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PERFORMANCE ANALYSIS OF A BROADCAST STAR LOCAL AREA NETWORK WITH COLLISION AVOIDANCE:
Part 1, Infinite Station Population Model

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Performance Analysis of a Broadcast Star Local Area Network with Collision Avoidance: Part 1, Infinite Station Population Model*

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Abstract

Packet collisions and their resolution create a performance bottleneck in random access LANs. As a solution to this problem, a broadcast star network with collision avoidance has been proposed and studied in [3 - 17]. In a broadcast star network, collisions of simultaneously transmitted packets are avoided by means of hardware called a collision avoidance switch. While the channel is being used by one station, the collision avoidance switch blocks other stations from using it. This network implements random access protocols without the penalty of collisions among packets and combines the benefits of random access (low delay when traffic is light; simple, distributed, and therefore robust protocols) with excellent network utilization.

In this paper, we analyze the performance of a broadcast star network, assuming synchronous operation of a network. In synchronous operation, the channel time is slotted, and stations transmit only at the beginning of a slot. The number of stations on a network is assumed to be infinite, and packets arrive at stations according to a Poisson process. An exact analysis is developed, and the distribution for the transmission delays is obtained. It is also shown through simulations that a broadcast star operating under synchronous mode yields better performance than that operating under asynchronous mode, where transmissions of packets are not confined to the beginning of slots, and stations start transmission any time.

1. Introduction

Since the ALOHA protocol was first proposed by Abramson in 1970 [1], random access protocols have found use in hundreds of networks. In random access protocols [2], transmission rights are simultaneously offered to a group of stations in the hope that exactly one of the stations has a packet to send. However, if two or more stations send packets simultaneously on the channel, these packets interfere with each other and none of them are correctly received by the destination stations. In such cases, a collision has occurred and stations retransmit packets until they are successfully received by the destination stations.

Random access protocols exhibit small transmission delays under light traffic conditions: stations transmit as soon as they want access to the channel, and the probability of a collision is low when traffic is light. Another attractive aspect of random access protocols is their simplicity, making them easy to implement at the stations. However, random access protocols have a performance bottleneck under heavy traffic conditions. When traffic is heavy, a large number of collisions occur. Such conditions result in a loss of channel utilization from the transmission of colliding packets which must necessarily be retransmitted later.

Most random access protocols handle collision resolution by using some channel capacity to establish a schedule of transmissions among contending stations. There is, therefore, an unavoidable loss of channel capacity when collisions occur. As the traffic increases in such networks, so do the chances for collisions, with reduced channel utilization and higher packet delays. It would be nice to have a protocol which has the benefits of random access (in particular, low delay in light traffic) but does not suffer from the lost channel capacity when traffic is heavier.

In order to solve a performance bottleneck due to collisions and their resolution in random access protocols, a new network architecture based on collision avoidance, called a broadcast star network, has been proposed and studied by many researchers [3 - 17], including the authors of this paper. In a broadcast star network, collisions of simultaneously transmitted packets are avoided by means of hardware called a collision avoidance switch. The important feature of a collision avoidance switch is that when two or more packets contend for the output line of a switch, it is guaranteed that one of the packets acquires the line and is successfully transmitted on it. Thus, no channel time is wasted in the transmission of collided packets, and the traditional penalty of random access is eliminated. A simple random access protocol can be used without the need for a collision resolution subprotocol.

Collision avoidance can be implemented with very little circuitry. Implementation examples of a collision avoidance switch are given in [3, 4, 9, 11]. Various station and switch protocols for a broadcast star network are discussed in [7 - 10]. An experimental broadcast star network and its performance measurement are found in [5, 6]. Papers [13, 14] model a broadcast star network as a polling system, and develop an approximate analysis assuming that the propagation delay between the stations and the switch is shorter than the packet transmission time. It is also assumed in [13, 14] that the broadcast star operates under asynchronous mode, where transmissions of packets are not confined to the beginning of slots, and stations start transmission any time. A tree network, a more general network architecture based on collision avoidance, has been proposed in [7, 8] and studied in [9 - 12, 15 - 17].

In this paper, we analyze the performance of a broadcast star network with collision avoidance. We assume synchronous operation of a network, where the channel time is divided into slots, and stations transmit only at the beginning of a slot. Propagation delay between the stations and the switch is arbitrarily long. (It can be longer than, equal to, or shorter than the packet transmission time.) An exact analysis is developed, and the distribution for the transmission delays is obtained. We also show, through simulations, that a broadcast star operating under synchronous mode yields better performance (i.e., smaller transmission delay and higher throughput) than that operating under asynchronous mode, where transmissions of packets are not confined to the beginning of slots, and stations start transmission any time.

The rest of the paper is organized in the following way. In section 2, we review a broadcast star network. In section 3, we present an exact analysis for a broadcast star network with an infinite station population and obtain the distribution of the transmission delays. Numerical results are presented in section 4.

2. Collision Avoidance Broadcast Star Network

In this section we review the switch architecture and the station protocol for a broadcast star network with collision avoidance. There are two possible operations of the network: synchronous and asynchronous operations. In synchronous operation, the channel time is divided into slots, and stations transmit only at the beginning of a slot. A broadcast star network operating under this mode is referred to as a slotted broadcast star (or simply, a broadcast star) in this paper. In asynchronous operation, transmissions of packets are not confined to the beginning of time slots, and stations may start transmission any time. An asynchronous broadcast star network is referred to as an unslotted broadcast star in this paper.

As it is shown in section 4, a slotted broadcast star yields better performance (i.e., smaller transmission delay and higher throughput) than its unslotted counterpart, we will only consider slotted (synchronous) operation of the network in this paper. We further assume that packets are of constant length, and transmission time of a packet is equal to a slot length. The switch architecture and station protocol of a slotted broadcast star is reviewed below.

In a broadcast star network, stations are connected to a central switch by full duplex channels. Each of these channels comprises an uplink and a downlink.

The switch may be viewed functionally as containing two components: the selector and the broadcaster. See Figure 1. In a slotted broadcast star network, two or more packets may arrive at the switch simultaneously. In such cases, the selector randomly selects one of the packets coming from the uplinks and blocks (or discards) all the other packets *. The selector transmits this selected packet to the broadcaster, which in turn broadcasts the packet from the selector on all the downlinks. It should be noted that a collision avoidance switch does not buffer packets; no memory is used to store-and-forward packets.

The selector has two states. It is busy from the time it has selected a packet to the time it has finished transmitting the packet to the broadcaster. Otherwise the selector is idle. While the selector is busy, all packets arriving on uplinks are ignored in their entirety. Upon going idle, the selector randomly selects one of the newly arriving packets.

The station protocol for the slotted broadcast star is very simple and is like slotted ALOHA [1]:

(1) A station transmits a packet in the first upcoming slot upon its arrival.

(2) After a propagation delay to and from the switch, the station monitors its downlink for the broadcast of its own packet.

(3) If the station does not see the start of its own packet, then it retransmits the packet immediately in the following slot,

(4) else the station does see its packet and knows that the packet has won the switch and will be broadcast in its entirety.

In ALOHA, in order to avoid endless recollisions, each station waits a random time after a collision before retransmitting. In the above protocol, stations do not defer retransmission. They resubmit their packets as soon as they learn of transmission failure. Since no collision with an ongoing transmission can occur in this broadcast star network, there is no need for

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* In reality, in the event of simultaneous arrivals of two or more inputs, switch could be designed in such a way that it, for instance, selects the input line with the lowest number.

such random delays as ALOHA requires.

3. Performance Analysis of a Broadcast Star with an Infinite Station Population

In this section, we present an exact analysis for a broadcast star network with an infinite station population and obtain the distribution of the transmission delays.

3.1 Model, Notations and Assumptions

In the analysis, we assume that the channel time is slotted and that the unit of time is one slot time. The length of a packet is assumed to be constant and its duration (packet length in bits divided by the channel speed) is equal to the slot length.

We assume an infinite station population, which collectively generates new packets according to a Poisson distribution with rate λ (packets/slot). Newly arrived packets are transmitted in the slots next to their arrival instants. More than one station may transmit packets in the same slot. In this case, we assume that the switch chooses one packet randomly and broadcasts it on the downlinks. The other packets are blocked at the switch. We assume that a station can determine whether its packet was selected or not as soon as it receives the first several bits of the broadcast. If a station learns of a transmission failure, it retransmits the packet in the next slot.

Stations are located at the same distance from the switch. R denotes the round trip propagation delay to and from the switch. The communication medium is assumed to be error free, and all the stations receive the same signal from the broadcaster.

We define the transmission delay D (slots) as the time from the beginning of the slot immediately following an arrival of a (new) packet to the time at which the packet is completely (and successfully) received by the destination station. See Figure 2. Let m be the number of retransmissions required for a packet to be successfully transmitted. Because it takes time R for a station to know whether a transmission is successful or not, and blocked packets are immediately retransmitted in the next slot, one retransmission requires $\lfloor R \rfloor + 1$ slots. Here, $\lfloor R \rfloor$ denotes the largest integer less than or equal to R. Further, a successful transmission takes $R+1$ (slots). Therefore, D is expressed as

$$D = m \times (\lfloor R \rfloor + 1) + R + 1. \tag{1}$$

From eq.(1), the mean and the variance of D become

$$E[D] = E[m](\lfloor R \rfloor + 1) + R + 1 \tag{2}$$

$$Var[D] = Var[m](\lfloor R \rfloor + 1)^2. \tag{3}$$

Higher moments of D can be also obtained from eq.(1).

In the following, we obtain the distribution of the number of retransmissions m, the unknown factor in equations (1), (2) and (3).

3.2 Conditional Moment of the Number of Retransmissions

Assume that n packets (let's call one of them test packet) are accessing a slot ($n \geq 1$). Let $P_n(m)$ be the conditional probability that the test packet requires exactly m more retransmissions (in addition to the retransmissions the test packet might have experienced so far) to be successfully transmitted, given that n packets (including the test packet itself) access the same slot. Note, if the test packet is a new packet which arrived in the previous slot, m is the total number of retransmissions required for successful transmission.

Since n packets are accessing the same slot, the probability that the test packet is successfully transmitted in this slot is $\frac{1}{n}$. Thus, for $n \geq 1$,

$$P_n(0) = \frac{1}{n}. \tag{4}$$

Otherwise the test packet is blocked with probability $1 - \frac{1}{n}$, and it is retransmitted $\lfloor R \rfloor + 1$ slots later. Call this slot the retransmission slot, and let k be the number of new arrivals in the slot immediately preceding the retransmission slot. Since we assume a Poisson process for new packet arrivals, the probability of having k arrivals in a slot is $\frac{\lambda^k}{k!}e^{-\lambda}$. The probability that the test packet requires $m-1$ more retransmissions to be successfully transmitted becomes $P_{n-1+k}(m-1)$, since $n-1$ blocked packets and k new packets access the retransmission slot. Thus, we have the following recursive equation:

$$P_n(m) = (1 - \frac{1}{n})\sum_{k=0}^{\infty} \frac{\lambda^k}{k!}e^{-\lambda}P_{n-1+k}(m-1) \qquad (m \geq 1, n \geq 1). \tag{5}$$

Let M_n^l be the l-th conditional moment of the number of retransmissions m, given that n packets access the same slot. That is,

$$M_n^l = \sum_{m=0}^{\infty} m^l P_n(m). \tag{6}$$

From eq.(6), $M_n^0 = 1$. From eq.(5), we have

$$\begin{aligned}
M_n^l &= P_n(0)0^l + \sum_{m=1}^{\infty} P_n(m)m^l \\
&= \sum_{m=1}^{\infty}(1 - \frac{1}{n})\sum_{k=0}^{\infty} \frac{\lambda^k}{k!}e^{-\lambda}P_{n-1+k}(m-1)m^l \\
&= (1 - \frac{1}{n})\sum_{k=0}^{\infty} \frac{\lambda^k}{k!}e^{-\lambda}\sum_{m=1}^{\infty}((m-1)+1)^l \times P_{n-1+k}(m-1) \\
&= (1 - \frac{1}{n})\sum_{k=0}^{\infty} \frac{\lambda^k}{k!}e^{-\lambda}\sum_{m=1}^{\infty}\sum_{r=0}^{l}\binom{l}{r}(m-1)^r \times P_{n-1+k}(m-1) \\
&= (1 - \frac{1}{n})\sum_{k=0}^{\infty} \frac{\lambda^k}{k!}e^{-\lambda}\sum_{r=0}^{l}\binom{l}{r}M_{n-1+k}^r.
\end{aligned} \tag{7}$$

In analyzing a random-service continuous-time M/G/1 queueing system, Kingman proved that an equation of the same form of eq.(7) has a unique solution which is a polynomial of degree l in n [18]. Therefore, we assume a solution to eq.(7) in the following form:

$$M_n^l = \sum_{k=0}^{l} a_k^l n^k \tag{8}$$

where a_k^l $(k = 0, 1, \cdots, l)$ are coefficients of the polynomial.

The first and second moments (M_n^1 and M_n^2) can easily be obtained from eqs.(7) and (8). From eq.(8), $M_n^1 = a_0^1 + a_1^1 n$ and $M_n^2 = a_0^2 + a_1^2 n + a_2^2 n^2$. Substituting these into eq.(7), we can determine the coefficients, and M_n^1 and M_n^2 becomes

$$M_n^1 = \frac{n-1}{2-\lambda} \tag{9}$$

$$M_n^2 = \frac{2(n^2 - 3n + 2)}{(2-\lambda)(3-2\lambda)} + \frac{(6-\lambda)(n-1)}{(2-\lambda)^2(3-2\lambda)}. \tag{10}$$

Taking the expectation of M_n^1 and M_n^2 over n, we have

$$E[m] = E_n[M_n^1] = \frac{1}{2-\lambda}(E[n] - 1) \tag{11}$$

$$E[m^2] = E_n[M_n^2] = \frac{2(E[n^2] - 3E[n] + 2)}{(2-\lambda)(3-2\lambda)} + \frac{(6-\lambda)(E[n]-1)}{(2-\lambda)^2(3-2\lambda)}. \tag{12}$$

In the next subsection, we obtain the distribution of n, and its first and second moments ($E[n]$ and $E[n^2]$).

3.3 Distribution of the Number of Packets in a Slot

We observe the system at the beginning (more precisely, immediately after the beginning) of slots where the transmission of a packet (say, test packet) takes place. The circles in Figure 2 denote these observation time points, or imbedded points.

Let q_i be the number of blocked packets at the i-th imbedded point. In other words, there were $q_i + 1$ busy stations (i.e., stations with a packet to send) accessing the channel at the i-th imbedded point, and one of these packets was successfully transmitted. Further, let v_{i+1} be the number of new packet arrivals in the slot immediately prior to the $(i+1)$-st imbedded point. See Figure 2. Then q_{i+1} is given by

$$q_{i+1} = \begin{cases} q_i + v_{i+1} - 1, & \text{If } q_i > 0. \\ max\{v_{i+1} - 1, 0\}, & \text{If } q_i = 0. \end{cases} \tag{13}$$

Let $Q_i(z)$ and $V_i(z)$ be the z-transforms for q_i and v_i:

$$Q_i(z) = \sum_{j=0}^{\infty} \Pr[q_i = j] z^j \tag{14}$$

$$V_i(z) = \sum_{j=0}^{\infty} \Pr[v_i = j] z^j. \tag{15}$$

We assume the steady state exists for q_i, namely,

$$\lim_{i \to \infty} q_i = q \tag{16}$$

$$Q(z) = \lim_{i \to \infty} Q_i(z) = \sum_{j=0}^{\infty} \Pr[q = j] z^j. \tag{17}$$

Since we assume Poisson arrivals, the steady state distribution for $v = \lim_{i \to \infty} v_i$ exists and is given by

$$\Pr[v = j] = \frac{\lambda^j}{j!} e^{-\lambda} \tag{18}$$

and its z-transform is given by

$$V(z) = \sum_{j=0}^{\infty} \Pr[v = j] z^j = e^{\lambda(z-1)}. \tag{19}$$

From eq.(13), if $q_i > 0$, then $q_{i+1} = q_i + v_{i+1} - 1$. Hence, we have

$$Q_{i+1}(z) = \frac{Q_i(z) - Q_i(0)}{z} V_{i+1}(z). \tag{20}$$

Again from eq.(13), if $q_i = 0$ and $v_{i+1} > 0$, then $q_{i+1} = v_{i+1} - 1$. Also, if $q_i = 0$ and $v_{i+1} = 0$, then $q_{i+1} = 0$. Hence, we have

$$Q_{i+1}(z) = Q_i(0)[V_{i+1}(0) + (\frac{V_{i+1}(z) - V_{i+1}(0)}{z})]. \tag{21}$$

From eqs.(20) and (21), we have

$$Q_{i+1}(z) = \frac{(Q_i(z) - Q_i(0))V_{i+1}(z)}{z} + Q_i(0)[V_{i+1}(0) + (\frac{V_{i+1}(z) - V_{i+1}(0)}{z})]. \tag{22}$$

By taking the limit where i goes to infinity, we have

$$Q(z) = \frac{(Q(z) - Q(0))V(z)}{z} + Q(0)[V(0) + (\frac{V(z) - V(0)}{z})]. \tag{23}$$

By solving the above equation with respect to $Q(z)$, we have

$$Q(z) = \frac{1}{z - V(z)} Q(0)V(0) = \frac{z-1}{z - e^{\lambda(z-1)}} Q(0)V(0). \tag{24}$$

By using L'Hopital's theorem and $Q(1) = 1$, we have

$$\begin{aligned}\lim_{z\to 1} Q(z) &= \lim_{z\to 1} \frac{z-1}{z-e^{\lambda(z-1)}} Q(0)V(0) \\ &= \frac{\frac{d}{dz}(z-1)}{\frac{d}{dz}(z-e^{\lambda(z-1)})} Q(0)V(0) = \frac{Q(0)V(0)}{1-\lambda} = 1. \end{aligned} \tag{25}$$

Thus, we have

$$Q(0)V(0) = 1 - \lambda. \tag{26}$$

By substituting eq.(26) to eq.(24), finally we obtain

$$Q(z) = \frac{(1-\lambda)(z-1)}{z-e^{\lambda(z-1)}}. \tag{27}$$

Next, from the distribution of q, we obtain the distribution of n, the number of the packets which access the slot immediately following the arrival of the test packet. Let $P(z)$ denote the z-transform for n. Since both blocked packets and newly arrived packets access a slot, $P(z)$ is given by the convolution of $Q(z)$ and $S(z)$, the z-transform for the conditional distribution of the number of new arrivals in a slot given that one or more packets arrive in the slot. $Q(z)$ is given by eq.(27), and $S(z)$ is given by

$$\frac{V(z) - V(0)}{1 - V(0)} \tag{28}$$

because the probability of having no arrival in a slot is $V(0) = e^{-\lambda}$. Therefore, we have

$$P(z) = Q(z)\frac{V(z) - V(0)}{1 - V(0)}. \tag{29}$$

From eqs.(19), (27) and $V(0) = e^{-\lambda}$, $P(z)$ becomes

$$P(z) = \frac{(1-\lambda)(z-1)}{z-e^{\lambda(z-1)}} \times \frac{e^{\lambda(z-1)} - e^{-\lambda}}{1-e^{-\lambda}}. \tag{30}$$

By substituting $z = 1$ in the i-th derivative of $P(z)$, the i-th moment of the distribution of n is derived. The first two moments are as follows:

$$P'(1) = E[n] = \frac{-(1+e^{-\lambda})\lambda^2 + 2\lambda}{2(1-\lambda)(1-e^{-\lambda})} \tag{31}$$

$$P''(1) = E[n(n-1)] = E[n^2] - E[n] = \frac{(1-e^{-\lambda})\lambda^4 - (4+2e^{-\lambda})\lambda^3 + 6\lambda^2}{6(1-\lambda)^2(1-e^{-\lambda})} \tag{32}$$

Thus, we can obtain $E[n]$ and $E[n^2]$. By substituting $E[n]$ and $E[n^2]$ into eqs.(11) and (12), we can derive $E[m]$ and $Var[m] = E[m^2] - (E[m])^2$. Finally, we can obtain $E[D]$ and $Var[D]$ from eqs.(2) and (3).

4. Numerical Results

In this section we show numerical results for a slotted broadcast star network based on the analysis presented in the previous section. We also show simulation results for an unslotted broadcast star for comparison purposes. We present the results graphically with the unit of time equal to one packet transmission time.

Figures 3 and 4 are for a slotted broadcast star network with an infinite station population. These figures are based on the analysis presented in section 3.

Figure 3 shows the mean transmission delay $E[D]$ as a function of the packet arrival rate λ for various values of R ($R = 0.05, 1, 5, 10$). The results for a particular value of R hold for any broadcast star whose ratio of R to the packet duration is equal to that particular value. The results for $R = 5.0$ hold for any broadcast star whose ratio of R to the packet duration is 5.0. For instance, these results hold for a network with a channel speed of 1 Gbits/sec, a distance of 500 meters from the stations to the switch, 1000 bit packets, and a signal propagation speed of 2×10^8 m/sec. In this case, one packet duration equals 10^{-6} seconds.

Figure 3 shows that the mean delays for various values of R have similar behavior. Delays grow rapidly when throughput exceeds 0.8. The maximum throughput for all cases is 1.0; in other words, for each value of R, the network saturates at an input load of 1.0. Under conditions of heavy traffic, it is very likely that all the channels are always busy. Therefore, there is a successful transmission in every slot, and a throughput of 1.0 is achieved.

Figure 4 shows the variance of transmission delay $Var[D]$ as a function of a packet arrival rate λ for the same networks in Figure 3. The vertical axis is logarithmic. The variance of delay increases slowly until the throughput exceeds 0.8, after which the variance grows rapidly to infinity.

Figures 5 and 6 show the simulation results for unslotted broadcast star networks with the same parameter values as those in Figures 3 and 4.

By comparing Figures 3 and 5, it can be seen that a slotted broadcast star gives the smaller mean delays than its unslotted counterpart for all values of R. The difference between the two becomes more significant as the value of R becomes larger. Further, an unslotted broadcast star reaches saturation at the input rate smaller than 1.0; a slotted broadcast star reaches saturation at the input rate of 1.0.

The reason that a slotted broadcast star yields smaller transmission delays can be intuitively explained below. Consider an example shown in Figure 7. In this example, two new packets ($P1$ and $P2$) arrive. Assume that the interarrival time of these two packets is shorter than a packet transmission time (or the slot length). In the unslotted case, packet $P1$ will succeed in transmission, but packet $P2$ will be blocked at the switch. In the slotted case, both packets will be successfully transmitted, since they will be transmitted in different slots. (This is very much analogous to the comparison of the slotted ALOHA and the pure ALOHA schemes.) Therefore, for the same packet arrival rate, the probability of successful transmission in a slotted broadcast star is larger than that in an unslotted broadcast star, and this leads to smaller transmission delays in a slotted broadcast star.

By comparing Figures 4 and 6, it can be seen that the variance of delay of a slotted broadcast star is smaller at the same throughput than that of an unslotted broadcast star.

90% confidence intervals of some of the simulation results used in Figures 5 and 6 are shown in Table 1. Confidence intervals of the mean delay are less than $\pm 1\%$ of the delay values, when the throughput is less or equal to 0.5, and are at most $\pm 3.5\%$ when the throughput is 0.8. Since confidence intervals are very small, they are not shown in Figure 5. Confidence intervals of the variance of delay are at most $\pm 10\%$ of the delay variance values. Since the vertical axis in Figure 6 is logarithmic, confidence interval values are not significant enough to be seen on the figure. Therefore, the confidence intervals are not shown in Figure 6.

5. Conclusion

In this paper, we presented an exact analysis for the performance of a broadcast star network with collision avoidance. This network has the potential of combining the benefits of random access with excellent network utilization.

In the analysis, an infinite number of stations are assumed on a network. Further, slotted (or synchronous) operation of a network is assumed. Through analysis, we obtained the distribution of the transmission delays. Through simulations, we showed that a slotted broadcast star achieves both smaller delay and higher throughput than its unslotted counterpart.

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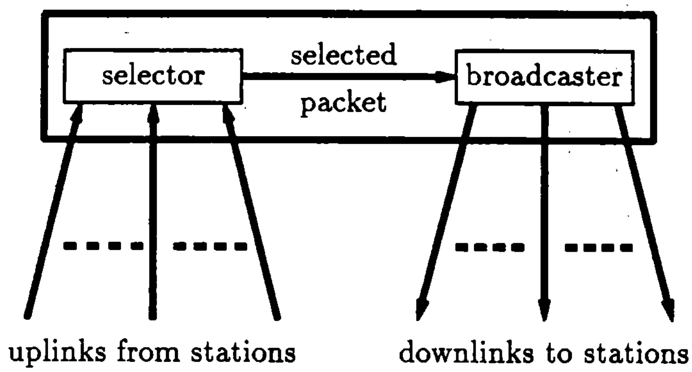


Fig.1 Broadcast Star Switch

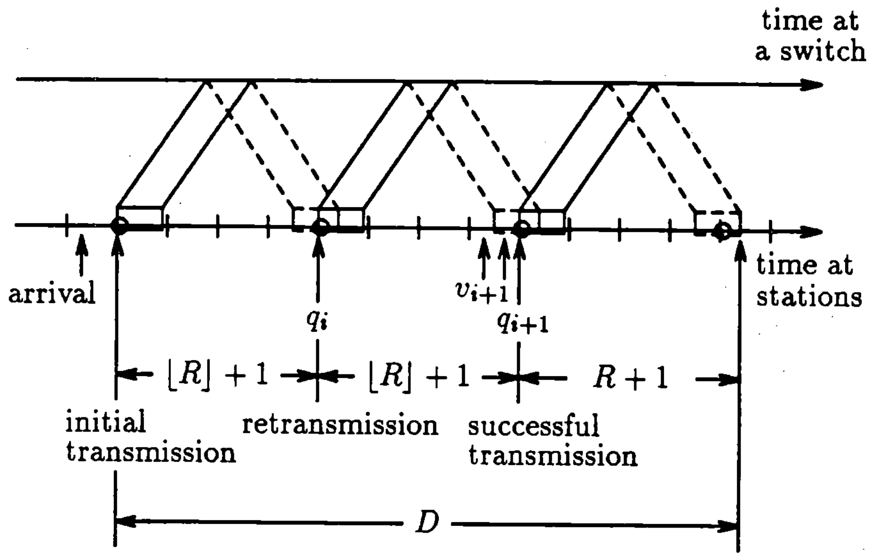


Fig.2 Packet Transmission in a Broadcast Star

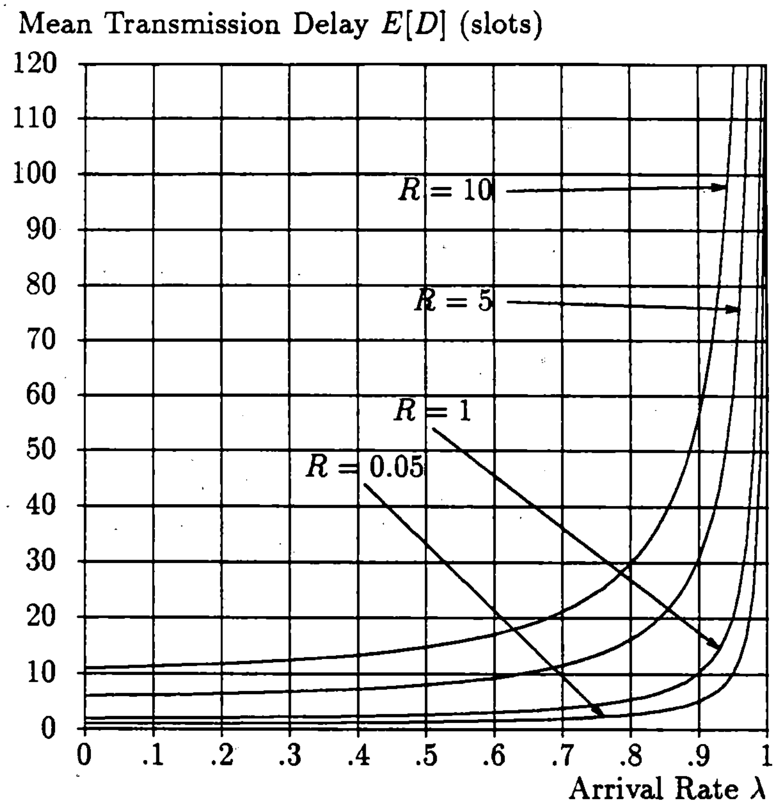


Fig.3 Mean Transmission Delay in a Broadcast Star with an Infinite Station Population ($R = 0.05, 1, 5, 10$)

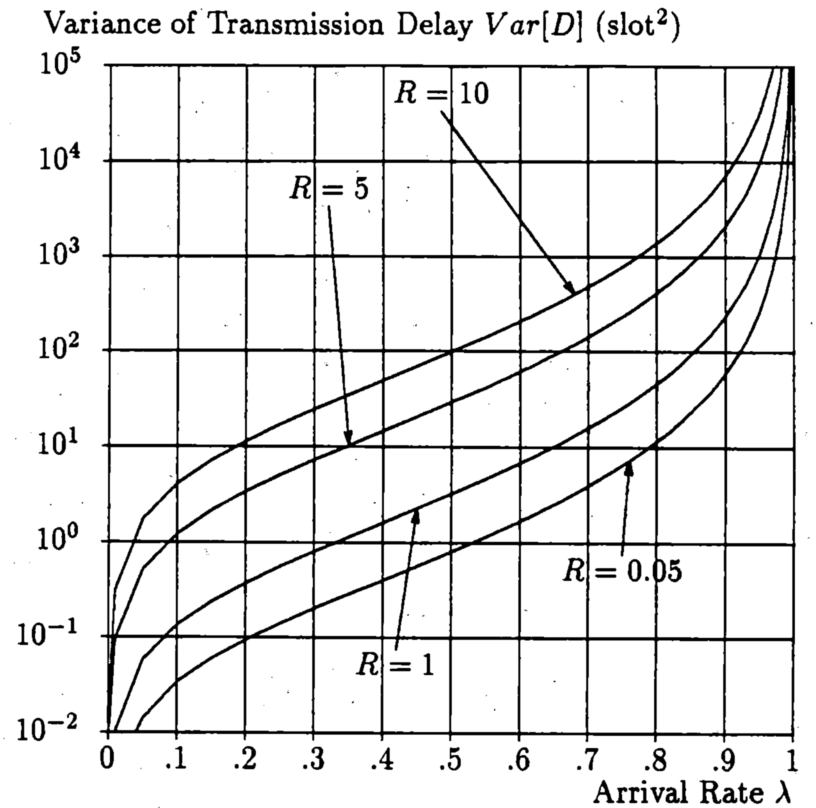
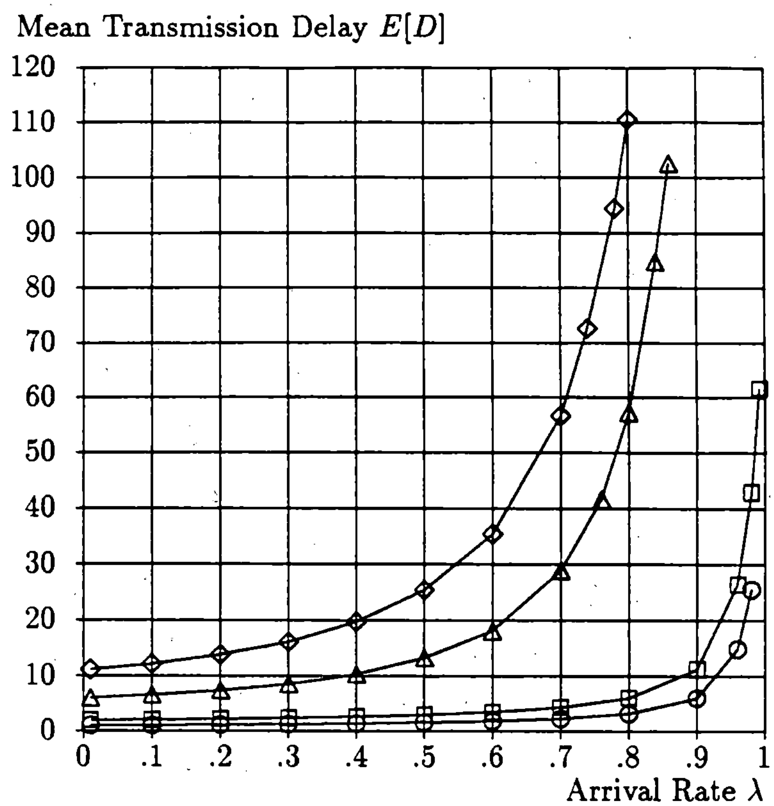


Fig.4 Variance of Transmission Delay in a Broadcast Star with an Infinite Station Population ($R = 0.05, 1, 5, 10$)



○: R=0.05 □: R=1 △: R=5 ◇: R=10

Fig.5 Mean Transmission Delay in an Unslotted Broadcast Star with an Infinite Station Population ($R = 0.05, 1, 5, 10$)

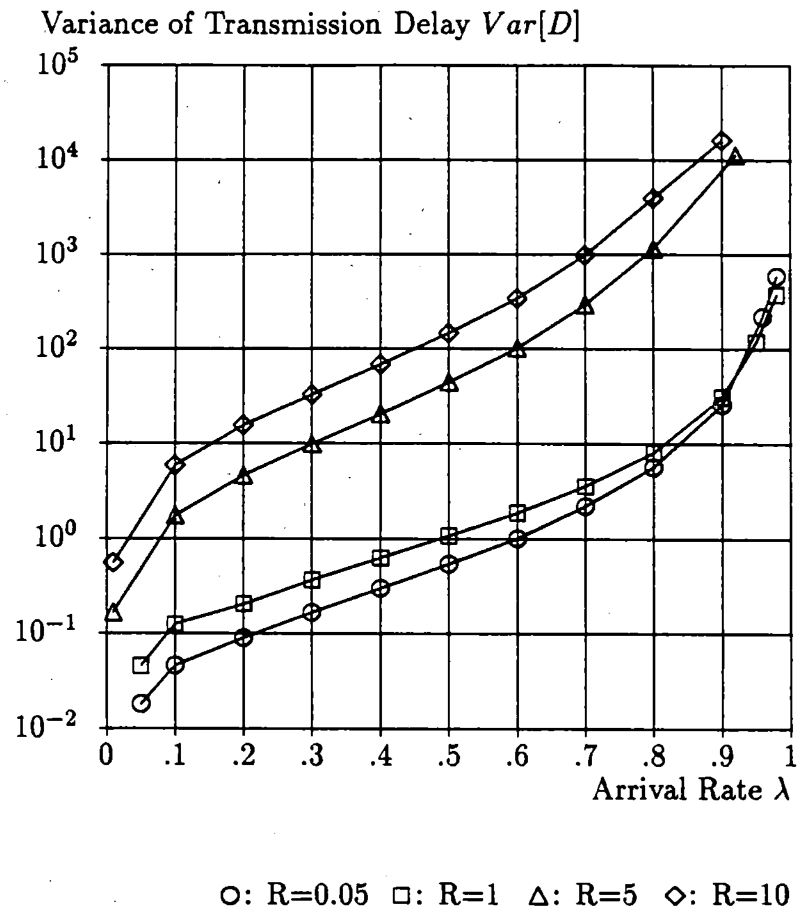
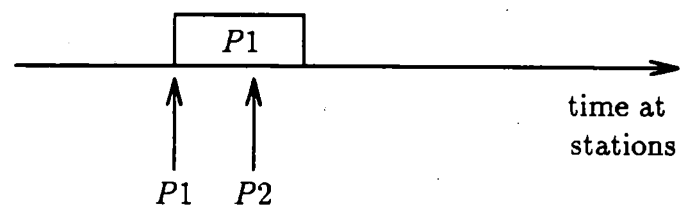


Fig.6 Variance of Transmission Delay in an Unslotted Broadcast Star with an Infinite Station Population ($R = 0.05, 1, 5, 10$)

Unslotted channel



Slotted channel

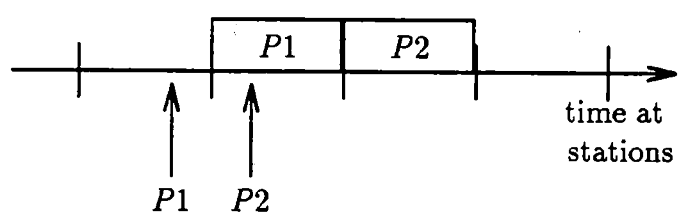


Fig.7 Example of Transmissions in a Slotted and an Unslotted Broadcast Star

Table 1. Simulation Results with 90% Confidence Intervals
(Unslotted Broadcast Star with Infinite Station Population, $R = 10$)

Throughput	Mean delay	Variance of delay
0.010	11.093 ±0.009	0.933 ±0.096
0.100	12.164 ±0.031	14.159 ±0.339
0.500	25.348 ±0.225	573.089 ±25.0
0.800	114.681 ±3.77	27033.167 ±1837