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Slotted Aloha in High Speed Bidirectional Bus Networks*

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SLOTTED ALOHA IN HIGH SPEED BIDIRECTIONAL BUS NETWORKS

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Abstract

We study the performance of the slotted ALOHA multiple access protocol in a high speed bidirectional passive bus network, where transmissions are in the form of packets of constant length. Slotted ALOHA is generally considered to have better throughput performance than unslotted ALOHA, whose maximum throughput is known to be 1/(2e), independent of station configuration. We show that, with a probabilistic station configuration, the throughput of slotted ALOHA can degrade to 1/(3e) when the end-to-end propagation delay is significantly larger than the packet transmission time. Nevertheless, in some very high speed bidirectional bus networks with a deterministic station configuration, the throughput of slotted ALOHA can be as high as 1/2.

1 Introduction

The slotted ALOHA multiple access protocol has been studied by many researchers. For broadcast communications, each transmission must be receivable by all stations, and the success of a transmission normally requires that there is no other transmission within the same slot. The maximum broadcast throughput for slotted ALOHA is well known to be 1/e [1]. In practice, the slotted ALOHA protocol may actually be used for point-to-point communications. Each transmission is designated for only one station, and the success of a transmission depends on its being free of collision only where and when the reception is intended. Due to propagation delay in bidirectional bus networks, packets transmitted within the same slot may overlap non-destructively. When this occurs, we say that there is channel reuse [2], [3]. In Figure 1, we make use of space-time diagrams to show how channel reuse is possible in a high speed bidirectional bus network. Space-time diagrams have been widely used in the literature for the analysis of multiple access protocols in bus networks: e.g. [4], [5]. Allowing for channel reuse, point-to-point transmissions are generally less demanding for channel resources than broadcast transmissions. One would expect the former to have better throughput performance because of channel reuse. Such distinction is seldom emphasized in the literature because the difference is insignificant in most conventional bidirectional bus networks whose speed of operation is low.

The speed of a bus network is often specified by the parameter a, which denotes the end-to-end propagation delay normalized with respect to the average packet transmission time. With current technology and cost trends, typical values of a in most existing bus networks range between zero and one. Advances in the technology of optical communications and the increasing demand for transmissions of relatively short packets promise future bidirectional bus networks with normalized end-to-end propagation delay exceeding one.

The fundamental limits of random access protocols have been widely studied [6]. It is common knowledge that in many contention-based multiple access protocols with carrier sensing, throughput performance degrades with a because the overhead for monitoring channel activities increases with a [7]. In our analysis of the slotted ALOHA protocol, we assume that there is no carrier sensing.

Many random access strategies for unidirectional bus networks operating at high speeds have been studied by Maxemchuk, who shows that for unidirectional bus networks, slotted protocols are always more efficient than unslotted protocols [8]. Our analysis shows that this is not the case in bidirectional bus networks. With a probabilistic station configuration, the throughput of slotted ALOHA can degrade to 1/(3e) when the end-to-end propagation delay is significantly larger than the packet transmission time, whereas the throughput of unslotted ALOHA is known to remain as 1/(2e).

The effect of propagation delay on the steady state behavior in the ALOHA systems has been investigated by Onozato, et.al., who show that propagation delay may stabilize such systems [9]. In this paper, we simplify the analysis of the slotted ALOHA protocol by assuming that it is possible to achieve statistical equilibrium.

The behavior of a very high speed regular bidirectional bus network where (1+a) equals exactly to the number of stations on the bus, has been studied by Levy and Kleinrock [10], [11]. They show that, provided there is no carrier sensing, the maximum throughput of any slotted contention-based multiple access protocol in such a network approaches 1/e as the number of stations becomes very large. In their model, a slot has the same length as the length of a packet transmission. We study slotted ALOHA in the same network, with the assumption that a slot lasts for a packet transmission time plus the end-to-end propagation delay. Our analysis indicates that, in such a network, the maximum throughput of slotted ALOHA is at least 1/2.

2 Slotted ALOHA

In this section, we review the slotted ALOHA protocol in a bidirectional bus, of length D=1, which is assumed to have perfectly non-reflecting terminations at both ends. Let there be N stations on the bus. Assuming that all packet transmissions are of a constant length, we show below the throughput performance of the protocol under the conventional assumption that there is no channel reuse.

In slotted ALOHA, time is divided into slots of length (1+a) units of packet transmission time, and a packet arriving at a station during a slot is transmitted at the beginning of the following slot. The length of a slot must be at least (1+a) units of packet transmission time, or the end-stations cannot communicate with each other. Each transmitting station receives an immediate error-free feedback about the success or failure of its transmitted packets. If a transmission fails, the packet is transmitted again in each subsequent slot with some fixed non-zero probability, independent of past slots and other packets. We summarize below the slotted ALOHA model used in this paper.

- Finite population of users;
- Synchronous transmissions at discrete points in time with period (1+a);
- Immediate feedback from receiver specifying success or failure;
- Offered traffic including retransmissions is approximately a memoryless random process;
- Symmetric traffic configuration;
- Statistical equilibrium.

Conventional analysis of the slotted ALOHA protocol without channel reuse is based on the assumption of a single receiver, so that a transmission in a given slot is successful only if there are no other transmissions within the same slot. Let G be the average offered traffic per slot, in packets per packet transmission time. The offered traffic is assumed to be uniform across all stations. By symmetry, each station is active during a slot with probability (1+a)G/N. Thus, the probability of success is

$$P_a(G) = \left\{1 - (1+a)\frac{G}{N}\right\}^{N-1} \qquad \text{for } a \geq 0 \qquad (1)$$

The throughput is then $S_a(G) = G.P_a(G)$. For large N,

$$S_a(G) = G\,e^{-(1+a)G} \qquad \text{for } a \geq 0 \qquad (2)$$

whose maximum with respect to G is

$$S_a{}^* = \left(\frac{1}{1+a}\right)\frac{1}{e} \qquad \text{for } a \geq 0 \qquad (3)$$

For point-to-point communications, the maximum throughput of unslotted ALOHA is well known to be 1/(2e) for all $a \geq 0$, independent of station configuration. Thus, without channel reuse, the maximum throughput of slotted ALOHA is indeed greater than that of unslotted ALOHA, only for $0 \leq a \leq 1$. Note that the maximum throughput of slotted ALOHA also vanishes as a becomes very large.

3 Vulnerable Regions

In any contention-based multiple access system, every transmission is vulnerable to collisions. If there were no propagation delay, then the vulnerability of a transmission may be characterized by the time interval over which any other packet transmitted could cause a collision. During this time interval, which is known as the vulnerable period, the given transmission is vulnerable everywhere on the bus. In a bidirectional bus network with propagation delay, the vulnerable periods do not adequately characterize the vulnerability of transmissions. We need to consider vulnerable regions in space and time, instead of vulnerable periods. A vulnerable region associated with a transmission is the space-time region over which any other packet arriving at the network could cause a collision. The size of the vulnerable regions is a limiting factor on the performance of a contention-based protocol. In general, for a given protocol, the larger the size of the vulnerable regions, the smaller is the probability of success of each transmission.

The conventional vulnerable region for broadcast communications in unslotted ALOHA is shown in Figure 2(a). The length of this vulnerable region is 2(1+a) units of packet transmission time. The vulnerable region for unslotted ALOHA with point-to-point communications is shown in Figure 2(b). Note that the space-time area of this vulnerable region is always equal to 2, regardless of the value of a.

In slotted ALOHA, the vulnerable region for a transmission in a given slot lies in the previous slot. For broadcast communications, the entire previous slot is normally taken to be the vulnerable region. Since the length of a slot is (1+a) units of packet transmission time, the vulnerable regions increase in size with increasing values of a. In this respect, the broadcast throughput of the slotted ALOHA protocol degrades as a increases, but with a factor of 2 more slowly than that of unslotted ALOHA.

Consider point-to-point transmissions for slotted ALOHA. No simultaneous transmissions are possible if $0 \leq a \leq 1$, because every vulnerable region coincides with the entire slot. Hence, for point-to-point communications, the maximum throughput of slotted ALOHA is given by (3) for $0 \leq a \leq 1$. For $a > 1$, the vulnerable regions may be considerably smaller than a whole slot. We will later show that as the slot length increases with a, the width of the vulnerable regions decreases in inverse proportion to a. Since the length of the slot is (1+a), the size of the vulnerable regions tends to a non-zero constant with increasing a. In this respect, the throughput of slotted ALOHA does not degrade indefinitely as a becomes very large.

In Figures 3(a) and 3(b), we show how two simultaneously transmitted packets may collide destructively in the same time slot. We call the V-shaped space-time region covered by a transmission a transmission region. In the first case, the packets collide with their respective transmission regions crossing each other. In the other case, the transmission regions overlap side-by-side each other. We examine these two cases separately.

In the first case, two transmission regions cross each other, and there is a potentially destructive collision. The collision is non-destructive if neither of the two designated receivers is located within the spatial interval where the transmission regions cross each other. This spatial interval is $(1/a)^-$ units long, where

$$(*)^- = \min(*,1) \qquad (4)$$

The spatial interval in which no other transmission may originate without causing a potentially destructive collision is called a potentially vulnerable interval. Note that this spatial interval does not exist if the position of the receiving station, $y \in [0,1]$, falls outside the following range.

$$Y_a(x) \equiv [\frac{1}{2}(x - \frac{1}{a}), \frac{1}{2}(x + \frac{1}{a} + 1)] \cap [0,1] \qquad (5)$$

where $x \in [0,1]$ is the position of the transmitting station. When $y \in Y_a(x)$, the potentially vulnerable interval is at most $(2/a)^-$ units wide. The width of the potentially vulnerable interval is smaller than $(2/a)^-$ when it falls partially outside [0,1]. For a>>1, such end effects are negligible, and the length of $Y_a(x)$ is approximately 1/2 because $Y_a(x) \cong [x/2,(x+1)/2]$. Suppose that y is uniformly distributed within the interval [0,1]. Then, one can show that the expected width of the potentially vulnerable interval is at most half of $(2/a)^-$, with equality if end effects are ignored.

In the second case, two transmitting stations are within $(1/a)^-$ units of distance from each other. There is a totally destructive collision. The spatial interval, in which no other transmission may originate without causing a totally destructive collision, is called a totally vulnerable interval. The width of this totally vulnerable interval is at most $(2/a)^-$. It is smaller than $(2/a)^-$ when the totally vulnerable interval falls partially outside [0,1]. For a>>1, such end effects are negligible. Assuming that x is uniformly distributed within the interval [0,1], one can easily show that the expected width of the totally vulnerable interval is at most $(2/a)^-$, with equality if end effects are ignored.

In Figure 4, we show a typical transmission, and its corresponding potentially and totally vulnerable regions, which are respectively specified by the potentially and totally vulnerable intervals. The throughput of slotted ALOHA depends on the size of the union of the vulnerable intervals, which we call the vulnerable interval-set. The union of the potentially and totally vulnerable regions will be referred to as the vulnerable union. The larger the size of the vulnerable union, the smaller is the maximum throughput of the protocol. As we show in Theorem 1 below, the space-time area of the vulnerable union for slotted ALOHA tends to a constant between 2 and 3, as the value of a becomes very large. On the other hand, the space-time area of the vulnerable region for unslotted ALOHA is always equal to 2. Hence, unslotted ALOHA is more efficient than slotted ALOHA for point-to-point communications in a very high speed bidirectional bus network.

4 Bounds on Maximum Throughput

In this section, we evaluate the throughput performance of slotted ALOHA in bidirectional passive bus networks, where transmissions are in the form of packets of constant length. We will consider two kinds of station configurations. In the probabilistic configuration, each station, except for the end-stations, is independently located at a uniformly distributed point on the bus. In the deterministic configuration, the positions of the stations on the bus are fixed. A special case of the deterministic configuration is the regular bus network, in which the spatial interval between any two adjacent stations is a constant.

4.1 Probabilistic Station Configuration

Theorem 1

Consider a bidirectional bus network with a probabilistic station configuration. For large N, the maximum throughput of the slotted ALOHA is bounded as follows.

$$\left(\frac{a}{3}\right)^+ \left(\frac{1}{1+a}\right)\frac{1}{e} \le S_a{}^* \le \left(\frac{2}{1+a}\right)^+ \left(\frac{1}{2e}\right) \quad \text{for } a \ge 0 \qquad (6)$$

where

$$(*)^+ = \max(*,1) \qquad (7)$$

Thus, for $0 \le a \le 1$, the maximum throughput of slotted ALOHA is the same as in (3). For very large a, the maximum throughput of slotted ALOHA is bounded between 1/(3e) and 1/(2e). Note that the lower bound in (6) is at least 1/(4e) for all $a \ge 0$.

The above bounds are shown in Figure 5.

Proof of Theorem 1

Let $V_a(x,y)$ be the space-time area of the vulnerable union associated with a transmission from a station located at $x \in [0,1]$ to a station located at $y \in [0,1]$. The probability of success is

$$P_a(G) = \int_0^1 dx \int_0^1 dy \left\{1 - V_a(x,y)\frac{G}{N}\right\}^{N-1} \qquad (8)$$

By Jensen's Inequality, we have

$$P_a(G) \ge \left\{1 - \frac{G}{N}\int_0^1 dx \int_0^1 dy \; V_a(x,y)\right\}^{N-1} \qquad (9)$$

Let V_a denote the expected value of $V_a(x,y)$ with respect to x and y. Let $V_a{}^p$ and $V_a{}^t$ represent the expected value of the space-time area of the potentially vulnerable region and that of the totally vulnerable region respectively. From the discussion in Section 3, we obtain the following bounds.

$$V_a{}^p \le \frac{1}{2}\left\{ (1+a) \left(\frac{2}{a}\right)^{-} \right\} \tag{10}$$

and

$$V_a{}^t \le \left\{ (1+a) \left(\frac{2}{a}\right)^{-} \right\} \tag{11}$$

Since $V_a \le \min\{(1+a),(V_a{}^p+V_a{}^t)\}$, it follows that

$$V_a \le (1+a)\left(\frac{3}{2}\left(\frac{2}{a}\right)^{-} \right)^{-} = (1+a)\left(\frac{3}{a}\right)^{-} = V_a{}^* \tag{12}$$

The throughput is then lower bounded as follows.

$$S_a(G) \ge G\left\{1 - V_a{}^* \frac{G}{N} \right\}^{N-1} \tag{13}$$

Maximizing with respect to G, we obtain the lower bound on $S_a{}^*$.

The proof for the upper bound is rather simple. For $0 \le a \le 1$, there is no channel reuse, and the maximum throughput of slotted ALOHA is the same as in (3). For $a \ge 1$, $S_a{}^* \le S_1{}^* = 1/(2e)$. The upper bound can also be derived from the space-time area of the totally vulnerable region.

Q.E.D.

4.2 Deterministic Station Configuration

We now consider a bidirectional bus network with a deterministic station configuration. For simplicity, we restrict our discussion primarily to a regular bus network of unit length, where the spatial interval between each pair of adjacent stations is 1/(N-1).

In Lemma 1, we derive an upper bound on the maximum throughput achievable with slotted transmissions. The upper bound is derived by considering only the totally vulnerable regions.

Lemma 1

Suppose that all packets are of the same length. For transmissions which may begin only at discrete points in time, with a regular interval of (1+a) units of packet transmission time, $S_a{}^*$, the maximum throughput is upper bounded as follows.

$$S_a{}^* \le \left(\frac{N}{1+a}\right)^{-} \le 1 \qquad \text{for } a \ge 0 \tag{14}$$

Proof of Lemma 1

For successful synchronous transmissions, no two packets may originate from stations that are less than D/a units of distance apart. Otherwise, there is a totally destructive collision. Let M be the maximum possible number of successful synchronous transmissions on the bus. Then, we have

$$(M-1)\,\frac{D}{a} \le D \qquad \text{for } a \ge 0 \tag{15}$$

It follows that

$$M \le (1+a) \qquad \text{for } a \ge 0 \tag{16}$$

And, we have

$$S_a{}^* \le \frac{M}{1+a} \le 1 \qquad \text{for } a \ge 0 \tag{17}$$

Since there are N stations, and $M \le N$, we obtain the upper bound on $S_a{}^*$.

Q.E.D.

Note that the above upper bound on $S_a{}^*$ is valid for any slotted protocol without carrier sensing, and for any station configuration. A family of the upper bounds on $S_a{}^*$ for various number of stations are shown in Figure 6.

In Lemma 2, we derive a lower bound on the maximum throughput.

Lemma 2

The maximum throughput of slotted ALOHA in a bidirectional bus network with a deterministic station configuration satisfies the following bound.

$$S_a{}^* \ge \left\{ \frac{N}{h_a(N)+1} \right\}\left(\frac{1}{1+a}\right)\frac{1}{e} \qquad \text{for } a \ge 0 \tag{18}$$

where $h_a(N) \le (N-1)$ is the maximum number of stations which can be located within the vulnerable interval-set associated with any given transmission.

Proof of Lemma 2

The probability of success is lower bounded as follows.

$$P_a(G) \ge \left\{1 - (1+a)\frac{G}{N}\right\}^{h_a(N)} \qquad \text{for } a \ge 0 \tag{19}$$

The throughput is then $S_a(G) = G.P_a(G)$. Maximizing $S_a(G)$ with respect to G, we obtain, for $a \ge 0$,

$$S_a{}^* \ge \left(\frac{1}{1+a}\right)\left\{ \frac{N}{h_a(N)+1} \right\} \left\{1 - \frac{1}{h_a(N)+1}\right\}^{h_a(N)} \tag{20}$$

It is easy to verify that

$$\left\{1 - \frac{1}{h_a(N)+1}\right\}^{h_a(N)} \ge \frac{1}{e} \qquad \text{for } h_a(N) \ge 0 \tag{21}$$

Hence, we have

$$S_a{}^* \ge \left\{ \frac{N}{h_a(N)+1} \right\}\left(\frac{1}{1+a}\right)\frac{1}{e} \qquad \text{for } a \ge 0 \tag{22}$$

Q.E.D.

For $0 \le a \le 1$, there is no channel reuse. Hence,

$$h_a(N) = (N-1) \qquad \text{for } 0 \le a \le 1 \tag{23}$$

For $a \geq (N-1)$, no stations are sufficiently close to each other to allow any simultaneous transmissions that are totally destructive. Moreover, there can be at most one station located within the potentially destructive interval of any transmission. Hence,

$$h_a(N) = 1 \qquad \text{for } a \geq (N-1) \qquad (24)$$

An example of such a very high speed bidirectional bus network with N=8 stations is shown in Figure 7.

In general, one can verify that

$$h_a(N) \leq \min\{(N-1), f_a(N)\} \qquad \text{for } a \geq 0 \qquad (25)$$

where

$$f_a(N) = \left(4 \left\lceil \frac{N-1}{a} \right\rceil - 3 \right)^+ \geq 1 \qquad (26)$$

Theorem 2

In a bidirectional regular bus network with N stations, the maximum throughput of slotted ALOHA is bounded as follows.

For $0 \leq a < (N-1)$,

$$w_a(N) \left(\frac{1}{1+a}\right)\frac{1}{e} \leq S_a{*} \leq 1 \qquad (27)$$

where

$$w_a(N) = \left(\frac{N}{h_a(N)+1}\right) \geq 1 \qquad (28)$$

represents the gain of maximum throughput over that of slotted ALOHA without channel reuse. A graph of $w_a(N)/N$ versus $a/(N-1)$ is shown in Figure 8.

For $a \geq (N-1)$,

$$\frac{1}{2}\left(\frac{N}{1+a}\right) \leq S_a{*} \leq \left(\frac{N}{1+a}\right) \leq 1 \qquad (29)$$

Note that the lower bound on $S_a{*}$ for $a \geq (N-1)$ can be as large as 1/2. This is the case when $a = (N-1)$.

Proof of Theorem 2

The upper bounds in both cases follow from Lemma 1.

The lower bound in (27), which is actually valid for all $a \geq 0$, follows from Lemma 2. For $0 \leq a \leq 1$, $w_a(N) = 1$. For $1 \leq a \leq (N-1)$, $w_a(N)$ increases monotonically with a. For $a \geq (N-1)$, $w_a(N) = N/2$. For $a \geq (N-1)$, we prefer the tighter lower bound in (29). This bound is derived by taking into consideration the absence of the potentially destructive regions for some transmissions.

The lower bound for $a \geq (N-1)$ is derived as follows. For large a, many stations fall outside the vulnerable interval-set. In the network of interest, a transmission can result in a destructive collision only if it is overlapped by another transmission at the receiving point in space and time. For each transmission, there are (N-1) potential receiving points. For each transmission, at least half of the potential receiving points are not vulnerable to any collision. Any of the remaining receiving points will suffer a destructive collision only if the one and only one station within the corresponding potentially vulnerable region is also transmitting a packet during the slot. By symmetry, each station is active during a slot with probability $(1+a)G/N$. Thus, the probability of success is

$$P_a(G) \geq \frac{1}{2} + \frac{1}{2}\left\{1 - (1+a)\frac{G}{N}\right\} \qquad \text{for } a \geq (N-1) \qquad (30)$$

It follows that

$$S_a(G) \geq \left\{1 - (1+a)\frac{G}{2N}\right\} G \qquad \text{for } a \geq (N-1) \qquad (31)$$

Maximizing with respect to G, we obtain

$$S_a{*} \geq \frac{1}{2}\left(\frac{N}{1+a}\right) \qquad \text{for } a \geq (N-1) \qquad (32)$$

Q.E.D.

When the stations are not regularly spaced, the maximum throughput for $a \geq (N-1)$ may be even higher because a smaller fraction of the potential receiving points are vulnerable to collisions. In Figure 9, we show a network, in which the fraction of potentially destructive collisions is small. It is obvious from the figure that the maximum throughput for slotted ALOHA in this network is very close to the upper bound in (29). It is natural to wonder, for a given number of stations on the bus, which station configuration offers the maximum throughput. We leave this open question for further research.

5 Conclusion

Channel reuse is part and parcel of many contention-based multiple access protocols. In this paper, we have evaluated the throughput performance of slotted ALOHA in a bidirectional bus network by giving special attention to the protocol's inherent channel reuse characteristics. We have shown that conventional analysis often overestimates the maximum broadcast throughput by neglecting the effect of propagation delay, and underestimates the maximum point-to-point throughput by not considering channel reuse. While the maximum broadcast throughput vanishes with increasing a, the maximum point-to-point throughput degrades rather gracefully with a. For a bidirectional bus network with a probabilistic station configuration, the maximum point-to-point throughput is no less than 1/(4e), regardless of the speed of operation. For a bidirectional bus netwrok with a deterministic station configuration, the maximum point-to-point throughput is underestimated with conventional analysis by at least a factor of $w_a(N) \geq 1$. In addition, if the stations are sparsely located along the bus, the maximum point-to-point throughput may exceed the classic limit of 1/e when $a \geq (N-1)$.

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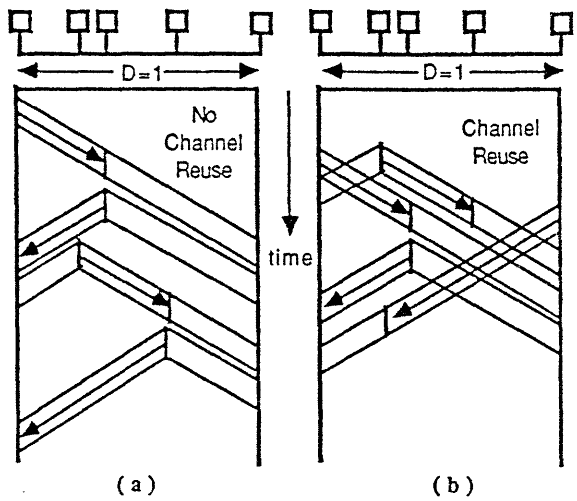
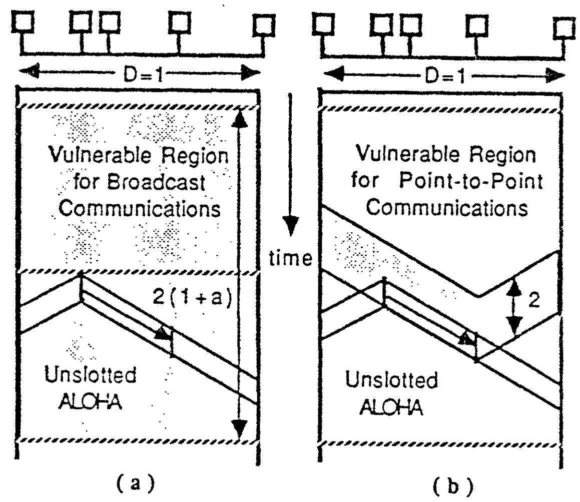


Figure 1



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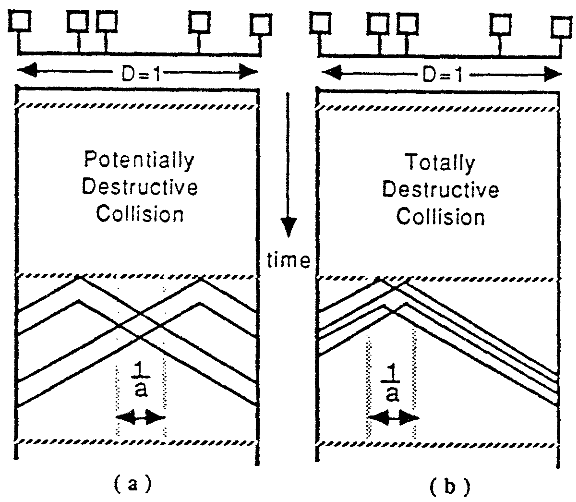

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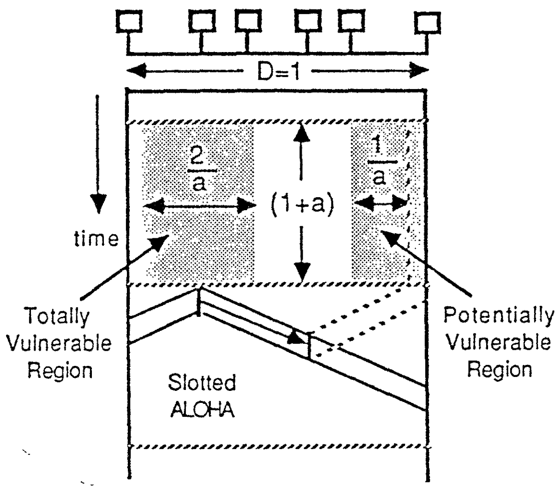

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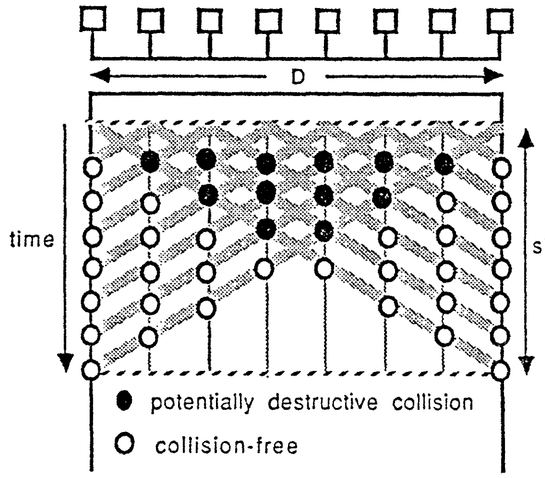

Figure 7

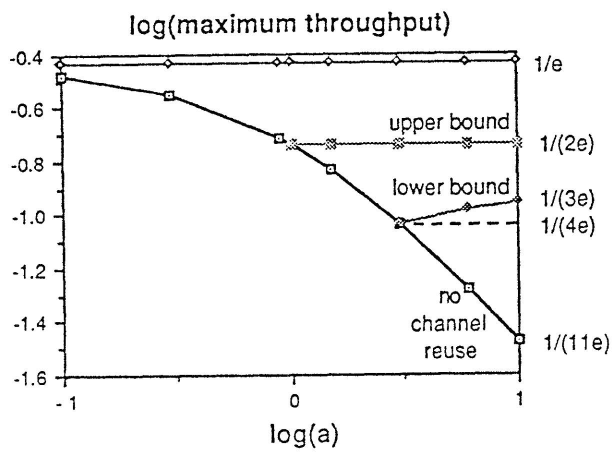

Figure 5

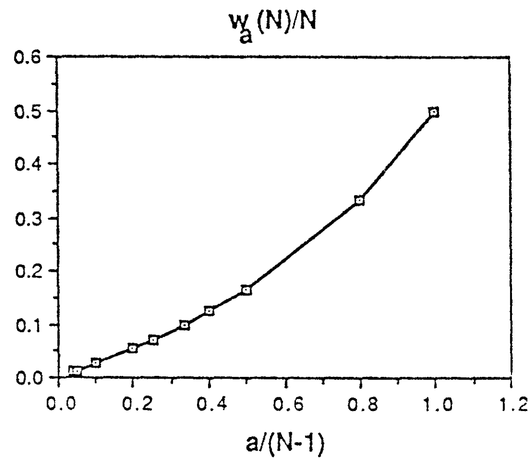

Figure 8

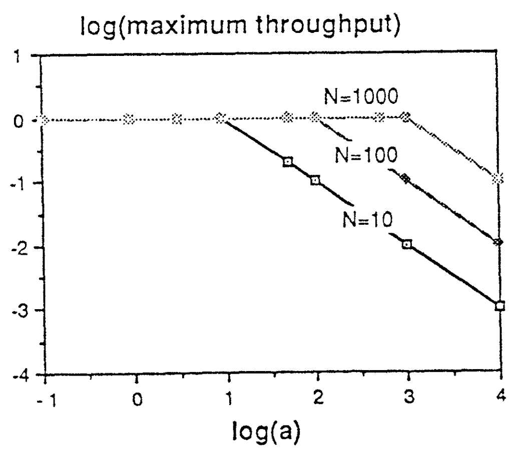

Figure 6

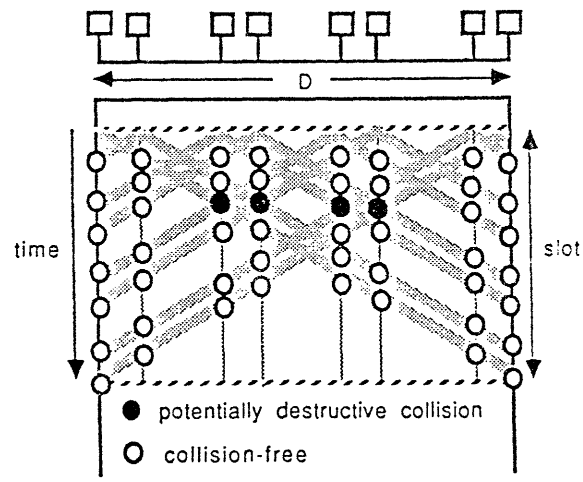

Figure 9