Dynamic Spatial Aggregation for Energy-Efficient Passive Optical Networks

A. Marotta*†, C. Centofanti*†, D. Cassioli*, F. Graziosi*, A. Pagano‡, N. Sambo§, L. Valcarenghi§
*University of L'Aquila, L'Aquila, Italy;
†WEST Aquila, L'Aquila, Italy;
‡Access Innovation, TIM-Telecom Italia, Torino, Italy;
§Scuola Superiore Sant'Anna, Pisa, Italy
Email: andrea.marotta@univaq.it

Abstract—**This paper introduces an approach to enhance energy efficiency in Passive Optical Networks (PONs) through dynamic spatial aggregation. The proposed architectural approach adapts to fluctuating traffic patterns. We evaluate our model against various traffic patterns and consider different PON power consumption scenarios and spatial system sizes. This approach can achieve up to 38% energy savings optimizing both bandwidth utilization and energy consumption.**

Index Terms—**PON, SDM, Energy Efficiency, Green.**

I. Introduction

In the quest to meet the ever-growing demands of modern communication networks, energy efficiency and densification of network infrastructures have emerged as paramount objectives. Densification, primarily driven by the advent of 5G and projected 6G technologies (encapsulating small cells, massive distributed MIMO and cell-free systems), and the shift towards Fiber-to-the-Everything deployments aim to accommodate the exponential increase in data traffic and connected devices. While capacity remains a foundational concern, the emphasis has progressively shifted towards creating networks that are not just scalable but also sustainable. As operational costs escalate, energy efficiency has emerged as a pivotal concern, both from an environmental and an economic perspective. To accommodate this, Passive Optical Networks (PONs) emerge as the best candidates due to their inherent capillarity which positions them perfectly to address the growing need for densification [1]. Simultaneously, they represent a promising platform to advance the "orthogonal" requirement of energy efficiency [2], [3].

The installation of new fibers is expected both due to traffic increase and the higher cell densification. The spatial dimension, in recent times, has emerged as a novel and promising direction to address these evolving needs of next-generation optical access networks. The foray into Spatial Division Multiplexing (SDM) offers the dual advantages of augmented capacity and heightened flexibility, addressing future imperatives around bandwidth. Efforts have been provided in leveraging the elevated capacity of SDM in PONs and harmonizing optical and radio access networks [4]. While there have been propositions for transmission systems geared towards SDM-PONs [5], there remains a relative paucity in exploration around resource assignment techniques that adeptly negotiate the complexities of multiplexing across space, wavelength, and time domains.

In this work, we introduce a novel PON architecture that leverages the spatial dimension for dynamic spatial lanes (e.g., *cores* in Multi Core Fibers (MCFs) or fibers in multi fiber scenarios) aggregation and disaggregation. The proposed architectural approach allows to adaptively activate and deactivate Optical Line Terminal (OLT) and Optical Network Unit (ONU) components in response to prevailing traffic conditions, aiming to optimize energy savings without compromising on performance. Through an examination of diverse traffic patterns, PON power consumption scenarios, and spatial system size, our findings highlight significant energy savings.

II. System Model

We consider the reference architecture shown in Fig. 1 where an OLT at the Central Office (CO) site is equipped with a number of OLT ports N. Each port serves an Optical Distribution Network (ODN) which allows to serve the ONUs through one or more splitting levels realized through optical splitters referred to as Remote Nodes (RNs). The ODN is organized in a primary ODN that starts from the OLT and leads to the primary splitting point. After the primary splitter, the optical paths can further split to serve even more ONUs. This subsequent segment of the ODN, from the primary splitter to the ONUs, is referred to as the secondary ODN. Here, we consider the primary ODNs being implemented either through traditional single mode fibers (resulting in a Multi-Fibre system) or through different cores in a MCF. Note that, as shown in Fig. 1a, the utilization of MCFs in the primary ODN implies the utilization of FAN-IN/FAN-OUT device to separate the cores and distribute geographically the fiber through the secondary ODN.

Differently from traditional PONs, the CO is equipped with an additional element, i.e. a *Reconfigurable Spatial Splitter/Combiner* which is able to aggregate/disaggregate multiple spatial lanes towards single/multiple OLT ports at the OLT. Users connected on the same OLT port share the access to the optical resources through well know Time Domain Multiplexing using one (TDM) or more (TWDM) wavelengths in upstream and downstream. Notice that in Fig. 1a, for the sake of simplicity, we consider a TDM system with one wavelength

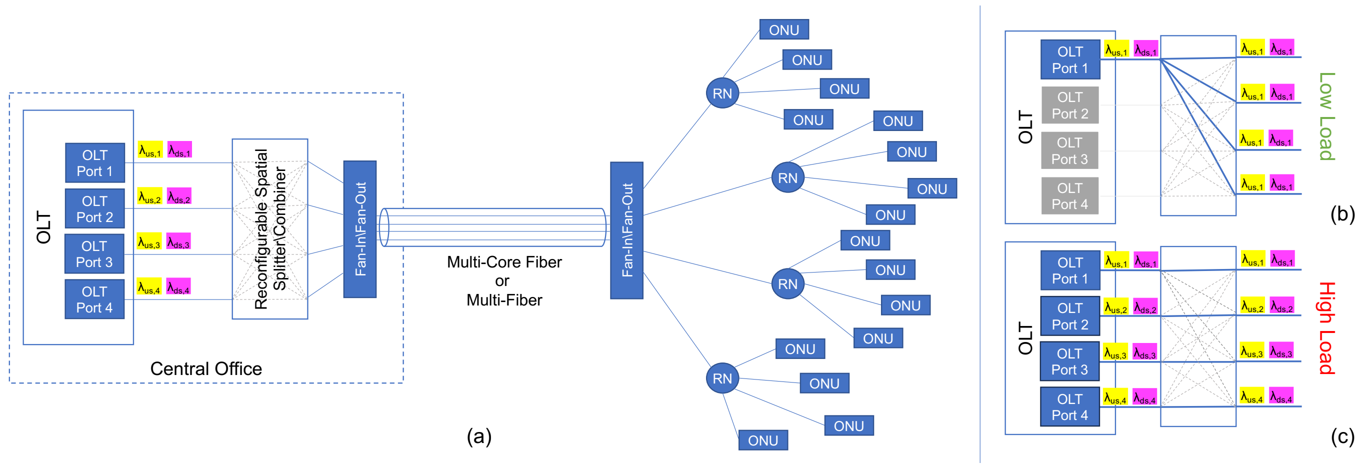


Fig. 1: Reference Architecture.

per direction represented as $\lambda_{us,i}$ and $\lambda_{ds,i}$, respectively, where i indicates the spatial lane and $N = 4$ total spatial lanes.

Since traffic generated by the ONUs on a single spatial lane varies during the day (see examples in Fig.2a), at low load conditions, the spatial splitter/combiner can be configured to direct all the spatial lanes on a single OLT port (Fig.1b) since the capacity of a single wavelength may be sufficient to serve all the users in a TDM manner. Compared to a benchmark traditional architecture where all the OLT ports remains active, this allows to switch off the unutilized OLT ports and achieve energy savings. In contrast, at high load conditions, the spatial split/combiner is configured to direct each spatial lane to a single OLT port (Fig.1c). In this case all the OLT ports are activated resulting in higher energy consumption.

The dynamic spatial aggregation mechanism is contingent on monitoring the traffic load on each spatial lane. The interaction between the OLT and the dynamic spatial splitter/combiner can be implemented either through a purposely designed interface or by exploiting software defined control of the involved components, e.g. through NETCONF protocol [6]. Another important factor to be taken into account is the proper allocation of the newly added ONUs in multiple access procedures and the time associated to *ranging* procedures when the low traffic ODN trees are switched away from their native OLT ports and are associated to a new OLT port that is kept alive. Finally, a crucial aspect in the proposed architecture is represented by the design of the dynamic splitter/combiner (also offering "multicasting") since it may result in different levels of insertion loss, spatial flexibility, and overall energy consumption. Numerous technological platforms have been explored to implement such an element [7], [8] and compatible solutions that emphasize multicasting, reconfigurability, low insertion loss, and low energy consumption have emerged [9], [10].

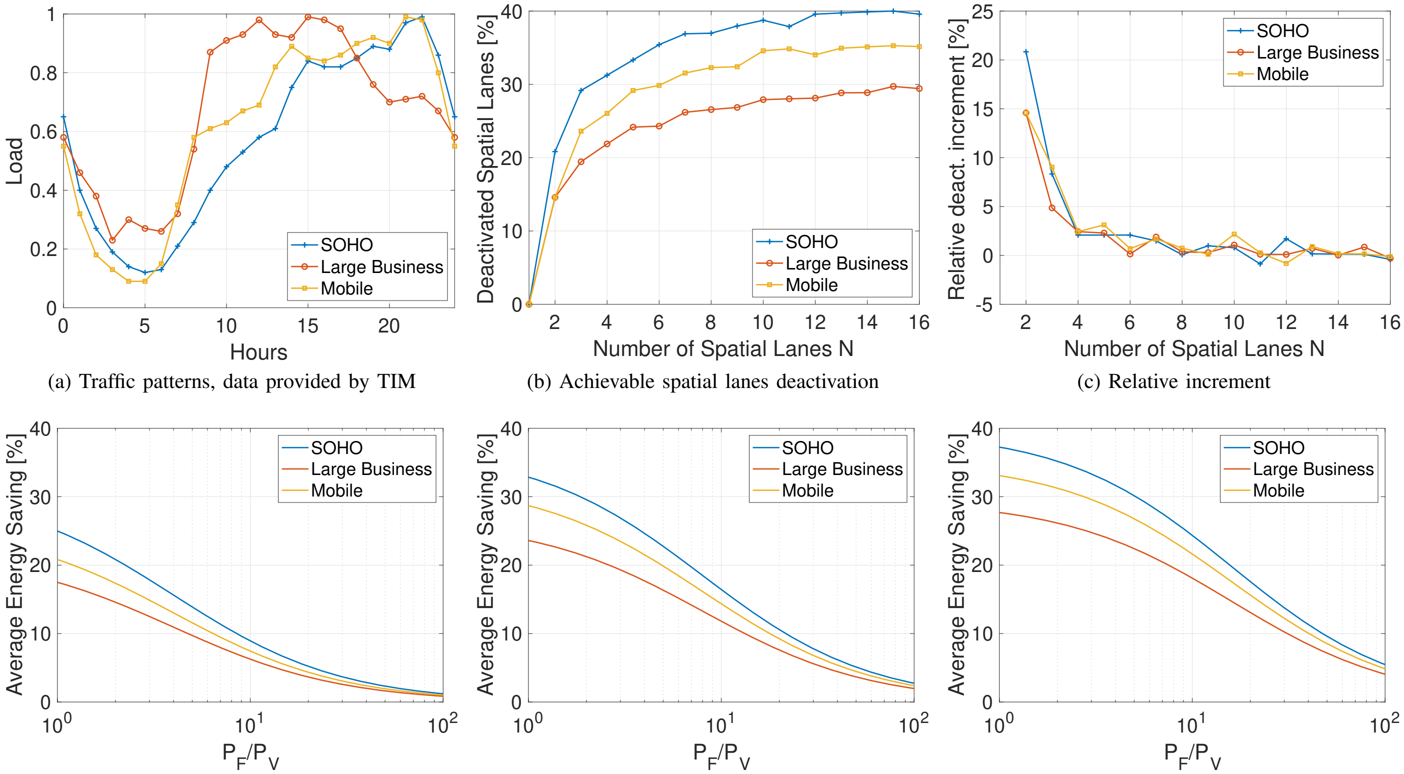
III. Results

As observed in Fig.2a three primary traffic patterns are considered, corresponding to different services supported by the PON infrastructure: Small Office/Home Office (SOHO), Large Business, and Mobile. Each of these patterns exhibits unique diurnal variations, and the aggregation mechanism adapts accordingly.

The primary metric for evaluating the performance of the proposed model includes the percentage of OLT ports/spatial lanes that can be dynamically deactivated. Fig.2b showcases the average number (calculated over a day) of spatial lanes that can be feasibly deactivated as a function of the total number of lanes N. It is expected that a higher number of available spatial lanes leads to greater potential aggregation. For all traffic patterns, an increase in the number of spatial lanes leads to an elevation in the potential lanes for deactivation and, in turn potential energy saving, with the SOHO pattern showing the most significant potential ($\tilde{4}$0%). It is worth noticing that the potential gain increases in the three cases up to a saturation level. As portrayed in Fig.2c, the relative increment in the percentage of saved spatial lanes shows a significant increase up to 8 spatial lanes. However, this relative increment becomes smaller when moving from 8 to 16 spatial lanes.

We model the power consumed by the OLT as the sum of a fixed component P_F which accounts for all the elements which are not dependent on the number of active spatial lanes such as shelter circuitry, ethernet interfaces, and fans and a variable component P_V which is associated with the activation and deactivation of spatial lanes and accounts for transceiver power consumption, and OLT port circuitry. Consequently, a critical parameter is represented by the ratio P_F/P_V. We assume aggregation/disaggregation decision being applied with a fixed periodicity of one hour, this implies that power savings are equivalent to energy savings.

Figs. 2d to 2f present the energy savings in comparison to a benchmark traditional architecture, which lacks spatial aggregation and OLT ports deactivation. These figures are associated with 4, 8, and 16 spatial lanes, respectively, as a function of P_F/P_V. The achievable energy savings show significant variations based on the traffic patterns and the number of lanes N. The energy savings exhibit a promising



(a) Traffic patterns, data provided by TIM

(b) Achievable spatial lanes deactivation

(c) Relative increment

(d) Saving with 4 spatial lanes

(e) Saving with 8 spatial lanes

(f) Saving with 16 spatial lanes

Fig. 2: Considered traffic patterns, achievable spatial lanes deactivation, and achievable energy savings.

trend with the ratio P_F/P_V. Very high energy savings of 18-38% can be obtained when $P_F/P_V = 1$. Reduced savings of 2-7% can be achieved when $P_V << P_F$, corresponding to $P_F/P_V = 10^2$, which, nonetheless, can represent significant reductions in operational costs for the network provider.

IV. Conclusion

This paper delved into the exploration of dynamic spatial aggregation as an innovative approach to enhance energy efficiency in PONs. Our results highlighted the potential of spatial lane deactivation in responding to varying traffic demands. Future work will explore experimental demonstration, delve deeper into control mechanisms able to seamlessly handover ONUs between spatial lanes without service interruption, and optimized spatial aggregation algorithms considering real-time traffic adjustments and impact of load variation on experienced latency thereby further refining the energy-saving potential of PONs.

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