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COM302T Computer Networks-Lecture Notes

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Local Area Networking

Roadmap: In this lecture, we shall explore strategies to create a local area network (a small network of nodes). In particular, design and performance analysis of the following topologies shall be discussed in detail.
1. IEEE 802.3 - Ethernet Bus - Carrier Sense Multiple Access/Collision Detection (CSMA/CD)
2. IEEE 802.5 - Token Ring
3. IEEE 802.11 - Wireless Fidelity (Wi-Fi)

IEEE 802.3

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. Let us consider the following specifications for our discussion.

- To create a 802.3 local area network (LAN) with 11 nodes. CAT 5 cables are used for base cable and for interconnecting nodes with the base cable. The distance between two T-connectors is 3m and the distance between a T-connector and a node is 1m.
- To transmit a packet of size 1000 bits on a 100Mbps link.
- $t_{trans} = \frac{1000}{100\times10^6} = 10\mu$ sec. $t^{bit}_{trans} = \frac{1}{100\times10^6} = 0.01\mu$ sec.
- $t^1_{prop} = \frac{1}{2.3\times10^8} = 0.004\mu$ sec. t^1_{prop}: the propagation delay between a node and a T-connector.
- $t^2_{prop} = \frac{3}{2.3\times10^8} = 0.01\mu$ sec. t^2_{prop}: the propagation delay between adjacent T-connectors.
- $t^3_{prop} = \frac{30}{2.3\times10^8} = 0.1\mu$ sec. t^3_{prop}: the propagation delay between the first and last T-connectors (end-end propagation delay).

How does 802.3 work?
A node wishing to send a packet, senses the media (base cable), and if the media is free (no transmission), then the node transmits a packet P. P leaves the NIC and enters the media (LAN) via a T-connector. Further, P travels to the left as well as the right of the T-connector. While P moves on either directions, all other nodes look at the packet's header and checks whether it is the intended recipient. This check is done by comparing the MAC address (NIC address) of the node and the MAC address of the recipient available in the header. The receiver alone accepts the packet and all others leave P untouched.

Let $\{a_1, \ldots, a_{11}\}$ be the set of nodes. As long as exactly one node transmits a packet, the system is stable, however, in practice two or more nodes may sense the media almost simultaneously. For example, a_1 wishes to transmit a packet P to a_{11} and sees that the media is free and at about the same time, a_7 senses the media and found that the media is free. Both a_1 and a_7 attempts a transmission almost simultaneously. Since the packet from a_7 travels on either directions, after a time frame, packets from a_1 and a_7 collide each other. This collision results in creation of a new packet with a higher voltage signals, called *jammed signal*. Similar to P, the jammed signal travels on either directions and after a while both a_1 and a_7 realizes that a collision has happened along the way and the packet did not reach the intendant recipient. Nodes wait for a while and go for a retransmission of the packet. We next analyze, if collision happens, then what is the best case time before the sender comes to know of the collision. Similarly, we shall discuss the worst case time.

For the given specifications, when a_1 attempts a transmission to a_{11}, the first bit of the packet sent by a_1 reaches a_2 at $t^{bit}_{trans} + t^1_{prop} + t^2_{prop} = 0.01 + 0.004 + 0.01\mu$ sec. In other words, a_2 knows at 0.024μ sec that the media is busy and it will not attempt a transmission. If a_2 attempts a transmission at time $t < 0.024\mu$ sec, then the media experiences a collision. On the similar line, the first bit of P sent by a_1, reaches a_3 at $0.01 + 0.004 + 0.01 + 0.01\mu$ sec. If there is an attempt by a_3 before this time frame, then a collision happens between packets of a_1 and a_3. Similarly, while a_1 is transmitting, if a_{11} attempts a transmission at time $t < 0.01 + 0.004 + 0.1$, then the media experiences a collision.

A natural question at this context is; when will the sender come to know about the collision? Note that after the collision, the jammed signal has to travel all the way from the point of collision to the originating node, and this travel time varies depending on the position of collision in the wire. We shall now estimate this travel time by looking at its best and worst case scenarios.

Best case: Collision happens between the two packets generated by the adjacent nodes. Let a_1 generates a packet P_1 and a_2 generates a packet P_2. Assuming, when P_1 is about to reach a_2, a_2 initiated a data transmission and thereby collided with P_2. The travel time for the first bit in this case is close to $0.004 + 0.01\mu$ sec and the jammed signal takes another 0.01μ sec to reach a_1. In general, it is at most $t^1_{prop} + 2 \times t^2_{prop}$. If we assume t^1_{prop} is negligible, then the best case scenario of packet collision can be detected in less than $2 \times t^2_{prop}\mu$ sec.

Worst case: Collision happens between the two packets generated by the farthest nodes. Let a_1 generates a packet P_1 and a_{11} generates a packet P_2. Assuming, when P_1 is about to reach a_{11}, a_{11} initiated the data transmission and thereby collided with P_2. The travel time for the first bit in this case is close to $0.004 + 0.1\mu$ sec and the jammed signal takes another 0.1μ sec to reach a_1. In general, it is at most $t^1_{prop} + 2 \times t^3_{prop}$. If we assume t^1_{prop} is negligible, then the worst case scenario of packet collision can be detected in less than $2 \times t^3_{prop}\mu$ sec.

Collision Avoidance (Minimization): From the above best and worst case scenarios, it is clear that if a node attempts a transmission within $t^3_{prop}\mu$ sec, then the media is likely to experience a collision. One approach to avoid collision is to assign time slots, say a time slot of $t^3_{prop}\mu$ sec for each packet. This also ensures that a node cannot hold control of the media for a long time. A node wishes to transmit a packet, senses the media, if it is free, then it performs a packet transfer for at most $t^3_{prop}\mu$ sec. The nodes that find the media busy after sensing will have to wait for $t^3_{prop}\mu$ sec. Even in this scheme, it may happen that the two nodes who waited for $t^3_{prop}\mu$ sec, may initiate a data transmission almost simultaneously.

We employ one more scheme to address collisions resulting from simultaneous packet transmission. On collision, the node that experienced the collision chooses a random number i in the range $[0..2^r]$ and wait for $i \times t^3_{prop}\mu$ sec. If $i = 0$, then it does not wait and initiates a retransmission immediately. Otherwise, it waits for $i \times t^3_{prop}\mu$ sec before it attempts a retransmission. r denotes the run of the transmission (iteration number). i.e., during the second transmission, if collision happens, the node chooses $i \in [0..4]$ and wait for i time slots. Even with this scheme, one cannot rule out the possibility of collision in each retransmission. In practice, a node makes 16 retransmissions and if it is unsuccessful in all of them, then the node gives up the transmission and it may try at a later time frame.

Recap: Until now, we have discussed how to create a LAN on 11 systems, what is a collision, how collision is detected and avoided. We next discuss the performance analysis to know about utilization, effective bandwidth, etc.

Performance of IEEE 802.3

For a successful transmission of a packet, a node is expected to get hold of the media; what is the probability that out of n nodes, exactly one node gets the media and performs a data transmission. The number of nodes attempting a transmission is a binomial random variable X and we are interested in `Probability`$(X = 1)$. Thus, the probability that exactly one node acquires the medium and perform the data transfer is;

a. $A = \ Prob(X = 1) \ = \ \binom{n}{1} \cdot p \cdot (1-p)^{n-1}$.

b. p: denotes the probability of success, i.e., the probability of transmitting a packet successfully during the time slot.

c. Note that, higher the probability, the better is the utilization of the link. Thus, the effective bandwidth also increases as EBW=Utilization $\times$ BW. Utilization refers to the percentage of bandwidth used at a particular point of time. Implicitly, it refers to how much percentage of total time is meant for data transmission.

d. Since the higher value of p is good for the data transmission, what is the maximum value of p that one can get in the above expression?

e. $\frac{dA}{dp} = n(\ (1-p)^{n-1} - p(n-1)(1-p)^{n-2} \ ) = 0$

f. $(1-p) - np + p = 0$; $np = 1$; $p = \frac{1}{n}$.

We now calculate the total time to transmit a packet from a given node to the other node. Since a node may experience a collision leading to retransmission of packets, the total time must include the time for retransmissions. However, in practice, the number of retransmissions is context specific. This calls for a study on the expected number of retransmissions. It is appropriate to look at this number to calculate the length of collision interval or contention interval.

Expected number of retransmissions: This is a geometric random variable as in a sequence of j retransmissions, the first $(j-1)$ results in a collision again (failures) followed by a successful transmission (the packet reaches the receiver).

$B = E[\text{retransmission}] = \sum_{j=1}^{\infty} j \cdot Prob(Y = j)$. Since A denotes the probability of acquiring a medium and hence a transmission,

$B = \sum_{j=1}^{\infty} j \cdot (1-A)^{j-1} \cdot A$.
$B = A[1 + 2(1-A) + 3(1-A)^2 + \ldots]$
$B = A[\frac{1}{A^2}]$
$B = \frac{1}{A}$
Having discussed best case and worst case scenario for collision, we now compute the total time with respect to these two scenarios.

Total time under best case scenario: $(t_{trans} + t^1_{prop} + t^2_{prop})$+ (expected number of retransmissions) $\times(t_{trans} + t^1_{prop} + t^2_{prop})$ + (expected number of retransmissions) $\times t^2_{prop}$. For simplicity, we split the above expression into
Total time (best case) $= T + U + V$, where
$T = (t_{trans} + t^1_{prop} + t^2_{prop})$ `this denotes the time for sending a packet from` a_i `to` a_{i+1}.
$U =$ (expected number of retransmissions) $\times(t_{trans} + t^1_{prop} + t^2_{prop})$ `this denotes the collision interval time in total`.
$V =$ (expected number of retransmissions) $\times t^2_{prop}$ `the time in total for the jammed packet to reach the sender`.

Total time under worst case scenario: $(t_{trans} + t^1_{prop} + t^3_{prop})$+ (expected number of retransmissions) $\times(t_{trans} + t^1_{prop} + t^3_{prop})$ + (expected number of retransmissions) $\times t^3_{prop}$.

Note:
1. Since t_{prop} is smaller than t_{trans}, in practice, the collision happens even before the sender sending the packet completely and hence the t_{trans} in the above expression is an over estimate of the transmission time. Similarly, t^1_{prop} is a negligible parameter and is usually neglected while calculating utilization.
2. Assuming the probability p of packet transmission is maximum, then $B = \frac{1}{A} = \frac{1}{(1-\frac{1}{n})^{n-1}}$.

Utilization

Utilization (best case) $= \frac{t_{trans}}{Totaltime(bestcase)}$

Utilization (worst case) $= \frac{t_{trans}}{Totaltime(worstcase)}$

For the given specification with $n = 10, 12, 20$ nodes;

1. $n = 10$. The value of $B = \frac{1}{(1-\frac{1}{n})^{n-1}} = \frac{1}{0.387} = 2.58$.
   Utilization (best case propagation delay)$= \frac{10}{(10+0.004+0.01)+(2.58)(10+0.004+0.01)+2.58(0.01)} = 27\%$
   Utilization (worst case propagation delay) $= \frac{10}{(10+0.004+0.1)+(2.58)(10+0.004+0.1)+2.58(0.1)} = 27\%$

2. $n = 12$. The value of $B = \frac{1}{(1-\frac{1}{n})^{n-1}} = \frac{1}{0.383} = 2.61$.
   Utilization (best case propagation delay)$= \frac{10}{(10+0.004+0.01)+(2.61)(10+0.004+0.01)+2.61(0.01)} = 27\%$

Utilization (worst case propagation delay) $= \frac{10}{(10+0.004+0.1)+(2.61)(10+0.004+0.1)+2.61(0.1)} = 27\%$

3. $n = 20$. The value of $B = \frac{1}{(1-\frac{1}{n})^{n-1}} = \frac{1}{0.377} = 2.65$.
   Utilization (best case propagation delay)$= \frac{10}{(10+0.004+0.01)+(2.65)(10+0.004+0.01)+2.65(0.01)} = 27\%$
   Utilization (worst case propagation delay) $= \frac{10}{(10+0.004+0.1)+(2.65)(10+0.004+0.1)+2.65(0.1)} = 27\%$

4. In general, what would be the value of utilization ? what would be the value of utilization for large n ?

It is interesting to note that when $n \to \infty$, the value of $B = \frac{1}{(1-\frac{1}{n})^{n-1}} = e$.
$\lim_{n\to\infty} \quad \frac{1}{(1-\frac{1}{n})^{n-1}}$
$\implies (1 - \frac{1}{n})^{-(n-1)}$
$\implies (\frac{n-1}{n})^{-(n-1)}$
$\implies (\frac{n}{n-1})^{(n-1)}$
$\implies (1 + \frac{1}{n-1})^{(n-1)}$
It is well-known that $\lim_{n\to\infty} \quad (1 + \frac{1}{n})^n = e$.
Therefore, $\lim_{n\to\infty} \quad (1 + \frac{1}{n-1})^{(n-1)} = e$.
The value of e is approximately 2.718.

Thus, the utilization of Ethernet bus for large n is given by;
Utilization (best case propagation delay)$= \frac{10}{(10+0.004+0.01)+(2.718)(10+0.004+0.01)+2.718(0.01)} = 26\%$
Utilization (worst case propagation delay) $= \frac{10}{(10+0.004+0.1)+(2.718)(10+0.004+0.1)+2.718(0.1)} = 26\%$

In practice, IEEE 802.3 gives a utilization of 30%. Thus, for a 100Mbps network, the effective bandwidth is 30Mbps.

Recap: So far, we have seen a strategy, namely Ethernet bus (IEEE 802.3) using which one can interconnect two or more systems. Since the underlying media is a shared media, simultaneous transmission by two or more nodes lead to a collision. We have presented a strategy to minimize collisions. Further, a thorough performance analysis by looking at the overhead due to collisions is presented. Due to collisions, the same packet is getting re-transmitted; on an average it is three re-transmissions and thereby the utilization is 30%. We next present another strategy using which we can completely avoid collisions. Also, there is a considerable improvement in the network utilization.

Token Ring - IEEE 802.5

In this section, we shall investigate the performance of Token ring, popularly known as IEEE 802.5. The poor performance of IEEE 802.3 is due to the contention interval (collision time) which the underlying media experiences as more than one system attempts a transmission simultaneously. It is natural to look for a strategy which ensures exactly one node accesses the media while other nodes are made to wait till the current node completes the transmission.

Token ring based local area networking follows the ring topology to create a network of nodes.

The ring has a special packet, namely `Token` which is of size 24 bits which is revolving around the ring. When the ring is set up, one of the nodes, usually the monitor node (the leader node) injects the token into the ring. The scheme works as follows: a node wishing to transmit a packet, first takes a control of the token, i.e., it drains the token off the ring. After possessing the token, the node transmits a data packet along the ring. As the data packet moves along the ring; while the intended recipient accepts the data, all other nodes leave the packet untouched. When the moving data packet reaches back the node, the node drains the packet from the ring. Subsequently, the token is released into the ring which moves to the next node in the clock-wise direction. Both data packet and token move in clock-wise directions.

Since possession of the token is must for a data transmission, a node wishing to transmit a packet senses the media until it gets the token. To ensure each node in the ring gets a fair chance to use the ring, a node can send exactly one data packet at a time. A node wishing to send two or more packets, has to release to the token after the first data packet and must wait till the token comes back to the node again for transmitting the second packet. It is now appropriate to ask, when would the token be released by the node? Should the node release the token immediately after the data packet transmission? or Should the node wait for the data packet to come back before it releases the token?.

Token Release

`Early Token Release:` Token is released immediately after the data packet transmission.
`Delayed Token Release:` Token is released after the data packet comes back to the node again. i.e., when the node sees the first bit of the data packet, the token is released.

We shall now analyze the performance by considering the above two strategies for token release. Similar to IEEE 802.3, we present both best case and worst case analysis.

Performance Analysis

Assume there are n nodes in the ring. Let $t_{trans}, t^T_{trans}, t_{prop}$ denote the transmission time of a packet, the transmission time of a token, and the propagation delay of the ring, respectively. Assuming the node a_1 has a data packet to transmit, we compute the utilization as follows;

1. Utilization under early release strategy $= \dfrac{\text{time to trasmit}}{\text{the total time}} = \dfrac{t_{trans}}{t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}}$.
   Note that the total time includes the overhead which includes the token transmission time t^T_{trans} and the time $\frac{t_{prop}}{n}$ to pass the token to the next node. As far as a node is concerned, the transmission time is said to be complete if it passes the token to the next node. Due to this reason, the total time includes the propagation delay for the token to move from the current node to the adjoining node which is $\frac{t_{prop}}{n}$.

2. **Limitations of early release strategy:** The node is unsure whether the ring is perfect and the destination node has received the packet or not. If the ring is perfect and the data packet comes back to the sender, then this scheme is perfect. If the data packet does not come back in t_{prop}, the node cannot retransmit the packet as it has already released the token. If there is a distortion of signals due to noise, the data packet may not come back to the sender. If the token is also corrupted due to noise, the monitor node injects a fresh token into the ring.

3. Utilization under delayed release strategy; We consider two cases: $\mathtt{t_{trans}} \geq \mathtt{t_{prop}}$ and $\mathtt{t_{trans}} < \mathtt{t_{prop}}$.
   Case ($t_{trans} \geq t_{prop}$): The node transmits the data packet, wait till the data packet rotates around the ring, and when it sees the first bit of the data packet, it releases the token into the ring. Since t_{trans} is more than the t_{prop}, even before the node completes its data transmission, the first bit would arrive at the node. Although, the sender sees the first bit at t_{prop}, it cannot release the token immediately and has to wait till t_{trans}.
   Utilization $= \dfrac{\text{time to trasmit}}{\text{the total time}} = \dfrac{t_{trans}}{t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}}$.
   Case ($t_{trans} < t_{prop}$): Since t_{prop} is more, the first bit arrives at the node at $t^{bit}_{trans} + t_{prop}$ where t^{bit}_{trans} is the transmission of a bit. Therefore,
   Utilization $= \dfrac{\text{time to trasmit}}{\text{the total time}} = \dfrac{t_{trans}}{t^{bit}_{trans} + t_{prop} + t^T_{trans} + \frac{t_{prop}}{n}}$.
4. **Advantages of delayed release strategy:** If the first bit of the packet does not come back to the sender in t_{prop}, the sender knows something is wrong in the ring. Since the token is with the sender, it waits for a while and go for a retransmission of the packet. The transmitted packet itself acts as a self-acknowledgement.

5. We shall now analyze the utilization of the ring by transmitting two packets. As mentioned before, a node cannot transmit two packets one after the other; the node transmits the first packet, releases the token, and wait for the token to come back for the transmission of the second packet. *Token Rotation Time (TRT)* refers to the time for a token to rotate around the ring from the current node to the node itself. TRT varies depending upon the network traffic, i.e., TRT is maximum if every other node as a data packet to send and is minimum if none of the other nodes has a data packet to send. We now analyze the utilization by considering two scenarios of TRT.

6. Utilization under early release strategy with TRT minimum (Best Case) $= \dfrac{\text{time to trasmit}}{\text{the total time}}$
   $= \dfrac{t_{trans} + t_{trans}}{t_{trans} + t^T_{trans} + t_{prop} + t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}}$.
   Note that after transmitting a packet and release of the token, the token comes back to the node at t_{prop} as every other node has no data packet to transmit. Further, it takes $t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}$ to transmit the second packet, to release the token again, and the token takes $\frac{t_{prop}}{n}$ to reach the adjoining node.

7. Utilization under delayed release strategy with TRT minimum (Best Case)
   Case ($t_{trans} \geq t_{prop}$): $\dfrac{t_{trans} + t_{trans}}{t_{trans} + t^T_{trans} + t_{prop} + t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}}$.
   Case ($t_{trans} < t_{prop}$): $\dfrac{t_{trans} + t_{trans}}{t^{bit}_{trans} + t_{prop} + t^T_{trans} + t_{prop} + t^{bit}_{trans} + t_{prop} + t^T_{trans} + \frac{t_{prop}}{n}}$.
8. Utilization under early release strategy with TRT maximum (Worst Case)
   $\dfrac{t_{trans} + t_{trans}}{t_{trans} + t^T_{trans} + \frac{t_{prop}}{n} + (t_{trans} + t^T_{trans} + \frac{t_{prop}}{n})(n-1) + t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}}$.
   The total time in the above expression consists of three components;
   (i) $t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}$: `the time to transmit the first packet by the node` a_1 `plus the overhead`
   (ii) $(t_{trans} + t^T_{trans} + \frac{t_{prop}}{n})(n-1)$: `the time taken by every other node` $a_2, \ldots, a_n$ `to transmit a token plus the overhead.`

(iii) $t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}$. `the time to transmit the second packet by the node` a_1 `plus the overhead`

9. Utilization under delayed release strategy with TRT maximum (Worst Case)
Case ($t_{trans} \geq t_{prop}$):
$\dfrac{t_{trans} + t_{trans}}{T + U + V}$ where
$T = t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}$
$U = (t_{trans} + t^T_{trans} + \frac{t_{prop}}{n})(n-1)$
$V = t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}$.

Case ($t_{trans} < t_{prop}$): $\dfrac{t_{trans} + t_{trans}}{T + U + V}$ where
$T = t^{bit}_{trans} + t_{prop} + t^T_{trans} + \frac{t_{prop}}{n}$
$U = (t^{bit}_{trans} + t_{prop} + t^T_{trans} + \frac{t_{prop}}{n})(n-1)$
$V = t^{bit}_{trans} + t_{prop} + t^T_{trans} + \frac{t_{prop}}{n}$.

10. In general, to transmit r packets;

Strategy	Utilization
Best Case	
Early Release	$\dfrac{t_{trans} \times r}{(t_{trans} + t^T_{trans} + t_{prop})(r-1) + t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}}$.
Delayed Release with $t_{trans} \geq t_{prop}$	$\dfrac{t_{trans} \times r}{(t_{trans} + t^T_{trans} + t_{prop})(r-1) + t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}}$.
Delayed Release with $t_{trans} < t_{prop}$	$\dfrac{t_{trans} \times r}{(t^{bit}_{trans} + t_{prop} + t^T_{trans} + t_{prop})(r-1) + t^{bit}_{trans} + t_{prop} + t^T_{trans} + \frac{t_{prop}}{n}}$.
Worst Case	
Early Release	$\dfrac{t_{trans} \times r}{T + U + V}$ where $T = (t_{trans} + t^T_{trans} + \frac{t_{prop}}{n})(r-1)$, $U = (t_{trans} + t^T_{trans} + \frac{t_{prop}}{n})(n-1)(r-1)$, $V = t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}$.
Delayed Release with $t_{trans} \geq t_{prop}$	$\dfrac{t_{trans} \times r}{T + U + V}$ where $T = (t_{trans} + t^T_{trans} + \frac{t_{prop}}{n})(r-1)$, $U = (t_{trans} + t^T_{trans} + \frac{t_{prop}}{n})(n-1)(r-1)$, $V = t_{trans} + t^T_{trans} + \frac{t_{prop}}{n}$.
Delayed Release with $t_{trans} < t_{prop}$	$\dfrac{t_{trans} \times r}{T + U + V}$ where $T = (t^{bit}_{trans} + t_{prop} + t^T_{trans} + \frac{t_{prop}}{n})(r-1)$, $U = (t^{bit}_{trans} + t_{prop} + t^T_{trans} + \frac{t_{prop}}{n})(n-1)(r-1)$, $V = t^{bit}_{trans} + t_{prop} + t^T_{trans} + \frac{t_{prop}}{n}$.

Case Study

$n = 10$, Packet size=1000 bits, Bandwidth (link speed) = 100 Mbps, $t_{trans} = 10\mu$sec. Circumference of the ring (the length of the media)=10m, $t_{prop} = \frac{10}{2.3\times10^8} = 0.04\mu$sec.

Strategy	Utilization
Early Release (One packet)	$\frac{10}{10+0.24+0.004} = 97\%$
Delayed Release (One packet) with $t_{trans} \geq t_{prop}$	$\frac{10}{10+0.24+0.004} = 97\%$
Delayed Release (One packet) with $t_{trans} < t_{prop}$, $t_{prop} = 50\mu$sec	$\frac{10}{0.01+50+0.24+5} = 18\%$
Two Packets (Best Case)	
Early Release	$\frac{20}{10+0.24+0.04+10+0.24+0.004} = 97\%$
Delayed Release with $t_{trans} \geq t_{prop}$	$\frac{20}{10+0.24+0.04+10+0.24+0.004} = 97\%$
Delayed Release with $t_{trans} < t_{prop}$, $t_{prop} = 50\mu$sec	$\frac{20}{0.01+50+0.24+50+0.01+50+0.24+5} = 12\%$
Two Packets (Worst Case)	
Early Release	$\frac{20}{10+0.24+0.004+(10+0.24+0.004)(9)+10+0.24+0.004} = 17\%$
Delayed Release with $t_{trans} \geq t_{prop}$	$\frac{20}{10+0.24+0.004+(10+0.24+0.004)(9)+10+0.24+0.004} = 17\%$
Delayed Release with $t_{trans} < t_{prop}$, $t_{prop} = 50\mu$sec	$\frac{20}{0.01+50+0.24+5+(0.01+50+0.24+5)(9)+0.01+50+0.24+5} = 3\%$

Some Technicalities

1. Each data packet has a certain number of bits (special bits) using which one can identify whether the receiver is up and the receiver has read the data packet. These special bits also help in multi-casting and broad casting.
2. Although the sender releases the token after seeing the first bit of the packet, it is the responsibility of the sender to drain the packet completely off the ring. It takes t_{trans} time to drain the packet. If this is not done, the data packet will be moving along the ring which occupies a considerable portion of the DB product unnecessarily.
3. From the analysis, it is clear that the larger the ring, the higher the propagation delay. The higher propagation delay leads to poor utilization of the ring. Therefore, the token ring outperforms IEEE 802.3 when $t_{trans} \geq t_{prop}$.
4. What if $t_{trans} = t_{prop}$? In this case, the first bit of the packet after rotating round is at the sender and the last bit of the packet just left the sender. This means, the packet size equals the delay-bandwidth product.
5. The header portion of the data packet contains the MAC address of the recipient (48-bits) and the data portion starts from 49^{th} bit onwards. When the data packet revolves around the ring, each node in the ring reads the first 48 bits and decides whether the node is the intended recipient or not in some nano seconds which is less than the transmission time of a bit. Thus, even before 49^{th} bit reaches the node, the node knows whether to read the data portion starting from 49^{th} bit or not. If the node is not the intended recipient, the node leaves the data portion of the packet untouched and the data packet goes to the next node.
6. It is important to highlight that in early release, since the token is released immediately after a node transmits a packet, more nodes in the ring can pump the data into the ring. Whereas, in delayed strategy, at any time, exactly one data packet is available on the ring.
7. Intuitively, early release strategy creates space for many nodes to perform data transfer along the ring. Thus, many data packets will be revolving around the ring; we now ask, how many data packets can be there along the ring in the worst case? Note that, having multiple packets lead to a better utilization of the ring.

8. The number of packets in the ring is $\frac{DB}{\text{packet size}}$. Can we always achieve this number? We shall now consider some specific scenarios to answer this question.
9. Suppose there are n nodes in the ring with `packet size` $= \frac{DB}{n}$. Intuitively, there can be n packets on the ring. However, we can have only $\frac{n}{2}$ packets on the ring. Consider a ring on 6 nodes. Assuming each node $a_1, \ldots, a_6$ has a packet to transmit to a_1. In the following scenario;
   a_1's packet is along (a_6, a_1)
   a_2's packet is along (a_5, a_6)
   a_3's packet is along (a_4, a_5)
   At this time, a_4 cannot pump in its packet as it has not received the token completely from a_3. Thus, 3 nodes can comfortably transmit a packet each and in general, for n nodes, there are $\frac{n}{2}$ packets on the ring. In this scenario, 50% of DB product is effectively used.
10. Suppose there are n nodes in the ring with $\frac{DB}{n} = n \times$ packet size. In this case, all n nodes can send one data packet each. The link (a_n, a_1) contains packets from all n nodes. In this scenario, although all n nodes transmitted a packet each, the link utilization is poor as only 10% of the DB product is used.

IEEE 802.11 - Wireless Fidelity(Wi-Fi)

In 802.3 multiple nodes attempt to access the shared media (Ethernet cable) as part of a data transmission. Since our atmosphere is electromagentic in nature which supports transmission/reception of radio waves, infrared waves and microwaves, it is natural to think of designing a network among nodes using this medium. Each node who is part of this media has a wireless antenna which is used for both transmission and reception. Essentially, the shared cable (wired medium) in 802.3 is replaced with a shared electromagnetic medium (wireless) in 802.11.

How does a wireless network work? Consider a network on 4 nodes, say A, B, C, D as

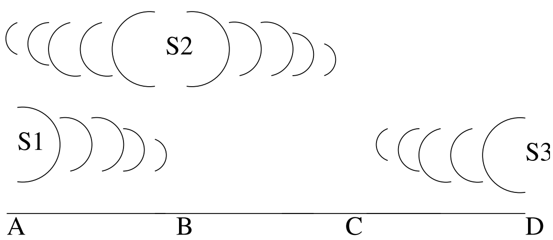

Fig. 1. A Wireless network on 4 nodes

illustrated in Figure 1. In general a boundary is fixed within which n nodes are distributed randomly. The signals transmitted at a node travels a maximum distance of 10m and loses its strength thereafter. Therefore, as long as two nodes are at a distance less than 10m, then, there is a scope for wireless transmission. Note that the higher the signal strength, the larger the signal's distance coverage. In the figure, the signal generated at A (Signal S1), travels until B and hence data transmission between A and B can take place. Similarly, B can perform data transmission with A and C. The signal S2 can reach both B and C. Data transmission between A and C, and B and D are not possible as the signal generated at $A(B)$ cannot travel until $C(D)$. Similar to 802.3, there is a scope for collision of data packets during the data transmission. For example, if A and C attempts a data transmission to B almost simulataneously, then after some time, the data packets of A and C collide at B. Unlike 802.3, in 802.11, it is possible to have simultaneous data transmission between two pairs of nodes. For example, the pairs (A, B) and (C, D) can initiate a data transmission which will not create a collision. We shall now discuss a strategy to minimize the number of collisions.

A node wishing to transmit a packet sends a special packet, namely, RTS (Request to Send) to the receiver. RTS packet contains the destination address and the value of holding time (how long the sender holds the media for transmission). If the sender and receiver are within reach and the receiver is willing to perform a data transfer, the receiver sends CTS (clear to send) signal in acknowledgement to RTS. While sending CTS, the holding time is echoed back to the sender. All other nodes who are within reach of B knows that B will be busy until holding time and therefore, they refrain themselves from data transmission. It is important to note that although the RTS sent by A to B was not seen by C, C knows B is busy as it has seen CTS sent by B to A. Therefore, while B is transmission mode, both A and C which are within reach of B wait until holding time. This implies that there is no scope for collision of packets at B. Similar arguments hold good at C. I.e., nodes B and D are aware of whether C is busy or not.

It is interesting to note that there may be collisions due to RTS packets as more than one node within reach of B may initiate a data transmission request leading to a collision. Similar to 802.3, a node wishing to transmit a data has to make a retransmission of RTS packet and the number of such retransmissions is a random variable. Thus, the utilization of 802.11 for the above configuration is;

$$\text{Utilization} = \frac{t_{trans}}{T + U + V}$$

$$T = t^{RTS}_{trans} + t^{RTS}_{prop} + \text{CTS-wait-time}$$
$$U = (\text{number of retransmissions of RTS})(t^{RTS}_{trans} + t^{RTS}_{prop} + \text{CTS-wait-time})$$
$$V = t^{pkt}_{trans} + t^{pkt}_{prop} + t^{ack}_{trans} + t^{ack}_{prop}$$

1. t^{RTS}_{trans} and t^{RTS}_{prop} refer to the transmission time and propagation time of RTS. After RTS is initiated, the receiver waits for `CTS-wait-time` to receive CTS signal from the receiver. If CTS is not received within this time, the sender goes for a retransmission of RTS signal, and retransmisson stops when the sender sees a CTS signal. Subsequently, the sender transmits the packet. After the data transmission is complete, the receiver sends ACK signal to the sender.

2. Limitations of this scheme is that a wireless network on a few systems can only be established. For example, in the above figure, this scheme does not support a data transmission between nodes A and D. To cater such transmission, we shall make use of `Wireless Access Points`.

3. Access points are placed at every 10m and the nodes within 10m range are attached to an access point. The communication between access points is through a distribution system (core switch) which is a wired network.

4. In the following figure, Access Point 1 caters nodes which are distributed between A and B and Similarly, Access Point 2 is for nodes residing between B and C. The node B which is in the intersection of the two can connect itself to either Access Point 1 or 2.

5. Modern access points support 54Mbps network speed and can cater a maximum of 21 nodes (users). A node under AP 1 wishing to transmit a packet to a node under AP 3, first sends

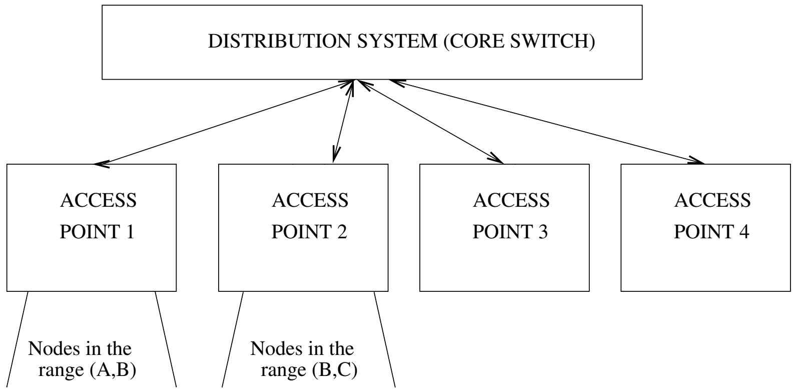

Fig. 2. A Wireless network with Access Points

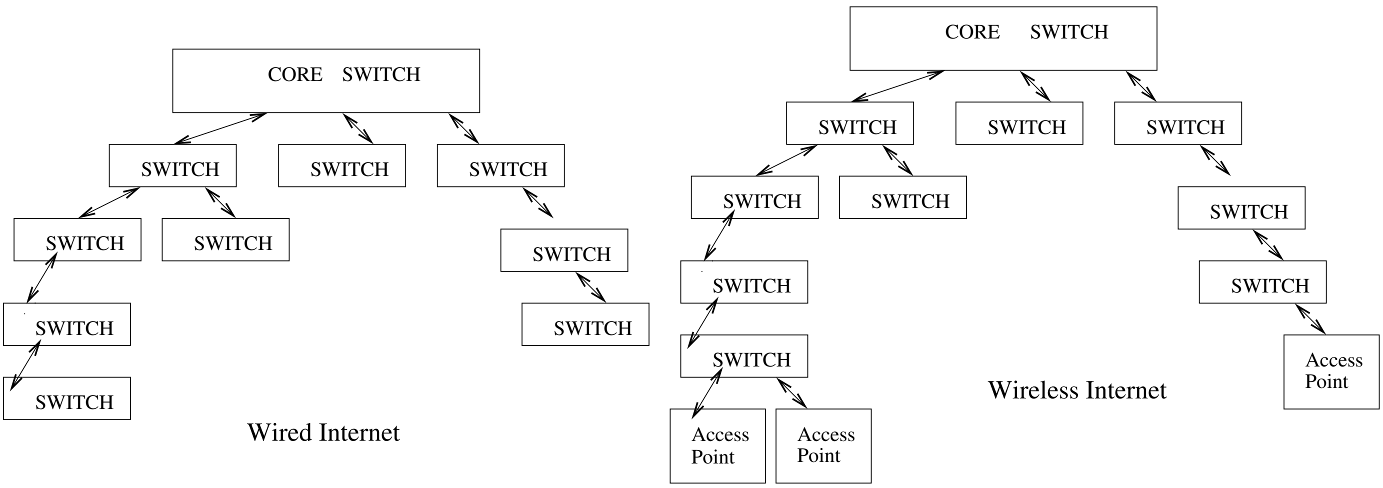

Fig. 3. A Typical Tree Toplogy with/without Access Points

a packet to the distribution system and inturn, it is forwarded to the destination via AP 3. The path followed for ACK packet is just the reverse of the path followed for the data packet.

6. It is important to note that there is no pure wireless network in practice, and what is feasible is a hybrid network (wired + wireless). Typically, in a wired network, the switch that connects end-users with the core switch may be replaced with a wireless access point. For example, a campus network (academia/industry) with tree topology has wireless access points as its leaves instead of 24-port(48-port) switches.

Utilization

The utilization of tree topology with only store and forward switches, and topology with switches and access points are analyzed in this section. Suppose there are x switches and t_{prop} denotes the propagation time between the sender and receiver.

$$\text{Utilization} = \frac{t_{trans}}{t_{trans}(x+1) + t_{prop} + t_{sdelay}(x)}$$

Suppose, the last level switch is replaced with an accesspoint both at the sender and receiver, then the number of switches is reduced to $(x-2)$. Thus,

$$\text{Utilization} = \frac{t_{trans}}{t_{trans}(x-1) + t_{prop} + t_{sdelay}(x-2) + 2 \cdot \text{access point delay}}$$

In practice, core switches have NICs that can support 1Gbps and swithces support 100Mbps. Suppose the utilization of the switch based network is 50%, then 50Mbps is distributed among 24 users (for 24 port switch) who are connected to that switch. Suppose the utilization of hybrid network is 40%, then 21.6 Mbps (40% of 54Mbps) is shared among 21 users. In practice, switch based network offers higher utilization than the hybrid network consisting of switches and access points.

Scalability: Both Ethernet bus and token ring offer poor utilization if the number of nodes increases linearly. Hence, 802.3 and 802.5 are preferred if the network size is small. For large networks (academia/industry), switch based network design is considered good. Further, based on the requirement, hybrid design is considered wherein wireless access points replace swithces present at the leaf level of the tree topology. One can also consider having 802.3 or 802.5 at the last level of the tree toplogy.