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COM302T Computer Networks-Lecture Notes

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Introduction to Computer Networks

Objective of this course: To expose you to technical details involved in setting up a local network, a campus network, etc. Towards this attempt, we shall investigate the following fundamental questions in detail.

1. How to connect two or more computers? What are the underlying network topologies, network components, etc. used?
2. What is the mechanism for placing a stream of binary data onto the wire (cable) or What is an Encoding scheme?
3. Who decides the speed? Network interface card vs Cable Bandwidth?
4. How is the data placed on the wire and how long does it take for a bit to travel from one end of the network to the other?
5. What if a bit is corrupted during transmission? How to do Error detection and correction ?
6. Can a sender send a data faster than the receiver's accepting rate? How to control the flow of packets?
7. How do we identify machines in a network? What are the addressing schemes ?
8. What is the mechanism followed for delivering a packet to the intended recipient? Or say, what is switching and routing ?
9. How do we create a small office network and do the design and performance analysis?

Understanding of these questions deeper, will help us to identify the right network topology (design) for a given application. Inferences and observations we make at each step of our investigation will reveal true insights into the theoretical analysis vs practical limitations.

Now, we shall begin this lecture with a tour of history of computer networks.

Telephone and its origin: Alexander Graham Bell was a prolific researcher in the area of Acoustics and Speech signal processing, during the years 1850-1860. In the 1860s, he was interested in designing an equipment which would transfer a speech signal (analog signal) from one place to the other. As a result of his persistent research, in the year 1876, Bell discovered the telephone using, which he established a communication between himself at San Francisco and Mr.Watson who was based at Newyork. Subsequently, his work was patented and a network of telephones was designed with communication among them accomplished. Over the years, researchers started appreciating Bell's discovery and created the first commercial PSTN (Public Switched Telephone Network) to cater to the needs of the public. This marked the beginning of telecommunication engineering. Modulation techniques, error detection and correction codes, and other technological developments such as Bluetooth, Wireless Fidelity (Wi-Fi) and Wimax paved the way for modern researchers. Many profound results were reported in the last five decades.

Computer Science meets Telecommunication: In the year 1950, researchers at IBM developed a maiden workstation which performed scientific calculations for defence applications.

Department of Defence (DoD) of United States had multiple offices across US and there was a need for constant communication among its offices. Telephone played a larger role in this and data were exchanged between computers using external storage devices such as magnetic disks. DoD commissioned ARPA (Advanced Research Project Agency) project to look into the feasibility of interconnecting computers in a way very similar to telephone network. Researchers at UCLA (University of Southern California, Los Angeles) and Stanford worked on this project for 6 years and as a result of their dedicated research, data transfer between those two universities was accomplished by the ARPA's team. Subsequently, researchers at Utah and UCSB (University of California, Santa Barbara) joined ARPA to enhance their vision. The success of ARPA attracted many universities to join this venture and by 1975, ARPA established a network of 111 nodes. By 1981, more than a 200 universities (nodes) were a part of this great venture. And as more and more universities joined ARPA, there was a need for developing standards for data communication to bring in uniformity among protocols (set of rules that implement network functionalities). TCP/IP (Transmission Control Protocol/Internet Protocol) was developed and a year later the commercial ARPANET was thrown to the public. Organizations/Academia started developing their own campus network (INTRAnet) using the TCP/IP standards. Over the years, INTRAnets were interconnected to form a larger network, namely, INTERnet. So, INTERnet, as the name suggests, is basically a network of network of network of ... nodes. Although, internet is collection of computers, the underlying science for data communication is similar to the one followed by telecommunication engineering. Every technological development in telecommunication engineering has a strong influence on computer networks. In particular, Bluetooth, Wi-Fi and Wimax have brought in a paradigm shift in establishing a communication between systems.

INTERnet vs WWW Until 1989, the focus of internet was to share files between systems for scientific applications. In 1990, researchers focused on knowledge dissemination through e-contents and this idea was considered to be a favorite topic of research then. HTML and WWW were discovered in the year 1991 which marked the beginning of the modern internet. During 1990-1995, researchers at Microsoft were working on designing personal computers with a user friendly operating system and office applications. Due to the entry of Internet Service Providers (ISPs), public started using the WWW through internet. Results of deep research in switching, routing table design, cryptography and network security were reported in the last two decades.

Note: Internet is just a collection of many intranets and WWW refers to the modern internet (www.google.com, www.stanford.edu, email, social network, etc.). However, in practice both are used interchangeably. Similarly, in the context of computer networks; a node, a computer and a system are used interchangeably.

Interconnecting Nodes: Topology

In this section, we shall look at how to interface two or more systems using network gadgets. We shall be following one of the following topologies (strategies) to interconnect two or more nodes.

1. **BUS:** In this scheme, to interconnect n nodes, we use one *base Ethernet cable*, n T-connectors, n Ethernet cables. The base cable is terminated at both ends. T-connectors are fixed in the base cable at equal distances and the cable drawn from a T-connector is connected to the Network Interface Card (NIC) of a node. An example is illustrated in Figure 1. Overall, we need $n+1$ Ethernet cables to interface n nodes using Bus topology.
   `Advantage:` It is easy to connect a new node. And the cost is lower as the cable requirements

are relatively smaller.
`Disadvantage:` If the main cable breaks, the entire network collapses. Hence, it might not be suitable for large networks.

2. **RING:** This topology is similar to the bus except that the base Ethernet cable is a ring. Packets (a small portion of data) always flow in one direction from a given node to the other, usually clockwise direction, through the ring. Here again, we need one base cable for creating a ring and n Ethernet cables to interface n individual nodes. So $n+1$ cables in all for n nodes.

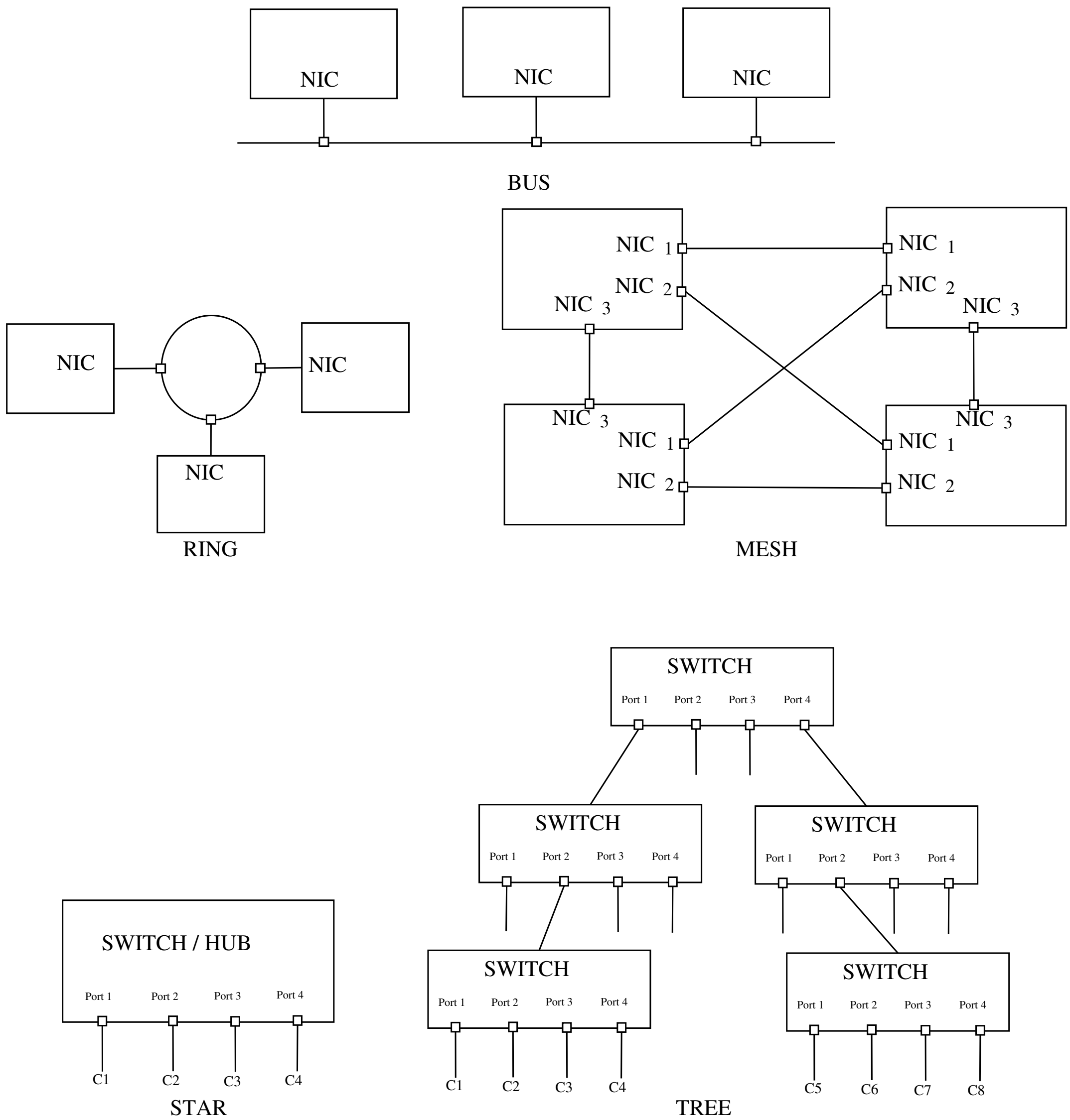

Fig. 1. Network Topology

3. **MESH:** Mesh is a fully connected topology, i.e., the topology is a complete graph on the n nodes. Each node has got $n-1$ NICs and is connected to every other machine using a

direct link provided with Ethernet cables. The number of links required for this topology is $\frac{n(n-1)}{2}$.
`Advantage:` It is easy to handle high volume traffic network and to maintain high security as the data travels along dedicated connection. It is also robust because even if one connection fails, everything else remains intact.
`Disadvantage:` There will be a lot of cables due to a lot of redundant connections.

4. **STAR:** This topology makes use of network components such as HUB and SWITCH for interconnecting n nodes. Hub/Switch consists of a specific number of ports, usually, 4/8/16/24/48 ports. In general, n links from n nodes are directly connected to the Hub/Switch. The internal organization of both Hub/Switch is a mesh network among n ports, i.e., a packet from port-1 of a hub/switch can be sent to any other port of the hub/switch. A hub has no processing ability and hence, a packet received from a port is simply forwarded to all other ports (broad casted to all ports). Whereas, a switch has some intelligence and hence, a packet received from a port is sent to a specific output port after checking the recipient's address available in the packet. Thus, a switch performs *unicasting* and a hub performs *broadcasting*. To interface n systems, we need n Ethernet cables and a switch/hub.

5. **TREE:** A campus network/academia network consists of many small networks. For example, a network among systems in a laboratory is a small network. Typically, laboratory network is a star and is created using a switch. Further, one can interconnect these small networks with another switch to get a larger network. For example, CS department network is created using CS laboratory networks. Further, a campus network is created using various departments' networks. Thus, a campus network is a hierarchical-type network built on top of many star networks. Such hierarchical networks are called tree networks and the underlying topology is a tree topology. The root of the tree is a switch and inturn, the switch is connected to many other switches, further these switches are connected to another set of switches and so on. Finally, at the last level of the hierarchy, the switches are connected to individual nodes. Suppose m switches are used to interface n nodes, then we need $m-1$ cables for interfacing the switches and n cables for interfacing the systems for a total of $m-1+n$ cables.
`Advantage:` Expansion of this type of network is easy. The segmented network and the point to point wiring for each segment helps in easy management and maintenance of the network and simplifies the error detection. And the damage in one segment does not affect the others.
`Disadvantage:` Maintenance starts to get slightly difficult as more number of nodes or small networks are added.

Media for Interconnection

This section explores various media used for interconnecting nodes and switches. Largely, it is divided into wired medium and wireless medium. As far as the wired medium is concerned, we use one of the following cables for interconnection.

Cable Type	Bandwidth	Repeater spacing	Limitations
Twisted Pair	10 to 100 Mbps	100 m	Subject to external interferences such as noise signal generated from motors; higher attenuation, i.e., frequent loss of signal; may have to face the issues of cross-talk
Coaxial Cable (Copper cable)	10 to 100 Mbps	500 m	Less susceptible to noise as the copper wire is shielded with plastic wrapper and a mesh. Moderate attenuation.
Fiber Cable	100-1000 Mbps	2 km	Lower attenuation. No interference due to noise signals as they are electromagnetic in nature. Interference due to light sources has an impact on the light signal transmitted.
Fiber Cable	100-2400 Mbps	40 km	-do-

Remark

1. Both twisted pair and coaxial cables are made of copper wires. A twisted pair cable consists of a pair of cables with twisting done at equal intervals. The purpose of twisting is to nullify (minimize) the effect of electromagnetic noise if in case the twisted pair cable running between a pair of nodes is passing through sources of electromagnetic noise such as electrical/mechanical motors. If it is only a single wire or a pair of untwisted wires, then each is exposed for a long time to the noise, making it highly prone for shorting. Twisting balances the disturbances by distributing the noise.

2. CAT6 Ethernet cables consists of 4 pairs of twisted pair cables with a different number of twisting for each pair. This is to ensure that there are no issues related to cross-talk, between the pairs. To reduce cross-talk, either coaxial cables or shielded twisted pair cables can be used. The mesh provided in a coaxial cable or shielded twisted pair absorbs the current generated due to external sources of noise, thereby protecting the signal passed through the internal copper wire.

3. Twisted pair cables are also used by telephone industry and coaxial cables by cable operators for broadcasting different channels without any external interferences.

4. In general, fiber cables are preferred for long distance communication, to interconnect two large networks which are physically far apart. To interface systems inside a large network, either a coaxial cable or shielded/unshielded twisted pair cable is preferred. Since there is a trade-off between cost and performance, intranets are created using twisted pairs and internet (interconnecting intranets) is created using fiber cables.

5. Signal, on travel, loses its strength after a point and hence, repeaters must be placed at equal distances between the two ends to ensure there is no loss in signal strength (referred to as Attenuation in the literature) during transmission. For example, for twisted pair cabling

network, a repeater must be placed at every 100m.

6. It is important to note that attenuation refers to a loss in signal strength whereas distortion refers to a change in the structure of the signal. During attenuation, the shape of the signal does not change and it remains intact.

Wireless Media

Now, we shall discuss wireless media which are of two types; wireless access point and satellite communication. For wireless communication both the sender and the receiver has an antenna and the antenna radiates electromagnetic energy in all directions.
Both access point and satellite communication use a parabolic antenna which sends electromagnetic signals in either uni-directionally or omni-directionally (in all directions).

Note: Modern wireless access points have a bandwidth of 54Mbps. Geosynchronous satellites are placed at an orbit which is at a distance of 22,000 miles from the earth. The satellite is placed in such a way that it moves at the same speed as the earth so as to remain stationary with respect to earth and maintain a constant communication between the earth and the satellite. To cover the entire earth, one must place three satellites 120 degrees apart. Each satellite takes care of one portion of the earth so that the base station gets constant updates about that portion of the earth from the satellite.
To establish a communication between two nodes using Geo-synchronous satellites, electro-

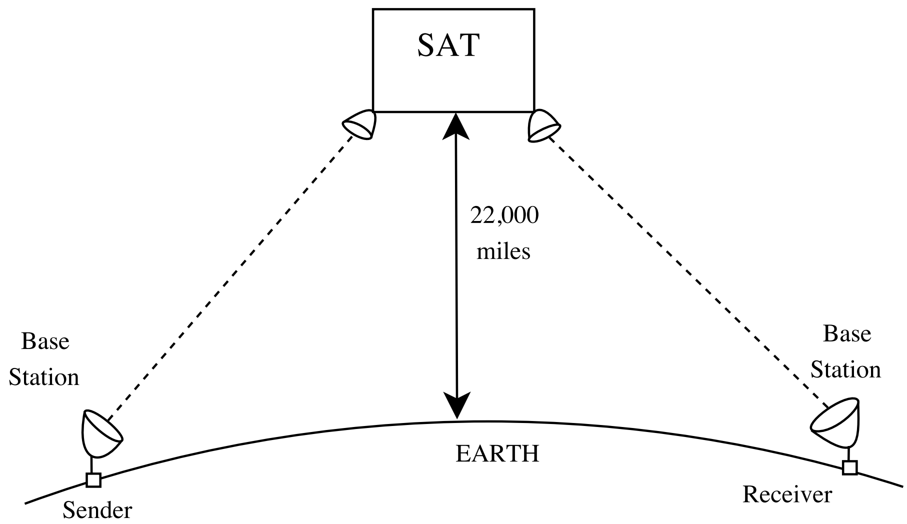

Fig. 2. Communication via a satellite

magnetic signals from the sender node is sent to the nearest base station and inturn the base station transmits signals to the satellite using parabolic antennas, by maintaining a line of sight. Further, the signal from the satellite is transmitted to the base station closest to the receiver node. See Figure 2.
Recap: We are now familiar with how to interface two or more nodes, an appropriate topology, a mode of communication, etc. We next discuss how a data transfer takes place between a pair of nodes.

Encoding - Bits vs Signals

This section deals with an important component in a data transmission, namely, *encoding*. Systems store data in the form of 0's and 1's while Ethernet cables transmit voltage or power signals. Thus, we need a conversion strategy for data transmission to send a binary data from one node to the other through a cable/fiber. Encoding is a process of converting binary data into signals. The network adapter in a system, contains a signalling component that actually encodes bits into signals at the sending nodes and decodes signals into bits at the receiving nodes. We shall present various encoding schemes discovered over the years, that are commonly used in practice. An example of how a digital data is encoded is given in Figure 4.

NRZ (Non-Return to Zero): A bit '1' is encoded as +5V and a bit '0' is encoded as 0V.

`Limitations:`
During the data transmission, both the sender and receiver maintains a clock. During encoding, each signal whether 0V or 5V stays in the same level for one clock cycle. It is important that while decoding the receiver correctly decodes the signal for which synchronization between the end nodes plays a crucial role. But here, a block of 0's or a block of 1's at the beginning may create synchronization issue between the sender and the receiver as we get a high or a low signal for a prolonged duration of time.
A block of x 0's (or 1's) may get recognized as $x - 1$ 0's (or 1's) if the clock is slow(say, the sender's clock pulse is 8ns whereas the receiver's clock pulse is 10ns).
A block of x 0's (or 1's) may get recognized as $x + 1$ 0's (or 1's) if the clock is fast(say, the sender's clock pulse is 10ns whereas the receiver's clock pulse is 8ns).

NRZ-I (Non-Return to Zero Invert): A sequence of 1's is encoded alternately as +5V and 0V. A bit '0' is encoded as 0V if the previous bit is encoded as 0V and a bit '0' is encoded as 5V if the previous bit is encoded as 5V. For the first bit, we follow NRZ encoding.

`Limitations:`
Though the problems of synchronization with a block of 1's is tackled as it alternates for a sequence of 1's, a block of 0's may still create synchronization issue between the sender and the receiver.

If the initial bits are 0 1 or 1 0, then in both NRZ and NRZ-I, receiver clock can be correctly tuned at the end of the voltage signal of the first bit. Synchronization is a concern if the data begins with a block of at least two 0's for both NRZ and NRZ-I and for NRZ synchronization is a concern if the data begins with a block of at least two 0's or at least two 1's.

Manchester: A bit '0' is encoded as 'low to high' signal (0V to 5V signal) and a bit '1' is encoded as 'high to low' signal (5V to 0V signal). See Figure 3. Since each signal consists of both low and high, there are no synchronization issues.

During a clock pulse itself we see both high and low voltage signal. At the sender, the shift from high to low for a bit '1' happens at the middle of the clock pulse, similarly, for a bit '0', the transition from low to high happens at the middle of the clock pulse. If the receiver clock is such that the middle of the clock pulse of the receiver coincides with high to low shift (low to high shift), then there is no synchronization issue, otherwise, the receiver has to tune its clock based on the shift. Thus, after seeing the voltage signal of the first bit, the receiver can tune its clock comfortably. The clock signal, in particular the middle point of the clock helps in both synchronization and bit identification.

Differential Manchester: Except for the first bit, there is no fixed scheme for encoding

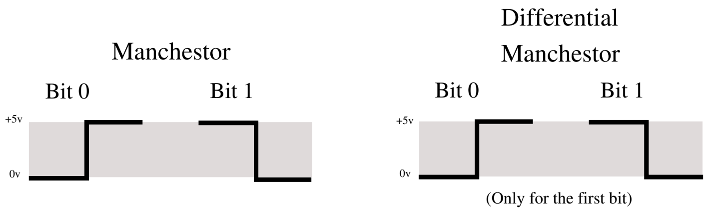

Fig. 3. Encoding Signal for Manchester and Differential Manchester

the remaining bits and the encoding varies based on the data. If the first bit is '1' then it is encoded as 'high to low' signal and if the first bit is '0' then it is encoded as 'low to high' signal. For the remaining bits, whenever the next bit is '0', then there is a sudden shift from 5V to 0V (0V to 5V) at the beginning of the signal followed by an appropriate encoding signal, i.e., if the sudden shift is from 5V to 0V at the beginning of the clock pulse, then the bit is encoded as 0V to 5V ('low' to 'high'). Similarly, if the sudden shift is from 0V to 5V at the beginning of the clock pulse, then the bit is encoded as 5V to 0V ('high' to 'low'). Whenever the next bit is '1', then there is no sudden shift at the beginning and the encoding scheme is based on the signal of the previous bit. If the previous bit is encoded as 0V to 5V, then the current bit '1' is encoded as 5V to 0V. Similarly, if the previous bit is encoded as 5V to 0V, then the current bit '1' is encoded as 0V to 5V.

In case of differential Manchester encoding, synchronization is done with the help of the middle point of the clock pulse. Whereas the bit identification component is taken care by the sudden shift at the beginning of a clock pulse. Unlike Manchester encoding, there is no fixed pattern for a bit '0' and a bit '1' except the first bit. Due to sudden shift at the beginning of the clock pulse for a bit '0', in a data transmission, a bit '0' will have two different encodings. Similarly, a block of 1's will have an encoding in which every second one gets a voltage signal which is a complement of the previous signal.

4 bit/5 bit: A stream of data is split into a block of 4 bits and for each block, an encoding scheme assigns a unique 5-bit code. The 5b encoding follows the property of having each 5b with at most one leading '0' and at most two trailing '0's. In this scheme, a block of 0's can not be more than three and a block of 0's can not appear at the beginning. Subsequently, the encoded data is further encoded using NRZ-I scheme. As there is no block of 0's at the beginning, there is no synchronization issue due to 0's with 5b encoding. Similarly, since NRZ-I is applied after 5b encoding, a block of 1's at the beginning will not create a synchronization issue. Thus, 5b encoding is free from synchronization issues. A sample 4b/5b encoding is given below. Note that only 16 out of 32 different 5 bit codes are chosen as many do not satisfy the constraints of 5 bit encoding scheme. Some of the unused but valid 5 bit codes are reserved for encoding *special bits.*

0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

In practice, one of the Manchester, the differential Manchester, and the 4b/5b encodings is used.

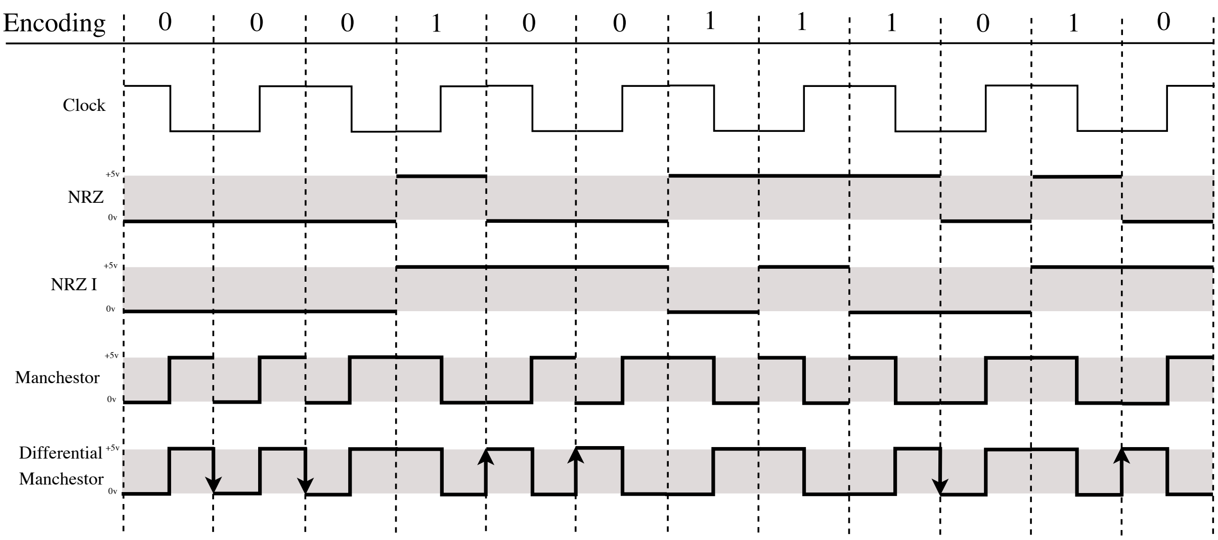

Fig. 4. Encoding of a Digital Data

Performance of a Network

An important component in the design of a network is the performance analysis which will help us to identify the right design for a given case study. We shall begin with the commonly used performance metrics using which one can analyze any network.

Bandwidth of a network (Network Speed): The network speed is the minimum of NIC speed and Ethernet cable speed. Typically, NIC speed is 100 Mbps and the speed of the Ethernet cable varies from 100 Mbps to 1000 Mbps. For a network with NIC speed 100 Mbps and

Ethernet cable speed 1000 Mbps (CAT 6 cable), the bandwidth is 100 Mbps.

Transmission time: The time taken by the NIC to place a bit (0 or 1) on the wire. For a 100Mbps network, the transmission time is 0.01 micro sec.

Propagation time: After a bit is placed on the wire by NIC, there is a time taken by that bit to travel from one end of the network to the other end. The propagation time refers to the time taken by a bit to travel from one end of the cable to the other end. This time depends on the length of the cable or distance between the two nodes, and the speed of propagation of the bit. Since, the exact estimate of the speed of propagation is not straight forward, we use an upper bound, which is the speed of light. Since no object can travel faster than the light, this seems appropriate.

Speed of light: In vacuum (air) = 3×10^8 m/s ; copper cable (coaxial cable) = 2.3×10^8 m/s ; fiber = 2×10^8 m/s.

Note: For a 100 Mbps network,

At sender	In propagation	At receiver
bit-1 is placed on the wire at 0.01 micro sec	bit-1 in propagation	bit-1 reaches at 0.01 + propagation time
bit-2 is placed on the wire after 0.01 micro sec, i.e., at 0.02 micro sec	bit-2 bit-1 in propagation	bit-2 reaches after another 0.01, i.e., at 0.01+0.01 + propagation time
bit-3 is placed on the wire after 0.01 micro sec, i.e., at 0.03 micro sec	bit-3 bit-2 bit-1 in propagation	bit-3 reaches after another 0.01, i.e., at 0.01+0.01+0.01 + propagation time
...	...	...
bit-r is placed	bit-r and the other bits are in progress	Reaches at $0.01 \times r$ + propagation time.

An illustration is given in Figure 5.

Total time for data transmission: To transmit r bits, the total time = $r\times$ bit transmission time + propagation time.

Switching Delays: An important Metric

To connect two or more systems, we make use of switches. They are of two types; store and forward switches and cut-through switches. We shall now analyse the performance metric by considering the switching delays depending upon whether the underlying switch is a store and forward or a cut-through. See Figure 6.

Store and Forward Switch: Let us assume that two nodes are connected via a store and forward switch (SF switch). A SF switch accepts the packet completely from the sender and processes the packet to identify the right output port. Then it retransmits the packet via the port. Thus, the total time to transmit r bits with a SF switch is
($r\times$ bit transmission time) + propagation time + switching delay + ($r\times$ bit transmission time) + propagation time.

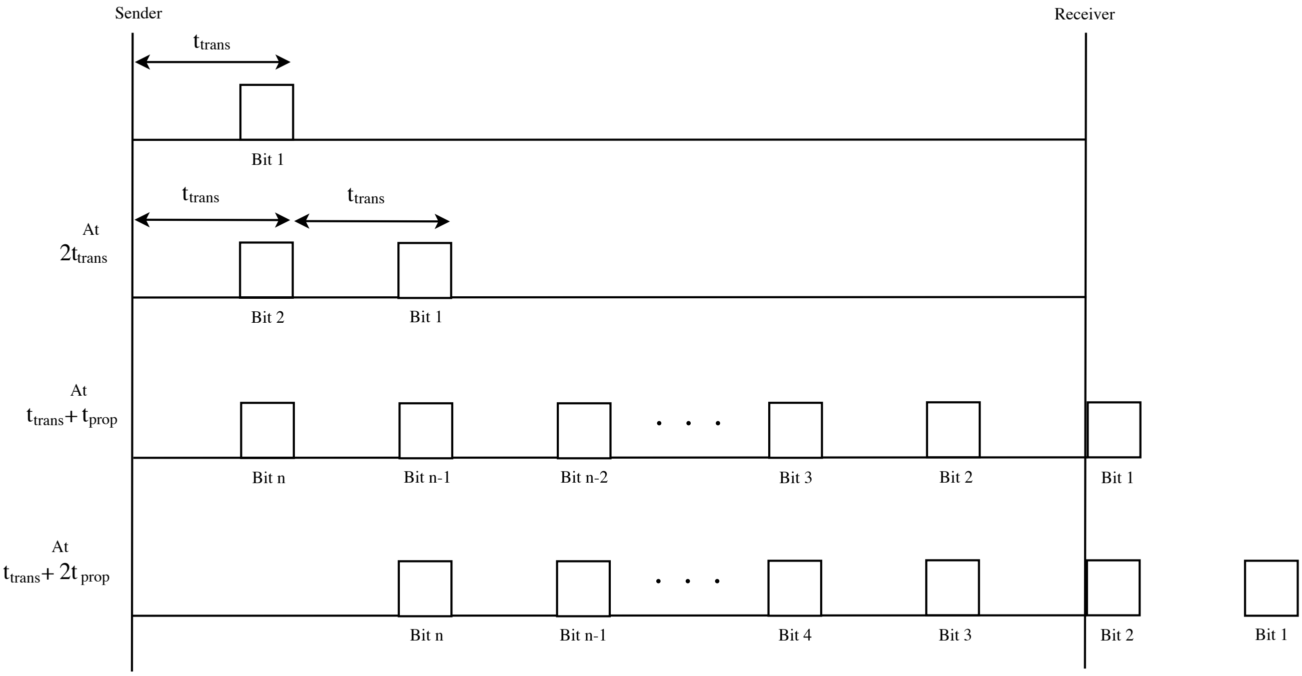

Fig. 5. Bit Propagation in Progress

Suppose two nodes are connected via n SF switches, then the total time is $(n+1)\times$ (transmission time for r-bits) + $(n+1)\times$ propagation time + $n\times$ switching delay.

Cut-through switch: Unlike a SF switch, a cut-through switch does not accept the packet completely. Instead, it accepts the first few bits of the packet (say 100 bits) and processes the 100 bits to identify the right output port of the recipient. While the switch processes the first 100 bits, the other bits sent by the sender will be made to wait till processing is done. Once the port is identified, the incoming line and the output port line will come in contact (the circuit is open while switch processes the 100 bits and subsequently it is closed with the right output port). Once the circuit is closed, the switch has to retransmit only the 100 bits as it was held by the switch. There is no retransmission for the other bits and they will flow like a stream of bits from the sender to receiver without actually knowing that there is a cut-through switch in between.

Thus, the total time to transmit r bits with a cut-through switch is $r\times$ bit transmission time + propagation time + switching delay for 100 bits + transmission time for 100 bits + propagation time.

In general, suppose two nodes are connected via n cut-through switches, then the total time is transmission time for r-bits at the sender + $(n+1)\times$ propagation time + $n\times$ switching delay for 100 bits + $n\times$ retransmission time for 100 bits. Note that the transmission of r-bits is done only at the sender and in all intermediate switches, it just a retransmission of 100 bits. Propagation delay cannot be neglected as the distance increases when more switches are added into the network.

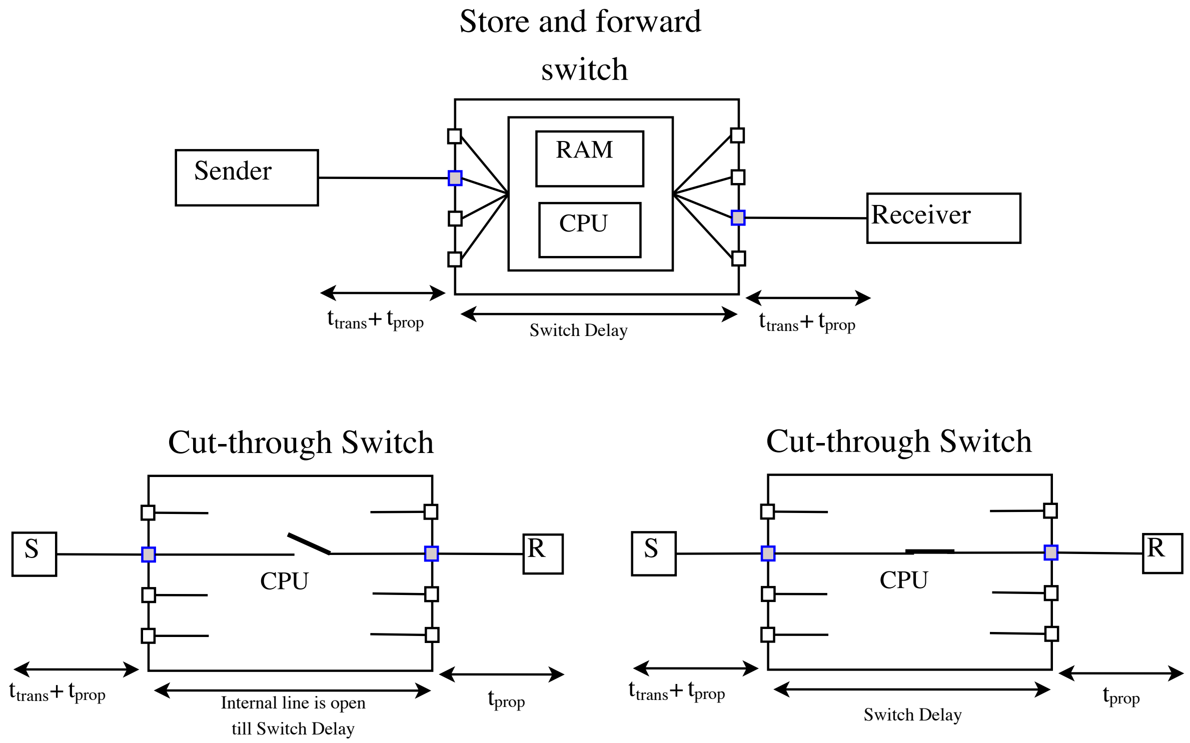

Fig. 6. Store and Forward, and Cut-through Switches

Other Time Metrics

Assuming there is a data transfer between A and B, when do we say the data transmission is complete ? Two commonly followed strategies are;

Strategy-1: Data transmission is complete if the last bit of the data reaches the receiver. When does this happen ? Assumings r-bits are transmitted by A, then the r^{th}-bit reaches B at time $t_{trans}+t_{prop}$ where t_{trans} is the transmission time for r-bits and t_{prop} is the propagation time.

Strategy-2: Data transmission is complete if there is an acknowledgement from the receiver. This happens at time
$t^P_{trans} + t_{prop} + t^A_{trans} + t_{prop}$,
where t^P_{trans} and t^A_{trans} refers to the transmission time of a packet at the sender and the transmission time of an acknowledgement at the receiver, respectively.

Round-trip time (RTT): How long it takes for a bit to travel from one end of the wire to the other end and back, is precisely the round-trip time. It is easy to see that RTT is $2 \times t_{prop}$.

Delay-Bandwidth Product Note that when the first bit of a packet leaves the sender, it takes t_{prop} time to reach the receiver. While the first bit is in propagation, the sender must have sent many more bits with t_{trans} delay between any two adjacent bits. Question: How many bits are there on the wire during t_{prop} time ? This number is precisely $t_{prop}\times$ bandwidth. For example, for 100Mbps network with $t_{prop} = 10ms$, it is $10ms \times 100Mbps = 10^6$ bits. This number is referred to as the delay-bandwidth (DB) product.

Remark:
1. The DB product for a pair of nodes connected via a store and forward switch is given by the sum of DB product of two links and the size of the storage buffer. Assuming 100Mbps link speed with 10ms t_{prop} delay and 5000 bits at the switch buffer; DB product is $2 \cdot 10^6 + 5000$.

2. The DB product for a pair of nodes connected via a cut-through switch is given by the sum of the DB product of two links and the number of bits held by the switch for processing. Typically, cut-through switches looks at the first 100 bits to decide the destination port. In such a scenario, the DB product is $2 \cdot 10^6 + 100$.

3. A Half-duplex link between a pair of nodes performs a data transmission in only one direction, i.e., either sender to receiver, or receiver to sender. Whereas, in a full-duplex link, the transmission between the sender to the receiver, and the receiver to the sender can take place simultaneously. In general, the DB product refers to the DB product of an half-duplex link and the twice of this number is the DB product of a full-duplex link.

Food for Thought:
1. Google 'speed test' and learn about speed test tool
2. Google 'what is my ip'
3. What is the ip address of www.iiitdm.ac.in, www.iitm.ac.in, www.stanford.edu ?
4. Google about 'google' ; what is the ip address of www.google.com, www.youtube.com
5. How many satellites does 'google earth' use? Where are they placed ?