# New and Improved approaches for Dynamic Bandwidth and Wavelength allocation in LR WDM/TDM PON

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***Abstract*—Dynamic Bandwidth Allocation is a major open research challenge in the migration of Passive Optical Network (PON) systems towards Long Reach PON, especially when hybrid WDM/TDM is used (LR WDM/TDM PON). New and efficient solutions for Dynamic Bandwidth and Wavelength Assignment are sought to address two main critical issues of such PON systems: how to schedule the transmissions over multiple wavelengths and how to efficiently exploit the bandwidth in presence of the long propagation delays that characterize long reach scenarios. While several DBAs have been proposed for long-reach single-wavelength PON system or for WDM/TDM hybrid PONs (with no regard to the long reach aspect), only few DBAs have been investigated in the case of combined LR WDM/TDM PON scenario. Regarding LR TDM PONs, one of the most performing and widely used dynamic allocation schemes is the Multi-thread polling. Although this algorithm has provided good results when applied in these kind of networks, it has never been implemented into a LR WDM/TDM PON. For what concerns this latter network configuration, one of the most straightforward methods for upstream bandwidth and wavelength allocation is the Earliest Finish Time (EFT) algorithm. In this work we implement the Multi-thread polling in a LR WDM/TDM PON providing results in terms of average packet delay. Moreover, we investigate the behaviour of both Multi-thread algorithm implemented in a hybrid WDM/TDM PON and EFT algorithm in different network scenarios where the number of wavelengths changes, in order to evaluate the improvement introduced by the statistical multiplexing. Based on such evaluations, we discuss some possible guideline to efficiently accomodate different types of traffic (e.g., data traffic, voice traffic) in combined structures as Fixed and Mobile converged (FMC) access networks.**

## I. Introduction

Long Reach Passive Optical Networks (LR-PONs) [1], an evolution of PONs where the reach of the optical segments is significantly extended, are expected to relevantly simplify the metro-access network architecture, by reducing the number of equipment interfaces, network elements and node placements, and, in turn, to reduce the network's Capital Expenditure (Capex) and Operational Expenditure (Opex). For example, through LR-PON technology, the access network headends can be located closer to the backbone network. Therefore these networks are considered as a promising technology to provide higher capacity and extended coverage of optical access systems.

A typical PON is composed of an Optical Line Termination (OLT) located at the Central Office (CO) and several Optical Network Units (ONUs). A common feeder fiber connects the OLT to a passive optical splitter/combiner through which the signal is conveyed to each ONU in the network. The ONUs share the upstream channel in the time domain, with Time Division Multiple Access techiques (TDMA) whereas the downstream channel is broadcasted to all ONUs. This basic implementation of PON can be also referred to as TDM-PON.

In the last few years, in order to increase the split ratio, the number of network users, and the offered bandwidth, several solutions using WDM (called WDM-PON) have been presented [2]. A simple version of WDM-PON, where a pair of wavelengths is assigned to each ONU, can provide a large amount of bandwidth to final users. However, this approach can lead to inefficiencies in the use of the available capacity because ONUs do not always transmit or use the entire channel capacity. This is why it is important to combine WDM with TDM in the access system in order to increase the channel utilization by sharing multiple wavelengths among several ONUs.

The evolution from LR TDM PON towards LR TDM/WDM PON is a quite recent research topic motivated by the need of such network architectures to support higher capacity. LR WDM/TDM PON system is an interesting high bandwidth, energy efficient future network solution and it combines the advantages of Long Reach and WDM and TDM systems.

The development of LR WDM/TDM PON architectures [3], [4], [5] poses a set of new research challenges both in terms of transmission technologies and in terms of control protocols. Among the latter, a challenging problem consists in developing new and efficient Dynamic Bandwidth and Wavelength Allocation (DBWA) algorithms for LR WDM/TDM PONs. These algorithms can provide an effective utilization of the upstream channel and should be devised with the aim of minimizing the average packet delay between the OLT and each ONU.

Among the proposed DBWA algorithms, the most straightforward and widely used DBWA method is the Earliest Finish Time (EFT) algorithm which allocates the transmissions on the first available wavelength. One enhancement of the EFT algorithm is the Earliest Finish Time with void filling (EFT-VF) algorithm for LR WDM/TDM EPON (Ethernet-based PON) [6], which is one of most promising scheduling method for such kind of networks. EFT-VF has a low complexity but it provides good results in terms of average packet delay and channel utilization. In this work we evaluate only DBAs for

EPON. The possible extension of these ideas to GPON has not been investigated and is out of the scope and objectives of this research.

The contribution of this work is threefold: i) we investigate the behavior of one widely used algorithm for LR-PON, the Multi-thread polling, by extending in the case of a LR WDM/TDM PON. To the best of our knowledge, the Multi-thread polling has never been applied to a hybrid WDM/TDM access network. ii) Moreover we study the network performance when the number of wavelengths is varied and different DBWAs are used. iii) Finally, based on the previous outcomes, we discuss possible novel LR WDM-TDM PON solutions to efficiently accomodate different services, and consequently different types of traffic, as in the case of convergence of fixed and mobile traffic backhauling.

The algorithms studied in this work use as a signalling protocol the Multi-Point Control Protocol (MPCP) in which five types of control frames are defined: REGISTER REQUEST, REGISTER, REGISTER ACK, REPORT and GATE. While the first three are used by the ONU during the discovery and registration procedure, the last two are used to plan the data transmissions. In particular the REPORT message is used by the ONU to communicate to the OLT the status of the queue. The GATE instead is used by the OLT for granting the upstream timeslot to each ONU.

The rest of the paper is organized as follows: in section II we present an overview of already proposed solutions for dynamic scheduling and wavelength assignment. In section III we present the basic idea of the EFT and EFT-VF algorithms which are used as a benchmark to evaluate the performance of our proposed implementation of the Multi-thread algorithm in LR WDM/TDM PON. Section IV is dedicated to the explanation of the basic functionalities of the Multi-thread polling and to its implementation in a LR WDM/TDM PON that we propose in our work. In section V we provide simulation analysis and illustrative results of the previously presented algorithm implementations. In section VI we evaluate different DBWAs under different network configurations, where we vary the number of wavelengths in the system. Section VII is devoted to the discussion of novel possible network solutions for the convergence of fixed and mobile (FMC) traffic backhauling. Finally, in section VIII, we give some concluding remarks.

## II. Related works

A certain number of DBWA scheduling has been presented in the last years, some of which are architecture dependent [7]. In fact, some of the recently proposed DBWA for LR WDM/TDM PON are designed for particular network solutions. The first of these is specifically designed for the STAR-GATE EPON [8]. Another architecture dependent DBWA is Slotted Medium Access Control (SMAC), designed for SPON [9]. Finally the Optical Burst Switching DBA (OBS-DBA) is specifically designed for SARDANA architecture [10].

Other solutions that have been proposed can be used for generic network architectures. Among them there is the GATE Driven DBA (GD-DBA) [11] which allows the OLT to send GATE messages to the ONU spontaneously, based on its current information of ONU requirements aquired from REPORT frames sent previously.

The Latest-Finish Time with Void Filling (LFT-VF), Distanced Based Grouping (DBG) and Earliest-Finish Time with Void Filling (EFT-VF) algorithms [6] take advantage of the distribution of the distances from the OLT to the ONUs, trying to remedy the inefficiencies in the utilization of the upstream channel given by this distribution. In the DBG algorithm ONUs are grouped by the distance from the OLT. In each group the ONUs have similar distances from the OLT and use the same wavelength to transmit. Each group of ONUs use a different wavelength. The idea of this algorithm is to avoid the formation of voids in the upstream channel. LFT-VF algorithm, instead, chooses the channel with the latest horizon. In particular the selected wavelength must have the latest finish time among all channels. The void filling part keeps track and tries to fill the voids left on the upstream channel. The same objective is at the base of the EFT-VF algorithm which chooses the channel where the previously scheduled transmission will end first. Basically these last three algorithms try to solve, using different strategies, the same problem solved by the Multi-thread algorithm [12] which aims to reduce the waste of bandwidth in each polling cycle adding two or more threads in the middle of the first one.

DBWA in LR WDM/TDM PONs, like generic DBA, can be viewed as consisting of grant sizing and grant scheduling problems [13]. In this work we focus on the decision of when to schedule the transmission of ONUs with the aim of reduce the average packet delay.

We assume that the grant sizing has already been solved during a preprocessing phase where it is calculated the maximum amount of data which can be transmitted by each ONU in each cycle time in order to grant a certain capacity to each ONU.

## III. EFT and EFT-VF Basic functionalities

The EFT algorithm [6], is the most straightforward method to allocate bandwidth and wavelengths in a LR WDM/TDM PON. Indeed, the EFT allocates a new transmission on the first available wavelength, which is the wavelength where the latest scheduled transmission will end first. The EFT-VF algorithm, which is an enhancement of the EFT algorithm, is based on the observation that in a PON, and even more in LR-PONs, there is a high variability among the possible distances between OLT and final users, and consequently very diverse round-trip-time values among the different ONUs. The result is what the authors in [6] refer to as scheduling voids. A scheduling void is a period of time between two subsequent transmissions where there is no scheduled transmissions on the channel and this usually happens when the time the gate takes to reach the ONU, plus time that data frames take to reach the OLT is very high. The Void Filling part of the EFT-VF algorithm aims at filling these voids by scheduling other transmissions during the time when the channel is unused. A void must be long enough to enable transmissions; a time period with this feature is called *eligible void* and its length in bytes is equal to the length of data requested by the ONU plus the REPORT message. Instead the EFT algorithm schedules the transmission on the wavelength that becomes available first. It has already been proven that the EFT-VF algorithm yields better performance than EFT. In our work, we use some features of this algorithm to find a scheduling strategy which improve the performance delay.

## IV. Multi-thread polling algorithm

### A. Multi-thread polling in LR TDM PONs

Multi-thread (MT) algorithm has been proposed as a solution to overcome the problem of the increased RTT in a LR TDM PON, with respect to TDM PONs, which leads in general to an increased average packet delay. Therefore, to achieve better performance in terms of packet delay in a LR-PON, the basic idea of the Multi-thread algorithm is to allow an ONU to send its REPORT before the previous GATE message is received. Practically, this allocation scheme exploits the benefits of having multiple polling processes running simultaneously. Users are enabled to send bandwidth requests before receiving acknowledgement from the OLT for the previously requested data. In such way, the ONUs do not have to wait until the end of data transmission of the previous thread to send a new REPORT message asking for a new transmission opportunity. With this strategy, the overall average packet delay of the LR-PON can then be lowered.

### B. Multi-thread implementation in LR WDM/TDM PONs

In this section, we introduce our proposed extension of the Multi-thread algorithm over hybrid LR WDM/TDM PONs to which we refer as WDM-MT. To the best of our knowledge, this is the first time that the Multi-thread is applied in LR WDM/TDM PONs. When MT is implemented in a WDM/TDM network, the basic idea of having multiple polling processes running simultaneously remains the same and furthermore the benefits of having more wavelengths are exploited. However, the transmission of a generic thread $t$, for $ONU_i$ must be scheduled after the end of the transmission of thread $t-1$, because a single ONU can only send one transmission at a time. As a consequence, it may happen that on a particular wavelength a transmission is not scheduled at the earliest available time of the channel, but it is forced to wait till the end of the previously granted transmission for the same ONU. We refer to this scheduling constraint as *thread coordination*. This constraint introduces an additional delay and it may lead to inefficiencies in the utilization of the channel.

By using multiple wavelengths, the average time between two subsequent transmissions of the same $ONU_i$ is significantly decreased. However, note that, the greater the number of wavelengths used, the more the thread coordination constraint affects the algorithm performance. The fact of having more wavelengths gives a higher possibility to allocate more transmissions at the same time. Unfortunately, the thread coordination constraint limits this possibility avoiding that different transmissions of the same ONU are allocated during the same period. If two different transmissions of the same ONUs can not be scheduled during the same time period, may happens that one of these two transmissions will be delayed until the end of the previous one. In such way, more voids are created in the channel.

## V. Illustrative numerical results

### A. Simulation Framework

To evaluate the performances of the proposed implementation of the MT algorithm, we implemented a network simulator based on the Discrete Event Simulation Library (DESL) [14], modified to simulate a LR WDM/TDM PON. This simulation tool only considers the implementation of the upstream transmissions. In order to reflect the property of the real Internet traffic, we generate self-similar traffic by aggregating multiple sub-streams, each consisting of alternating Pareto-distributed ON/OFF periods, with a Hurst Parameter of 0.8. The simulator generates packets in the forms of Ethernet frames with a length distributed between 64 and 1518 bytes. The buffer size of each ONU has a limited length of 10 Mbytes. The polling cycle time is 2 ms and according to this value the amount of bytes ($B_{max,i}$) that each ONU can transmit in each cycle time is 7687 bytes, where the $B_{max,i}$ is the same for each ONU. The guard band time between two subsequent transmissions is 1 $\mu s$. Our topology includes 128 ONUs all transmitting over all the 8 wavelengths. Each channel, consisting of a single wavelength, has a bit rate of 1 Gbit/s which gives a total capacity of 8 Gbit/s. As we simulate a Long-Reach scenario, the distances from the OLT to the ONUs are uniformly distributed between 80 km and 100 km. The load offered to the network by the ONUs varies during the simulation from 0.05 to 1 and, at this load the bit rate of each ONU is 62.5 Mbit/s. In our simulations we used a number of threads is equal to 2.

### B. Numerical Results and Discussion

We compare our results with pure EFT and with the EFT-VF algorithms to evaluate the improvement provided by our proposed implementation of the Multi-thread allocation scheme. All the DBWAs that we discuss and present have a similar computational cost which basically depends on the number of wavelengths of the LR-PON.

In Fig. 1 we plot the average packet delay versus the offered load. We can observe that our proposed implementation of the MT algorithm in a LR WDM/TDM PON introduces a significant improvement regarding the packet delay compared to both the EFT and the EFT-VF algorithms. For low loads, this improvement is particularly relevant whereas for medium loads it starts to decrease. Unfortunately, for relatively high loads the average delay provided by this scheme becomes very high. This behavior is due to the thread coordination effect introduced in Section IV which does not allow to efficiently exploit the multiple wavelengths. Note that, for low/medium loads, the average delay in the WDM-MT algorithm tends to

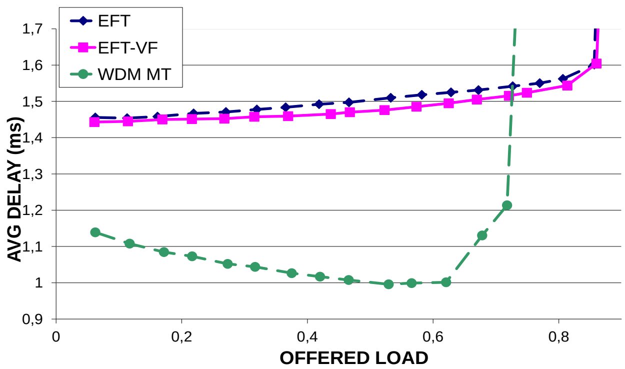


Fig. 1. Average packet delay comparison between EFT, EFT-VF, and Multi-thread over LR WDM/TDM PON algorithms.

become smaller for increasing traffic. This behavior is counter-intuitive, but it can be reasonably explained considering the transmission of control messages. In fact, at low loads, the length (in byte) of the packets emitted by the ONUs tends to be short, and so control messages are sent very often, negatively impacting algorithm performance. Conversely, when the load increases and the length of data packets becomes higher, the number of control messages is smaller, and less time is wasted in the control phase, allowing us to take more advantage from multiple and simultaneous polling processes. The EFT-VF algorithm shows an average packet delay slightly lower with respect of the EFT scheme. Such difference depends on the features of the access network where this allocation is applied. In fact the authors in [6] apply their algorithm in a very particular architecture, similar to SARDANA and SUCCESS, where the distances from ONUs to the OLT are very diverse. Conversely, we tested the EFT-VF scheme in a LR WDM/TDM PON where all the ONUs are at a very large distance from the OLT.

## VI. DBWA PERFORMANCE EVALUATION VARYING THE NUMBER OF WAVELENGTHS

### A. Simulation Framework

In this section we present the simulation framework of the EFT and the WDM-MT algorithms for diverse scenarios. With this study we aim at evaluating the gain introduced by the statistical multiplexing in a LR WDM/TDM PON for different DBWA algorithms. In Table I we define the values of the network parameters used in our simulations, where $N$ is the number of ONUs connected to the network and $W$ is the number of wavelengths. The *Bandwidth per ONU* ($B_{onu}$) is the maximum rate at which each ONU is allowed to transmit. Note that the values of the *Bandwidth per ONU* are computed by dividing the entire capacity of the network by the number of ONUs, so the normalized offered traffic load for different values of $W$ is kept constant by increasing $B_{onu}$. By doing so we expect our results to shw the pure gain due to statistical multiplexing. For both algorithms, the $B_{max,i}$ is the same for each $ONU_i$ and it is computed in order to have, for each network scenario, a maximum polling cycle duration equal to 2 ms, for the EFT algorithm, and equal to 4 ms, for WDM-MT algorithm. The guard band time between two subsequent transmissions is 1 $\mu s$. Finally, for WDM-MT algorithm, the number of threads used is T = 2.

TABLE I
NETWORK PARAMETERS FOR DIFFERENT NETWORK SCENARIOS

| | $W$ | $N$ | Capacity per ONU | Capacity per $\lambda$ |
|---|---|---|---|---|
| WDM EFT | 1<br>2<br>4<br>8 | 128 | 7.8125 Mbit/s<br>15.625 Mbit/s<br>31.25 Mbit/s<br>62.5 Mbit/s | 1 Gbit/s |
| WDM MT | 2<br>4<br>8<br>16 | 128 | 15.625 Mbit/s<br>31.25 Mbit/s<br>62.5 Mbit/s<br>125 Mbit/s | 1 Gbit/s |

### B. Numerical Results and Discussion

We evaluate the performance of the EFT and WDM-MT algorithms in network scenarios with different number of wavelengths.

Figure 2 shows the average delay of the EFT algorithm in network configurations with different number of wavelengths. From Fig. 2 we note that by increasing the number of wavelengths it is possible to decrease the average network delay. Moreover, we can also notice that the gain introduced by doubling the number of wavelengths decreases when the number of wavelengths increases. In other words, the gain provided by a network scenario with W = 2 with respect to a scenario with W = 1 is much higher than the gain achieved by a scenario with W = 4 with respect to a case with W = 2.

In Fig. 2 we can also notice that congestion (i.e., when the average delay measured tends to assume very high values) in the different network scenarios occurs at different loads. This is due to the time per polling cycle which can not be used to transmit data due to the presence of guard band times which must be allocate between consecutive transmissions of different ONUs. In fact, increasing the number of wavelengths the average number of ONUs per cycle that transmit over a single wavelength decreases. Consequently, the average amount of guard band time per cycle, over each wavelength, decreases.

Figure 3 shows the average delay versus the offered load of the WDM-MT algorithm when this is adopted in network scenarios with different number of wavelengths. Like in the case of the EFT algorithm, Fig. 3 shows that when the number of wavelengths is increased the average delay decreases. Also using the WDM-MT allocation method, the gain introduced by doubling the number of wavelengths of the network decreases when the number of wavelengths increases.

Based on these observations, we can conclude that while in a LR WDM/TDM PON it is possible to improve the network performance by increasing the number of wavelengths, however it is not very convenient to add a high number of

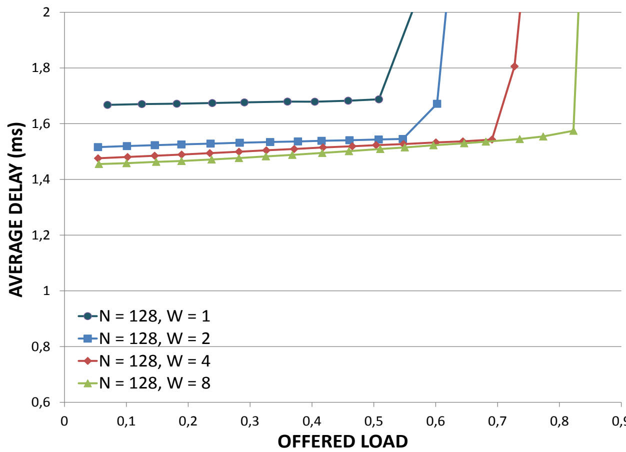


Fig. 2. Average packet delay of EFT algorithm in network scenarios with different wavelengths.

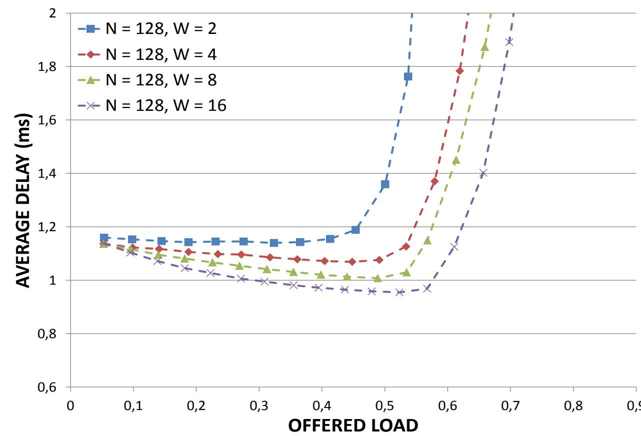


Fig. 3. Average packet delay of WDM-MT algorithm in network scenarios with different wavelengths.

wavelength since the improvement of the performance saturates soon. Note that this statement applies if the bandwidth assigned to each ONU ($Bonu$) is dimensioned in order to saturate the total network capacity.

## VII. Novel LR WDM/TDM PON Architecture and Solutions for FMC Backhauling

Based on the previous results in our work, we discuss some guidelines for the implementation of a optical access system which can efficiently serve different types of traffic, as in the case of an FMC architecture, by using a LR WDM/TDM PON.

In our work we have studied the performance of different bandwidth and wavelength allocation algorithms, namely the EFT and the WDM-MT algorithms, in scenarios with different number of wavelengths. By doing so, we have evaluated how the network performance in term of average delay varies if a LR TDM PON is used or a hybrid WDM/TDM PON with different numbers of wavelengths is exploited. In this study we have not included the analysis of the pure WDM PON for two main reasons: i) in WDM PONs each ONU transmits on a separate wavelength and it is provided a large bandwidth. Due to the bursty nature of the traffic, each ONU is not always transmitting, and the wavelength capacity is not efficiently exploited. Therefore, to install a pure WDM acces network can be very inefficient. ii) In our work we aim at evaluating the gain provided by the statistical multiplexing which can not be considered in a WDM PON. To provide such kind of analysis we use DBWAs, which are not used in WDM PON since there is no risk of collision between transmission of different ONUs. The results provided by our simulations show that with respect to a pure TDM PON (with a single wavelength) if a WDM/TDM PON is adopted we can improve the performance of the traffic, in term of average packet delay. Moreover, we noticed that the gain obtained by introducing more wavelengths decreases when the number of wavelengths increases. Based on this observation we can state that using a hybrid WDM/TDM PON can significantly improve the performance of the network even without dedicating an entire wavelength to each ONU. Based on Fig. 2 we can state that it is not necessary to add a high amount of wavelengths in order to improve the performance of the network. This result can lead to some interesting preliminary observations. First of all, if we are able to obtain a limited average delay allowing ONUs to transmit over a limited number of wavelengths we can design the access network dividing the entire spectrum of wavelength into subgroups in order to create a set of virtual PONs. Each virtual PON could be devoted to serve different sets of ONUs by dividing them, for example, on the basis of the types of service. In such way, the LR WDM/TDM PON could become an attractive solution to implement a FMC system, which by definition, has to serve different services with different performance requirements (e.g., average delay, maximum delay). The second reason is related to the cost of the network. The cost of a tunable transceiver depends also on the width of its tuning range (i.e., the number of wavelengths that a transceiver must be able to tune): the higher the tuning range, the higher the cost of a device [15], [16]. So, if we are able to achieve satisfying network performance with reasonably narrow tuning range of the lasers, we could be able to install multiple LR WDM/TDM PON with a small amount of wavelengths (also called virtual PONs), which can have a limited cost, instead of a single large WDM/TDM PON requiring transceivers with wide tunability.

## VIII. Conclusion

In this work we have presented, analyzed and evaluated different strategies for LR WDM/TDM PON to perform upstream scheduling and wavelength assignment. Simulation results show that the implementation which provides lower average packet delay, for low/medium traffic load, is our proposed implementation of the WDM-MT algorithm. For medium/high loads the MT algorithm, more than the other EFT solution, suffers from a sudden increase of delay. So, in a LR WDM/TDM PON, the pure application of Multi-thread algorithm does not replicate the same gain achieved in LR TDM PONs with respect to single thread polling, at least fo high loads.

We also provided some preliminary results regarding the dimensioning of the tuning range which can be used in a LR WDM/TDM PON. Based on these results we also provide some guideline to design, over LR WDM/TDM PON, an FMC system which serves both mobile and fixed traffic. We only provide preliminar ideas based on the observations of our simulation results. Further studies on this topic include, depending on the different types of service (and on their performance requirements), the study of an optimal number of wavelengths and the study of optimized methods to assign the bandwidth in a FMC, e.g, if we need to jointly allocate fixed and mobile traffic.

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