Full-Service MAC Protocol for Metro-Reach GPONs

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***Abstract*—An advanced medium access control protocol is presented demonstrating dynamic bandwidth allocation for long-reach gigabit-capable passive optical networks (GPONs). The protocol enables the optical line terminal to overlap the idle time slots in each packet transmission cycle with a virtual polling cycle to increase the effective transmission bandwidth. Contrasting the new scheme with developed algorithms, network modeling has exhibited significant improvement in channel throughput, mean packet delay, and packet loss rate in the presence of class-of-service and service-level differentiation. In particular, the displayed 34% increase in the overall channel throughput and 30 times reduction in mean packet delay for service-level 1 and service-level 2 optical network units (ONUs) at accustomed 50% ONU load constitutes the highest extended-reach GPON performance reported up to date.**

***Index Terms*—Class of service (CoS), dynamic bandwidth allocation (DBA), fiber-to-the-home (FTTH), gigabit-capable passive optical network (GPON), long-reach passive optical network (long-reach PON), quality of service (QoS), service level agreement (SLA).**

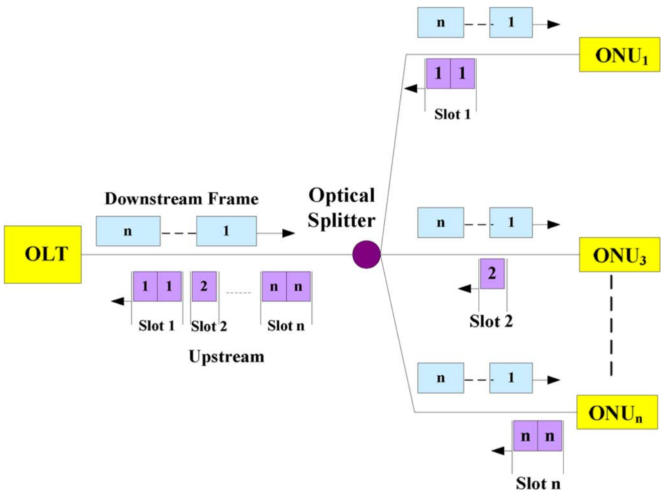

Fig. 1. Data propagation in GPON architectures.

I. Introduction

IN contrast to the widely deployed broadband networks currently, such as digital subscriber loop (DSL) and WiFi, gigabit passive optical networks (GPONs) can provide much higher aggregate bandwidth at longer connection distances that could typically span up to 25 km [1]. For the purpose of decreasing the cost of access network terminations, while reducing the number of central offices (COs) in the field, there has been growing interest in the development of a larger split, longer reach network for the implementation of a metro-reach PON with up to 100 km link lengths [2].

Reducing the number of COs in the field would impose a significant decrease in capital expenditures (CAPEX) as well as operational expenditures (OPEX). In addition by directly communicating the network traffic from the subscribers' premises to an edge switch at a long-haul network, the quality of service (QoS) for various multimedia services such as high-definition TV (HDTV) and video-on-demand (VoD) can be further enhanced since service providers and internet service providers (ISPs) could directly apply centralized management of optical network unit (ONU) requirements [3], [4]. However, typical long-reach schemes, using time-division multiplexing (TDM) to share bandwidth, have been limited to architectures which can only be shared by approximately 16 to 32 subscribers. To extend the number of subscribers while further increasing the network bandwidth in a cost effective manner, there has been a trend towards developing hybrid wavelength-division multiplexing (WDM)/TDM long-reach PONs [2], [5]–[7].

These hybrid architectures are generally implemented by applying a wavelength router before the optical splitter, forming multiple virtual TDM-PONs, each assigned, in a form similar to standard TDM-PON topologies, with one or two explicit wavelengths for bidirectional transmission. Downstream data destined to an individual virtual PON is modulated to a dedicated wavelength, combined and routed through the feeder fibre to the corresponding optical splitter and then split to N copies for N ONUs, as shown in Fig. 1. Similarly, the reversed path will be adapted for upstream transmission [2], [5]–[7].

Since in these extended-reach PON architectures individual virtual TDM-PONs work independently, each virtual PON can be driven by an autonomous dynamic bandwidth allocation (DBA) algorithm. However, by reason of the long propagation intervals associated with the extended link spans, the direct implementation of developed DBA protocols will provide low channel utilization and high packet delay. In most widely cited DBA algorithms, such as the service level agreement (SLA) aware DBA (SLA-DBA) [8], two-layer bandwidth allocation

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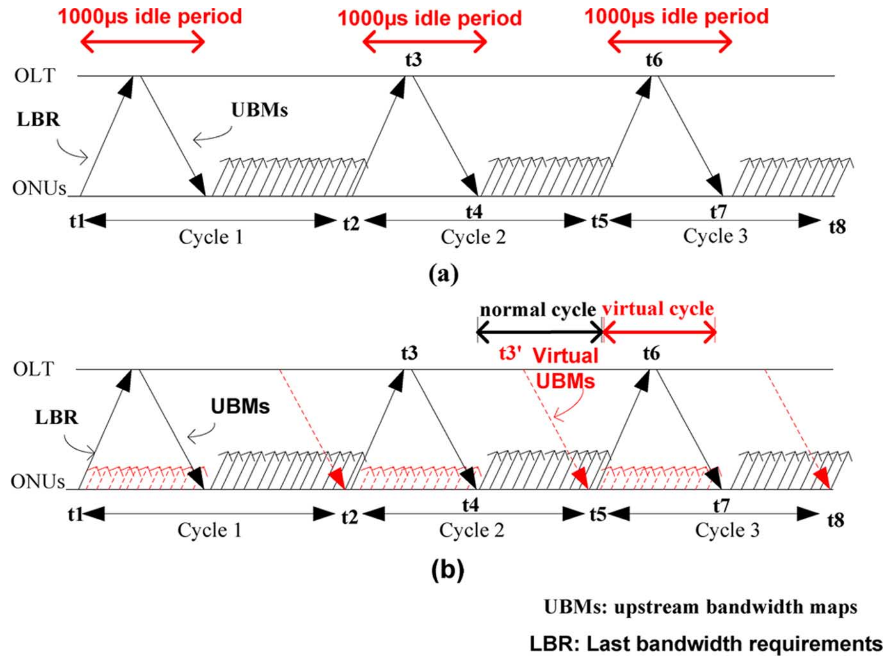

Fig. 2. Upstream time slots for typical (a) DBA and (b) TSD algorithms in a 100-km-reach GPON. (a) DBA transmission mechanisms adaptation in long-reach GPONs. (b) TSD transmission mechanism in long-reach GPONs.

(TLBA) [9], dynamic bandwidth allocation with multiple services (DBAM) [10], and modified start-time fair queuing (M-SFQ) [11], to achieve SLA and QoS integration, the optical line terminal (OLT) has to first receive all ONU bandwidth requirements before it imparts the corresponding grant messages to notify them about their allocated windows. As a result, each polling cycle will remain idle for the period between the last ONU transmitted its bandwidth request till the first ONU starts uploading information. In view of a 100 km typical long-reach PON [1], additional time slots will remain idle in each polling cycle, as shown in Fig. 2(a), in comparison to standard GPONs. This is due to an up to 400 μs increase in packet propagation time from 100 μs in 20 km PONs.

To overcome these issues, the focus of the work presented in this paper is to implement a novel DBA protocol for long-reach GPON architectures, aiming to utilize every idle time slot, thus increasing the available transmission bandwidth in the presence of class of service (CoS) and SLA. In this case, ISPs can dynamically select between single and multiple service provision to provide quality per service while demonstrating network integrity according to subscriber service levels.

II. Extended Reach Algorithm

A. Dynamic Minimum Bandwidth Allocation

Research in DBA algorithms for standard GPONs has produced a novel dynamic minimum bandwidth (DMB) protocol demonstrating QoS and SLA at reduced mean packet delay [12]. In the DMB algorithm, the OLT provides ONUs with three service levels at different weights, W_t, to represent a typical priority mechanism used to access commercial networks. At a first stage, the algorithm automatically assigns to each ONU a guaranteed minimum bandwidth, $B^t_{\min}$ to satisfy their basic service requirements at the various service levels, t [12]. $B^t_{\min}$ is defined as the supplement of a constant basic bandwidth, B_{basic}, available to all ONUs independently of service level and what we call an extra guaranteed bandwidth, B^t_{ex}. In order for the OLT to dynamically assign more bandwidth to higher service level ONUs at variable data rates, the extra bandwidth, B^t_{ex}, for service level t is assigned with respect to the maximum network capacity B_{total} and the allocated network weights W_t, as follows:

$$B^t_{\text{ex}} = (B_{\text{total}} - k \times B_{\text{basic}}) \frac{W_t}{\sum_{t=1}^{3} W_t N_t} \tag{1}$$

where k is the number of ONUs comprising the network and N_t is the number of ONUs subscribed to service level t.

Furthermore, the OLT apportions any unused bandwidth as an extra assigned bandwidth, $B_{\text{ex\_assigned}}$, to ONUs according to their buffer queuing status [12]. Therefore, following probable variations in network capacity, it is capable of readjusting the guaranteed minimum and unused bandwidth among ONUs to comply with subscriber contracts. As shown in (2) for service level t, the maximum allocated bandwidth for ONU_i will be equal to the addition of $B^t_{\min}$ and $B_{\text{ex\_assigned}}$. Otherwise, if the bandwidth requirement, R_i, is smaller than the maximum allocated bandwidth, the allocated bandwidth, $B^i_{\text{allocated}}$, will be equal to R_i [12]

$$B^i_{\text{allocated}} = \min \begin{pmatrix} B^t_{\min} + B^i_{\text{ex\_assigned}} \\ R_i \end{pmatrix}. \tag{2}$$

B. Two-State DMB Assignment

Although a pipeline mechanism has been utilized in most of the DBA protocols presented in the previous sections [8]–[13] to prevent accumulation of waiting time in each polling cycle, upstream polling cycles are not yet fully utilized due to the formation of idle periods. To achieve acceptable channel throughput and packet delay performance, a novel, two-state DMB (TSD) algorithm is developed to significantly increase the channel utilization rate. Accordingly, the 1000 μs idle time slots shown in Fig. 2(a) will constitute in view of the TSD algorithm virtual polling cycles, during which the ONUs can transmit data by means of an innovative prediction method to estimate their bandwidth requirement.

As specified in Fig. 2(b), each upstream polling cycle comprises two sections, namely, the "normal cycle" and the "virtual cycle." The upstream bandwidth maps in cycle 2, for example, will be imparted downstream at time instant t_3, subsequent to the reception by the OLT of all ONU bandwidth requirements for this polling cycle, R_i^g, where i and g denote the ONU number and time instant indicator, respectively. As a result, the effective time slots engaged for data transmission in cycle 2 are limited between t_4 and t_5, representing the "normal cycle" section for polling cycle 2. To take advantage of the succeeding idle period or "virtual cycle" t_5 to t_7 in cycle 3, as shown in Fig. 2(b), the protocol utilizes the "normal" transmission period of cycle 2 to communicate a virtual bandwidth, BW_i, in the sense of virtual grant packets scheduled to reach ONUs before t_5, denoting the beginning of polling cycle 3. Therefore, as shown in Fig. 2(b), ONUs can effectively utilize the "virtual cycle" period t_5 to t_7 for significant data transfer.

The amount of virtual bandwidth BW_i, allocated to each ONU will be determined by the TSD algorithm, with each 1000 μs idle period regarded as the maximum polling period parameter, in terms of an estimated bandwidth requirement. According to the traffic self-similarity [10], [14], since the data arrival rate can be similar in a short period of time (<2 ms polling cycle time), the estimated required bandwidth, $R_i^{3'}$, for ONU_i during the cycle 2 period t_2 to t_5, will be directly proportional to its actual bandwidth requirement R_i^3 in cycle 1 period from t_1 to t_2, as follows:

$$R_i^{3'} = \left(\frac{t_5 - t_2}{t_2 - t_1}\right) R_i^3. \quad (3)$$

Equally important, since ONUs have already started transmitting traffic at the "virtual cycle" of polling cycle 3, the actual bandwidth requirement at t_6 should account for the packet transfer already carried out and determine an actual requirement in bandwidth of ONU_i based on the "normal cycle" available bandwidth between t_7 and t_8. With respect to the overall allocated bandwidth $B_{\text{allocated}}^i$ in each polling cycle, this would correspond to the summation of the "normal cycle" assigned bandwidth $B_{\text{allocated\_normal}}^i$ and the "virtual cycle" assigned bandwidth $B_{\text{allocated\_virtual}}^i$, as depicted in the following equation:

$$B_{\text{allocated}}^i = B_{\text{allocated\_normal}}^i + B_{\text{allocated\_virtual}}^i. \quad (4)$$

III. Network Modeling and Simulation Results

To evaluate the proposed algorithm in terms of channel throughput, packet delay, and packet loss rate, a 100 km-span, 16-split model is developed using the industrial standard OPNET Modeller. Three service levels, $\mathrm{SL}_t, t = 1, 2, 3$, from low to high have been considered in the analysis to comply with typical service provisioning [12], [15]. The number of ONUs in each service level is set to 8, 6, and 2 for service levels low to high, respectively. To comply with the developments in GPONs, each ONU is dispensed a maximum information rate of 100 Mbps, at a total 1 Gbps aggregate capacity. A standard maximum cycle period of 2 ms has been assigned with a fixed 125 μs downstream frame, a flexible upstream frame and 96 bits guard time between two ONU upstream time slots to establish packet transfer between the OLT and ONUs. The network traffic is also implemented by a Pareto self-similar traffic model with a typical Hurst parameter of 0.8 to simulate practical network patterns.

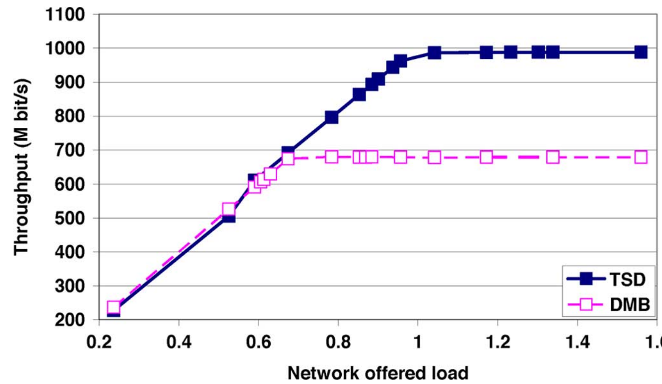

Fig. 3. Channel throughput versus network load.

In the absence, to the best of our knowledge, of published long-reach GPON medium access control (MAC) protocols, the proposed algorithm performance is best evaluated by contrasting it to the DMB algorithm, having outperformed competitive GPON protocols [12], applied to the current long-reach GPON model.

Fig. 3 confirms superior performance of the TSD protocol in terms of the achieved network throughput versus network load, allowing for network load values, defined as the proportion between the sum of each ONU loading and the network capacity, to increase up to around 987 Mbps, compared to the DMB that stalls at only 680 Mbps. As a result, apart from the 45% improvement in channel utilization rate, the measured 98.7% maximum channel capacity figure displays network utilization comparable to the application of the DMB protocol in standard GPONs [12].

To examine the data transfer performance, Fig. 4 exhibits the mean packet delay for all three SLs versus ONU offered load, defining the proportion between each ONU loading and the simulated ONU capacity for each algorithm. It can be observed that the threshold ONU loadings for DMB and TSD to achieve low transmission delay are 0.39 and 0.59, respectively. This two points verify that the long-reach GPON with DMB or TSD can always provide low delay transmission when the overall network offered load is less than 624 or 944 Mbps, respectively ([0.39 or 0.59] $\times$ 100 Mbps $\times$ 16 ONUs $=$ 624 or 944 Mbps). The increased 320 Mbps represent a 50% improvement in view of the TSD algorithm. The TSD algorithm demonstrates significantly lower mean packet delay figures than DMB, exhibiting almost 30 and 25 times reduction at around 55% ONU loading for SL_1 and SL_2, respectively, and approximately eight times reduction at an extended 70% loading for SL_3. It also becomes evident from this figure that the ONU offered load, before packet delay reaches the 5 ms limitation for time-sensitive traffic, has

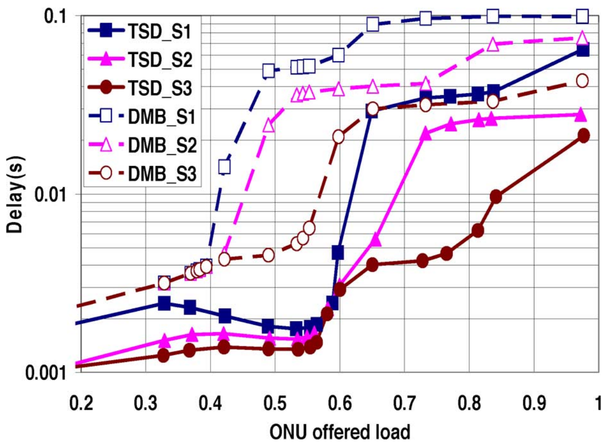

Fig. 4. Mean packet delay versus ONU offered load.

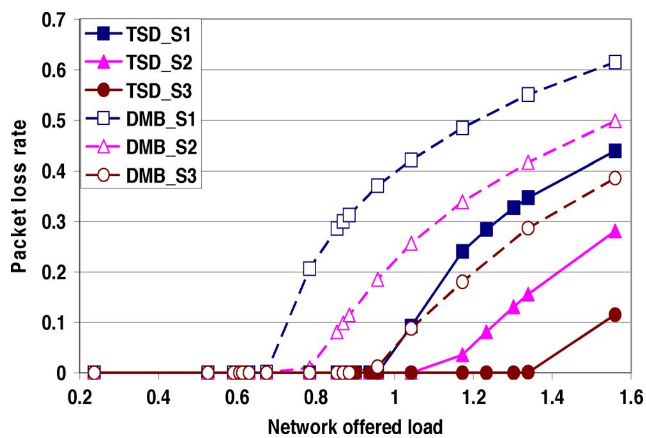

Fig. 5. Packet loss rate versus network offered load.

been extended from 39, 42, and 53 Mbps to 59, 65, and 78 Mbps for SLs 1, 2, and 3 ONUs, respectively. The gained 20, 23, and 25 Mbps bandwidth for SLs 1, 2, and 3 ONUs can then be utilized to support additional multimedia services for each ONU, such as online gaming, education-on-demand, and video conferencing [16].

Furthermore, as shown in Fig. 5, the proposed scheme also provides considerable improvement in terms of packet loss rate versus network load. Comparing the responses of the two protocols for the worst-case scenario SL_1, loss-free transmission is extended from network load 674 Mbps (1000 Mbps $\times$ 0.674) to 956 Mbps (1000 Mbps $\times$ 0.956) providing an extra 282 Mbps network capacity for ISPs either to provide more real-time services to subscribers or support higher number of subscribers.

IV. Class-of-Service Differentiation

A full service access network (FSAN) is expected to support diverse multimedia services with varying transmission requirements. In view of the GPON standard [17], in order to demonstrate transparent propagation, the FSAN group has defined five kinds of CoS, each delivered in a transmission container (T-CONT). T-CONTS signify the buffer each generated packet is stored in the ONU depending their CoS. Among these, T-CONT 1 traffic represents fixed data rate services, while T-CONT 5 is a class reserved for system providers [17]. As a result the simulation model used for evaluating the performance of the DMB and TSD algorithms has accounted for T-CONTs 2 to 4 with a priority order to access the network from high to low. According to FSAN, T-CONT 3 traffic in GPONs resembles to assured traffic and T-CONT 4 to best effort traffic. With respect to the individual traffic's performance tolerance range [17], a longer packet delay and larger packet loss rate is acceptable for T-CONT 4 traffic, which suggests that bandwidth assignment for T-CONT 4 users could be temporarily deferred to prioritize the delivery of T-CONT traffic 2 and 3. Similarly, T-CONT 3 traffic will be relinquished at continuously increasing load to T-CONT 2.

For the purpose of adapting FSAN functionality, the guaranteed minimum bandwidth, $B^t_{\min}$, in the DMB and TSD algorithms is dynamically assigned to satisfy the basic service requirements, corresponding to T-CONT 2 and part of T-CONT 3 traffic. Since the value of $B^t_{\min}$ in each polling cycle is calculated dynamically according to the overall network capacity and ONUs' service levels, system providers could directly add and remove services to a subscriber's access without affecting other network users. Furthermore, since not all subscribers are expected to fully utilize in each cycle their dispensed $B^t_{\min}$ bandwidth, the unutilized bandwidth can be allocated by means of an extra assigned bandwidth, $B_{\mathrm{ex\_assigned}}$, to support T-CONT 4 traffic.

In addition, when ONUs receive their upstream bandwidth maps, the strict priority queue method could allow sequential delivery of T-CONT2, T-CONT3, and finally, T-CONT 4 traffic by means of high-priority queuing packets, e.g., T-CONT2, accessing the network first. As a result, all traffic types are expected to benefit from sufficient transmission bandwidths under low network load while experience buffering when the overall traffic exceeds the maximum network capacity with QoS as a reference measure. To that extent, longer packet delay and packet loss rate are expected for T-CONT 4 at high network load, allowing for bandwidth to be effectively allocated to higher priority traffic classes. Similarly, T-CONT 3 traffic will start experiencing longer packet delay and packet loss rate for further increasing load.

To consider the CoS differentiation in the long-reach network and to simulate a realistic network model, 20% of the generated packets are assigned to T-CONT 2 and the rest 80% are averaged to T-CONT 3 and 4, respectively [2], [18]. To provide a direct figure of service level performance in the presence of CoS with regards to the recorded packet delay, Fig. 6 exhibits T-CONT 2 traffic performance at all three SLs with increasing ONU offered load for both the TSD and DMB algorithms.

In contract to a 5 ms maximum allowable packet delay specified in GPON for T-CONT 2 traffic [19], the 0.76 ms peak delay value in the TSD algorithm exhibits the capability of the scheme to resourcefully transmit T-CONT 2 traffic. In addition, a threefold reduction is presented at around 50% of the ONU offered load demonstrating the ability of the TSD protocol to administrate congestion in the backbone network.

In similarity with the profile for T-CONT 2 traffic, T-CONT 3, as shown in Fig. 7, exhibits in view of the TSD algorithm, very low packet delay for all three ONU service levels. A clear

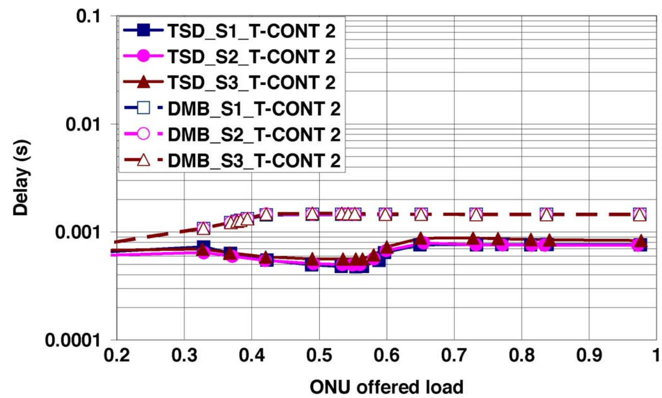

Fig. 6. Mean packet delay for T-CONT 2 services under three kinds of ONU service levels.

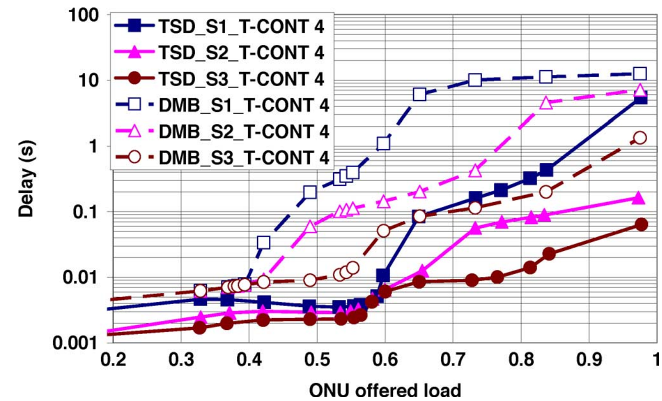

Fig. 8. Mean packet delay for T-CONT 4 services under three kinds of ONU service levels.

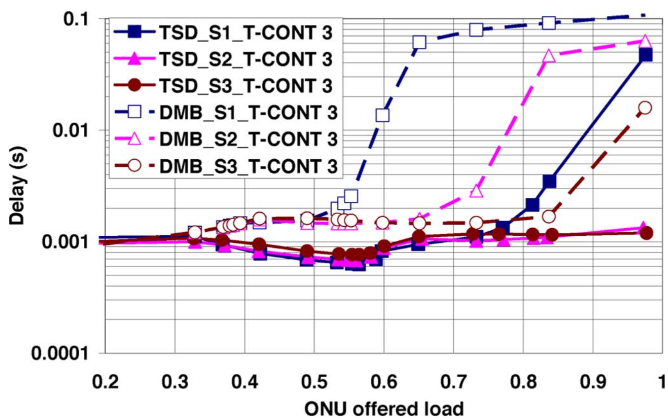

Fig. 7. Mean packet delay for T-CONT 3 services under three kinds of ONU service levels.

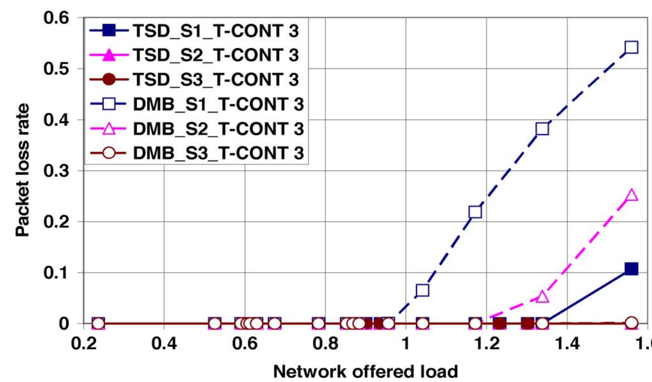

Fig. 9. Mean packet loss rate for T-CONT 3 services under three kinds of ONU service levels.

characteristic with almost 70 times reduction in delay is demonstrated for the least priority service level, SL_1, between 65 and 77 Mbps of ONU offered load. Correspondingly, 50 and 15 times reduction in delay are also presented for SL_2 and SL_3 ONUs, respectively, at around 90% of ONU load.

The maximum ONU throughput for T-CONT 3 traffic is significantly improved from 55, 73, and 83 Mbps in DMB to 77, 100, and 100 Mbps in TSD for SL_1, SL_2, and SL_3 ONUs, respectively. Derived from these transfer characteristics, an approximate 20 Mbps increase in capacity for each ONU independently of service level would be sufficient to accommodate the extra bandwidth required for error free T-CONT 3 service transmission. In contrast to a 100 ms maximum allowable packet delay specified in the GPON standard for T-CONT 3 traffic [19], a 47 ms peak delay value has been recorded in view of the TSD algorithm to release the transmission time pressure in the backbone network.

Comparing with T-CONT 2 and T-CONT 3 traffic, the time insensitive service T-CONT 4 has the lowest priority in accessing the network and as a result expected to present the worst performance in packet delay. This is confirmed in Fig. 8, displaying significantly increased delay figures among the three service levels. In any case though the displayed delay in view of the TSD algorithm is still significantly less than that observed with any other algorithm.

Considering the traffic responses for SL_1 ONUs, TSD presents roughly ten times reduction in packet delay for ONU loads ranging between 42 and 83 Mbps. Similarly, around 6--12 times decreased figures are observed for SL_2 and SL_3 ONUs between 50 and 100 Mbps. In addition, the maximum ONU throughput in Fig. 8 for T-CONT 4 traffic is also extended from 39, 42, and 55 Mbps in DMB to 59, 65, and 83 Mbps for SL_1, SL_2, and SL_3 ONUs in TSD. The significance of the reduced delay values for each SL ONU in real network deployment scenarios is crucial since it represents corresponding reduction in ONU buffer packet waiting times. This property allows the feeder section in the PON to accommodate increased volume of burst streams depending on network penetration and service level distribution among ONUs.

In addition to mean packet delay the network packet loss rate versus network load is another critical performance measure to guarantee QoS for all T-CONT traffic. Since time-sensitive traffic, T-CONT 2, can always be communicated with low packet delay, no packet loss is expected for 100 km reach GPONs in the presence of the TSD protocol. Subsequently, T-CONT 3 and 4 traffic characteristics are presented in Figs. 9 and 10, respectively. For T-CONT 3 traffic, considering the worst-case scenario SL_1 ONUs, the loss-free transmission is

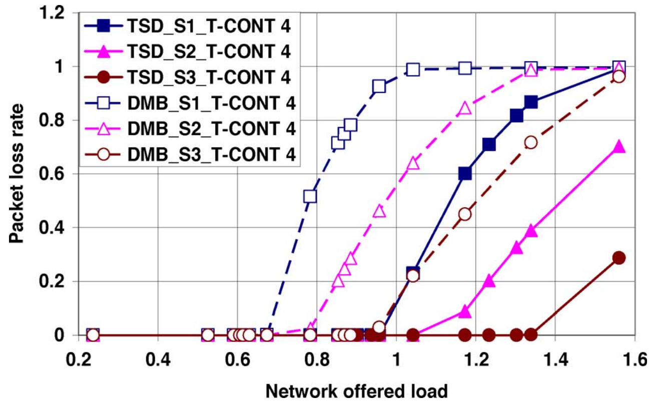

Fig. 10. Mean packet loss rate for T-CONT 4 services under three kinds of ONU service levels.

extended from 950 Mbps (1000 Mbps $\times$ 0.95) with DMB to 1330 Mbps (1000 Mbps $\times$ 1.33) in TSD providing an extra 380 Mbps network capacity to ISPs.

Similarly, the loss-free transmission for the time-insensitive traffic, T-CONT 4, is still extended from 670, 780, and 950 Mbps to 950, 1040, and 1340 Mbps providing an extra 280, 260, and 390 Mbps network capacity for SL_1, SL_2, and SL_3, respectively.

V. Conclusion

By reason of extending the PON application to effectively terminate widely scattered subscribers and considerably reduce the number of COs in a combined access/metro network, this paper has described and demonstrated the performance of an innovative algorithm which exhibits service level and CoS differentiation with highly efficient bandwidth assignment for a 100 km reach, 16-split GPON. In particular, the dynamic TSD protocol manages to overlap the idle time slots in each data transmission cycle with a virtual polling cycle to increase the effective transmission bandwidth by means of a prediction method to estimate the bandwidth requirement of each ONU. Network performance investigations of the TSD scheme versus a developed algorithm have displayed significant 300 Mbps increase in channel throughput with an improvement in packet delay and packet loss rate to allow high network utilization rates over extended network loads.

In particular, the displayed 30 times reduction in mean packet delay for SL_1 ONUs at accustomed 50% ONU load constitutes the highest improvement of GPON overall packet delay reported to date. It is also demonstrated that by considering CoS in the ONUs, low delay transmission is achieved for T-CONT 2 time-sensitive traffic, demonstrating the efficiency of the algorithm in supporting QoS for VoD and/or HDTV services, under any network offered load condition. Additionally, a maximum 70 and 12 times reduction in packet delay is achieved for T-CONT 3 and 4 traffic, respectively, signifying the advancements offered by the TSD protocol in efficiently and flexibly arranging the network capacity to support increased volume multimedia services. To present an alternative evaluation merit of the TSD protocol performance, the application of the developed algorithms over 100 km reach GPONs has demonstrated comparable performance figures in terms of channel utilization rate, packet delay, and packet loss rate to currently deployed GPONs at a superior 400% wider network coverage.

References

[1] Gigabit-capable Passive Optical Networks (GPON): General Characteristics 2003, ITU-T G.984.1.

[2] G. Talli and P. D. Townsend, "Hybrid DWDM-TDM long-reach PON for next-generation optical access," *J. Lightw. Technol.*, vol. 24, no. 7, pp. 2827–2834, Jul. 2006.

[3] S.-M. Lee, S.-G. Mun, and C.-H. Lee, "Consolidation of a metro network into an access network based on long-reach DWDM-PON," in *Proc. Opt. Fiber Commun. Conf. Nat. Fiber Opt. Eng. Conf.*, 2006, p. 6.

[4] S.-M. Lee, S.-G. Mun, M.-H. Kim, and C.-H. Lee, "Demonstration of a long-reach DWDM-PON for consolidation of metro and access networks," *J. Lightw. Technol.*, vol. 25, no. 1, pp. 271–276, Jan. 2007.

[5] C. Bock, J. Prat, and S. D. Walker, "Hybrid WDM/TDM PON using the AWG FSR and featuring centralized light generation and dynamic bandwidth allocation," *J. Lightw. Technol.*, vol. 23, no. 12, pp. 3981–3988, Dec. 2005.

[6] D. J. Shin, D. K. Jung, H. S. Shin, J. W. Kwon, S. Hwang, Y. Oh, and C. Shim, "Hybrid WDM/TDM-PON with wavelength-selection-free transmitters," *J. Lightw. Technol.*, vol. 23, no. 1, pp. 187–195, Jan. 2005.

[7] F. Payoux, P. Chanclou, T. Soret, N. Genay, and R. Brenot, "Demonstration of a RSOA-based wavelength remodulation scheme in 1.25 Gbit/s bidirectional hybrid WDM-TDM PON," presented at the presented at the Opt. Fiber Commun. Conf. Expo. Nat. Fiber Opt. Eng. Conf. (OFC/NFOEC), Anaheim, CA, 2006.

[8] D. Nowak, P. Perry, and J. Murphy, "Bandwidth allocation for service level agreement aware ethernet passive optical networks," in *Proc. Global Telecommun. Conf. (GLOBECOM) IEEE*, Dallas, TX, 2004, vol. 3, pp. 1953–1957.

[9] J. Xie, S. Jiang, and Y. Jiang, "A dynamic bandwidth allocation scheme for differentiated services in EPONs," *IEEE Commun. Mag.*, vol. 42, no. 8, pp. S32–S39, Aug. 2004.

[10] Y. Luo and N. Ansari, "Bandwidth allocation for multiservice access on EPONs," *IEEE Commun. Mag.*, vol. 43, no. 2, pp. S16–S21, Feb. 2005.

[11] N. Ghani, A. Shami, C. Assi, and M. Y. A. Raja, "Intra-ONU bandwidth scheduling in ethernet passive optical networks," *IEEE Commun. Lett.*, vol. 8, no. 11, pp. 683–685, Nov. 2004.

[12] C.-H. Chang, P. Kourtessis, and J. M. Senior, "GPON service level agreement based dynamic bandwidth assignment protocol," *J. Electron. Lett.*, vol. 42, pp. 1173–1174, 2006.

[13] K. Kanonakis and I. Tomkos, "Efficient scheduling disciplines for next generation QoS-aware GPON networks," presented at the presented at the Int. Conf. Transparent Opt. Netw. (ICTON), Athens, Greece, 2008.

[14] G. Kramer and B. Mukherjee, "Supporting differentiated classes of service in ethernet passive optical networks," *Opt. Netw.*, vol. 1, pp. 280–298, 2002.

[15] C. H. Chang, N. M. Alvarez, P. Kourtessis, and J. M. Senior, "Dynamic bandwidth assignment for multi-service access in long-reach GPON," presented at the presented at the 33rd Eur. Conf. Exhibition Opt. Commun. (ECOC), Berlin, Germany, 2007.

[16] C.-H. Lee, S.-M. Lee, K.-M. Choi, J.-H. Moon, S.-G. Mun, K.-T. Jeong, J. H. Kim, and B. Kim, "WDM-PON experiences in Korea [invited]," *OSA J. Opt. Netw.*, vol. 6, pp. 451–464, 2007.

[17] Gigabit-Capable Passive Optical Networks (GPON): Transmission Convergence Layer Specification 2005, ITU-T G.984.3.

[18] K.-H. Ahn, K.-E. Han, and Y.-C. Kim, "Hierarchical dynamic bandwidth allocation algorithm for multimedia services over ethernet PONs," *J. ETRI*, vol. 26, pp. 321–331, 2004.

[19] A. Cauvin, J. Brannan, and K. Saito, "Common technical specification of the G-PON system among major worldwide access carriers," *IEEE Commun. Mag.*, vol. 44, no. 10, pp. 34–40, Oct. 2006.

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