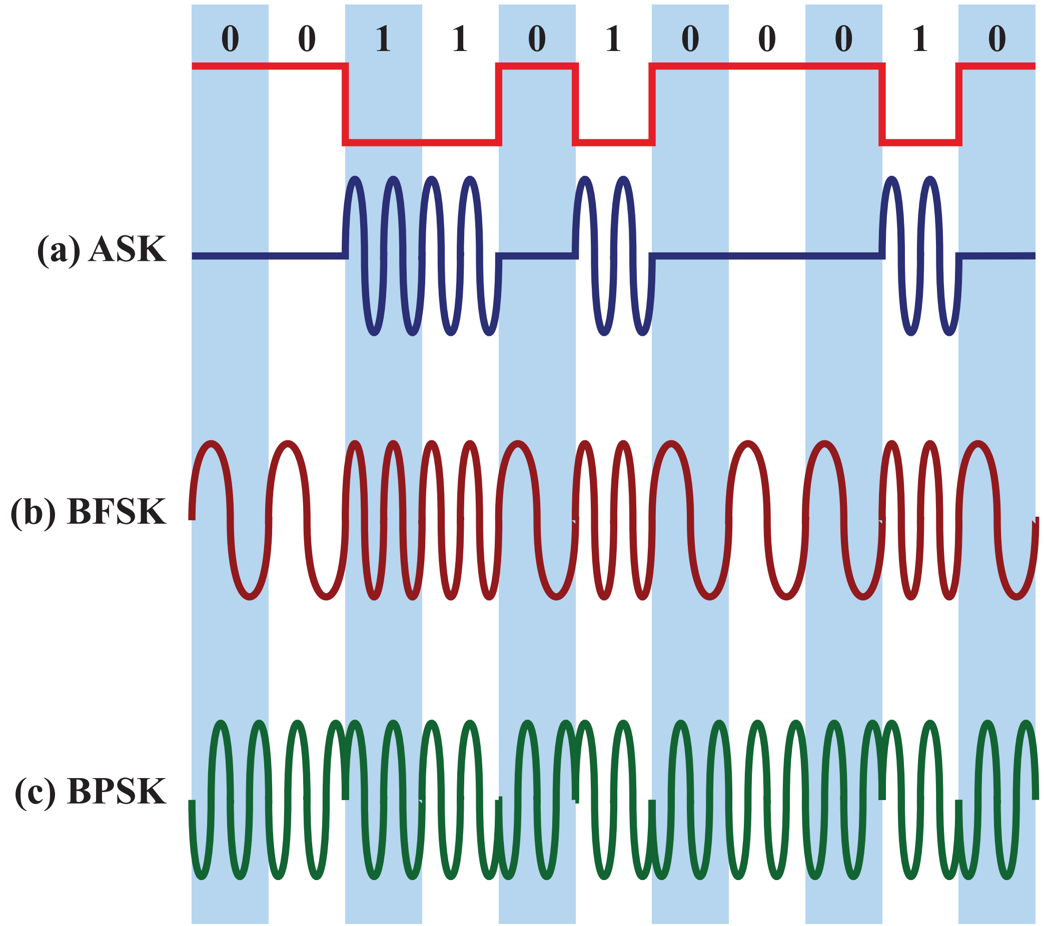
- By means of **analog signal**:



PHY Layer: Transmission of Digital Data using Analog Signals

- Some transmission media will only propagate analog signals
  - E.g., optical fiber and unguided media

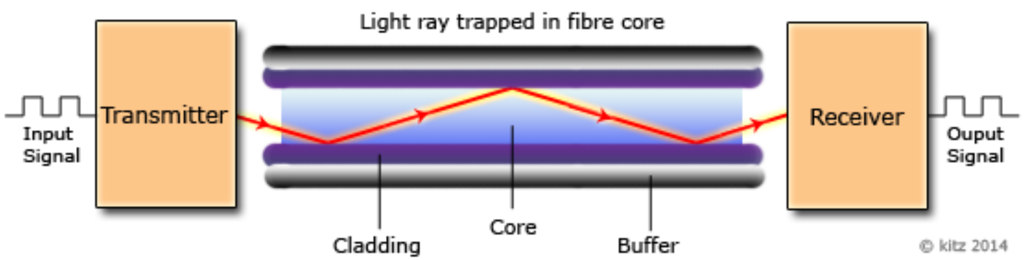
- The **data bit** stream modulates a carrier sinusoid wave changing sinusoid parameters



TÉCNICO LISBOA

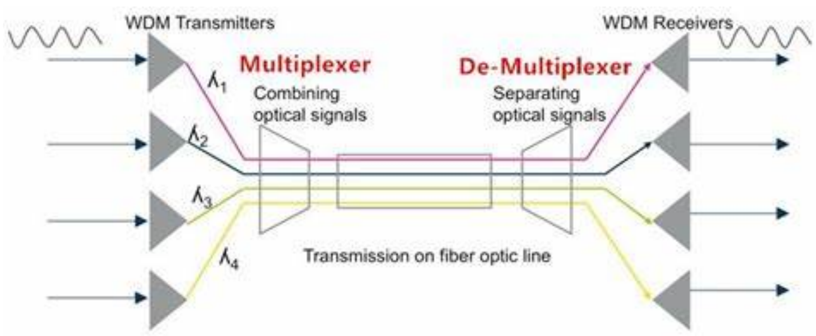
PHY Layer: Optical Fiber

- Optical fiber: flexible, transparent fiber made by drawing glass (silica) or plastic to a diameter slightly thicker than that of a human hair
- Guided medium
- Light-emitting diode (LED) or injection laser diode (ILD) used to encode data by the presence or absence of light (ASK, on-off keying)
- Wavelengths: 800 nm to 1600 nm
- Data rates as high as 400 Gbit/s
- Optical fiber advantageous in the vicinity of high voltage lines due to the possibility of Ground Potential Rise (GPR)
- Attenuation Loss:
  - $P_d[dBm] - P_0[dBm] = -\alpha \cdot d[km]$
  - $\alpha \cong$ 0.1-5.0 dB/km



PHY Layer: Transport Technologies

- Wavelength Division Multiplexing (WDM):
  - WDM is the technique used for transmitting multiple optical signals in the same fiber.
  - Each signal is encoded as a different optical frequency and is referenced by its frequency or by the equivalent wave length (lambda). Each lambda is a distinct optical channel.
  - ITU published a list of acceptable frequencies, known as "grids". Each grid determines a set of uniformly spaced wavelengths used for a certain application.
  - For instance, for Coarse WDM (CWDM) there is a grid of 18 lambdas with a 2500 GHz (20nm) between lambdas.
  - For Dense WDM (DWDM), there are several grids with typical spacing of 100, 50 or 25 GHz.

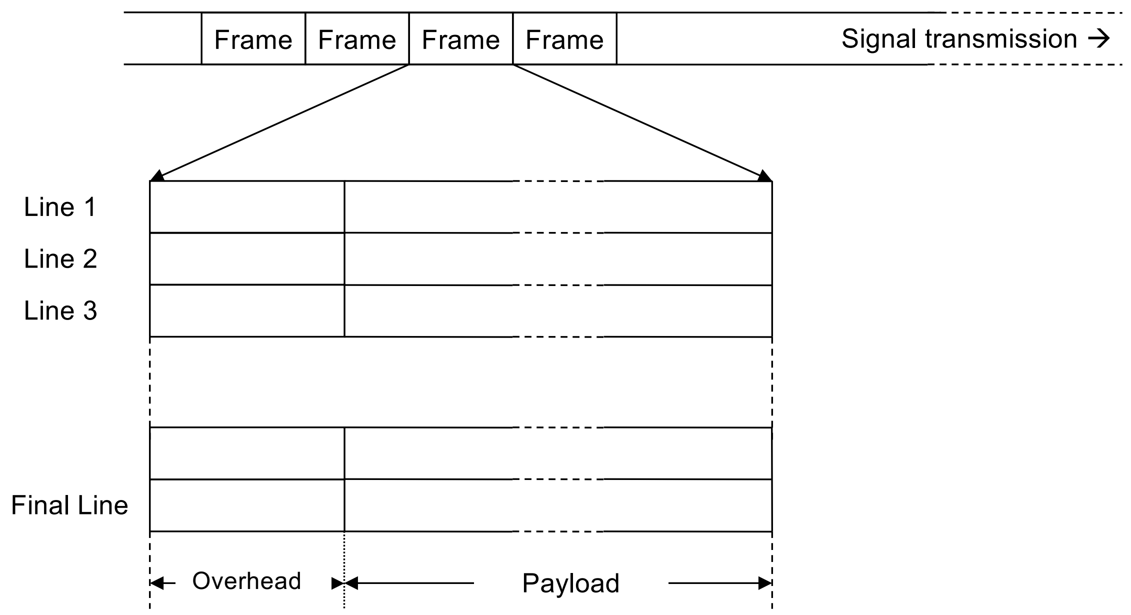


PHY Layer: Transport Technologies

- Time Division Multiplexing (TDM):
  - The transmitted signal is segmented into frames (this frame is different from a layer 2 frame)
  - Each frame is a sequence of bytes to be transmitted into the cable or fiber.
  - There is a fixed frame rate per second, depending on the frame size and the line speed. The usual rate is 8000 frames/s.
  - Each frame consists on several groups of bytes, where all groups have the same fixed size. Each group is called a "line". Lines are multiplexed into the transmission medium in increasing order.
  - The first bytes in each line have control information and the remaining application information (payload).
  - For each traffic flow, a certain number of lines is assigned, so that flows can get different fractions of the total bandwidth.

PHY Layer: Transport Technologies

- Time Division Multiplexing (TDM):



TDM Signal

PHY Layer: Transport Technologies

- Synchronous Digital Hierarchy (SDH) and Synchronous Optical Network (SONET) are two recognized TDM standards.
- SDH and SONET are very similar, although they differ in a few details.
- SONET is used in North America.
- SDH is used elsewhere (e.g. Europe).

PHY Layer: Transport Technologies

- Multiplexing rate for SONET (USA) and SDH (Synchronous Digital Hierarchy) (Europe):

SONET		SDH	Data rate (Mbps)		
Electrical	**Optical**	**Optical**	**Gross**	**SPE**	**User**
STS-1	OC-1		51.84	50.112	49.536
STS-3	OC-3	STM-1	155.52	150.336	148.608
STS-9	OC-9	STM-3	466.56	451.008	445.824
STS-12	OC-12	STM-4	622.08	601.344	594.432
STS-18	OC-18	STM-6	933.12	902.016	891.648
STS-24	OC-24	STM-8	1244.16	1202.688	1188.864
STS-36	OC-36	STM-12	1866.24	1804.032	1783.296
STS-48	OC-48	STM-16	2488.32	2405.376	2377.728
STS-192	OC-192	STM-64	9953.28	9621.504	9510.912

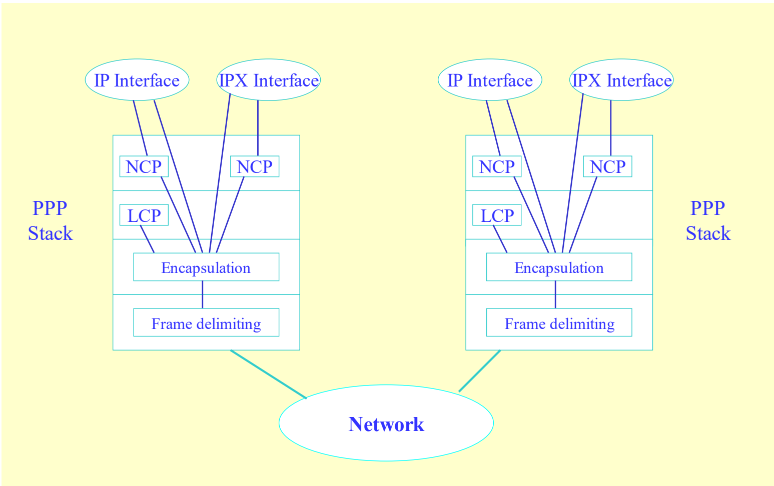
*: rarely used

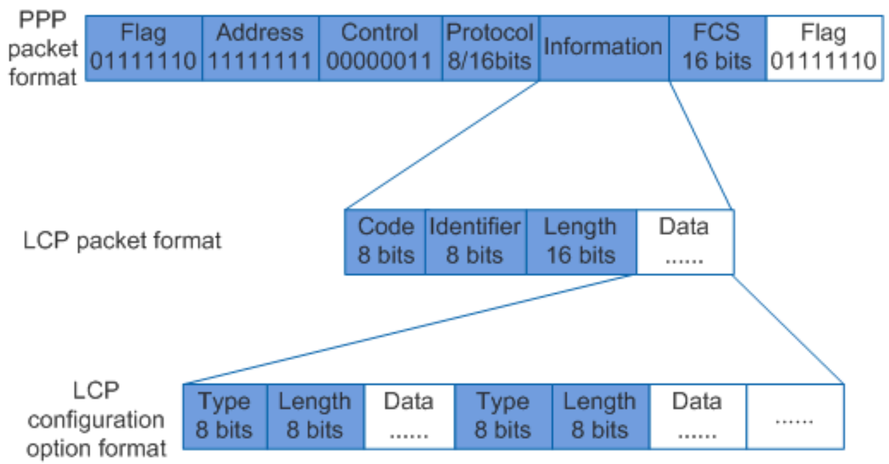
Link Layer: PPP

- Point-to-Point Protocol (PPP) defines a single L2 layer between a pair of systems over the L1 layer.
- PPP is described in RFC 1661.
- Contains a self-configurable mechanism for variable sized packet transfer over serial, full-duplex and point-to-point links.
- It is widely used as layer 2 protocol to connect residential users to an ISP.
- Its main function is isolating higher layers from the multiplexing and frame delimitation mechanisms associated with the use of point-to-point links.
- PPP supports authentication: PAP, CHAP, EAP.
- PPP supports encryption: ECP.

Link Layer: PPP

- PPP functions:
  - Frame delimiting
  - Transparency in layer 3 information transportation
  - Support for multiple network protocols
  - Error detection
  - Link state detection
- PPP is defined at three levels: Frame delimiting and encapsulation, Link Control Protocol (LCP) and Network Control Protocol (NCP).
- Frame is based on HDLC frame, adding 2 bytes in the header.
- Traffic in the link is a mixture of NCP and LCP control messages, and information messages.



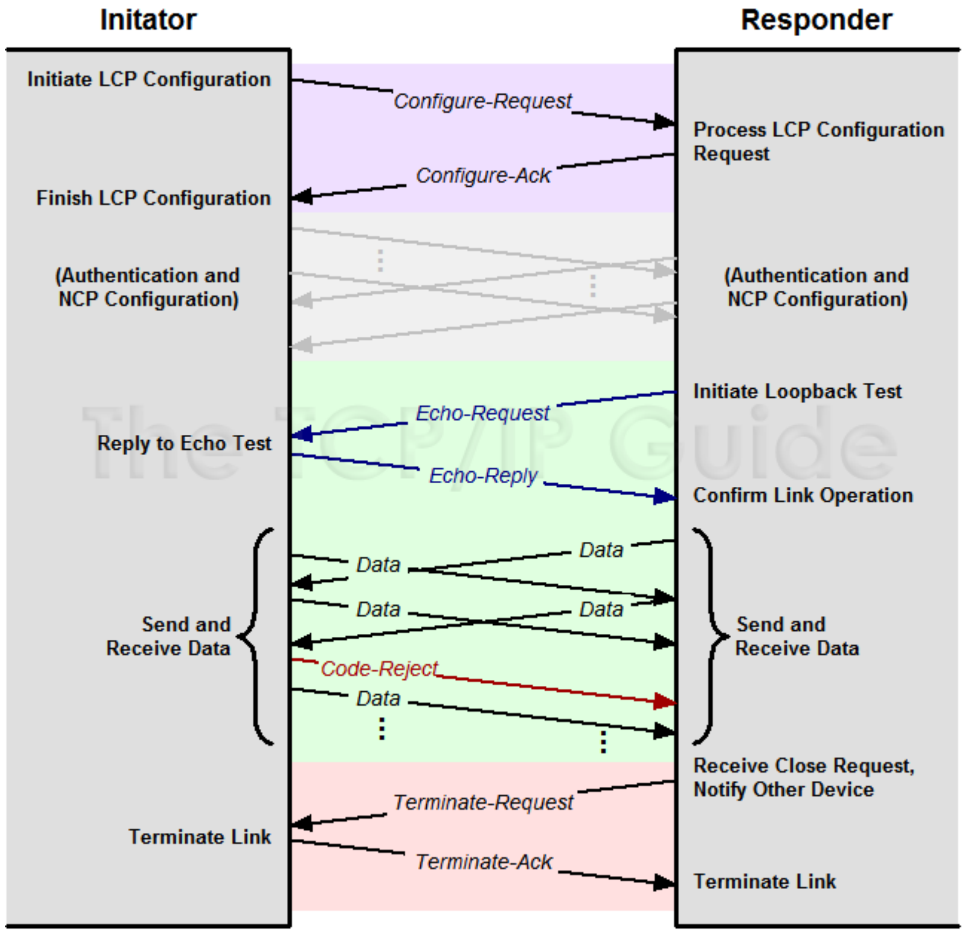


Link Layer: PPP

- Link Control Protocol (LCP)
  - LCP role is to provide parameter self-configuration common to all network protocols sharing the link. These parameters include: link state, encapsulation format options, packet size limits in both directions, authentication of the identity of its peer on the link, link quality monitoring and configuration of failure detection.
  - LCP messages are carried within PPP frames with a protocol field equal to C021H.
  - When a link is established, the LCP protocol determines if the link can be considered operational.
- Network Control Protocol (NCP)
  - NCPs are used for negotiating the parameters and facilities for the network layer.
  - For every higher-layer protocol supported by PPP, one NCP is there.
  - E.g., Internet Protocol Control Protocol (IPCP) − IPCP establishes and configures Internet Protocol (IP) over a PPP link. It configures the IP addresses in addition to enabling/disabling IP protocol modules on either end of the PPP link.
  - After LCP declares a link as operational, each NCP starts negotiating with its peer in the link to determine if the link is adequate for the objectives of the protocol supported.
  - NCP control messages are transported within PPP frames.

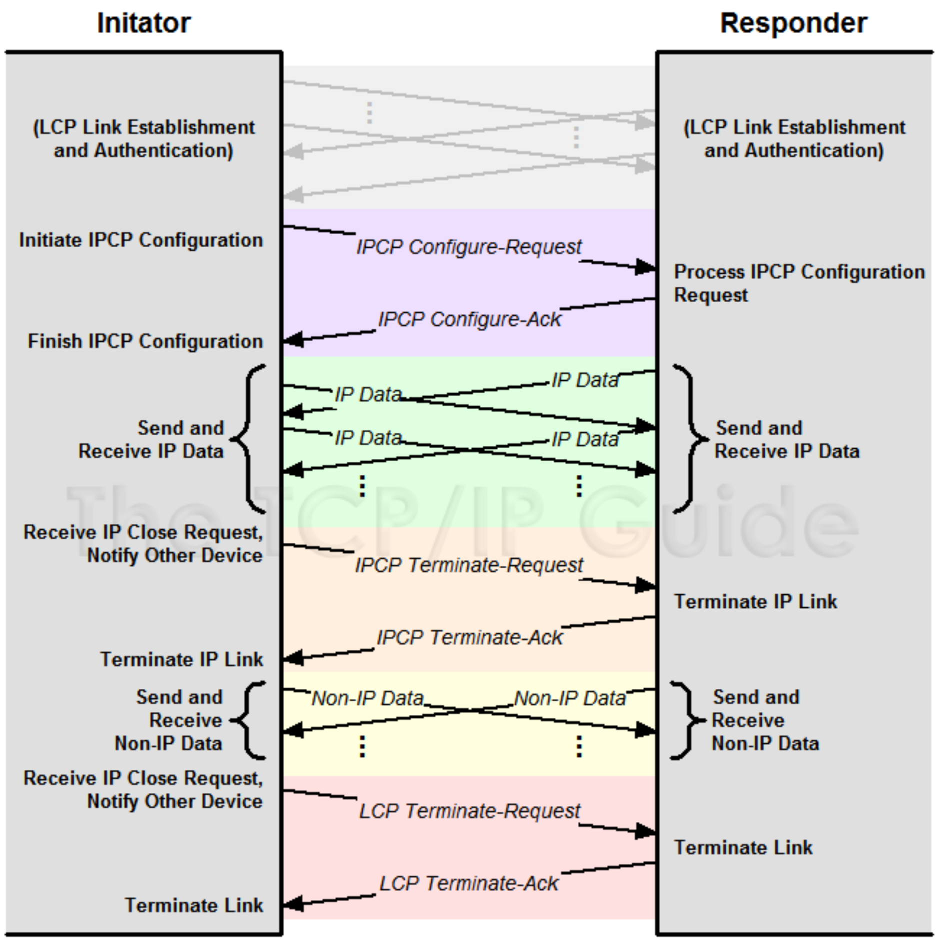
Link Layer: PPP

- PPP link establishment (generic):



Link Layer: PPP

- PPP link establishment (IPCP = NCP for IP):

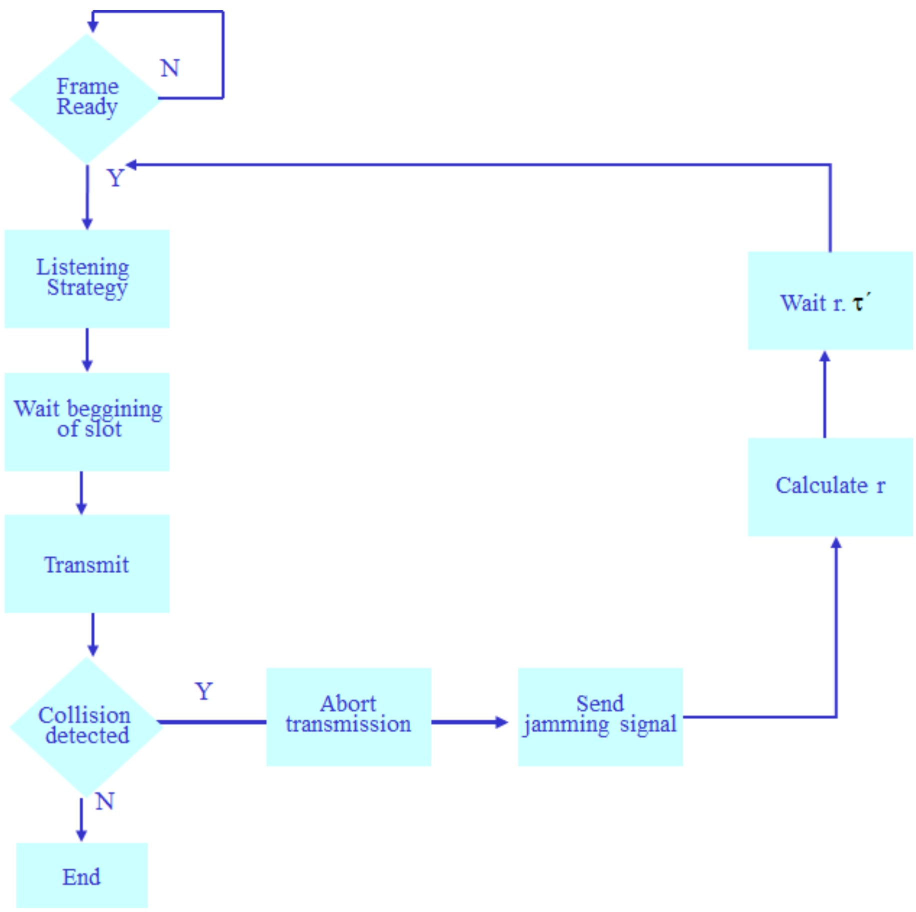


Link Layer: Ethernet

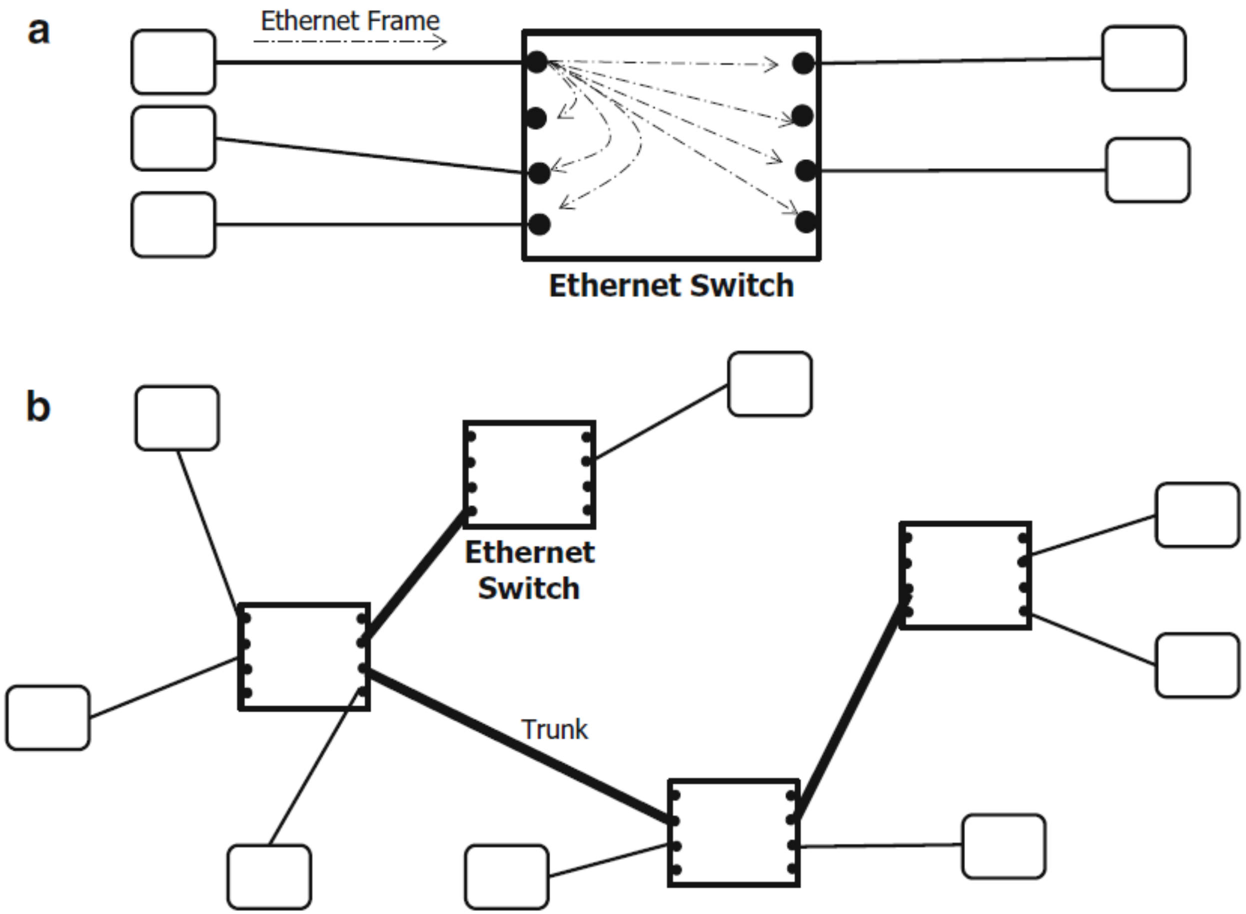
- Protocol originally developed by XEROX. The final specification was jointly done by XEROX, DEC and INTEL for the Ethernet system.
- IEEE 802.3 standard for LANs is based on the Ethernet specification.
- Ethernet is a MAC layer protocol and uses a Carrier Sense Multiple Access with Collision Detection (CSMA/CD) algorithm.
- CSMA/CD can be: non-persistent or 1-persistent.
- Collisions are detected by monitoring the signal directly in the channel. When signals of two or more terminals overlap, the waveform is altered.

Link Layer: Ethernet

- When a collision is detected, frame transmission is immediately aborted, a jamming signal is transmitted and a waiting scheme similar to CSMA is entered. All other terminals receiving the jamming signal also abort their transmissions.
- A terminal that has a frame to send takes the following actions:
  - If the channel is free: transmits the frame
  - If the channel is busy:
    - non-persistent: the frame is placed in stand-by and the listening strategy algorithm is executed.
    - 1-persistent: waits for the channel to be free to transmit.

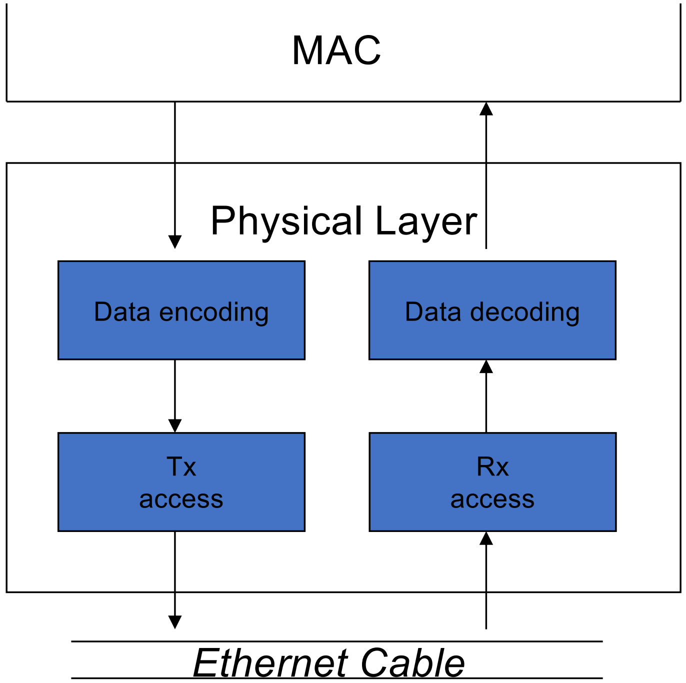


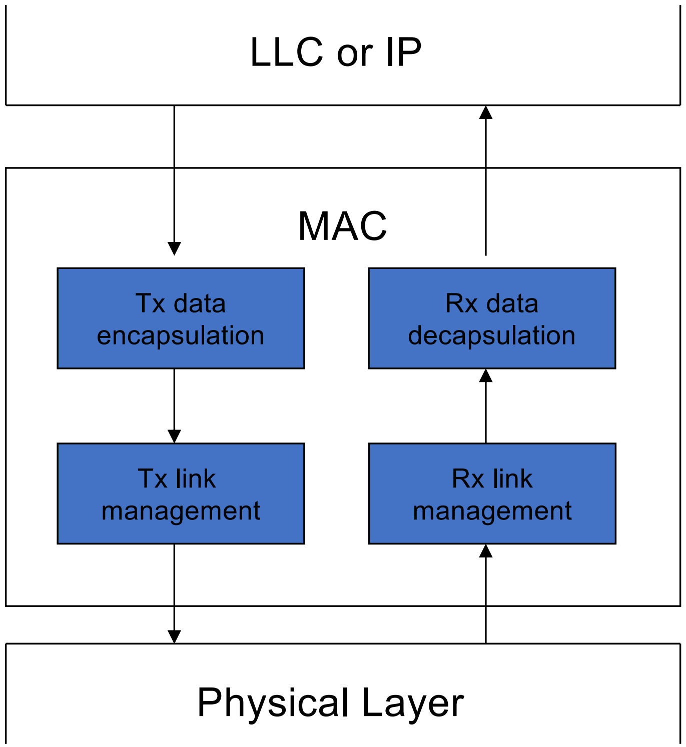
Link Layer: Ethernet



Link Layer: Ethernet

- Protocol stack:





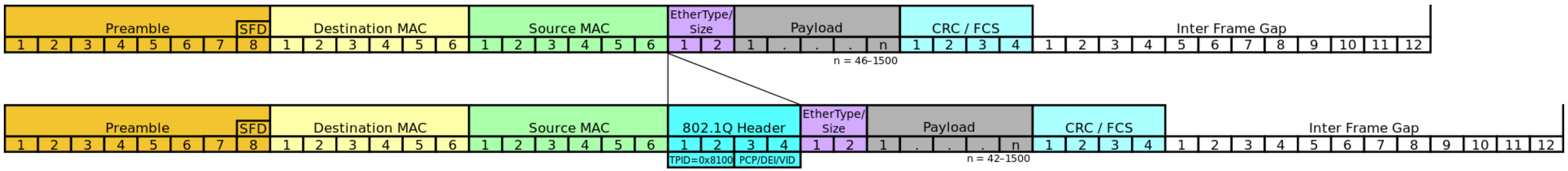
Link Layer: Ethernet

- Ethernet frame:
  - Preamble: set of alternating 1s and 0s, terminating with a 0 bit. Used for synchronization.
  - SFD (Start of Frame Delimiter): 10101011
  - Addresses: can have 16 or 48 bits, depending on the implementation. Should be of the same size for all LAN terminals.
  - Size/Protocol: number of bytes of the data field, or the higher layer protocol (value ≥1536).
  - Pad: bytes to guarantee a minimum frame size.
  - FCS: frame check sequence calculated over all fields, except Preamble and SFD.
  - Minimum inter-frame gap: 12 bytes

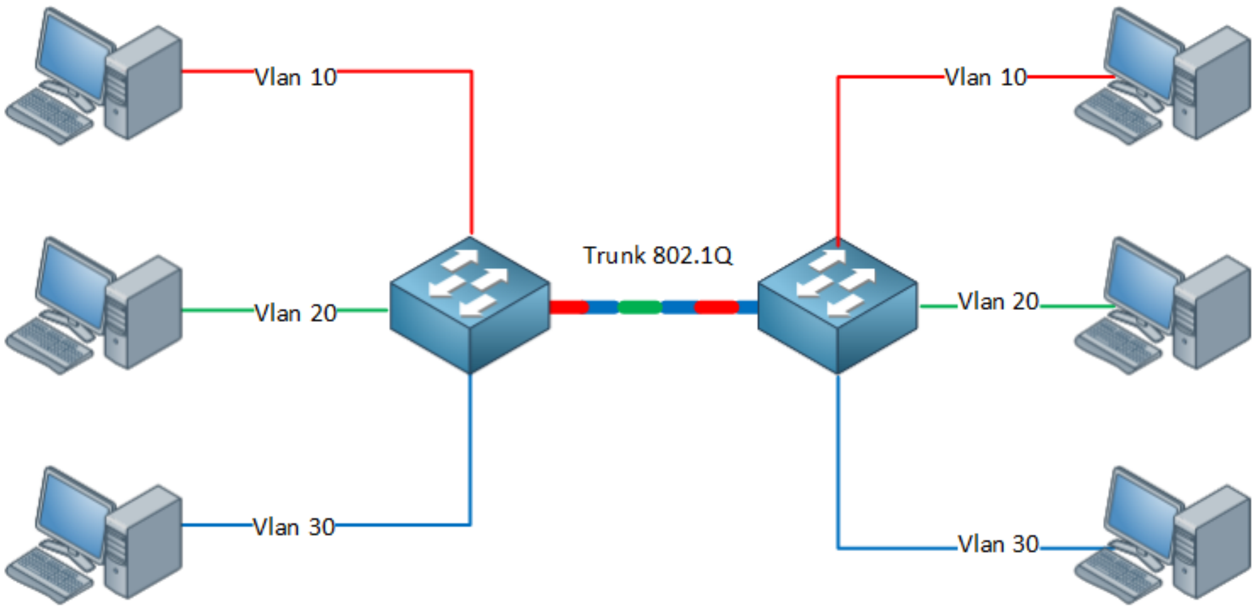
7	1	2/6	2/6	2	<------- 46-1500	-------->	4	Bytes
Preamble	SFD	Destination address	Source address	Size/ Protocol Type	Data	*Padding*	FCS	

SFD: Start of Frame Delimiter
FCS: Frame Check Sequence

Link Layer: IEEE 802.1Q Ethernet VLAN



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



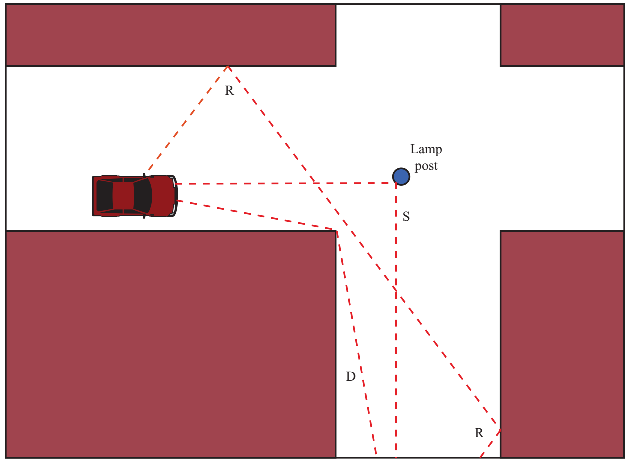
https://networklessons.com/switching/802-1q-encapsulation-explained

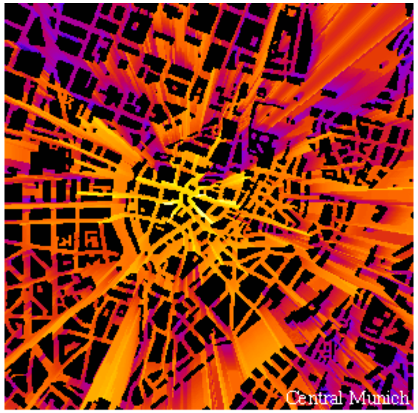
Link Layer: IEEE 802.1Q Ethernet VLAN

- Tag protocol identifier (TPID):
  - A 16-bit field set to a value of 0x8100 in order to identify the frame as an IEEE 802.1Q-tagged frame.
- Tag control information (TCI)
  - A 16-bit field containing the following sub-fields:
    - Priority code point (PCP):
      - A 3-bit field which refers to the IEEE 802.1p class of service and maps to the frame priority level.
    - Drop eligible indicator (DEI):
      - A 1-bit field, which may be used separately or in conjunction with PCP to indicate frames eligible to be dropped in the presence of congestion.
    - VLAN identifier (VID):
      - A 12-bit field specifying the VLAN to which the frame belongs.

PHY Layer: Electromagnetic Waves

- Air, Vacuum (less effective underwater)
- Unguided medium
- Antenna: electrical conductor or system of conductors:
  - Transmission - radiates electromagnetic energy into space
  - Reception - collects electromagnetic energy from space
  - May be directional
- Propagation effects:
  - path loss, reflection, refraction, diffraction, scattering, Doppler, noise, interference
- Frequencies: 3 kHz – 1 PHz
- Data rates as high as multi Gbit/s



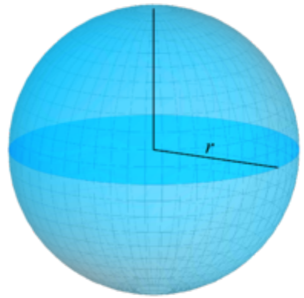


PHY Layer: Electromagnetic Waves

Elements of Data Communication Networks
Classification of Networks
Elements of Packet Communication
Data Communication Technologies
Communication Network Architectures for Smart Grids

- Signal attenuation with distance:
  - Free Space Propagation (Friis model):

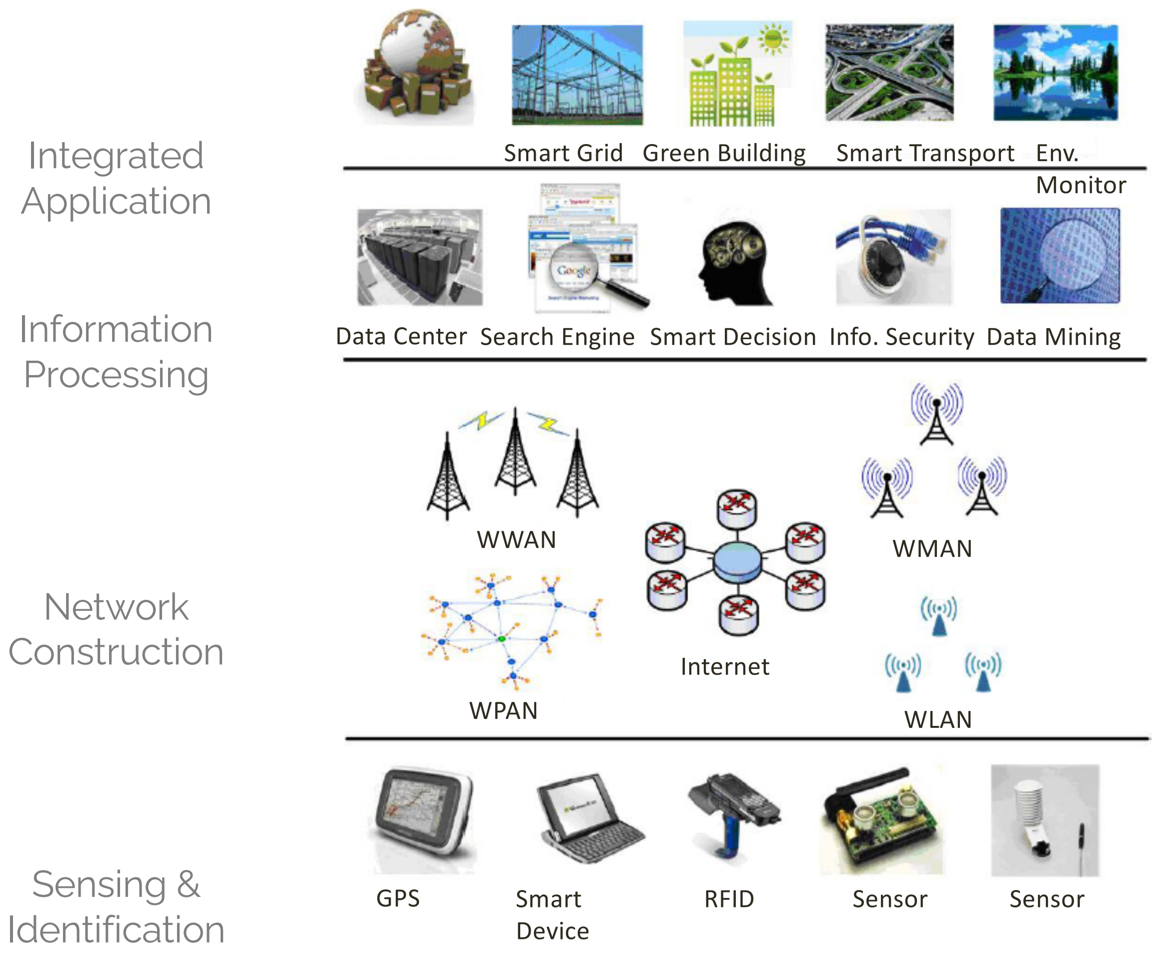
$$\frac{P_t}{P_r} = \frac{PL}{G_t G_r} = \frac{(4\pi d)^2}{G_t G_r \lambda^2} = \frac{(4\pi d f)^2}{G_t G_r c^2}$$



  - Log-Distance model (more general):
    - *Path Loss (PL) = Transmit Power (Pt) – Received Power (Pr)*

$$PL_{d_0 \to d}(dB) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + \chi \qquad d_f \le d_0 \le d$$

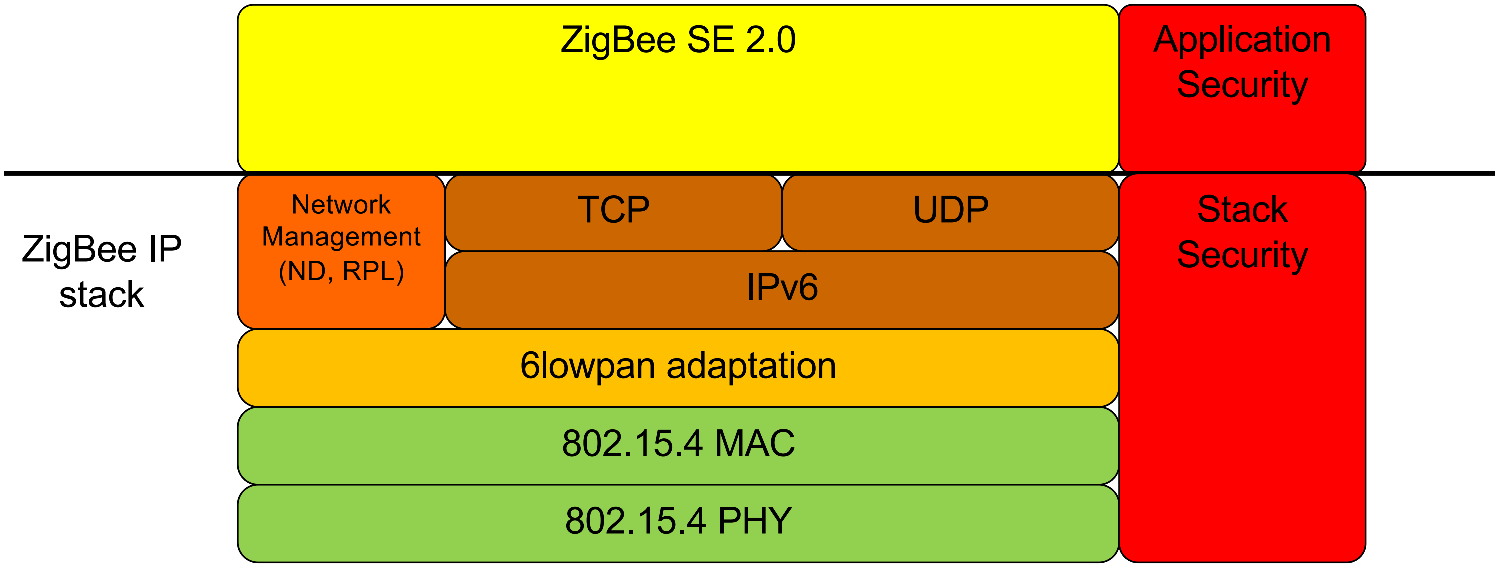
IoT



Integrated Application
Smart Grid
Green Building
Smart Transport
Env. Monitor
Information Processing
Data Center
Search Engine
Smart Decision
Info. Security
Data Mining
Network Construction
WWAN
WMAN
Internet
WPAN
WLAN
Sensing & Identification
GPS
Smart Device
RFID
Sensor
Sensor

Link Layer: IEEE 802.15.4

- ZigBee Smart Energy (SE) protocol stack:



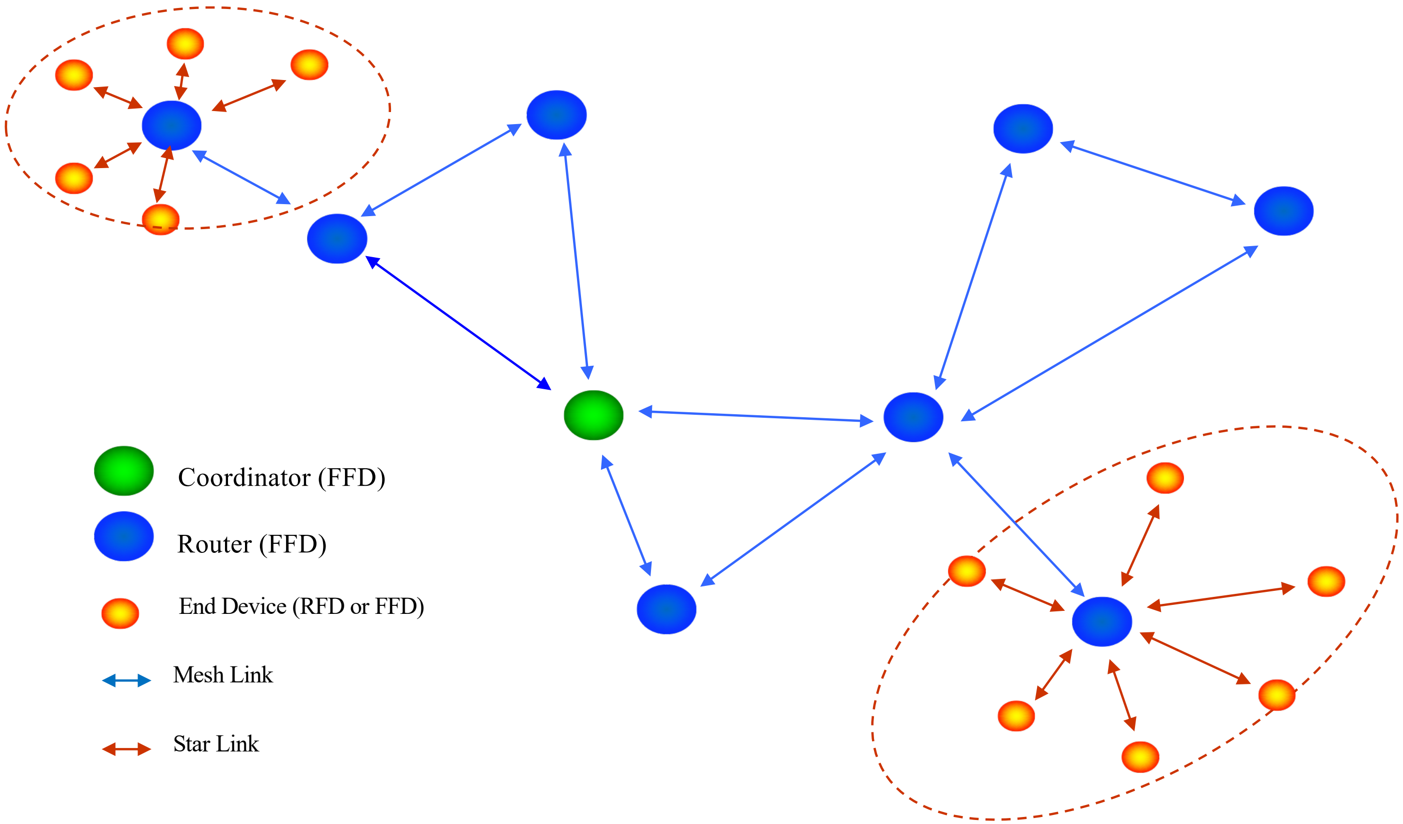
Link Layer: IEEE 802.15.4

- Frequencies and Data Rates (2006):

	BAND	COVERAGE	DATA RATE	# of CHANNELS
2.4GHz	ISM	Worldwide	250kbps	16
868 MHz		Europe	20kbps, 100kbps, 250kbps	1
915MHz	ISM	Americas	250kbps, 40kbps	10

Link Layer: IEEE 802.15.4

- Mesh network architecture (e.g., using AODV routing):



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Link Layer: IEEE 802.15.4

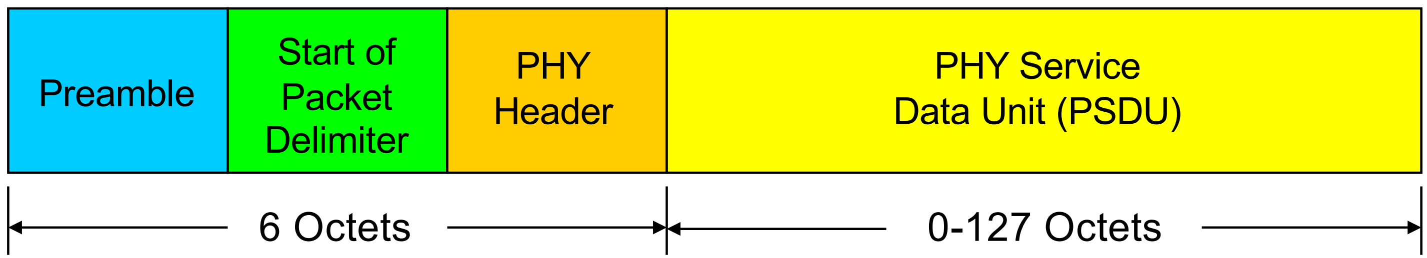
- Addressing:
  - All devices have 64 bit IEEE addresses
  - Short addresses can be allocated
  - Addressing modes:
    - Network + device identifier (star)
    - Source/destination identifier (peer-peer)

Link Layer: IEEE 802.15.4

- IEEE 802.15.4 PHY frame:

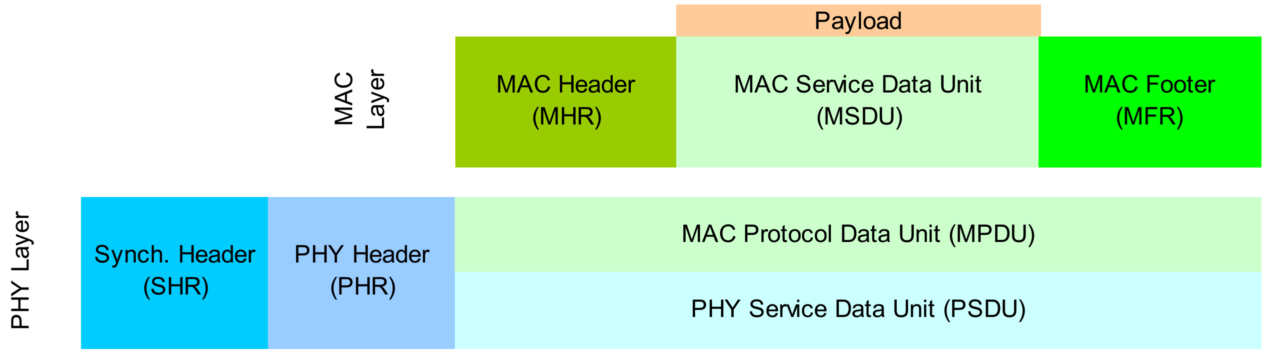
PHY Packet Fields

- Preamble (32 bits) – synchronization
- Start of Packet Delimiter (8 bits)
- PHY Header (8 bits) – PSDU length
- PSDU (0 to 1016 bits) – Data field



Link Layer: IEEE 802.15.4

- MAC frame encapsulation:



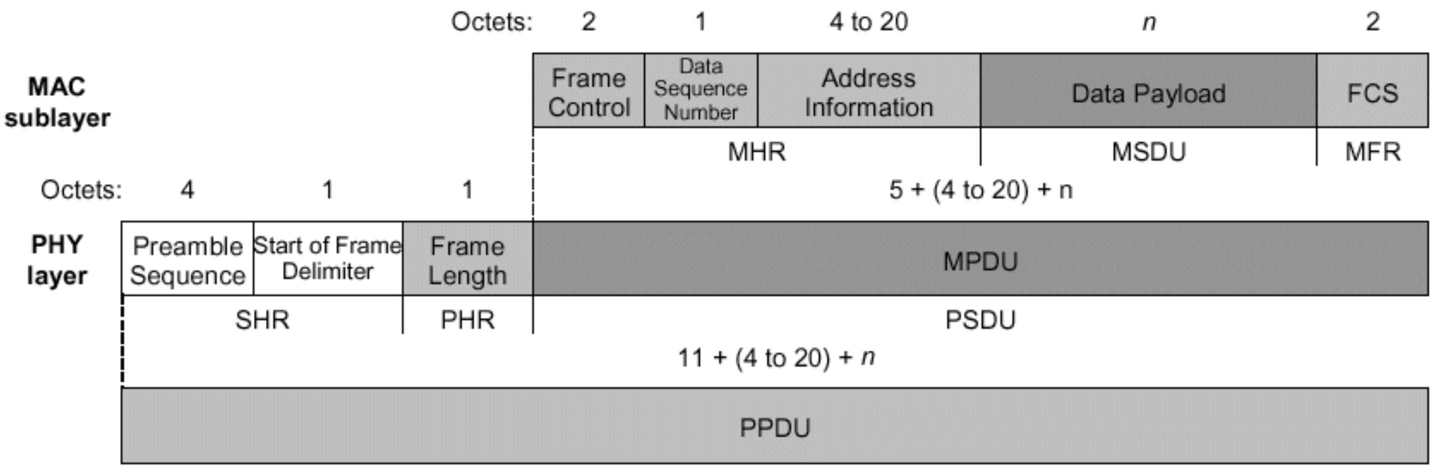
4 Types of MAC Frames:

- Data Frame
- Acknowledgment Frame
- MAC Command Frame
- Beacon Frame

Link Layer: IEEE 802.15.4

Elements of Data Communication Networks
Classification of Networks
Elements of Packet Communication
Data Communication Technologies
Communication Network Architectures for Smart Grids

- Data frame format:



One of two most basic and important structures in 802.15.4

Provides up to 104 byte data payload capacity

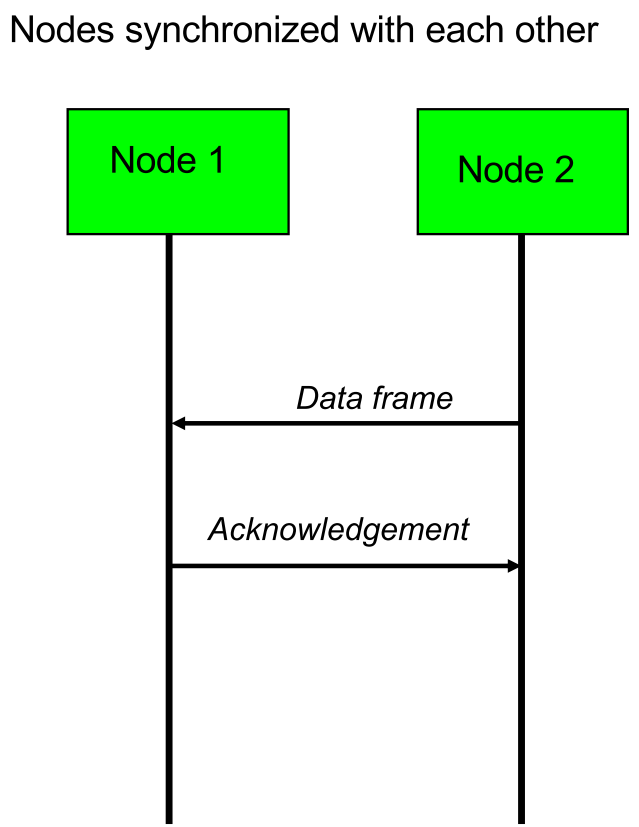
Data sequence numbering to ensure that packets are tracked

Robust structure improves reception in difficult conditions

Frame Check Sequence (FCS) validates error-free data

Link Layer: IEEE 802.15.4

- Peer-to-peer transfer:



TÉCNICO LISBOA

Network Layer: Internet Protocol (IP)

- Functions:
  - Addressing
  - Forwarding
  - QoS
  - Protocol Multiplexing
  - Error Detection
  - Fragmentation
  - Loop Elimination

Network Layer: Internet Protocol (IP)

Elements of Data Communication Networks
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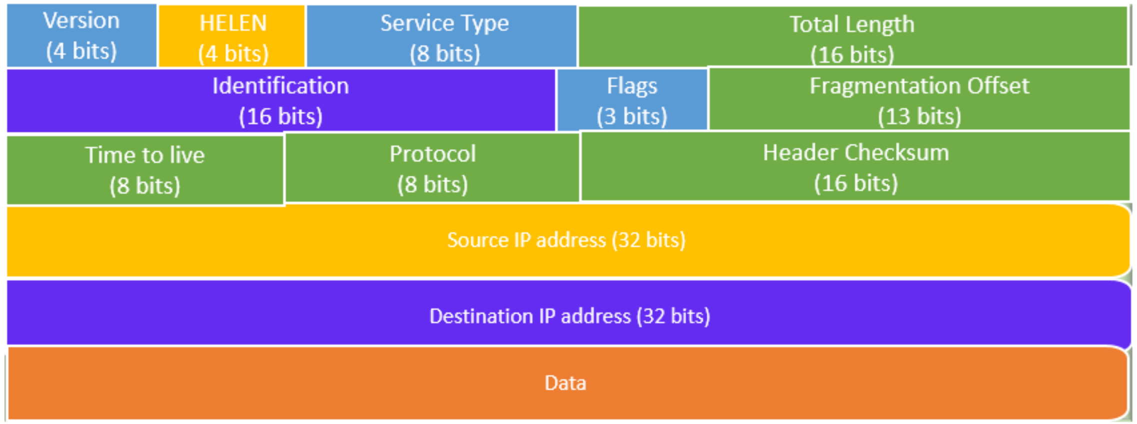
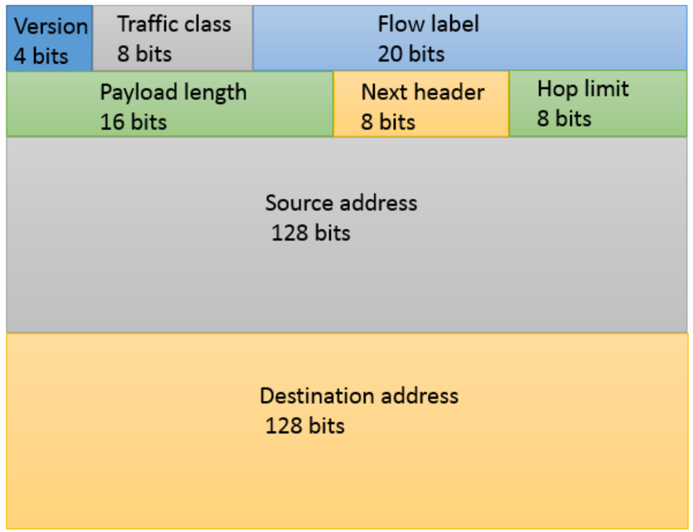
- IPv4
  - Addressing:
    - Classless Inter-Domain Routing (CIDR) notation:
      - Network address: comprises 4 integers between 0 and 255, separated by '.'. Each of these integers occupies 1 octet.
      - Symbol '/'
      - Length of the subnetwork mask: an integer between 1 and 32.
    - The subnetwork mask indicates the number of bits, counting from the left, which correspond to the subnetwork prefix.
      - The remaining bits identify the specific interface within the subnetwork.
    - E.g., 10.2.1.4/24:
      - In binary notation: 00001010.00000010.00000001.00000100
      - Subnetwork prefix: 10.2.1
      - Specific interface: 4
  - Header:



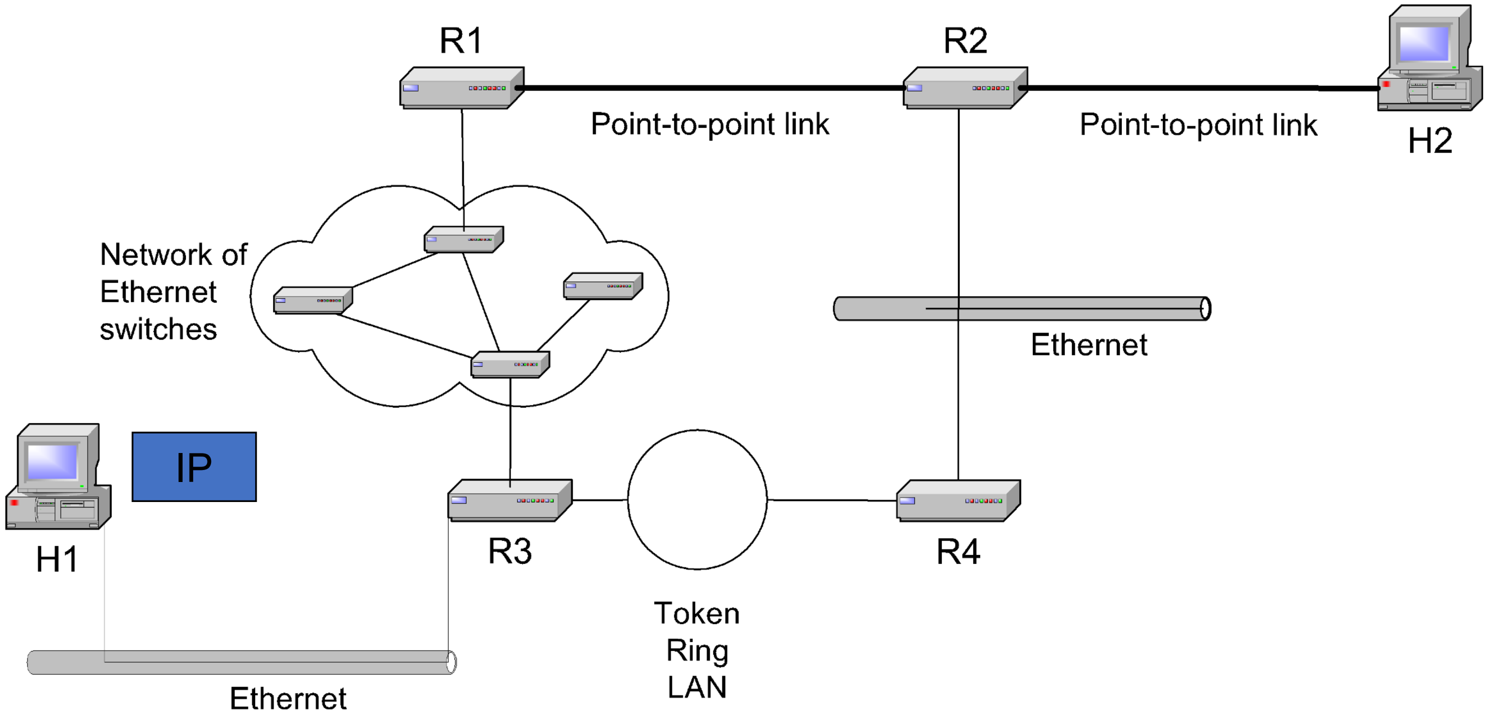
Network Layer: Internet Protocol (IP)

- IPv6
  - Addressing:
    - Network Prefix (64 bits) + Interface ID (64 bits)
    - Representation rules in RFC 5952:
    - Leading zeros in each 16-bit field are suppressed.
    - "::" is used to shorten just a single 0 field.
    - Representations are shortened as much as possible. The longest sequence of consecutive all-zero fields is replaced by double-colon. If there are multiple longest runs of all-zero fields, then it is the leftmost that is compressed.
    - Hexadecimal digits are expressed as lower-case letters.
    - Some special addresses:
      - Loopback: ::1/128
      - Link local: fe80::/10
      - Multicast: ff00::/8
  - Header:



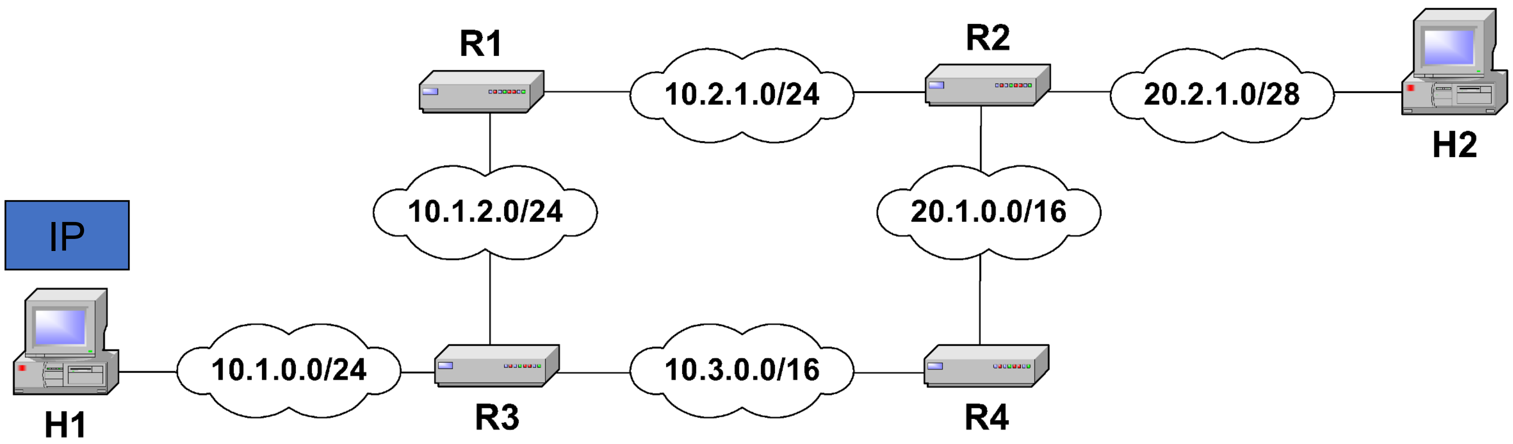
Network Layer: Internet Protocol (IP)

- IP Forwarding (view at the Data Link layer):
  - Internetwork is a collection of LANs or point-to-point links or switched networks that are connected by routers



Network Layer: Internet Protocol (IP)

- IP Forwarding (view at the IP layer):
  - An IP network is a logical entity with a network number
  - We represent an IP network as a "cloud"
  - The IP delivery service takes the view of clouds, and ignores the data link layer view



Network Layer: Internet Protocol (IP)

- Routing Tables:
  - Each router and each host keeps a routing table which tells the router how to process an outgoing packet
  - Main columns:
    - Destination address: where is the IP datagram going to?
    - Next hop and local interface: how to send the IP datagram? Next hop = IP address of the next hop node's interface; local interface (direct) = identifier of the local interface through which the packet is to be sent.
  - Routing tables are set so that a datagram gets closer to its destination
  - Routing tables populated by routing protocols, e.g., OSPF, RIP, IS-IS, etc.

Destination	Next Hop
20.2.1.0/28	R4
10.1.0.0/24	direct
10.1.2.0/24	direct
10.2.1.0/24	R4
10.3.1.0/24	direct
20.1.0.0/16	R4

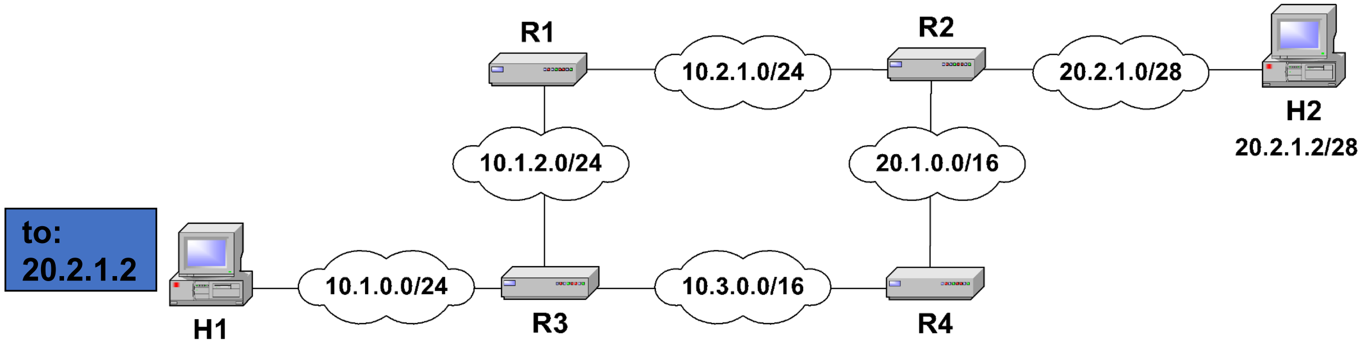
Network Layer: Internet Protocol (IP)

- Forwarding with Routing Tables:

Destination	Next Hop
10.1.0.0/24	R3
10.1.2.0/24	direct
10.2.1.0/24	direct
10.3.1.0/24	R3
20.2.0.0/16	R2
30.1.1.0/28	R2

Destination	Next Hop
10.1.0.0/24	R1
10.1.2.0/24	R1
10.2.1.0/24	direct
10.3.1.0/24	R4
20.1.0.0/16	direct
20.2.1.0/28	direct

Destination	Next Hop
10.1.0.0/24	R2
10.1.2.0/24	R2
10.2.1.0/24	R2
10.3.1.0/24	R2
20.1.0.0/16	R2
20.2.1.0/28	direct



Destination	Next Hop
10.1.0.0/24	direct
10.1.2.0/24	R3
10.2.1.0/24	R3
10.3.1.0/24	R3
20.1.0.0/16	R3
20.2.1.0/28	R3

Destination	Next Hop
10.1.0.0/24	direct
10.1.2.0/24	direct
10.2.1.0/24	R4
10.3.1.0/24	direct
20.1.0.0/16	R4
20.2.1.0/28	R4

Destination	Next Hop
10.1.0.0/24	R3
10.1.2.0/24	R3
10.2.1.0/24	R2
10.3.1.0/24	direct
20.1.0.0/16	direct
20.2.1.0/28	R2

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Transport Layer: TCP

- Elements of Data Communication Networks
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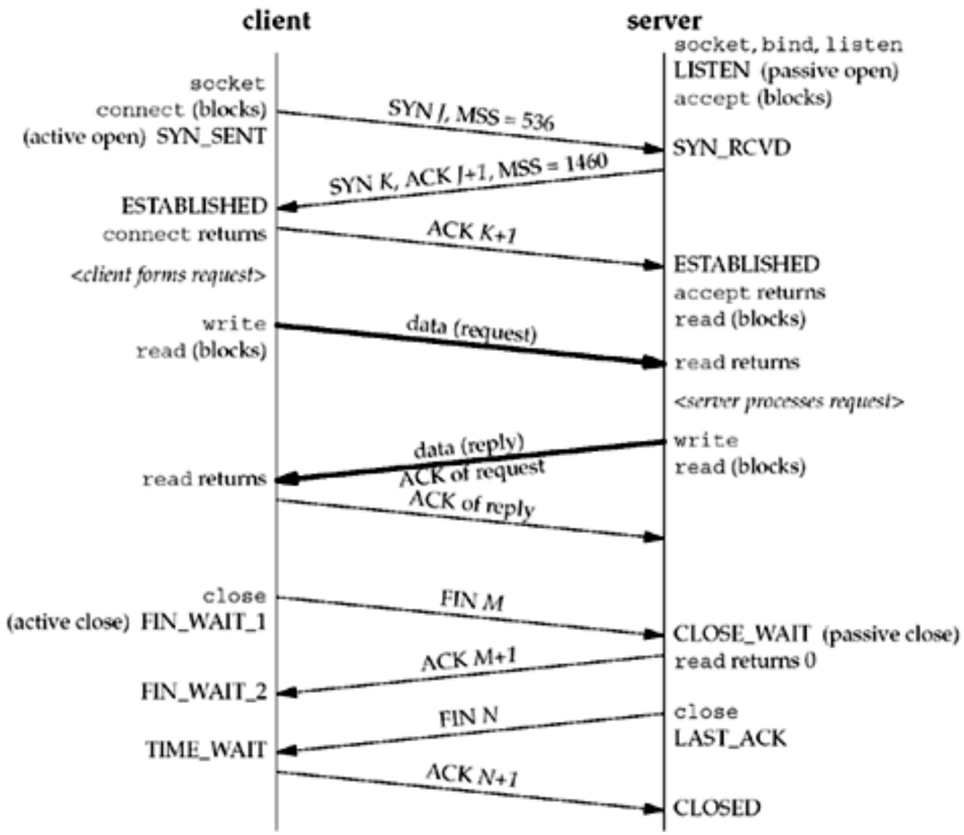
- The Transmission Control Protocol (TCP) (RFC 793)
  - A reliable, ordered transport for a stream of bytes
  - TCP is connection oriented, forming a pairing between 2 hosts using a 3-way handshake
  - Positive ack windowing is used with flow control
  - Congestion control mechanism critical for the Internet
- TCP is not suitable for every application
  - Support for unicast communications only
  - Reacts badly to e.g. wireless packet loss
  - Not all protocols require total reliability
  - TCP connection not suitable for very short transactions



Transport Layer: TCP

- TCP header:

<table>
<tr><th>Offsets</th><th>Octet</th><th colspan="8">0</th><th colspan="8">1</th><th colspan="8">2</th><th colspan="8">3</th></tr>
<tr><th>Octet</th><th>Bit</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th><th>31</th></tr>
<tr><th>0</th><th>0</th><td colspan="16">Source port</td><td colspan="16">Destination port</td></tr>
<tr><th>4</th><th>32</th><td colspan="32">Sequence number</td></tr>
<tr><th>8</th><th>64</th><td colspan="32">Acknowledgment number (if ACK set)</td></tr>
<tr><th>12</th><th>96</th><td colspan="4">Data offset</td><td colspan="3">Reserved
0 0 0</td><td>N
S</td><td>C
W
R</td><td>E
C
E</td><td>U
R
G</td><td>A
C
K</td><td>P
S
H</td><td>R
S
T</td><td>S
Y
N</td><td>F
I
N</td><td colspan="16">Window Size</td></tr>
<tr><th>16</th><th>128</th><td colspan="16">Checksum</td><td colspan="16">Urgent pointer (if URG set)</td></tr>
<tr><th>20
...</th><th>160
...</th><td colspan="32">Options (if data offset > 5. Padded at the end with "0" bytes if necessary.)
...</td></tr>
</table>

Transport Layer: UDP

- The User Datagram Protocol (UDP) (RFC 768)
- Used to deliver short messages over IP
- Unreliable, connectionless protocol
- Can be used with broadcast and multicast
- Common in streaming and VoIP, DNS and network tools

- UDP header:

Offsets	Octet	0								1								2								3							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	0	Source port																Destination port															
4	32	Length																Checksum															