WDM Dynamic Bandwidth Allocation Schemes for Ethernet PONs

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Abstract. WDM based dynamic bandwidth allocation schemes are proposed as potential future-proof upgrade solutions for access PON systems. The schemes represent cost-efficient ways to exploit the virtually unlimited bandwidth afforded by passive optical architectures whilst remaining fully compatible with the IEEE Ethernet standard for the first mile (EFM 802.3ah).

Keywords: Ethernet, passive optical network (PON), wavelength division multiplexing, MPCP, MAC, polling, dynamic bandwidth allocation.

1 Introduction

Network operators are facing significant challenges in trying to satisfy the growing customer demand for new broadband services. Due to the economics, large scale deployment of optical technologies has not occurred yet in the access layer. However recent evidence indicates that point-to-multipoint passive optical network (PON) architectures implemented using only passive components along the optical transmission paths, are considered a viable solution for the most cost-sensitive network segment.

The deployment of PON can take various forms, such as fibre-to-the-home (FTTH), fibre-to-the-building (FTTB), or fibre-to-the-kerb (FTTK). Regardless of these various physical implementations, the fundamental operating principles for all the above systems are consistent. An optical line terminal (OLT) is located at the local central office, and optical network units (ONU) are either placed at the customer's premise, building, or kerb side depending on the degree of fibre penetration. The PON architectures utilise one wavelength channel each for upstream and downstream directions, and the medium access controls (MAC) are based on polling mechanisms or cyclic rotation. The MACs described in [1-6] arbitrate the access from ONUs to ensure that no collisions occur in the fibre trunk.

However both polling and cyclic rotation based MACs have an inherent problem in which the cycle time (or polling cycle) increases linearly as the number of attached

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ONUs are scaled up as shown in [7] and [8]. The longer cycle time (or polling cycle) means that an ONU will have to wait longer before the next transmission window to arrive thus contributing to an increased delay and poor QoS.

In this paper, two new wavelength division multiplexing (WDM) based dynamic bandwidth allocation schemes are proposed where a number of wavelength channels are established for communicating in both upstream and downstream directions. The WDM MACs are capable of supporting a large number of ONUs (64 or more) where bandwidth is dynamically allocated according to the load of individual ONUs.

2 WDM PON

One of the solutions that can be easily adopted in PONs to overcome increasing demand is to apply WDM techniques where the connection bandwidth can be multiplied by establishing new transmission channels at other wavelengths. This approach requires new terminal devices at both ends of the system to support simultaneous wavelength transmissions. Nevertheless the cost for this upgrade plan is still comparatively small compared to the cost required to lay new fibres [9,10].

Fig. 1 illustrates a WDM PON system where two upstream and two downstream wavelengths are employed. Each wavelength is operating at a line rate of 1Gbit/s; therefore a total bandwidth of 2Gbit/s is available for each direction. In the downstream direction, different services can utilise any of the downstream channels for transmission, the signal being fanned out to every ONU by the optical splitter. In the upstream direction, the ONU is scheduled to transmit packets by the OLT. Signals from ONUs are merged into a shared section of fibre via a combiner. To ensure that no collision or overlapping of signals from different ONUs occurs in the upstream channels, a WDM medium access control is required.

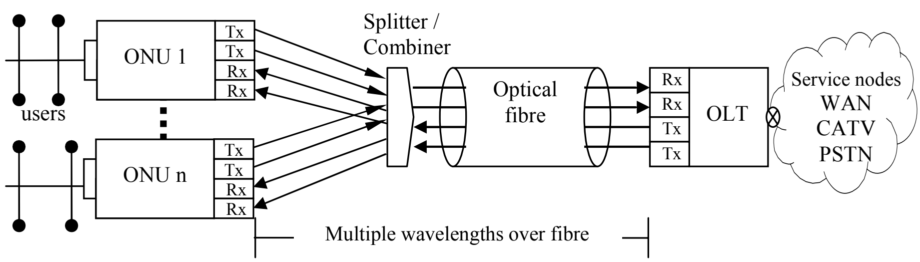


Fig. 1. WDM PON system

3 Control Message

IEEE 802.3ah EFM has defined two control messages - GATE and REPORT - to be used with the multi-point control protocol (MPCP) operation of Ethernet PONs [11]. The GATE message is used by the OLT to inform ONUs of transmissions, and the REPORT message is released by ONUs at the end of each transmission to notify the

OLT about its queue status which is then used as an input by the OLT for bandwidth allocation purposes.

To achieve collision-free transmission on all upstream channels, the GATE message has to be delivered to the ONU in advance so that the recipient ONU can start its transmission precisely at the time stated in the message. Thus the first bit of the ONU transmission arrives at the OLT just after the last bit of the previous ONU transmission (plus a guard time).

The GATE message is scheduled according to:

$$G[x]^{[i+1]} \le T[x]^{[i]} + \frac{r^{[i]}}{2} + \frac{W[x]^{[i]}}{R_u} + B - r^{[i+1]} . \tag{1}$$

where,

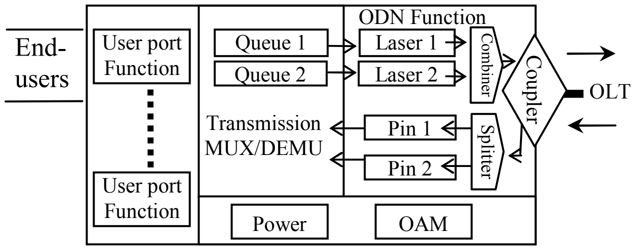
$G[x]^{[i+1]}$	– Time when the next GATE message to i+1th ONU is transmitted on any of the downstream channel;
$T[x]^{[i]}$	– Time when the ith ONU start its transmission on upstream channel x;
$r^{[i]}$	– Round-trip time for the ith ONU;
$W[x]^{[i]}$	– Transmission windows size for ith ONU (including transmission of REPORT message) on channel x;
R_u	– Transmission speed (bit rate);
B	– Guard time (in μs);

Equation (1) defines when a GATE message should be delivered to schedule the next ONU for transmission. In general, the OLT should transmit the GATE message for i+1th ONU at time $G[x]^{[i+1]}$ or before but not later. This guarantees that all upstream channels avoid collision and only a minimum guard time exists between ONUs transmissions thus achieving high throughput.

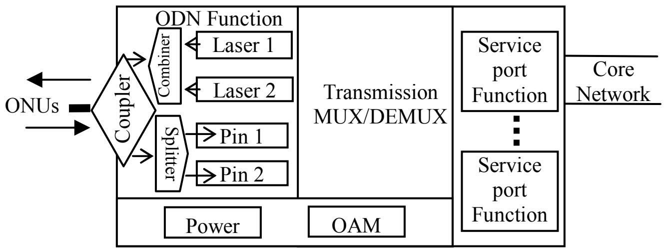
4 WDM IPACT

The first WDM MAC proposed is referred to as WDM IPACT, a direct extension from the single channel IPACT scheme (i.e. single wavelength) described in [1-3]. Fig. 2(a) and Fig. 2(b) illustrates the ONU and OLT modules respectively of a 2-channel WDM IPACT in which two wavelength channels are established in both upstream and downstream directions.

Since there are multiple upstream channels, the ONUs and OLT are required to be equipped with transceivers that can operate at different wavelengths simultaneously. For the 2-channel case, each ONU is equipped with two pairs of transceivers, each configured to operate on one of the downstream channels constantly receiving signal broadcasts from the OLT. Each transmitter can be individually configured to operate on one of the upstream channels. Two independent physical queues are located inside the ONU storing incoming packets from end-users and each of the queues is attached



(a) The ONU Logical Structure



(b) The OLT Logical structure

Fig. 2.

to a transmitter. When a packet arrives at the ONU, it is forwarded to one of the queues according to a distribution mechanism. Each queue is scheduled for transmission independently by the OLT; thus queue 1 of all ONUs will be scheduled in turn for transmission over the first upstream channel and queue 2 will share the bandwidth of the second upstream channel.

Two polling tables are used in the OLT to record bandwidth requests made by ONUs. The polling tables hold information on identity (NID), round-trip time (RTT), and request bytes (V). The transmission starting time and transmission window length of each ONU is calculated and assigned by the OLT according to the information passed on by the ONU during the previous transmission. The OLT utilises polling table 1 to schedule ONUs to transmit packets stored in queue 1 on upstream channel 1, and polling table 2 for allocating bandwidth to ONUs to transmit packets stored in queue 2 on upstream channel 2.

The length of transmission window allocated to each individual ONU is assigned by the OLT and can be a predefined (fixed) or a variable value based on some algorithm that use the request from each ONU as an input for the allocation. In this paper, the Fixed, Limited, and Gated assignment schemes from [1-3] are used. In the Fixed assignment scheme, the OLT will allocate each ONU a fixed length of transmission window (W_{MAX}). In the Limited assignment scheme, the OLT will allocate an ONU the amount of bandwidth it has previously requested if the request is smaller than the upper bound limitation (W_{MAX}); otherwise W_{MAX} is assigned. In the Gated assignment scheme, the ONU will be granted a transmission window of the size it has requested regardless. The largest possible window size will be equal to the maximum length of the ONU's queue.

5 WDM IPACT-ST

The second WDM MAC discussed in this paper is referred to as WDM IPACT with single polling table (WDM IPACT-ST). The ONU and OLT modules in this MAC are similar to those in the WDM IPACT described above, except that a tuneable laser replaces the multiple fixed transmitters within the ONU. A single queue is attached to the tuneable laser instead of the multiple queue structure.

Transmission windows are assigned to ONUs in a round robin fashion allowing them to transmit on the first available upstream channel. Only one polling table is used to perform the scheduling process and bandwidth allocation to ONUs transmitting on the upstream channels. To apply this MAC, the OLT has to know which upstream channel will turn idle first.

The OLT keeps track of all upstream channels by calculating their next idle time. Since the OLT knows the round trip time (RTT) of all ONUs and the transmission window size (WS) assigned to ONUs for transmission on upstream channels (this information is recorded in the polling table), it can predict exactly when a particular upstream channel becomes idle by:

$$T_{idle[x]} = T[x] + \frac{W[x]}{R_u} + \frac{r}{2}. \quad (2)$$

$T_{idle[x]}$ is the time when upstream channel x becomes idle and available for the next transmission. $T[x]$ is the time when the previous ONU starts transmission on upstream channel x. $W[x]$ is the transmission window size that was assigned to the previous ONU on upstream channel x. R_u is the transmission bit rate between the ONU and the OLT. And r (round trip time) is amount of time required by a bit to travel from the OLT to ONU and return.

Based on (2), the OLT knows exactly when a transmission will be finished on all upstream channels soon after it releases the GATE messages to the ONUs. Therefore, with knowledge of the next idle time, the OLT can schedule an ONU to transmit on the upstream channel that has the smallest value of $t_{idle[x].}$ Again, the Fixed, Gated, and Limited assignment schemes can be used by the OLT to determine the length of transmission window allocated to each ONU.

6 Simulations

In the simulation, all ONUs support identical traffic loads. The line rate of the distribution section from the ONU to an individual end-user is assumed to be 100Mbit/s. The line rate of each wavelength channel operating in the section between the OLT and the ONUs is 1Gbit/s. The guard time between ONU transmissions is fixed at 5μs. The queue size of each ONU is 10Mbytes, and W_{MAX} is set to 15000 bytes.

Fig. 3 summarises the simulation results for the single channel IPACT system [1-3] as a function of the number of ONUs. As the number of connected ONUs increases, the IPACT system quickly reaches saturation e.g. when the ONU number increases to 64, the IPACT system will become unstable even when the ONU is only providing a load of 20Mbit/s.

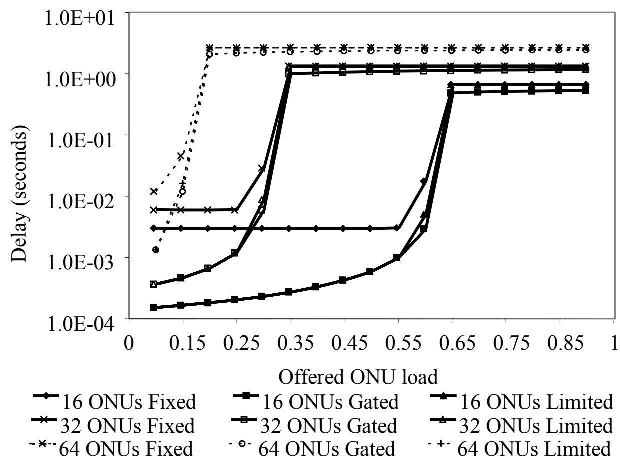


Fig. 3. Average packet delay for single channel IPACT

Fig. 4 plots the simulation results for a 2-channel WDM IPACT system, together with a 2-channel WDM IPACT-ST system. In these simulations, the OLT is connected to 24 ONUs, and each ONU is connected to a group of end-users via 100Mbit/s Ethernet.

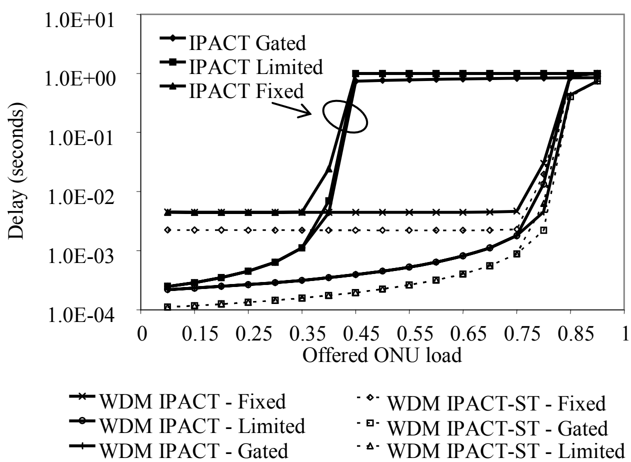


Fig. 4. 2-channel WDM PON versus single channel IPACT

Both WDM IPACT and WDM IPACT-ST perform better than the single channel IPACT. In the WDM system the saturation point has been deferred to 0.85 overall offered ONU load (OOL), compared to 0.45 in the single channel case.

Fig. 5 shows the simulation result for a 3-channel WDM PON system where the OLT is connected to 32 ONUs. In this configuration, the maximum traffic aggregation from all ONUs can reach 3200Mbit/s and the single channel IPACT

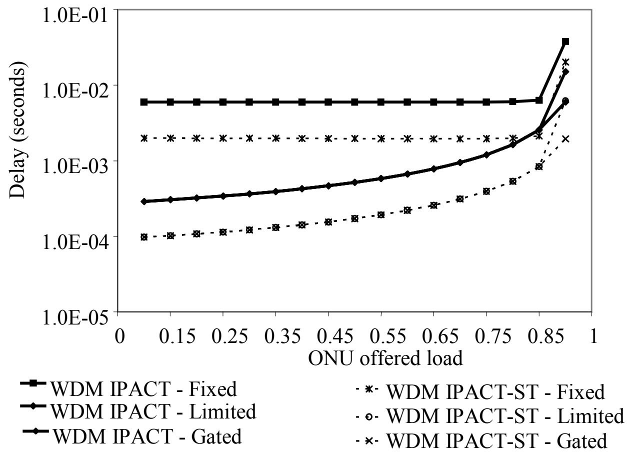


Fig. 5. 3-channel WDM IPACT versus 3-channel WDM IPACT-ST

system saturates even when each ONU is providing 35Mbit/s of traffic (Fig. 3). The results show that the WDM upgrade solutions proposed here has successfully resolved the bandwidth demand problem caused by the increase in ONU terminals.

In general, the performance of WDM IPACT-ST is 50-70% better than the WDM IPACT as a consequence of its shorter cycle time.

7 Differentiated Services WDM IPACT-ST

The principle of differentiated services (DiffServ) [12] is based on class discrimination where packets from end-users are categorised into a number of priority groups. Network resources are then distributed among these groups with varied proportions so that higher priority groups are always allocated more resources than the lower priority groups.

The WDM IPACT-ST is chosen to integrate with DiffServ as it has a far superior performance than the WDM IPACT. To support differentiated services over WDM IPACT-ST, the ONU is installed with an array of physical queues where each queue is used to store a particular class of traffic. When a packet arrives at the ONU, it will be first categorized into one of the priority groups according to its content and then placed into one of the queues accordingly.

In this paper, the Limited assignment scheme is used as an example to illustrate how the differentiated services can be integrated into WDM IPACT-ST. In the simulation, five different priority groups are defined (P1, P2,…, P5). Packets arriving at the ONU will be classified and placed into one of the five physical queues (Q1, Q2,…, Q5). Weighted Fair Queueing (WFQ) is used in the ONU to reserve bandwidth for these five priority groups. Through WFQ, each priority groups can reserve different weighted proportions in the next transmission window. For example, the ONU can reserve up to 35%, 30% 20% 10% and 5% of W_{MAX} to Q1, Q2, Q3, Q4, and Q5 respectively. Therefore, when the next GATE message arrives, the ONU can

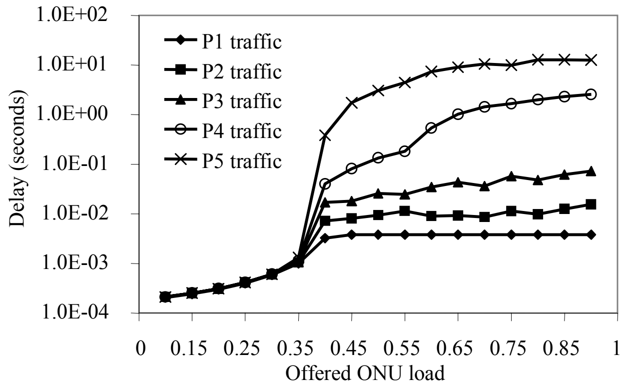


Fig. 6. Average delay of 3-channel DiffServ WDM IPACT-ST (64 ONUs)

transmit packet from priority queues (Q1,…, Q5) up to the amount it previously reserved. Fig. 5 shows the average delay for the DiffServ WDM IPACT-ST in which 3 wavelength channels are utilised in each direction, and 64 ONUs are connected to the OLT.

In the simulation, each ONU is said to support two E1 line emulations allowing a total of 64 PSTN phone calls simultaneously. E1 emulation packets are defined as the highest priority traffic (P1). The rest of the offered load is composed of P2, P3, P4 and P5 traffic with a ratio of 1:2:3:4. P2 and P3 traffic are said to be premium and normal business users; P4 and P5 are premium and normal home users. P1 traffic is constant bit rate, the rest of the traffic is generated by using self-similar traffic sources.

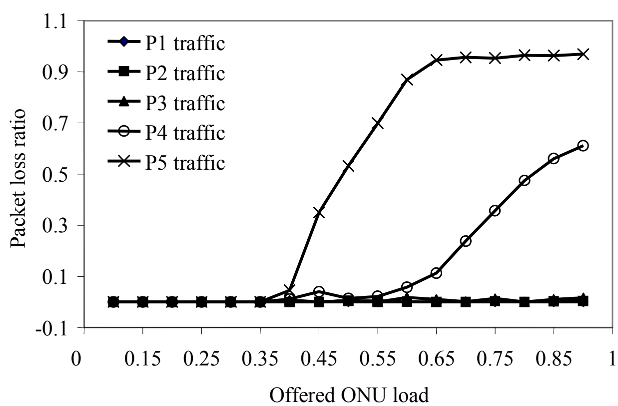


Fig. 7. Packet loss ratio of 3-channel DiffServ WDM IPACT-ST (64 ONUs)

8 Conclusions

Two WDM dynamic bandwidth allocation schemes are proposed here as potential future-proof upgrade solutions for PON systems. When facing increasing bandwidth demand caused by new customer subscriptions or new revenue generating services, the network operator's preferred solution are techniques that elegantly increase the level of usage of the deployed architectures. In the case of PONs, although the proposed MACs require the installation of new transceiver pairs in both the ONU and the OLT, the costs of this upgrade strategy is still comparatively small when compared to laying new OLT-ONU trees.

The proposed WDM MACs resolves the bandwidth bottleneck problem by introducing new upstream channels. As shown in the simulation results, the performance of the WDM PON improves dramatically when compared to the single channel case.

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