TDMA FTTH Networks with Bus Topology

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Abstract—The considerable concern about the high constructing and maintaining costs is the bottleneck of rapid and worldwide fiber-to-the-home (FTTH) deployment. However, it is also important to maintain high communicative performance of FTTH networks as suppressing the constructing and maintaining costs. In order to reduce the constructing and maintaining costs of FTTH networks, this paper proposed a bus structure with TDMA to constitute FTTH networks. Because the number of fibers used in the structure and the number of central offices required for the FTTH access network are simultaneously reduced, the constructing and maintaining costs of the bus FTTH network can be greatly suppressed. Based on the analysis of the waiting time on optical TDMA networks, traffic-control approaches are exploited to logically distribute medium access among optical network units (ONUs). Putting traffic-control approaches to use on FTTH networks can result in the ideal fair behaviour of networks. Hence, the FTTH networks can satisfy the commercial contracts agreed by customers and network managers. Otherwise, to implement traffic control on the proposed FTTH network can keep high performance from degradation even if the network is with full load.

Index Terms—Delay estimation, Fibre to the home, Optical fibres, Traffic control, Time-division multiple access.

1 Introduction

According to the strong demand on the quality of service from service providers in recent years, the required bandwidth on access networks is exponentially increasing. Because the provided bandwidth and transmissible distance on traditional access networks are subject to twisted pairs, network managers have being enforced to develop the fibre-to-the-home (FTTH) access network [1], [2], [3], [4], [5]. The deployment of FTTH access networks is taking off in several regions [6], [7], [8], but the considerable concern about the high constructing and maintaining costs is the bottleneck of rapid and world-wide FTTH establishment [9], [10], [11], [12], [13], [14], [15], [16], [17]. Therefore, it is an important topic to explore how to suppress the constructing and maintaining costs but keep the optical communicative performance from degradation.

Public access networks can be considered as bridges between backbone networks and customers. Wider bridges can carry more traffic. The capacity of a union of optical fibres, which comprises upstream and downstream channels, is much larger than that of a twisted pair. The required bandwidth of each customer is so small that the capacity of a union of optical fibres should be shared by lots of customers. Therefore, it is feasible to establish medium-sharing environment on FTTH access networks to suppress constructing cost.

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 protocol is appropriate for supporting optical medium-sharing networks. On TDMA networks, there is no collision. Therefore, the bandwidth utility of TDMA networks can approximate to its medium capacity. Though control protocols with tokens are also adopted to establish the optical medium-sharing environment, their packet delays are larger than that of TDMA systems [18].

To establish medium-sharing environment by TDMA on FTTH networks can suppress constructing cost, but the optical TDMA network has the unfair-access problem due to its topology. From the traditional realization of the distributed-queue dual-bus networks (DQDB), which was recommended as the IEEE 802.6 protocol in 1990 [19], the unfair-access problem indicates that the access of a node is higher than that of its downstream node. Because of the unfair problem, the optical TDMA network can not tally with the ideal fair behaviour of networks. The ideal fair behaviour represents that a node within networks must experience the same performance when its nodal position is moved but its load does not change [20]. Since the access control method of the DQDB is so complex, to resolve the unfair problem is very difficult [20], [21], [22], [23]. It had been laid for more than ten years.

Based on observing the use of TDMA slots on media, the unfair problem has been precisely analysed and resolved [24], [25], [26]. The analysed performance is the average waiting time (waiting mean) of the segment in the top buffer of nodal queues which attached to the optical TDMA network. The access of TDMA nodes can be estimated by the waiting mean. The analysis exhibits that the waiting mean of high-speed TDMA nodes is in inverse proportion to nodal traffic regardless of network topology. Based on this property, it is inferred that optical TDMA networks are inherent in the ideal fair behaviour of networks if their medium access control protocols perform traffic control. The analysis urges optical TDMA networks to become a suitable option for constructing FTTH networks.

In order to explain the feasibility of adopting optical TDMA networks to constitute FTTH networks, the analysis of waiting means is summarized in the next section. The analysis obviously shows the influence of traffic control on the performance of optical TDMA networks. The

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related work for FTTH construction is described in Sec. 3. Various topologies of FTTH networks are compared with one another from the perspective of constructing and maintaining costs. The proposed bus FTTH network is presented in Sec. 4. The structure, normal operations and out-of-order events which cause the stoppage of the proposed network are discussed. The last section is conclusions.

2 The Analysis of 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 node becomes large, the waiting mean of the node will be reduced. 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. The relationship between the nodal waiting mean and nodal traffic is summarized as the following.

In the analysis, it is assumed that the access of every slot is competed by all nodes and the network is with full load. The slot rate of the network is R slots per second. The number of nodes within the network is N. Let T(n) denote the traffic transmitted by the nth node, where n is the ordinal number of nodes, n = 0, 1, …, N–1. Then T(n) can be represented as

$$T(n) = r(n) / R, \tag{1}$$

where r(n) is the number of slots that the nth node seizes to transmit messages for a second.

From the perspective of the nth 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 that the nth node can exploit. Free slots may or may not be preserved by the nth node. In a stable network, the probability that free slots pass through the nth node must be equal to or greater than T(n). Since the traffic transmitted by the nth node is T(n), the probability that a slot seized by the nth node is also T(n).

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

$$p_W(n,i) = T(n)\left(1-T(n)\right)^{i-1}. \tag{2}$$

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

$$M(n) = R - r(n) + 1. \tag{3}$$

Substituting (1) for r(n) into (3), M(n) can be rearranged as

$$M(n) = R\left(1-T(n)\right)+1. \tag{4}$$

Then, the waiting mean of the nth node, denoted by μ(n), can be presented as

$$\begin{aligned}\mu(n) &= \sum_{i=1}^{M(n)} i p_W(n,i) = \sum_{i=1}^{M(n)} iT(n)\left(1-T(n)\right)^{i-1} \\ &= \left[1-\left(1-T(n)\right)^{M(n)}\left(1+M(n)T(n)\right)\right]\Big/T(n).\end{aligned} \tag{5}$$

Substituting (4) into (5), the waiting mean of the nth node can be rearranged as

$$\mu(n) = \left[1-\left(1-T(n)\right)^{R(1-T(n))+1}\left(1+\left(R\left(1-T(n)\right)+1\right)T(n)\right)\right]\Big/T(n) \tag{6}$$

Equation (6) shows that the waiting mean of the nth node is only reliant on the nodal traffic when the slot rate is fixed. It is irrelevant to nodal positions. It is also not correlative to the MAC protocol supporting the medium-sharing environment.

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

$$\begin{aligned}\lim_{R\to\infty}\mu(n) &= \lim_{R\to\infty}\left\{\left[\begin{array}{l}1-\left(1-T(n)\right)^{R(1-T(n))+1} \\ \left(1+\left(R\left(1-T(n)\right)+1\right)T(n)\right)\end{array}\right]\Big/T(n)\right\} \\ &= 1/T(n).\end{aligned} \tag{7}$$

Equation (7) 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 waiting means are in inverse proportion to nodal traffic regardless of nodal positions is inherent for the networks. The inherent property can be manifested when the MAC protocol of the 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. The simulation perfectly validating the analysis was exhibited in [24].

Due to the analysis, it is manifests that adopting optical TDMA networks with traffic control to construct FTTH networks is feasible. The constructed FTTH network can naturally reduce cost. Otherwise, customers' performance not only will not vary with nodal position but also can be kept from degradation even if FTTH networks are with full load.

3 The Related Work For FTTH Construction

For the sake of establishing medium-sharing environment to construct FTTH networks, several multi-access structures have been proposed for constituting FTTH access networks [27], [28], [29], [30], [31], [32], [33]. Due to the number of optical network units (ONUs) sharing the capacity of a union of optical fibres, these multi-access structures can be classified into two categories. In the first category, every union of fibres is connected with one ONU [27], [28], [29], [30], [31], [32]. In the second category, more than one ONU are attached to a union of fibres [33]. The topology of the network proposed by [33] forms a ring. The ends of the ring terminate at the optical line terminal (OLT) located in central offices (COs). An OLT consists of two slot transmitters and two slot receivers. One couple of the transmitter and receiver is for the upstream flow and the other is for the downstream flow. The directions of the two flows differ from each other. On the other hand, there are two topologies in the first category. One of the topologies is trees [27], [28], [29], [30], [32] and the other is stars [27], [28], [31]. In stars, a CO is the centre of the star and fibres are radiantly distributed from the centre to ONUs. For trees, COs are the roots of trees and splitters/passive-fibre branching points are sub-centres. Fibres are fanned out/branched off from a sub-centre to ONUs. Otherwise, an optical link between the OLT and a sub-centre can be regarded as a trunk comprising upstream and downstream channels. The trunk carries downstream messages sent by the OLT and concentrates upstream messages transmitted by ONUs.

Due to the low bandwidth utilization on optical fibres, to construct the FTTH network of the first category requires a large number of fibres. Because the number of fibres is so large, to establish the FTTH networks of the first category must pay high constructing cost for fibres. On the ring FTTH network, its bandwidth utilization is higher than that of star/tree FTTH networks. Hence, the number of fibres used to establish ring FTTH networks will much smaller than that used to construct star/tree FTTH networks. So, the constructing cost paid for fibres establishing ring FTTH networks will be much smaller than that paid for fibres constructing tree/star FTTH networks. However, the distance between a CO and the farthest ONU in ring FTTH networks will be much shorter than that in tree/star FTTH networks. This effect will increase the number of COs. The longer the distance between a CO and the farthest ONU, the smaller the number of COs. The constructing cost for setting up COs will be reduced as the number of COs becomes small. Hence, to compare the star/tree with the ring from the perspective of constructing cost, the decreased constructing cost resulting from the reduction of fibres in the ring topology makes up for the increased constructing cost paid for establishing the addition of COs. And the decreased constructing cost resulting from the reduction of COs in star/tree topologies makes up for the increased constructing cost paid for the enlargement of the number of fibres. On the other hand, the maintaining cost of FTTH networks is also dependent on the number of fibres. A large number of fibres in an optical network will not only complicate the distribution of fibres but also enhance the difficulty in the management and maintenance of these fibres. This will increase the maintaining cost of FTTH networks. Consequently, to simultaneously reduce the number of fibres and the number of COs can lower not only the constructing cost but also the maintaining cost of FTTH networks.

In the FTTH medium-sharing environment, most FTTH networks exploit the techniques of time-division multiplexing/time-division multiple access (TDM/TDMA) on downstream/upstream channels [29], [31], [32], [33]. Except the control and maintaining messages, most traffic on the downstream channel should be the response of services actuated by customers. The TDM approach can fairly transmit respondent messages to ONUs, but the approach can not efficiently exploit the capacity of the channel. Otherwise, the respondent traffic of a customer varies with the service actuated by the customer, but the bandwidth distributed by the TDM approach can not flexibly vary with services. Hence, applying the TDM approach on the downstream channel can not tally with the commercial behaviour on public access networks. For the upstream channel, the senders using the channel are all the ONUs attached to the OLT. According to the requests sent by the equipments attached to an ONU, TDMA systems provide the requested bandwidth to the ONU [29], [34], [35]. When some ONUs are activated as the upstream channel is in heavy-load duration, these ONUs can not immediately take the requested bandwidth and must wait for a period. Increasing the number of ONUs will extend the heavy-load duration. The period waiting for the requested bandwidth will be lengthened according to the extension of the heavy-load duration. On the other hand, in a communicative system, some control procedure such as the usage parameter control (UPC) [36], which performs control functions i.e. connection admission control, resource management, priority control etc., is invoked to prevent unpromised traffic from entering the backbone network to take limited resources. The control procedure will reject partial traffic of an ONU when the transmitted traffic of the ONU has exceeded the maximum traffic promised by the commercial contract. This will result in the retransmission of the rejected traffic between the ONUs and the backbone network. Cyclic retransmission will ineffectively occupy the bandwidth of upstream channels. This ineffective occupation will not only lower the throughput of ONUs but also extend the heavy-load duration. The phenomenon will lengthen the waiting time of messages queuing in ONUs. In order to suppress the constructing and maintaining costs, the number of ONUs attached to an OLT must be enlarged. The heavy-load duration will usually appear and be extended as the number of ONUs is increased. Therefore, the performance of FTTH networks will be greatly degraded when the constructing and maintaining costs are reduced.

Traffic control is an important process for public commercial networks. For commercial behaviour, customers pay for required bandwidth. The more the required bandwidth, the more the payment. If the traffic of an ONU can be controlled in accordance with the commercial contract signed by customers and network managers, the retransmission caused by a control procedure, such as the UPC, will disappear. Therefore, the capacity of a TDMA channel can be fully and logically allotted among nodes. Otherwise, when the access of a TDMA channel is distributed among nodes by traffic control, the network can keep its performance from degradation even if the network is with full load. Therefore, traffic control should be adopted on FTTH networks to increase the number of ONUs so as to effectively suppress the constructing and maintaining costs but keep the high communicative performance of the networks from degradation.

Based on the discussion above, this paper proposes a structure for constituting FTTH networks. The proposed topology is a bus structure which consists of a pair of fibres. The TDMA technique establishes medium-sharing environment on the fibres. The capacities of both fibres are shared by the OLT and the attached ONUs respectively. The medium access control protocol of the OLT and ONUs performs traffic control to distribute access among ONUs. Because the FTTH network is with bus topology, the distance between a CO and the farthest ONU will be much larger than the ring FTTH network. The number of fibres used to construct bus FTTH networks can be much smaller than that used to construct star/tree FTTH networks due to high utilization on bandwidth. Simultaneously, the number of COs established for bus FTTH networks can also be smaller than that established for ring FTTH networks due to the great distance between a CO and its farthest ONU. Therefore, the constructing and maintaining costs will be naturally suppressed. Because of the usage of traffic control for medium access, the proposed FTTH network can not only fully and logically distribute bandwidth among ONUs but also maintain high communicative performance even if the network is with full load.

4 TDMA FTTH NETWORKS WITH BUS TOPOLOGY

Due to the analysis of the waiting time on TDMA networks, it is manifested that traffic control can result in ideal fair behaviour on optical TDMA networks regardless of the topology of the network. Because the capacity of a union of fibres is much larger than that a customer requests, it is feasible to establish a medium-sharing environment on FTTH networks. In order to increase the number of customers on a FTTH network to reduce constructing and maintaining costs, this paper proposes the bus topology with TDMA technique to establish medium-sharing environment on FTTH networks. The structure of the proposed FTTH network is shown in Fig. 1.

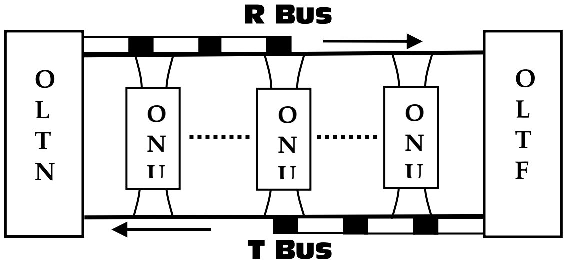

Fig. 1. The structure of bus FTTH networks

A pair of fibres is exploited in the structure. One is used as a transmitting bus (T Bus). The other is regarded as a receiving bus (R Bus). OLTs in the structure are partitioned into two parts. The first part located inside or near COs is called OLTN (the OLT part near COs). The second part terminating fibres in the outside plant and far from COs is named OLTF (the OLT part far from COs).

Both the OLTN and OLTF comprise one slot generator and one slot terminator. The TDMA slot flow on the T Bus is sent by the slot generator in the OLTF and sinks into the slot terminator in the OLTN. On the other hand, the TDMA slot flow on the R Bus is sent by the slot generator in the OLTN and sinks into the slot terminator in the OLTF. The OLTN transfers segments between the FTTH and backbone networks. The T Bus is an upstream channel and the R Bus is a downstream channel. The segments carried by slots on the T Bus are destined for customers supported by backbone networks. The segments in the slots on the R Bus are received by the ONUs attached to the FTTH network.

All the ONUs attached to a FTTH network are interfaces between the FTTH network and customer's private networks. The private network comprises various customer premise equipments (CPEs). Various CPEs and their interfaces may be connected with ONUs directly or through wireless networks, coaxial networks, various local area networks and so on. The medium access control protocol of every ONU must perform traffic control as sending segments onto the T Bus. The maximum traffic that an ONU can send is subject to the commercial contract signed by network managers and customers. The promissory maximum traffic can be regarded as a parameter for traffic control. The parameter should be dynamically varied with the maximum traffic changed in the commercial contract.

So as to transmit segments to ONUs in the outside plant, there are queues within the OLTN. Every queue corresponds to an ONU. The corresponding queue of an ONU temporarily stores segments which will be destined for the ONU. Though the OLTN is the unique equipment sending segments to ONUs, the corresponding queues within the OLTN are the actual devices sharing the capacity of the R Bus. Hence, the TDMA slots on the R Bus are competed by these queues. In order to fairly and logically distribute access among these queues, the MAC of the OLTN executing traffic control must starts when a queue is going to write segments onto slots. The maximum traffic that a queue can transmit to its corresponding ONU depends on the commercial contract between the network manager and the customer. Because the TDMA technique is exploited on the R Bus, the FTTH network can flexibly and fairly satisfy customers' dynamic demand on bandwidth to enhance the bandwidth efficiency of the R Bus.

According to bus topology, the distance between a central office and the farthest ONU will be much longer than that in ring FTTH networks. The serviced area of the CO with bus FTTH networks will be much greater than that of the CO with ring FTTH networks. Hence, not only the number of COs but also the number of fibres can be greatly reduced. Consequently, the constructing and maintaining costs will be significantly suppressed. Due to performing traffic control on medium access, the access of the T and R Buses can be logically distributed among ONUs and their corresponding OLTN queues respectively. Otherwise, the FTTH network can present high performance even if the network is with full load.

After describing the normal operations, out-of-order events affecting the entire operations of bus FTTH networks are discussed as follows. Because the normal operations of the FTTH network are dependent on the slot flows on the T and R Buses, the disappearance of the two slot flows will stop all operations on the network. Two out-of-order events will result in the stoppage that all ONUs can not communicate. One of them is the disconnection of two fibres. The other event results from an out-of-order OLTF/OLTN. Wherever either fibre is disconnected, the stoppage of the network will take place. An out-of-order OLTF/OLTN influences the presentation of slot flows. The troubles of an out-of-order OLTF/OLTN may be the functional failure of slot generators and/or slot terminators. It also may be caused by the loss of public power and/or damaged rechargeable batteries. In order to protect the network from the stoppage, it must be concretely performed in practice to automatically and periodically examine the disconnection of fibres [37], [38], [39], [40], the function of OLTFs/OLTNs and their power systems.

5 CONCLUSION

In order to speed up the world-wide deployment of FTTH networks, this paper proposes a bus structure with the TDMA technique to constitute FTTH access networks. The proposal is based on the analysis of waiting time on TDMA networks. The analytical result shows that the nodal waiting mean of optical TDMA networks is in inverse proportion to nodal traffic regardless of the topology of networks. Hence, controlling traffic on FTTH networks can logically distribute the access among ONUs according to the commercial contract and keep the communicative performance of the FTTH network from degradation.

The bus structure is recommended in an attempt to reduce the constructing and maintaining costs of FTTH networks. A pair of fibres is exploited in the structure. The directions of slot flows on the two fibres are different from each other. One of the slot flows is a TDMA upstream channel that concentrates segments from ONUs and transmits them to backbone networks. The other is a TDMA downstream channel which receives data from backbone networks and distributes them to ONUs. OLTs in the structure are partitioned into two parts. They are the OLTN and the OLTF. The OLTN is located in/near the CO and the OLTF is in the outside plant. All ONUs are attached to the buses to share their capacities.

Comparing with ring structure, the distance between the OLTN and the farthest ONU can be lengthened to extend the serviced area of COs because the OLTF is in the outside plant. Comparing with the tree/star structure, the bandwidth utilization of the proposed bus TDMA FTTH network will be much higher than that of the tree/star FTTH network. Otherwise, the number of ONUs attached to buses can be increased due to the usage of traffic control. These effects can reduce both the numbers of optical fibres and COs simultaneously. Consequently, the constructing and maintaining costs will be naturally lowered.

Since the out-of-order events of the OLTF/OLTN and fibres will result in the stoppage of bus FTTH networks, automatic and periodic examinations for discovering the disconnection of fibres, the damage of the OLTF/OLTN and their power system are very important for the stability of the network. How to monitor the FTTH network to warn network operators against the out-of-order events so as to prevent the network from stoppage in advance or quickly restore to normal operations after the stoppage takes place is the future work after proposing the network.

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