Network Planning for 802.11ad and MT-MAC 60 GHz Fiber-Wireless Gigabit Wireless Local Area Networks Over Passive Optical Networks

G. Kalfas, N. Pleros, L. Alonso, and C. Verikoukis

***Abstract*—We present a study concerning the network planning of 60 GHz gigabit wireless local area networks (WLANs) over existing passive optical network (PON) infrastructures. Two fiber-wireless configurations for gigabit WLAN network formations are investigated: i) the Radio & Fiber (R&F) approach that considers several 802.11ad access points connected to conventional gigabit passive optical network (GPON) optical network units, henceforth termed as the GPON-plus-802.11ad approach; and ii) the Radio-over-Fiber (RoF) paradigm that employs several remote access units operating under the medium-transparent MAC (MT-MAC) protocol, hence termed as the MT-MAC-over-PON approach. Simulation-based throughput and delay results are obtained for both network scenarios, revealing the dependence of the 60 GHz enterprise network performance on several network-planning parameters such as load, traffic shape, number of optical wavelengths in the backhaul, and optical backhaul fiber length, highlighting in each case the prevailing architecture. Based on the respective findings we also study a hybrid multitier architecture, termed the GPON-plus-MT-MAC approach, that fuses the abilities of both the RoF and R&F architectures in order to optimally combine their properties and set a framework for next-generation 60 Ghz fiber-wireless networks.**

***Index Terms*—Fiber/wireless; Medium-transparent MAC; Radio-over-fiber; Radio & Fiber; 60 GHz WLANs.**

I. Introduction

The modern communication patterns of home and enterprise mobile users, such as e-health/telemedicine [1], high-definition (HD) real-time multimedia streaming, and remote wireless display applications [2] require the exchange of unprecedented amounts of data, resulting in the placement of excessive load and strain on the existing wireless infrastructure. This has forced mobile operators and hardware manufacturers to gradually expand their activities from global system for mobile communications/WiFi-centric networks, which currently employ frequencies up to 5 GHz, to higher portions of the wireless spectrum such as the millimeter-wave band between 57–64 GHz. The strong commercial interest for millimeter-wave communications can be witnessed by the significant number of recently issued 60 GHz standards such as 802.11ad [3], 802.15.3c [4], and WirelessHD [2]. Nonetheless, the unparalleled 60 GHz capacity comes at the expense of shorter coverage range due to the inherent high propagation losses, limiting so far the millimeter-wave wireless connectivity to wireless personal area networks (WPAN) applications [2–4].

The turn towards 60 GHz wireless local area network (WLAN) home and enterprise networking seems to call for fiber-based backhauling infrastructures, as offered by 60 GHz Radio-over-Fiber (RoF) technologies, in order to overcome the coverage and Line-of-Sight (LOS) requirements. Recent research in 60 GHz RoF solutions has underscored their credentials in delivering very high throughput (VHT) services over km-long fiber down to the wireless end terminal [1,5], but has been mainly restricted in experimental proof-of-concept demonstrations without encompassing any true WLAN capabilities. Among others, the transition to real 60 GHz WLAN infrastructures exploiting RoF technology inevitably necessitates new medium access control (MAC) schemes for arbitrating both the optical and wireless channel capacity. We have recently demonstrated a medium-transparent MAC (MT-MAC) protocol that is capable of negotiating traffic requests directly between the central office (CO) and the 60 GHz wireless clients (i.e., over both the optical and wireless media), which are distributed among multiple remote antenna units (RAUs) [6–8]. The proposed MT-MAC scheme has relied on a dynamic wavelength allocation scheme as well as on a centralized polling and scheduling approach, and has been shown to efficiently transform 60 GHz RoF networks into extended Gigabit WLAN environments [6,7] operating successfully even for a great number of RAUs and for unequal distribution of clients [8].

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G. Kalfas (e-mail: gkalfas@csd.auth.gr) is with the Aristotle University of Thessaloniki, Greece and the Technical University of Catalonia (UPC), Barcelona, Spain.

N. Pleros is with the Department of Informatics, Aristotle University of Thessaloniki, Greece.

L. Alonso is with the Technical University of Catalonia (UPC), Barcelona, Spain.

C. Verikoukis is with the Telecommunications Technological Center of Catalonia, Castelldefels, Spain.

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Being inherently based on the currently distinct wired and wireless communication genres, hybrid RoF approaches must be tested over existing architectures and well-established infrastructural paradigms in order to qualify for commercial and deployed fiber systems. In the fiber domain, a series of advantages such as cost effectiveness, energy savings, service transparency, and signal security over all other last-/first-mile technologies have established passive optical networks (PONs) as the predominant and most widely used optical fiber architecture [9]. This forces all possible future Fiber-Wireless (FiWi) solutions to strive for and ensure PON compatibility [10]. In addition, the significant properties of the millimeter-wave bands, such as the vast spectrum capacity and possibility of compact, high-dimensional antenna arrays, has undoubtedly established the millimeter-wave communications as an integral part of every future access network design, therefore raising the importance of investigating the behavioral and interoperability properties of converged millimeter-wave/PON architectures.

In this work, we present an extensive study on the formation, convergence, and interplay of various 60 GHz gigabit WLAN over GPON architectures. Two possible network scenarios are investigated for the establishment of extended-range millimeter-wave WLANs, the first one being based on a recent standardization effort and the other on a recent promising research outcome: i) the Radio-and-Fiber (R&F) scenario, termed as GPON-plus-802.11ad, which considers several 802.11ad routers attached to an equal number of optical network units (ONUs) employing the GPON network as the fiber backhaul infrastructure; and ii) the RoF scenario termed as MT-MAC-over-PON, which substitutes the GPON's ONUs with RAUs while the GPON's CO facilities are upgraded so as to operate under the MT-MAC paradigm. Extensive simulation-based throughput and delay results are obtained for a plethora of network scenarios, revealing the dependence and denoting the benefits and shortcomings of these architectures on several network-planning parameters: load of the network, number of available optical wavelengths, percentage of intra-LAN and internet-destined network traffic, as well as the PON's total fiber length.

Driven by these findings we study for the first time, to the best of our knowledge, a hybrid RoF/R&F architecture under the scope of millimeter-wave communications. This multitier mixed architecture, termed as GPON-plus-MT-MAC, considers a short-length MT-MAC (RoF) network in a bus topology attached to a GPON ONU that serves the intra-WLAN or intra-cell communication demands, whereas any inter-cell claims are forwarded by the MT-MAC access gate (MTAG) to the GPON network through an existing MTAG/ONU interface. The results derived by GPON-plus-MTMAC's extensive performance evaluation confirm that the latter architecture combines the properties of the MT-MAC-over-PON and GPON-plus-802.11ad approaches, balancing their tradeoffs in an optimal manner.

The paper is outlined as follows: Section II describes the RoF and R&F architectures MT-MAC-over-PON and GPON-plus-802.11ad, respectively. Section III presents and compares the performance evaluation results for the RoF and R&F architectures for several network parameters. Section IV introduces the hybrid GPON-plus-MTMAC approach and presents its performance evaluation against the pure RoF and R&F architectures. Finally, Section V concludes the paper.

II. RoF and R&F Architectures for Millimeter-Wave Communications

The FiWi network paradigm defines two approaches for the integration of optical and wireless networks: RoF and R&F. In RoF systems, the CO modulates RF signals onto an optical carrier which in turn travels over an analog fiber link toward simple RAU (Optical/Electrical/Optical + Antenna) modules. RoF's centralized architecture allocates all network complexity to the CO and thus overall implementation and operational costs drop while handover and operational maintenance procedures become simpler. Moreover, the use of simplified RAUs enables the physical expansion of the network dimensions with spatiotemporal centralized resource allocation. However, the added distance that wireless signals must propagate through the (usually) several kilometer long interleaved fiber can cause significant problems in the operation of the wireless MAC protocols (i.e., timeouts, etc.) thus limiting the maximum physical reach of the network. The latter becomes increasingly a problem in the 60 GHz domain since timeout constraints are even stricter, thus further decreasing the maximum network length. In addition, the remote nature of centralized control becomes a bottleneck in a volatile wireless environment where frequent link establishments dictate the exchange of control packets that are otherwise optional in wired networks. RoF implementations inherently operate as backhauling architectures since packets traverse the entire network. This can be beneficial for packets destined toward internet destinations, as the former travel faster by remaining at the MAC layer, thus avoiding the delays produced by higher layers like the IP. However, the opposite is true for packets destined for close-proximity nodes since they will be indiscriminately forwarded to the CO and therefore acquire significant delay overheads.

In R&F systems, discrete optical and wireless networks are merged in order to form one single integrated network that utilizes different optical and wireless MAC protocols. This means that intra-WLAN traffic does not propagate toward the optical network and therefore all client-to-client ad hoc connections avoid the fiber's extra propagation delay. This feature also alleviates all wireless MAC restrictions from the optical portion of the network such as the maximum fiber length. However, within the context of 60 GHz communications, providing large-scale coverage would require massive active equipment installations, which in turn translates to higher costs and lower energy efficiency. In addition, the range of millimeter-wave WLANs (<10 m as specified in 802.11ad [3]) requires the physical presence of the nodes within a very confined area, thus making them impractical for broad adoption.

This paper attempts a head-to-head comparison between the predominant RoF and R&F FiWi specifications in order to determine the optimal conditions and identify the tradeoff points for a variety of network conditions so as to function as a future guide for the upcoming 60 GHz hybrid optical/wireless network implementations. Both tested RoF and R&F architectures utilize tree-based PON infrastructures, since the latter are generally considered the strongest candidate for widespread deployments. Figure 1(a) depicts the RoF approach operating under the MT-MAC paradigm, termed as the MT-MAC-over-PON architecture. The full operational details of the MT-MAC protocol are presented in [6–8]. In this scenario, an MTAG that includes the necessary hardware resources for generating the RoF optical channels is placed at the location of a conventional GPON CO. The MTAG is in turn connected to an optical distribution network (ODN) with L km length that employs a 1:N passive splitter. The ODN's fibers terminate in the RAUs that provide the mobile users with 60 GHz wireless connectivity. By transferring all functionalities to the MTAG and substituting the active access point (AP) units with RAUs, the MT-MAC architecture forms an extended-range WLAN that bypasses the inherent limitations of the 60 GHz medium in a cost-effective way. Moreover, the MT-MAC scheme employs a dynamic wavelength allocation algorithm that assigns optical capacity only to RAUs with active wireless clients, therefore permitting the physical reach extension of the RoF network by allowing the deployment and operation of a greater number of antenna units with fewer optical resources. This way, a MT-MAC architecture with N RAUs and ℓ available wavelengths offers N 60 GHz wireless channels to the users, ℓ of which can function concurrently, whereas data backhauling is operated in an ℓ-channel WDM PON fashion.

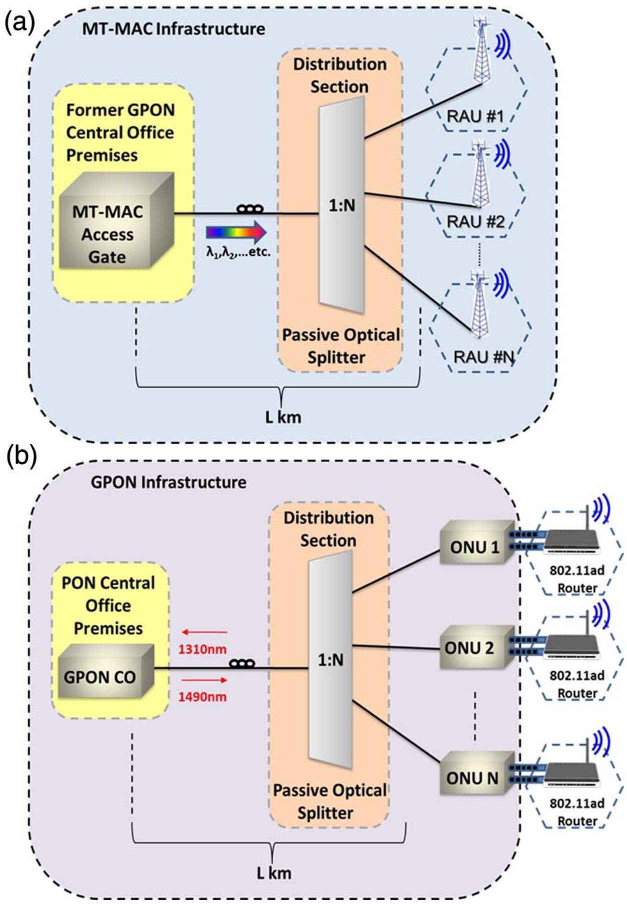

Fig. 1. (a) MT-MAC-over-PON architecture and (b) GPON-plus-802.11ad architecture.

Figure 1(b) displays the R&F architecture, termed the GPON-plus-802.11ad approach. This approach stems from the well-investigated subject of FiWi integration as the latter has been extensively presented in the literature, with the majority of work revolving around ethernet passive optical network/GPON integration with WiMAX/LTE/DOCSIS [11–14] or 802.11 [15] and mesh networks [16,17]. The authors have recently presented a first approach regarding the convergence of PONs with newly introduced 60 GHz wireless networks by studying the GPON/802.11ad integration [18]. This paper extends the work presented in [18] by introducing additional network parameters into the GPON-plus-802.11ad performance evaluation such as the optical capacity, fiber length, and various intra-/inter-WLAN traffic shapes, and comparing the produced results to those of the MT-MAC-over-PON scheme. The GPON-plus-802.11ad architecture is comprised of N 802.11ad Access Points (ADAPs) that are bridged to equally numbered ONUs and consequently backhauled through the GPON's ODN. The employed GPON network features 2.5 Gbps downlink and 2.5 Gbps uplink capabilities whereas the ONU–ADAP communication is handled by their common protocol translation interface that mainly consists of the GPON encapsulation method (GEM) scheduler and the GEM classifier. The GPON-plus-802.11ad network offers N continuously operating 60 GHz wireless channels to the users alongside buffering and local routing functionality (packets traveling to intra-cell destinations stay within the MT-MAC portion of the network), whereas only the packets that head to destinations residing in other ADAPs of the network traverse through the GPON infrastructure.

In order to assess the performance of the RoF versus R&F 60 GHz WLAN formations, we perform a comparative evaluation of the MT-MAC-over-PON network versus the GPON-plus-802.11ad network. Both configurations are based on a 10 km long PON network with 1:32 splitting ratio. In the GPON-plus-802.11ad network, each of the ONUs is attached through the G-PON/802.11ad interface to an ADAP, whereas in the MT-MAC-over-PON network, the PON fibers terminate directly in RAUs. Both radios provide a 6.5 m radius millimeter-wave coverage, and therefore each of the network configurations provides $32 * \pi * 6.5^2 \approx 4245\ \mathrm{m}^2$ of 60 GHz service area. Every ADAP or RAU unit services five randomly placed clients in its range, and sector scanning is employed prior to the first packet exchange with a specific client in order to enable the required directionality in the transmission. For the communication part, we focus on the uplink transmission direction. Regarding the 802.11ad, every non-AP station contends for its transmission opportunities based on the distributed coordination function operation. To obtain

TABLE I
SIMULATION PARAMETERS

GPON-Plus-802.11ad		MT-MAC-Over-PON		Common	
RTS	160 bits + PHY Header	ID Packet Size	64 bytes	Control PHY header	40 bits
CTS	208 bits + PHY Header	POLL Packet Size	64 bytes	SC PHY header	64 bits
ACK	112 bits + PHY Header	1st Cont. Policy	Static Interval	MAC Header	320 bits
G-PON downlink	2.5 Gbps	1st Cont. Interval	5 ms	Data Packet Payload	2000 bytes
G-PON uplink	2.5 Gbps	RRF size Policy	Flexible	Number of ONUs	32
SIFS	3 μs	Minimum RRF Slots	3	Control PHY Rate (MCS0)	27.5 Mbps
DIFS	13 μs	SuperFrame Size Policy	Gated	SC PHY Rate (MCS4)	1155 Mbps
Slot time σ	5 μs	Data Serving Policy	Round Robin	SC PHY Range	6.5 m
Min CW size (CW_{min})	16	ACK Policy	Immediate	G-PON fiber Length	$L = 10$ km
Max CW size (CW_{max})	480	Number of wavelengths	Variable	Clients per AP/RAU	5

results for the GPON-plus-802.11ad, we implemented an event-driven simulator based on the Pamvotis 802.11 WLAN simulator [19] that was extended to support 802.11ad and GPON operation whereas, for the MT-MAC network, an event-driven simulator was implemented in Java. The full list of simulation parameters is presented in Table I.

A. Dependency on Traffic Load

Figures 2 and 3 illustrate the architectures' performance behavior versus various intra-/inter-cell traffic shapes and load conditions. The generated load ranges from 0.1 up to 1 packet generation per timeslot per RAU/ADAP, where the timeslot is defined as the transmission delay of a single data packet for the given data channel rate. Two traffic shapes are considered: i) traffic shaped under the traditional 80/20 rule [20], meaning that 80% percent of the traffic is destined for intra-WLAN destinations whereas 20% of the traffic goes beyond the local subnet and heads to the GPON's CO (Fig. 2); and ii) the more modern 20/80 rule, meaning that 20% percent of the traffic is destined for intra-WLAN destinations and 80% of the traffic heads to GPON's CO (Fig. 3). In this paper, we employ this distinction in order to categorize traffic based on the backhauling requirements relative to existing PON infrastructures for interfused optical/wireless networks. The term intra-WLAN is interpreted as intra-cell in order to maintain a clear comparative platform between the different architectures, whereas the cell is defined as the 60 GHz radio service area provided by a single RAU or ADAP. The 80/20 ratio is studied because it closely describes the usual millimeter-wave applications such as cable replacement scenarios, e-health applications, and highly secure enterprise networks that restrict internet traffic. On the other hand, the 20/80 ratio represents other types of applications such as server farms and/or other web-based computing scenarios where most of the data exchange is between service providers (ISPs, cloud computing, cloud storage companies, etc.) and their customers.

As can be observed in Fig. 2(a) (80/20 traffic ratio), the GPON-plus-802.11ad throughput curves increase with load until throughput reaches its saturation plateau. For the RoF architecture represented by the MT-MAC-over-PON scenario we note that, for low wavelength availability such as two wavelengths, throughput appears to be already saturated even for 10% traffic load conditions (0.1 packet/slot/RAU) since all packets have to traverse the entire network length (10 km in this scenario) both in the uplink and downlink direction for the establishment of the

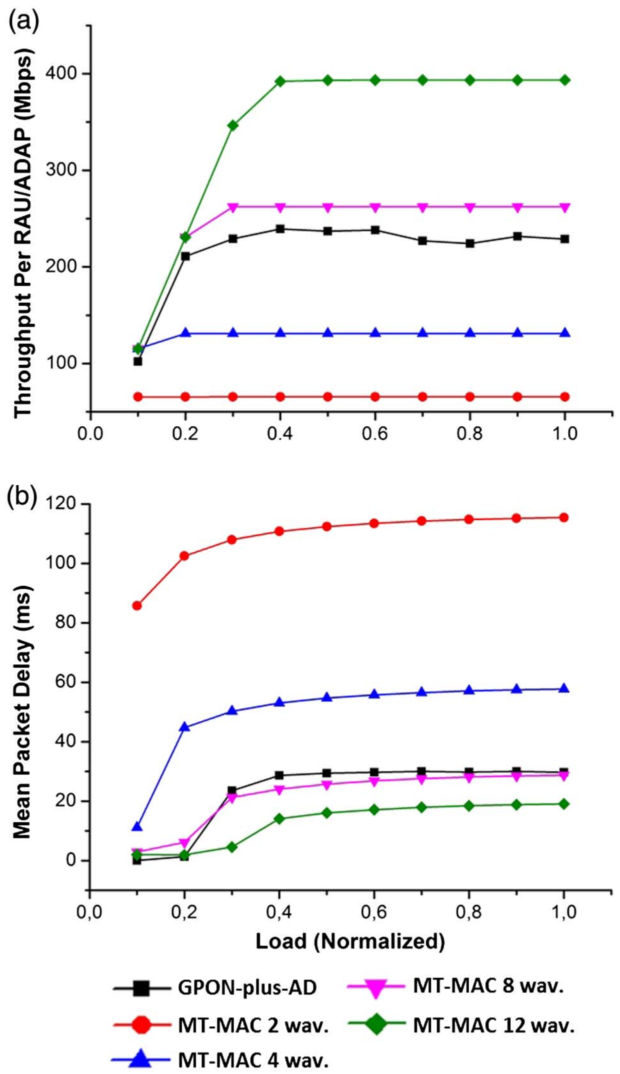

Fig. 2. Throughput and delay for 80/20 traffic (80% stays within the cell).

communication link and data exchange. This adds up to significant delays, especially for the packets that head toward nearby intra-cell destinations. However, by employing the MT-MAC's inherent capability to utilize a larger set of optical wavelengths, the MT-MAC-over-PON can operate in a wavelength division multiplexing (WDM)-PON fashion, causing throughput values to rise as more wavelengths are added, up to the point where the MT-MAC-over-PON's performance surpasses that of the GPON-plus-802.11ad network. As seen in Fig. 2(a), with eight employed wavelengths, the MT-MAC-over-PON manages to match and surpass the GPON-plus-802.11ad's performance by an average of 16%. This throughput improvement escalates even further to an average of 75% for 12 wavelengths. The witnessed performance increment stems from the higher number of optical wavelengths, which in turn leads to less time-consuming wavelength (de)allocation activities as well as longer SuperFrame lengths, thereby increasing the protocol's efficiency. Therefore, the performance improves with an increasing number of wavelengths, and when the protocol's saturation capacity is extended to higher load values. Going beyond 12 wavelengths will further increase the saturation point to higher load conditions and also provide an additional performance gap between the MT-MAC-over-PON and GPON-plus-802.11ad architectures. The proportional relationship of optical resources to the maximum achieved throughput also indicates that the support of specific application types is subject to the number of available optical wavelengths, i.e., resource-heavy applications will demand higher optical capacity to be adequately supported. However, it becomes evident that a broad range of application services can be supported by employing the necessary number of available wavelengths. Delay values, depicted in Fig. 2(b) for the same configuration, follow an ascending path as load increases before becoming essentially stable at the point where throughput saturates. Beyond throughput's saturation point, any excessive packet arrivals become immediately dropped after birth due to buffer overflow. Note here that measured delay refers only to the packets that get delivered, whereas dropped packets are excluded from this metric.

Figures 3(a) and 3(b) present the same results but for traffic shaped under the more modern 20/80 ratio. Here, throughput and delay values follow the same curvature as in Figs. 2(a) and 2(b), with the difference that GPON-plus-802.11ad performance drops significantly lower while corresponding MT-MAC-over-PON performance remains unchanged. Specifically, GPON-plus-802.11ad's throughput saturation value drops from ~250 Mbps to ~125 Mbps per ADAP. This performance degradation is caused by the quadrupled extra-cell traffic that places a heavy burden upon GPON's limited uplink capacity, where only one wavelength is employed toward servicing the upstream traffic from all ONUs, thereby causing buffer overflows and packet drops in the GPON/ADAP interface.

This section provides a head-to-head comparison regarding the performance of the two tested architectures versus load for various optical capacities (2, 4, 8, and 12 wavelengths) and also displays how the RoF and R&F architectures compete against each other. In this work, we are not proposing a specific number of wavelengths to be used universally since the criteria for this selection spans across multiple decision factors such as desired service level, hardware cost, energy efficiency, upkeep costs, etc. This work focuses on the individual as well as comparative performance aspects of the tested RoF and R&F architectures supporting VHT wireless over optical communication so as to identify the optimal architecture given the relevant network parameters.

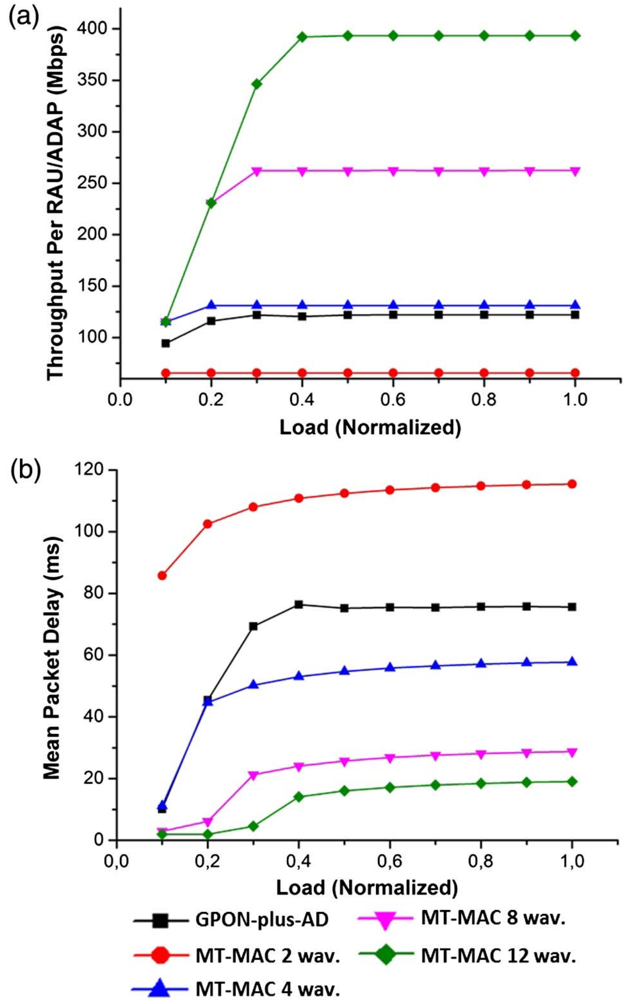

Fig. 3. Throughput and delay for 20/80 traffic (80% heads to destinations outside the cell).

B. Dependency on Percentage of Intra-/Inter-Cell Traffic Ratio

To get a more detailed insight into the impact of the intra-/inter-cell traffic ratio, Figs. 4(a) and 4(b) focus on the performance under various inter- and intra-cell traffic shapes ranging from 10% up to 100% of traffic heading toward internet destinations. The results are shown for a constant load generation of 0.5 packets per slot time per RAU/ADAP. As can be seen in Figs. 4(a) and 4(b), the

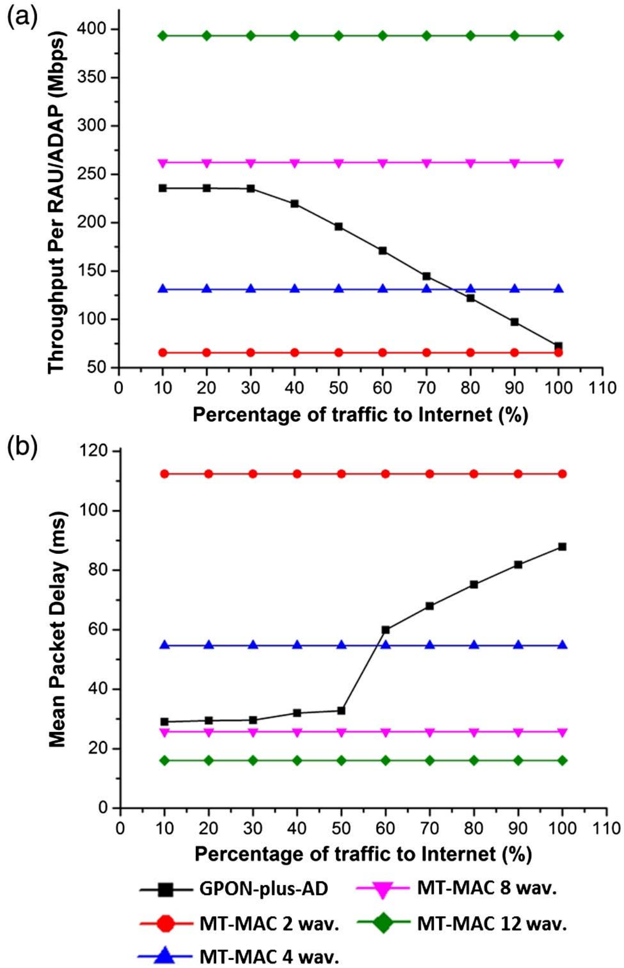

Fig. 4. Throughput and delay versus percentage of traffic heading toward internet destinations.

MT-MAC-over-PON's throughput and delay performance remain constant regardless of the intra-/inter-LAN traffic ratio fluctuations, and depend solely on the number of available wavelengths since packets have to traverse the whole network irrespective of the traffic shape. On the other hand, the GPON-plus-802.11ad's throughput values remain constant only while the ratio of internet-heading traffic is lower that 30%, whereas beyond that point, throughput drops almost linearly due to congestion in the single-wavelength GPON backbone. The same is true for delay performance depicted in Fig. 4(b), where the average packet delay remains almost stable while the extra-cell traffic is lower than 30% but increases soon after, reaching its maximum value of 88 ms when all traffic heads beyond the cell. Notably, the equilibrium point regarding the two architectures' throughput performance varies depending on the number of the MT-MAC available wavelengths. For two available wavelengths, for instance, the equilibrium point is set at around 100% of the traffic heading beyond the cell whereas, for four wavelengths, this value drops to 75%. Beyond four wavelengths, there is no equilibrium point since MT-MAC-over-PON surpasses the performance of 802.11ad-plus-GPON for all traffic shapes. This is due to the fact that, when increasing the number of wavelengths, the MT-MAC-over-PON architecture essentially operates in a WDM–PON fashion, thereby gaining a significant advantage in data backhauling toward the existing single-wavelength GPON implementations. However, when traffic demands concern mostly intra-cell destinations [leftmost part of Figs. 4(a) and 4(b)], GPON-plus-802.11ad manages to achieve the same performance with only a single wavelength in the optical backbone due to the close proximity of the ADAP with the wireless clients, making it very efficient for very-short-range applications. We also observe that, for the same throughput values, the MT-MAC-over-PON architecture exhibits lower delays with their respective difference progressively increasing as the inter-cell ratio rises.

C. Dependency on the Optical Capacity

To better understand the role of the optical wavelength availability, Fig. 5 displays the relation between performance and optical capacity for both competing architectures.

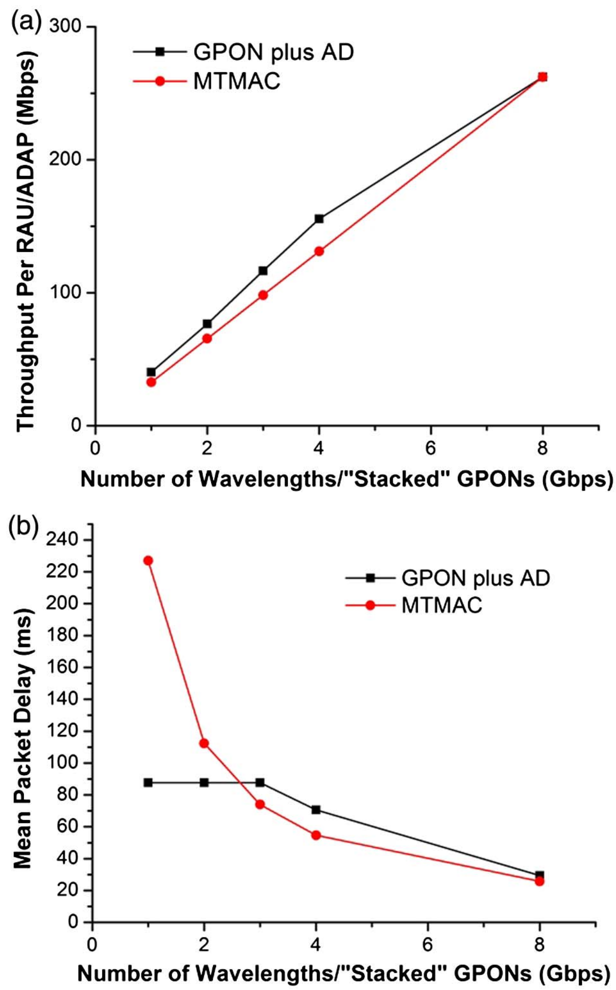

Fig. 5. Throughput and delay versus number of available wavelengths in the MT-MAC-over-PON scenario or stacked GPONs in the GPON-plus-802.11ad scenario.

Regarding GPON-plus-802.11ad, we consider a variable number of "stacked" GPON networks with 1.25 Gbps downlink and uplink capacity. The "stacked" GPON solution is one of the dominant candidate technologies according to the NG-PON2 [21] paradigm, where multiple GPON subnetworks share the same optical distribution infrastructure by employment of WDM mechanisms. As far as the MT-MAC-over-PON architecture is concerned, Fig. 5's x axis depicts the number of available optical wavelengths, each one having a capacity equal to that of the wireless channel (1.155 Gbps). The results are shown for a constant load generation of 0.5 packets per slot time per RAU/ADAP. As has been expected, both architectures benefit greatly from the increase of the optical availability in terms of throughput [Fig. 5(a)] as well as delay [Fig. 5(b)]. Specifically in the MT-MAC-over-PON case, throughput increases linearly with optical capacity whereas delay decays at an exponential rate, proving the direct relationship between the MT-MAC architecture's performance and the wavelength availability. Regarding the GPON-plus-802.11ad network, throughput performance increases with optical capacity [Fig. 5(a)]. The increment rate is linear at lower optical capacities, where the GPON part of the network is the main communication bottleneck. However, the throughput's increment rate drops as more GPONs are stacked on the fiber portion of the network since the bottleneck gradually shifts from the fiber backhaul to the wireless portion of the network. Notably, the wireless bottleneck phenomenon does not appear in the RoF architecture since the system will continue to derive gains until there is a 1:1 relationship between the number of wavelengths and the RAUs present in the network. Beyond that point, no further performance increment is possible since no more than one wavelength can be assigned to every RAU. Note that the produced throughput is derived based on the optical capacity scale (depicted as the x axis), which is 1.25 Gbps for GPON-plus-802.11ad and 1.15 Gbps for MT-MAC-over-PON, thus giving an advantage to the former in terms of absolute throughput performance displayed in Mbps. Regarding the average packet delay [Fig. 5(b)], delay remains constant at lower optical capacities where the optical part of the network experiences saturation, since the GPON's design enables a steady service delivery rate for the packets that fit into the offered buffer space. At higher optical capacities the communication bottleneck shifts from the optical network to the wireless domain, causing a decrease in the delay as more stacked-GPON facilities are added into the network.

D. Dependency on Fiber Length

In the interest of future long-reach PON applications, Fig. 6 reviews the performance of both architectures versus the length of the ODN, ranging from 5 to 40 km of fiber. The results are shown for a constant load generation of 0.5 packets per slot time per RAU/ADAP whereas, in order to produce results relative to the ODN size, 100% of the generated traffic is considered to target internet destinations. As can be noted in Fig. 6(a) the GPON-plus-802.11ad architecture sustains only minor throughput performance degradation as the fiber length increases whereas the MT-MAC-over-PON architecture is strongly affected and its performance is shown to decrease with the ODN size. This performance drop is attributed to the added delays introduced in the contention periods of the MT-MAC protocol that burden the remote arbitration scheme in increased fiber lengths. On the other hand, the employment of the purely optical GPON protocol in the backhaul of the R&F architecture allows the latter to operate more efficiently in longer lengths since packet transmission solely through cable is more robust and the usual time-consuming functions present in the wireless domain such as collision avoidance and/or acknowledgement mechanisms are omitted. The same performance behavior is evident in the delay values as well [Fig. 6(b)], where it can be observed that delay increases with distance in the MT-MAC scenario whereas delay remains relatively constant in the GPON-plus-802.11ad case. This effect highlights the drawback of the remote arbitration scheme employed by the MT-MAC protocol and its inherent weakness to operate in great fiber lengths for the reasons described in

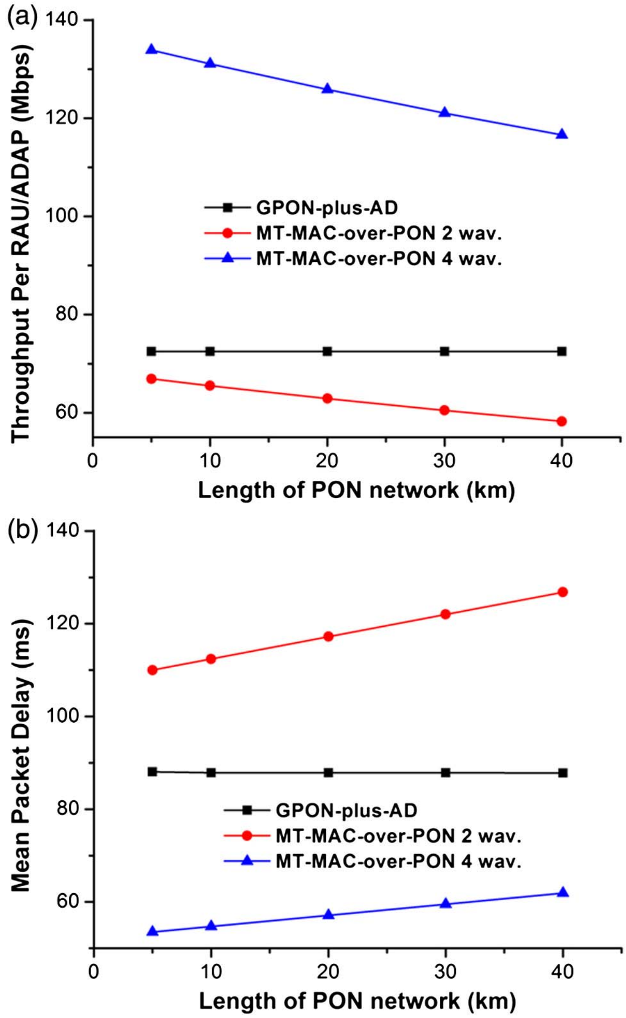

Fig. 6. Throughput and delay versus length of PON network.

Section II, whereas it displays the benefit of employing a multitier architecture such as the GPON-plus-802.11ad when it comes to long range passive optical network (LR-PON) deployment.

E. MT-MAC-Over-PON Versus GPON-Plus-802.11ad Comparative Summary

The direct comparison of the two tested architectures reveals several aspects regarding the operation and respective differences of the RoF and R&F paradigms concerning the formation of next-generation converged wireline and wireless networks. As described by the results, the GPON-plus-802.11ad architecture (R&F approach) operates very efficiently when the majority of traffic demands head toward intra-cell destinations due to the close proximity of the ADAPs to the wireless clients that lead to local and therefore faster traffic arbitration. In addition, the distinction between the wired and wireless domain offers two significant advantages: i) it allows for shortest communication paths when nodes reside within the same cell area and ii) it avoids time-consuming operations in the optical part of the network that are necessary in the wireless links like the ACK mechanism, since optical MAC protocols (such as GPON's MAC operation) have been specifically designed and optimized for fiber links. This provides a clear advantage over the RoF approaches, such as the MT-MAC protocol, that cannot distinguish between the wired and wireless transmission part of the wireless packets and therefore have to employ stricter MAC standards over the whole network length. However, the benefits of the GPON-plus-802.11ad approach come at the cost of massive active AP equipment, a parameter that becomes of greater importance when referring to the very short range (<10 m) millimeter-wave communications, deeming such installations impractical for massive deployment.

The MT-MAC-over-PON architecture enables the formation of extended range 60 GHz WLANs by shifting all intelligent operations to one single, easily manageable, and upgradable location, while coverage is provided through simple RAU modules. MT-MAC's dynamic wavelength allocation mechanism also provides the framework for interactive network control by shifting resources to active RAUs while withdrawing capacity from silent ones. In addition, the remote physical location of the MTAG acts as a natural relay for inter-cell traffic, making the RoF scheme more effective for the modern 20/80 telecom paradigm as has also been shown by the results. Nonetheless, optical capacity abundance through WDM techniques as well as relatively short fiber lengths are a restricting technical necessity in order to achieve nominal network operation.

III. GPON-Plus-MT-MAC Performance Evaluation

RoF architectures lack some of the critical features of the R&F implementations, such as fast access resolution in the wireless domain, local routing capabilities, and long-reach PON support. On the other hand, R&F architectures require massive active equipment installations, which in turn produce higher deployment, maintenance, and upgrade costs as well as lower energy efficiency—factors that become increasingly severe in the dense millimeter-wave antenna deployment scenarios. To this end, this work studies the conjoined performance of a hybrid RoF/R&F architecture termed as the GPON-plus-MT-MAC approach, a multitier scheme that combines the properties of both the RoF and R&F network topologies, such as the flexibility and cost-effective WLAN extension properties of the RoF MT-MAC scheme, along with the long-reach and traffic-discrimination capabilities of the GPON-plus-802.11ad network. As shown in Fig. 7, the GPON-plus-MT-MAC approach splits the network into two counterparts: i) the GPON that covers the majority of the network, usually employing a several kilometers long fiber; and ii) the short-range MT-MAC network that offers wireless access in the users' premises. This distinction follows the current backhaul/fronthaul differentiation paradigm that is predominant in Cloud-RAN/5G research efforts. The hybrid GPON-plus-MT-MAC scheme allows the overall architecture to offer quick WLAN access control due to the close proximity of the MTAG to the RAUs and also provide fast and efficient multi-km-long backhaul capabilities for connection with the service providers. In this way, the hybrid scheme establishes the level of performance displayed by R&F architectures but without the massive access point installations and also without the fiber length limits imposed by RoF architectures. In the GPON-plus-MT-MAC specification, the MT-MAC network lies in a bus topology with the MTAG being attached to a short-length fiber that is connected to a series of RAUs. The MTAG communicates with a conventional GPON ONU, with the protocol translation taking place at their interface. The MTAG-ONU interface undertakes the task of encapsulating MT-MAC data frames (MTDFs) destined for points outside the WLAN directly into the GEM frame format, whereas it reroutes packets destined for intra-WLAN destinations. In turn, the ONU buffers the GEM frames as they arrive and transmits them at specific time slots defined at the upstream bandwidth map by the OLT, according to the GPON's operational rules. Depending on its size, each MTDF is mapped either to a single frame or fragmented into multiple GEM frames. By occupying a single ONU for the same wireless coverage area, the GPON-plus-MTMAC approach offers great flexibility in the design and possible extension of the currently deployed fiber PONs to enter the FiWi era, since the latter architecture can offer multiple wireless area coverages while enabling concurrent operation with other services already linked to the GPON's ONUs.

The rest of this section presents the comparative performance evaluation of the GPON-plus-MT-MAC architecture versus the GPON-plus-802.11ad and MT-MAC-over-PON networks. All configurations are again based on a 10 km long PON network with 1:32 splitting ratio. In the GPON-plus-MT-MAC network, the MTAG is attached through a fiber bus to 32 RAUs with 13 m of intra-RAU fiber interleaves, creating an RoF network with 416 m of total fiber length that offers the same coverage area as the RoF

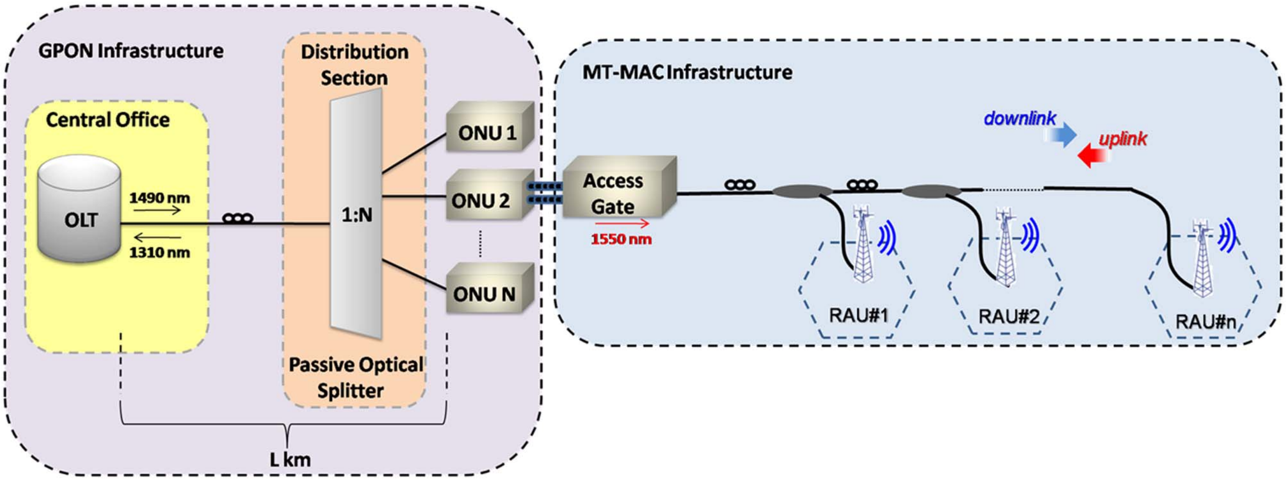

Fig. 7. Hybrid RoF/R&F multitier architecture "GPON-plus-MT-MAC."

and R&F architectures studied in the previous section ($\approx$4245 m^2). The MTAG communicates with one of the GPON's ONUs through the GPON/MT-MAC interface. The GPON-plus-802.11ad network follows the same specifications as presented in the previous section. In order to provide a fair comparison with the R&F and RoF architectures, the ONU's buffer size has been set to hold the maximum number of packets that can be provided by the wireless clients. This is calculated as the sum of the buffers of the served clients multiplied by the percentage of traffic that is heading toward the OLT, i.e., 80% or 20% based on the traffic-generation pattern. Considering 2000 bytes per packet, this is equal to 12 Mbytes of buffer space for the 20/80 traffic and 3 Mbytes for the 80/20 traffic.

A. Dependency on Traffic Load

Figure 8 illustrates the architectures' performance behavior versus various intra-/inter-cell traffic load conditions. The generated load ranges from 0.1 up to 1 packet generation per timeslot per RAU/ADAP. Figures 8(a) and 8(b) display the derived throughput and delay results, respectively, for traffic that follows the traditional 80/20 rule, meaning that 80% percent of the traffic is destined for intra-cell destinations whereas 20% of the traffic goes beyond the local subnet and heads to the GPON's CO. Throughput and delay values follow the same track as with the corresponding results presented in Fig. 2. Specifically, it can be witnessed that throughput values rise with load until the point at which the latter reaches its saturation value. For the GPON-plus-MTMAC architecture, this saturation point depends on the number of employed optical wavelengths and fluctuates from <0.1 packet/slot/RAU for 2 wavelengths up to 0.4 packets/slot/RAU for 12 wavelengths. As can be noted, an optical capacity of eight wavelengths is needed for GPON-plus-MTMAC to outperform the GPON-plus-802.11ad architecture by an average of 20%, a performance enhancement that is also 4% higher than the respective MT-MAC-over-PON value. Delay results

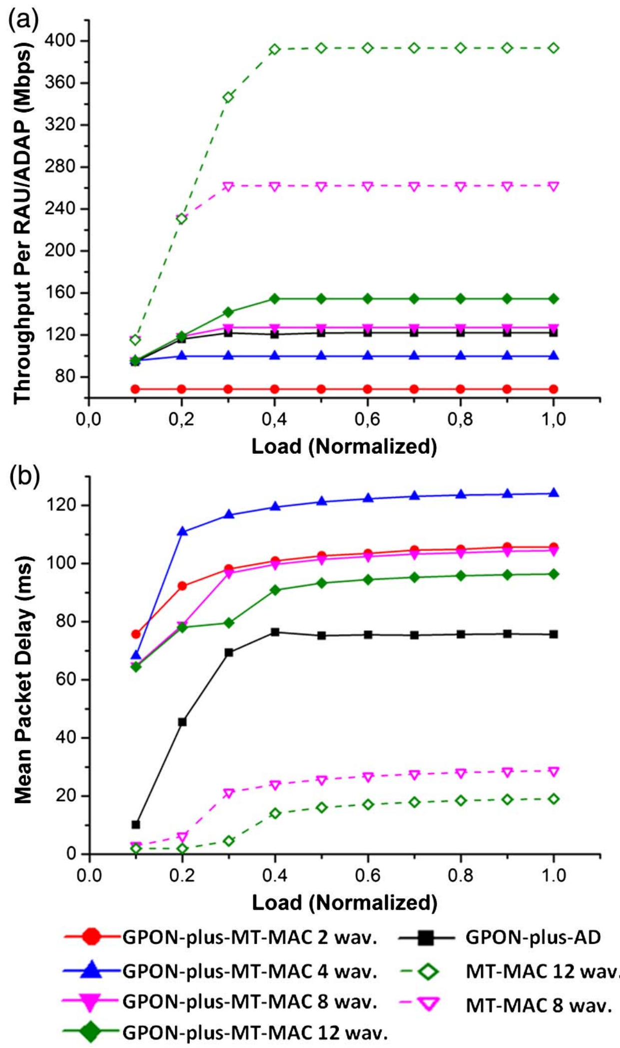

Fig. 8. Throughput and delay for 80/20 traffic (80% stays within the cell).

depicted in Fig. 8(b) start at a low point and increase rapidly when the offered load approaches the throughput's saturation point. When load exceeds the saturation point, delay values remain almost constant since the excessive packets get dropped due to buffer overflow and are thus discarded from the delay metric. Regarding the GPON-plus-MT-MAC architecture, when load exceeds 0.4 packets per slot per RAU, delay values for the 12-wavelength setup are greater than the ones corresponding to 8 wavelengths. This is due to the fact that the increment from 8 to 12 wavelengths increases throughput and decreases delay in the MT-MAC subsection of the combined network; but, on the other hand, this higher throughput directly adds to the GPON's load and therefore its delay. Since the delay increase in GPON is greater than the corresponding drop in the MT-MAC subsection, we notice a phenomenon in which the increase in the MT-MAC's optical capacity causes increase in the overall mean packet delay. The same reason also accounts for the fact that, above the saturation point, the MT-MAC-over-PON architecture exhibits fewer delays than the GPON-plus-MT-MAC network, although the former performs marginally worse in the throughput domain compared to the latter.

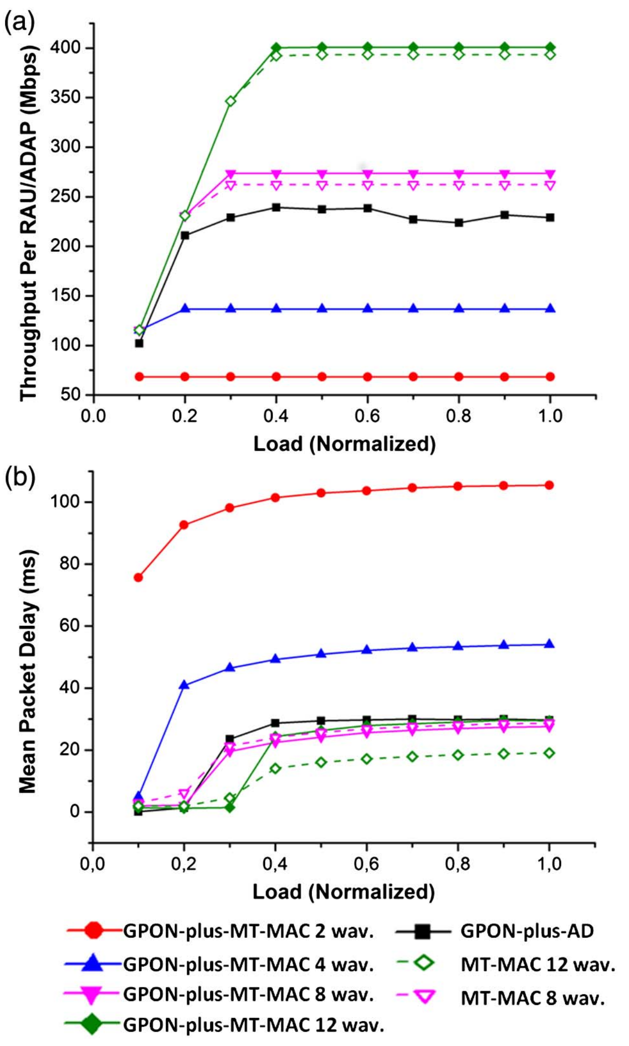

Fig. 9. Throughput and delay for 20/80 traffic (80% heads to destinations outside the cell).

Figures 9(a) and 9(b) present the same results but for traffic shaped under the more modern 20/80 rule, meaning that 80% of it is destined beyond the cell's subnet whereas only 20% is intended for intra-cell destinations. Here, throughput and delay values follow again the same curvature as in Figs. 8(a) and 8(b), but now the two architectures that employ GPON for backhauling (GPON-plus-MT-MAC and GPON-plus-802.11ad) exhibit less throughput and higher delay values since the massive amount of uplink traffic faces the limited capacity of the single-wavelength GPON network and thus a significant portion of the offered load gets discarded at the GPON-RAU/ADAP interface due to buffer overflow. However, by comparing these two architectures, we notice that the results maintain the same performance ratio regarding the optical wavelength availability as in the case of the 80/20 traffic. A significant point raised by Fig. 9 is that the GPON-plus-MTMAC and GPON-plus-802.11ad architectures are negatively affected by the increase of extra-cell traffic, since both of them rely on the limited-capacity GPON for backhauling, making the MT-MAC-over-PON scheme a better fit for traffic resembling the 20/80 model whereas, as per Fig. 8, the opposite is true for the 80/20 model.

B. Dependency on Percentage of Intra-/Inter-Cell Traffic Ratio

Figure 10 provides a better insight regarding the hybrid architectures' performance versus the ratio of intra-/inter-cell traffic, with the results being shown for a constant load generation of 0.5 packets per slot time per RAU/ADAP. Regarding the GPON-plus-MT-MAC architecture, throughput and delay results follow the same trajectory as the GPON-plus-802.11ad network, meaning that throughput values drop and delay values rise while the percentage of traffic that heads beyond the cell increases. As depicted in Fig. 10(a), throughput's highest point is located on the leftmost portion of the graph when the majority of traffic heads toward intra-cell destinations, while its absolute value is dependent on the tested configuration. Throughput values remain relatively steady, as the percentage of traffic that heads outside the cell increases until GPON reaches its maximum service capacity. Beyond GPON's saturation point, throughput decreases gradually since all excess traffic gets immediately dropped at the interface due to buffer overflow. The lowest throughput value of ~72 Mbps per RAU/ADAP is derived for 100% of inter-cell traffic and it is common for all of the tested configurations since it corresponds to GPON's uplink capacity divided by the number of RAUs/ADAPs (32 in this case). As described in the previous section, given the specific PON configuration, the GPON-plus-MT-MAC architecture requires at least eight wavelengths (1/4 the total number of RAUs) to overcome GPON-plus-802.11ad's performance. Delay values depicted in Fig. 10(b) abide in general to the following curvature: remain steady while throughput

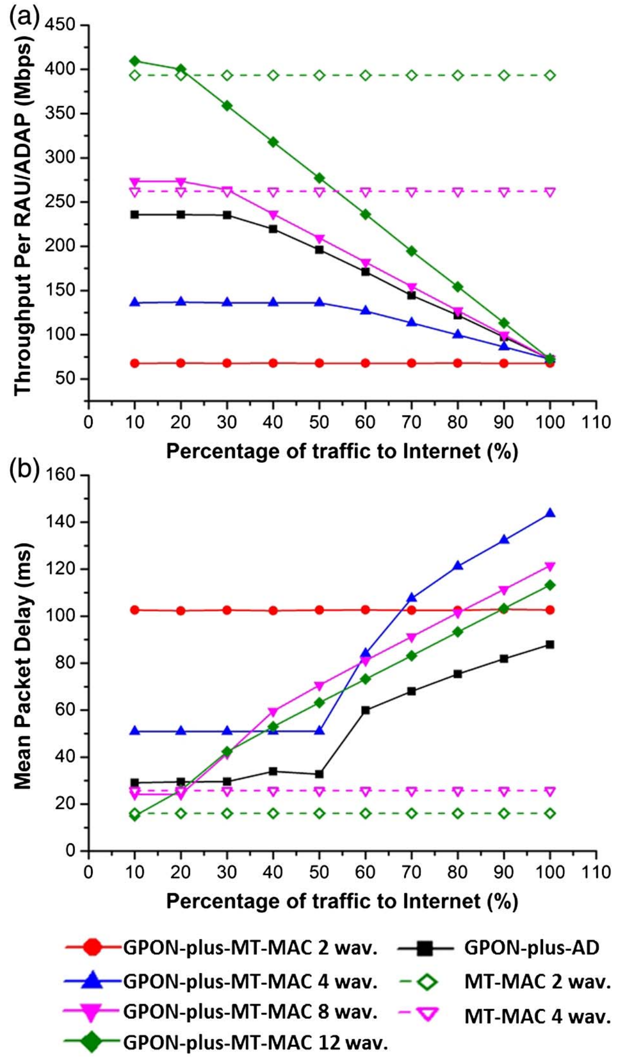

Fig. 10. Throughput and delay versus percentage of traffic heading toward internet destinations.

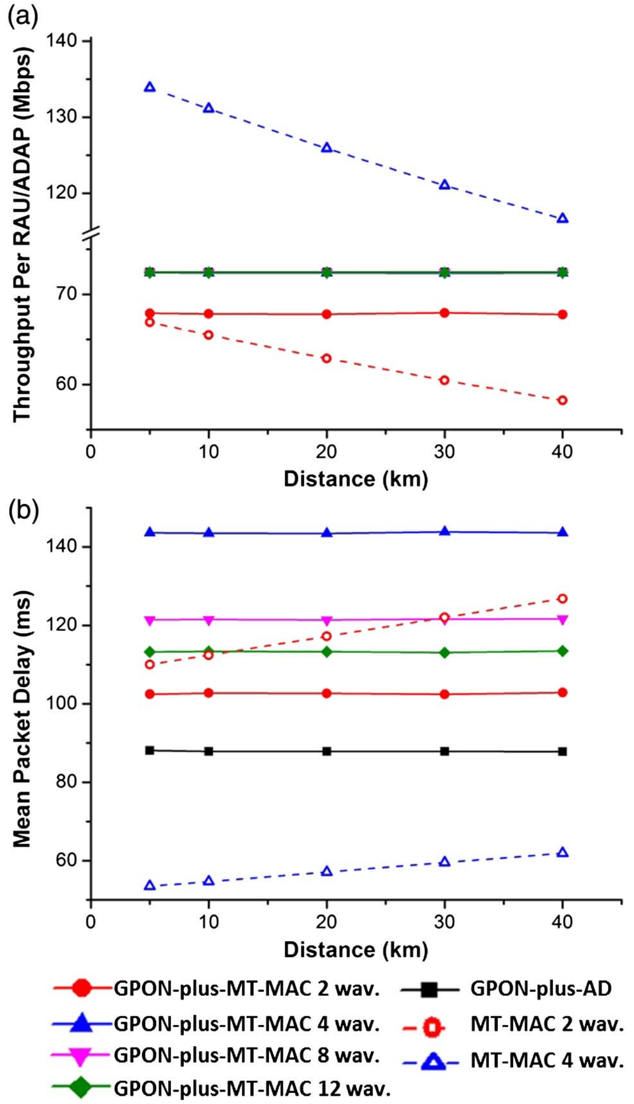

Fig. 11. Throughput and delay versus number of available wavelengths in the MT-MAC-over-PON scenario or stacked GPONs in the GPON-plus-802.11ad scenario.

remains steady, increase rapidly when the intra-/inter-cell traffic is nearing the GPON's saturation point, and increase with steady rate after the latter point. The specific x points notating these three distinct regions depend on the configuration (i.e., the number of employed wavelengths). As is evident in Fig. 10, throughput and delay results can be divided into two categories. On one side are the GPON backhauled architectures that are negatively affected by the increase of the extra-cell traffic due to GPON's limited capacity. On the other side is the MT-MAC-over-PON architecture that exhibits steady performance regardless of the network size since all performance aspects of the latter remain independent of the intra-/inter-cell traffic ratio due to indiscriminate packet backhauling. This fact highlights once again that when the majority of the traffic is destined for backhauling, RoF implementations offer higher performance due to their inherent backhauling nature, whereas in high intra-cell traffic conditions, the hybrid RoF/R&D architecture yields better results.

C. Dependency on the Optical Capacity

In order to fully comprehend the role of the optical resource availability, Fig. 11 displays the relation between performance and optical capacity for the considered FiWi architectures. Regarding the GPON backhauled schemes, we considered a variable number of "stacked" GPON networks with 1.25 Gbps downlink and uplink capacity, respectively, whereas specifically for the GPON-plus-MT-MAC architecture each of the curves depict a different optical capacity value in the MT-MAC portion of the network. As far as the MT-MAC-over-PON architecture is concerned, Fig. 11's x axis depicts the number of available optical wavelengths, each one having a capacity equal to that of the wireless channel (1.155 Gbps). The results are shown for a constant load generation of 0.5 packets per slot time per RAU/ADAP. As can be noted, all architectures benefit greatly from the increase of the optical availability in terms of throughput [Fig. 11(a)] as well as in terms of delay [Fig. 11(b)]. With the exception of the MT-MAC-over-PON architecture, whose throughput values increase purely linearly, it can be observed that in the other architectures throughput values increase linearly with each addition in the GPON stack only up to the point that any further increase causes no further performance increase since the bottleneck factor shifts from the GPON to the 802.11ad/MT-MAC portions of the architecture. The same trend can be seen in the delay results depicted in Fig. 11(b), where we witness the exponential decline of the mean packet delay while more wavelengths are added to the GPON backhaul, up to the point where delay stabilizes and equals the delay produced by the 802.11ad or MT-MAC parts of the network. Results also reveal that GPON-plus-802.11ad retains an advantage over GPON-plus-MT-MAC for less than eight available wavelengths due to the local arbitration scheme in the wireless part of the network, which directly benefits the delay values. However, given enough optical capacity availability, the MT-MAC manages to alleviate the performance difference and provide greater throughput and lower delay values while maintaining the advantage of the flexible, future-proof, and cost-efficient architecture.

D. Dependency on Fiber Length

Regarding long-reach PON applications, Fig. 12 reviews the performance of all the architectures versus the ODN length, ranging from 5 to 40 km of fiber. The results are shown for a constant load generation of 0.5 packets per slot time per RAU/ADAP, whereas in order to produce results relative to the ODN size, 100% of the generated traffic is considered to target internet (extra-cell) destinations. As Fig. 12(a) depicts, with the exception of the case of the low wavelength availability (two wavelengths), all configurations exhibit the same throughput values in all specifications since in the case of the 100% extra-cell traffic, the GPON remains the main bottleneck parameter. In addition it can be observed that the GPON backhauled architectures remain relatively immune to changes in the ODN's length since both rely on GPON for the long-distance backhauling that, although limited to a single wavelength, is a very efficient protocol specifically designed and optimized for fiber communications. In this way, the multitier GPON-plus-MTMAC architecture alleviates the drawback of the MT-MAC-over-PON scheme that suffered performance losses in great fiber distances due to the remote arbitration of the wireless medium. Another point is that the GPON-plus-802.11ad architecture exhibits less delay than the GPON-plus-MT-MAC scheme for the same throughput values [Fig. 12(b)]. This is due to the fact that, besides the GPON delay, packets get served continuously by the 802.11 access points, whereas in the GPON-plus-MTMAC scheme, transmission is intermittent by intervals when clients wait for wavelength assignment in the RAU. However, GPON-plus-802.11ad's superiority at this point comes at the cost of the active access point equipment as

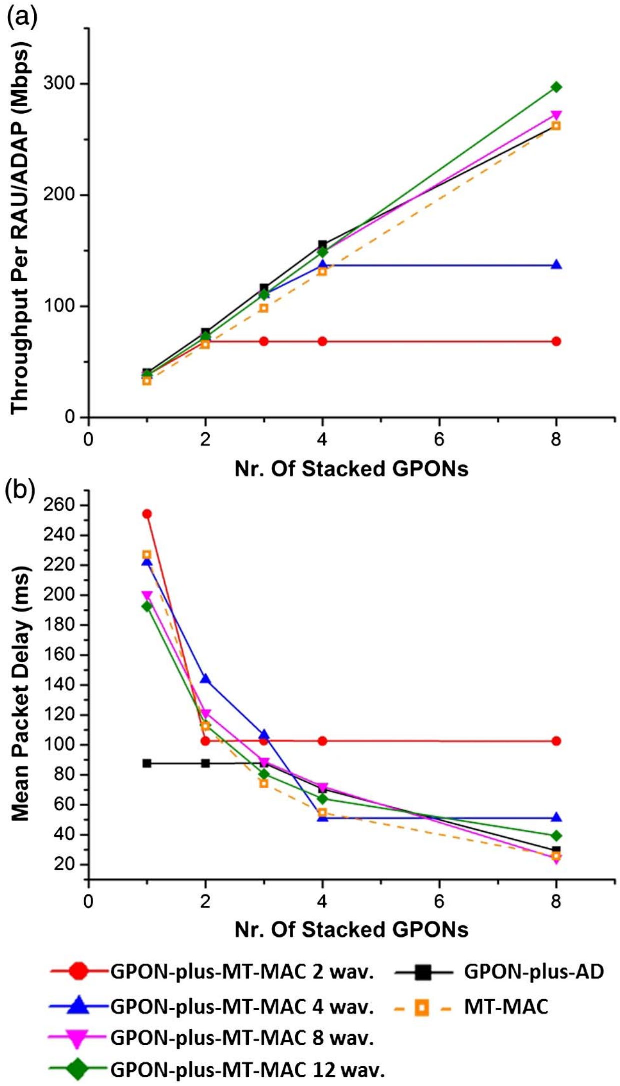

Fig. 12. Throughput and delay versus length of PON network.

well as the fact that the former architecture "captures" one GPON ONU port for every ADAP, making it a rather inefficient way to provide widespread 60 GHz coverage given the very restricted (<10 m) range of the specific medium. Finally, it is noteworthy that the MT-MAC-over-PON network yields superior performance to that of the single-wavelength GPON backhauled architectures when four or more wavelengths are employed, therefore also making it a valid candidate for next-generation PONs when multiwavelength resources are available.

E. GPON-Plus-MT-MAC Architecture and Overall Performance Evaluation

The performance results reveal the nature and specific characteristics of the hybrid RoF/R&F GPON-plus-MT-MAC architecture toward the formation of a multitier architecture. As constituted by the respective results, the GPON-plus-MT-MAC scheme operates very efficiently

TABLE II
SUMMARY OF PREVAILING CONDITIONS FOR EACH ARCHITECTURE

Metric			MT-MAC-Over-PON	GPON-Plus-802.11ad	GPON-Plus-MT-MAC
Traffic shape	Modern 20/80 rule	High inter-ONU traffic High inter-cell traffic	√	×	×
	Classical 80/20 Rule	High intra-cell traffic	×	√	√
Optical backhaul capacity requirements			HIGH	LOW	LOW
PON fiber length tolerance			LOW	HIGH	HIGH
Area of wireless coverage per PON ONU			LOW	LOW	HIGH

under the 80/20 traffic ratio, improving the performance gain of the MT-MAC-over-PON scheme by an average of 4%. In addition, the distinction of the wired and wireless portion of the network allows the GPON-plus-MT-MAC architecture to operate for longer fiber backhaul lengths, thus being able to cooperate with future-generation LR-PONs. Finally, the latter architecture is the most suitable for future FiWi extensions of currently deployed PONs since it occupies only a fraction of the GPON's ONUs, thereby enabling concurrent utilization with already existing GPON services.

Table II summarizes the architectures' overall comparison results, displaying the conditions in which each one prevails or is mostly well suited for. According to the presented results, the MT-MAC-over-PON architecture is suitable for high inter-cell traffic but requires high optical availability and operates efficiently only for short fiber lengths. GPON-plus-802.11ad is predominant in high intra-cell traffic and low optical availability in the optical PON backhaul and is very efficient for great fiber distances such as in the case of LR-PONs, but at the expense of acquisition and employment of active AP equipment. The GPON-plus-MTMAC architecture optimally combines the advantages of both architectures and is highly efficient in increased intra-cell traffic and low optical availability in the optical backhaul, can operate effectively in long fiber distances, and captures only one ONU per each deployed RoF network.

F. WDM–PON Operation Under the NG-PON2 Paradigm

Throughout this work, we have considered the Time Wavelength Division Multiplex (TWDM)–PON or "PON stacking" paradigm as the major solution toward providing a next-generation PON compatible functionality. This choice was based on the fact that the TWDM–PON scheme has been formally submitted and approved by the full service access network community as the primary solution for NG-PON2 since it is less disruptive and less expensive than other approaches, primarily due to the reuse of existing components and technologies [22]. However, in the open topic of the NG-PON2 formation and standardization, there have been several proposals concerning the WDM–PON approach which presume a dedicated wavelength channel to each optical network unit. The WDM–PON paradigm transforms the PON to an uncontested delivery line with static transmission/propagation delays. Due to the dedicated nature of the optical capacity, every ONU receives N times more capacity than in the TWDM–PON scenario, where N is the number of ONUs sharing the same wavelength pairs through a dynamic bandwidth allocation mechanism. This provides a manifold increment of the traffic limit imposed by the optical backhaul, thus establishing the wireless network as the predominant performance factor given that the aggregated wireless traffic is lower than the average uplink service rate. In case the aggregated arrival rate from the wireless network is greater than the capacity of the optical backhaul, the PON becomes again the bottleneck and sets the upper limit to the throughput of the conjoined optical/wireless network. Regarding the three architectures reviewed in this work, the transition to a WDM–PON operation would impact performance in the following ways:

1) GPON-Plus-802.11ad: In this case, the backhaul WDM–PON network will immediately propagate the data packets to the OLT as soon as they arrive on the head of the ONU buffer, since no contention is taking place. Given a Poisson generation model traffic, this translates to small or zero queuing delays in the ONU as long as the mean aggregated arrival packet rate from the wireless 802.11ad access point λ_{AD} is less than the maximum packet service rate R_{ONU} supported by the WDM–PON. Above R_{ONU}, the queue becomes unstable and any excess traffic is dropped. Therefore, in the R&F scenario, all packets that arrive at the ONU will be immediately forwarded to the OLT provided that $\lambda_{\mathrm{AD}} < R_{\mathrm{ONU}}$, whereas the aggregated delay of the packets arriving at the OLT will be the sum of the delay produced by the 802.11ad network (MAC functions and corresponding transmission/propagation delays) plus the transmission/propagation delays of the optical network (no access control and queuing delays). For all values of λ_{AD} that are less than R_{ONU}, the optical throughput will rise linearly with load since there is no contention access and all uplink timeslots are available for transmission. If λ_{AD} approaches or exceeds R_{ONU}, the optical throughput will enter the saturation zone and any further increment will cause excess packets to be dropped at the ONU. Compared to the TWDM–PON described in the paper, the absence of contention for uplink traffic as well as the dedicated optical capacity in the WDM–PON results in higher throughput and lower delays in the unified R&F network for the packets that are destined toward the OLT.

2) MT-MAC-Over-PON: In the case in which the MT-MAC protocol has a 1:1 wavelength to RAU ratio, each RAU has a permanently assigned wavelength and no contention will take place in the optical domain (termed as first contention in the MT-MAC operation). This creates an effect similar to the previous case, and as a consequence all delays and throughput limitation caused by the sharing of the optical resources are alleviated. In this configuration, throughput is limited by the MAC functions in the wireless domain (termed as second contention period) and the respective transmission/propagation delays in both the optical and wireless domains. Therefore, as long as the aggregated traffic of all wireless clients λ is lower than the maximum capacity offered by the optical wavelength $R_{\max}$, throughput will rise linearly and delay will be the sum of the transmission/propagation delays in both the optical and wireless domains. If λ is in the vicinity of or higher than $R_{\max}$, then throughput will enter its saturation regime and any additional traffic will be dropped from the wireless clients' buffers. Overall, compared to the classic MT-MAC approach where optical wavelengths are limited, graphs are expected to follow the same curvature but offer higher throughput results and lower delays. This has already been reported in Ref. [6], where a 1:1 wavelength/RAU ratio in the MT-MAC has already been tested and presented.

3) GPON-Plus-MT-MAC: In the case of the hybrid RoF-plus-R&F approach, replacing the TWDM–PON with a WDM–PON offers the same advancement as in the case of GPON-plus-802.11ad, meaning that any performance hindering and added delays caused by the sharing of the uplink wavelength are alleviated due to the dedicated optical wavelengths in the backhaul. The multiplication of the per-ONU optical capacity due to the dedicated wavelength association as well as the lack of time-consuming access control mechanism in the uncontested medium causes the immediate throughput increment and significant drop in the delay values. Specifically, given that $\lambda_{\text{MT-MAC}}$ is the aggregated packet arrival rate at the ONU–MTAG interface and R_{ONU} is the service rate of the WDM–PON ONU, if $\lambda_{\text{MT-MAC}} < R_{\text{ONU}}$, the throughput in the optical part of the network will rise linearly with the load and delay will be very low. If $\lambda_{\text{MT-MAC}}$ is close to or greater than R_{ONU}, then the throughput of the WDM–PON will enter the saturation regime and all excess traffic will be dropped at the ONU buffer. Therefore, the adoption of the WDM–PON infrastructure multiplies the R_{ONU} as well as enables the use of simpler access control mechanisms, and will yield better performance and lower delay values in the cases where $\lambda_{\text{MT-MAC}} < R_{\text{ONU}}$.

IV. Conclusion

We have presented an extensive study regarding the network planning and formation of 60 GHz gigabit WLAN enterprise networks over existing GPON infrastructures. Three possible architectures were studied: i) the RoF approach MT-MAC-over-PON, ii) the R&F approach GPON-plus-802.11ad, and iii) the hybrid RoF/R&F GPON-plus-MT-MAC approach that combines the properties of both the aforementioned architectures. Extensive simulation results were presented, revealing the dependence of the 60 GHz enterprise network performance on several network-planning parameters: load of the network, number of optical wavelengths available to the network, percentage of intra-LAN and internet-devoted network traffic, and the PON's total fiber length. Results have shown that the MT-MAC-over-PON architecture is suitable for high inter-cell traffic but requires high optical availability and short fiber lengths. The GPON-plus-802.11ad architecture is predominant in high intra-cell traffic and low optical availability, and operates efficiently even for great fiber distances but at the expense of acquiring and operating abundant active AP equipment. The GPON-plus-MT-MAC architecture optimally combines the advantages of both architectures, being highly efficient in increased intra-cell traffic, low optical availability, and long fiber distances. Moreover, the latter architecture is the most suitable for future FiWi extensions of currently deployed PONs since it offers increased freedom and flexibility regarding network planning.

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