Efficient Resource Management via Dynamic Bandwidth Sharing in a WDM-PON Ring-Based Architecture

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ABSTRACT

In this work we propose an efficient resource management approach for WDM-PON ring architectures that supports dynamic bandwidth allocation and sharing of downstream wavelengths. We propose a modification in the ONU design, to dynamically setup virtual circuits for inter-ONU communication. The reservation mechanism is arbitrated by the OLT, which also monitors the traffic imbalances of downstream channels.

Keywords: Passive Optical Networks (PONs), Optical Burst Transport, Dynamic Bandwidth Allocation (DBA)

1. INTRODUCTION

Passive Optical Network (PON) technology is emerging as a viable solution for next-generation broadband access networks [1]. Among the different variants of PON architectures single-wavelength TDM-PON or multiple-wavelength WDM-PON are the most promising candidates. In TDM-PONs the single wavelength is shared by all Optical Network Units (ONUs) based on a TDMA algorithm which is arbitrated by the Optical Line Terminal (OLT). In contrast, in WDM-PONs a dedicated wavelength is assigned to each ONU for OLT/ONU communication. WDM-PONs can be considered as an evolutionary scenario of existing TDM-PONs [1], however, numerous scalability and bandwidth allocation issues exist, when employing WDM-PON networks. For example, wavelength capacity cannot be reallocated or shared, resulting in the inefficient use of resources. Furthermore, the communication among end-users (Optical Network Units (ONUs)) is performed via the Optical Line Terminal (OLT) that unnecessarily increases network traffic and delay, while the addition of new ONUs does not always scale with cost and wavelengths. A WDM-PON ring-based architecture was recently proposed, [2], **Error! Reference source not found.**, that allows for the dynamic sharing of downstream wavelength channels. Based on the aforementioned WDM-PON ring architecture, with a slight modification in the ONU design, we propose a novel approach for dynamic bandwidth allocation for LAN traffic and dynamic downstream bandwidth reallocation that results in efficient traffic resource management.

The proposed architecture uses a WDM ring of ONUs as the optical distribution (feeder) network and supports all-optical sub-wavelength connectivity for inter-ONU communication and downstream wavelength sharing. Lightpaths for inter-ONU communication are dynamically created bypassing intermediate ONUs, thus avoiding unnecessary electronic processing.

2. RING ARCHITECTURE & ONU DESIGN

The WDM-PON architecture utilized connects the ONUs in a ring topology, constituting the feeder network, and the OLT is connected to the ring via a bidirectional fiber link (Fig. 1a). Each ONU is assigned two wavelengths, namely a dedicated wavelength for downstream/upstream traffic from/to the OLT and a wavelength denoted as λ_{LAN} that is shared by all ONUs across the ring [2]. We envision the use of this common wavelength for lightpath connectivity, supporting flexible private networking capabilities. Fig. 1a displays the ring architecture and the ONU block design. Each ONU is equipped with a pair of lasers and receivers; λ_i is used for OLT-to-ONU downstream/upstream communication and λ_{LAN} for inter-ONU communication (termed as LAN traffic). A Fiber Bragg Grating (FBG) reflects back the λ_{LAN} wavelength from the upstream signal heading to the OLT and allows it to re-circulate around the ring. This common wavelength can be used for lightpath connectivity to support flexible and dynamic private networking capabilities. The main inter-ONU communication involves the aggregation of packets heading for each other ONU in a separate queue (Virtual Output Queuing), which are then transmitted in burst mode over the ring using the λ_{LAN} wavelength. An 1x2 optical switch in the ONU is used to either extract bursts heading for the same ONU or transparently forward them to the destined ONU. Burst-mode transmission technology is mature as it is being used in commercial TDM PONs, and it involves ONUs transmitting bursts of packets during time-slots pre-allocated by the OLT. By extracting bursts that reach their destination via the optical switch (destination stripping) the common wavelength can be spatially reused by downstream nodes, leading to an increased capacity in supporting private networking. Fast switches and burst-mode transceivers are also the building blocks of Optical Burst Switching (OBS), which has been extensively researched in backbone networks and metropolitan rings, [4], for sub-wavelength capacity provisioning.

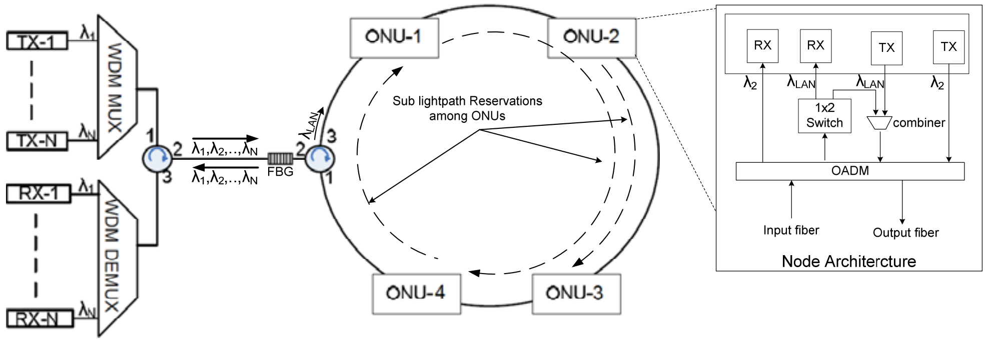

Fig.1: WDM-PON ring-based architecture with proposed ONU design

The incorporation of a common wavelength for inter-ONU communication employs a significant advantage. It can be used for offloading congested downstream channels, by re-directing excess traffic through one or more uncongested ONUs. This is extremely beneficial as the network can react to short term traffic pattern changes of hours, or even days, by dynamically reallocating and sharing the capacity of the downstream wavelengths. The added scheduling complexity (at the OLT) is negligible as network utilization is in-advance known to the OLT. Specifically, it is the OLT that arbitrates the sub-wavelength connectivity of λ_{LAN} and also monitors temporal traffic imbalances among the downstream channels.

3. DYNAMIC BANDWIDTH ALLOCATION ALGORITHM FOR LAN TRAFFIC

The objective of the proposed architecture is to provide sub-wavelength resource sharing and dynamic bandwidth allocation. This can be achieved by setting up virtual circuits, which are envisioned to support flexible high-capacity private networking among the ONU users. In what follows, we detail a reservation mechanism, where the OLT is commissioned to collect bandwidth requests from ONUs and schedule/setup virtual circuits over the λ_{LAN} wavelength. It is also responsible for keeping track of the reserved link capacity over the PON ring. To make the process of resource reservation more efficient, time is discretized in fixed time-slots of duration τ and nodes are assumed to be synchronized with a reference clock, extracted from the OLT's downstream traffic. The utilization profile of each link is divided in a reservation window of K time-slots, numbered from 0 to K - 1. This allows the reserved capacity of each link to be stored in a binary vector, where '0's correspond to reserved slots and '1's to free slots. It must be noted here that the number K actually determines the bandwidth granularity.

Connection requests arrive at the OLT in the form of a 3-tuple (*s,d,c*), where *s* is the originating ONU, *d* the destination and *c* the bandwidth requirement (e.g., the flow peak rate) discretized in a number of slots per reservation window. The OLT executes a dynamic bandwidth allocation (DBA) algorithm to satisfy the request, by allocating *c* slots per link over the path from node *s* to node *d*. Specifically, the OLT performs a binary AND operation of the corresponding link utilization capacity vectors, after performing a *right circular shift* operation to compensate for the link propagation delay. The number of shift positions is derived from the propagation delay in τ time units. The result of the AND operation yields the binary path utilization profile, with '1's being the free (unreserved) slots. In the sequence, the scheduler searches for a set of free consecutive slots that satisfy the connection request (First Fit algorithm) and if one is found, it reserves the capacity and accordingly updates the link capacity vectors of all intermediate nodes. It also informs all ONUs for the new reservation, so that to synchronize bypass operation of their 1x2 optical switches and schedule the transmission of packets stored in the queues. An example set of capacity vectors can be seen in Fig. 2, which correspond to the virtual circuits setup in the PON Ring of Fig. 1. It must be noted here that the propagation delay is not always an integral number of τ time units, resulting in a timing error of at most $\tau/2$. This can be mitigated by using a sufficiently small time unit so that the timing error can be compensated by the guard time, which is set to 1μs. In the case that the connection cannot be served, it may be either blocked or scheduled in the future at the first time that the requested link's bandwidth becomes available. It is clear that connections that span over short source-destination pairs have higher success probabilities, and thus fairness issues may arise. This can be solved ensuring that all ONUs are serviced at least once per round, or limiting the number of overall connections that can be setup from a single originating node.

ONU1	0	0	1	1	1	1	1	1
ONU2	1	0	0	0	0	1	1	1
ONU3	1	1	1	0	0	1	1	1
ONU4	0	0	1	1	1	1	1	1

t

Fig.2: Example of outgoing binary capacity vectors per ONU

4. DYNAMIC DOWNSTREAM BANDWIDTH REALLOCATION

The λ_{LAN} channel can also be exploited to absorb temporal overloads in the network by redirecting traffic from a congested ONU through another uncongested one as pointed out in [2]. For example, assuming a heavily loaded wavelength channel λ_i dedicated to ONU_i and a lightly loaded channel λ_k dedicated to ONU_k, part of the downstream traffic destined to ONU_i can be transported via λ_k and terminated at ONU_k (transient traffic). The transient traffic is stored in the corresponding VOQ buffer of ONU_k and is retransmitted over the λ_{LAN} to reach its final destination, i.e. ONU_i. The problem of redirecting transient traffic from congested to uncongested ONUs is two-fold: (a) first the congested/uncongested ONUs must be identified and (b) the most suitable uncongested ONUs to match the congested ones must be determined. For solving the first problem, we use the notion of *effective bandwidth*. Effective bandwidth is the amount of the bandwidth required for the satisfaction of a quality-of-service (QoS) constraint (specifically the buffer overflow probability *e*). Norros formula is an effective bandwidth formula that applies to self-similar traffic [5]:

$$C_{EB} = \mu + \left[B^{H-1} k(H) \sqrt{-2\alpha\mu \ln e}\right]^{\frac{1}{H}}, \tag{1}$$

where $k(H) = H^H (1-H)^{1-H}$, B is the buffer size (in bits), μ the traffic mean rate (in bps), H the Hurst parameter of the traffic, and a the coefficient of variance. Thus, the OLT can calculate the effective bandwidth for each downstream channel by estimating the underlying traffic parameters via traffic measurements. Lightly-loaded channels are the ones with $C_{EB} < C$ and highly loaded those with $C_{EB} \geq C$, where C is the nominal wavelength capacity. The difference between the effective bandwidth and link capacity corresponds to either the excess bandwidth that must be redirected (for congested ONUs) or the unused capacity (for uncongested ONUs). The OLT performs online traffic measurements and periodically updates the effective bandwidth calculations for each downstream channel. After identifying a congested ONU, it attempts to match and redirect the excess bandwidth over one or more uncongested ones in combination with the availability of λ_{LAN} for the associated ONU links. The λ_{LAN} utilization profile is known to the OLT, since it is the OLT that arbitrates bandwidth allocations for the ONUs. Thus, the maximum data rate that can be redirected from the congested ONU_i to the uncongested ONU_k, given $A_{k,i}$ the available bandwidth from ONU_k to ONU_i in the λ_{LAN} channel and $C_{EB}^{(k)}$ the effective bandwidth of downstream channel λ_k is:

$$R_{k,i} = \min(C - C_{EB}^{(k)}, A_{k,i}). \tag{2}$$

With respect to the second problem (determination of the most suitable uncongested ONUs) it is clear from (2) that matching a congested ONU with the closest uncongested ones in the upstream direction maximizes the spatial reusability gains of λ_{LAN}, as the number of hops of the transient traffic flows is minimized. Thus, for each congested ONU, upstream uncongested ONUs are considered sequentially, until all excess bandwidth from that congested ONU is redirected through one or more uncongested ONUs. In general, the excess downstream traffic of ONU_i can be split in N sub-flows, each one redirected to an uncongested ONU_k such that $\sum_N R_{k,i} \geq C_{EB}^{(k)} - C$ starting from the closest ones in the upstream direction. In the case there is no bandwidth availability in either the λ_{LAN} channel or the downstream channels there is no traffic re-direction. This will result in either buffer overflow or excess packet delay.

5. PERFORMANCE EVALUATION

Simulation experiments using the ns-2 simulator for a network with 16 ONUs were performed for the proposed schemes. We modelled communication between each source-destination pair of ONUs and between each OLT-ONU pair as a separate traffic source that generates packets according to an M/Pareto self-similar process, with H=0.7 and a varying traffic load. Out of the 16 ONUs, 4 were randomly selected with input load $\geq$ 1.0 to simulate traffic overload and 4 with input load $\leq$ 0.7 (uncongested ONUs). Wavelength capacity was set to 1 Gbps, buffer size to 3MB and the reservation window to 1000 slots of duration τ=1μs. LAN load was uniformly distributed to all ONUs. Figures 3a and 3b display the aggregated throughput of congested ONUs vs. downstream load, without LAN load but for different loads of the uncongested ONUs (Fig. 3a) and for different LAN loads but constant load (ρ=0.1) for uncongested ONUs (Fig. 3b). For reference, the case of no redirection is also shown. From Fig. 3a and 3b, it can be seen that the proposed architecture can effectively take advantage of unused capacity of uncongested ONUs as long as there is sufficient bandwidth availability in the λ_{LAN} channel. In particular, for the case of 1.8 load, the throughput of congested ONUs reaches 1.57 Gbps for an uncongested ONU load of ρ=0.1 and gradually converges down to 1Gbps, when the load of the uncongested ONUs increases (see Fig.3a). The same is also recorded with the gradual increase of LAN load (Fig.3b). This is a significant improvement, having in mind that most of the transient traffic would have been lost if new bandwidth resources were not added in the network. Fig. 3c displays the corresponding end-to-end queuing delay measured as the time that a packet enters the OLT until it reaches the destined ONU. It can be seen that redirection of traffic does not result in higher queuing delays and thus the QoS for delay sensitive services does not deteriorate.

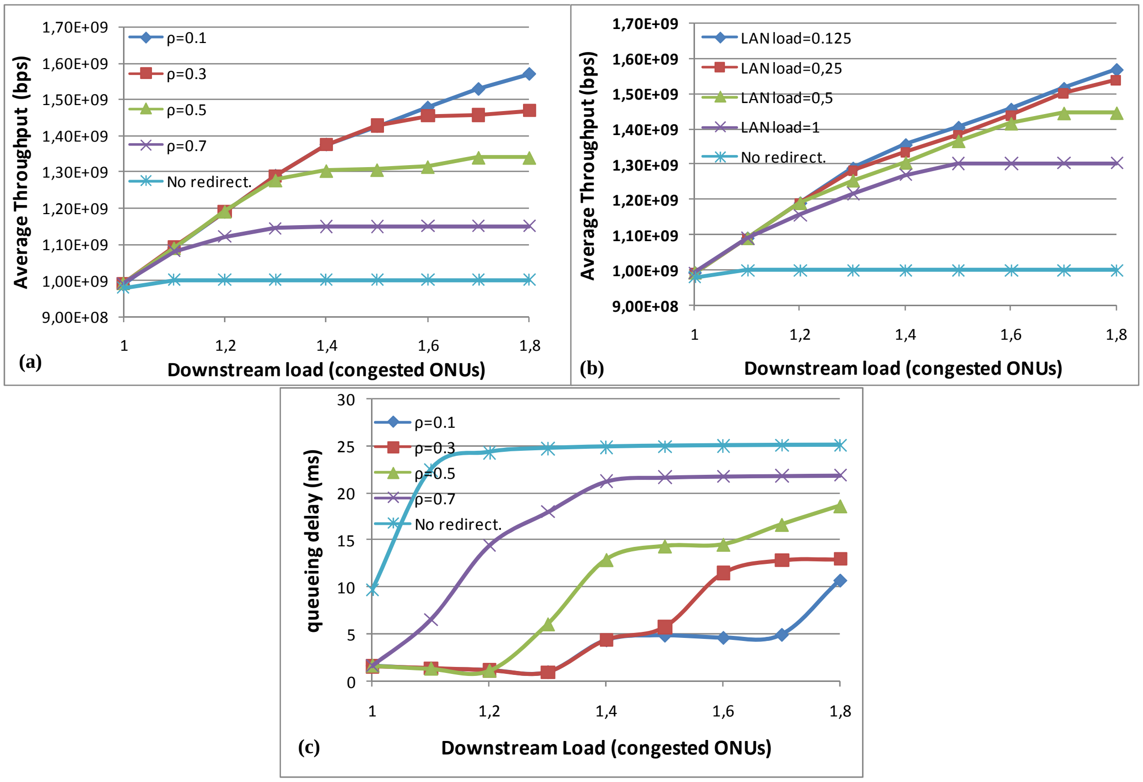

Fig.3: Average throughput of congested ONUs vs. downstream load for (a) different uncongested ONU loads and no LAN load (marked ρ), (b) different LAN loads and ρ=0.1, and (c) downstream traffic delay vs. load

6. CONCLUSIONS

In this work a new WDM-PON architecture was proposed, that supports the dynamic re-allocation and sharing of downstream wavelengths. In the proposed architecture, lightpaths for inter-ONU communication are dynamically created bypassing intermediate ONUs, thus avoiding unnecessary electronic processing. A dynamic bandwidth allocation algorithm was also proposed for resource reservation of LAN traffic. The reservation mechanism is arbitrated by the OLT, which monitors the traffic imbalances of downstream channels. It was shown through simulation that the proposed architecture can cope with temporal traffic overloads by redirecting traffic over uncongested wavelengths.

ACKNOWLEDGEMENTS

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