Performance Comparison of CSMA/RI and CSMA/CD with BEB

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***Abstract* - In this paper, we analyze our previously proposed protocol - CSMA/RI, and its closest related protocol - CSMA/CD. Our models include the widely used retransmission algorithm - The Truncated Binary Exponential Backoff (BEB) algorithm. The analysis is performed under two realistic traffic scenarios - the saturation and the disaster scenarios. The performance comparison of CSMA/RI and CSMA/CD is also presented. The analytic results are verified by simulations and are found to be accurate.**

I. INTRODUCTION

Since the appearance of the Ethernet protocol [1] in mid 70s, it has been extensively analyzed. The Ethernet protocol is based on 1-persistent Carrier Sense Multiple Access with Collision Detection (CSMA/CD) [1] with the implementation of the Truncated Binary Exponential Backoff (BEB) [1] retransmission algorithm. Due to the complexity of the protocol, most analyses relied on model simplifications. Many of the analyses focus only either on the access part (CSMA/CD) or the retransmission part (BEB) of the protocol. Moreover, the Poisson arrival process is often used in these studies. Since an accurate model of the entire Ethernet protocol was not developed and validated, and the use of the Poisson traffic for evaluating MAC protocols has been considered inadequate [2], the applications of such analyses have been somewhat limited.

Furthermore, the Ethernet protocol suffers from two drawbacks: (i) it is unstable under certain traffic conditions, and (ii) it does not support multiple services with different QoS requirements. In [3], we have introduced the CSMA/RI (CSMA with Reservations by Interruptions) protocol. We have demonstrated there with extensive simulation experiments that CSMA/RI performs better and is more stable than CSMA/CD. In this paper, we present the analysis of CSMA/RI and CSMA/CD, both using the BEB retransmission algorithm. The performance of these two protocols are analyzed under two realistic scenarios - the saturation and the disaster scenarios.

The saturation scenario represents a continuous overload condition. The results of this scenario indicate a fundamental limit of a protocol – its worst performance for a given number of stations. Whereas, the disaster scenario [4] models the response of a protocol to the recovery (power up) from a major failure. This situation is likely to occur in the local area networks when the shared channel in the network is temporarily inaccessible due to, for example, a broken cable or a long period of noise.

Molle [5] has developed an approximate model to analyze BEB. In this paper, his results are incorporated into the analysis of the CSMA/RI and CSMA/CD protocols. The accuracy of Molle's BEB approximate analysis has been verified in [5]. Here, we verify by simulations the accuracy of our analysis of CSMA/CD and CSMA/RI which uses Molle's results.

The remainder of the paper is organized as follows. In Section II, the CSMA/RI protocol is revisited. In Section III, we present the analysis of CSMA/RI and CSMA/CD. Finally, in Section IV, we verify the analytic results by simulations.

II. CSMA/RI

We consider a worst-case star topology network whereby the propagation delay between any pair of stations in the network is equal to τ. The channel is assumed to be slotted with 2τ being the slot duration [3,6]. The concept of a *ready station* is introduced to refer to a station that has a packet or more for transmission.

According to [3] (or Fig. 1), for both CSMA/RI and CSMA/CD, stations sense an idle channel τ unit of time after the end of a packet transmission. A successful packet transmission is detected τ unit of time after it is started. If a collision is detected, all collided stations stop their transmissions and schedule their retransmissions based on the BEB algorithm. The 1-persistent CSMA version is considered here so that when the channel turns from busy to idle, it may be accessed immediately.

In CSMA/CD, when a successful transmission is detected, all ready stations must wait until the transmission is completed before they can access the channel. During the packet transmission, more stations may become ready, and the same rule applies. As soon as the packet transmission is completed and the channel is sensed idle, all ready stations transmit immediately into the next slot. Thus a collision will occur if the number of the ready stations is greater than one.

On the other hand, in CSMA/RI, apart from all CSMA/CD operations, an RI mechanism is introduced. When a successful transmission is detected, instead of waiting for the transmission to end, all ready stations pick an integer random number, r, between number two and the number of slots of

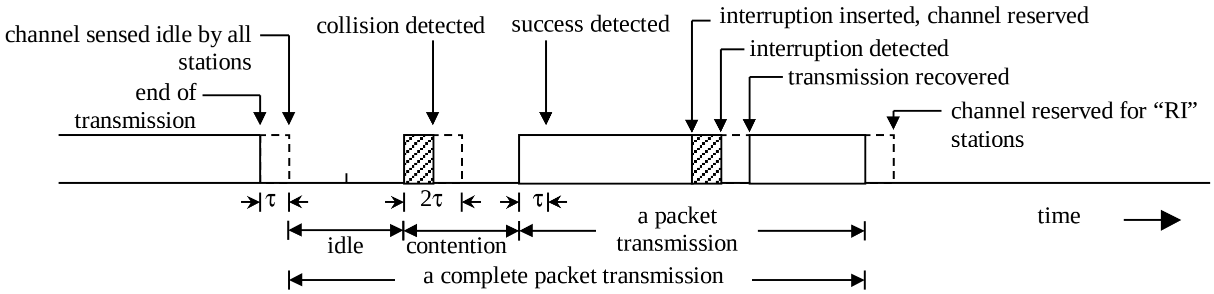

Fig. 1. A snapshot of the broadcast channel of CSMA/RI

the ongoing packet being transmitted, to attempt a reservation (by interruptions). Note that the first slot is used for the detection of the successful transmission, therefore it is non-interruptible. After choosing r, a ready station then interrupts the rth slot of the ongoing packet by sending pseudo-noise for a duration of τ. Since the pseudo-noise only lasts for τ unit of time, it vanishes within the same slot. The sender then resumes the packet transmission from the point where the packet was interrupted. Because of the slotted assumption, the receiver will be able to paste the fragmented packets [3]. Once the first interruption occurs in that packet transmission, all other ready stations detect the interruption and immediately abort their interruption attempts to become *backlogged stations*. The stations that performed the interruptions shall be called *RI stations*.

When the packet transmission is completed and the channel is sensed idle, the channel is reserved to RI stations in the way that only RI stations can transmit, all backlogged stations remain silent until the next successful packet transmission is detected. In this case, a collision will occur if the number of the RI stations is larger than one.

In CSMA/RI, stations which become ready during an ongoing packet transmission may interrupt the ongoing packet transmission when they are ready if no interruption has been carried out by other stations.

With the RI mechanism, ready stations are divided into two groups: the RI stations and the backlogged stations. This division reduces the number of stations participating in the contention. Thus it is expected that CSMA/RI will perform better than CSMA/CD. More details on CSMA/RI can be found in [3].

III. PERFORMANCE ANALYSIS

A. Models, Scenarios and Basic Concepts

We first consider that a network consists of a fixed number of stations, m. Under the saturation scenario, stations are saturated in the sense that after a completion of each packet, the station immediately generate a new packet. In this scenario, we focus on the throughput performance of the network and the average delay experienced by the stations.

Next, we consider the disaster scenario where at a particular time instance, all m stations become ready and transmit their packets at the same time. In this scenario, each station attempts only one packet transmission until all m packets are successfully transmitted. Here, we derive the time required for all m packets to be successfully transmitted. We also derive their average delay in slots.

To model CSMA/RI and CSMA/CD, as described above, we first assume that the channel is slotted, the duration of a slot is 2τ. Time is expressed in slots. Moreover, the packet size, b, is fixed. Since the channel is slotted, we follow the assumption made in [3] where the overhead of recovering an interruption is assumed to be a timeslot.

By following the classical analysis in [7], we observe that the channel is repeating a cycle that consists of: (i) an idle period, (ii) a contention period and (iii) a packet transmission period. All cycles are statistically identical. Let $I(m)$ denote the idle period, $C(m)$ denote the contention period, and $T(m)$ denote the packet transmission period for the case of m stations, and they are expressed in slots. Furthermore, let $T_u(m)$ be the period in the packet transmission that the channel carries useful information, and $T_w(m)$ be the overhead period within the packet transmission. These two periods are exhaustive, that is, $T(m) = T_u(m) + T_w(m)$.

As usual, define the channel throughput, S, to be the fraction of time that useful information is carried on the channel. By definition:

$$S = \frac{E[T_u(m)]}{E[I(m)] + E[C(m)] + E[T_u(m)] + E[T_w(m)]} \qquad (1)$$

where $E[I(m)]$, $E[C(m)]$, $E[T_u(m)]$, and $E[T_w(m)]$ are the expectations of random variables $I(m)$, $C(m)$, $T_u(m)$, and $T_w(m)$ respectively.

B. The Contention Period

The analysis of the BEB retransmission algorithm has been performed in [5] by Molle. Here, we briefly describe the important part of Molle's work, readers are referred to [5] for more details.

To calculate the mean number of slots required for a successful transmission if m stations collide at the particular timeslot, Molle first determines the probability that a particular station accesses the channel at each timeslot after the *Big Bang* of m stations. Under BEB, a station can make

16 transmission attempts of the same packet. A station may attempt its transmission at the nth slot for any of its 16 attempts, where the first slot, n=1, is the slot the Big Bang occurs. Let $P_n(c)$ be the probability that a station accesses the nth slot for its (c+1)th attempt, then the probability, P_n, that a station accesses the nth slots after the Big Bang is:

$$P_n = \sum_{c=0}^{15} P_n(c), \quad n = 1,2,\ldots \tag{2}$$

According to BEB, a station must access the first slot (i.e. n=1) for its first attempt (i.e. c=0). If the attempt is unsuccessful, it will randomly choose a slot from the next $2^{\min(c,10)}$ slots to retransmit the same packet. A station may access the nth slot for its (c+1)th attempt if its cth attempt occurs at one of the slots n-1, n-2, …$2^{\min(c,10)}$. Hence the probability that a station make its (c+1)th attempt at nth slot is:

$$\begin{aligned}
&P_1(0) = 1, P_1(c) = 0 && c > 0 \\
&P_n(0) = P_{n-1}(15) && n > 1 \\
&P_n(c) = \sum_{k=\max(1,n-2^c)}^{n-1} \frac{P_k(c-1)}{2^c} && n > 1, c < 10 \\
&P_n(c) = \sum_{k=\max(1,n-2^{10})}^{n-1} \frac{P_k(c-1)}{2^{10}} && n > 1, c \geq 10 \quad .
\end{aligned} \tag{3}$$

Assuming all stations that participate in the Big Bang are independent, a successful transmission will occur at nth slot only if exactly one out of m stations accesses the channel at nth slot, and no successful transmission is obtained in all the previous n-1 slots. Thus the mean number of slots required for obtaining a successful transmission (including the first successful slot) after the Big Bang of m stations can be accurately approximated by the following formula:

$$\begin{aligned}
L_m &= \sum_{n=1}^{\infty} n\left[\left(mP_n(1-P_n)^{m-1}\right)\cdot \prod_{j=1}^{n-1}\left(1-mP_j(1-P_j)^{m-1}\right)\right] \\
&= \sum_{k=1}^{\infty}\left[\prod_{j=1}^{k-1}\left(1-mP_j(1-P_j)^{m-1}\right)\right].
\end{aligned} \tag{4}$$

By (4), the average contention period (excluding the successful slot) of CSMA/CD is thus:

$$E[C_{CD}(m)] = L_m - 1 . \tag{5}$$

Due to the reservations by interruptions mechanism in CSMA/RI, not all m ready stations participate during the contention period, instead, only RI stations are contending for the channel. Recall that the number of RI stations is the number of stations which make the first interruption during the packet transmission. In slotted channel, for a packet size of b slots, we recognize that the first slot in the packet is not interruptible as it is used for the detection of a successful transmission [3]. Thus, the interruption can only appear between the second slot and the last slot (inclusive) of the ongoing packet, hence the number of RI stations has the following distribution:

$$P_{RI}(x,r) = \begin{cases} \displaystyle\sum_{i=1}^{b-2}\binom{r}{x}\left(\frac{1}{b-1}\right)^x\left(1-\frac{i}{b-1}\right)^{r-x} & ,1 \leq x \leq r-1 \\ \displaystyle\left(\frac{1}{b-1}\right)^{x-1} & ,x = r \end{cases} \tag{6}$$

with $\binom{r}{x} = \frac{r!}{x!(r-x)!}$, the binomial coefficient, x, the number of RI stations, and r, the total number of ready stations attempting reservations. Hence the contention period after a packet transmission of b slots with m ready stations attempting reservations can be computed by conditioning and unconditioning on the number of RI stations:

$$E[C_{RI}(m)] = \sum_{i=1}^{m}\left[(L_i - 1)\cdot P_{RI}(i,m)\right] . \tag{7}$$

C. *The Saturation Scenario*

Under the saturation scenario, after a successful packet transmission by each station, a new packet is immediately generated. Thus, $I(m)$=0. We consider that the sender is unable to interrupt its own packet transmission, so that for m fixed number of stations in the network, only m-1 stations are involved in the reservation process. Thus under the saturation scenario, for CSMA/RI, we obtain:

$$\begin{aligned}
&E[I(m)] = 0 \\
&E[C(m)] = \sum_{i=1}^{m-1}(L_i - 1)P_{RI}(i, m-1) \\
&E[T_u(m)] = b \\
&E[T_w(m)] = \begin{cases} 1+½ & ,m > 1 \\ ½ & ,m = 1 \end{cases}
\end{aligned} \tag{8}$$

where $T_w(m)$ includes the overhead for recovering the interrupted slot (one slot) and the overhead for the detection of the end of the transmission (half slot). Notice that if there is only one station in the network, no interruption will appear, i. e. $E[T_w(m)]$=½. The throughput for CSMA/RI in saturation throughput, S_{SRI}, is obtained by substituting (8) into (1).

For CSMA/CD, $E[I(m)]$ and $E[T_u(m)]$ are the same as for CSMA/RI, but $E[C(m)]$ follows (5), and $E[T_w(m)]$=½ because the recovery of the interruption during packet transmission does not apply here. Hence under the saturation scenario, for CSMA/CD, we get:

$$\begin{aligned}
&E[I(m)] = 0 \\
&E[C(m)] = L_m - 1 \\
&E[T_u(m)] = b \\
&E[T_w(m)] = ½ .
\end{aligned} \tag{9}$$

The throughput for CSMA/CD in the saturation scenario, S_{SCD}, is computed by (1) and (9).

To compute the mean delay experienced by all stations, we first notice that at any time, there are *m* stations waiting for transmission. Furthermore, since each arrival and departure occur at the same time, the arrival rate is equal to the departure rate. Therefore the mean delay can be obtained using Little's formula [8]:

$$\overline{L} = \overline{\lambda} \cdot \overline{W} \tag{10}$$

where

$$\overline{L} = m$$

$$\overline{\lambda} = \frac{1}{E[I(m)] + E[C(m)] + E[T_u(m)] + E[T_w(m)]} .$$

Thus the mean delay of CSMA/RI, D_{SRI}, and CSMA/CD, D_{SCD}, are readily obtainable by (8), (9) and (10).

D. The Disaster Scenario

In the disaster scenario, all stations starts to transmit at the same time and each station transmits only one packet in the entire process. Here we focus on the total time required for all *m* packets to be transmitted successfully. We recognize that this entire process consists of *m* cycles of which the first cycle can be seen as the saturation scenario of *m* stations, the second is that of *m*-1 stations, and so on. Therefore, the duration of the entire process can be expressed by:

$$T_T = \sum_{i=1}^{m} \left(E[I(i)] + E[C(i)] + E[T_u(i)] + E[T_w(i)] \right) . \tag{11}$$

For CSMA/RI, when the disaster scenario begins, all *m* stations transmit together so that the first contention period is the *m*-station Big Bang duration given by (5). However, due to the reservations in CSMA/RI, the duration the following *m*-1 contention periods is given by (7). In addition, since the interruption does not occur in the last packet transmission, and the process ends as soon as the last packet departs the network, the overhead period within the last packet transmission is zero. Thus under the disaster scenario, for CSMA/RI, we yield:

$$\begin{aligned}
&\sum_{i=1}^{m} E[I(i)] = 0 \\
&\sum_{i=1}^{m} E[C(i)] = \sum_{i=1}^{m-1} \left(\sum_{j=1}^{i} (L_j - 1) P_{RI}(j,i) \right) + (L_m - 1) \\
&\sum_{i=1}^{m} E[T_u(i)] = m \cdot b \\
&\sum_{i=1}^{m} E[T_w(i)] = \frac{3}{2} \cdot (m-1) .
\end{aligned} \tag{12}$$

Similarly, under the disaster scenario, for CSMA/CD, we obtain:

$$\begin{aligned}
&\sum_{i=1}^{m} E[I(i)] = 0 \\
&\sum_{i=1}^{m} E[C(i)] = \sum_{i=1}^{m} (L_i - 1) \\
&\sum_{i=1}^{m} E[T_u(i)] = m \cdot b \\
&\sum_{i=1}^{m} E[T_w(i)] = \frac{1}{2} \cdot (m-1) .
\end{aligned} \tag{13}$$

The duration of the disaster scenario of *m* stations in CSMA/RI, T_{TRI}, and CSMA/CD, T_{TCD}, can be obtained by substituting (12) into (11), and (13) into (11) respectively.

We shall now turn our focus on the average delay of the *m* stations in the disaster scenario. The average delay, D_D, can be expressed as follows:

$$D_D = \frac{d_1 + d_2 + d_3 + \cdots + d_m}{m} \tag{14}$$

where d_k is the mean delay experienced by the *k*th station departing from the network. For CSMA/RI, based on (8) and (9), the d_k values are computed by the following recursive equations:

$$\begin{aligned}
d_1 &= (L_m - 1) + (b+1) \\
d_k &= (d_{k-1} + ½) + \left[\sum_{i=1}^{m-k+1} (L_i - 1) P_{RI}(i, m-k+1) \right] + (b+1) \\
&\quad for\ k = 2,3,\ldots,m-1 \\
d_m &= (d_{m-1} + ½) + b .
\end{aligned} \tag{15}$$

Notice that the delay of the first departing station is the sum of the Big Bang duration of *m* stations (L_m-1), the time required for transmitting the packet (*b* slots), and the overhead for recovering the reservation (one slot). The delay experienced by the second departing station is the delay of the first station (i. e. d_1) plus the duration of detecting the end of the first transmission (half slot), the duration of the second contention period (the sum of (L_i-1)P_{RI} (*i*,*m*-*k*+1) for *i*=1 to *m*-*k*+1), packet transmission period (*b* slots), and the overhead of the reservation during the packet transmission (one slot). Also notice that the last contention period in this process is zero, and the last packet transmission does not contain any interruption.

For CSMA/CD, the d_k values are obtained in a similar way to be given by:

$$\begin{aligned}
d_1 &= (L_m - 1) + (b) \\
d_k &= (d_{k-1} + ½) + (L_{m-k+1} - 1) + (b) \\
&\quad for\ k = 2,3,\ldots,m .
\end{aligned} \tag{16}$$

Having obtained (14), (15), and (16), the average delay in CSMA/RI, D_{DRI}, and CSMA/CD, D_{DCD}, can be computed.

IV. SIMULATIONS

In this section, we present the simulation results of the two scenarios and compare them with the above analytic results. As assumed before, the channel is slotted with the duration of each timeslot equals twice of the propagation delay. A fixed packet size is considered. Furthermore, the following parameters are used in the simulation experiments:

TABLE 1
Parameters for simulations

Channel Bit Rate	10Mbit/s (0.1μsec bit time)
Propagation Delay, τ	25μsec (256 bit time)
Slot Time	2τ
Cost of a collision	one slot
Cost of an interruption	one slot
The time required for detecting a transmission end	τ
Station Number, m	1,2,3,…,500
Packet Size, b	(i) 5 slots (320 bytes) (ii) 25 slots (1,600 bytes)

As shown from Fig. 2 to Fig. 9, the analytic (plotted in lines) and simulation results (drawn with symbols) are indistinguishable. Notice that the only approximation used in the analysis is the Molle's equation (4). This approximation is known to be very accurate. This paper further confirms the accuracy of this approximation. The saturation throughput is presented in Fig. 2 and Fig. 3 with different packet sizes. We see that although there is not much benefit gained for using CSMA/RI for short packets when all stations are saturated, the benefit becomes very significant for longer packets. As demonstrated in Fig. 3, the saturation throughput of CSMA/RI for b=25 remains above 75% with as many as 200 saturated stations in the network while CSMA/CD achieves only 28% throughput level. Furthermore, CSMA/RI manages to sustain above 65% throughput level for 500 saturated stations. In contrast, only around 15% achieved by CSMA/CD under the same condition.

The comparison of normalized mean delay for CSMA/RI and CSMA/CD in the saturation scenario is presented in Fig. 4 and Fig. 5 with two different packet sizes. The mean delay in seconds shown (in bracket) in the figures is based on the simulation parameters given in Table 1. As can be seen, stations using CSMA/CD suffer longer packet delay than those using CSMA/RI in both cases: average of 3.5 seconds experienced by 500 saturated stations in CSMA/CD with packet size of 320 bytes, while only 1.3 seconds in CSMA/RI; 4.0 seconds and only around 0.9 seconds of delay experienced by the same number of saturated stations with longer packets (1.6k bytes) in CSMA/CD and CDMA/RI respectively.

Similar results are found in the disaster scenario given in Fig. 6 to Fig. 9. In both cases of packet sizes, CSMA/RI offers shorter mean delay and the duration of the disaster scenario compared to CSMA/CD.

V. CONCLUSIONS

We have analyzed the performance of CSMA/RI and CSMA/CD. Our models include not only the access part of the protocols (CSMA/CD or CSMA/RI), but also the retransmission algorithm (BEB) that is used in the Ethernet protocol. The analysis has been performed under two realistic traffic scenarios (saturation and disaster). We verified that our models are robust, and we again demonstrated that CSMA/RI performs better than CSMA/CD in all cases studied.

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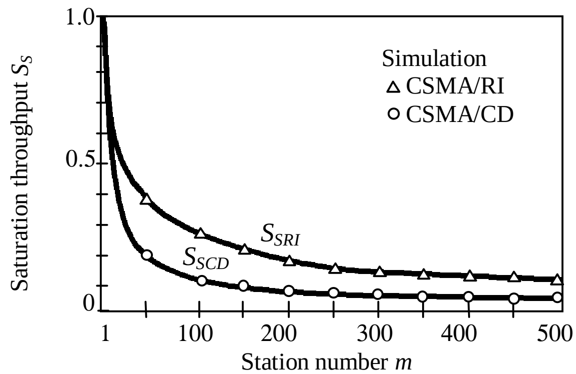

Fig. 2. The saturation throughput for *b*=5

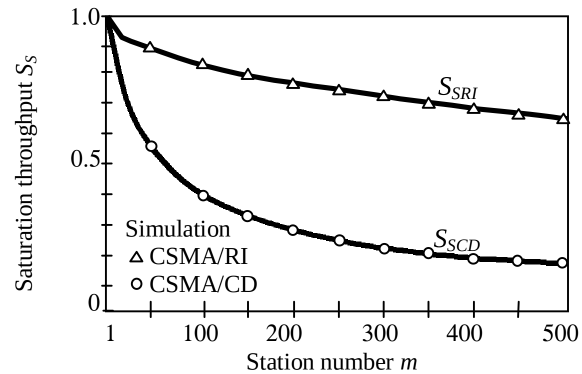

Fig. 3. The saturation throughput for *b*=25

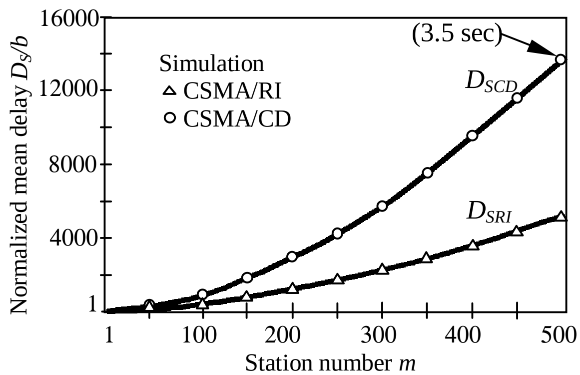

Fig. 4. The normalized mean delay in the saturation scenario for *b*=5

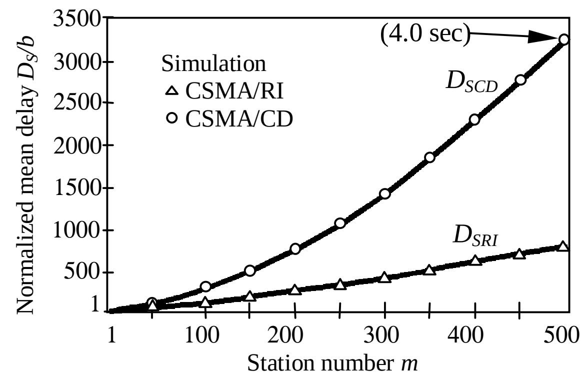

Fig. 5. The normalized mean delay in the saturation scenario for *b*=25

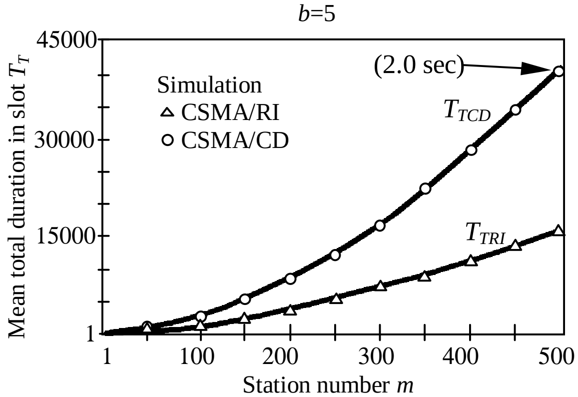

Fig. 6. The total duration in the disaster scenario for *b*=5

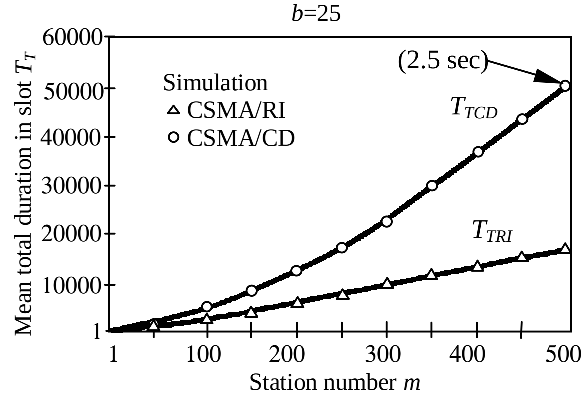

Fig. 7. The total duration in the disaster scenario for *b*=25

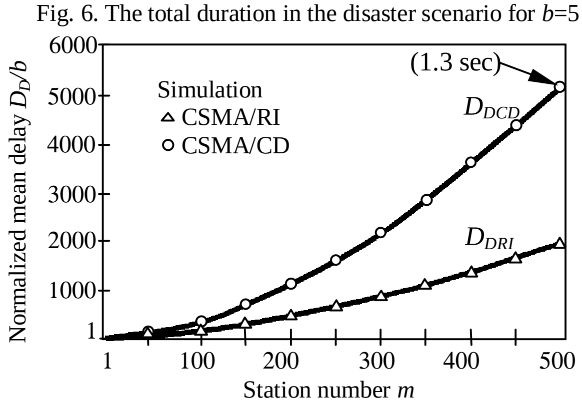

Fig. 8. The normalized mean delay in the disaster scenario for *b*=5

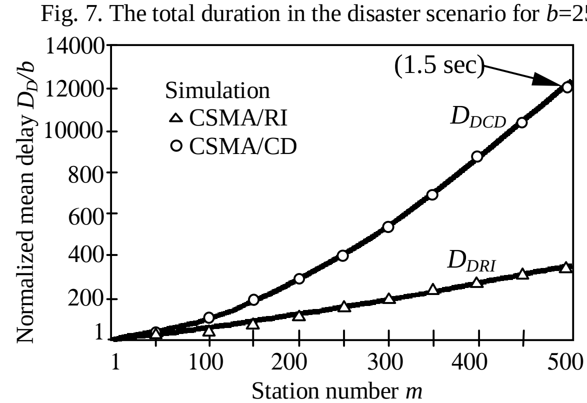

Fig. 9. The normalized mean delay in the disaster scenario for *b*=25