The Performance of Optical Networks with TDMA

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ABSTRACT

Due to the traditional realization of distributed-queue dual-bus (DQDB) networks, the optical network with the technique of time-division multiple access (TDMA) has the unfair-access problem. This problem protects users from adopting optical TDMA networks. In order to establish a fair-access medium-sharing environment on optical networks, this paper analyzes the performance of full-load TDMA networks. The performance that is exploited to estimate nodal access indicates the average waiting time of TDMA nodes. After deducing the average waiting time on optical TDMA networks, it is exhibited that the average waiting time of a node is in inverse proportion to nodal traffic regardless of network topology. Based on the deduction, it can be inferred that an optical TDMA network inherently has ideal fair behavior. This property can be manifested if the access protocol of the optical TDMA network performs traffic control. Referring to the property of the waiting time, the optical TDMA network can be considered as a subnetwork of the public. On the other hand, the unfair-access problem of DQDB networks will become solvable. Therefore, DQDB networks should be available in future.

Keywords: Optical communication; Metropolitan area networks; Delay estimation; Time-division multiple access; Traffic control.

1. INTRODUCTION

According to the Hartley-Shannon theorem (the channel /information capacity theorem), media with low noise and wide bandwidth can provide high capacity. Contrasting optical fibers with twisted pairs, optical fibers have very low noise and much wide bandwidth. Therefore, communication networks have been gradually replacing twisted pairs by optical fibers. Because optical fibers support high capacity and good communicative performance, how to promote bandwidth utility and lower constructional cost is an important and interesting topic. It is worthwhile to discuss.

Medium-sharing networks naturally have high bandwidth utility. Their topologies are so simple that low constructional cost will be taken easily. Every variety of medium access control (MAC) protocol, such as carrier sense multiple access (CSMA), carrier sense multiple access with collision detection (CSMA/CD), token ring, token bus, time-division multiple access (TDMA) and so on, is exploited by medium-sharing networks to control access among nodes. The TDMA technique is appropriate for supporting optical-fiber medium-sharing networks. On TDMA networks, there is no collision. Therefore, its bandwidth utility can approximate to its capacity even if networks are with overload. Though protocols with tokens are also adopted to establish medium-sharing environment on optical fibers, their packet delays are larger than that of TDMA systems [1]. However, the TDMA network has an unfair-access problem due to topology [2]. The problem indicates that the access of upstream nodes will be higher than that of downstream nodes in optical TDMA environment. The problem had been fervidly explored [3]~[39] before and after the IEEE 802 committee recommended optical TDMA networks to form the IEEE 802.6 LAN/MAN protocol, which is named distributed-queue dual-bus (DQDB) networks, in 1990 [40]. Many approaches were proposed to improve the unfair problem [5]~[9], [12]~[14], [17]~[20], [23], [28], [29], but it is yet to be resolved. Because users within an optical TDMA network may be independent of one another, the unfair distribution of access among nodes becomes very troublesome for establishing optical medium-sharing environment.

The unfair distribution of access influences the distributed-queue delay of DQDB nodes [3], [4]. In order to understand the characteristics of distributed-queue delays, several approaches were taken to analyze DQDB networks [33]~[39]. All these analyses are based on the model Bisdikian proposed [39]. Bisdikian introduced an approximate single-node analytical model. Due to the model, the steady-state generation function of the number of requests queued ahead of an arriving packet is expressed. Given this number, the distributed-queue delay of an arriving packet can be easily obtained. Analytical results show that the performance of DQDB networks is dependent on nodal positions. In a word, these approaches are in accordance with the detailed operations of the MAC protocol of the network to analyze the distributed-queue delay of every node. Because the MAC protocol of the network is so complex that the modeling and performance analysis of the network is very difficult [11], [16], [20], [24]~[27], [36], [39]. To make an exact analysis on the distributed-queue delay by considering detailed operations of the MAC protocol is almost impossible [20]. Consequently, these analyses cannot make a contribution to solve the unfair-access problem.

From the perspective of TDMA networks, the distributed-queue delay on DQDB networks is the same as the waiting time on TDMA networks [3], [4], [39]. So, both the distributed-queue delay and the waiting time have same properties. If the waiting time depends on network topology, i.e. the average waiting time of TDMA nodes (the waiting mean) is functions of nodal positions, optical TDMA networks would inherently accompany the unfair-access problem. When the exactness of the inherent property could be verified, to completely solve the unfair-access problem should be impossible. Otherwise, this unfair-access problem can be solved after the waiting mean is analyzed. Under this concept, this paper first analyzes the waiting mean to distinguish whether the unfair-access problem can be completely solved or not.

For stable TDMA networks, the carried load must be equal to the offered load whichever the MAC protocol is used. Therefore, the waiting time can be analyzed by observing the use of TDMA slots on media regardless of the operation of MAC protocols. The waiting time of a segment generated by a node associates with the probability that the next available slot appears for the node. This probability is affected by the traffic...
distribution among nodes and the medium capacity of the network. Based on the realization, the waiting mean of TDMA nodes will be completely deduced in this paper.

The deduction shows that the waiting mean is in inverse proportion to nodal traffic as the medium capacity is high. This manifests that nodes with larger traffic will have lower waiting means. Meanwhile, if MAC protocols implement traffic control, waiting means will be irrelevant to both nodal positions and the distance between adjacent nodes. This is completely in accordance with the ideal fair behavior defined by Conti et. al. [24]. In other words, the unfair-access problem will not exist if optical TDMA networks control nodal access by traffic control.

So as to examine the exactness of the deduction, some working conditions for simulating optical TDMA networks are assumed in this paper. Based on these working conditions, an approach performing traffic control is proposed to control access among nodes. The root-mean-square (rms) differences between simultaneous and analytical data are calculated to validate the precision of simulations. On the other hand, in order to take optimal trade-off between precision and efficiency of simulative systems, the method proposed by Chiou [41] is exploited to adaptively choose maximums of random variables generating nodal traffic for each interesting scenario in simulations.

In the next section, the waiting mean of TDMA nodes will be analyzed. The working conditions assumed for simulations and the traffic control approach for controlling medium access among nodes are presented in Sec. 3. Simulations and validations are illustrated in Sec. 4. Conclusions will include in the last section.

2. THE DEDUCTION FOR WAITING MEANS

For TDMA networks, a node must send requests to preserve empty slots when it is going to transmit messages. More requests preserve more slots. As the number of preserved slots of a requesting node becomes large, the waiting mean of the node will be reduced. Therefore, if a node has more traffic, its waiting mean will be decreased. When the waiting mean of TDMA nodes is considered as a criterion for estimating the access owned by nodes, a node will have more access when the node generates more traffic. In other words, TDMA nodes compete with one another for medium access by nodal traffic. The relationship between the waiting mean of TDMA nodes and nodal traffic is derived as follows.

The deduction for the waiting mean of TDMA nodes is based on three operative conditions. The first operative condition assumes that the network is with full load. The next operative condition is that every request preserves one slot. The third operative condition indicates that the number of slots requested by each node is not limited by the access control protocol. Due to the three operative conditions, the access of every slot is competed by all nodes.

For a stable TDMA network, let \( R \) denote the slot rate of the network. The number of nodes within the network is \( N \). Let \( T(n) \) denote the traffic transmitted by the \( n \)th node, where \( n = 0, 1, \ldots, N-1 \). Then \( T(n) \) can be represented as

\[
T(n) = r(n) / R,
\]

(1)

where \( r(n) \) is the number of slots that the \( n \)th node seize to transmit messages for a second.

According to the first operative condition and Eq. (1), the sum of \( T(n) \) can be shown as

\[
\sum_{n=0}^{N} T(n) = 1.
\]

(2)

From the perspective of the \( n \)th node, the slots on media can be classified into three kinds. They are busy slots, preserved slots and free slots. Busy slots are the slots that have been used by upstream nodes. Preserved slots are the slots that have been preserved by downstream nodes. Free slots are the \( n \)th node can exploit. Free slots may or may not be preserved by the \( n \)th node. In a stable network, the probability that free slots pass through the \( n \)th node must be equal to or greater than \( T(n) \). Since the traffic transmitted by the \( n \)th node is \( T(n) \) and the network is with full load, the probability that a slot seized by the \( n \)th node is also \( T(n) \).

For a segment generated by the \( n \)th node, it must enter the top buffer of queues attached to the bus and wait for a free slot. It is assumed that the \( i \)th slot appearing to the \( n \)th node after the segment enters the top buffer is a free slot for the node, where \( i = 1, 2, \ldots, R \). Let \( p(n,i) \) denote the probability that the segment is written into the \( i \)th slot. Then \( p(n,i) \) can be represented as

\[
p(n,i) = T(n) \left[ 1 - T(n) \right]^{i-1}.
\]

(3)

Because the \( n \)th node must seize \( r(n) \) slots per second, the maximum of its waiting times, denoted by \( M(n) \), can be represented as

\[
M(n) = R - r(n) + 1.
\]

(4)

Substituting Eq. (1) for \( r(n) \) into Eq. (4), \( M(n) \) can be rearranged as

\[
M(n) = R \left( 1 - T(n) \right) + 1.
\]

(5)

The waiting mean of the \( n \)th node, denoted by \( \mu(n) \), can be presented as

\[
\mu(n) = \sum_{i=1}^{M(n)} i p(n,i) = \sum_{i=1}^{M(n)} i T(n) \left[ 1 - T(n) \right]^{i-1}
\]

\[
= \left[ 1 - \left( 1 - T(n) \right)^{M(n)} \right] \left[ 1 + M(n) T(n) \right] / T(n).
\]

(6)

Substituting Eq. (5) into Eq. (6), the waiting mean of the \( n \)th node can be rearranged as

\[
\mu(n) = \left( 1 - \left( 1 - T(n) \right)^{M(n)} \right) / \left[ 1 + \left( R \left( 1 - T(n) \right) + 1 \right) T(n) \right] / T(n).
\]

(7)

Eq. (7) shows that the waiting mean of the \( n \)th node only relies on the nodal traffic when the slot rate, \( R \), is fixed. It is irrelevant to both nodal positions and the relative distance between the \( n \)th node and other nodes. It is also not correlated to the MAC protocol supporting the medium-sharing environment.

For high-speed networks, \( R \) can approach infinite. Then, the \( \mu(n) \) of high-speed networks can be shown as

\[
\lim_{R \to \infty} \mu(n) = \lim_{R \to \infty} \left[ 1 - \left( 1 - T(n) \right)^{M(n)} \right] / \left[ 1 + \left( R \left( 1 - T(n) \right) + 1 \right) T(n) \right] / T(n)
\]

\[
= \left[ \frac{1}{T(n)} \right].
\]

(8)

Eq. (8) represents that the waiting mean of TDMA nodes is in inverse proportion to nodal traffic as TDMA networks are with high speed. In a word, for high-speed TDMA networks, the larger the traffic of a node, the smaller the waiting mean of the node. This property obviously exhibits that the waiting mean on a high-speed TDMA network is independent of network topology. In other words, the medium access of a TDMA node varies with its traffic. So, MAC protocols with proper traffic control can effectively and logically distribute medium access among nodes.

Because optical TDMA networks are high-speed networks, the property that nodal waiting means are in inverse proportion to nodal traffic regardless of nodal positions and relative distances between nodes is inherent for the network. The inherent
property can be manifested when the MAC protocol of optical TDMA networks implements traffic control. Consequently, the access on an optical TDMA network can be fairly and logically distributed among nodes if its MAC protocol performs traffic control. Based on the comprehension, the unfair-access problem of DQDB networks will be completely solved because they consist of two independent optical TDMA networks.

3. WORKING CONDITIONS AND TRAFFIC CONTROL

In order for examining the deduction of waiting means on optical TDMA networks, several working conditions of optical TDMA networks are assumed for simulations. Due to these working conditions, a medium access control protocol implementing traffic control is described. Fig. 1 shows the structure of optical TDMA networks.

![Figure 1. The structure of optical TDMA networks.](image)

In the figure, the medium between the slot generator and the slot terminator is an optical fiber. The slot flow on optical fibers is sent by slot generators and sinks into slot terminators. The number of nodes within the network is \( N \). Nodes are numbered from 0 to \((N-1)\). The ordinal number of every node also relates to the nodal position in the topology. The period that the slot generator just completely sends a slot onto optical fibers is called a slot time. A slot length is the distance that a slot spreads on the optical fiber. Other working conditions concerning the space between adjacent nodes, the length of messages and the traffic distribution among nodes are described as follows.

Every pair of adjacent nodes has the same space in an interesting scenario. The space is several times slot lengths. In order to check whether the waiting mean of nodes varies with the space or not, the space in a scenario will be changed but the traffic distribution in the scenario will not be varied. Messages are similar in length for all scenarios. Every message can be contained in the payload of a slot.

The traffic distribution among nodes affects the operation of traffic control. The distribution of traffic must vary with scenarios so as to examine the ideal fair behavior of optical TDMA networks. For the benefit of easily performing traffic control, a basic traffic denoted by \( T_b \) is introduced. The amount of \( T_b \) is dependent on the defined distribution of traffic. In a scenario, the traffic of some node is several times the amount of \( T_b \). In other words, the minimum nodal traffic in a scenario is equal to \( T_b \). Based on the introduction of \( T_b \), traffic control can accomplish easily for various traffic distributions defined on optical TDMA networks.

The MAC protocol performing traffic control is described as below. In this paper, slot frames are used to implement traffic control. The slot flow on optical fibers is partitioned into frames. There are \( 1/T_b \) slots in a frame. When a frame is passed to the \( n^{th} \) node, the node can consecutively write messages into empty slots within the frame. The maximum number of messages that can be consecutively sent out must be less than or equal to \( T(n)/T_b \), where \( T(n) \) is the traffic of the \( n^{th} \) node. The maximum number of messages that can be consecutively sent out has to be loaded into a countdown counter ahead of an arriving frame. As the number of messages in queues is greater than \( T(n)/T_b \), the loaded maximum of the countdown counter will be equal to \( T(n)/T_b \). Otherwise, the loaded maximum of the countdown counter must be equal to the number of messages in queues. Then, the counter will count down when messages are sent out. Until the countdown counter returns to zero, the node must immediately stop writing messages out regardless of whether its queue is empty or not. After the moment, the node waits for the arrival of the next frame to restart the controlling process.

4. SIMULATIONS

The main objective of the simulation is to examine the ideal fair behavior of the optical TDMA network whose MAC protocol implements traffic control. The ideal fair behavior represents that the average waiting mean of a node on the optical TDMA network must not vary with its relative position in the network as its traffic is not changed. The relative position connects with nodal positions and the space among nodes. Therefore, the traffic distribution among nodes and the space between adjacent nodes will vary with interesting scenarios. On the other hand, Eq. (8), presenting the analytical waiting mean of nodes, will be used to validate simulative results. The rms difference between the simulative and analytical data, denoted by \( D_{rms} \), is defined as

\[
D_{rms} = \left( \frac{1}{N-1} \sum_{n=0}^{N-2} (\mu(n) - \mu(n)) \right)^{1/2}
\]

where \( \mu(n) \) and \( \mu(n) \) are the simulative and analytical waiting means of the \( n^{th} \) node respectively.

In figures that show simulative results, the horizontal axis is the ordinal number of nodes. Because the ordinal numbers of nodes are discrete, all curves in figures consist of piecewise lines. The waiting mean of nodes on the vertical axis is expressed in slot times.

In order to comprehend the effect of nodal traffic on both waiting means of nodes and the ideal fair behavior of the optical TDMA network, three traffic patterns are defined for simulations. In the three traffic patterns, the traffic of every node is several times the amount of \( T_b \). Because the optical fiber is a one-way bus and all messages are not transmitted out of the network, the \((N-1)^{th}\) node does not generate any traffic in three traffic patterns.

In the first traffic pattern, let \( T_1(n) \) denote the traffic of the \( n^{th} \) node. The amount of \( T_1(n) \) is defined as

\[
T_1(n) = (N - n - 1)T_b, \quad n = 0, 1, ..., N - 2
\]

In the first traffic pattern, the node with maximum traffic is near the slot generator. The distribution of nodal traffic is gradually reduced when the ordinal number of nodes increases. Based on the definition, the maximum number of slots the \( n^{th} \) node can seize in a frame is \((N-n-1)\), which is equal to \( T_1(n)/T_b \).

Because the network is with full load. Hence,

\[
1 = \sum_{n=0}^{N-2} T_1(n) = \sum_{n=0}^{N-2} (N-n-1)T_b = N(N-1)T_b / 2
\]

According to the traffic pattern, the number of slots in a frame, denoted by \( F_1 \), is

\[
F_1 = 1/T_b = N(N-1)/2
\]
The small $D_{\text{rms}}$ validates the simulative precision and verifies the deductive exactness of waiting means on optical TDMA networks simultaneously.

$$D_{\text{rms}} = \left( \frac{1}{N-1} \sum_{n=0}^{N-2} (\mu_n - \mu) \right)^{1/2} = 0.073485. \quad (13)$$

In the second traffic pattern, the distribution of nodal traffic gradually increases as the ordinal number of nodes becomes large. Let $T_2(n)$ denote the traffic of the $n^{th}$ node. The amount of $T_2(n)$ is defined as

$$T_2(n) = (n+1)T_0, \quad n = 0, 1, ..., N - 2 \quad (14)$$

In the second traffic pattern, the node with minimum traffic is nearby the slot generator. Based on the definition, the maximum number of slots the $n^{th}$ node can seize in a frame is $(n+1)$. The number of slots in a frame, denoted by $F_2$, is also $[N(N-1)]/2$, which is equal to $F_1$.

Fig. 3 shows the waiting mean of nodes on the network with the second traffic pattern.

The solid and dot curves are respectively corresponding to the analytical and simulative data. The $D_{\text{rms}}$ between the analytical and simulative data is 0.047958. Similar to Fig. 2, two curves in Fig. 3 completely overlap each other in the figure. Let $n_1$ and $n_2$ represent the ordinal numbers of nodes in Fig. 2 and Fig. 3 respectively. Comparing Fig. 2 with Fig. 3, it obviously exhibits that the waiting mean of the $n_1^{th}$ node will be equal to that of the $n_2^{th}$ node if $T_2(n_1)$ equals $T_2(n_2)$ regardless of whether $n_1$ is equal to $n_2$ or not. This represents that the waiting mean of every node is only dependent on its own traffic and irrelevant to its position in the network when the optical TDMA network implements traffic control for medium access.

From the two simulations, it can be predicted that all nodes will be similar in the waiting mean if the traffic pattern of the network is uniform distribution. In order to examine the prediction, the third traffic pattern is uniform distribution. Let $T_3(n)$ denote the traffic of the $n^{th}$ node for the third traffic pattern. Then $T_3(n)$ will be equal to $1/(N-1)$ which is the $T_0$ of the third traffic pattern. The number of slots in a frame is $K(N-1)$, where $K$ is an integral constant. The maximum number of slots every node can seize in a frame is $K$. The $K$ chosen in the simulation is 2. Fig. 4 shows the simulative result.

In the following, the effect of the space between adjacent nodes is inspected. In three previous scenarios, the space between adjacent nodes is equal to one slot length. From now on, the space between adjacent nodes is equal to three slot lengths. All working conditions in new scenarios are similar to that in the previous scenarios except the space between adjacent nodes. Fig. 5, 6 and 7 are the simulative results of new scenarios corresponding to three traffic patterns respectively.
5. CONCLUSIONS

In this paper, the waiting mean of nodes on an optical TDMA network is deduced. The deduction exhibits that the waiting mean of a TDMA node is in inverse proportion to the traffic of the node for high-speed networks. This implies that an optical TDMA network is inherent in the ideal fair behavior of networks. This property will be manifested if its MAC protocol performs traffic control. The property can be referred to solve the unfair-access problem on DQDB networks.

On the other hand, an approach performing traffic control is introduced in order for simulating the medium access of optical TDMA networks. Simulative results show that the rms difference between the simulative and analytical data approximates to zero. This verifies the deduction and validates the simulation simultaneously.

Traffic control is an important process for public commercial networks. For commercial behavior, customers pay for required bandwidth. The larger the required bandwidth, the more the payment. Therefore, it is reasonable that a user takes lower waiting mean if his traffic is higher than the other. In public networks, if optical TDMA networks are subnetworks of the public, users within subnetworks can communicate with any customer served by the public. Most of the traffic generated by a user within the subnetwork may be destined for users out of the subnetwork. Therefore, the nodal traffic of subnetworks is independent of the topology of subnetworks. The traffic pattern designed for controlling traffic in subnetworks must be in accordance with the individual requirement of each user.

6. REFERENCES


[40] Distributed Queue Dual Bus (DQDB) Subnetwork of a Metropolitan Area Network (MAN), IEEE STD 802.6 1990.