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Flexibility Level Adjustment in Reconfigurable WDM-TDM Optical Access Networks

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Abstract—Optical access networks have been widely adopted to support the exponential growth in bandwidth demand. To further fulfill the growth efficiently, reconfigurable wavelength division multiplexing–time division multiplexing optical access networks have been proposed in which optical network units can be reallocated to another wavelength on demand. Thus, the reconfigurability allows dynamic sharing of both wavelengths and timeslots. However, it requires a substantial addition to capital expenditure per user, which is prohibitive in access networks. This paper investigates an approach to preserve the merits of reconfigurability while significantly reducing the network complexity, thus cost by adjusting the level of flexibility. We define a parameter designated as the degree of flexibility to indicate the level of flexibility of a network. Then, we evaluate the performance of various degrees of flexibility based on the traffic capacity and the power consumption. The results suggest that introducing limited wavelength flexibility to the network significantly improves the performance in comparison to the static network while a highly or fully flexible network can further improve the performance but with smaller additional margins. Finally, we apply this result to a well-known reconfigurable architecture, the broadcast-and-select, to illustrate how the limited flexibility can help to reduce the network cost in terms of the optical power budget.

Index Terms—Optical fiber networks, time division multiplexing (TDM), wavelength division multiplexing (WDM).

I. INTRODUCTION

Optical access networks are becoming the widely adopted solution to solve the bandwidth bottleneck in the last mile. In fact, optical access networks have been gradually visible to end users or the workhorse behind other interfaces. One gigabit per second per home has been predicted in [1] to enable applications such as cloud computing which turns the Internet into a global computer where optical networks are high-speed buses. Google, an Internet service giant, announced the deployment of an experimental fiber network to provide 1 Gb/s to at least 50,000 and potentially up to 500,000 people [2]. Google is impatient and tries to shorten the innovation cycle: “bandwidth-intensive killer applications → bandwidth demand → bandwidth availability → novel bandwidth-intensive killer applications.” Hence, this cycle requires optical access networks to further upgrade the capacity by scaling up the transmission capacity per wavelength and the number of wavelengths per fiber in an economical manner.

Recently, 10 Gb/s gigabit-capable passive optical network (XG-PON) and Ethernet PON (10G-EPON) have been standardized in ITU-T G.987 and IEEE 802.3av, respectively. These standards specify up to 128 users sharing a single wavelength channel (one downstream and one upstream wavelength) in a time division multiplexing fashion. Beyond these standards, the wavelength capacity continues scaling up by advanced techniques such as polarization multiplexing [3], [4], multilevel modulation formats, coherent detection [5], [6], and orthogonal frequency division multiplexing [7], [8] since these techniques are becoming commercially available for long-haul applications.

On the other hand, wavelength division multiplex PON (WDM-PON) is not yet standardized but it has been already successfully deployed [9], [10]. The network can be a pure WDM-PON with a dedicated wavelength per user or additional per-wavelength multiplexing such as time division multiplexing (WDM-TDM PON). A straightforward implementation called static WDM-TDM PON, also known as wavelength stacked PONs, employs an arrayed waveguide grating (AWG) and power splitters within the optical distribution network (ODN) to statically demultiplex and route M wavelength channels, each feeding a number of optical network units (ONUs) as depicted in Fig. 1(a).

The static WDM-TDM PON can be seen as a set of M independent virtual TDM-PON subnetworks as shown in Fig. 1(b). Since access traffic patterns are highly dynamic, one or several subnetworks might be congested while the others have a lighter load. The local congestion can be solved if the network is able to reallocate traffic, meaning that the ONU(s) are reallocated from a congested sub-network to a light-loaded one as depicted in Fig. 1(c). The networks with such capability are referred as flexible or reconfigurable networks [11]. As a result, flexible networks are able to provide bandwidth-on-demand, have larger statistical multiplexing gain, and reduce power consumption by enabling network capacity as needed and powering-down unused capacity. The Cisco global IP traffic forecast states that the peak-hour traffic is growing more rapidly than the average traffic [12]. The peak-hour traffic will increase fivefold in the period between 2010 and 2015, while the average traffic will increase fourfold. This fact supports the need for reconfigurable
networks since they are designed to deal with the fluctuation of traffic in an efficient manner.

Reconfigurability comes with certain complexities, implying higher costs, which up to now is the biggest obstacle to enable flexibility in WDM-TDM PONs. In the literature, there are extensive studies proposing reconfigurable architectures focusing on functionality [13]–[15], cost-effectiveness [16], [17], migration [18], and the enabling devices [19]. These architectures certainly have different levels of flexibility, thus leading to different performance and cost. Furthermore, they also can be fine tuned to yield an optimal tradeoff between flexibility and cost. The performance of these architectures was initially compared in [20]. This paper further provides in-depth quantitative evaluation of the traffic capacity gain and power saving by reconfigurability with new results. The evaluation leads to suggestions for flexibility adjustment in reconfigurable optical access network (ROAN) design.

This paper is organized as follows. Section II gives an overview of ROANs and defines parameters for the analysis. Section III shows the congestion probability and the power consumption analytical model. The numerical results and discussions are given in Section IV. Based on the results in Section IV, a specific example of the tradeoff is shown in Section V. The conclusion is drawn in Section VI.

II. ROANs

Optical backbone and metro networks have evolved gradually from static to reconfigurable by employing all-optical routers such as multidegree reconfigurable optical add/drop multiplexers. Although the requirements for access are different, a similar idea has been proposed for access networks because the traffic in access (low aggregate level) is more agile than that in backbone (high aggregate level) [21], [22]. The ROAN allows ONUs to be reallocated from one wavelength to another wavelength if needed as illustrated in Fig. 1(c). In this example, the ONUx is reallocated to PON3 (wavelength channel 3) because its bandwidth request cannot be granted by PON1 (wavelength channel 1). For convenience, we only refer to downstream wavelengths since a downstream wavelength always couples with an upstream wavelength to form a duplex channel.

Basicly, there are two locations to handle reconfigurability: at the ONU by wavelength selection or at the remote node (RN) by wavelength routing. In the first option, the ONU selects the working wavelength channel among several or all wavelength channels by tunable filters (for downstream) and tunable lasers (for upstream). The passive RN can broadcast [15] or multicast wavelength channels to ONUs [16], [17]. This option allows the use of passive ODN but requires expensive ONUs and excessive power budget. The second option, on the other hand, employs a wavelength router in the RN [13], [14], [19] to decide the working channel for ONUs. Therefore, the ONU has comparable cost to the one in the static network but the ODN is no longer passive. Besides these two locations, interesting architectures have been proposed in [23] and [24] in which the ONU is addressed by tunable transmitters in the optical line terminal (OLT) in the downstream. In this architecture, the ONUs across multiple ODNs will share a limited number of transceivers in the OLT. However, it is not a true ROAN as it is basically a dynamic OLT transceiver-sharing scheme across multiple ODNs. In the upstream direction, the architecture in [23] can be classified as wavelength selection as tunable lasers are employed in ONUs for reconfigurability.

Despite the differences amongst ROAN architectures, they can be always seen as a set of subnetworks, each equivalent to a conventional PON, as illustrated in Fig. 1(b). From this point of view, the difference between reconfigurable networks and the static WDM-TDM PON is that ONUs in such networks are movable amongst subnetworks. However, while some architectures allow ONUs to move to any subnetwork, others allow ONUs to move only within a limited and predefined number of subnetworks. To differentiate these networks in terms of flexibility, we propose a new parameter designated as the degree of flexibility $F'$. It is defined as the number of possible subnetworks to which an ONU can be relocated. Although each ONU within a network in principal may hold different degrees of flexibility, we only consider the uniform but realistic case where the degree of flexibility is the same for every ONU. Therefore, the degree of flexibility has the range from 1 to $M$ where a static WDM-PON has $F = 1$ and a fully flexible one has $F = M$.

Fig. 2 illustrates the conceptual representation of the degree of flexibility where a ROAN with given $F$ is divided to distinct bandwidth pools. A bandwidth pool is shared amongst the member ONUs by dynamic wavelength and timeslot assignment. For example, the $F = 2$ network is partitioned in $M/2$ bandwidth pools, each contains two wavelength channels. The ONU in this network can be reallocated between two wavelength channels.

To quantitatively evaluate the difference in handling the traffic load, we consider the network traffic capacity as the
metric. The traffic capacity is defined as the traffic load with which only 1 out of 100 bandwidth requests is rejected. Besides the capability of handling the traffic load, the power consumption is another important merit since ROANs are able to reduce the power consumption by allocating ONUs to several wavelength channels and powering down unused channels in off-peak hours. The power consumption for each degree of flexibility is also evaluated and compared.

III. TRAFFIC CAPACITY AND POWER CONSUMPTION ANALYSIS MODEL

A. Traffic Capacity

In order to find the traffic capacity at 1% congestion probability, we derive a model to yield the congestion probability $P_r$ for a given bandwidth request load. Since aggregate capacity of a system with given $F$ is divided into independent bandwidth pools as depicted in Fig. 2, the system $P_r$ can be found from the congestion probability in individual bandwidth pools $P_{rF}$.

We consider networks with different $F$, each serving $N$ ONUs, which are uniformly distributed over all bandwidth pools. These networks have the same aggregate capacity which consists of $M$ wavelength channels, each with a data transport capacity $B$ Mb/s. We assume that an ONU, when active, requests a capacity of $R$ Mb/s. Therefore, a network with given $F$ is divided to $M/F$ bandwidth pools, each containing $F$ channels and $N_F = F \times (N/M)$ ONUs.

The congestion occurs in a bandwidth pool when the sum of requested bandwidths is larger than the capacity of bandwidth pool. Since each active ONU requests $R$ bandwidth, the congestion occurs when the number of active ONUs is larger than the threshold of $D_F = (F \times B)/R$. The traffic model of an ONU is modeled as an ON/OFF process with probability $p$ in ON state. As we assume that ONUs behave independently, the probability that $k$ out of $N$ ONUs are active is given by the binomial distribution

$$P_{rF}[k] = \binom{N}{k} p^k (1-p)^{N-k}.$$  \hspace{1cm} (1)

Using Chernoff’s upper bound, with the moment generating function $M_k(s)$ of $P_{rF}[k]$ and parameter $s > 0$, we find

$$P_{rF}[k > D_F] \leq e^{-sD_F} M_k(s).$$ \hspace{1cm} (2)

where

$$M_k(s) = E[e^{sD_F}] = \sum_{k=0}^{N_F} e^{sk} P_{rF}[k] = \{p(e^s - 1) + 1\}^{N_F}.$$ \hspace{1cm} (3)

The tightest bound is [25]

$$\min_{s>0} e^{-sD_F} M_k(s).$$ \hspace{1cm} (4)

We can find $s$ by solving

$$d \left( e^{-sD_F} M_k(s) \right) \bigg|_{ds} = 0.$$ \hspace{1cm} (5)

Solving (5), we obtain

$$e^s = \frac{(1-p)}{p(N_F-D_F)}.$$ \hspace{1cm} (6)

Hence, (2) becomes

$$P_{rF}(k > D_F) \leq \left( \frac{p}{D_F} \right)^{D_F} N_F \left( \frac{1-p}{N_F-D_F} \right)^{N_F-D_F}.$$ \hspace{1cm} (7)

Since bandwidth pools can be considered as independent stochastic systems, the upper bound of the system congestion probability experienced by an incoming request $P_r$ is the average of $P_{rF}$ of individual bandwidth pool. In a particular case, if all bandwidth pools are identical in terms of ONUs, capacity, and offered load, $P_r$ is directly given by (7).

B. Power Consumption

By leveraging the network reconfigurability, a simple strategy can be used to save the power consumption in which ONUs are concentrated to several wavelength channels and allowing the other channels to be in standby mode during off-peak hours. Let $e_C$ and $t_P$ (kW) denote the power consumption by a channel in the OLT (the channel line card and related parts) and number of peak hours per day, respectively. Assuming that all $M$ channels need to be enabled to accommodate the peak load, we can derive the energy consumption (kWh) during peak-hours

$$E_P = t_P M e_C.$$ \hspace{1cm} (8)

Hence, the energy consumption (kWh) in off-peak hours in one day

$$E_O = (24 - t_P) m_O e_C$$ \hspace{1cm} (9)

where $m_O$ is the number of active channels in off-peak hours. Since a network with given $F$ contains $M/F$ independent bandwidth pools, we can derive the number of active channels in off-peak hours

$$m_O = \left( \text{number of active channels in a bandwidth pool} \right) \times \left( \text{number of pools} \right) = \text{ceil}(F \times L_O/C_F) \times (M/F)$$ \hspace{1cm} (10)
where $L_Q$ (Mb/s) is the actual traffic load in a bandwidth pool in off-peak hours, $C_F$ (Mb/s) is the capacity of a bandwidth pool, and the ceil function returns the nearest integer that is greater than the argument.

Apart from the energy consumption by channels, we consider a baseline consumption $E_B$ which accounts for 20% of the maximum line card consumption $E_{MAX}$ (20% of $24M C_r$). Finally, we can derive the daily energy consumption at the OLT normalized to the maximum consumption

$$E_{OLT} = \frac{E_Q + E_F + E_B}{E_{MAX} + E_B} = \frac{t_P M + (24 - t_F)M_Q + 4.8 M}{28.8 M}.$$  

(11)

IV. NUMERICAL RESULTS

The numerical results are computed for networks with 16 wavelengths ($M$), each with a net capacity of 10 Gb/s. In addition to the static network ($F = 1$ network) and the fully flexible network ($F = 16$ network), we also investigate network with limited flexibility $F = 2, 4,$ and 8. The total number of ONUs in each network is 512, thus 32 ONUs per wavelength channel in average. The bandwidth request of each ONU $R$ is 500 Mb/s.

Since the analytical result gives the upper bound of congestion probability, which can be considered as the worst case performance, a simulation model is developed in OPNET using the same specifications to obtain most likely congestion probability. In the simulation model, the resource reservation map shown in Fig. 3 is the central entity for the book keeping of occupied and free bandwidth. The scheduling algorithm uses the map as the reference for guaranteed bandwidths it should provide to the ONUs. Basically, the map is a 2-D array in which rows represent wavelengths and each element represents a bandwidth block of 1 byte in a 125 $\mu$s scheduling round. Based on the flexibility constraint, the reservation algorithm finds wavelengths with enough free blocks in the bandwidth pool for reservation else the incoming request is rejected if no available wavelength is found. When more than one available wavelength is found, the least occupied wavelength is selected. For example, a request of 500 Mb/s connection in a fully flexible network is equivalent to finding the least occupied channel and reserving 7813 free blocks if there are enough of them. The reserved blocks for a connection are changed to the free state when the teardown signal is received. In an ONU, the connection request interarrival time and the hold time follow the exponential distribution.

Both the worst case performance and the most likely performance are shown in Fig. 4 in solid lines and dash lines, respectively. The simulation results converge with the analytical bounds in low congestion probability because Chernoff’s bound is tighter for the lower tail of the binomial distribution. The bounds become looser when the congestion probability is higher. However, simulation results show a similar trend to the analytical results: the traffic capacity (the normalized offered load at 1% blocking) of flexible networks does not linearly increase with the degree of flexibility. The $F = 2$ network has the worst case traffic capacity of 0.436 which is 21.1% higher than that of $F = 1$ network. When we upgrade from $F = 8$ network to $F = 16$ network, the improvement drops to only 5.3%.

This trend is clearly shown in Fig. 5 for various values of bandwidth request. The absolute values of traffic capacity for each bandwidth requests are different but they all express the same trend: the network with very limited flexibility ($F = 2$ or $F = 4$) can significantly improve the traffic capacity while highly flexible networks can further improve the capacity but with much lower margins.

In fact, the demand from each ONU can be different and change over time. Our model cannot directly give the traffic capacity in that case. However, the traffic capacity still falls in a region defined by two curves in Fig. 5. For example, if the bandwidth request is somewhere between 400 and 600 Mb/s, the region is defined by the highest and the lowest curve in Fig. 5. In the model, the ONU reallocation time is neglected. However, the ONU reallocation time is not always zero and not the same for different architectures and dependson the protocol employed. For instance, the ONU reallocation time can be zero if a make-before-break reallocation can be realized in the architecture proposed in [16]. In other architectures, the reallocation time cannot be zero as the laser tuning time should be considered. The model also does not consider the logical limitations. It assumes that a wavelength channel can be shared by
any number of ONUs. However, it might be not true in practice since GPON-like protocols only allows up to 128 ONUs per PON but EPON-like protocols allows up to 32 767 ONUs (virtually unlimited). Therefore, the exact performance is different from case to case but we believe that the nonlinear trend still holds true.

The OLT daily energy consumption depicted in Fig. 6 is obtained by evaluating (11) for networks with $F = 1, 2, 4, 8,$ and 16. We assume that in peak hours, all of 16 channels are active to accommodate 100% traffic and in off-peak hours, the traffic is 30% of the peak traffic. Regardless of the number of peak hours per day, the $F = 1$ network (static) consumes the same power because in any case, it is not able to move ONUs out of a channel in order to power down the transceiver. Another intuitive observation is that there is no power saving in flexible networks when the number of peak hours is 24. However, at a typical value of 5 or even 10 peak hours per day, the figure reveals an trend analogous to the traffic capacity analysis. The networks with a limited flexibility can thus significantly reduce the power consumption, while highly flexible networks can further reduce the consumption but in a small amount.

The trend is clearly shown in Fig. 7 in which there is a sharp decrease in the consumption when the degree of flexibility changes from 1 to 2. The $F = 2$ network indicates a saving of 33% in the OLT daily energy consumption in case of 5 peak hours per day, while $F = 16$ network can only save 13% more. Even then there is no difference between the consumption of $F = 1$ and $F = 2$ because they have to enable the same number of channels in off-peak hours. The off-peak traffic assumption (30% of the network capacity) leads to this phenomenon.

To investigate how the level of off-peak traffic affects the power saving, we vary the off-peak traffic load as shown in Fig. 8. In this figure, the number of peak hours is fixed to be 5 hours per day. The plot confirms an intuitive prediction that there is no saving when off-peak traffic load is almost equal to network capacity. The network with $F = 2$ is able to save the power when the off-peak traffic load is lower than 50%. Since in off-peak hours networks are usually under 50% utilization, the $F = 2$ network is potentially saving considerable power although ONUs in this network can be only reassigned between two wavelength channels. A lower level of off-peak traffic is more favorable for highly flexible networks. However, $F = 2$
can still provide more than half of the saving achieved by the fully flexible network at the level of 10%.

The power consumption analysis uses a basic model of real traffic that varies smoothly from the peak to the bottom during 24 hours, as can be seen in a typical access traffic trace [22]. To compute the daily energy consumption for a real traffic profile, our model is still applicable since we can break down the 24 h trace to segments, each of which covers a small period, e.g., 5 min. Since the segment is relatively short, the traffic in the middle timestamp or the average traffic volume can approximate the representative traffic volume of each segment in that period. Then, we can yield the energy consumption of each segment by applying the model. Finally, the daily energy consumption is obtained by the sum of all segments.

We apply this method to an actual traffic trace captured at a KPN central office (CO) in Amsterdam which is shown in Fig. 9. The profile is the aggregate Internet traffic from mixed consumers and businesses in a high take-rate access network. Because of the high-take rate, it can show a worst case scenario power saving. While in networks with a low take rate (in early years of deployment), the peak utilization is usually far below 50% of the capacity resulting in a much higher power saving. In this profile, the load reaches the lowest level around 4–8 AM since both consumer and business tend to be inactive in this period. From the start of office hours, the load increases gradually and reaches the highest level around 9 PM in the evening. The energy consumption based on this profile for each degree of flexibility is shown in Fig. 10 where the nonlinear trend is confirmed. The $F = 2$ and $F = 4$ networks indicate a saving of 18.8% and 32.7%, while the $F = 8$ and $F = 16$ networks save 37.0% and 39.5%, respectively. Assuming the OLT consumes 100 W power when fully active, the $F = 2$ and $F = 4$ networks potentially save 164.7 and 286.5 kWh/OLT/year, respectively. Furthermore, if the equipment power consumption reduces, we can simultaneously save power in the cooling system (rack and building cooling). Therefore, the energy bill for the CO, where the OLTs are located, is lowered considerably indicating a reduction in the operating expenditure and in the CO$_2$ footprint of access networks.

In this section, the broadcast-and-select architecture shown in Fig. 11(a) is considered to be modified to $F = 2$ flexibility. The modified architectures are then compared with the original one and the static architecture in terms of power budget to evaluate how $F = 2$ can help to reduce the network cost.

The broadcast-and-select architecture is a prominent candidate for ROAN because the ODN is passive and compatible to current TDM PONs. All the wavelength channels are broadcast to ONUs by one or more power splitting stages and ONUs select the working channel by a tunable transceiver. This architecture is fully flexible since an ONU is exposed to all the wavelengths but requires excessive power budget because of its broadcasting nature. For example, the broadcast-and-select with 16 wavelength channels and 32 ONUs per channel requires theoretically 27 dB only for the splitting loss (1:512) while a practical loss in the field can be as high as 32 dB due
to imperfections such as splitter nonuniformities and splice losses [26].

Limiting the degree of flexibility to 2 while the network performance is still largely preserved as proved in the previous section can reduce the excessive power budget requirement. Accordingly, the power splitter can be replaced by a combination of AWG, combiners, and splitters, which can be realized by discrete components or an integrated device, as shown in Fig. 11(b). If the wavelength planning allows the cyclic property of the AWG to be exploited, we can further reduce the insertion loss by the architecture shown in Fig. 11(c). In fact, an architecture with $F = 3$ has been proposed in [17]. In the same fashion, the $F = 4$ network can be achieved by using the fourth order of AWG free spectral range. This method provides a smooth path to upgrade network capacity and degree of flexibility without any change in the ODN.

The accumulated worst case insertion loss in the RN of various networks, each with 16 wavelength channels and 512 ONUs, is shown in Fig. 12. The worst case 1:2 splitting loss of 3.55 dB is used as a base for the splitting ratio scaling [26]. By limiting the flexibility, the architecture in Fig. 11(c) saves 8.65 dB compared to the broadcast-and-select and requires 3.55 dB more power when compared to the static network [see Fig. 1(a)]. The power saving allows more users to be supported, longer reach, lower cost transceivers while avoiding the use of optical amplifiers in the field.

Furthermore, limited flexibility also makes the network scalable in terms of wavelength and ONU dimensioning. Fig. 13 shows the RN worst case insertion loss when the number of wavelength channels is increased. As the number of ONU per wavelength is kept at 32, it is clear to see that the insertion loss for the broadcast-and-select increases with the number of wavelengths. On the other hand, $F = 2$ and static networks can maintain almost the same insertion losses because the splitting ratio for each wavelength is the same (1:64 for $F = 2$ and 1:32 for static). A slight increase in the insertion losses is due to the AWG insertion loss, which is a component of RN insertion loss, increasing slightly with port count. However, a commercially available 88-channel 50 GHz spaced AWG induces only 5.5 dB insertion loss at most [27]. However, the broadcast-and-select can be a suitable architecture for low channel count since there is no significant difference in the insertion loss when the number of wavelength is less than 8.

VI. CONCLUSION

In this paper, we have shown that ROANs can reduce network congestion in peak hours and reduce the power consumption in nonpeak hours. Furthermore, the analysis shows that it is not necessary to have a high or full flexibility since an architecture with limited flexibility can largely achieve the merits of reconfigurability. The most limited-flexibility network, when $F = 2$, can improve the traffic capacity by 21.1% and reduce the OLT daily energy consumption by 18.8% in comparison to the static network. Based on some specific assumptions, the OLT of such network can potentially save 164.7 kWh/OLT/year. A highly or fully flexible network can further reduce the congestion and the power consumption but the difference is marginal. Therefore, we conclude that the flexible WDM-TDM access networks improve the network efficiency considerably and it is not necessary to have a fully flexible network with its increased costs. However, we do not specify the optimal value for the degree of flexibility since the optimal value is not the same for different traffic scenarios, deployment scenarios, user types, number of wavelengths, and business policy amongst the plethora of considerations.

Furthermore, we have presented the impact of limited flexibility for the wavelength-selection-based architectures. The limited flexibility requires a lower power budget and is more scalable than the fully flexible broadcast-and-select. One can also apply this method to wavelength-routed architectures [13], [14] to reduce the number of switching elements in the RN.

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