SOFTWARE-DEFINED OPTICAL LOCAL AREA NETWORK ARCHITECTURE AND PRIORITY TRAFFIC PERFORMANCE ANALYSIS

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ABSTRACT

A software-defined (SD) solution for optical LANs is presented in our study. The SD approach implements the control plane for the LAN servers orchestration in order for the data plane to adopt a slotted efficient MAC protocol to avoid packet loss, reaching high performance. As opposed to many studies which suppose that the control plane is carried out in the electrical domain, our proposal adopts that the control communication is carried out in the optical domain, synchronized to the data transmissions. The coordinated operation of the data and control planes can be guaranteed for the adopted MAC protocol effective operation. A simple analysis is developed for the maximum throughput formula derivation, assuming several traffic volumes to adopt high traffic diversity in LANs. The adopted SD LAN architecture along with the MAC algorithm could be followed in several optical LAN paradigms, such as intra-data center networks, and enterprises or institutional LANs.

Keywords: optical local area network, software-defined network, WDMA protocol.

1 INTRODUCTION

Nowadays, the requirement for broadband access in any type of access networks is getting more intensive. Especially under the prism of multiple cloud applications that constantly gain ground, this requirement arises as a key factor when assessing the on-line cloud services performance. For optical access networks, the demand for high bandwidth utilization has greatly to do with the used optical technology capabilities that are gradually upgraded, providing solutions of high data rate up to more than 100 Gbps per channel. Thus, several types of optical access local area networks (LANs) are expanding globally, aiming to serve multiple kinds of time-sensitive services, such as health-care applications (Wong et al. 2017; Habiby 2006; Valkanis et al. 2020), aerospace services (Kantelis et al. 2020), data center networks (Tziroglou et al. 2019; Ni et al. 2014), Tactile Internet (Cheng et al. 2017) etc.

In this framework, the efficient exploitation of the optical bandwidth in order for each one LAN server to be able to use a high part of it, is of great interest. The medium access control (MAC) protocol followed plays a critical role for the determination of the bandwidth utilization level achieved, while it is closely related to the used optical transceivers and switching technology. Most commonly, the enormous fiber bandwidth is divided into several parallel logical channels using the wavelength division multiplex (WDM) technique. In this way, the channels data rate appropriately complies to the modern optical transceivers data rate capabilities. Based on this compliance, several WDM access (WDMA) schemes have been proposed in literature to exploit the fiber bandwidth in an optical LAN. Some of them, like Habbab, Kavehrad, and Sundberg (1987), consider asynchronous transmission schemes over the WDM channels, providing simple access algorithms without any requirement for synchronization cost, but with limited performance. On the other hand, several synchronous transmission WDMA algorithms have been also proposed (Habbab, Kavehrad, and Sundberg 1987; Baziana 2018; Cai et al. 2019), achieving higher performance at the cost of time alignment. It is remarkable that for currently dominant optical LANs, the enhanced performance becomes challenging enough, especially as their data rate constantly increases. Regardless the synchronization criterion, different access schemes have been already studied in literature, like the Aloha-type one (Habbab, Kavehrad, and Sundberg 1987) or some from the CSMA-family (Habbab, Kavehrad, and Sundberg 1987; Zheng, and Sun 2020), under diverse traffic assumptions.

The software-defined (SD) paradigm has already been explored in optical local scale networks. Although the SD networks (SDNs) effective performance requires that the control plane is ensured to operate in orchestrated cooperation with the data plane, this is not guaranteed in many studies for optical LANs, like in Cai et al. (2019) and Cai, Luo, and Zhou (2016). Especially in these studies, suitable control information is proposed to be exchanged over an electrical control channel before the optical data communication coordination, in order to support diverse slotted access algorithms. Despite the performance improvement achieved, the networks suffer from high complexity and lack of reliability since the control plane communication is carried out in the electrical domain with no reception acknowledgement guarantee for the control messages.

In this study, we propose an optical SDN for local scale networks that ensures the synchronized and parallel operation of the data and the control planes. Based on this insurance, we adopt a slotted WDMA scheme of combined access over the data and the control channels, in order to achieve total collision-free control and data communication. Especially, we assume a time division multiplexing access (TDMA) algorithm over the control and data WDM wavelengths and we effectively coordinate the transmissions during appropriately assigned time slots, avoiding any packets loss due to collisions. Our study takes under consideration the high traffic diversity in modern optical LANs, like in Benson, Akella, and Maltz (2010). Thus, we assume different traffic types of various volumes and priorities that require differentiated service level. Therefore, the proposed WDM-TDM access scheme, takes provision to effectively serve the different traffic types according to their priority rules. The performance analysis provides the maximum throughput achieved as a function of the different traffic volumes. The analysis results are verified by extensive simulations for different performance parameters values. The proposed SDN and the relative access scheme achieve high bandwidth utilization that reaches more than 90% under high offered load conditions. Thus, they, could be efficiently applied to diverse access level optical networks, such as optical intra-data center networks, enterprises and institutional LANs, to support high performance and efficiency under high traffic variability.

The remaining of our study is presented as follows: The architecture of the proposed SDN and the proposed WDM-TDM access scheme are given in Section II. In Section III, the throughput model is analyzed. Section IV studies the performance evaluation based on both the simulation results and the analysis. The conclusion is given in Section V.

2 SDN AND SD COMMUNICATION

Figure 1 presents the layered communication diagram of the adopted SDN. In the center of the structure the control layer is shown. There the SDN controller operates as the network central point, defining the control plane for the network orchestration. The underlying data layer includes the optical LAN infrastructure. In particular, in the LAN there are F servers that are interconnected via a passive coupler using optical fibers.

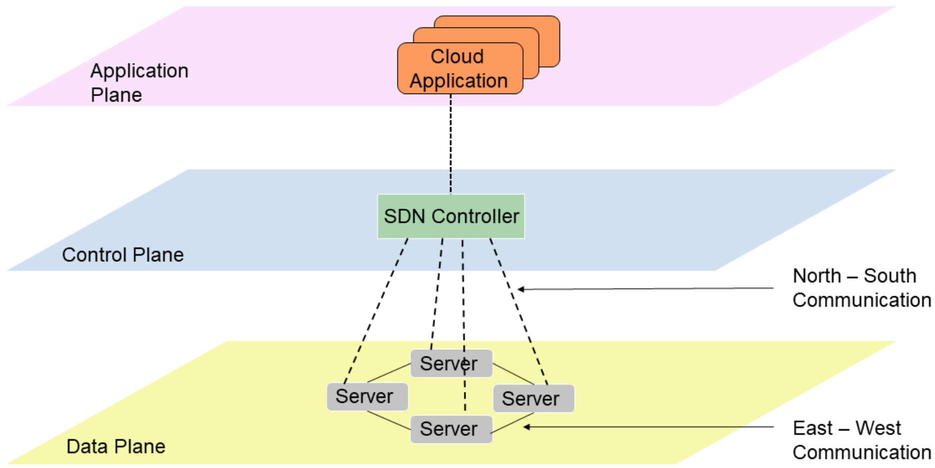

Figure 1: Layered communication for the software-defined LAN.

Thus the SDN controller performs control activities to the underlying data layer and communicates with the servers through its north–south application programming interfaces (APIs). Furthermore, the servers communicate with each other through their local west-east APIs, as Fig. 1 shows. Finally, the SDN controller communicates with the upper application layer for the variable applications service.

In particular, the control interconnection between the LAN servers and the SDN controller is carried out on a separate control WDM wavelength in the optical domain, denoted as λ_1. Moreover, the data interconnection among the servers within the LAN is also carried out in the optical domain, through the passive coupler. Each server uses an optical fiber with C=4 WDM wavelengths, i.e. λ_2, λ_3, λ_4, λ_5, for the connection to the passive coupler.

Based on recent studies (Zheng, and Sun 2020; Benson, Akella, and Maltz 2010), we assume that the generated traffic at each server consists of three different types of packets: (a) those packets that require immediate service and are referred as high priority packets, while they are usually short control messages, (b) those that are messages from clients' applications and are served with a medium priority, while their volume is either short or long, and (c) those packets which are generated by time-insensitive applications and can be served with the lowest priority, while their volume is either short or long. Each server holds three electrical buffers to accommodate the generated traffic according to its priority level, till its transmission.

The time is organized into equal slots. The slot duration is denoted by D. The interconnection among the servers on the data wavelengths λ_2, λ_3, λ_4, λ_5, as well as between the servers and the SDN controller over the control wavelength λ_1, is considered to be slotted. This means that all the servers follow the same clock for synchronized transmissions and receptions during a time slot. The synchronized and parallel operation in the optical domain has been experimentally demonstrated in Moralis-Pegios et al. (2018). Furthermore, for the data communication over the data channels λ_2, λ_3, λ_4, λ_5, the slot duration is divided into x parts which are called mini-slots, while the maximum limit x_{max} of the number x per time slot is explored in the next section.

Each server occupies five optical burst mode transceivers, where each of them is tuned to one of the data channels λ_1, λ_2… λ_5. Specifically, the transceiver that operates at the control channel λ_1 supports the interconnection to the SDN controller, whilst the four transceivers which are tuned to the data wavelengths λ_2, λ_3, λ_4, λ_5 support the communication with the other servers in the LAN. Also, a multiplexer/demultiplexer is used by each server for the adaptation to the optical fiber.

The SDN controller is responsible for the LAN administration. At first, it performs the servers registration whenever a new server is dynamically added to the network. Also, it recognizes a servers' dynamic withdrawal due to any reason. During the network operation, the SDN controller handles the MAC protocol performance and for the appropriate bandwidth assignment to each server, ensuring the collision-free communication within the LAN. Especially, each server that is about to transmit a data packet during a time slot, it has first to inform about its purpose the SDN controller, during the previous time slot. Thus, it transmits a transmission request message to the SDN controller though the north-south API, as Fig. 1 depicts. Then, the SDN controller responds to the server with a reply message through the same API, informing it about the MAC protocol outcome about its transmission intent: This means that the SDN controller either allows or forbids the data packet transmission during the next slot, considering the transmission requests by all the servers in order to guarantee the data transmissions without collisions. Thus, the communication between the SDN controller and the servers is carried out in two phases: the request transmission phase and the reply reception phase that both take place during the previous slot, while the data communication follows during the next time slot, as Fig. 2 shows. In specific, Fig. 2 shows the adopted network scenario. In both the control and data communication, no packets collisions occur grace to the proper slots assignment to the servers by the SDN controller.

Specifically, the SDN controller receives all the transmission request messages by all the servers and executes the followed MAC scheme. According to this, the SDN controller assigns to each requesting server the appropriate mini-slot over the data channels for transmission during the next time slot. Thus, according to the MAC scheme followed, if a data packet transmission is allowed, the SDN reply message properly informs the server about the mini-slot that has been allocated to the server to transmit during the next slot, taking into account the transmission requests by all the servers in order to guarantee the collision-free transmission on the data wavelengths and at destination. In total, based on the MAC protocol outcome, the SDN controller transmits the SDN reply message to all the servers, thus they schedule their transmissions and receptions during the next slot without any loss.

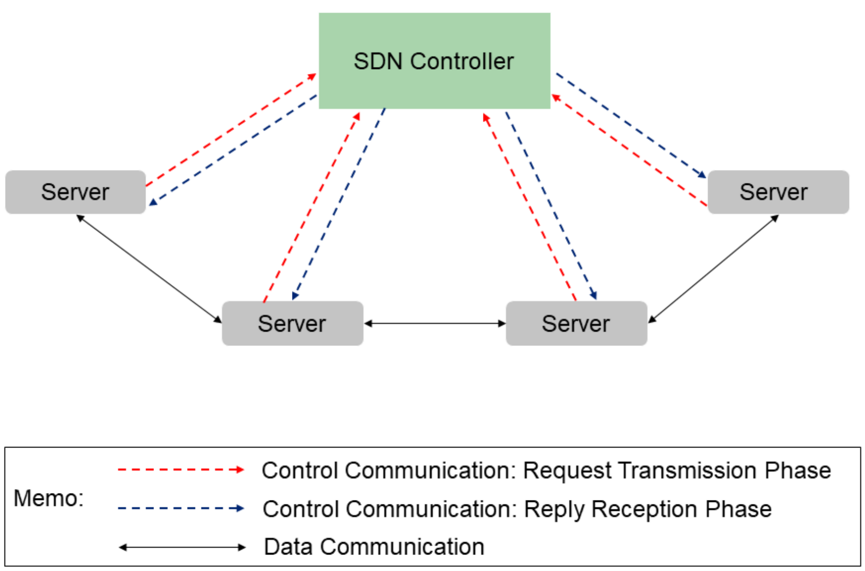

Figure 2: SDN controller and servers communication in the control and data plane.

3 ANALYSIS

As previously described, we adopt two main packet volumes: the short and long packet volumes (Zheng, and Sun 2020; Benson, Akella, and Maltz 2010). Without restricting generality, it is considered that the long packets volume equals to the Ethernet packet Maximum Transfer Unit (MTU) 1500 Bytes, while the short packets volume is that of the shortest Ethernet packet i.e. 64 Bytes. We denote by *Max* and *Min* the transmission times in seconds of the long and short packets volume respectively. Also, we assume that the slot duration is equal to *Max*, i.e. *D*=*Max*. It is evident that the number *W* of short data packets that can be transmitted during the time period *Max* is:

$$W = \left\lfloor \frac{Max}{Min} \right\rfloor \quad (1)$$

where: : $\lfloor y \rfloor$ denotes the floor function of the real number *y*.

For the data communication over the data channels $\lambda_2 \ldots \lambda_5$, the slot duration is divided into *x* mini-slots (x=1, 2,…x_{max}), where:

$$x_{max} = \begin{cases} F, & \text{if: } F < W \\ W, & \text{else} \end{cases} \quad (2)$$

In order to analytically study the MAC protocol performance, we define the maximum throughput Smax that the proposed MAC protocol reaches as the maximum data rate achieved during a time slot on the data channels λ_2, λ_3, λ_4, λ_5. In our analysis, we take into account that a long packet transmission requires a whole time slot duration, while a short packet transmission could be combined with other short packets transmissions during the same time slot for the optimum bandwidth utilization achievement. Thus, we assume that during a time slot, the maximum throughput is achieved on average when the maximum number of short data packets is transmitted over two data channels, let's say the data channels λ_2 and λ_3, while one long data packet is transmitted over the other two data channels λ_4 and λ_5.

For the S_{max} determination, we study two different cases regarding the relationship between the number *F* of servers in the LAN and the maximum number *W* of short data packets which are allowed to be transmitted during the slot. Thus:

Case I: *F*<*W*

In this case, it is:

$$S_{max} = \frac{C}{2} \times \left(\frac{r \times s + (F-r) \times (s-1) \times Min}{Max} + \frac{Max}{Max} \right) \times R \quad (3)$$

where: R is the transmission rate of each channel in Gbps, $r = (W \bmod F)$ and $s = (W \operatorname{div} F + 1)$. The equation (3) is simplified as follows:

$$S_{max} = \frac{C}{2} \times \left(\frac{64}{1500} \times (F \times s - F + r) + 1 \right) \times R \quad (4)$$

Case II: *F*≥*W*

In this case, it is:

$$S_{max} = \frac{C}{2} \times \left(\frac{W \times Min}{Max} + \frac{Max}{Min} \right) \times R \quad (5)$$

while it is simplified as follows:

$$S_{max} = \frac{C}{2} \times \left(\frac{W \times 64}{1500} + 1\right) \times R \tag{6}$$

As (4) and (6) prove, the S_{max} depends on the number *C* of data wavelengths in the LAN, the data rate *R* and the size *Min* and *Max* of the shortest and longest data packet respectively.

4 PERFORMANCE EVALUATION

The investigation about the performance of our SDN proposal along with the MAC scheme is given in this section. For this reason, a network simulator in the C++ program environment is implemented. The simulator follows discrete time simulation rules and provides results for the LAN delay and throughput. It is preferred as compared to commercial simulators since it enhances the capability to adjust more network performance parameters.

For the simulations, the adopted SDN configuration is the following: the number of servers in the LAN is *F*=64, whilst the number of data channels are *C*=4 and there is one control channel. All wavelengths data rate is *R*=40 Gbps. The aggregated traffic in the LAN obeys Poisson statistics, whilst the generated traffic by each one server individually also follows Poisson distribution. The distributions of the three priority traffic types are according to Zheng and Sun (2020). For simplicity reasons, we neglect the propagation delay, as well as the processing time of the SDN controller. The guard band time between consecutive transmissions is 2 ns (Benjamin et al. 2020; Gerard et al. 2020).

Figure 3 studies the throughput per server versus the normalized load in the LAN, for various number of servers *F*=44, 64, 84 and *C*=4 data channels. As it is illustrated for the same *F* value, the throughput per server increases with load. As an example for *F*=64, it is: 0.99 Gbps for load =0.4, 1.51 Gbps for load =0.6, and 2.02 Gbps for load =0.8. The same behavior is noticed for the other curves too that correspond to *F*=44 and *F*=84. This is explained by the fact that as the offered load in the LAN is getting higher, each server manages to transmit more data packets, both short and long ones. Thus, the throughput per server increases with the load, since no congestion has been reached. Also, as it is shown for *F*=64, the maximum throughput per server achieved is 2.41 Gbps for load=1. It is remarkable that the total throughput of the LAN is *F* times higher than the throughput per server value, for all loads, since the MAC scheme gives on average fair access rights to all the servers. Thus, the maximum total throughput is approximately *F*×2.41 Gbps =155 Gbps, according to the simulation results presented in Fig. 3. This value conforms to the theoretical analysis results and it is equal to the S_{max} value given by (6). We conclude to the same result for the other two curves studied in Fig. 3: the *F*= 44 and the *F*=84 curves. Especially, as Fig. 3 shows based on the simulation results, the maximum total throughput for load=1 is: *F*×3.45 Gbps =151.8 Gbps for *F*=44, and *F*×1.85 Gbps =155.4 Gbps for *F*=84. Similar, these values are almost equal to the theoretical value from (6) S_{max}=158 Gbps. The slight deviation of the simulation throughput per server results from the theoretical S_{max} one has to do with the assumption made for the theoretical S_{max} definition that it is achieved on average when the maximum number of short data packets is transmitted over two data channels, while the other two data channels carry one long data packet each. During the simulations, this assumption seems to slightly change since during some time slots not only two but three data channels may carry long data packets, providing on average higher theoretical throughput per server values. Finally, it is remarkable that for any *F* value, the maximum throughput obtained is very high, close to the nominal data rate of 4×40 Gbps=160 Gbps. This means that the bandwidth utilization achieved is very high. Especially it is: 94.8% for *F*=44, 97% for *F*=64, and 97.3% for *F*=84. This fact is based on the optimum mini-slots assignment procedure that the MAC scheme follows in order to give fair access to all the servers, while ensuring no collisions either on the control/data channels or at the receiver. Thus, bandwidth is consumed without carrying any data packet only due to the required guard band between consecutive transmissions and the remaining bandwidth within a slot (*Max*-*W*×*Min*). Its value is extremely low: 5.2% for *F*=44, 3% for *F*=64, and 2.7% for *F*=84.

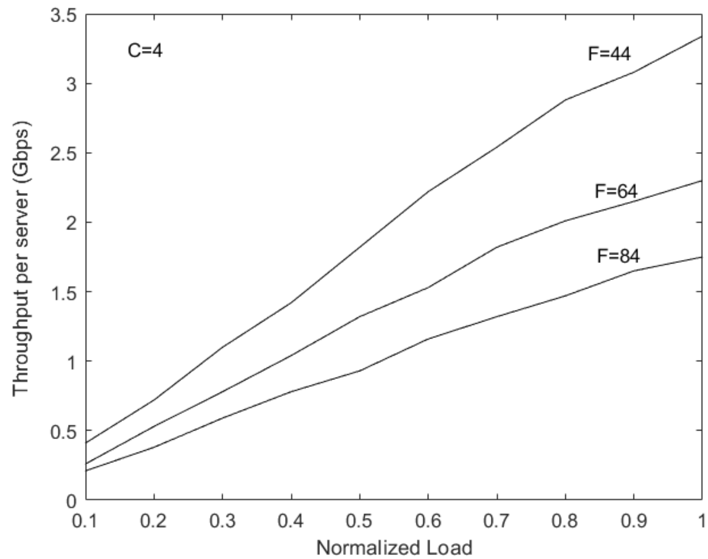

Figure 3: Throughput per server vs load (*F*=84, 64, 44 and *C*=4).

The overall performance is studied by Fig. 4 which shows the total delay as a function of the throughput per server for the network configuration with *C*=4 data channels and *F*=44, 64, 84 servers. As it is proved, the performance is enhanced as the number of servers *F* is getting lower. This is because, in this case the overall delay is getting lower. In other words, for the same load value, throughput per server decreases with *F* as Fig. 3 depicts, while the delay increases as Fig. 4 shows. This is understood since as *F* increases, the number of mini-slots over each data channel that the SDN controller assigns to each server for transmission is getting lower, providing higher queuing delay that a data packet experiences at the output buffers, regardless its volume. Finally, as Fig. 4 shows for each *F* value, there is a sharp variance between the throughput and delay that corresponds to the load conditions where high congestion conditions are met.

The performance change with respect to the number of data wavelengths *C* change is presented in Fig. 5.

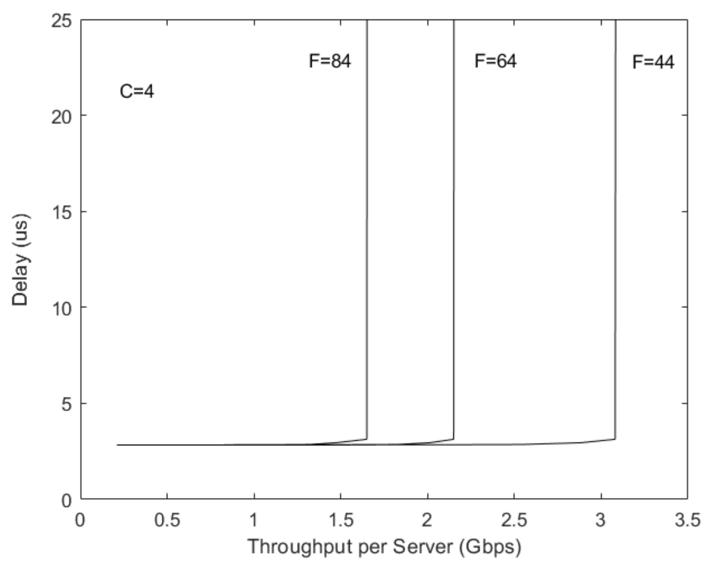

Figure 4: Average delay vs throughput per server (*F*=44, 64, 84 and *C*=4).

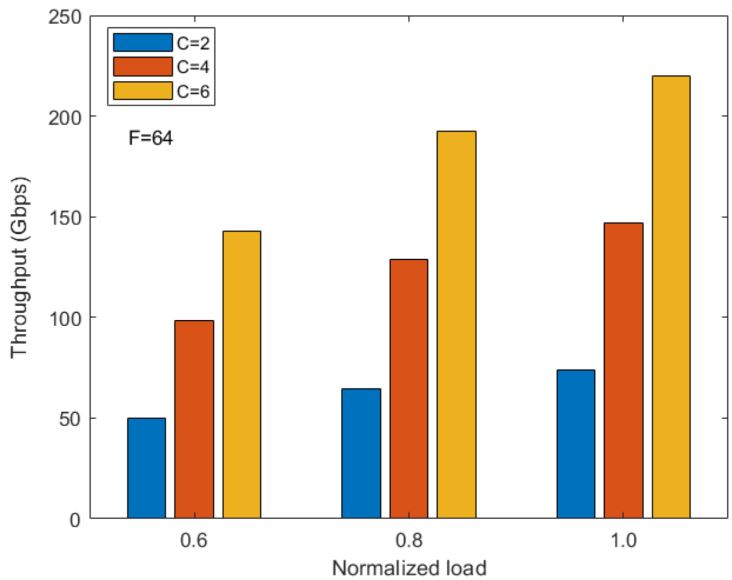

Figure 5: Average throughput vs load (*F*=64, and *C*=2, 4, 6).

This figure presents the overall throughput in the LAN as a function of the normalized load for *F*=64 servers and *C*=2, 4, 6 data channels. For the same load it is observed that the throughput increases with *C*. Thus, for example if load =0.6, it is: 50 Gbps if *C*=2, 96.6 Gbps if *C*=4, and 148.9 Gbps if *C*=6. This is understood since as the number *C* is getting higher, the number of available mini-slots that the servers can exploit for data packets transmission during a time slot increases. This fact provides higher throughput since the transmissions are ensured to be without any collision. Also, it is depicted that for all *C* values, the maximum throughput achieved by the simulations is almost equal to the theoretical value given by (6). Thus according to (6), S_{max} is: 237 Gbps for *C*=6, and 79 Gbps for *C*=2. This values are validated by the simulations, as Fig. 5 presents. Also, it is worth mentioning that for all values of *C*, the bandwidth utilization achieved is higher than 95%. Especially, it is: 98.7% for *C*=2, 97% for *C*=4, and 96.8% for *C*=6. As previously noticed, since the packet loss probability is zero, the unused bandwidth comes from the remaining bandwidth within a slot (Max-W×Min) and the required guard band time.

Finally, the study of the service of each one traffic priority type grace to the MAC scheme followed, is challenging enough. In Fig. 6 we illustrate the end-to-end delay experienced by the packets of each one traffic priority type, i.e. the low, medium and high priority packets, as a function of normalized load, for *F*=64 and *C*=4. As it is depicted, the service level that each traffic priority type experiences is according to the priority rule, for any load. Thus, let's study for load=0.8 where the packet delay experienced is: 0.35 μs for the high priority packets, 2.2 μs for the medium priority packets, and 75 μs for the low priority ones. Even for the nominal load of 400 Gbps (i.e. for normalized load=1), the delay experienced is very low for the high priority packets, lower than 1 μs, while for the medium and low priority packets it is lower than 20 μs and 150 μs respectively. These end-to-end delay values are low enough and can guarantee the efficient service of various cloud and time-sensitive applications, such as multiple IoT or even Tactile Internet and Industry 4.0 services. Since the end-to-end delay is the most critical criterion when assessing optical LANs like intra-data center networks, the low delay values that the proposed MAC scheme achieves provides a significant advantage as compared to other similar optical LANs, like Cai et al. (2019).

It is remarkable that the above results can be easily validated also for the case of F<W. Since this case is not general enough due to the low number of servers in the LAN, no simulation results are provided, although the mathematical analysis for the maximum throughput is given by (4).

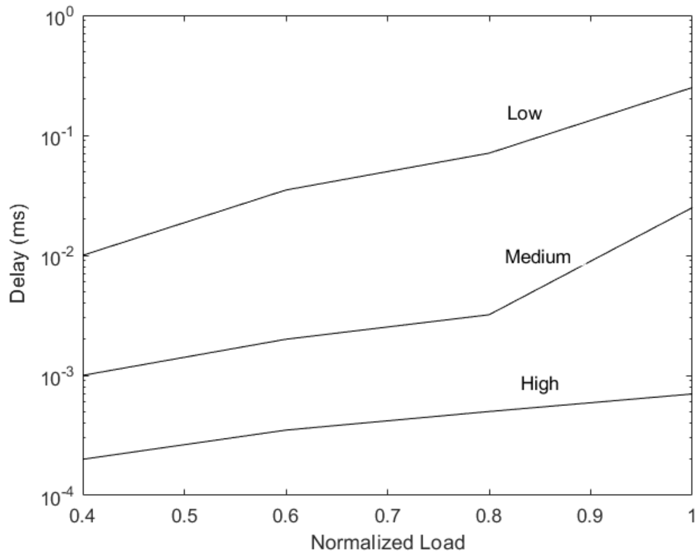

Figure 6: Average delay vs load for diverse traffic priority types (*F*=64, *C*=4).

5 CONCLUSIONS

Many different implementations of optical access local scale networks have been introduced in literature, while one of the main parameters for their performance evaluation is the packet end-to-end delay experienced in them. In this study we present an optical SDN proper for access LANs that ensures very low end-to-end packet delay in the order of μs, while the decreased value can be guaranteed for all traffic priorities assumed. The SDN control plane performs the orchestration operations within the LAN, based on the control messages exchanged in the optical domain between the LAN servers and the SDN controller. In this way, the parallel operation with the data plane is successfully addressed in the optical domain. An efficient slotted MAC scheme is adopted for the communication within the WDM LAN, that eliminates the packets loss over the data and the control WDM channels and at the destination. The adopted MAC scheme achieves very high bandwidth utilization, which is higher than ninety five per cent for all studied LAN configuration cases. Our SDN proposal's benefits could be exploited in various optical access networks like intra-data center networks and local scale enterprises' LANs.

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