Slide supporting material

Lesson 1: An Introduction and the OSI Model

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Queuing Theory and Telecommunications: Networks and Applications
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"The most important thing is to never stop questioning."

Albert Einstein

"Write to be understood, speak to be heard, read to grow."

Lawrence Clark Powell

Course Outlook
[about 60 teaching hours]

- **Lesson 1**: An Introduction and the OSI Model
- **Lesson 2**: X.25, ISDN, Frame Relay, and TDM Hierarchy, SDH Transport
- **Lesson 3**: Random Variables, Stochastic Processes; Traffic Engineering, QoS
- **Lesson 4**: Access Protocols: Aloha, CSMA, and Token Ring; Exercises
- **Lesson 5**: ATM Networks, 1st part
- **Lesson 6**: Queues and Markov Chains
- **Lesson 7**: M/G/1 Queuing Systems Analysis
- **Lesson 8**: ATM Network, 2nd part
- **Lesson 9**: Advanced M/G/1 Methods and Examples
- **Lesson 10**: WiFi and WiMAX MAC Analysis
- **Lesson 11**: Solved M/G/1 Exercises
- **Lesson 12**: IP Layer and Routing
- **Lesson 13**: MPLS Networks
- **Lesson 14**: QoS in IP Networks: IntServ and DiffServ
- **Lesson 15**: Transport Layer, TCP and UDP
- **Lesson 16**: Different TCP Versions, Analytical Details and Implementation
- **Lesson 17**: Models for Traffic Sources
- **Lesson 18**: Networks of Queues and Exercises
- **Lesson 19**: Matlab® Tools for Teletraffic Engineering
- **Lesson 20**: Satellite Networks

Main Milestones in Telecommunications and Networking

Milestones in Telecom. Networks

- **1844**: S. Morse gave a first public demonstration of his telegraph. Transmissions were of two symbols (Morse code).
- **1859**: The first successful laying of an Atlantic Ocean submarine cable for telegraph transmissions between UK and USA. The telegraph network was the first worldwide network for data transmissions.
- **1876**: A. G. Bell demonstrated and patented the telephone for voice transmissions at distance. However, the real inventor has to be considered A. Meucci, who was too poor to protect his invention with a patent.

Milestones in Telecom. Networks (cont'd)

- **1890**: Telephone networks were available with human-operated analogue circuit-switching systems (i.e., plug-boards).
  - In few years important improvements were adopted in telephone networks:
    - Automatic electro-mechanical switches,
    - Hierarchic network organization (local exchanges, regional exchanges),
    - Long-distance links between switching offices by means of the "pupinization" technique.
      - This technique invented by the physician M. I. Pupin around 1900 was based on the insertion of inductance coils at regular distances (about 1800 m) along the transmitting wires in order to reduce both signal distortion and attenuation.

Milestones in Telecom. Networks (cont'd)

- **1864**: J. C. Maxwell equations characterizing electromagnetic waves.
- **1888**: H. R. Hertz built an apparatus to generate radio waves.
- **1895**: G. Marconi was successful in sending a radio wave in the famous "hill experiment" in his villa in Pontecchio Marconi (Bologna, Italy).
  - Marconi transmitted signals at a distance of over two kilometers, overcoming the natural obstacle of a hill. From that date he carried out many other experiments with signals sent even across continents. These experiments represent the birth of wireless telecommunications (he named the "wireless telegraph"). Radio transmissions of voice appeared at the beginning of 1900s. In 1909, Marconi was awarded of the Nobel prize in Physics.

Milestones in Telecom. Networks (cont'd)

- **1945**: A RAF electronics officer and member of the British Interplanetary Society, A. C. Clarke, wrote an article in the Wireless World journal entitled "Extra Terrestrial Relays - Can Rocket Stations Give Worldwide Coverage?" describing the use of 'manned' satellites in orbits at 35,800 km altitude, thus having synchronous motion with respect to the earth. These characteristics suggested him the possible use of these GEOstationary (GEO) satellites to broadcast television signals on a wide part of the earth.

Milestones in Telecom. Networks (cont'd)

- **1948**: C. Shannon published two fundamental papers on Information Theory, containing the basis for data compression (source encoding), error detection and correction (channel encoding).
- **1960**: Laser invention and use of optical signals guided by optical fibers.
- **1969**: Internet experiments started with the US ARPANET project (few nodes inter-connected).
- **1973**: The first local area network, named Ethernet, was invented by R. Metcalfe at Xerox, allowing transmissions from 1 Mbit/s to 10 Mbit/s.

Milestones in Telecom. Networks (cont'd)

- **1978**: TCP/IP protocol suite for ARPANET
- **1980**: OSI (Open System Interconnection) reference model with stacked protocols divided in 7 layers
- **1983**: ISDN full-digital network
- **1989**: Important tools were defined at CERN to share documents using the Internet.
  - The HyperText Markup Language (HTML) to write Web documents;
  - The HyperText Transfer Protocol (HTTP), an application layer protocol to transmit Web pages;
  - A Web browser client software program to receive and interpret data and to display results. His design was based on hypertext, that is links embedded in text to refer to other Web documents.

Milestones in ICT

- **1991**: The World Wide Web (WWW) was born. The first really friendly interface to the Internet (browser) was developed at the University of Minnesota; it was named 'gopher' from the University mascot.
- **1997**: Google search engine was defined (http://www.google.it/).
- **1998:** Next Generation Networks (NGN), a packet-based network able to provide services to users by means of multiple broadband, QoS-enabled transport technologies and in which service-related functions are independent of the underlying transport technologies.
- **1999**: WiFi, the wireless local area network.

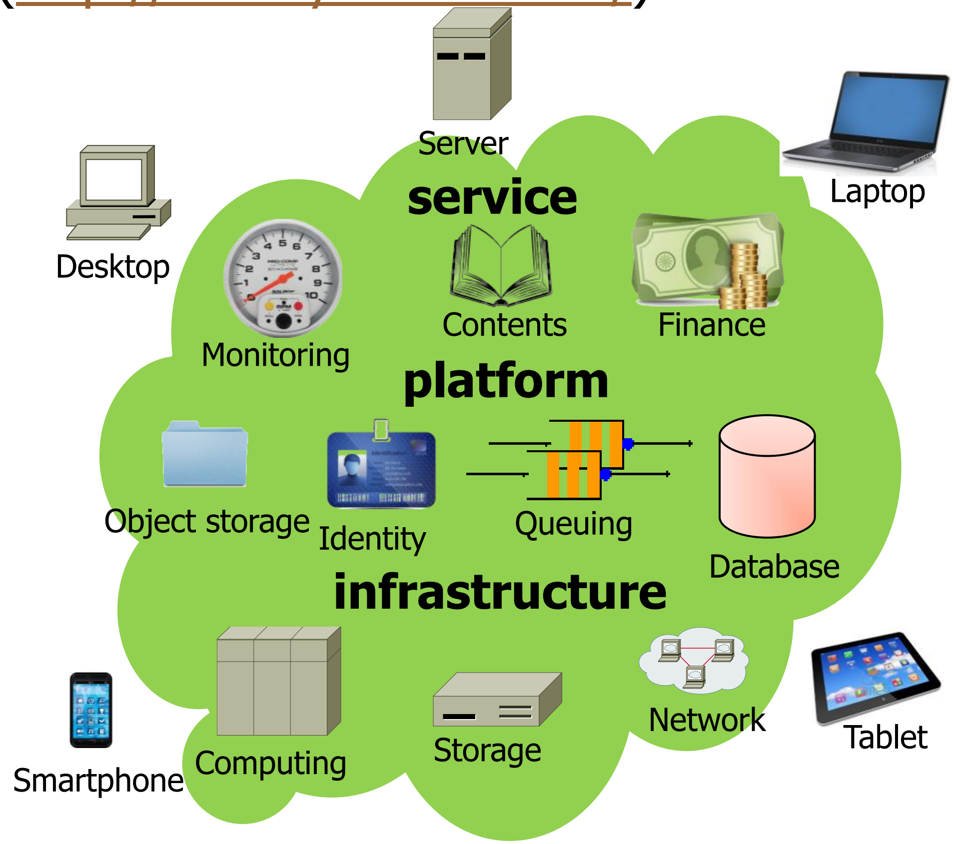
Milestones in ICT (cont'd)

- **2000**: Wikipedia, the free multi-language online encyclopaedia that anyone can edit … 'wiki' is an Hawaiian term meaning 'fast' (founded by J. Wales, http://it.wikipedia.org/).
- **2000**: IEEE protocols for Mobile Ad-hoc NETworks (MANETs). MANET is a self-configuring infrastructure-less network of mobile devices connected via wireless links.
- **2001**: Vehicular Ad-Hoc Network (VANET) is a technology that uses moving cars as nodes to create a mobile network. There are different ad hoc technologies for VANTEs, such as: WiFi IEEE 802.11p, WAVE IEEE 1609, WiMAX IEEE 802.16, Bluetooth, ZigBee, etc.
- **2004**: Facebook social network (M. Zuckerberg founder of Facebook, http://www.facebook.com/).

Milestones in ICT (cont'd)

- **2005**: YouTube is a video-sharing website on which users can upload, share, and view videos (http://www.youtube.com/).

- **2007**: Cloud computing
  - Cloud computing is the delivery of computing as a service rather than a product, whereby shared resources, software, and information are provided via the network (typically the Internet).
  - End users access cloud-based applications through a web browser or a light-weight desktop or mobile smart device, while the business software and data are stored on Internet servers at a remote location.



Milestones in ICT (cont'd)

- **2008**: Software-Defined Networking (SDN)
  - SDN allows network administrators to manage network services through a **virtualization approach**. This is achieved by decoupling the system that makes decisions on traffic routing (control plane) from the underlying system that forwards traffic (data plane).
  - The Internet principle does not allow the destinations to move without changing their identities. The network interface destinations are attached to, determine their identity.
  - SDN permits to evolve from this scenario by allowing network operators to specify network services, without coupling these specifications with network interfaces.
  - An example of a currently-available SDN approach is **OpenFlow** that allows an abstract definition of routing schemes and rules (virtualization). A software platform for OpenFlow can be found at: http://mininet.org/

Introduction

International Standardization Bodies for Telecoms

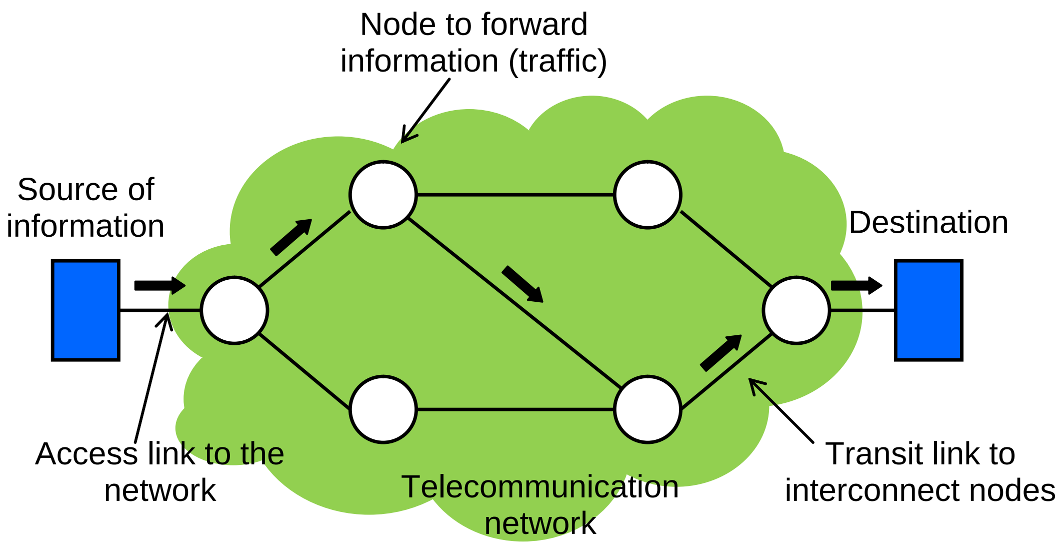
- International Telecommunication Union (ITU):
  - ITU has two main sectors: telecommunication systems (ITU-T) and radiocommunications (ITU-R)
- International Standard Organization (ISO)
- The Institute for Electrical and Electronics Engineers (IEEE)
- Internet Engineering Task Force (IETF)
- European Telecommunications Standards Institute (ETSI) in Europe
- The American National Standards Institute (ANSI)

Telecommunication Networks: General Concepts

- Historically, communication systems have started with point-to-point links to directly connect the users needing to communicate by means of a dedicated circuit.
- As the number of connected users increased, it became infeasible to provide a circuit to connect every user to every other, thus introducing the concept of multiplexing.
- Telecommunication networks have been developed with intermediate nodes and interconnection among nodes.

Telecommunication Networks: General Concepts

- A telecommunication network can be defined as a set of equipment elements, transmission media and protocols.



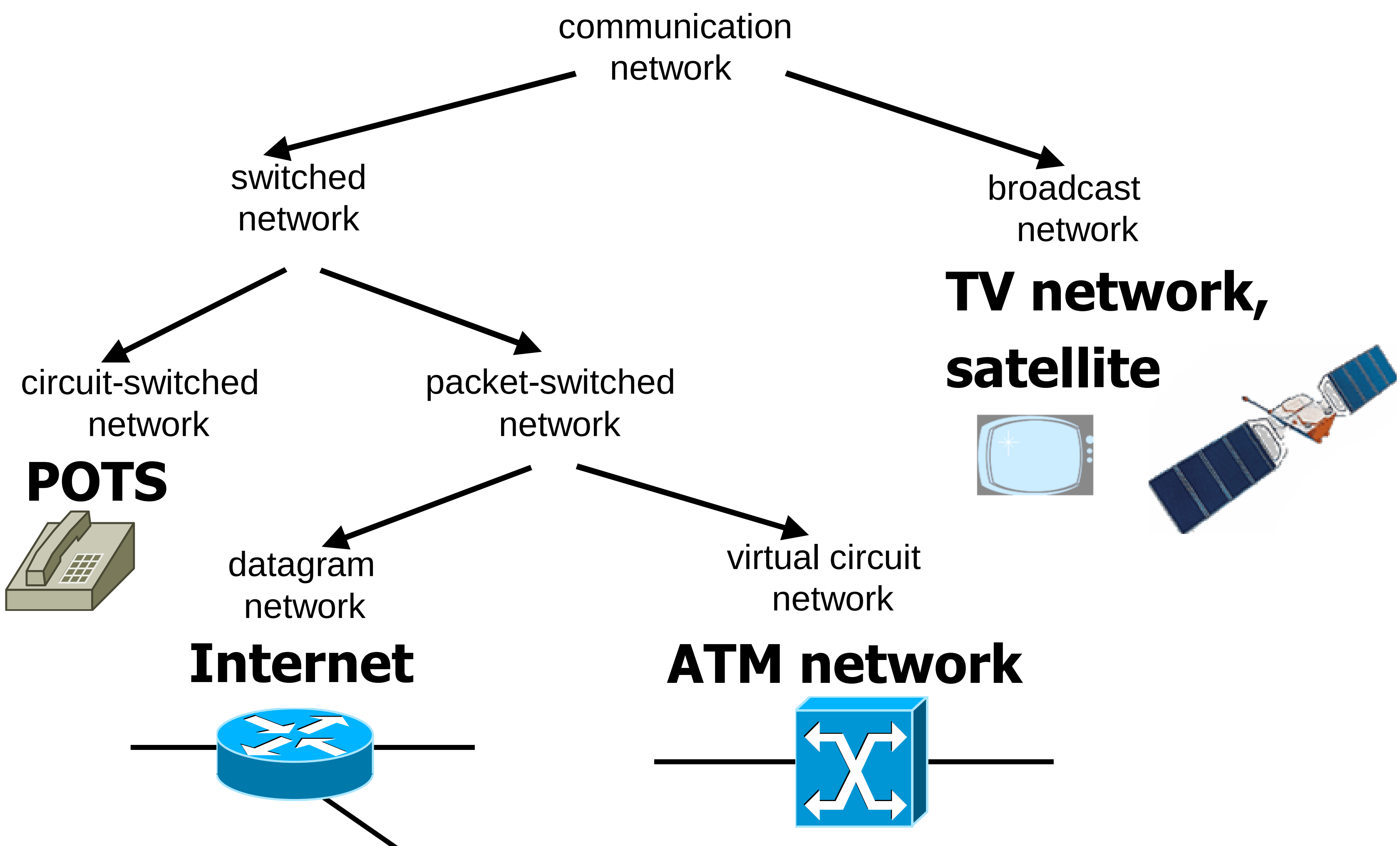
- In the **full mesh** topology every node is connected to every node. In the case of n nodes, **the number of required bidirectional links is:**

$$\sum_{i=1}^{n-1} i = \frac{n(n-1)}{2} \quad \text{(Gauss sum)}$$

Switching Techniques in the Network

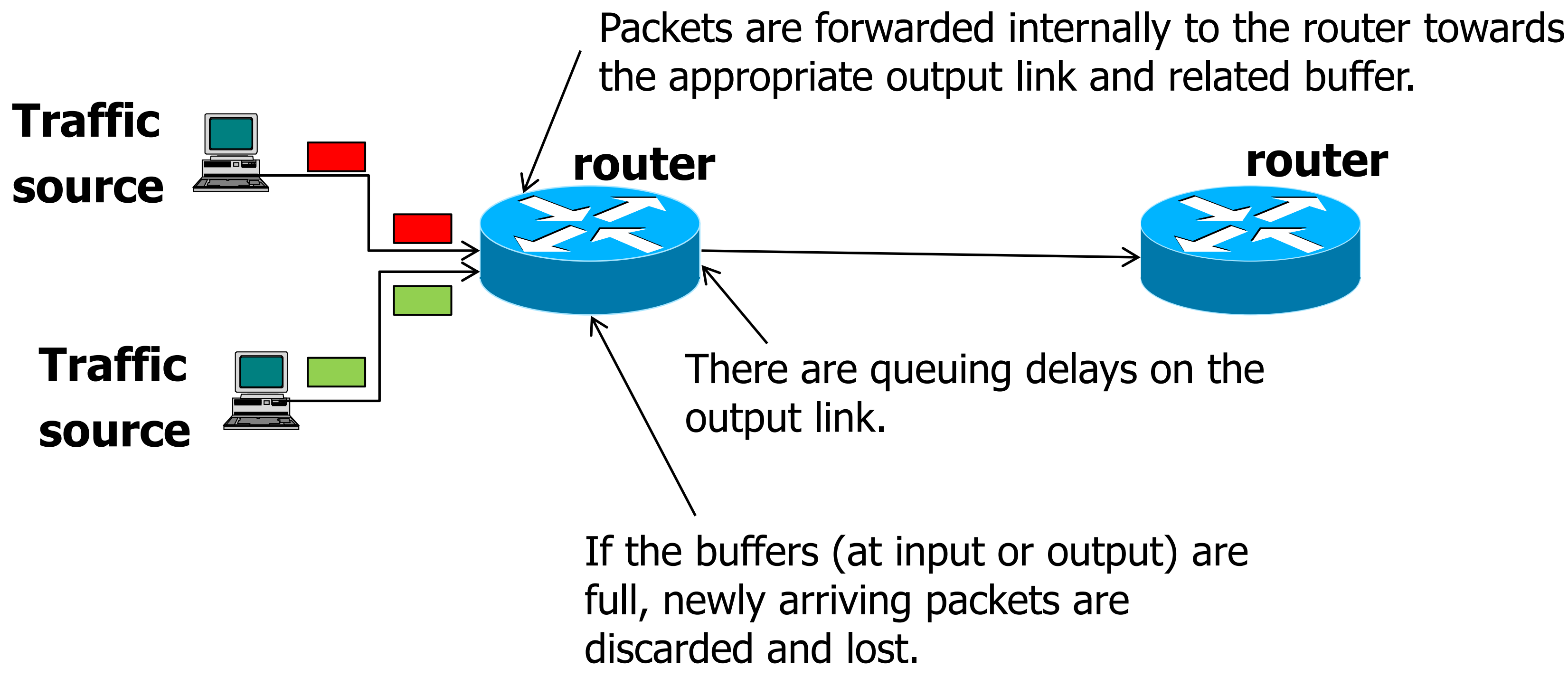
- There are two main techniques according to which data are transferred across the network:
  - **Circuit-switching**: there is a circuit assigned to support a source-destination traffic flow for its entire duration.
  - **Packet-switching**: messages of a session utilize link resources upon request and, therefore, there can be time spent (along the path) waiting for an available link. Forwarding decisions can be taken on a packet basis.

Telecommunication Networks: Different Types



Network Nodes: Packet Delays and Losses

The transmission of packets in the network may suffer from delays and losses at each node due to buffer congestion.



ISO/OSI Reference Model and Protocols

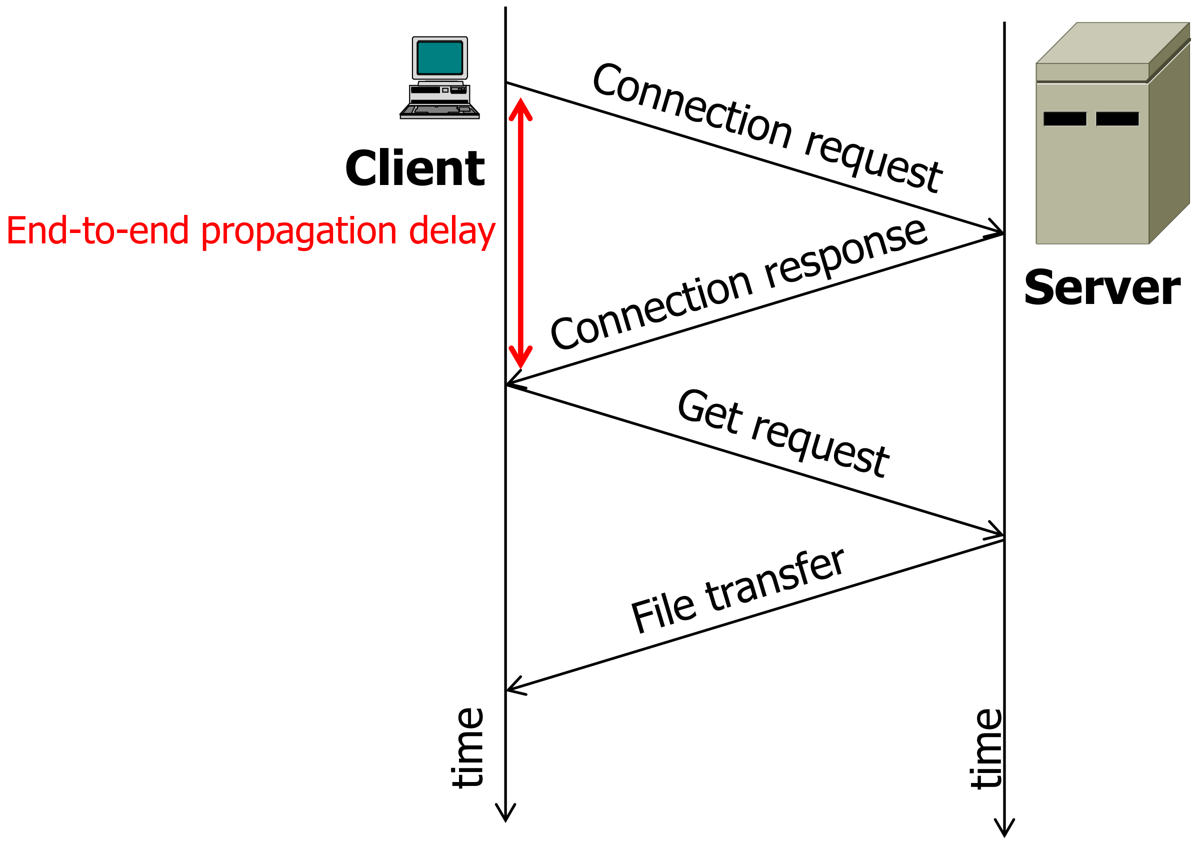
Basis of Layering: Shannon's Separation Theorem

- Shannon proved that the **layers** of source compression (source coding) and coding for reliable transmissions over a communication channel (channel coding) may be implemented separately and independently.
  - Separate optimization greatly reduces theoretical complexity and allows modularity and standardization.
  - The end-to-end delivery of information adopts a group of stacked protocols at each node along the path.

C. Shannon and W. Weaver. *The Mathematical Theory of Communication. Urbana*, Illinois: University of Illinois Press, 1949.

A Protocol Example

A protocol entails a set of messages and actions to be taken as consequence of these messages.

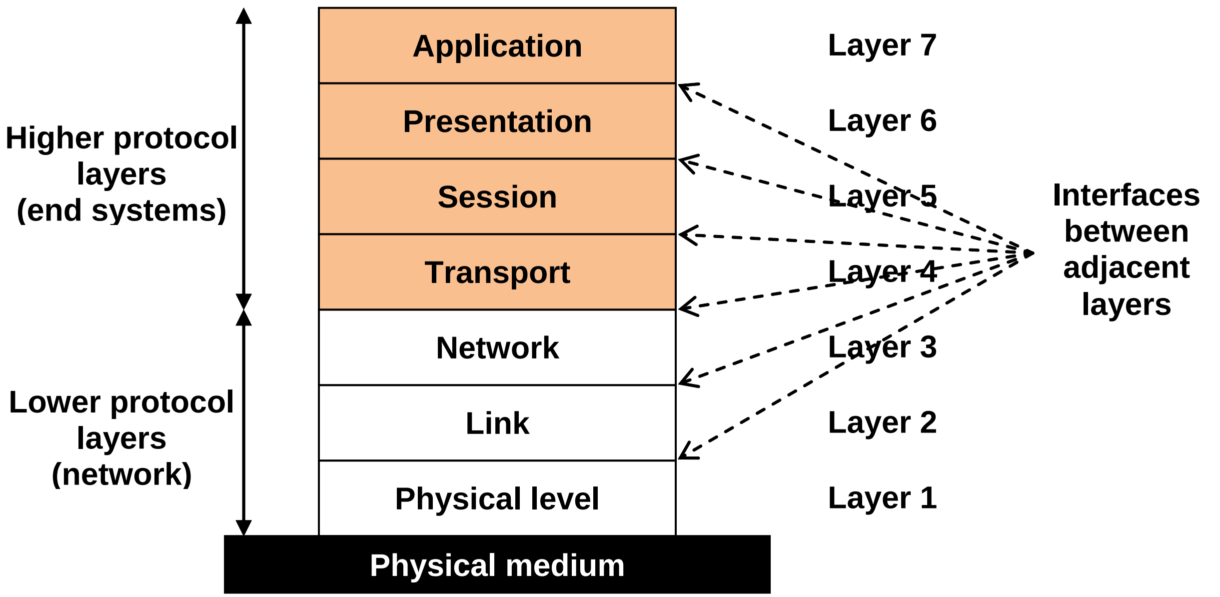


ISO/OSI 7 Protocol Layers

- The ISO/OSI reference protocol stack is a **1-D model with 7 layers** (current networks adopt a 3-D protocol stack; Internet has only 5 layers).

- A **protocol** is characterized as: (i) a set of **formats** according to which data exchange between peer entities occurs; (ii) a set of **procedures (signaling)** to exchange data. Standardization bodies define the different protocols.

- Lower-layer (white) protocols are in both end-systems and intermediate hosts. Higher-layer (reddish-orange color) protocols are only present in end-systems (end-to-end protocols).



7 Protocol Layers: Functional Description

- **Layer 1** is the physical level that directly operates the transmission in the physical medium.
- **Layer 2** or data link layer has the main function to regulate the access to physical layer resources and to recover error transmissions through re-transmission techniques (Automatic ReQuest repeat, ARQ, protocols). Example: Ethernet protocol.
- **Layer 3** or network layer has the task to route the traffic along the network from source to destination. Example: IP layer and routing protocols.
- **Layer 4** or transport layer has the task to control the end-to-end traffic flow from source to destination. Specific tasks are flow control (to avoid to overwhelm the destination with too much traffic that it cannot manage) and congestion control (to avoid to inject too much traffic in the network that may cause congestion at a node). Example: TCP protocol.

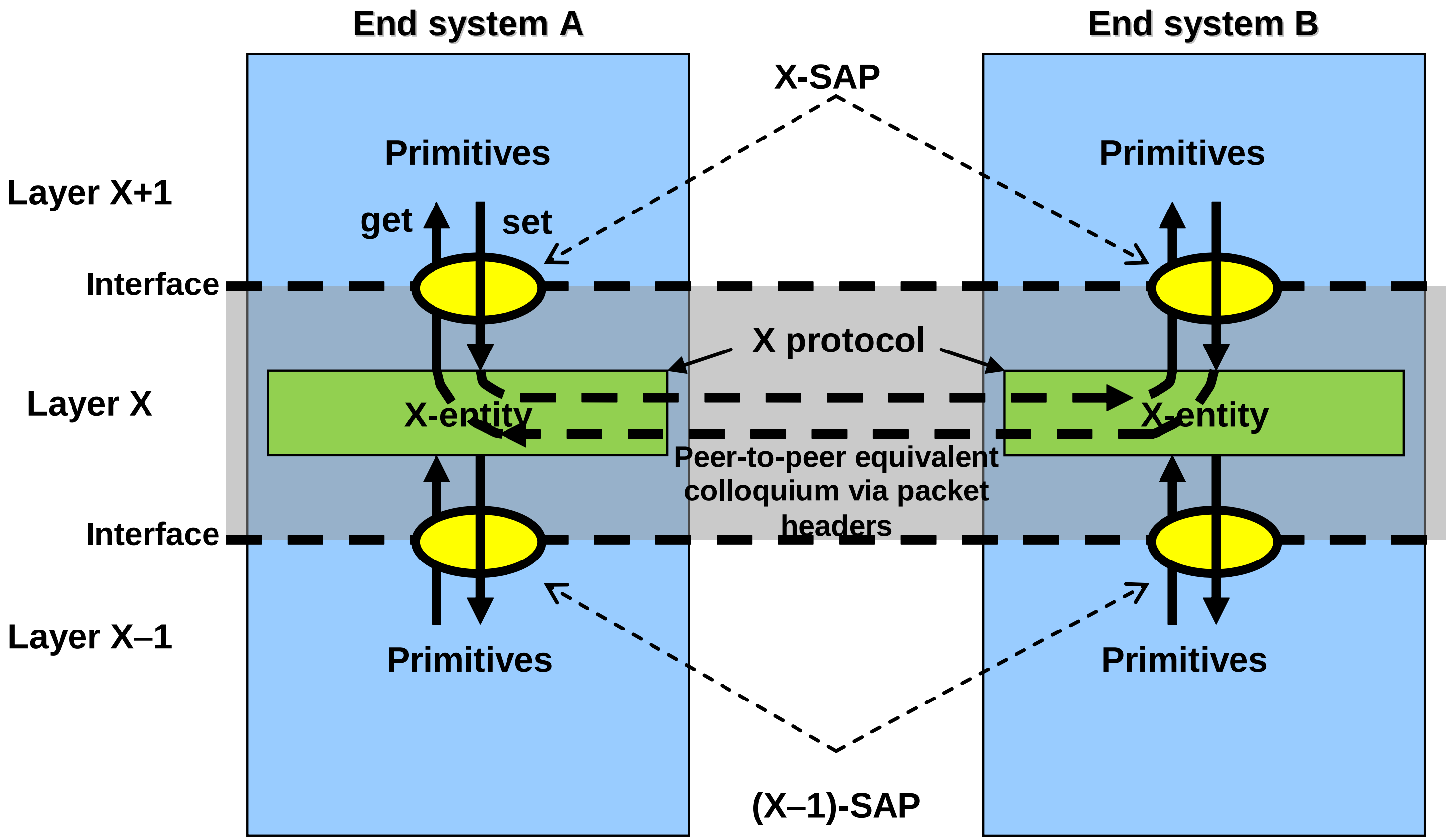
7 Protocol Layers: Functional Description (cont'd)

- **Layer 5** or session layer manages the dialogue by two end-application processes.
- **Layer 6** or presentation layer is used to unify the representation of information between source and destination. This protocol interprets and formats data, including compression, encryption, etc.
- **Layer 7** or application layer represents the high-level service that the user has direct contact with. E.g., HTTP, FTP, Telnet, etc.

Generic Protocol Layer

- The generic protocol layer X ∈ {1, 2, …, 7} is composed of functional groups, named **entities**. A layer can contain more entities.
- Each entity provides a service to the upper layer through an **interface**. Upper-layer entities access to this service through a **Service Access Point (SAP)**; there may be different SAPs at the interface between two layers. Each SAP is identified by a unique SAP address.
  - In the Internet, **port numbers** represent together with protocol ID and IP address the Transport Layer SAPs (T-SAPs), also known as *socket*, between transport and application layers. Port numbers are specified by IANA (http://www.iana.org/protocols/).
- The exchange of messages between two layers is made by means of **primitives**. Each entity also receives services from lower-layer protocols through the lower-level SAP.

Generic Protocol Layer



Signaling

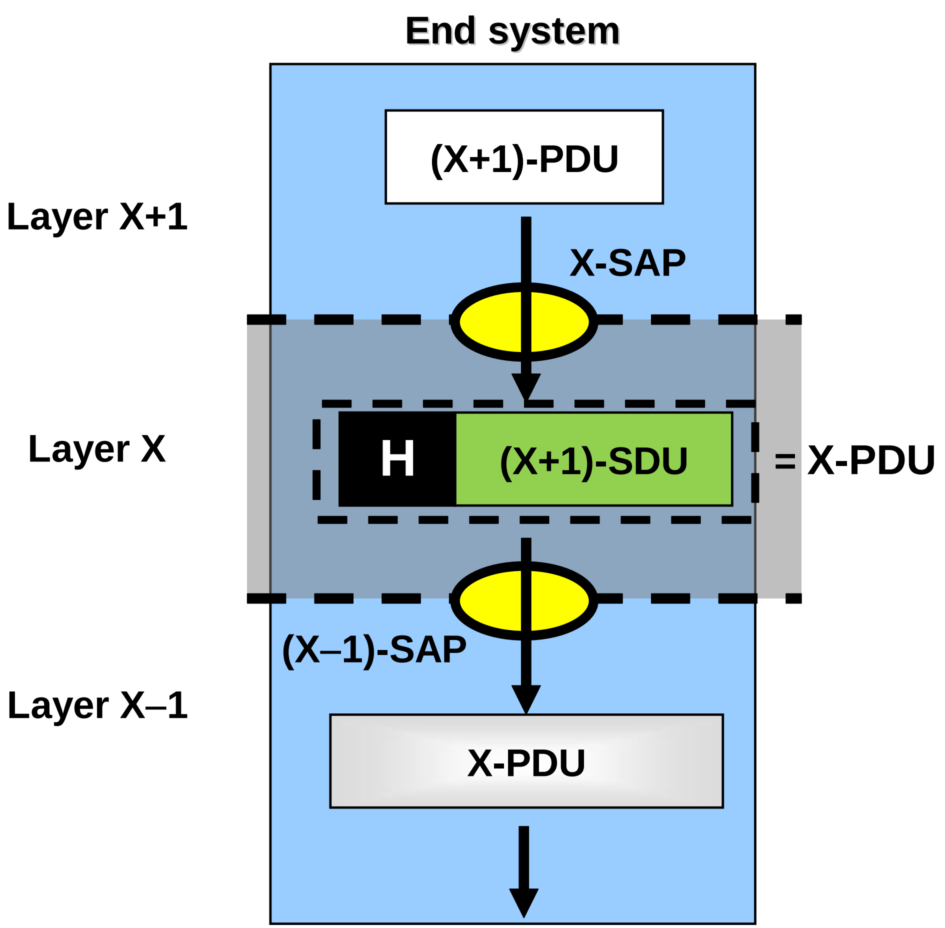
- Signaling denotes a set of messages for controlling communications.
- Signaling systems can be classified as follows:
  - **In-band signaling**: the PDU header has some control fields carrying peer-to-peer control messages together with the related data payload.
  - **Out-of-band signaling**: with signaling commands (i.e., primitives) operating vertically at a SAP between two adjacent protocol layers. This signaling (get/set primitives) is used to exchange commands on the internal state of the protocols. Basically **out-of band signaling requires an independent protocol stack with respect to user data**; this is an evolution of the classical ISO/OSI model.

PDU

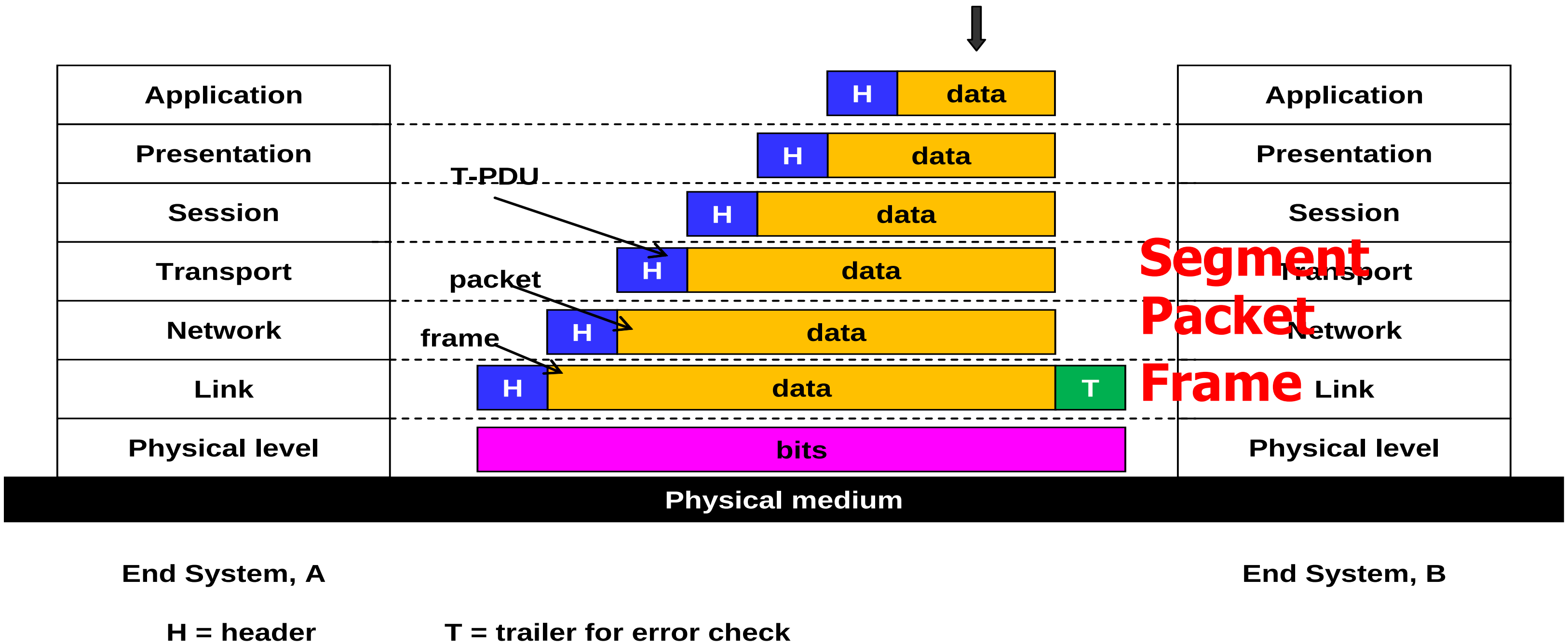
- The protocols of a given layer format their messages in transfer units, generally called Protocol Data Units (PDUs).
- The PDUs at various layers can be very different, from the user information at layer 7 to the bits to be transmitted on the physical medium at layer 1.
- Information is exchanged by means of PDUs through SAPs between adjacent layers.
- For instance, a PDU of layer X+1 is received by the lower layer through a SAP and is considered as a Service Data Unit (SDU) of layer X. This SDU can be in turn enriched with a header containing additional control information for layer X; we therefore obtain a PDU of layer X.

PDU

- The control information inserted in the X-layer header is used to operate the X-layer protocol. The description of the meaning of the different fields of the header bits allows describing the X-layer protocol.



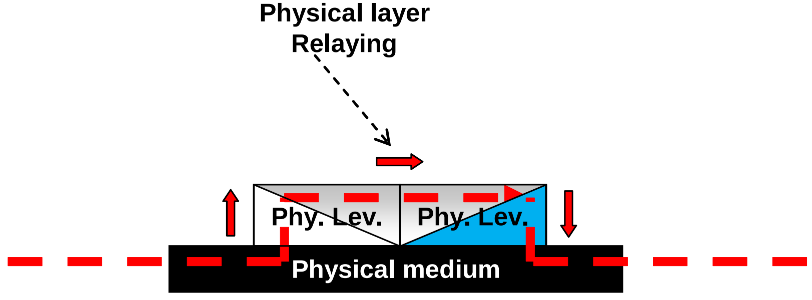
SDU Encapsulation Process at Different OSI Layers



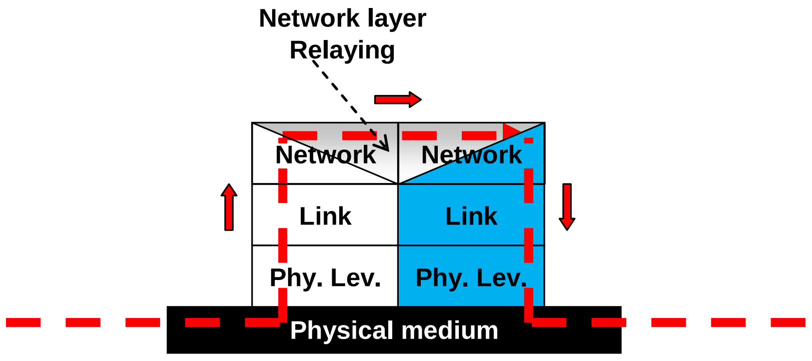
- The link layer also adds a trailer for error checking.
- The physical layer uses coding to protect data or to make data signal spectrum more suitable for the physical medium (line coding).

Relaying Function at Intermediate Nodes

- Relaying can be performed at different layers depending on the network type:
  - PHY in the case of circuit switching
  - MAC in the case of packet switch (use of virtual circuits)
  - NET in the case of a router (packet switching with datagrams)
  - Transport in the case of a gateway.

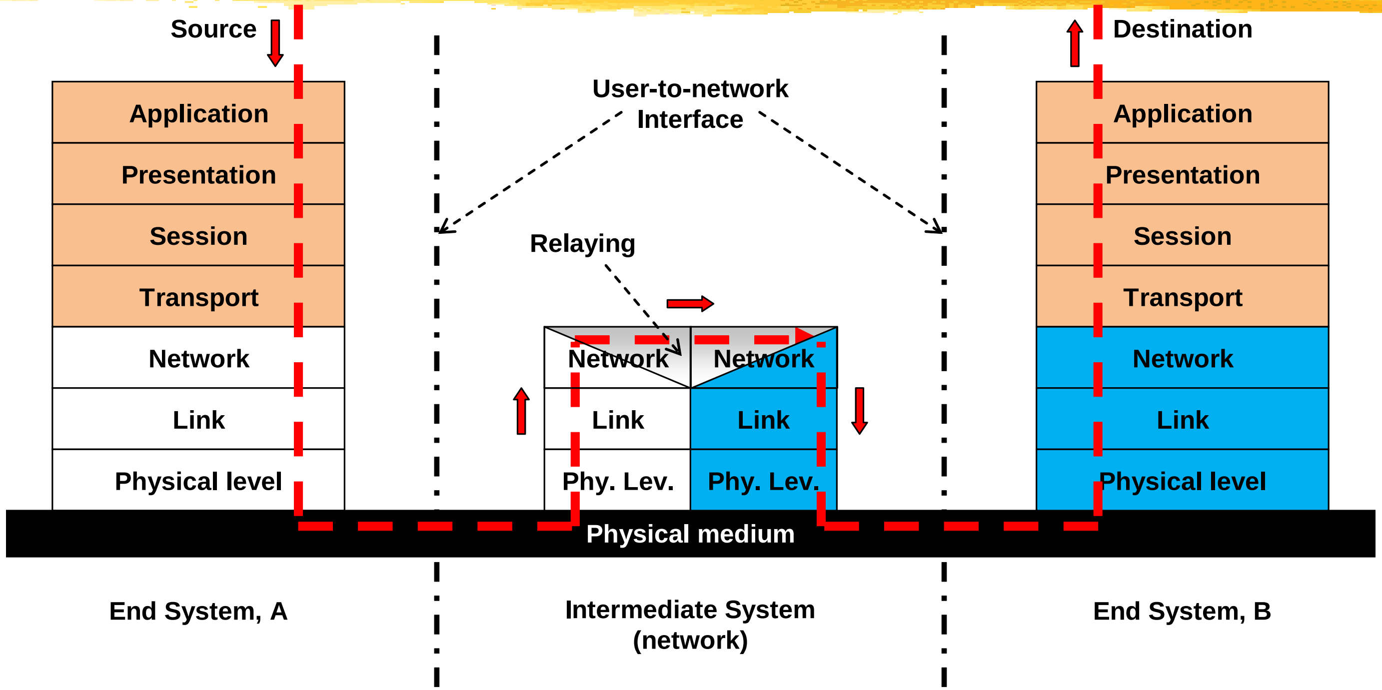


Intermediate System
(network)



Intermediate System
(network)

End-to-end Dialogue



- Strict-layered system: each layer in the OSI model has a companion layer at the receiving end.
  - Exchange of data between adjacent levels (vertical exchange), but virtual horizontal communication between peer protocol layers.
- Protocols on different layers are independent; they interact through well-defined and static interfaces.
  - Changes in one layer do not require changes in the other layers.

The Key Role of the Network Layer for IP Networks

- Since the information exchange must occur between two generic terminals connected by the network, two important functionalities of layer 3 (network layer) are:
  - **Addressing** (identifying the destination)
  - **Routing** with the task of defining a path from source to destination.

- The layer 3 of intermediate nodes has to support two important functions:
  - **Routing**, in order to select the appropriate output port for the PDU; This functionality requires to determine the appropriate output port for each destination address; this is obtained through a routing table managed according to a suitable routing protocol among routers.
  - **Forwarding**, in order to transfer the PDU from the input port to the output one.

Networks and Protocols Examples

In many cases a protocol provides a so strong characterization of a network that practically it gives the name to the network itself.

Networks	*Circuit-switched*	*Packet-switched*
	PSTN, ISDN	ISDN, Digital Network, B-ISDN, Ethernet, LANs, WiFi, Internet, NGN

Protocols	*Name*	*OSI level(s)*	*Related networks*
	X.25	1, 2 and 3 (user to network interface)	Digital Network
	LAP-B	2	X.25-based network
	LAP-D	2	ISDN
	Frame relay	2	Digital Network
	Aloha	2	AlohaNET
	IEEE 802.x family	1 and 2	LANs: Ethernet, Token-based, WiFi, etc.
	ATM	2	B-ISDN, Internet
	IP	3	Internet, NGN
	ARP	3	Internet, NGN
	OSPF	3	Internet, NGN
	BGP	3	Internet, NGN
	MPLS	2+	Internet, NGN
	TCP	4	Internet, NGN
	UDP	4	Internet, NGN
	RTP	4+	Internet, NGN
	FTP	7	Internet, NGN
	Telnet	7	Internet, NGN

Transmission technologies (layer 1)	*Name*	*Related Networks*
	PCM, plesiochronous hierarchy	PSTN, Digital Networks
	BRI	ISDN
	PRI	ISDN
	ADSL	PSTN, Internet
	SONET/SDH	B-ISDN, MPLS, Internet
	DWDM	GMPLS, Internet, NGN

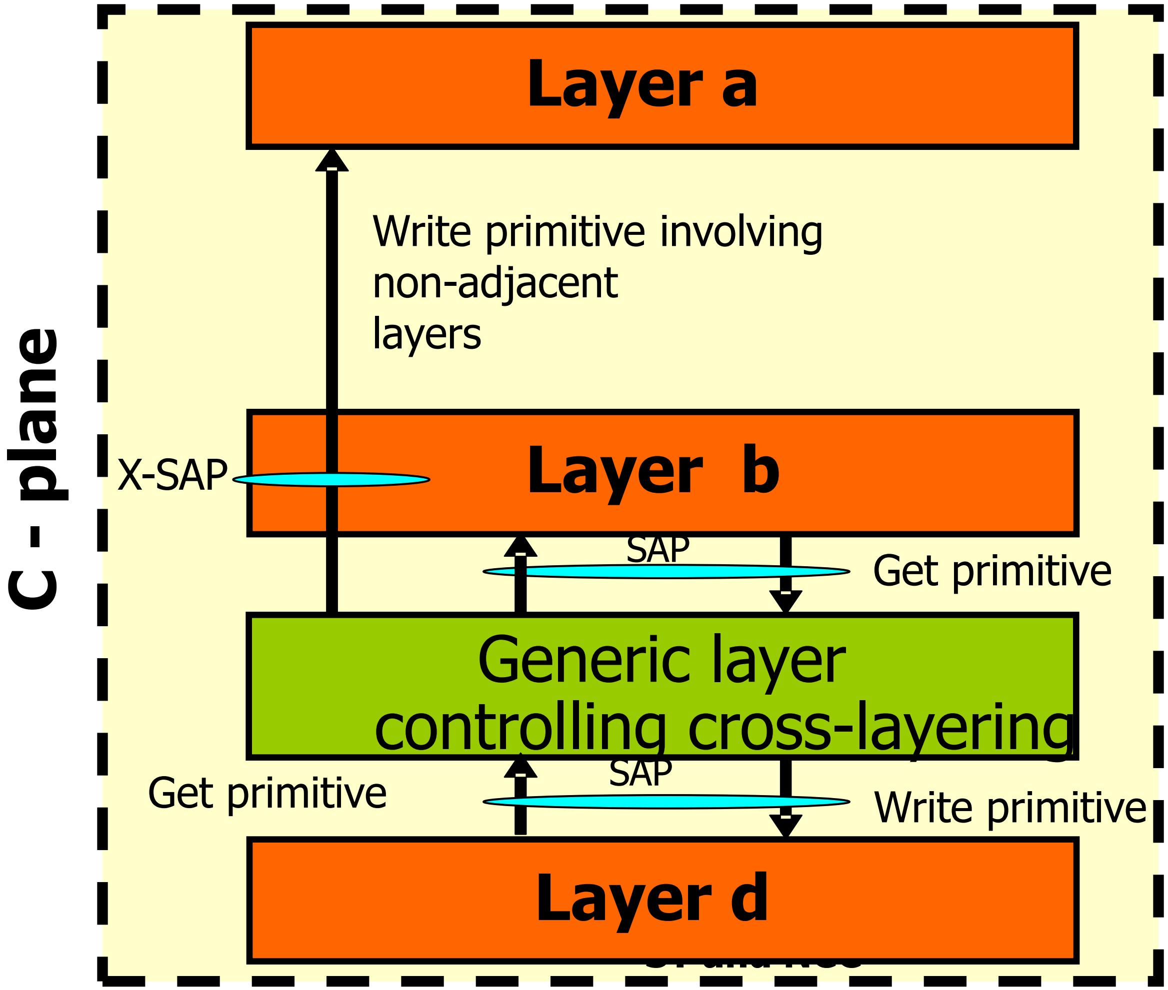
Cross-Layer Design

- Especially in the case of **mobile/wireless networks**, protocol architectures have been proposed where the reference ISO/OSI layered model is enriched with **interactions** between protocols at non-adjacent layers.
  - This is **cross-layering** and entails a violation of the classical ISO/OSI layered approach and layer independence principium.
- Cross-layer is still an art since every case is different.
- **Core of the approach: to understand and exploit interactions among different layers.**

Cross-Layering: Signaling Management

- The coordination of signaling could be made by a protocol layer (**horizontal approach**) or an external element that is common to all the layers (**vertical approach**).
  - **Horizontal approach:** the coordinating protocol layer can have interfaces only with adjacent layers; note that the application layer or the MAC layer could trigger the signaling, thus respectively having an Application-centric approach or a MAC-centric one.
  - **Vertical approach:** a global coordinator of different protocol layers could be considered having interfaces with all layers; the coordinator is considered to acquire internal state information from different protocols to store it in a shared memory and to set the internal state variables of these protocols as a response to suitable external events.
- Cross-layer can be based on a **centralized** (a control center manages cross-layer interactions) or a **distributed** control (each terminal manages cross-layer interactions).

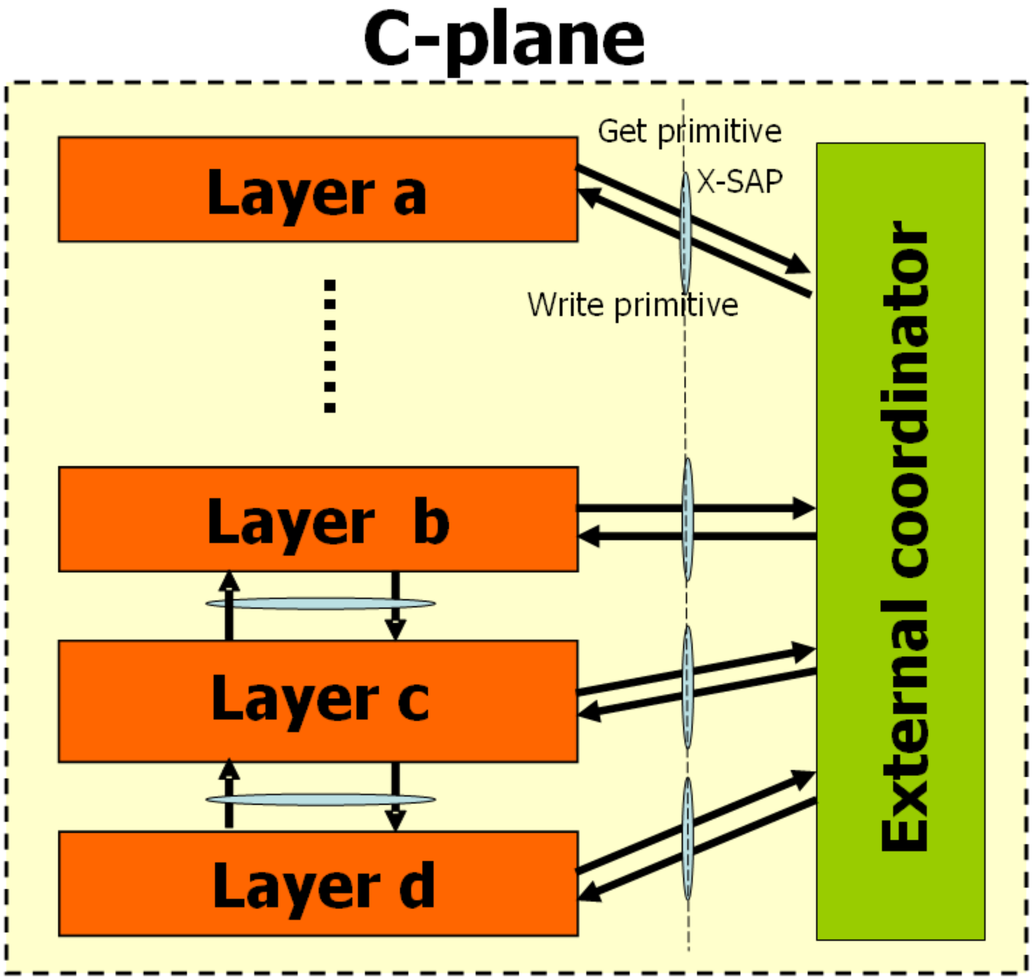
Cross-Layering: Horizontal Approach



X-SAPs are used for primitives allowing interactions among non-adjacent layers

In this scheme, one OSI layer has the control of X-SAP signaling.

Cross-Layering: Vertical Approach



X-SAPs are used for primitives allowing interactions with the global coordinator that has the control of X-SAP signaling.

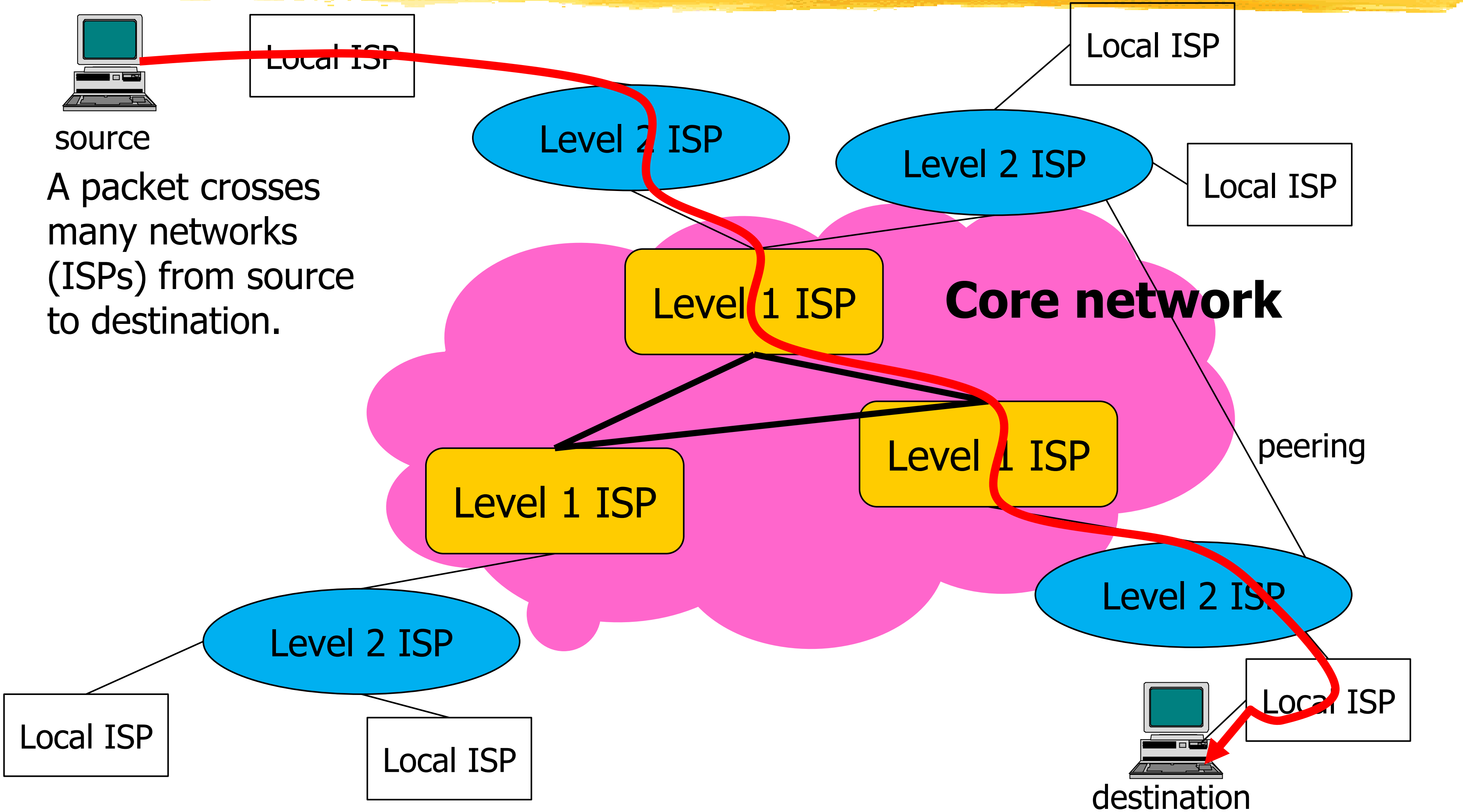
Networking

The Structure of the Internet

- Internet has a hierarchical architecture.
  - **Layer 1 Internet Service Providers (ISPs)** provide national and international coverage and form the so-called core network.
    - Layer 1 ISPs are connected each other according to a mesh topology.
  - **Layer 2 ISPs** are at the national or regional level. Layer 2 ISPs can only be connected to layer 1 ISPs or other layer 2 ISPs.
    - A layer 2 ISP has to pay a layer 1 ISP for the connectivity towards the rest of the network.
    - **Two directly-connected ISPs are called peers**.

The Structure of the Internet (cont'd)

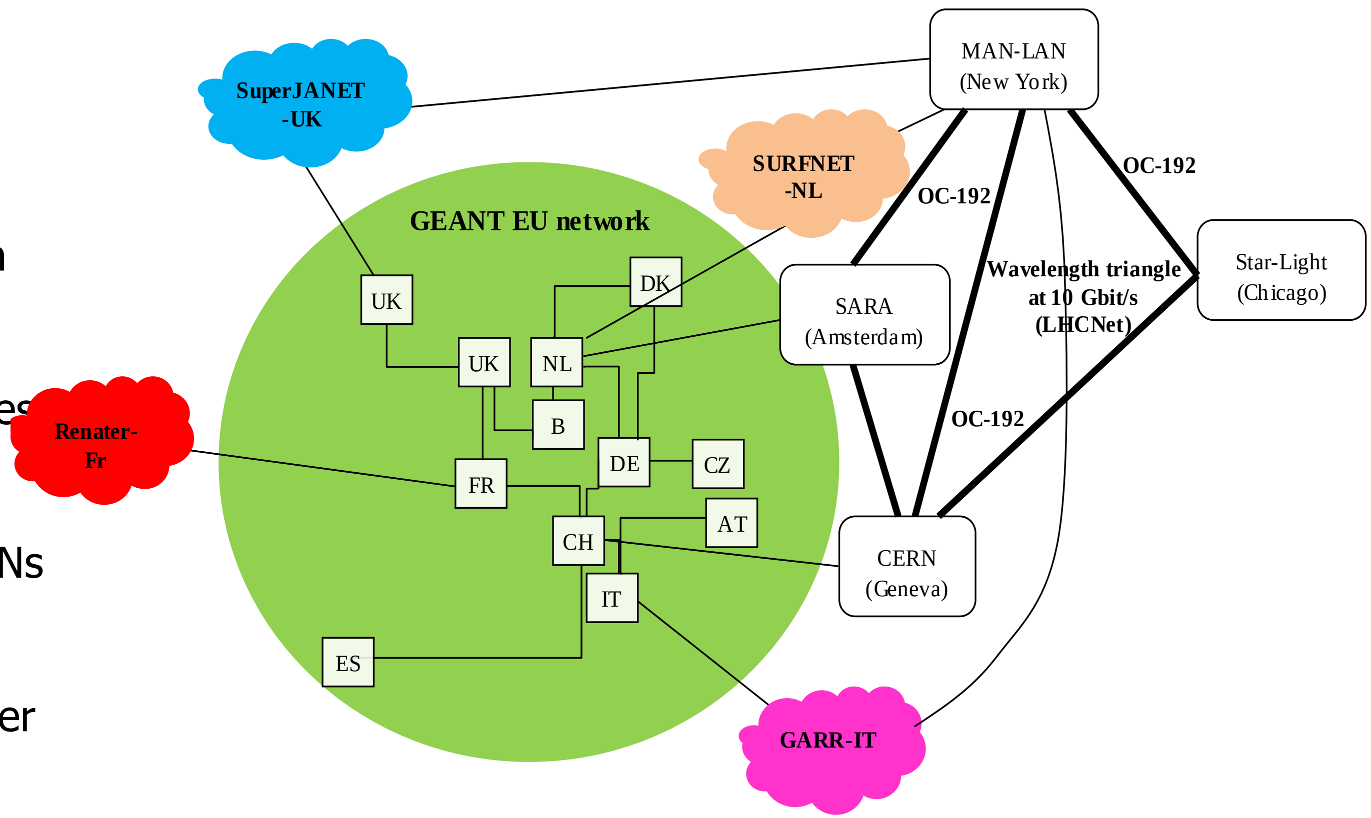
A packet crosses many networks (ISPs) from source to destination.



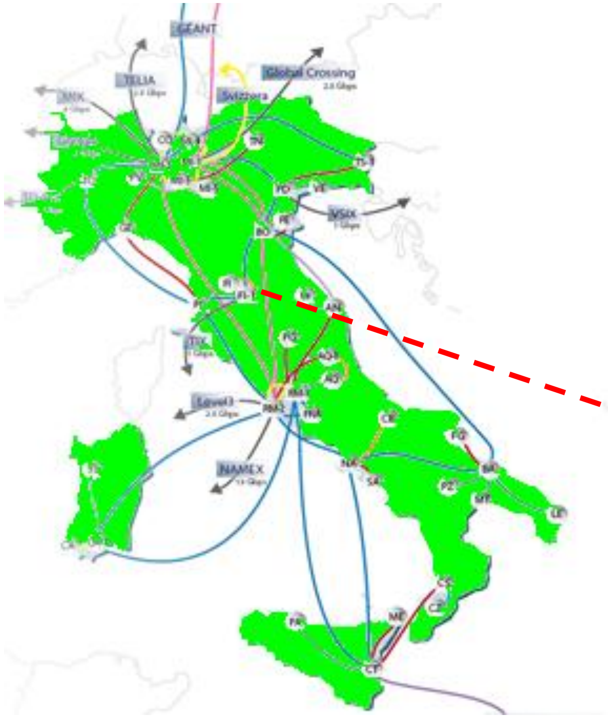
An Example of Core Network: the EU GÉANT 1, 2, and 3

The core network is typically a meshed network of nodes that interconnects systems.

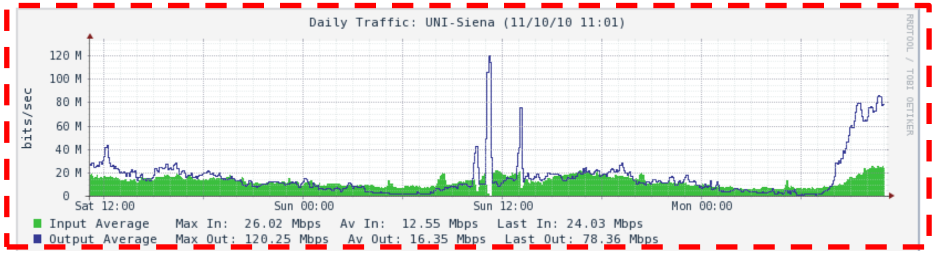
This slide shows a simplified representation of the GÉANT core network (showing some PoPs with Juniper T-series routers and optical fiber links at 10, 20 and 40 Gbit/s), connecting NRENs in different European countries and some transatlantic links to other regions (peering). MAN-LAN and Star-Light are examples of international peering points.



The Italian University Network: GARR



The GARR (“Gruppo per l’Armonizzazione delle reti della Ricerca”) network was born at the end of ’80 in order to harmonize the networks of universities and public bodies in Italy.

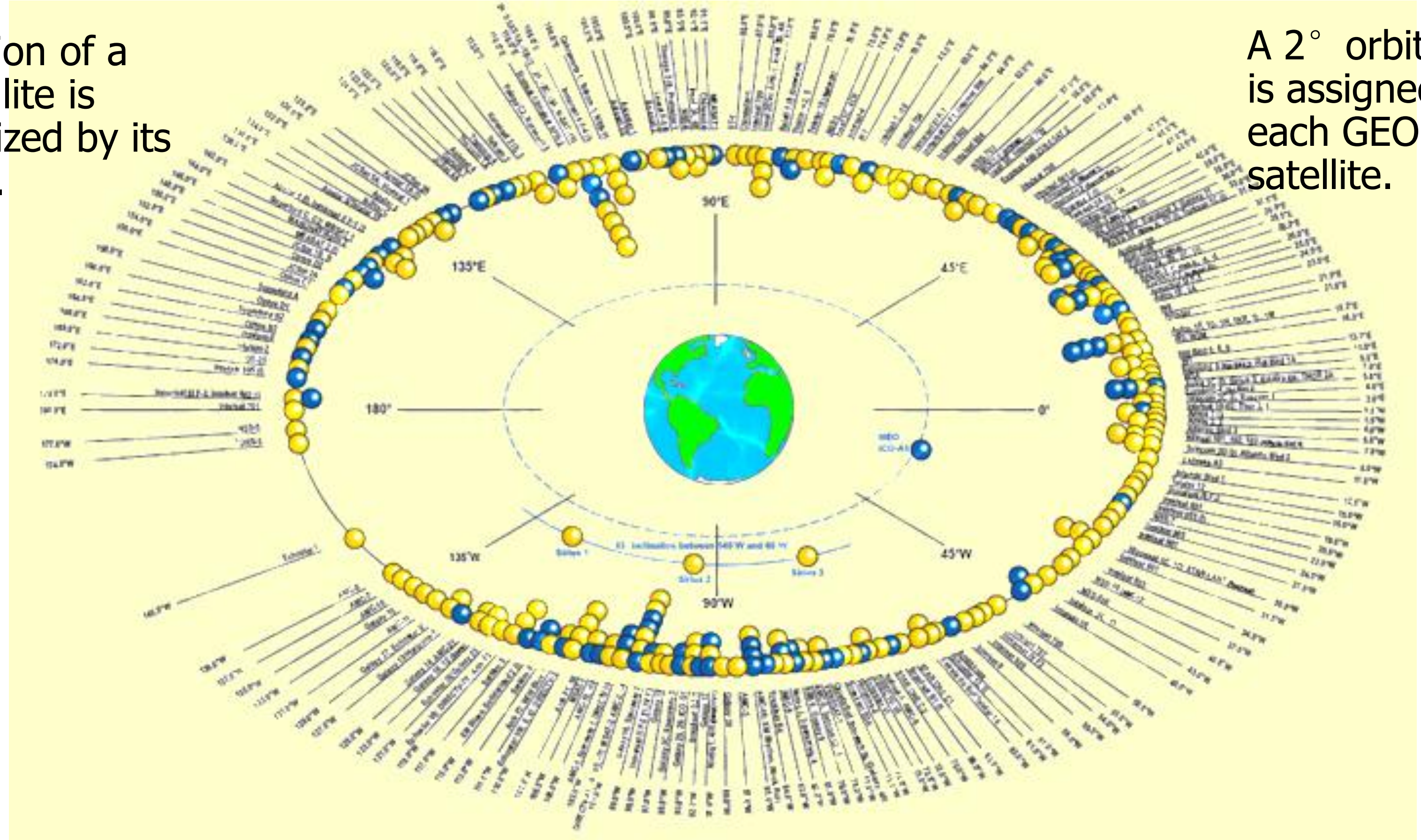


GARR-G network ensures its community the **interconnection with the Internet core**.

The GARR-G network is part of the worldwide system of Research and Education Networks (NRENs). It connects to other NRENs in Europe and worldwide through a 10 Gbit/s link (plus 2.5 Gbit/s backup link) to the GÉANT2 pan-European backbone.

GEO Satellites for Global-Scale Connectivity

The position of a GEO satellite is characterized by its longitude.



A 2° orbital slot is assigned to each GEO satellite.

There is a hole in the GEO satellites over the Pacific Ocean (differently from the Atlantic Ocean) since this is a too big area with a very reduced and sparse population.

Exponential Traffic Growth

- A growing number of people are using the Internet; this is also evident from the different bandwidth-intensive applications supported by Internet (e.g., cloud computing) and by the considerable number of Internet books, video, etc.
- Digital information and data traffic worldwide are experiencing an **exponential growth** that represents a challenge to be addressed by system designers and network planners.
- Internet traffic has globally grown eight times in the period 2008-2012 (five years) and is expected to increase threefold in the next three years. The annual global IP traffic will surpass the Zettabyte (i.e., 10^{21} bytes) threshold by the end of 2016.
  - This is related to the **Moore law** on the density of transistors on chips.
- This situation requires **a careful design of the network to be able to support the ever increasing traffic load**.

Thank you!

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