Optical Switching and Networking 28 (2018) 1–7

Contents lists available at ScienceDirect

Optical Switching and Networking

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

Energy consumption and bandwidth allocation in passive optical networks

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ARTICLE INFO

Keywords:
Passive optical network
Energy consumption
Bandwidth allocation
Quality of service

ABSTRACT

A compromise between the energy consumption, at the central office (CO), and the maximum bandwidth capacity, offered to end users of passive optical networks (PON), is demonstrated. Four classes of PON are considered: two are based on consolidated technologies (GPON and XG-PON), and the others are the emerging TWDM-PON and OFDM-PON. By means of the proposed algorithm, we evaluate the distribution of users in a Manhattan topology model regarding power consumption and quality of service (QoS) in two scenarios: 1) fixed split ratio and; 2) flexible power division. According to the results in the first scenario, it is possible to provide bit rates up to 178.1 Mb/s per user, for GPON, and 713.6 Mb/s per user, for XG-PON, without affecting the QoS even in a high activity network. The second scenario explores "where" and "when" network operators should migrate to higher capacity technologies (when providing bit rates up to 1 Gb/s per user) by means of deployment of TWDM-PON and/or OFDM-PON, while keeping a QoS above 20%.

1. Introduction

Passive Optical Network (PON) technology is currently being developed and deployed, in a large market scale, by many network operators around the world and shall play a crucial role for future broadband access networks [1]. For these next generation equipment, wireless and fixed line technologies are expected to be integrated in the so-called 5 G framework [2]. However, in a scenario where a continuous increase in broadband data consumption drives the telecom industry, wireless and fixed optical-line networks operate with distinct patterns of energy consumption. For the wired network, nearly 70% of total energy is consumed at the end-user segment, thus only ~ 30% is due to the operating costs, i.e. Operation Expenditure (OPEX). On the other hand, for mobile networks, 90% of the total energy consumption is related to OPEX, leaving only 10% to be allocated to the mobile user [3]. Overall, disregard the network infrastructure, combining energy efficiency with broadband provisioning will remain a challenge to be faced by operators. One strategy for approaching these issues is to analyze the balance between power consumption and broadband operation in separate segments of the network (i.e. "wireless & wired", as well as "at the central office (CO) & at the end user sides").

In this context, passive optical networks can meet both requirements thus providing high capacity with substantial reduction in energy consumption [4]. Therefore, under a network expansion perspective, it becomes strategic to evaluate those aspects in emerging PON technologies, such as Time and Wavelength Division Multiplexing (TWDM-PON) and Orthogonal Frequency Division Multiplexing (OFDM-PON), both configured with direct detection schemes. Considering that Gigabit PON (GPON) and 10 Gigabit PON (XG-PON) are already classified as legacy [5], in a migration scenario TWDM-PON (already standardized and more mature [6]) and OFDM-PON (still in R & D stage [7]) must be planned to coexist with these consolidated PON. Conceptually, TWDM-PON stacks multiple XG-PON cards using a spectral multiplexing technique (WDM), where 4 pairs of wavelength can withstand aggregated downstream (DS) rates of 40 Gb/s and 10 Gb/s in the upstream (US). When it is difficult to upgrade the data rate per wavelength in a TWDM-PON, OFDM-PON may be introduced to meet the growing demand in bandwidth requirements with higher spectral efficiency. As an example, by employing advanced modulation formats, such as quadrature amplitude modulation (QAM), combined with fast Fourier transform (FFT), it is possible to generate digital OFDM signals that will modulate a number of WDM channels [8].

In this work we evaluate the energy efficiency gain, in comparison to PON legacy (GPON and XG-PON), that can be obtained by the use of TWDM-PON and OFDM-PON in an analysis the focuses on the energy consumption at the central office, only. This way, by applying the model proposed by Lambert et al. [9,10] in a Manhattan topology [11], we

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[1] This research received funding from CAPES (9155340).

http://dx.doi.org/10.1016/j.osn.2017.10.004
Received 3 April 2017; Received in revised form 7 September 2017; Accepted 23 October 2017
Available online 24 October 2017
1573-4277/

investigate the advantage of planning passive optical networks by targeting the compromise between energy consumption and maximum bandwidth capacity in two scenarios: with a fixed split ratio and with a flexible power division. After calibrating our algorithm with results found in the literature, we assume a scenario where a broadband demand should be provided at the lowest possible energy expenditure, without compromising the delivered quality of service, QoS,[1] which refers to the network ability of ensuring an acceptable level of packet loss, set by contract, for a specific application. It should be pointed out that this is a partial solution and, to complement the present analysis, other segments of the network should be also analyzed. As an example, a study on the power consumption at the optical access customer premises may be found in [13] and for both sides of the wireless access network (i.e. service provider and mobile end user), in [14].

In order to accomplish these goals, the paper is organized as follows: Section 2 describes the adopted energy consumption model, the base for the network planning method presented in Section 3. The results and discussion are presented in Section 4 and the conclusion in Section 5.

2. Energy consumption model

Models that describe the area of implantation of a PON can be classified into two groups: geographic models and geometric models [15]. Geographic models assume a specific area constructed from well-defined geo-referenced data, finding optimal solutions that employ maps of real cities using geographical coordinates of streets, buildings, and others [16]. In this way, exact locations of remote nodes (RNs), trenching and ducts are calculated very precisely, taking advantage, as much as possible, of the sharing of fiber infrastructure, so that trenching and ducts can be shared by different fiber links [17]. Generally, these models apply during the detailed planning stage of the passive optical network.

Geometric models for an access network usually assume a uniform distribution of subscribers over a given area, adapting their parameters and also carrying out the first general analyzes. This models are sufficiently precise in planning steps, such as strategic network planning for a preparatory economic analysis and general business case decision. What's more, they are very useful in placement decisions as well as in a preliminary list of PON configuration materials [15]. Such approach may lack from precision but, if adjusted properly, can provide an initial approach of a real situation. Among various geometric models, the Manhattan structure captures the underlying physical topology of typical PONs in urban and suburban areas with a reasonable accuracy. Regarding network deployment costs (or Capital Expenditure, CAPEX), the Manhattan model allows a practical estimation of the infrastructure requirements, and has been used to predict costs of access networks [11]. As reinforced by Fernandez et al. [15], it is fairly easy to find cities with the standard Manhattan model, such as the L′Eixample district in Barcelona, Portland and Melbourne. Thus, the Manhattan model is the appropriate option for the purpose of this study.

Fig. 1 illustrates the Manhattan model where subscribers are distributed uniformly. As indicated, the side of each block contains n subscribers and the distance between subscribers is represented by l. Thus, each remote node serves n^2 customers. The model shows a distribution of N blocks on each side of the larger square, and the distance between RNs is denoted by L. In this set up, a CO serves N^2 RNs and a total of $N^2 \times n^2$ subscribers [11].

With this topology, the number of passive network elements, as well as the number of Optical Line Termination (OLT) ports and of OLT chassis, can be calculated by [11]:

$$OLTports = N^2 \times \frac{n^2}{Split} \quad (1)$$

$$OLTchassis = \frac{OLTports}{OLTportsperchassis} \quad (2)$$

After estimating the number of OLT ports and chassis, the next step is the power consumption estimation. This parameter may be evaluated from both sides, client (in this case, the Optical Network Unit, ONU) and service providers (CO), where the OLT units are placed. According to [9], at the operator side, three power consumption contributions must be taken into account:

1. OLT ports (calculated by multiplying the number of OLT ports by the power consumption of each port);
2. Layer 2 switching, packet processing and traffic generation/management, calculated from the product:

$$OLTchassis \times \frac{PONs}{chassis} \times Bandwidth(DS + US) \times 1\frac{W}{Gb/s} \quad (3)$$

(where W/Gb/s refers to the power, in Watt, per Gigabit per second; DS and US to downstream and upstream, respectively);
3. Uplink ports (calculated by multiplying the number of OLT chassis by the uplink power consumption).

The uplink power consumption, which includes the power overload of the chassis and the switching cards structure, is associated with the uplink capacity. According to Lambert et al. [9], the uplink capacity is obtained by the bidirectional combination of the uplink ports, with aggregated capacity of 1, 10, 40, 100, 400, and 1000 Gb/s, consuming 7, 38, 105, 205, 560 and 1100 W, respectively.

Fig. 2 illustrates the general components of a passive optical access network for the energy consumption estimation, as proposed by Lambert et al. [9]. The network element counting (number of OLT ports and OLT chassis) and the required uplink transmission capacity are estimated in accordance with the user demand and the expected QoS level. For the equipment installed at the CO, two factors are also considered [9]:

1. For including the AC/DC conversion loss, the results are multiplied by a factor of 1.25 [18].
2. For including the power consumed by auxiliary equipment, such as batteries, air conditioning and power units, the results are multiplied by a local factor of 1.70 [18].

Once the total energy consumed at the CO is obtained, its value is divided by the number of connected users in order to obtain the power consumption per subscriber [9,10].

3. Network planning method

When planning a PON infrastructure, an important parameter that must be evaluated is the bandwidth availability as a function of the network usage activity. Normally, customers are not active all the time but, eventually, their activities may exceed the network capacity, thus affecting the offered QoS. These aspects are addressed in this section.

3.1. User demand and service availability

Here, the objective is to estimate the probability, P_{av}, for a user to receive a given bit rate, B_{av}, as a fraction of the optical bit rate, B_{opt}. In this scenario, the probability $A[k]$ of existing k active users out of a total of N users connected to the network, where each client presents the same probability, p, of being active, may be calculated by [19]:

[1] "Quality of Service is a term adopted to express the totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service", [12].