Computer Networks

TELCOM 2310

Dr. Taieb F. Znati

Department of Computer Science
Telecommunication Program
University of Pittsburgh

''Today communications systems that send voice, data, and video signals span the earth. Information is bounced off satellites and shot through cables that cross entire oceans. Computer Based systems operate in the dead of night receiving messages from places where it is high noon. And the organization that turns a blind side to how communications and computer technologies together are transforming the world will be outperformed and outmaneuvered by its competitors-competitors that can move data from any country on earth.''

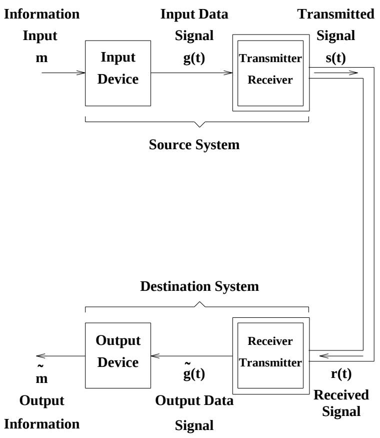
Course Objectives

- **The course emphasizes basic principals and topics of fundamental importance in computer communications networks.**
  - **When practical, a quantitative approach is used to discuss these topics.**
- **The main main objective is to provide a good understanding of the fundamental concepts involved in the design, implementation and performance of computer communication networks and related protocols.**

Communication Models

- **The fundamental purpose of data communication is to exchange Information between two entities.**
  - **Information is represented as data and carries meaning currently assigned to those data.**
    - **Data represents facts, concepts, or instructions in a formalized manner suitable for communication, interpretation, or processing by human or machines**

Simple Communications Model



Simple Communications Model

- m: **original information message created by sending agent**
- $g(t)$: **time varying signal, not suitable for transmission**
- $s(t)$: **signal obtained by converting $g(t)$ into a form that matches the characteristics of the transmission medium**
- $r(t)$: **received signal which may be different from $s(t)$**
- $\tilde{g}(t)$: **signal obtained by converting $r(t)$ into a form suitable for output**
- $\tilde{m}$: **estimated message produced by destination agent**

Simple Communications Model

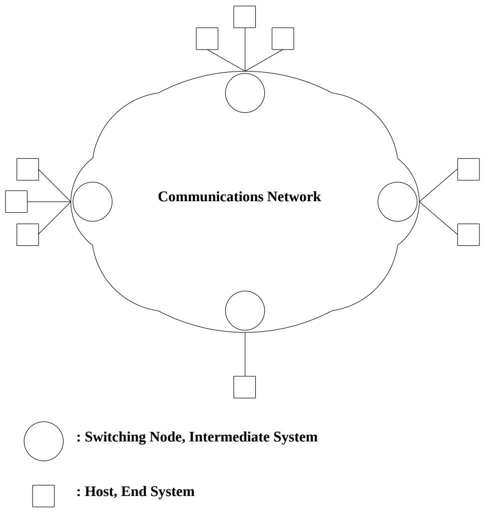
- **Although Simple, the model highlights several communication tasks:**
  - **Interfacing,**
  - **Signal generation**
  - **Synchronization**
  - **Error detection and correction**
  - **Flow control**
  - **Framing, message formatting**

Data Communications Networks

- **Point-to-Point communication is the simplest form of data communication**
  - **Not practicl to provide a dedicated wire between each pair of devices**
- **Communication networks provide efficient means for data communication between multiple devices**

Communications Networks

- Network, a collection of nodes capable of transporting data between pairs of attached stations.



What is a Computer Network?

- Software and hardware infrastructure:
  - It allows access to different types of resources (original purpose)
    - Computing resources, input/output devices, files, databases...
  - It provides a medium through which geographically dispersed users communicate (e.g., email, chatting, teleconferencing, ...)
  - An electronic village
  - an information highway, national information infrastructure
  - Cyberspace- ''A consensual [environment] experienced daily by billions of operators, in every nation, ...''

Network Communications Tasks

- Several tasks need to be performed to provide computer network functionalities
  - Ensure that transmission facilities exist between end points.
  - Provide physical interfaces to control modems and adapters.
  - Provide access techniques to effectively share resources.
  - Provide addressing, routing, buffering and flow regulation of packets.
  - Accommodate peculiarities of users.
  - Provide management functions and mechanisms to support distributed applications.

Classes of Networks

- Networks are usually defined according to
  - Geographical Extent.
  - Purpose.
  - Implementation.

Classes of Networks

- Based on geographical extent, the following classes of are identified :
  - Local Area Networks (LANs).
  - Wide Area Networks (WANs).
  - Metropolitan Area Networks (MANs).
  - Radio and Satellite Networks.

Local Area Networks (LANs)

- By far, most commonly used class of networks.
  - Maximum distance between nodes is limited to few kilometers.
  - Usually owned by the same organization.
  - Typical data transmission ranges between 10 Mbps (Coax cable) to 100s of Mbps (Fiber optic).
  - Several architectures have been standardized (802 LANs) :
    - Ethernet (CSMA/CD), Fast Ethernet.
    - Token Bus.
    - Token Ring.
    - FDDI.

Wide Area Networks (WANs)

- Covers a wide geographical area.
- Communication links are provided by phone companies, or other common carriers.
- Transmission speed are usually restricted.
- Transmission qualities is inferior to LANs qualities.
- Their architectures are usually more complex.
  - Need for efficient routing and congestion control algorithms.
- ARPANET, SNA, DNA are many implementations of vendor architectures for WANs

Metropolitan Area Networks (MANs)

- A relatively new class of networks, intermediate between MANs and LANs.
- Support moderate (Data, Voice and Video at 1 Mbps) to high data rate.
- MANs are optimized for a larger geographical area than LANs, ranging from several blocks of buildings to entire cities.
- Coaxial cable and fiber optics are the most commonly used communication media.
- Standards include FDDI, FDDI-II and IEEE 802.6 (DQDB)

Radio and Satellite Networks

- There are two basic subclasses
  - Terrestrial radio networks.
  - Satellite networks.

Communication Networks

- Communication Networks can be further classified as :
  - Broadcast networks, or
  - Switched networks

Broadcast Networks

- In broadcast networks, stations communicate over a shared medium.
- No need for intermediate nodes.
  - Three types of broadcast networks
    - Packet Radio Networks,
    - Satellite Networks, and
    - Local Area Networks.

Switched Networks

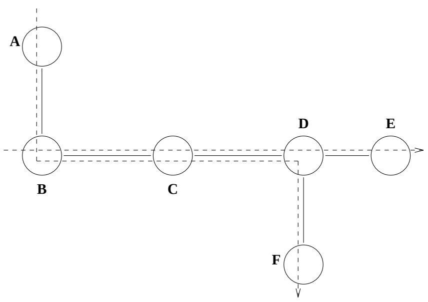
- In switched networks, communication facilities are shared among users.
  - Three primary switching techniques
    - Circuit switching,
    - Message switching, and
    - Packet switching.

Switching Techniques
Circuit Switching

- **Commonly used in the public telephone system.**
  - ○ **Exclusive dedication of a portion of the links available bandwidth to carry traffic between source and destination.**
  - ○ **Allocation of the required bandwidth is achieved using :**
    - □ **Frequency Division Multiplexing**
    - □ **Time Division Multiplexing**

Circuit Switched Networks

- **Telephone, network typically**
  - ○ **All resources (e.g. communication links, buffers) needed by a ''call'' are dedicated to that call for its entire duration**
    - □ **Resource reservation, i.e. resources are always available when needed by a call, guarantees ''Quality-of-Service'' (QoS).**

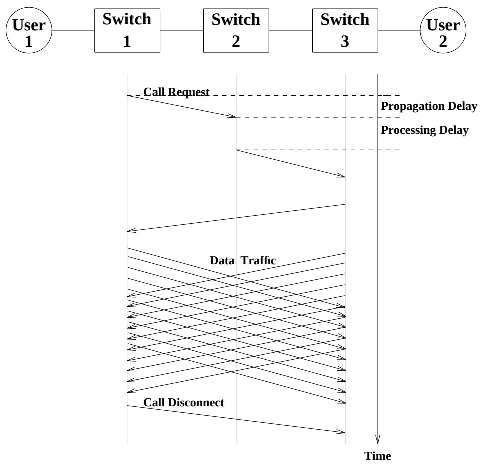


- **Note: Assuming one circuit/link, A $\Rightarrow$ F call blocks B $\Rightarrow$ E call**

Circuit Switching

- **Call requires three phases :**
  - ○ **Connection phase, a circuit is set up between source and destination.**
  - ○ **Transmission phase, traffic exchange takes place.**
  - ○ **Termination phase, the call is disconnected.**

Circuit Switching



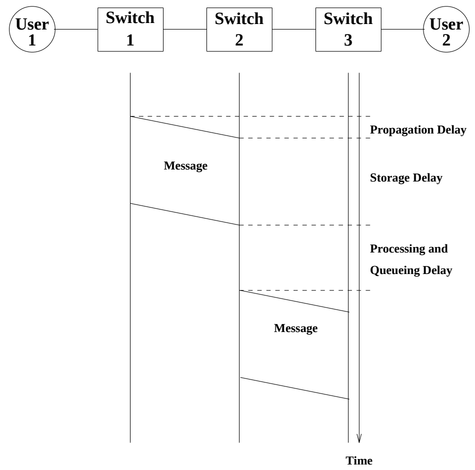
Circuit Switching

- Delays for setting up connections can be high.
  - Ordinary telephone lines :
    - Call setup is on the order of 5 to 25 sec after completion of dialing.

Message Switching

- A physical circuit is shared among multiple users.
  - Leased communication facilities are used.
- Data enters the network in the form of ''messages''
  - Messages are stored and subsequently forwarded.
    - No circuit switching delays are involved.
    - Queueing delays occur.
    - Message lengths are slightly longer because of headers.

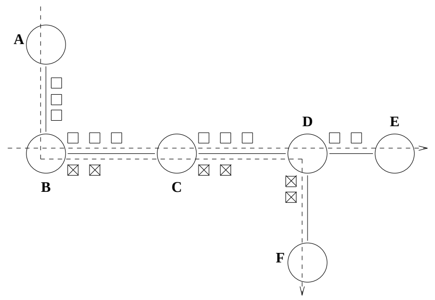
Message Switching



Packet Switching Networks

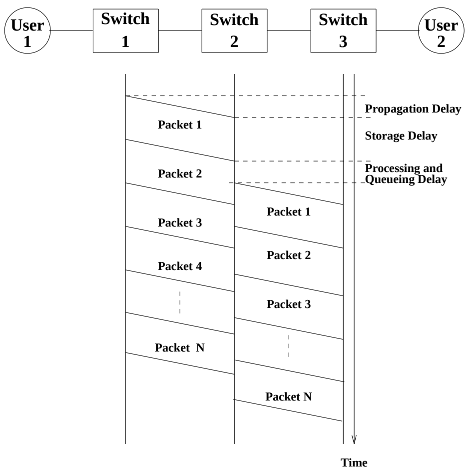
- Equivalent to message switching for short messages.
  - Maximum message length for transmission is imposed.
  - Any message exceeding the maximum is broken up into shorter units called, ''packets''.
- Packets traversing network share networks resources with other packets

Packet Switching Networks



- Demand for resources may exceed resources available: contention
  - Statistical Sharing of resources

Packet Switching



Performance Tradeoffs

- **Three types of Delay :**
  - **Propagation Delay, time for the signal to propagate**
    - □ **Generally negligible (The speed of electromagnetic signals through a wire medium is $2 \times 10^8 m/s$.**
  - **Transmission Time, time it takes to send out a block of data**
    - □ **1 sec to transmit 10,000-bit block onto 10-kbps communication line**
  - **Queueing Delay, time for the node to process data being switched**
    - □ **variable, depending on the processing speed and the network load**

Performance Tradeoffs
Circuit Switching

- **Circuit switching may lead to smaller delays if large amount of data are exchanged.**
  - **Elimination of the header.**
  - **Elimination of intermediate node queueing.**

Performance Tradeoff
Packet Switching

- A major benefit, the pipelining effect.
- Simultaneous use of communications circuits allows :
  - Considerable gain in efficiency.
    - Shorter delays, despite inclusion of headers for each packet.
  - Lower probability of retransmission.
    - Shorter messages are less likely to have errors than longer ones.
    - Errors do not cause retransmission of entire messages, but only of relatively shorter packets.
  - Packets can be routed independently, possibly minimizing congestion.

Performance Tradeoffs

- Packet switching provides flexibility in meeting the users need.
  - Example: the needed rate is 75 kbps while the channel rate 64 kbps.
    - The use of packet switching meets the demands of the user, more easily.

Performance Tradeoffs

- Statistical sharing of resources can be more efficient
  - Consider a 1 Mbps communication link
  - Each user requires 100 Kbps when transmitting, but sends 10% of the time
- Circuit Switching
  - Each caller is allocated 100 Kbps capacity.
  - At most 10 callers are supported
- Packet Switching
  - With 35 ongoing calls, probability that 10 or more callers are simultaneously active is less than 0.0004!
  - Can support many more callers, with small probability of contention
- If user traffic is ''bursty'' (on/off), then packet switching can be more efficient than circuit switching

Performance Tradeoffs

- The relative performance of circuit switching and packet switching depends on:
  - The quality of service requirements of the application
    - End-to-end delay bounds
    - Jitter control
  - The traffic pattern
    - Burstiness vs constant bit rate
  - Connection setup overhead

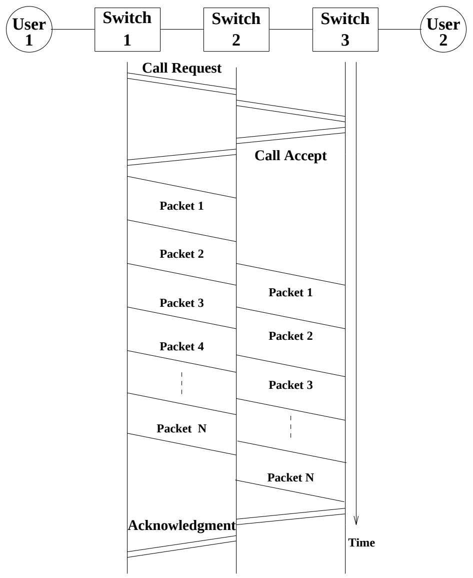
Packet Network Switching Techniques

- **Two basic approaches to packet switching are common :**
  - **Datagram Packet Switching**
  - **Virtual Circuit Packet Switching**

Virtual Circuit Packet Switching

- **An initial phase is used to setup a fixed route.**
  - **Similar to circuit switching, except that a delay occurs at each node**
    - **Call request and call Accept must both wait their turns for transmission**

Virtual Circuit Packet Switching



Virtual Circuit Packet Switching

- **Upon path set-up, the virtual circuit appears to the user as a dedicated circuit**
  - **In reality, the circuit is shared among multiple users**
- **Destination address no longer required**
  - **Only a virtual circuit number is needed**
  - **Packets have shorter headers.**

Datagram Packet Switching

- Datagram Packet Switching does not require a call setup
- For short transactions, it may be faster
- Individual datagrams are routed independently
  - ○ Increases processing overhead at the router
    - □ Routing table lookups

Virtual Circuit Service Characteristics

- Guaranteed, reliable delivery.
  - ○ Powerful error control
  - ○ Sequencing of packets.
  - ○ Detection and suppression of duplicates.
- Congestion control minimizes queueing delays.
  - ○ Delays, however, are more variable than they are with dedicated circuits.
- Enhanced security.

Datagrams Service Characteristics

- The network makes a ‘‘best effort’’ attempt to deliver the packets
  - ○ Each packet is treated as a separate entity, with no prior route determination.
    - □ Packets may follow different paths to destination.
  - ○ No guarantees for reliable delivery.
    - □ Packets may be lost, duplicated, or may arrive out of order.
- The network relies on the user application to enhance the basic datagram service

Analogy

- Telephone service $\longleftrightarrow$ Virtual Circuit.
  - ○ User must set up the call, transmit and finally disconnect.
  - ○ End users have the illusion that they communicate through a dedicated circuit.
  - ○ Data is transmitted in the order they have been received.
- Regular postal service $\longleftrightarrow$ Datagram.
  - ○ Letters are handled independently.
  - ○ No guaranteed delivery. Losses are the user's responsibility.
  - ○ Letters are not necessarily delivered in the order they have been sent.

Analogy

- **User perspective :**
  - **''Unsophisticated'' users prefer virtual circuits.**
    - **The communication subnet handles most of the functions required to provide the requested service.**
  - **''Sophisticated'' users prefer datagram service**
    - **Datagram service provides more flexibility to implement particular features.**

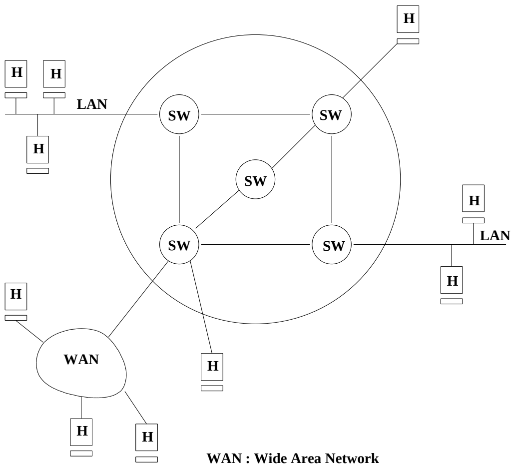
Analogy

- **Application perspective:**
  - **Prior establishment of connection, although desirable, may lead to unacceptable delays for certain types of applications.**
    - **Request/Reply.**
  - **Features such as error control may be detrimental to time bound applications, such as voice.**
    - **Few bits in error is far more preferable than lengthy retransmission delays.**
    - **For voice application a connection set up may be needed but no error control is required.**

Connection Semantics

- **Literature often uses the term connection oriented and connectionless to refer to different network services.**
  - **Virtual circuit transmission is a special case of connection oriented transmission.**
  - **Datagram service is a special case of connectionless transmission.**

Internetworking



WAN : Wide Area Network
LAN : Local Area Network
H : Host (Workstation or Terminal)
SW : Switching Node

Internetworking

- The main goal is to provide a universal network formed out of physically different networks.
- Internetworking involves complex issues :
  - Different addressing and naming schemes.
  - Different routing techniques.
  - Different congestion control techniques.
  - Different hardware interfaces.

Characteristics of Protocols

- A protocol is a set of mutually agreed upon rules that regiment the interactions between the communicating entities.
  - The key elements of a protocol are :
    - □ Syntax - defines the structure of information communicated, including the data format, the coding, and signal representations.
    - □ Semantics - defines the meaning of the exchanged signals, including control information for coordination and error handling.
    - □ Timing - defines the time at which data should be exchanged.
- In summary, the key elements of the protocol define **what** is communicated, **how** it is communicated and **when** it is communicated.

Network Architectures

- The task of designing a communication network is too complex to be handled as a monolithic unit.
- An alternative, a structured approach.
  - Divide the communication task into manageable parts.
  - Need to describe the communication functions in terms of an architecture
    - □ The architecture defines the relationship and interactions between network services and functions through common interfaces and protocols.

Layered Architecture

- The architecture is divided into multiple layers.
- Each layer performs a related subset of functions required for communication, and adds value to the services provided by lower layers.
  - Layer N relies on services of layer N-1 to provide a service to layer N+1
  - Service required from lower layer is independent of how that service is implemented
    - □ Information and complexity hiding
    - □ Changes in layer N do not affect other layers

Layered Model Interfaces

- Boundaries between adjacent layers in the same system are called interfaces.
  - Interface protocols define the interaction between adjacent layers in the same system

Network Architecture
System Design Perspective

- ''Best Effort'' vs ''Reliable'' service
- Can the network be totally trusted?
- Where should reliability belong?

End-to-End Argument

- ''Making good judgement about where to place functionalities in a complex system is what system design is all about''
- End-to-End argument states that a function, such as reliability or ordered delivery, should not be provided in the lower levels of the system unless it can be completely and correctly implemented at that level
  - Functional redundancy can be allowed if performance optimization is sought
    - Example : error control on a hop-by-hop basis

''Statefull'' vs. ''Stateless''

- Connection oriented networks require full state management
  - Establishment of a new connection causes a state change in the switch
  - A direct side effect, fate sharing
    - Fate of the end-to-end connection depends on the state of intermediate nodes
- Connectionless network are stateless
  - Simple and more robust
  - Only task required is to maintain end-to-end routing tables

‘‘Statefull’’ vs. ‘‘Stateless’’

- **Are simplicity and robustness obtained by trading ‘‘state’’ complexity for more routing and processing requirements at intermediate systems?**
  - **Switching have to perform address processing on packet basis**
- **Not necessarily true, as successive packets usually refer to the same address**
  - **Caching routing computation greatly reduces processing requirements**

ISO/OSI Communication Model

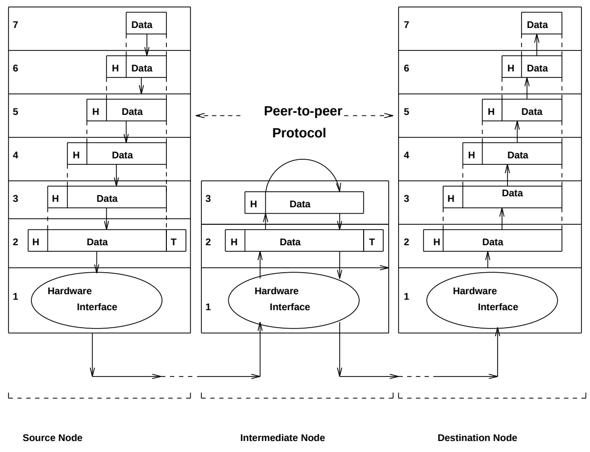
- **The layered architecture viewpoint has been adopted by the International Standard Organization (ISO) in defining its Reference Model**
- **The model referred to as the Open System Interconnection (OSI) defines a framework for the specification of protocol standards for connecting heterogeneous computers.**
  - **The model provides the basis for two open systems that conform to the reference model and the associated standards to exchange information.**

ISO/OSI Communication Model

- **The basic goals of the model :**
  - **Define the rules and conventions for various functions within each layer.**
  - **Specify the general relations among these functions.**
  - **Determine the constraints on the types of functions and their relations.**

ISO/OSI Communication Model

1. Physical Layer
2. Data-link Layer
3. Network Layer
4. Transport Layer
7. Application Layer
5. Session Layer
6. Presentation Layer



H: Header
T: Trailer

ISO/OSI Communication Model Architecture

- The ISO reference model defines seven layers:
  - Application layer.
  - Presentation layer,
  - Session layer,
  - Transport layer,
  - Network layer,
  - Data link layer, and
  - Physical layer,

ISO/OSI Communication Layers

- Application Layer
  - Process to process communication
  - All layers exist to support this layer
  - Applications include email, teleconferencing, WWW, ftp, distributed databases
- Presentation Layer
  - Conversion of data to conform to a common format (e.g., little endian, big endian, byte orders, integer and floating point representation, ...)
- Session Layer
  - Bind two communicating entities into a ‘‘relationship’’
    - Session setup (authentication), failure recovery (broken session)

ISO/OSI Communication Layers

- Transport Layer
  - End-to-end data delivery
    - End-host to end-host communication
    - Multiplexing of multiple data streams from higher layers
    - Flow control between sender and receivers
- Network Layer
  - Data transmission and delivery between hosts
    - Controls access to the network
    - Provides routing of packets within the network
    - Manages contention and bottlenecks within the network

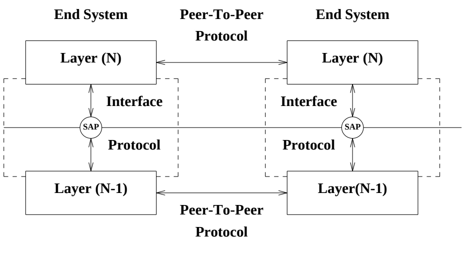
ISO/OSI Communication Layers

- Data Link Layer
  - Error free communication over a single link between adjacent nodes
  - Speed matching between senders and receivers
- Physical Layer
  - Transmission of raw bits (0/1) over physical wires
    - Interfacing, Data encoding, synchronization, ...

ISO/OSI Communication Model

- Direct communication between peer layers in two different machines is only achieved at the physical layer.
- The interlayer interface defines a framework for standards
  - No details of the implementation, no definition of the interlayer interfaces.

ISO/OSI Communication Model
Interfaces



SAP : Service Access Point

Interfaces

- Communicating systems need not implement the same interlayer interfaces, since these are not visible from the outside.
- The interface is used to access services provided by a lower layer to a higher layer
- The point at which service is provided is called Service Access Point (SAP).

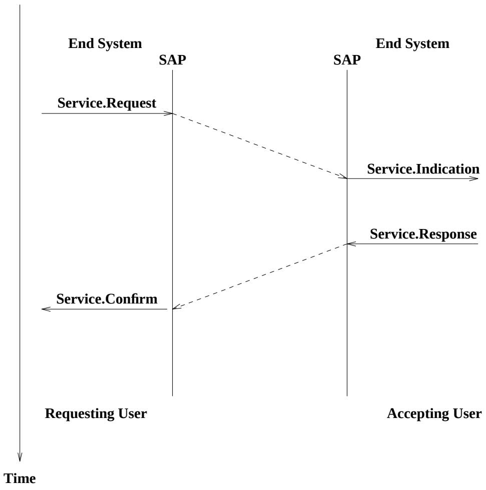
ISO/OSI Service Primitives

- Interactions between adjacent layers are managed by communication primitives.
  - A primitive initiates an action or reports a result.
  - These primitives can occur at various instances of the dialogue

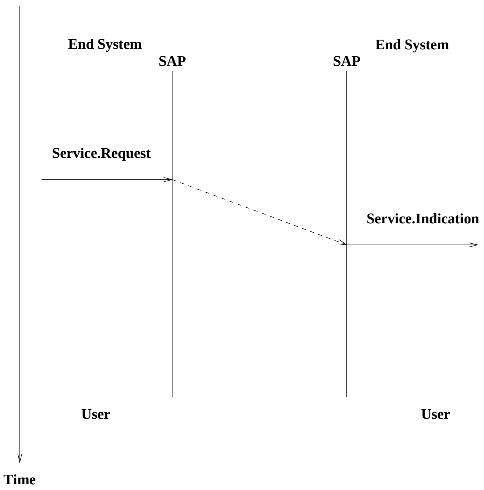
ISO/OSI Service Primitives and Service Types

- **Four basic primitives are defined :**
  - **Service.Request() : Invokes the services of the lower layer and passes the needed parameters.**
  - **Service.Indication() : Advises the higher layer of the requested service.**
  - **Service.Response() : Used to reply to an indication issued by the lower layer.**
  - **Service.Confirmation() : Used to acknowledges the completion of a request previously invoked by higher layer.**
- **Three types of Services**
  - **Confirmed Service**
  - **Unconfirmed Service**
  - **Provider Initiated**

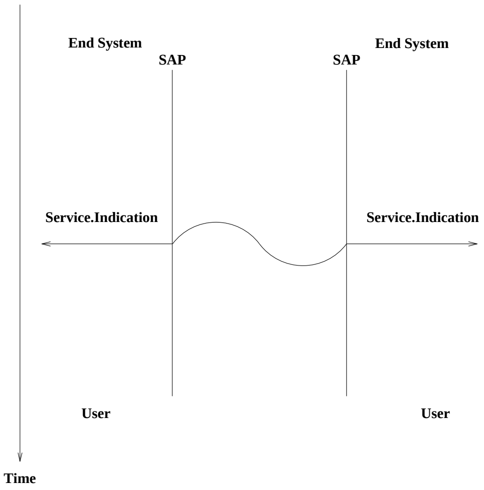
Confirmed Service



Unconfirmed Service

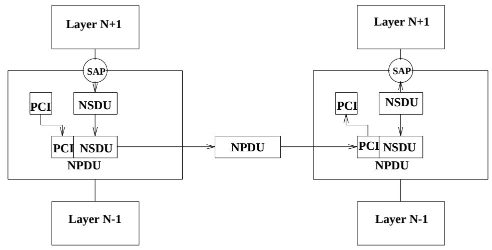


Provider Initiated Service



Protocol Data Unit

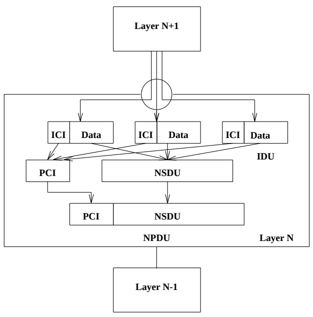
- A layer accepts a Service Data Unit and adds Protocol Control Information to a Protocol Data Unit



SAP : Service Access Point
SDU : Service Data Unit
PDU : Packet Data Unit
PCI : Protocol Control Information

Interface Data Unit

- A set of Interface Data and its associated ICI makes and IDU, the data unit passed across abstract interfaces at the SAP



ICI : Interface Control Information
IDU : Interface Data Unit
SDU : Service Data Unit
PDU : Protocol Data Unit
PCI : Protocol Control Information

Model Limitations

- The model is complex
- Focus entirely on listing of details, with no motivation for techniques adopted
  - ○ Every reasonable suggestions becomes an option
  - ○ This results in an excessive number of options, for a protocol architecture that is supposed to be an international standard
- The layering structure of the model is arbitrary
  - ○ Appropriate placement of features in layers is not always obvious

Model Limitations

- The development of the model has been dominated by a communication mentality
  - ○ Techniques from communication fields have been sometimes inappropriate
    - □ Use of interrupts, when implementation calls for use of a procedure call
    - □ Initial focus entirely on connection oriented, rather than connectionless.
    - □ Connectionless service is currently being provided, but as an afterthought
- The model does not allow explicit bypassing of adjacent layers when not needed.
  - ○ May lead to redundancy of functionalities
  - ○ May result in inefficiency

Model Limitation

- In general, layering has many conceptual advantages but may be ''harmful or difficult''
  - Fanatical adherence to layering as a religion may be problematic
    - Layer N may duplicate lower layer functionality (e.g., error-recovery on both hop-by-hop and end-to-end basis)
    - Different layers may need same information (e.g., timestamps)
    - Layer N may need to know layer N-2 information (e.g., fragmentation)

Network Architecture, DoD Model

- Three main reasons for continued development of the DoD architecture
  - Communication requirements specific to DoD have not originally been reflected in the OSI model
  - Philosophical differences concerning the appropriate nature of a communications architecture and protocols
  - DoD protocols have been specified and used extensively, while large parts of the OSI Model have not been implemented yet

DoD Model vs OSI Model

- Hierarchy versus Layering
- Importance of Internetworking
- Utility of connectionless services
- Approach to management

DoD Model (Continued)

- The approach resulted from extensive research and practical experience of ARPANET, currently ARPA Internet
- The fundamental principle of the architecture
  - Communication between local and remote processes can be accomplished by first identifying the remote host and then identifying the remote process within the remote host.

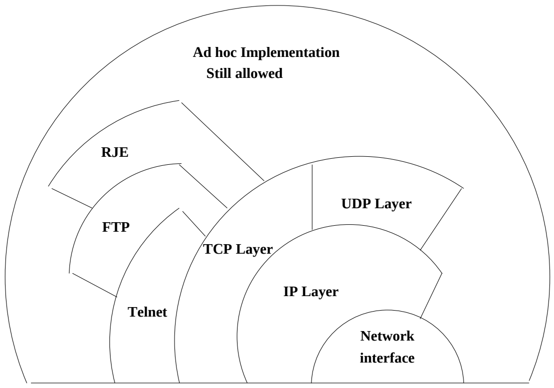
DoD Model

- The actions of identifying the network and the remote process can be handled independently.
  - The task of the network is reduced mainly to routing data between hosts.
  - The network need not be concerned with how the data is directed to the remote process within the host

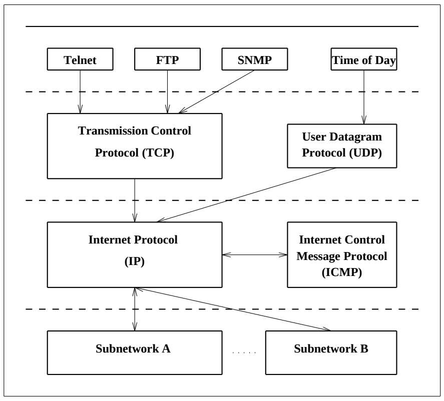
DoD Model

- Based on the above concept, the architecture was conceived as a hierarchical ordering of protocols that can be organized into four layers:
  - The application layer, the transport layer, the Internet layer and the network layer
  - Higher layers may bypass an adjacent layer and directly use the services of a lower layer

DoD Hierarchical Model



DoD Protocol Standards

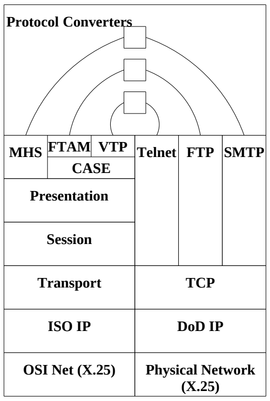


DoD Protocol Standards

ISO-DoD Correspondence

ISO	DoD
Application	Process
Presentation	Process
Session	Process / Host-to-Host
Transport	Host-to-Host
Network	Internet
Data Link	Network Access
Physical	Network Access

DoD-ISO Migration



CASE : Common Application Service Element
FTAM : File Transfer Access and Manipulation
VTP : Virtual Terminal Protocol

ISO and DoD

- ISO adopted a three-sublayered network protocol
  - Connectionless Internet Protocol (ISO-IP) corresponds to the Internet Protocol
    - The existence of this sublayer removes one of the major points of disagreement in the ISO OSI and TCP/IP layering models

ISO Stacks

ISO-OSI	GOSIP Protocols (Version 2 Primary Stack)				
	ODA				
7 Application What : ISO : CCITT :	VT (login) ISO 9040	FTAM (Files) ISO 9571	MHS (Messages) ISO 10021 X.400	Directory (Directory Service) ISO 9594 X.500	
	ISO 8850 : ACSE				
6 Presentation	ISO 8823				
5 Session	ISO 8327				
4 Transport	ISO 8073 : TP4				
3 Network Internet Convergence Subnet	CLNS ISO 8473 : CLNP (ISO-IP)				
2 Data Link	ISO 8802-3 IEEE 802.3	ISO 8802-2 ISO 8802-4 IEEE 802.4	ISO 8802-5 IEEE 802.5	ISO 7776 X.25 LAPB	ISDN
1 Physical	(various Protocols)				

ISO Stacks

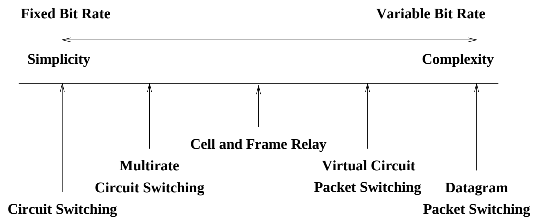
ISO-OSI	GOSIP Protocols (Version 2 Secondary Stack)			
7 Application What : ISO : CCITT :	VT (login) ISO 9040	FTAM (Files) ISO 9571	ODA MHS (Messages) ISO 10021 X.400	Directory (Directory Service) ISO 9594 X.500
	ISO 8850 : ACSE			
6 Presentation	ISO 8823			
5 Session	ISO 8327			
4 Transport	ISO 8073 : TP4			
3 Network Internet Convergence Subnet	CONS ISO 8878 : X.25			
2 Data Link	ISO 7776 X.25 LAPB (HDLC)			ISDN
1 Physical	(various Protocols)			

Future Trends of Communication Networks

- **In recent years, a large technological progress has occurred both in the field of electronics and the field of optics**
- **Technological progress has opened the door to a new class of applications, Real-Time Applications.**
  - **These applications create the need for :**
    - **Greater flexibility in the transfer mode,**
    - **Transport of services other than pure data,**
    - **Transport of high bit rate services**
    - **Development of higher speed systems**

Switching Revisited

- **A transfer mode is characterized by the switching technique used in the switching nodes.**



Circuit Switching Transfer Mode

- **Circuit Switching is very inflexible**
  - **The bit rate is fixed**
  - **In PCM, the basic time slot duration is 8 bits per 125 μsec, giving rise to channels of 64 kbps**
- **Circuit switching is very unsuitable for real-time services characterized by variable bit rates.**

Multirate Circuit Switching Transfer Mode

- Multirate circuit switching overcomes the single bit rate in pure circuit switching
- A single connection can allocate multiple basic channels
  - Synchronization of the individual channels is required

Multirate Circuit Switching Transfer Mode

- The selection of the basic rate is difficult
  - A low basic rate may result in high number of basic channels to construct a high bit rate connection
  - A large basic rate may result in wasted bandwidth
- The use of multiple basic rate adds to the complexity of the channel management

Packet Switching Transfer Mode

- Acceptable end-to-end performance require complex protocols
  - Low quality links require link-by-link error control
  - Low speed links and limited buffers require link-by-link flow control
  - Variable packet length require complex buffer management
- Higher complexity substantially increases the processing requirements
- The technique, however, is more flexible than circuit switching

Frame Relay

- This technique reduces the networking functionality, taking advantage of the increasing quality of the links
  - Higher throughput may be achieved

Functional Differences

Functionality	Current Packet Switching (X.25)	Relay
Frame Boundary Recognition	Y	Y
Bit Transparency	Y	Y
CRC Generation	Y	Y
Error Control	Y	N
Flow Control	Y	N
Logical Channels Multiplexing	Y	N

Cell Relay
Asynchronous Transfer Mode

- **ATM reduces the functionality of the header to an absolute minimum**
- **Uses fixed packet length, known as cells**
- **Operation is asynchronous, in the sense that cells do not have an identified position in time**
  - **Provides greater flexibility to handle variable bit rate services**

Fundamental Concepts
Summary

- **Introduced the basic concepts of communication networks.**
- **Discussed switching techniques.**
- **Presented different classes of communication networks.**
- **Introduced the concept of Internetworking.**
- **Introduced the concept of a protocol.**
- **Introduced the main network architectures**
- **Discussed future trends of communication networks**