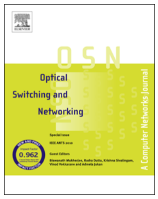
Optical Switching and Networking 10 (2013) 465–474

Contents lists available at ScienceDirect

Optical Switching and Networking

journal homepage: www.elsevier.com/locate/osn



Performance analysis of ONU-wavelength grouping schemes for efficient scheduling in long reach-PONs ☆

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ARTICLE INFO

Available online 23 March 2013

Keywords:
Long-reach passive optical networks
Dynamic bandwidth allocation algorithms
ONU grouping

ABSTRACT

Long Reach PONs (LR-PON) were proposed to extend the benefits of Passive Optical Networks (PON) to more users and to a larger area. This paper considers a Dynamic Bandwidth Allocation (DBA) based on a hybrid combination of Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM). The time complexity of the DBA algorithm is typically $O(n \log n)$, where n denotes the number of ONUs. Since the maximum number of supported ONUs in an LR-PON can be as high as 2048, the computation time required for computing a schedule will be very high and directly impacts the overall network performance. In this paper, we have presented a grouping strategy to reduce the computation requirements. The number of ONUs is split into mutually exclusive groups with the OLT scheduling each group independently and in parallel. With the static grouping strategy every user is assigned to a group and the assignment of wavelength resources is fixed. However, with non-uniform loads, we observed that static grouping was not found to be suitable as the delay variation was significant across the groups. To address this gap, we introduce the concept of dynamic grouping and define three dynamic grouping heuristics that adapt to the current network load conditions and (re)allocate the ONUs and wavelength resources suitably. The proposed schemes have been compared in terms of delay variation and wavelength utilization. Of the three heuristics, *ONU to Least Loaded wavelength group* (OLL) and *Least Wavelength Resources* (LWR) heuristics balance the packet delay across ONUs assigned to different groups and *Proportional Wavelength Usage* (PWU) heuristic reduces power consumption by allocating fewer wavelength resources.

1. Introduction

This paper deals with the design of Long Reach PON (LR-PON) access networks. Current generation Passive Optical Networks (PON) connect a Central office (CO) port to multiple subscriber equipments called the Optical Network Units (ONU). This is achieved by connecting the fiber strand from the Optical Line Terminal (OLT), the central office equipment, to an electrically passive Remote Node (RN). Every ONU is connected to the RN using a fiber strand. The network between the OLT and the ONU is referred to as the Optical Distribution Network (ODN), and

☆ The initial version of the paper was presented at IEEE International Conference on Advanced Networks and Telecommunication Systems 2011 held at Bengaluru, India.

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1573-4277/$ - see front matter
http://dx.doi.org/10.1016/j.osn.2013.03.006

it spans over a distance of 30 km [1] connecting up to 64 subscribers. Due to the RN technology limitations and power budget considerations, the optical fiber bandwidth is largely underutilized in this network configuration.

LR-PON networks were introduced to increase the number of subscribers and to better utilize the available bandwidth. An LR-PON incorporates an electrically active node referred to as access or amplifier node (AN) that can be used to relax the power budget considerations. The LR-PON can have one or more ANs between the OLT and to any ONU. The typical network topology of an LR-PON is presented in Fig. 1. The RN component can be merged into the AN, so that more number of subscribers can be connected. With LR-PON, an ODN can support up to 2048 subscribers [2] and can be extended to cover 200 km [3]. The larger coverage offered by LR-PON is comparable to that of Metropolitan Area Networks (MAN). Thus, an LR-PON paves the way for a simplified and integrated network that serves as a MAN and as an access network.

An LR-PON can use Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM) or Hybrid (combination of both TDM and WDM) for sharing the fiber optic link between the OLT and the AN across the subscriber base. For TDM, mechanisms such as Interleaved Polling with Adaptive Cycle Time (IPACT) [4] are used to time-share the trunk link. With *IPACT*, the OLT centrally computes the transmission schedule for all the ONUs using a Dynamic Bandwidth Allocation (DBA) algorithm and intimates the transmission start time and duration using a *Grant* message. An ONU adheres to the schedule and transmits the data packets in this duration. Towards the end of the transmission cycle, the ONU Reports its buffer backlog to the OLT using a *Report* message. This is used by the OLT for computing the transmission schedule for the ONU in the subsequent cycle. Gigabit PON (GPON) supporting 1 Gbps and Ethernet PON (EPON supporting 1.25, 2.5 and 10 Gbps) have been standardized. Assuming fair sharing of the trunk link bandwidth across 2048 subscribers, one subscriber will get around 512 Kbps with a 10 Gbps EPON. A TDM LR-PON uses an Optical Splitter (OS) as part of the AN.

In WDM PONs, every ONU is assigned an exclusive wavelength for transmission to the OLT. With WDM, the OLT will need to have an array of receivers one for each wavelength. A WDM LR-PON uses Array Waveguide Grating (AWG) as part of the AN. This provides about 100 Gbps

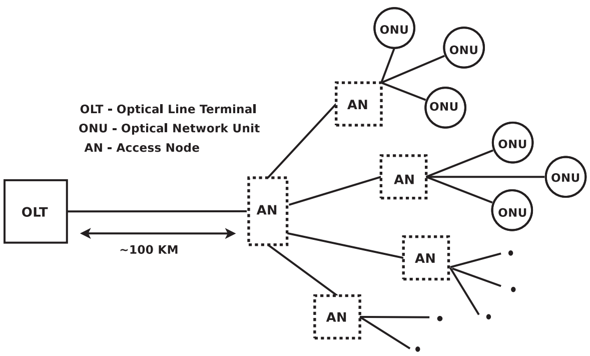

Fig. 1. Typical LR-PON architecture.

raw bandwidth for every subscriber which may be beyond the current subscriber bandwidth consumption levels. Corporates and Mobile back-haul networks can subscribe to WDM PON; however, the bandwidth offered is at least one order of magnitude higher than the current consumption levels of the subscribers in this segment.

A Hybrid PON system uses both TDM and WDM techniques for multiplexing. Usually the first AN from the OLT uses WDM for multiplexing and the second AN or RN uses TDM for multiplexing the data packets originating at the ONUs. Since hybrid PON uses both WDM and TDM techniques, it offers consumable bandwidth on a per subscriber basis apart from covering larger areas. We further consider hybrid PON in this work which uses 64 wavelengths to support 1000 or more subscriber equipments. *SIPACT* [5] extends *IPACT* to support schedule computation across multiple wavelengths.

With increase in the number of subscribers in an LR-PON, the number of ONU allocations per cycle also increases. Assuming the cycle time to be 2 ms, when supporting 64 subscribers in a single wavelength TDM PON, around 31 μs (2 ms/64) is available for computation of the DBA for one subscriber. When the same algorithm, used for 64 subscribers, is used for 1024 subscribers, the cycle time increases to 32 ms (31 μs $\times$ 1024). When this implementation option is chosen, there will be multi-fold increase in the overall delay incurred by a packet passing through the network. Alternately, 16 or more processors can be used in parallel to bring down the computation time. However, this involves careful consideration of resource locking which introduces additional computational overhead. Without this, when different processors execute the wavelength selection procedure at the same time, the same wavelength may wrongly be chosen for allocation.

When more than one wavelength is supported by an Hybrid PON, the time complexity of DBA algorithm computation increases. When computing the schedule for a given ONU, the earliest available wavelength across all the 64 wavelengths, when using Coarse WDM, is determined in *SIPACT*. Thus an additional step of selecting the wavelength is introduced. This involves finding the minimum of the wavelength free times which can be carried out in the order of number of wavelengths say $O(W)$ with an unordered set of wavelength free times, where W is the total number of wavelengths.

In this paper, we introduce the concept of grouping of wavelengths and ONUs in order to reduce the schedule computation time. In [6], we considered simplification of the DBA algorithms for LR-PON environments based on Hybrid PONs. We discussed grouping as a strategy to partition the input set. A simple approach is to fix the ONU-to-wavelength or wavelength group association, regardless of the ONU load. This is referred to as *static grouping* strategy. With this strategy, the computation time used by the DBA algorithms was reduced by an order of magnitude without any significant impact on the network performance in terms of delay. However, static grouping was not well suited for non-uniform ONU loads as shown in Section 2. In this paper, we propose *dynamic grouping* strategies where the association of an ONU to its