Coverage Capabilities of a Multi-Wavelength Passive Optical Network Architecture

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***Abstract*—We present a coverage capability analysis for a multi-wavelength passive optical network architecture that is designed for supporting broadband xDSL access. The analysis takes into account the physical layer impairments of optical fibers and components and, via extensive simulations, provides results concerning the reach that can be obtained and the number of wavelengths that can be utilized. Given the physical layer study results, we evaluate the applicability of the proposed scheme in real networking topologies and determine the number of end-users that can be served and the line rates they can enjoy for nine application scenarios in rural, semi-urban, urban and dense urban areas. Our results show that the proposed architecture is perfectly suitable for attaining the 2020 Digital Agenda objectives in terms of penetration and end-user bandwidth.**

Keywords—passive optical networks; wavelength division multiplexing; physical layer study; access coverage analysis

I. INTRODUCTION

Passive optical networks (PONs) enable the low-cost and broadband communication between central offices (COs), which house core network equipment of the provider, and remote optical network units (ONUs) that are utilized to provide access to end-users. In a typical PON architecture, a passive remote node (RN) is utilized to distribute the optical signal from the CO to all connected ONUs (downstream direction). The two most important PON standards namely Ethernet PONs (EPONs) and Gigabit PONs (GPONs) have been produced by IEEE and ITU, respectively. EPONs are designed primarily for non-time-critical data transfers, while GPONs and their latest advancement XG-PONs are designed to also provide service to applications with stringent timing requirements, including telephony. The latest XG-PON standard defines a single-wavelength PON that utilizes symmetric (10 Gb/s upstream and downstream) or asymmetric (10 Gb/s downstream and 2.5 Gb/s upstream) line rates and achieves split ratios (number of interconnected ONUs) of over 32. For a split ratio of 32, each ONU is allocated with a bandwidth of ~320 Mb/s and end-users are served with a portion of this bandwidth, depending on their aggregation scheme on the ONU. Still, contemporary broadband access technologies (VDSL for example) define end-user line rates of ~100 Mb/s and a significant increase is expected in future end-user access standards. Even if the line rate does not necessary translate to guaranteed bandwidth, as operators limit the guaranteed rates for cost-saving reasons, the aforementioned access trend indicates that XG-PONs will not be able to efficiently serve more than a few hundreds of users in the near future. As a result future next generation PONs (NGPONs) will be required to provide additional capacity, well beyond the currently standardized 10 Gb/s.

Three trends exist for the implementation of NGPONs, and they can be summarized in (a) utilizing more wavelengths to provide increased capacity [1], (b) utilizing more efficient modulation formats to better exploit existing capacity [2], and (c) utilizing different access schemes (for example OCDMA) [3]. The utilization of more wavelengths looks at the present time as the most promising candidate, since it is compatible with existing PON standards and architectures and also builds upon the well-established WDM technology [4], and a four-wavelength PON standard has reached strong industrial consensus [5]. Within this context, we recently proposed a multi-wavelength PON architecture that is illustrated in Fig. 1

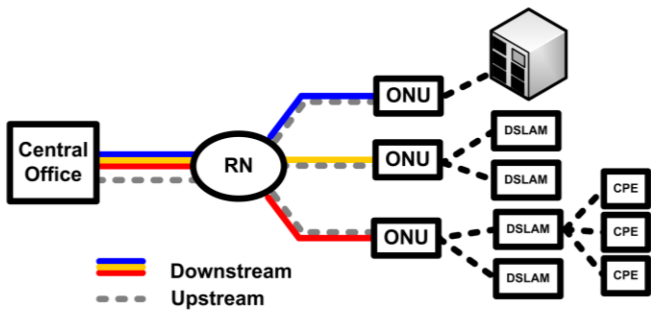


Figure 1. The proposed multi-wavelength PON architecture.

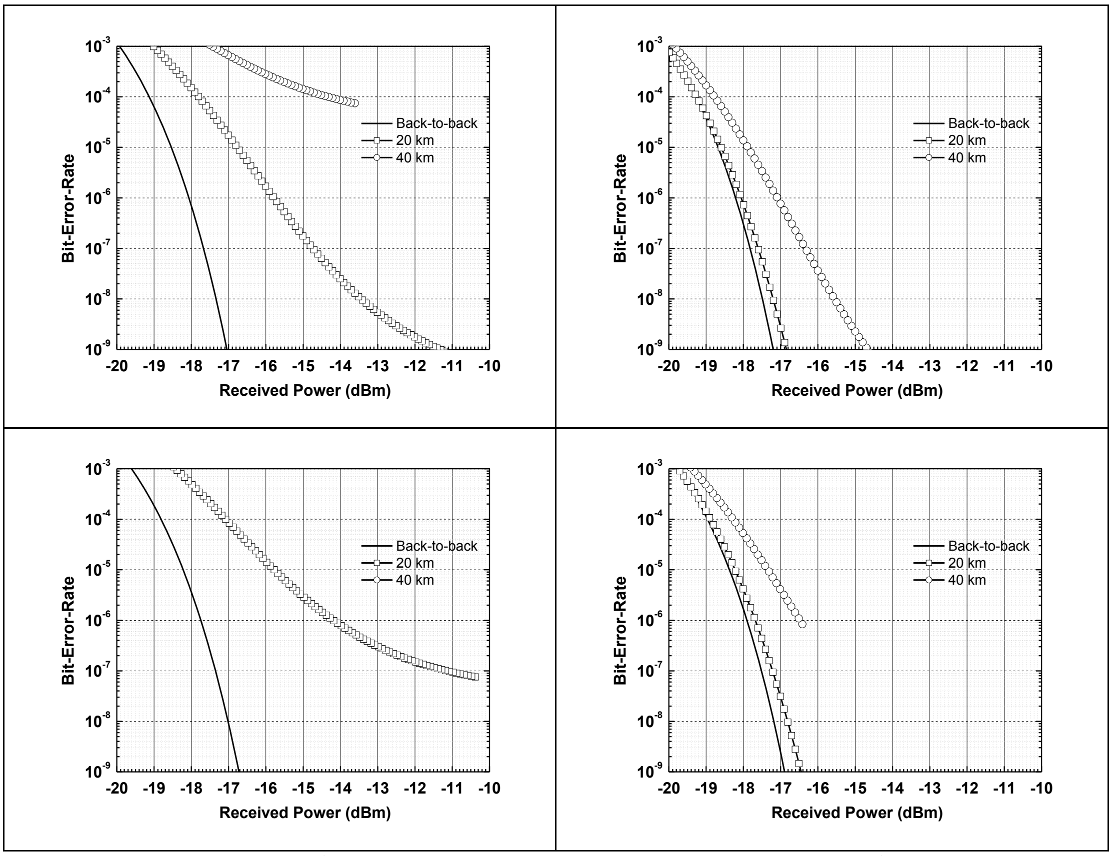


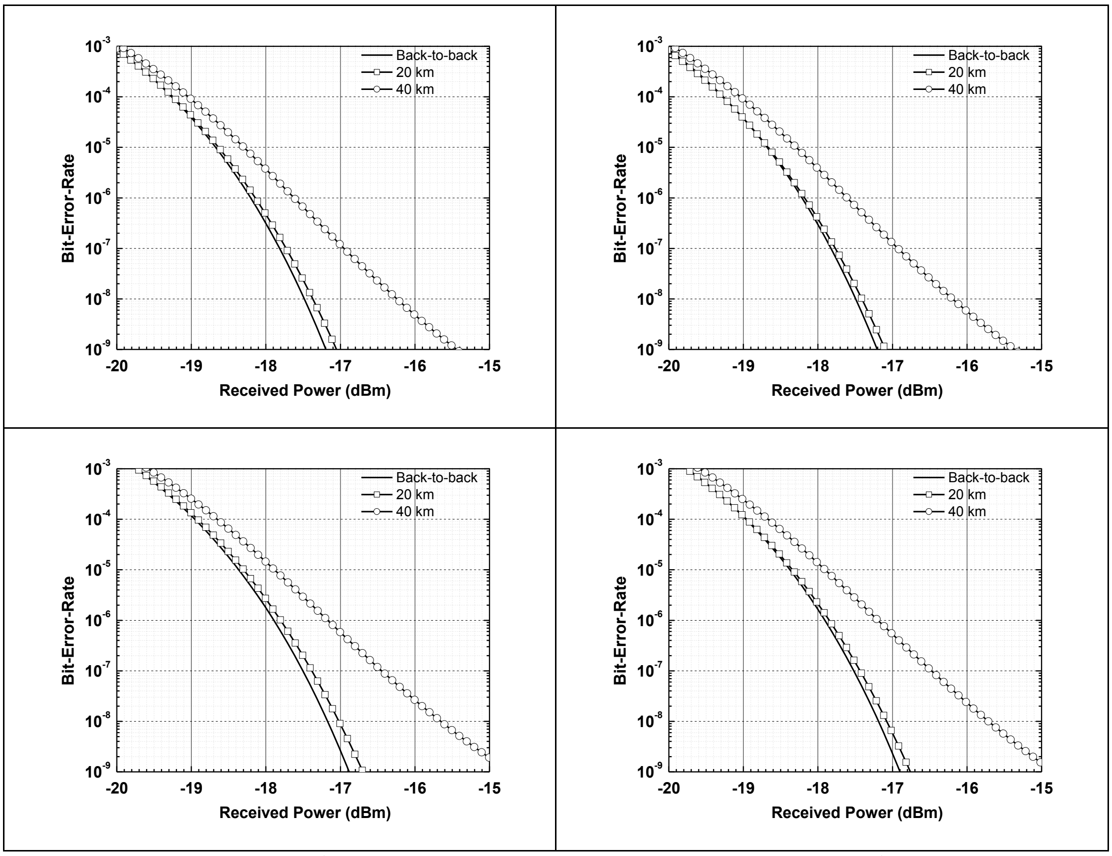
Figure 2. Physical layer performance evaluation for the splitter-based PON architecture. The number of wavelengths equals 64 (top row) and 128 (bottom row).

[6]. The architecture supports a single 10 Gb/s downstream wavelength per ONU, enabling the aggregation of a larger number of end-users. Moreover, all ONUs share a common 10 Gb/s upstream wavelength similar to symmetric XG-PON with a goal to minimize the modifications that are required on the XG-PON MAC layer and thus maintain a strong compatibility between XG-PONs and the presented architecture.

In the current work we discuss the coverage capabilities of the proposed architecture. To this end, we first perform in Section II a physical layer evaluation of the proposed multi-wavelength PON architecture aiming to determine the number of wavelengths that can be utilized, as well as the PON reach (distance between CO and ONUs). We demonstrate via simulations that the number of wavelengths is mainly limited by the total launched optical power in the PON, since it gives rise to non-linear phenomena that cross-couple optical channels and negatively affect their bit-error-rate (BER) performance. Provided that specific requirements regarding the channel spacing and RN structure are met, our simulation results show that a PON radius of 40 km can be achieved for up to 128 wavelengths. Having established the physical layer limits of the PON, we then discuss in Section III its geographical and population coverage capabilities in real-world access network scenarios and the four most common access cases (rural, semi-urban, urban and dense-urban areas) in Greece. Our analysis shows that the previously proposed multi-wavelength PON architecture is perfectly suitable for providing adequate end-user bandwidth in all contemporary access scenarios, while in the same time it allows for mid-to-long term access upgrade within the objectives of EU 2020 Digital Agenda.

II. Physical Layer Study

The physical layer study has been performed using the VPI Transmission Maker simulation suite. All relevant optical subsystems (CO, RN, ONU and optical fibers) were modeled in the simulation suite in compliance with the XG-PON PHY standard. With respect to the CO, the signals from an array of optical sources were multiplexed and transmitted over the optical fiber. All sources emitted optical powers within the limits sets by the XG-PON specification, the channel placement coincided with the standardized ITU wavelength grid in the L/C bands (1520-1625 nm) and the channel spacing was set equal to either 50 or 100 GHz depending on the impact of the non-linear impairments. Two different RN architectures were also considered, due to the existence of multiple wavelengths in the PONs: in the first architecture (splitter-based) the RN was modeled as a passive optical splitter that fed all wavelengths to ONUs. This approach simplifies the RN structure but increases the split losses. As a result, the PON type is determined (following the XG-PON convention) as E2 and the transmitted power per optical source is set to 16.5 dBm. In the second architecture (WDM-based) the RN was modeled as a wavelength demultiplexer that fed a single wavelength to each ONU. The split losses are significantly



50 GHz spacing 100 GHz spacing

Figure 3. Physical layer performance evaluation for the WDM-based PON architecture. The number of wavelengths equals 64 (top row) and 128 (bottom row).

improved, but still very accurate wavelength tuning is required at the CO, especially when the channels are closely spaced. The PON type is determined as N1 in this case and the transmitted power per optical source can be lowered to 6 dBm. Concerning the ONU, a single optical filter was placed before the receiver so as to isolate its corresponding receiving wavelength regardless of the RN implementation. Finally, standard ITU-T G.652 optical fibers were considered in the simulation, while the simulation took into account all relevant linear and non-linear physical layer impairments, including optical losses, dispersion, self-phase modulation, cross-phase modulation (XPM), four-wave-mixing (FWM) and Raman scattering. The key parameters of the simulation are summarized in Table I.

The simulations results for the splitter-based architecture are presented in Fig. 2. The presented results correspond to the center wavelength, still equivalent performance is observed for the rest of the channels. The figure clearly demonstrates that the physical layer impairments introduce a very significant power penalty in the multi-wavelength PON operation. When the channel spacing equals 100 GHz, a 0.5 dB power penalty is observed for the 20 km PON radius (the BER level is 10^{-9}) irrespective of the number of utilized wavelengths. As the radius increases to 40 km the power penalty also increases to 4.0 dB when 64 wavelengths are active, while a similar trend is observed for 128 wavelengths. It should be noted that even though the maximum allowable power is launched, the received power in the splitter-based architecture is barely adequate to achieve BERs in the order of 10^{-6} and additional techniques (for example forward-error-correction) must be deployed to enhance the link reliability. Moreover, the channel spacing may not be reduced to less than 100 GHz in the splitter-based architecture, since the detrimental effect of non-linear impairments, and especially the XPM and FWM, grows as the channels are packed closer together. This becomes evident from the left column of Fig. 2, where error floors and/or greatly exaggerated power penalties begin to appear even at a 20 km radius. Similar conclusions have also been drawn for 16 and 32 wavelengths, even though the corresponding results are not included due to the limited extent of the presentation.

TABLE I. SIMULATION PARAMETERS

Parameter	Value	
Line Rate	10 Gb/s NRZ	
Transmitted Power	16.5 dBm (splitter)	6 dBm (WDM)
Channel Spacing	50 or 100 GHz	
Wavelengths (L/C band)	16, 32, 64 or 128	
PON Radius	20 or 40 km	

Following the above, the physical layer performance of the splitter-based architecture can be problematic and this mainly owes to the high transmission powers that are required to compensate for the RN split loss. In contrast, the WDM-based architecture lowers the power requirements by a factor of 10 and it is expected that fiber nonlinearities will play a less

TABLE II. NETWORKING REQUIREMENTS

		Area Type				
		Dense Urban	Urban	Sub-urban	Rural	Total
xDSL Penetration 50.5%						
Number of Subscribers		125069	183684	51997	3619	364370
xDSL Subscribers per Local Exchange (LE)		11370	15307	4727	452	
xDSL Subscribers per Cabinet		69	78	77	50	
30 Mb/s to 50% of the users and 10 Mb/s to the rest	Data Rate (Gb/s)	2501	3674	1040	72	7287
	Data Rate/LE (Gb/s)	227,4	306,1	94,5	9,0	
	Data Rate/Cabinet (Gb/s)	1,38	1,57	1,54	1,01	
30 Mb/s to all users	Data Rate (Gb/s)	3752	5511	1560	109	10931
	Data Rate/LE (Gb/s)	341,1	459,2	141,8	13,6	
	Data Rate/Cabinet (Gb/s)	2,07	2,35	2,31	1,51	
100 Mb/s to 50% of the users and 30 Mb/s to the rest	Data Rate (Gb/s)	8129	11939	3380	235	23684
	Data Rate/LE (Gb/s)	739,0	995,0	307,3	29,4	
	Data Rate/Cabinet (Gb/s)	4,49	5,10	5,00	3,27	
xDSL Penetration 75%						
Number of Subscribers		185732	272777	77217	5375	541100
xDSL Subscribers per Local Exchange (LE)		16885	22731	7020	672	
xDSL Subscribers per Cabinet		103	116	114	75	
30 Mb/s to 50% of the users and 10 Mb/s to the rest	Data Rate (Gb/s)	3715	5456	1544	107	10822
	Data Rate/LE (Gb/s)	337,7	454,6	140,4	13,4	
	Data Rate/Cabinet (Gb/s)	2,05	2,33	2,28	1,49	
30 Mb/s to all users	Data Rate (Gb/s)	5572	8183	2317	161	16233
	Data Rate/LE (Gb/s)	506,5	681,9	210,6	20,2	
	Data Rate/Cabinet (Gb/s)	3,08	3,49	3,43	2,24	
100 Mb/s to 50% of the users and 30 Mb/s to the rest	Data Rate (Gb/s)	12073	17731	5019	349	35172
	Data Rate/LE (Gb/s)	1097,5	1477,5	456,3	43,7	
	Data Rate/Cabinet (Gb/s)	6,67	7,57	7,42	4,85	
xDSL Penetration 100%						
Number of Subscribers		247642	363703	102956	7166	721467
xDSL Subscribers per Local Exchange (LE)		22513	30309	9360	896	
xDSL Subscribers per Cabinet		137	155	152	100	
30 Mb/s to 50% of the users and 10 Mb/s to the rest	Data Rate (Gb/s)	4953	7274	2059	143	14429
	Data Rate/LE (Gb/s)	450,3	606,2	187,2	17,9	
	Data Rate/Cabinet (Gb/s)	2,74	3,10	3,05	1,99	
30 Mb/s to all users	Data Rate (Gb/s)	7429	10911	3089	215	21644
	Data Rate/LE (Gb/s)	675,4	909,3	280,8	26,9	
	Data Rate/Cabinet (Gb/s)	4,11	4,66	4,57	2,99	
100 Mb/s to 50% of the users and 30 Mb/s to the rest	Data Rate (Gb/s)	16097	23641	6692	466	46895
	Data Rate/LE (Gb/s)	1463,3	1970,1	608,4	58,2	
	Data Rate/Cabinet (Gb/s)	8,90	10,09	9,90	6,47	

pronounced role in its physical layer performance. The simulation results for the WDM-based architecture are presented in Fig. 3. Clearly, a very limited power penalty of less than 0.5 dB is observed for a 20 km PON radius, while the power penalty increases to 2.1 dB at 40 km. Moreover, the channel spacing can be set to as low as 50 GHz, since very similar performance is observed for both channel spacings under consideration. Finally, an even better performance was observed for 16 and 32 wavelengths, where the physical layer power penalty was further reduced by approximately 0.3 dB.

III. POPULATION AND GEOGRAPHICAL COVERAGE

In the current section we discuss the utilization of the proposed multi-wavelength PON architecture to provide end-user access within the scope of the EU 2020 Digital Agenda Objectives, and in particular providing data rate coverage of 100 Mb/s to 50% of the network subscribers and at least 30 Mb/s to the rest. To this end, we have considered three VDSL penetration scenarios that correspond to current, short-term and long-term access evolution, where the xDSL penetration equals 50.5% (current), 75% and 100% over the total number of installed access lines, respectively. In addition we considered three different bandwidth evolution scenarios that describe the gradual upgrade of end-user access from ADSL2+ to VDSL, namely (a) guaranteed 30 Mb/s to 50% of the users and 10 Mb/s to the rest, (b) guaranteed 30 Mb/s to all users, and (c) guaranteed 100 Mb/s to 50% of the users and 30 Mb/s to the rest.

The networking requirement for all nine possible scenarios are summarized in Table II, and have been obtained from real access network topologies that have been provided from the Hellenic Telecommunications Organization for dense urban, urban, sub-urban and rural areas. It should be noted that although these data were obtained from a number of real access network implementations, they should not be considered as reflecting the Greek access network as a whole (i.e. they correspond to a subset that is not statistically large enough to be representative for Greece's access network, which is in any case constantly differentiating and evolving with time). The table shows that with current aggregation terms the total required capacity at the xDSL aggregation cabinets does not exceed the bandwidth of a single wavelength (10 Gb/s). In the

TABLE III. REQUIRED NUMBER OF WAVELENGTHS

Scenario	Area Type	xDSL Penetration		
		50.5%	75%	100%
30 Mb/s to 50% of the users and 10 Mb/s to the rest	Dense Urban	24	42	55
	Urban	33	49	66
	Semi-urban	11	16	21
	Rural	1	2	2
30 Mb/s to all users	Dense Urban	42	55	83
	Urban	49	98	98
	Semi-urban	16	31	31
	Rural	2	3	3
100 Mb/s to 50% of the users and 30 Mb/s to the rest	Dense Urban	83	165	165
	Urban	196	196	196
	Semi-urban	31	62	62
	Rural	3	5	9

TABLE IV. GEOGRAPHICAL COVERAGE (XDSL LIMITED)

Nominal Rate (Mb/s)	Coverage Distance	Coverage for Different Areas				Total Coverage
		Dense-Urban	Urban	Sub-Urban	Rural	
100	150m	98,4%	86,0%	19,1%	37,7%	80,20%
>80	500m	100%	100%	96,1%	85,1%	99,30%
>50	900m	100%	100%	100%	87,9%	99,88%
>30	1200m	100%	100%	100%	88,9%	99,89%

short term evolution scenario (a), the required cabinet capacity is limited to approximately 3 Gb/s irrespective of the xDSL penetration percentage, and as a result the proposed multi-wavelength PON architecture is capable of fully serving end-users, assuming that one or more cabinets are aggregated over ONUs. A similar observation can be made for the mid and long evolution scenarios (b) and (c), where the required capacity does not exceed 5 and 10 Gb/s per ONU, respectively.

As far as the actual number of wavelengths that are required for implementing the PON is concerned, they are summarized in Table III, which details the PON architecture that is better suited for all scenarios under consideration. In dense urban areas, 24 wavelengths are required initially, but this number will increase to 165 as more users join the network and require broadband VDSL access. This leads to the conclusion that multiple PON instances will be required due to physical layer considerations and dense urban areas will have to be logically segmented and served over more than one COs located in the same local exchange (LE). Urban areas prove even more challenging, mainly because the user aggregation on cabinets is higher, as it can be verified from Table II. 33 wavelengths are initially required for urban areas, and they ultimately increase to 196, so multiple PONs will be required for urban areas, as well. With respect to semi-urban areas, an upper limit of 62 wavelengths is predicted, and these can be easily served with the proposed multi-wavelength PON. The same holds true for rural areas, where a modest number of 9 wavelengths will be sufficient to cater for all future needs. Due to their limited requirements, the rural and possibly sub-urban areas may not require a separate PON, but could be part of an urban PON provided that the distance between the urban and sub-urban/rural settlement is less than 40 km, as it has been suggested by the physical layer study.

Regarding the geographical coverage that can be expected from the proposed architecture, the access network length in contemporary implementations is limited to 18 km even for rural areas. As a result the PON can theoretically attain a 100% geographical coverage, but in practice it is the xDSL segment that limits the total attainable coverage of the architecture. The results of the geographical coverage are summarized in Table IV, where it becomes evident that it will be very challenging to provide full rural and sub-urban coverage at 100 Mb/s, since the respective users are located over 240 m on average from the closest cabinet. Still, the vast majority of users resides in urban and dense urban-areas, and as a result practically 100% of end-users can enjoy at least 30 Mb/s access, while over 80% of the users can attain 100 Mb/s thus satisfying the EU 2020 Digital Agenda Objectives.

IV. CONCLUSION

We have performed a coverage capability analysis for a multi-wavelength PON architecture designed to provide xDSL access in both the short and the long term. We first performed a simulation study of two variants of the PON architecture and demonstrated that physical layer impairments limit the number of wavelengths that can be utilized to 128 and the maximum PON radius to 40 km. Given these constraints we studied the population coverage capabilities for nine application scenarios that correspond to the (a) end-user access upgrade from ADSL to VDSL, and (b) the gradual increase of broadband access penetration to 100%. Our results show that multiple PON instances are required in urban and dense-urban areas, while semi-urban and rural areas can be served with significantly less than 128 wavelengths. With respect to the geographical coverage, we demonstrated that the xDSL rather than the optical access segment limits 100 Mb/s access to semi-urban and rural users, still practically 100% of the users can enjoy access rates of at least 30 Mb/s and over 80% of the users can receive 100 Mb/s.

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