Abstract - Ethernet has been the most important local area network (LAN) technology for low cost and popular deployment. However, its medium access control (MAC) protocol, CSMA/CD, is inefficient and can’t support multiple services with different quality-of-service (QoS) requirements. It severely restricts network carriers to provide new Internet services based on Ethernet networks. An enhancement on CSMA/CD protocol, coined CSMA with Priority Reservations by Interruptions (CSMA/PRI), is proposed in this paper. The proposed protocol uses a hierarchical reservation approach to improve the efficiency of Ethernet networks and guarantee the QoS for different services. In order to meet the increasing need for providing real-time services over Ethernet, our enhancement firstly reserves network resources for real-time traffic and uses different collision resolution algorithms for different types of traffic. The performance of our proposed enhancement is seriously studied under realistic traffic scenarios and is compared with CSMA/CD and CSMA with Reservations by Interruptions (CSMA/RI). The theoretical analyses show that CSMA/PRI offers much shorter delay and higher channel utilization than CSMA/CD and CSMA/RI.

Keywords - Quality of Service (QoS); Medium Access Control (MAC); Ethernet; real-time communication.

I. INTRODUCTION

Due to low cost and global acceptance, Ethernet has widely been deployed and become the most important LAN technology. Because the network using Ethernet can carry variable-length IP packets efficiently and is easy to be managed, Ethernet is recently extended to MANs and WANs [1]. In the first/last mile of communication networks, Ethernet passive optical network (EPON), which uses Ethernet frames to carry all data, has been considered as the most promising solution for next-generation access networks. In [2], a method, which uses CSMA/CD as the upstream multiple access protocol in EPON, was proposed and demonstrated to achieve high upstream channel efficiency. By employing CSMA/CD in EPON, the upstream access control is distributed among all ONUs and the synchronization mechanism between OLT and ONUs is removed. Therefore, the network management operation in EPON is largely simplified and the channel bandwidth occupied by MAC messages is saved. In the current access network, the upstream traffic is much lower than downstream one. Therefore, most of upstream packets can be transmitted without collision at 100Mbps upstream rate [3]. Thus, CSMA/CD is suitable for upstream access control in EPON by considering both transmission collision probability and network operation cost simultaneously.

However, CSMA/CD has some important deficiencies, which negatively impact the new emerging Internet services provided to residential users over Ethernet. These emerging Internet services such as real-time voice/video communications usually have specific QoS requirements. In order to efficiently support the Internet services over Ethernet, its MAC protocol must be enhanced to have better channel utilization efficiency and to provide different QoS guarantees for different types of services [4]. The study, which intends to develop an efficient, reliable and simple MAC protocol for Ethernet, has been an important research topic recently [5-7] and many research efforts have been made [8-12].

In this paper, an enhancement to CSMA/CD, coined CSMA with Priority Reservation by Interruptions (CSMA/PRI), is proposed to improve the efficiency of Ethernet networks and to provide different QoS guarantees for different services. The proposed enhancement categorizes all packets for transmission into a few priority grades and only allows the stations with the highest priority packets to interrupt a success transmission for reserving the bandwidth resources. If more than one station become the reservation station simultaneously, an improved Truncated Binary Exponential Backoff (BEB) policy, which assigns different re-transmission times according to the types of traffic, is used to resolve the collision. In order to improve transmission efficiency under the situation of shorter packets and to smooth the delay jitter of
real-time traffic, a station with real-time packets is permitted to successively transmit several packets when it obtains channel resource. Two network parameters are used to control the amount of packets that the station can send successively.

The rest of the paper is organized as follows. In Section II, the CSMA/PRI is discussed. In Section III, the performance analyses of CSMA/PRI under realistic traffic scenarios are conducted. Finally, conclusions are made.

II. CSMA/PRI

In order to simplify the analyses and explanations of the proposed CSMA/PRI, we consider a slotted system with the fixed-length time interval $T$. Nevertheless, this protocol can also be implemented in a non-slotted system. We denote the propagation delay between any pair of stations in the network is $t$. Therefore, for detecting collisions correctly, the minimum duration of a slot is $2t$. In the paper, we categorize the packets into three grades: grade 0 for the urgency information packets (e.g., signaling information or real-time traffic), grade 1 for guaranteed service packets (e.g., the services only have throughput or fairness requirement) and grade 2 for best-effort packets. Grade 0 is of the highest priority. Let $P$ denote the grade value of a packet. When the station generates a packet, it must tag the packet with the grade value based on the packet transmission requirement.

At first, if the channel is sensed idle, every ready station transmits its packet immediately. After some slots (e.g., a Big Bang interval [13]), a ready station can successfully transmit its packet in the channel. Upon detecting a successful transmission, each ready station will transmit a pseudo-noise for the duration of $t$ in the slot $P+2$. This pseudo-noise is broadcasted to all stations on the network. If a ready station heard a pseudo-noise before performing the first reservation, the station exits the competition and becomes a backlogged station. Otherwise, the station believes that it can make the second reservation. But the stations with the lowest priority packets don’t need to make the priority reservation. If they didn’t hear the pseudo-noise before the slot $P_{low}+2$, where $P_{low}$ is the value of the lowest priority grade, these stations carry out the second reservation operation immediately.

The second reservation operation is carried out immediately after the first reservation finished. Each of stations, which are permitted to carry out the second reservation, waits for a random number of slots to initiate the second reservation procedure. The random waiting number has a discrete uniform distribution based on the size of ongoing packet. During the waiting time, the stations are required to monitor the channel to detect if other stations have made reservations. If no other station has made a reservation before the station’s waiting timer expires, the station performs the reservation by interruption and becomes a reservation station. Otherwise, the station aborts its reservation attempt and becomes a backlogged station. Upon the completion of the ongoing packet transmission, the reservation station transmits its packet into the channel immediately. A backlogged station can become a ready station, if it finds that the channel is idle for at least a slot after a successful transmission.

If more than one station become the reservation station, each of the stations reschedules the retransmission individually to some later time based on an improved BEB policy, in which we assign different re-transmission times according to the type of traffic. In order to meet the different demands of schedule re-transmission, we give shorter re-transmission time to real-time packets and assign longer re-transmission time to non-real-time packets. After the reservation procedure ends, the sender of ongoing packet continues the packet transmission from the point where it was interrupted by the pseudo-noise. By monitoring the channel and recording the length of sending section, without adding any additional information to the packet, the sender can send the residual packet from the point where the transmission was interrupted. By buffering the received part of ongoing packet, the receiver can reassemble the fragmented packets successfully.

When some stations with real-time traffic packets compete for the channel simultaneously, the method of reservation by interruption can reduce the network efficiency due to the short length of these packets. In addition, since some stations select a longer random delay to make reservation, they can’t access the channel in a long time interval. As a result, it increases the delay jitter of real-time traffic. In order to overcome these problems, in the proposed enhancement, a station with real-time packets is permitted to transmit a few consecutive packets without releasing channel resource. The amount of packets that the station can send successively is decided by two factors. One is the maximal packet length permitted by the network. The total length of successive packets must less than the maximal packet length permitted by network. Another is the waiting time of real-time packets in sender buffer. The station with longer waiting time packets is permitted to send more packets. By employing the above approach, the network efficiency, when shorter packets are transmitted, is improved and the delay jitter of real-time traffic is reduced.

In order to avoid the transmission of useless packets, a parameter of lifetime is assigned to every packet in sender buffer by every station. The higher priority packet is assigned the shorter lifetime. Before the packet is sent successfully, if the lifetime timer expires, the station will discard the packet. Based on the rule, the network resource is saved. It can also help the lower priority traffic obtain the channel under peak-loaded situation.

According to our enhancement, only the stations, having higher priority packets, can make the second reservation and become the reservation stations. Then, the number of the stations competing for the second reservation will be decreased sharply, and the likelihood of multiple stations choosing the same waiting time in the second reservation will be very low. Thus, the overhead slots caused by the collision are decreased and the mean channel assignment delay (MCAD) is shortened. Furthermore, by employing our enhancement, the differentiable services for different subscribers can be achieved and the QoS for different services can be guaranteed.
III. PERFORMANCE COMPARISON AND EVALUATION

The performance of CSMA/PRI was evaluated by mathematical analyses under a realistic traffic scenario – the disaster scenario [14]. We compare the CSMA/PRI with CSMA/CD and CSMA/RI in terms of total duration, channel utilization and mean delay performance for real-time traffic. Suppose the number of stations in the network is \( m \) and the slot size of all packets is fixed, \( b \). Let \( L_c(m) \) be the idle period for different grade, \( C_i(m) \) be the contention period for different grade, \( T_{w1}(m) \) be the period that the channel carries useful information for different grade, and \( T_{w2}(m) \) be the overhead period for different grade. Here, \( i \) is the value of different priority grade, which is 0, 1, or 2. \( E[L_i(m)], E[C_i(m)], E[T_w(m)] \) and \( E[T_{w2}(m)] \) are the expectations of random variables \( I_i(m) \), \( C_i(m) \), \( T_{w1}(m) \) and \( T_{w2}(m) \) respectively.

The BEB retransmission policy has been analyzed in [13] by Molle. Based on Molle’s work [13], we derive the formula on the mean backoff slots, \( L_m \), required for obtaining a successful transmission after the Big Bang of \( m \) stations.

\[
L_m = \sum_{i=0}^{m} \left( mP_i(1 - P_i)^{m-1} \right) \prod_{k=1}^{i} (1 - mP_k(1 - P_k)^{m-1})
\]

(1)

where \( P_i \) is the probability that a station accesses the \( n \)th slot after the Big Bang. According to our enhancement, we obtain the distribution of the number of reservation stations in the second reservation operation:

\[
P_{\text{PRI}}(x, r, l) = \begin{cases} 
C_i^x \left( \frac{1}{b^2-2} \right)^x \left( 1 - \frac{i}{b^2-2} \right)^{-x}, & l = 0 \\
\sum_{i=1}^{m} C_i^x \left( \frac{1}{b^3-3} \right)^x \left( 1 - \frac{i}{b^3-3} \right)^{-x}, & l = 1, l = 2
\end{cases}
\]

(2)

with \( C_i^x \), the binomial coefficient; \( x \), the number of reservation stations; \( r \), the total number of ready stations; and \( i \), the value of priority grade for the packet in the ready station. Hence, the mean contention period for different priority grades in CSMA/PRI with \( m \) ready stations attempting reservations can be computed as follows.

\[
E[C_i(m)] = \sum_{i=1}^{m} \left( L_i - 1 \right) P_{\text{PRI}}(i, m, l)
\]

(3)

A. The Total Duration in the Disaster Scenario

In the disaster scenario, we believe that the entire process for \( m \) stations consists of \( m \) cycles. In the cycles, the first cycle can be seen as the case of \( m \) stations competing channel, the second is that of \( m-1 \) stations and so on. Therefore, with our enhancement, the duration of the entire process (\( m \) ready packets are transmitted successfully), \( T_{\text{DPRI}} \), can be expressed as follows.

\[
T_{\text{DPRI}} = \sum_{k=0}^{2} \sum_{i=0}^{m_k} \left[ E[I_i(i)] + E[C_i(i)] + E[T_{w1}(i)] + E[T_{w2}(i)] \right]
\]

(4)

where \( m_k \) \((k=0, 1, 2)\) is the number of ready stations which have the packet of grade \( k \). According to our enhancement, under the disaster scenario, we have:

\[
\begin{align*}
\sum_{k=0}^{2} \sum_{i=0}^{m_k} E[I_i(i)] & = 0 \\
\sum_{k=0}^{2} \sum_{i=0}^{m_k} E[C_i(i)] & = \sum_{k=0}^{2} \sum_{j=0}^{m_k} \sum_{j=1}^{L_i - 1} P_{\text{PRI}}(i, j, k) + (L_{m_k} - 1) \\
\sum_{k=0}^{2} \sum_{i=0}^{m_k} E[T_{w1}(i)] & = \sum_{k=0}^{2} m_k b = mb \\
\sum_{k=0}^{2} \sum_{i=0}^{m_k} E[T_{w2}(i)] & = \sum_{k=0}^{2} \left[ 2.5(m_k - 1) + 1.5(m_k - 1) \right]
\end{align*}
\]

(5)

Thus, the duration of the disaster scenario of \( m \) stations, \( T_{\text{DPRI}} \), can be obtained by substituting (5) into (4). In the following simulation, suppose the slot time is \( 2t \) and the proportion of \( m_0, m_1, m_2 \) is 3:3:4. The comparison of the total duration for CSMA/PRI, CSMA/RI and CSMA/CD in the disaster scenario is presented in Figs. 1 and 2. The stations using CSMA/PRI suffer shorter total duration than those using CSMA/CD or CSMA/RI in both cases. In the short packet case \((b=5)\), especially, the total duration of 500 stations in CSMA/PRI is only 26.6% of that in CSMA/CD and about 75% of that in CSMA/RI. With longer packets \((b=10)\), the total duration experienced by 500 stations in CSMA/PRI is about 23% and 80% of that in CSMA/CD and CSMA/RI respectively.
B. The Channel Utilization

As usual, we define the channel utilization, \( CU \), to be the percentage of the time used for transmitting useful information. Then

\[
CU = \frac{\sum_{k=0}^{m} E[T_u(m)]}{\sum_{k=0}^{m} (E[I_u(m)] + E[C_u(m)] + E[T_w(m)] + E[T_c(m)])}
\]  

Thus, the channel utilization in the disaster scenario of \( m \) stations in our enhancement can be obtained by substituting (5) into (6). In Figs. 3 and 4, the channel utilization of CSMA/PRI is compared with that of CSMA/CD and CSMA/RI for different packet sizes. In both cases, CSMA/PRI always achieves the highest channel utilization among three. In the short packet case, for 500 stations, the channel utilization in CSMA/PRI is 375% of that in CSMA/CD and 130% of that in CSMA/RI. With longer packets, CSMA/PRI sustains above 65% channel utilization level for 500 stations. Under the same condition, the channel utilization in CSMA/CD only achieves 15% and that in CSMA/RI is about 55%.

C. The Real-Time Packet Mean Delay

Under the disaster scenario, according to our enhancement, the mean delay which the \( k \)th real-time packet departs from the network, \( d_k \), can be expressed as follows.

\[
d_k = (L_{m_k} - 1) + (b + 2) + \frac{1}{2^k} \left[ \sum_{i=1}^{m_k/k} (L_i - 1) P_{PRI} (i, m_0 - k + 1, 0) \right] + (b + 2)
\]

\[
k = 2, 3, ..., m_0
\]

Thus, we can obtain the mean delay of real-time packets passing the network, which is the mean value of all \( d_k \). The simulation results are given in Figs. 5 and 6. In both cases, CSMA/PRI offers much shorter mean delay for real-time packets than both CSMA/CD and CSMA/RI can. From Figs. 5 and 6, in CSMA/PRI, the mean delay for real-time packets for 500 stations is only 17.6% and 23.4% of that in CSMA/RI and about 5% of that in CSMA/CD. It shows that our proposed enhancement can provide better service for real-time traffic than both CSMA/CD and CSMA/RI can. Through selecting different priority grade, CSMA/PRI can provide different QoS guarantee for different demanded services.
IV. CONCLUSIONS

We proposed an enhancement to MAC protocol of Ethernet, coined CSMA/PRI. Under the proposed enhancement, ready stations interrupt an ongoing packet transmission twice to reserve the channel resource. The enhancement improves the network transmission efficiency and reduces the mean channel assignment delay by decreasing the number of stations competing for channel resource simultaneously. By reserving hierarchical network resource and using different collision resolution algorithms for different types of traffic, the differentiable services for different subscribers are achieved and the QoS for different services is guaranteed. Theoretical analyses based on realistic traffic scenarios are conducted. It is shown that CSMA/PRI remarkably reduces the mean delay for real-time packets and greatly improves the channel utilization. Moreover, the proposed enhancement provides much shorter total duration under the disaster scenario than both CSMA/CD and CSMA/RI can.

ACKNOWLEDGMENT

This work was supported by the National High Technology Research and Development Program of China (863 Program) under Grant 2002AA122032.

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