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Provisioning 1 Gb/s Symmetrical Services with Next-Generation Passive Optical Network Technologies

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ABSTRACT

Service providers spend billions upgrading their broadband access networks to the latest access standards. Fiber has become the technology of choice in the medium and long term, thanks to its speed, reach, and future-proofness. A differential advantage of fiber over other broadband access technologies is that it makes it possible for operators to deliver symmetric-rate services. Most of today's commercial offers based on regular PON range from 10 to 100 Mb/s of committed information rate, and higher rates are advertised as peak rates with unspecified guarantees. In this article we focus on delivering symmetrical 1 Gb/s access to residential users with a target temporal guarantee at the least cost using next-generation PON technologies. We compare four NG-PON standard access technologies, GPON, XGPON, WDM-PON, and the emerging TWDM-PON, from technical and economic perspectives. The study shows that if a service provider wants to keep up with the growing user traffic pattern in the long run, only TWDM-PON can provide 1 Gb/s nearly guaranteed at a moderate cost with respect to the fully dedicated 1 Gb/s point-to-point connection available in WDM-PON technologies.

INTRODUCTION

At present, 1 Gb/s downstream Internet access services are offered by some service providers in the United States, Europe, and Asia even though the number of fiber subscribers (12.4, 22, and 93 million, respectively), fiber market maturity, and penetration rate (10, 10–50, and 45–70 percent, respectively) are very different across the continents [1]. This 1 Gb/s service is being offered as a peak data rate with different levels of guarantee in addition to a minimum multi-megabit-per-second committed information rate. While basic services may not require such a high rate, other factors like user experience enhancement, the increasing amount of connected devices at home, and low latency requirements for interactive gaming and other coming applications (UHD 3D immersive gaming and video conferencing, cloud computing, infrastructure as a service, etc.) are expected to boost the demand for symmetric 1 Gb/s access capacity with certain quality of service (QoS) guarantees in the near future.

Deploying 1 Gb/s symmetrical services with optical fiber is expensive due to the high investment costs associated with civil works. Some service providers may opt to take maximum advantage of their existing twisted-pair copper infrastructure in the design. This strategy leads to fiber to the cabinet (FTTC) and fiber to the node (FTTN) deployments, combining fiber with very high rate digital subscriber line version 2 (VDSL2) [2]. However, this configuration also involves costs of installation, powering, and maintenance of intermediate active devices, as well as additional delay, and hence, installing fibers up to the customer premises, either residential or business (FTTH/FTTB), seems to be the best long-run approach to keep up with bandwidth and latency requirements of future applications.

There is passive optical network (PON) technology available to provide 1 Gb/s services to end users, and a number of next-generation PON (NG-PON) standards to be completed very soon. This article aims to compare gigabit PON (GPON), XGPON, and wavelength-division multiplexing (WDM)-PON standards with the new time-shared WDM (TWDM)-PON approaches concerning the provisioning of 1 Gb/s symmetrical connectivity to residential customers. Such a comparison addresses both technological and economic aspects, with the aim to provide a reference for network operators willing to migrate to the next-generation access services. A number of questions are investigated throughout this article: Which kind of FTTH technology is most suitable to offer 1 Gb/s symmetrical services? Can 1 Gb/s be guaranteed 100 percent of the time? Which parameters must be considered in the network design? What is the cost per user associated with each technology? A greenfield scenario deployment of a dense area with 5000 users is considered to answer all these questions.

This article is organized as follows. The following section provides a taxonomy of FTTH access protocols that are capable of supporting 1 Gb/s symmetrical services. After that, we quickly review the basic methodology used in capacity planning with oversubscription, often used by network operators. Then we make a technical and economic comparison of four access protocols including capital expenditures (CAPEX) and operational expenditures (OPEX). The final

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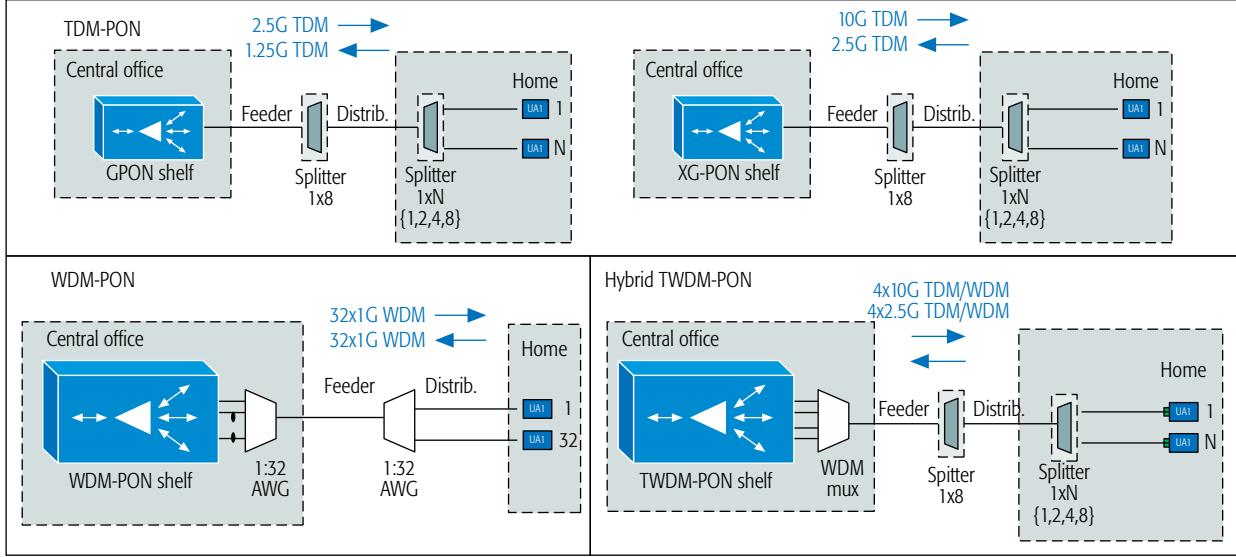


Figure 1. Taxonomy of PON fiber access protocols.

section concludes this article with a summary of its main results along with future work worth investigation.

TAXONOMY OF FIBER ACCESS PROTOCOLS TO PROVIDE 1 GB/S SYMMETRICAL SERVICES

According to the FTTH Council [3], an *access protocol* is “*a method of communication used by the equipment located at the ends of the optical paths to ensure reliable and effective transmission and reception of information over the optical paths.*” The physical fiber topology that connects the operator’s premises and subscriber’s premises, also called an optical distribution network (ODN), can be point-to-point, point-to-multipoint (often referred to as PON), or ring, although hybrid ring-tree topologies can also be found in relevant research works [4]. The design of access protocols is conditioned by the type of underlying topology. This article focuses on protocols for PON topologies, currently the most widely deployed. Figure 1 shows a taxonomy of the PON fiber access protocols under study: time-division multiplexing (TDM-PON), WDM-PON, and a hybrid version, TWDM-PON.

TDM-PON

This technology uses a shared point-to-multipoint approach with one or two wavelengths in the downstream direction (from a central office, CO, to users) and one wavelength in the upstream (from users to a CO). TDM-PON uses a 1:N passive splitter/combiner to divide the optical signal among all users in the downstream direction and aggregate the users’ data in the upstream direction. The optical line terminal (OLT) uses a dynamic bandwidth assignment (DBA) algorithm to arbitrate access to the shared channel in the upstream direction, avoid collisions, assign bandwidth to the users, and provide QoS for different types of flows.

For example, GPON (International Telecommunication Union — Telecommunication Standardization Sector, ITU-T, G.984) uses the 1490 nm wavelength at 2.5 Gb/s for downstream data

traffic (optionally, the 1550 nm wavelength can be used to carry RF video separately), and the 1310 nm wavelength at 1.25 Gb/s for upstream traffic. Recent enhancements like XG-PON (ITU-T G.987) offer 10G/2.5G in the down- and upstream direction, respectively. Besides, there are also symmetrical TDM-PON standards like 2.5G/2.5G GPON or 10G/10G (XG-PON2), but these are not considered in this article due to the lack of deployments.

WDM-PON

In this case, a single wavelength is redirected to an end user from the central office via a passive wavelength router located in the outside plant (OSP). In this case, the power splitter/combiner is replaced by a wavelength selective filter, usually an array waveguide grating (AWG), thus setting up a single wavelength with symmetric bandwidth between each user and the central office. Unlike TDM-PON, WDM-PON provides a *dedicated* point-to-point connection between users and the CO, that is, there is no bandwidth sharing between users. Advantages of WDM-over TDM-PON are scalable bandwidth, long reach (given the low insertion loss of filters, optional amplification), troubleshooting [5], security (users do not see other users’ traffic), and the possibility to individually adapt bit rates on a per-wavelength basis.

There are several flavors of WDM-PON technologies available in the market, each with a different implementation technology: injection-locking, tunable lasers, wavelength reuse, and coherent detection [6]. This article considers only the AWG-based injection-locking WDM-PON flavor with 1:32 splitting ratio (1:64 AWG still not commercially available), specified in the standard ITU-T G.698.3.

TWDM-PON

This technology was selected as the primary solution for the NG-PON stage 2 (NG-PON2) project of the Full Service Access Network (FSAN) community, and is currently standard-

| | GPON | XG-PON | TWDM-PON | WDM-PON |
|---------------------------------|-------------|-------------|-----------------------|---------------|
| Standard | ITU-T G.984 | ITU-T G.987 | ITU-T G.989 | ITU-T G.698.3 |
| Availability | In market | In market | In trial | In market |
| Feeder rate (C_{DL}/C_{UL}) | 2.5G/1.25G | 10G/2.5G | 40G/10G | 32G/32G |
| Security | No | No | No | Yes |
| Outside Plant | Splitter | Splitter | Splitter with WDM mux | AWG |
| Price | Lower | Medium | Medium | Higher |
| Power budget (dB) | 28 (B+) | 35 (E2) | 38.5 | 15 |

Table 1. Summary of features for PON technologies.

ized (ITU-T G.989 series, completed in October 2015). TWDM-PON takes one step forward with respect to XGPON, leveraging the research and development effort of the PON industry on this technology. Essentially, TWDM-PON increases the aggregate PON rate by stacking multiple XGPONs on different pairs of wavelengths, which yields an aggregate $N \times 10$ Gb/s downstream and $N \times 2.5$ Gb/s upstream. In a prototype shown in [7], $N = 4$, and each TWDM-PON optical network unit (ONU) is equipped with colorless transmitters and receivers operating at 10 Gb/s downstream and 2.5 Gb/s upstream. As in TDM-PONs, bandwidth is shared across several subscribers. This solution is called hybrid since it combines the flexibility of TDM-PONs with the increased capacity of WDM technology.

The advantages of TWDM-PON over pure WDM-PON are its high fanout and “graceful evolution” capability, since it is compatible with older TDM-PON versions, like GPON and XGPON, allowing coexistence within the same ODN.

Table 1 provides a summary of the main features of the four PON technologies under study. Based on a number of real deployments and market interest, the next section studies the suitability of GPON, XGPON, AWG-based WDM-PON, and TWDM-PON to provide 1 Gb/s symmetrical services to residential customers. Such suitability is quantified from both technical and economic perspectives in a hypothetical green field deployment.

CAPACITY PLANNING

This section considers the capacity planning for each PON branch, following the architecture of Fig. 1. As noted, GPON, XGPON, and TWDM-PONs have a first fixed splitting stage, 1:8, and a second one, 1: N , that can be configured ($N \in \{1, 2, 4, 8\}$). This section studies how many users can coexist on the same PON branch sharing its bandwidth so that they experience 1 Gb/s symmetrical service most of the time. The analysis is performed only for the uplink direction since it is a more limiting factor than the downlink case.

GPON, XG-PON, AND TWDM-PON WITH OVERSUBSCRIPTION

Most packet-switched telecommunication services rely on the concept of oversubscription; the access network is not an exception. Capacity planning based on oversubscription works because of the

empirical observation that only a small portion of subscribers are simultaneously active at a given random instant [8, 9]. Network designers leverage this fact to provide access to a large number of users at a moderate expense of resources. Essentially, the $b_{peak} = 1$ Gb/s bandwidth cannot be guaranteed to all users during 100 percent of the time, but only a portion of it.

Now, let n_{tot} refer to the maximum number of users physically attached to the same PON branch. As noted from Fig. 1, the total number of users can take the values $n_{tot} \in \{8, 16, 32, 64\}$ depending on the second splitting stage. This range of n_{tot} only applies to GPON, XGPON, and TWDM-PON technologies since for WDM-PON deployments, we consider $n_{tot} = 32$ fixed (Fig. 1).

Let n_{act} refer to the random variable that considers the number of active users at a given random time. Clearly, $0 \leq n_{act} \leq n_{tot}$. For simplicity, we consider that every user can be active with probability q , and that all users are uncorrelated and have the same behavior, that is, they are active with probability q or idle with probability $1 - q$. In other words, n_{act} follows a binomial distribution, $n_{act} \sim B(n_{tot}, q)$.¹ As observed in many measurement studies, the value of q is very small for residential users.

Concerning bandwidth, let us define b as the rate observed per individual user in the PON branch, as follows:

$$b = \frac{C_{UL}}{n_{act}}$$

where C_{UL} is the upstream capacity of each NG-PON technology (Table 1). Clearly, b is a discrete random variable that depends on the number of active users: the higher the value of n_{act} , the lower the bandwidth rate experienced per user. In addition, network operators can limit the bandwidth rate experienced by users to b_{peak} when the number of active users is small (i.e., when $b > b_{peak}$). On the contrary, when all users are active ($n_{act} = n_{tot}$), all users are guaranteed at least a minimum rate of $(C_{UL})/(n_{tot})$. In light of this, the random variables b and n_{act} are related as follows:

$$P\left(b \geq \frac{C_{UL}}{k}\right) = P(n_{act} < k), \text{ with } n_{act} \sim B(n_{tot}, q) \quad (1)$$

meaning that, when k users are active, the uplink capacity C_{UL} is equally shared among them.

In general, it is very unlikely to have many active users when q is sufficiently small. This allows network operators to leverage statistical multiplexing gains. Network designers often use the term *oversubscription ratio* o to refer to the maximum carried traffic divided by the maximum bandwidth capacity promised to the users, in other words:

$$o = \frac{C_{UL}}{n_{tot} b_{peak}}$$

Finally, let β refer to the probability that b_{peak} is guaranteed to the users in the oversubscription model. Clearly, b_{peak} is guaranteed when no more than $n_{act}^{(max)}$ users are active, namely:

$$n_{act}^{(max)} = \left\lfloor \frac{C_{UL}}{b_{peak}} \right\rfloor \quad (2)$$

¹ It is worth remarking that the probability density function (PDF) of the binomial distribution $B(n, q)$ follows: $P(X=k) = \binom{n}{k} q^k (1-q)^{n-k}$, $k = 0, 1, \dots, n$.

Thus, β equals the probability that no more than $n_{act}^{(max)}$ users are simultaneously active; in other words:

$$\beta = P(n_{act} \leq n_{act}^{(max)}).$$

Thanks to the properties of the binomial distribution, β can also be thought of as the percentage of time in which b_{peak} is guaranteed.

NUMERICAL EXAMPLE AND ANALYTICAL RESULTS

Consider a GPON ($C_{UL}^{(GPON)} = 1.25$ Gb/s) with $q = 0.15$ (i.e., 15 percent activity per user) and $n_{tot} = 32$ users, that is, the second splitting stage is 1:4. First of all, the maximum number of active users in order to guarantee $b_{peak} = 1$ Gb/s is $n_{act}^{(max)} = 1$ user, that means, one active user at most (two active users would share 1.25 Gb/s). Following the Binomial distribution, the average number of active users is: $E(n_{act}) = n_{tot}q = 4.8$ users, and the average bandwidth is $E(b) = 327$ Mb/s.²

In the unlikely event that all users are active, that is, $n_{act} = n_{tot}$, which occurs with probability

$$P(n_{act} = 32) = q^{32} = 4.3 \cdot 10^{-27},$$

the bandwidth experienced per active user is only $b = 39$ Mb/s. This is the minimum absolute guaranteed bandwidth 100 percent of the time.

Now, since most users are idle most of the time, the next stage is to see the probability that only $n_{act}^{(max)} = 1$ user is active in the PON branch, thus receiving b_{peak} bandwidth. Following the binomial distribution, the probability of having 1 active user or less in the PON is only 3.7 percent.

Now, consider that the operator's requirement is that all users must receive $b_{peak} = 1$ Gb/s at least $\beta = 20$ percent of the time. Then the value of n_{tot} can be no larger than 18 total users, since $P(n_{act} \leq 1) = 0.22$ when $n_{act} \sim B(n_{tot} = 18, q = 0.15)$ but $P(n_{act} \leq 1) = 0.198$ when $n_{act} \sim B(n_{tot} = 19, q = 0.15)$. Since $n_{tot} \leq 18$, the maximum split ratio in the second stage must be at most 1:2 ($n_{tot} = 8 \times 2 = 16$ total users per PON branch). In this case, the average bandwidth experienced by users is now $E(b) = 637$ Mb/s.

In the case of XG-PON, when $C_{UL}^{(XG-PON)} = 2.5$ Gb/s, $b_{peak} = 1$ Gb/s is guaranteed when there are no more than $n_{act}^{(max)} = 2$ active users in the PON branch. For the same $\beta = 20$ percent criteria as before and $q = 15$ percent, the maximum number of users in the PON branch rises to $n_{tot} \leq 27$. Again, the maximum split in the second stage is 1:2 (16 users at most), which yields an average bandwidth rate $E(b) = 1.27$ Gb/s, limited to $b_{peak} = 1$ Gb/s.

Figure 2 shows the cumulative distribution function (CDF) of b for GPON with different split ratios (Eq. 1) along with the average bandwidth rate $E(b)$. As shown, cases 1:64 and 1:32 provide very small percentages where 1 Gb/s is guaranteed (3.67 and 0.04 percent, respectively) and small values of average bandwidth.

Furthermore, Table 2 shows the average rate $E(b)$ observed and the percentages of time β where b_{peak} is guaranteed for all NG-PON technologies and different split ratios. The values of TWDM-PON have been computed taking into account that a stack of four XG-PON technologies is shared among n_{tot} users. In other words,

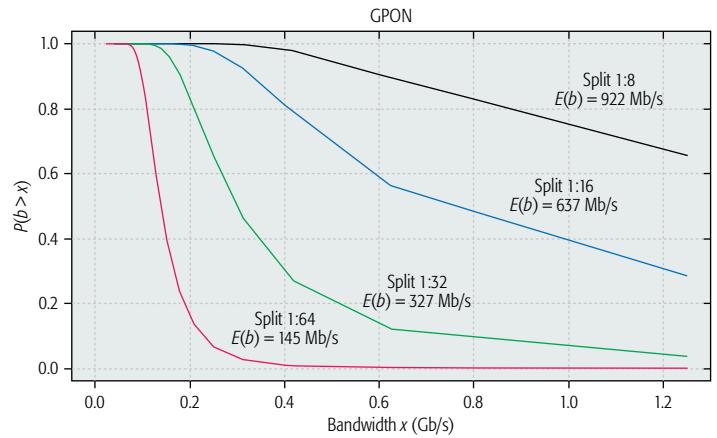


Figure 2. GPON: CDF of b and average bandwidth for different split ratios, $q = 15$ percent.

we have computed the $E(b)$ and b values for an XG-PON with $(n_{tot})/4$ users.

When $q = 15$ percent, XG-PON significantly improves the results of GPON providing 1 Gb/s rate at least 50 percent of the time for the split ratios 1:8 and 1:16. TWDM-PON provides 1 Gb/s most of the time for split ratios 1:32 and below. When large user activity periods are expected (e.g. $q = 50$ percent), only TWDM-PON with 1:8 and 1:16 split ratios can provide 1 Gb/s bandwidth for a substantial percentage of time.

Finally, it is worth remarking that WDM-PON provides a dedicated point-to-point connection between each user and the OLT with 1 Gb/s guaranteed 100 percent of the time for $n_{tot} = 32$ users regardless of user activity q .

ECONOMIC STUDY FOR AN URBAN AREA

This section studies the total cost of ownership (TCO), including both CAPEX and OPEX, required for the deployment of a hypothetical green field urban scenario with 5000 users. Only those FTTH technologies capable of achieving 1 Gb/s symmetrically for a minimum of $\beta = 20$ percent of the time have been considered ($q = 15$ percent assumed). For example, GPON 1:16 is selected because it achieves 28.4 percent (higher than 20 percent), while XGPON 1:32 only achieves 12.2 percent (lower than 20 percent) and therefore is not considered (Table 2). Oversubscription factors beyond the feeder fiber (i.e. from the OLT toward the metro) are not considered.

The calculus of CAPEX is based on commercial prices available from selected undisclosed vendors, complemented with pricing information and network considerations from [10]. Cost of equipment not commercially available yet (TWDM-PON) is derived from market costs of components. Figure 3 shows the resulting cost per user in such a green field deployment relative to the cost per user of the most expensive technology, WDM-PON in this case. The cost includes the following factors.

Central Office: The cost of core cards of the OLT shelves, one-time software licenses, and everything necessary for in-service operation. The cost of uplink transceivers, which is dependent on split ratio, packet loss, and demand distribution, is not included. The reader can find

² The average bandwidth rate perceived by the users is computed as

$$E(b) = \frac{\sum_{k=1}^{n_{tot}} \frac{c}{k} P(n_{act} = k)}{1 - P(n_{act} = 0)}$$

which weights the rate perceived by the users (for the cases where at least one user is active) multiplied by their probability.

| | 1:8 | 1:16 | 1:32 | 1:64 |
|---------------|------------------|------------------|------------------|------------------|
| $E(b), \beta$ | $q = 15\%$ | | | |
| GPON | 922 Mb/s, 65.7% | 637 Mb/s, 28.4% | 327 Mb/s, 3.7% | 145 Mb/s, 0.04% |
| XGPN | 1000 Mb/s, 89.5% | 1000 Mb/s, 56.1% | 654 Mb/s, 12.2% | 290 Mb/s, 0.2% |
| TWDM | 1000 Mb/s, ~100% | 1000 Mb/s, 98.8% | 1000 Mb/s, 89.5% | 1000 Mb/s, 56.1% |
| WDM-PON | – | – | 1000 Mb/s, 100% | – |
| $E(b), \beta$ | $q = 50\%$ | | | |
| GPON | 369 Mb/s, 3.5% | 168 Mb/s, ~0% | 80 Mb/s, ~0% | 40 Mb/s, ~0% |
| XGPN | 738 Mb/s, 14.5% | 337 Mb/s, ~0% | 162 Mb/s, ~0% | 79 Mb/s, ~0% |
| TWDM | 1000 Mb/s, ~100% | 1000 Mb/s, 68.7% | 738 Mb/s, 14.5% | 337 Mb/s, ~0% |
| WDM-PON | – | – | 1000 Mb/s, 100% | – |

Table 2. Bandwidth comparison between the four NG-PON technologies: average bandwidth and percentage of time where $b_{peak} = 1$ Gb/s is guaranteed.

an uplink analysis based on Monte Carlo simulations in [9]. For TWDM-PON, the cost of the WDM mux is also included here.

OLT: The cost of OLT line cards for each technology. OLT line cards are equipped with 16 ports for GPON, 4 ports for XG-PON/TWDM-PON, and 1 port for WDM-PON.

ONT: The lowest cost of commercially available units equipped with at least four Gigabit Ethernet ports toward the user. In the case of a TWDM-PON ONT, since it is not commercially available yet, the cost is derived from market costs of components of the product.

Passive-Street Cabinet: The cost of the cabinet, splitters, or AWG where appropriate (both first and second stage costs are included), and the cost of splicing the fibers. For GPON, XGPON, and TWDM-PON, the two-stage splitting architecture of Fig. 1 is considered, following [10]. That is, a first fixed 1:8 split stage, placed at the street cabinet, followed by a second variable split stage (1:1, 1:2, 1:4, and 1:8), which is placed at the bottom of the building. In the case of WDM-PON, a 1:32 AWG is assumed and is located at the street cabinet;

Feeder and Distribution Segment: The cost of digging and preparing the trench, manholes, and finer deployment in each segment. As seen in Fig. 1, for GPON, XGPON, and TWDM-PON, feeder fiber is the fiber between the CO and the first 1:8 split, and distribution fiber is the fiber between the first and second splits; while for WDM-PON, feeder fiber is the fiber between the CO and the 1:32 AWG, and distribution fiber is the fiber between the AWG and the ONT. Following [10], the length of the feeder segment in an urban area is assumed to be 850 m, whereas the length of the distribution segment is 80 m. Cost of digging and preparing the trench for an urban area has been assumed USD 120/m;

In-House Segment: The cost of the optical distribution frame (ODF), patch cable, and fiber access terminal in the basement.

Concerning OPEX, only first-year costs are considered, including system support and energy consumption, as a markup of the active (4 percent) and passive (1 percent) infrastructure [10, 11]. Since they are considered as a percent-

age, OPEX costs are uniformly distributed over the CAPEX costs. System support considers the technical and maintenance support required for the installed equipment. Energy consumption represents the yearly cost of energy (in watts) consumed by the equipments.

As expected, the largest part of the CAPEX lies in the physical infrastructure [12] (in-house segment, distribution segment, street cabinet, feeder segment, and CO), which represents between 50 and 80 percent of the total investment. All technologies under consideration are deployed with a single fiber in the feeder segment, and a single fiber between the remote node and the ONT. Thus, the main difference in terms of TCO corresponds to the CO, OLT, passive-street cabinet (splitter or AWG), and ONT.

Other observations include:

- The shared cost of the OLT should decrease as the split ratio increases. However, in all TDM-PON and hybrid options, the TCO for 1:16 is slightly more expensive than in the 1:8 case. This arises as a penalty for choosing a fixed 1:8 first stage, which means that extra 1:2, 1:4, and 1:8 splitters have to be dimensioned for higher split ratios.

- ONTs are cheaper in GPON due to electronics managing less bandwidth; XG-PON ONTs come next, followed by TWDM-PON and WDM-PON.

- The cost of the passive-street cabinet in TWDM-PON 1:16 is slightly higher than in WDM-PON. This is due to the assumption of a 1:8 split at the first stage for all TDM-PON and TWDM-PON technologies [10]. In this case, for example, for 32 users, a single 1:32 AWG is enough for WDM-PON but would require $4 \times 1:8$ in the first split + $8 \times 1:2$ for TWDM-PON 1:16, that is, although the cost of a 1:32 AWG is much more expensive than the cost of a single 1:16 power splitter, the topology under consideration actually compares 1×32 AWG against $12(4+8)$ power splitters (in the case of TWDM-PON 1:16).

- GPON is the cheapest technology with 1:8 split ratio, and is capable of providing 1 Gb/s for a large portion of the time. However, GPON does not scale up when q increases (Table 2).

- The cost per user of XGPON 1:8 and 1:16 is very similar to TWDM-PON 1:32 and 1:64, respectively, and also provides very similar performance. This is a consequence of the fact that TWDM-PON stacks four XG-PONs.

- TWDM-PON with 1:8 and 1:16 split ratios provide 1 Gb/s nearly 100 percent of the time when $q = 15$ percent with a substantial cost reduction with respect to WDM-PON, which is the most expensive flavor. However, it is worth remarking that WDM-PON provides 1 Gb/s guaranteed 100 percent of the time regardless of user activity q .

- The high cost of WDM-PON is mainly due to the electronics at the OLT (one laser per user is required) and the lower shelf density (256 users per shelf). The OLT and CO costs dominate in this technology.

SUMMARY AND DISCUSSION

This article has compared four different flavors of fiber access protocols capable of offering 1 Gb/s symmetrical services for residential users. In particular, GPON, XGPON, WDM-PON, and the emerging TWDM-PON technologies with dif-

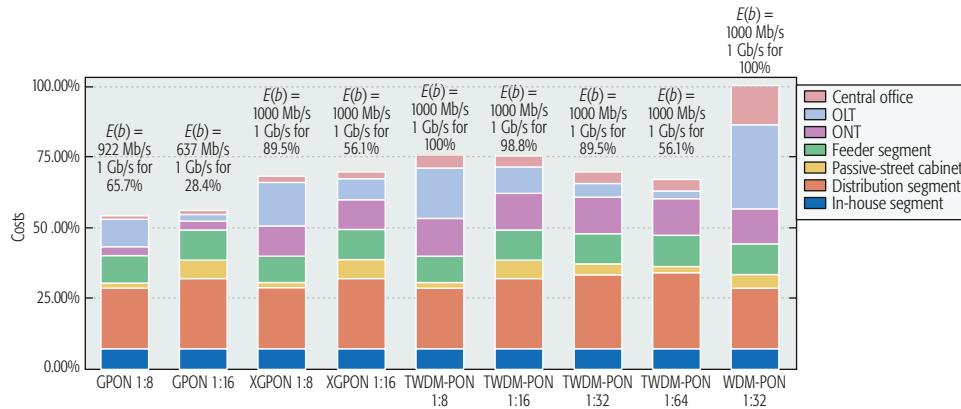


Figure 3. Details of TCO (CAPEX and OPEX) for FTTH options for providing 1 Gb/s symmetrical (bandwidth values for $q = 15$ percent).

ferent split ratios have been analyzed for a green field deployment of 5000 users in a typical urban area. Market prices of either available commercial equipment (GPON, XGPON, and WDM-PON) or prototypes (TWDM-PON) have been used.

The results show that GPON 1:8 and 1:16, XGPON 1:8 and 1:16, TWDM-PON, and WDM-PON are good candidates to enable 1 Gb/s symmetrical services for residential users in terms of both cost and performance for next-generation optical access. However, as the user activity pattern increases, both GPON and XGPON will become insufficient. Only TWDM-PON and WDM-PON can guarantee 1 Gb/s at high levels of user activity (for a fraction of time typically used in design today in the case of TWDM-PON).

Other services than residential (business services and wireless backhaul), which require higher bandwidth, lower latency and physical separation of traffic (for security purposes) than residential scenarios, may require the use of dedicated point-to-point connectivity with absolute bandwidth guarantees, in other words, WDM-PON. In light of this, WDM-PONs with bandwidth provisioning beyond 1 Gb/s have been proposed [13], some supporting up to 10 Gb/s.

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The shared cost of the OLT should decrease as the split ratio increases. However, in all TDM-PON and hybrid options, the TCO for 1:16 is slightly more expensive than in the 1:8 case. This arises as a penalty for choosing a fixed 1:8 first stage, which causes that extra 1:2, 1:4 and 1:8 splitters have to be dimensioned for higher split ratios.