# Limited flexibility

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# Limited Flexibility: a Cost-Effective Trade-off for Reconfigurable WDM-TDM Optical Access Networks

**Nguyen-Cac Tran, Ton Koonen, Chigo Okonkwo, Eduward Tangdiongga**
*COBRA Research Institute, Eindhoven University of Technology, P.O. Box 513, Eindhoven, 5612 AZ, The Netherlands,*
*c.tran.nguyen@tue.nl*

**Abstract:** We analyze the congestion probability and energy consumption of WDM-TDM optical access networks with different degrees of flexibility. Cost-effective limited flexibility can reduce congestion by 23% and consumed energy at the OLT by 33%.

**OCIS codes:** (060.2330) Fiber optics communications; (060.4256) Network optimization

## 1. Introduction

Optical access networks are widely deployed and are mainly based on Gigabit-capable passive optical network (GPON) or Ethernet PON (EPON). To further upgrade their capacity, a wavelength division multiplexing (WDM) dimension can be added along with increasing transmission bit rate per wavelength channel. The network can be a pure WDM-PON with a dedicated wavelength per single user or additional per-wavelength multiple access such as time division multiple access (WDM-TDM PON). WDM-TDM PONs, also known as wavelength stacked PONs, are considered as the natural evolution of TDM-PONs (GPON, EPON) [1]. A straightforward implementation called static WDM-TDM PON employs a fixed waveguide grating (AWG) and power splitters in the remote node (RN) to statically demultiplex and route $M$ wavelength channels, each feeding a number of optical network units (ONUs) as depicted in Fig. 1a.

The static WDM-TDM PON can be seen as a set of $M$ independent and separate TDM-PON sub-networks as shown in Fig. 1b. Due to fluctuations in access traffic, one or several sub-networks might be congested while the others have a lighter load. The local congestion can be solved if the network is able to reallocate traffic, which means the ONU(s) from a congested sub-network being reallocated to a light-loaded one in order to balance the load as depicted in Fig. 1c. The networks with such capability are called flexible or reconfigurable networks [1]. This feature can be handled either in the RN by wavelength routing [2-4] or in ONUs by wavelength selection [5,6]. As a result, the flexible networks are able to provide bandwidth-on-demand, have larger statistical multiplexing gain, and save energy consumption by enabling network capacity as needed and powering-down not-used capacity. However, this flexibility feature increases network complexity and thus costs which up to now is the biggest obstacle to enabling flexibility in WDM-TDM PONs. Do we have a way to overcome this obstacle? The study reported in this paper discusses a possible solution by optimizing the network architecture.

In this paper, we investigate trade-offs between network flexibility and cost when designing future optical access networks. A new parameter designated as the degree of flexibility $F$ is introduced to indicate the level of flexibility in a network. It is defined as the number of possible sub-networks to which an ONU can be relocated. 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 $F = M$. In a network with only $F = 2$, where an ONU in this network can be reallocated only between two specific sub-networks in $M$ sub-networks, the analytical results indicates a dramatic reduction in the congestion probability and the energy consumption at the OLT.

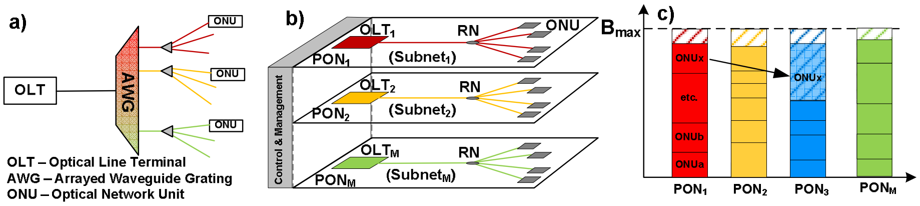

Fig. 1. a) Schematic representation of static WDM-TDM PON, b) The high level view of WDM-TDM PON with M channels, c) An example of bandwidth allocation over a flexible WDM-TDM PON

## 2. Congestion Probability and Energy Consumption Analysis

The congestion probability $P_b$ is analyzed for networks with different degree of flexibility $F$, each serving $N$ ONUs uniformly distributed over all wavelength channels. All networks have $M$ wavelength channels, each with a data transport capacity $B$. We assume that an ONU, when active, needs a capacity of $R$. The traffic model of an ONU is modeled as an ON/OFF process with probability $p$ in ON state. As we assume that the ONUs behave independently, the probability that $k$ out of $N$ ONUs are active is given by the binomial distribution

$$\Pr[k]=\binom{N}{k}p^{k}(1-p)^{N-k} \tag{1}$$

Using Chernoff's upper bound, with the moment generating function $M_k(s)$ of Pr[k] and parameter $s$>0, we find [7]

$$\Pr[k>D]\le e^{-sD}M_k(s) \tag{2}$$

By optimizing $s$ such as the bound is as tight as possible, we can derive

$$\Pr[k>D]\le\left(\frac{p}{D}\right)^{D}N^{N}\left(\frac{1-p}{N-D}\right)^{N-D} \tag{3}$$

With the network degree of flexibility $F$, the system is divided to $M/F$ independent subsets of wavelength channels with $F$ channels per subset. An ONU freely moves within the subset it belongs to. The congestion occurs in a subset when the number of active ONUs is larger than the threshold of $D_F = F\times(B/R)$ with number of $N_F = F\times(N/M)$ ONUs per subnet. Hence the upper bound of congestion probability experienced by an incoming request is

$$\Pr_F(k>D_F)\le\left(\frac{p}{D_F}\right)^{D_F}N_F^{\;N_F}\left(\frac{1-p}{N_F-D_F}\right)^{N_F-D_F} \tag{4}$$

In the flexible networks, a simple strategy can be used to save energy consumption in which ONUs are concentrated to several wavelength channels and let other channels go to standby mode in non-peak hours. Where $e_c$ denotes the energy consumption per hour by a channel (the channel line card at the OLT and related parts) and $h_p$ is number of peak hours per day, we derive the power consumption in peak hours as $h_pMe_c$. The power consumption in non-peak hours is $(24-h_p)m_ae_c$ where $m_a$ is number of channels in active mode. The baseline energy consumption is 20% on top of the maximum line card energy consumption (*20% of* $24Me_c$). Finally, we can derive energy consumption at the OLT per day normalized to the maximum energy consumption:

$$E_{OLT}=\frac{h_pMe_c+(24-h_p)m_ae_c+0.2\times 24Me_c}{24Me_c+02\times 24Me_c}=\frac{h_pM+(24-h_p)m_a+4.8M}{28.8M} \tag{5}$$

In non-peak hours, the system enables just enough wavelength channels to accommodate non-peak traffic $L_{non\text{-}peak}$, therefore $m_a$ = *(number of active channels in a subset)×(number of subsets)* = $ceil(F\times L_{non\text{-}peak}/L_{peak})\times(M/F)$. The ceil function return the smallest integer that is greater than the argument.

## 3. Numerical Results and Discussions

By applying Eq. (4) to the systems with number of wavelength channels $M$ = 16, wavelength transport capacity $B$ of 1.25Gbps, number of ONUs N of 512, request capacity $R$ of 63 Mbps and degree of flexibility $F$ of 1, 2, 4, 8, and 16, we obtain the graph in Fig. 2a. The figure also includes the simulation results from a proprietary simulation model built in OPNET. The analytical bounds can be seen as the worst-case performance while the simulated results can be seen as the most-likely performance. The simulation results converge with the analytical bounds when the probability reduces 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 in which the traffic capacity (the normalized offered load at 1% blocking) of flexible networks is not linearly increasing with the degree of flexibility. The trend is depicted in Fig. 2c where the network with very limited flexibility ($F$=2) can significantly improve the traffic capacity while highly flexible networks can further improve the capacity but with much lower margin.

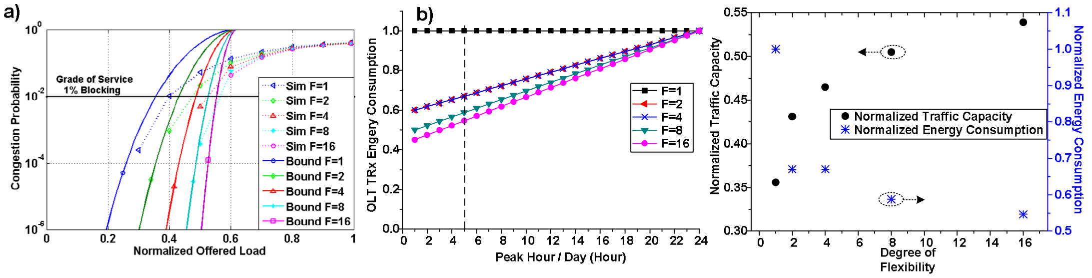

Fig. 2. a) Congestion probability for request of 63 Mbps in networks with different degree of flexibility (F), b) Energy Consumption of OLT TRx and related parts in networks with different F relative to the maximum energy consumption, c) Traffic capacity at 1% blocking and energy consumption at 5 peak hours per day

Using Eq. (5), Fig. 2b shows the results of evaluating the OLT energy consumption with different degrees of flexibility. We assume that in peak-hours all of the 16 channels are active to accommodate 100% traffic and in non-peak hours the traffic is 30%. The figure also reveals the analogous trend to the congestion analysis. The network with very limited flexibility ($F$=2) can significantly reduce the energy consumption while highly flexible networks can further reduce the consumption but with much lower margin as also depicted in Fig. 2c. There is no difference between the energy consumption of *F*=2 and *F*=4 network because they have to enable the same number of channels in non-peak hours. At a typical value of 5 peak hours per day, the network with *F*=2 indicates a saving of 33% in the OLT energy consumption per day compared to the static network. Assuming the OLT consumes 100 W when fully active, with *F*=2, the network saves 289.1 kWh/OLT/year. Generally, if the equipment energy consumption reduces, we also save energy for the cooling system (rack and building cooling). Therefore, the energy bill for the central office, where the OLTs are located is reduced considerably.

Limiting the network flexibility also has further advantages when we look at the fully flexible network architecture. Take the broadcast and select architecture shown in Fig. 3a as an example, all the wavelength channels are broadcasted to every ONUs in the RN by a power splitter. The fully flexible configuration requires extremely high optical power budget, e.g., 27 dB only for 1:512 splitting loss excluding transmission loss. If the network flexibility is limited to 2, the power splitter can be replaced by a combination of an AWG, combiners, and splitters as shown in Fig. 3b. If wavelength planning allows using the cyclic property of the AWG, we can further reduce the optical loss as the architecture shown in Fig. 3c. The accumulated insertion loss in the RN of various systems with 16 wavelength channels is shown in Fig. 3d. By limiting the flexibility, the architecture in Fig. 3c saves 7 dB compared to the broadcast&select and requires 3 dB more power when compared to the static network. The saving power allows to have more users, increase reach, use low-cost receivers or avoid using optical amplifiers in the field.

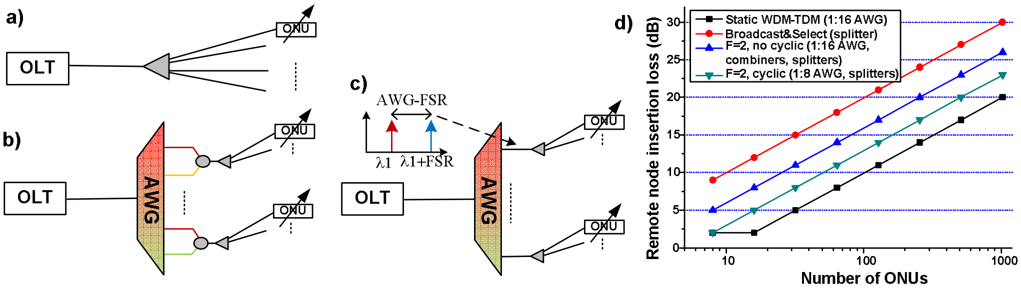

Fig. 3. a) Schematic representation of broadcast&select architecture, b) Schematic representation of F=2 architecture, the ONUs are uniformly distributed to each branch, c) Schematic representation of F=2 architecture exploiting cyclic property of the AWG, d) Accumulated insertion loss in the remote node of various architectures

## 4. Conclusion

We analyzed the congestion probability and the energy consumption of WDM-TDM optical access networks with different degrees of flexibility. The evaluation shows that a degree of flexibility of 2 can significantly reduce the congestion and the power consumption compared to the static network. With some specific assumptions, we showed that the OLT of such network can potentially save 289.1 kWh/OLT/year. The fully flexible network can further reduce the congestion and the energy consumption but the difference is marginal. Therefore, we conclude that the flexible WDM-TDM access networks improve the network efficiency considerably but it is not necessary to have a fully flexible network with its increased costs.

We further presented the impact of limited flexibility for the broadcast&select architecture. A saving of 7 dB in the power budget was shown for the optical distribution network. One can also apply this method to wavelength routing architectures [2-4] to reduce switching elements in the RN. We believe that our study can help to design future optical access networks to provide high bandwidth to end-users with minimal cost and energy consumption.

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