Performance of Interoperator Fixed-Mobile Network Sharing

Ireneusz Szcześniak*, Andrzej R. Pach† and Bożena Woźna-Szcześniak‡
*Częstochowa University of Technology, Institute of Computer and Information Sciences
ul. J. H. Dąbrowskiego 73, 42-201 Częstochowa, Poland
†AGH University of Science and Technology, Department of Telecommunications
al. Mickiewicza 30, 30-059 Kraków, Poland
‡Jan Długosz University in Częstochowa, Institute of Mathematics and Computer Science
al. Armii Krajowej 13/15, 42-200 Częstochowa, Poland

***Abstract*—We evaluate the downstream performance of our novel interoperator fixed-mobile network sharing, in which operators exchange data in their access networks. We propose a performance evaluation algorithm, and report credible performance evaluation results obtained for 204600 randomly-generated passive optical networks. We show that with the proposed sharing, operators can increase their access network performance even *twofold* with software-defined upgrades, and with no or minimal new hardware required.**

I. Introduction

New network architectures and business models are required to further increase the network performance and availability, and still to cut costs and save energy. One of them is sharing, being both a network architecture and a business model [1]. Currently, network operators do share, but the physical infrastructure only (buildings, towers, etc.) [2]. Some operators *merge* their networks into a single network to own and use it in a marriage-like fashion.

We proposed the interoperator fixed-mobile network (FMN) sharing, and demonstrated impressive *availability* improvement [3]. Fig. 1 illustrates the proposed sharing, where one operator (O1) can divert its access-network traffic to the other operator (O2) with the *interoperator communication* (IC), either for performance or availability reasons. The diverted traffic is then sent back to O1 through the aggregation network with either Q-in-Q or MAC-in-MAC tagging.

While the proposed sharing could be used with any access network technology, we concentrate on the passive optical networks (PONs), because they are economical and wide-spread. PONs are also attractive for the emerging fifth-generation (5G) radio access networks [4]. As shown in Fig. 2, the sharing can be implemented by the interoperator-communicating optical network units (IC-ONUs), i.e., the interconnected ONUs of different operators. An IC-ONU can offer the communication with the aggregation network in the same way as the optical line terminal (OLT) does, while the remaining ONUs are non interoperator-communicating ONUs (NIC-ONUs). The data of the first operator can be diverted by an active remote node (RN) to the access network of the other operator.

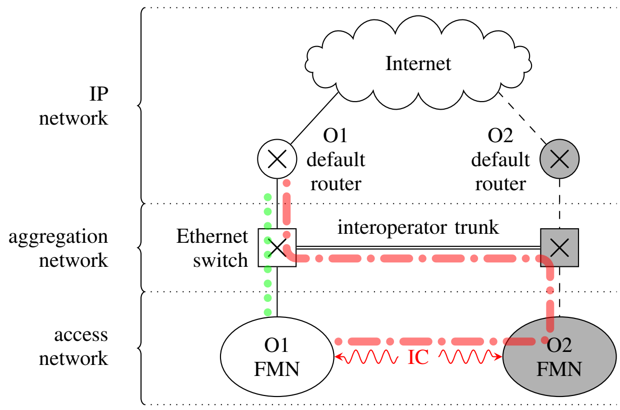

Fig. 1: General network architecture, where is the normal traffic, and is the diverted traffic.

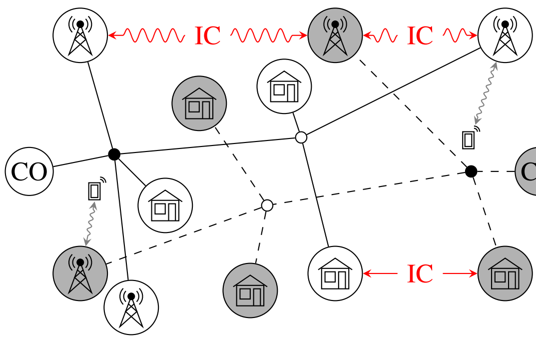

Fig. 2: Interoperator FMN sharing: a central office (CO), the interoperator communication (IC), a passive remote node •, an active remote node ○, a mobile user, a base station, and a fixed user.

The contribution of our work is the evaluation of the performance improvement brought by our sharing along with the evaluation software under the General Public License [5].

In Section II we review related works, in Section III we state the problem, in Section IV we propose a solution to the problem, which we harness in Section V to produce credible performance results. Finally, Section VI concludes the article.

II. Related works

Mobile network sharing has long been used, allowing for roaming or virtual mobile network operators, where a mobile operator accepts traffic *directly from the users* of a different operator, and the network of that different operator does not carry that traffic. In [2] the authors study this traditional sharing in the virtualization context. Our work does not subscribe to this mainstream research – the hallmark of our proposed sharing is the *interoperator communication*, where traffic is exchanged by different operators between their access networks.

PONs are successful mainly because of the cost-effective tree topology. First, the feeder fiber starts at the optical line terminal (OLT) in the central office (CO), and ends at the first remote node (RN) in some district. From there, the distribution fibers lead to further RNs in various neighborhoods, possibly through further RNs. Finally, the last-mile fibers deliver the service to customer premises.

NG-PONs should support direct communication between ONUs, without the OLT relaying the data, in order to support direct communication between BSs (connected to ONUs) required by future RANs. However, in legacy PONs, ONUs do not communicate directly with each other, but through the OLT. To this end, in [6] the authors propose two novel NG-PON architectures. Interestingly, the authors propose to cleverly use a circulator as a passive RN, which would allow for some limited communication between BSs without the OLT. Another solution is to use the active RNs, which would also enable NG-PONs to have larger splitting ratios and longer reach [7].

In [8], the authors propose a number of wireless protection methods for FMNs, which could also be used to increase performance. There a single network is considered, without sharing it with a different operator. Wireless access points connected to a PON are allowed to offer connectivity to those wireless access points which lost the PON connectivity.

PONs are vulnerable to service disruption, because of the tree architecture. Failure of the OLT or the feeder fiber brings down the entire PON. Making a PON resilient is becoming more important, but requires expensive redundant infrastructure, fibers and hardware. In [9] the authors review PON resiliency mechanisms and propose their own mechanism for cost-effective resiliency on request. *The redundant hardware can be used to improve the PON performance.*

FMNs are being broadly researched and developed to deliver the required performance and resiliency [10]. Radio access technologies (RATs) have been proposed to use cognitivity, virtualization, coordinated multipoint transmission (CoMT), and more sophisticated modulation formats. The backhaul is evolving from the copper or microwave networks to passive optical networks (PONs), and even possibly to radio-over-fiber (RoF) networks. PONs are currently being deployed as the backhaul, and the NG-PONs are being intensively researched for FMNs [6].

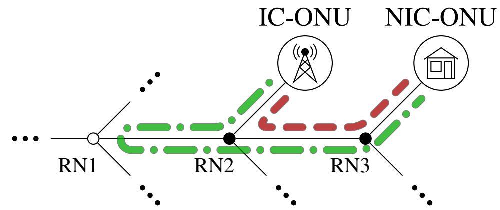

Fig. 3: Example of finding a correct shortest path between an IC-ONU and an NIC-ONU, where • is a passive RN, ∘ is an active RN, (green dash-dotted line) is the correct path, and (red dashed line) is the wrong path.

III. Problem statement

We are given a specific PON P, i.e., a PON with the topology, and the types of the RNs and ONUs given. The number of ONUs is N, the number of RNs is R, and the downstream capacity is c.

The problem is to evaluate the *upper bound* of the downstream performance p of PON P under the offered load $1 \leq l \leq 2$, where $l = 1$ is the full offered load, and $l = 2$ is twice the full offered load. We define p as the average of the downstream performance values of all ONUs in a PON. In turn, we define the downstream ONU performance as the ratio of the downstream bitrate (DB) granted to an ONU to the DB requested by that ONU. The DB can be granted either by the OLT or by an IC-ONU. When P is able to completely service the offered load l, performance $p = 1$. Even though the proposed evaluation algorithm (described in Section IV) can handle non-uniform traffic, for simplicity, we load the PON with uniform traffic: we try to grant the same DB $b = cl/N$ to every ONU.

The DB granted by the OLT is guaranteed to reach the aggregation network. However, we assume that the DB granted by an IC-ONU is *potential* only: even though the bitrate is granted by an IC-ONU within the PON, the other operator might actually reject it. The *sharing rules* should regulate whether the potential DB is guaranteed by the other operator. We make this assumption to study the upper bound of the performance, without considering the sharing rules.

Fig. 3 illustrates the corollary problem of finding a correct shortest path from an IC-ONU to an NIC-ONU traversing a passive RN. It is a problem unusual for legacy PONs where downstream data frames travel downstream only, while with the proposed sharing the downstream data frames sent from an IC-ONU travel upstream first, are diverted by an active RN, and then travel downstream to finally reach an NIC-ONU. If we apply a shortest path algorithm (e.g., the breadth-first search algorithm or the Dijkstra algorithm) directly on P, we get the dashed (red) path, which is wrong, instead of the dash-dotted (green) path, which is correct.

In the next section we describe the algorithm which evaluates the performance of a single PON. To make the evaluation of the proposed sharing statistically sound, in Section V we use the algorithm to evaluate the performance of PON populations.

Algorithm 1 calculate performance
Input: PON P, load l, capacity c, number of ONUs N
Output: performance p

$\mathbf{A} = (A_n) \leftarrow$ find alternatives (P)
$Q \leftarrow$ make priority queue $(\mathbf{A})$
$b \leftarrow cl/N$
for each $n \in \{$ONUs of $P\}$ **do**
  Q.push (n)
while $Q \neq \emptyset$ **do**
  $n \leftarrow Q$.pop $()$
  $p_n \leftarrow$ grant DB $(P, n, b, A_n)/b$
return $p \leftarrow$ average (p_n)

Algorithm 2 find alternatives
Input: PON P
Output: alternatives $\mathbf{A}$

$\mathbf{A} = (A_n \leftarrow \emptyset)$
$P' \leftarrow$ split RNs(P)
for each $i \in \{$OLT and IC-ONUs of $P\}$ **do**
  $T_i \leftarrow$ breadth-first search (P', i)
  for each $n \in \{$ONUs of $P\}$ **do**
    $A_{i,n} \leftarrow$ trace (T_i, n)
    if $A_{i,n}$ exists **then**
      A_n.push $(A_{i,n})$
return $\mathbf{A} = (A_n)$

IV. Algorithm

In order to evaluate performance p, we need to calculate performance p_n of ONU n. In a PON without sharing, the DB is granted by the OLT only, but with sharing, an ONU can have the DB granted also by IC-ONUs, and so the performance evaluation is more complicated, as we have to consider all the alternatives an ONU has. An *alternative* for an ONU is a shortest path (i.e., a path with the smallest number of hops) to that ONU from either the OLT or an IC-ONU. An ONU has at least one alternative: the one from the OLT.

PON performance can be evaluated in various ways and with different accuracy depending on the PON type, the traffic type, and a plethora of technical details. We propose a simple method of assessing the performance: we start with an unloaded PON, and try to grant the same DB b to every ONU.

We serve the ONUs in the order of increasing number of alternatives they have, since the more alternatives an ONU has, the more likely it is to get the DB. If an ONU being served has more than one alternative, we try to grant the DB along the shortest alternative, and continue with the longer alternatives when needed. The DB is granted to an ONU by allocating the DB on the edges of a single alternative.

Algorithm 1 recaps the described performance evaluation. Function 'find alternatives' returns vector $\mathbf{A}$ of alternatives A_n for ONU n in P sorted in the increasing order of the number of hops. Q is the priority queue of ONUs sorted in the increasing order of the number of alternatives the ONUs have. Q is given the alternatives $\mathbf{A}$ at the construction time, and then uses $\mathbf{A}$ to maintain the order of the nodes pushed into Q. Function 'grant DB' tries to grant DB b to ONU n (i.e., it allocates the bandwidth on all the edges of an alternative), and returns the value of the actually granted DB. The 'while' loop iterates over the ONUs requesting service, finishing when there are no more ONUs to service.

In the search for the correct alternatives, we use the breadth-first search algorithm (BFS) on a modified graph as described next. However, a different solution would be to adapt the BFS algorithm: make the label of a passive RN also take the direction with which that passive RN was reached. However, we opt for modifying P, since we find it more elegant.

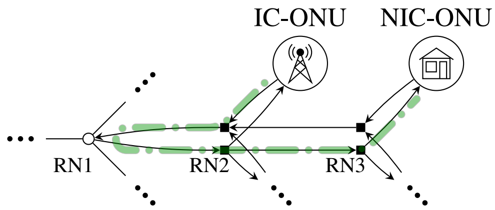

Fig. 4: Example of modifying a graph by splitting passive RNs, where ▪ is a split passive RN, ∘ is an active RN, and is the correct path.

We find the correct alternatives by searching for shortest paths in a *modified* graph P', where a passive RN is modeled with two vertexes: one vertex for the downstream direction with the downstream-directed edges only, and the other vertex for the upstream direction with the upstream-directed edges only, as shown in Fig. 4. A shortest-path search from a given IC-ONU keeps going upstream through a passive RN (without being derailed there) to an active RN, where it turns back to continue downstream, passes again through the passive RN, and finally reaches an NIC-ONU.

For every node i providing service, which is the OLT or an IC-ONU, we search for the shortest-path tree T_i from node i to all other nodes of the PON, where the search stops. The search starting at an IC-ONU also stops at the OLT, even though the OLT could divert downstream the upstream traffic to reach an NIC-ONU, since the OLT is an active node. This, however, would be pointless, since the OLT can service the NIC-ONU, without the IC-ONU, and without taking the upstream capacity.

Algorithm 2 calculates the alternatives, returned as vector $\mathbf{A}$. A_n is a priority queue, where alternatives for node n are sorted in the increasing order of their number of hops. There are two nested loops. The outer loop iterates for each node i providing service, and the inner loop iterates for each node n receiving service. In the outer loop the shortest-path tree T_i is calculated, which is subsequently used in the inner loop to find, using function 'trace', a single shortest path $A_{i,n}$ from node i to node n. We make sure $A_{i,n}$ does exist, since it could very well be that it does not, as when there is no active RN on the way from an IC-ONU to an NIC-ONU.

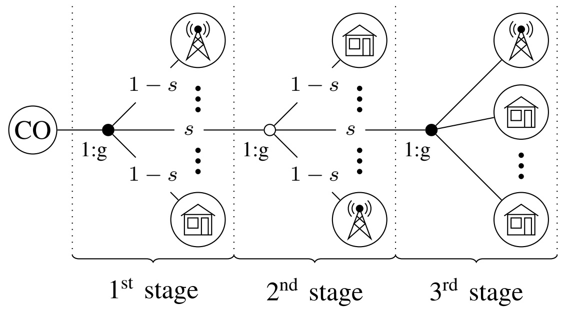

Fig. 5: PON: a central office (CO), a passive remote node •, an active remote node ○, a base station, and a fixed user.

V. Performance evaluation

We evaluate the performance of a given PON population under a given offered load l. In order to obtain credible estimated results for a population, we produce a sample of 300 specific randomly-generated PONs. Performance p is calculated by the proposed algorithm for every PON in the sample under load l, and then the obtained PON performance values are averaged to yield the sample PON performance mean. We deem the obtained means credible, as their relative standard errors are below 1%.

We evaluate the performance improvement when the proposed sharing is used for PON populations of two scenarios. Both scenarios use populations of a generic PON shown in Fig. 5 with the depth of three stages. The PON can have many second-stage and third-stage RNs, but in the figure we show only one of each. The scenarios differ in the location of the active RNs: in the first scenario the location is given upfront, while in the second scenario the location is chosen at random.

The RNs of every stage have the 1:g splitting ratio. At the first and the second stage, a fiber coming out of a RN goes to the next stage with probability s, and, conversely, to an ONU, i.e., a fixed user or a base station, with probability $(1-s)$. At the third stage, all fibers coming out of a RN go to ONUs.

For the studied PON network, the mean number of ONUs is $N = g(1-s+gs(1-s+gs))$, and $R = 1+gs(1+gs)$. For the evaluation we assume $s = 0.3$ and $g = 32$, and so $N \approx 3187$ and $R \approx 103$, which is reasonable for the next-generation PONs. For example, the XG-PON currently can handle 1024 ONUs. Furthermore, we assumed the PON offers the downstream capacity of $c = 10$ Gb/s, and the upstream capacity of 2.5 Gb/s. IC-ONUs can send data to the other operator with the bitrate of 2.5 Gb/s.

In Figures 6 and 7, we plot as the white surface the PON performance with the proposed sharing, and as the gray surface the PON performance without the proposed sharing. The difference between these surfaces is the performance improvement brought by our sharing.

We implemented the proposed performance evaluation in C++ with the Boost Graph Library (BGL) as a high-quality and high-performance multithreaded program under the Debian GNU/Linux operating system.

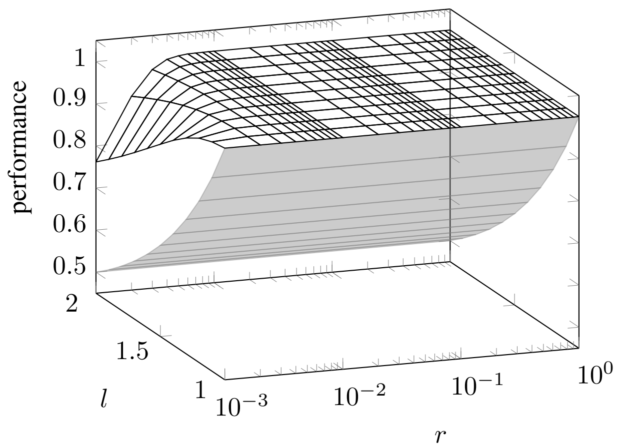

Fig. 6: Performance in the 1st evaluation scenario.

A. First scenario

In the first scenario, for the offered load l, we evaluate the performance of a PON population characterized by probability r that an ONU is capable of the IC. When a specific PON is generated, a given ONU becomes capable of the IC with probability r, and incapable otherwise.

There are 31 populations, each with a different value of r = {0, 0.001, 0.002, …, 0.009, 0.01, 0.02, …, 0.09, 0.1, 0.2, …, 1.0}. We evaluate the performance of a population for 11 values of l = {1, 1.1, 1.2, …, 2}, totaling 341 values of the population performance. We evaluate the performance for $1 \leq l \leq 2$, because the sharing helps for overloaded networks.

The location of the active RNs is given upfront as shown in Fig. 5. At the first stage we install a passive RN, which is typical for the incumbent PONs. The high 1:32 splitting ratio, which is also typical, and possibly long feeder and distribution fibers may require an active RN, which we install at the second stage. There are on average $gs = 9.6$ active RNs required in a PON, which is about 10% of all RNs. *Today active RNs are already used to extend the PON reach.* The last-mile fibers are typically short, and so passive RNs at the third stage suffice.

Fig. 6 shows as the white mesh surface the population performance with the proposed sharing as a function of r and l. There are 341 data points obtained from 102300 PON performance values (11 values of offered load × 31 populations × 300 PONs in a population sample). For comparison, we also plot as the gray surface the PON performance without the proposed sharing as a function of l only, since r is irrelevant.

The results show the *proposed sharing improves the PON performance twice* for the values of r as small as 3×10^{-3}, which for a PON with $N \approx 3187$ ONUs translates to about ten IC-ONUs. For $r = 10^{-3}$, which translates to about only three IC-ONUs, the PON performance improves from 50% to 100% depending on the offered load. The PON performance without sharing caves in as the offered load increases.

For $r = 0$, the sharing cannot take place as there are no IC-ONUs, and so the white and gray surfaces should meet, but it cannot be plotted in the logarithmic scale in Fig. 6.

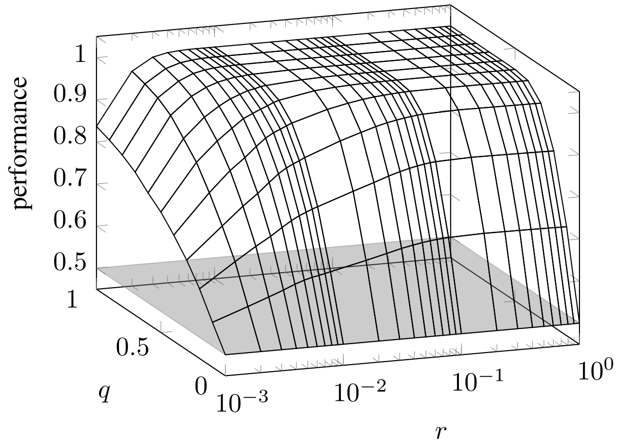

Fig. 7: Performance in the 2nd evaluation scenario.

B. Second scenario

In the second scenario, for the offered load $l = 2$, we evaluate the performance of a PON population described by the probability r that an ONU is capable of the IC, and by the probability q that an RN is active. When a specific PON is generated, a given RN becomes active with probability q, and passive otherwise.

For a given population, the location of active RNs is not fixed, but is random instead. For $q = 0$, there are no active RNs, and so there should be no performance improvement, as the active RNs are indispensable for the proposed sharing. For $q = 1$, all RNs are active.

We have 341 populations, since there are 31 values of r = {0, 0.001, 0.002, ..., 0.009, 0.01, 0.02, ..., 0.09, 0.1, 0.2, ..., 1.0}, and 11 values of q = {0, 0.1, ..., 1}. We are interested in how the proposed sharing improves performance, when a PON is offered a load twice its capacity, and therefore for each population we evaluate the performance only for a single value of the offered load $l = 2$.

Fig. 7, shows as the white mesh surface the population performance with the proposed sharing as a function of r and q. There are 341 data points obtained from 102300 PON performance values (1 value of offered load $\times$ 341 populations $\times$ 300 PONs in a population sample). For comparison, we also plot as the gray surface the PON performance without the proposed sharing.

The results show that the proposed sharing improves the PON performance, but not as impressively as in the 1st scenario. For instance, in the 1st scenario, about 10% strategically-placed active RNs at the second stage and about 1‰ IC-ONUs suffice to improve the PON performance about 50%, while in this scenario 10% randomly-placed active RNs and also about 1‰ IC-ONUs improve the PON performance about only 10%.

The performance improvement in this scenario is worse than in the 1st scenario, because the active RNs which end up at the third stage are not as useful as they would be, had they been placed at the second stage as in the 1st scenario, where they would be able to service more ONUs. We call it life.

VI. Conclusion

We evaluated the performance of the interoperator fixed-mobile network sharing in the context of the passive optical networks. The results suggest that the performance can be improved twofold by providing interoperator communication to as little as 1‰ of all optical network units.

In the optimistic case, no new hardware is required. If active remote nodes are already installed, their software upgrade could be sufficient to implement the proposed sharing. Interoperator communication, in turn, could be software-defined and implemented wirelessly between base stations. In the pessimistic case, the proposed sharing would need the installation of a few strategically-placed active remote nodes, and providing the interoperator communication with fiber to a few optical network units. The proposed sharing is amenable to the pay-as-you-grow deployment, where the active nodes and intercommunicating optical network units are deployed in stages when and where needed.

Future work could concentrate on 1) extending the dynamic bandwidth allocation protocol to allow for the sharing, 2) studying the sharing rules, or 3) generalizing the sharing to any number of operators.

Acknowledgments

This work was supported in part by the postdoctoral fellowship number DEC-2013/08/S/ST7/00576 from the Polish National Science Centre. The numerical results were obtained using PL-Grid, the Polish supercomputing infrastructure.

References

[1] L. Doyle, J. Kibiłda, T. Forde, and L. DaSilva, "Spectrum without bounds, networks without borders," *Proceedings of the IEEE*, vol. 102, no. 3, pp. 351–365, March 2014.

[2] A. Khan, W. Kellerer, K. Kozu, and M. Yabusaki, "Network sharing in the next mobile network: TCO reduction, management flexibility, and operational independence," *IEEE Communications Magazine*, vol. 49, no. 10, pp. 134–142, Oct 2011.

[3] I. Szcześniak, P. Chołda, A. R. Pach, and B. Woźna-Szcześniak, "Interoperator fixed-mobile network sharing," in *Proceedings of the 19th International Conference on Optical Network Design and Modeling (ONDM)*, May 2015, pp. 192–197.

[4] J. Beas, G. Castañon, I. Aldaya, A. Aragon-Zavala, and G. Campuzano, "Millimeter-wave frequency radio over fiber systems: a survey," *IEEE Communications Surveys and Tutorials*, vol. 15, no. 4, pp. 1593–1619, Fourth Quarter 2013.

[5] I. Szcześniak. (2016, April) The website of the PERFOR software. Http://www.irkos.org/perfor.

[6] M. Ali, G. Ellinas, H. Erkan, A. Hadjiantonis, and R. Dorsinville, "On the vision of complete fixed-mobile convergence," *Journal of Lightwave Technology*, vol. 28, no. 16, pp. 2343–2357, 2010.

[7] C. Chan, M. Attygalle, and A. Nirmalathas, "Remote repeater-based EPON with MAC forwarding for long-reach and high-split-ratio passive optical networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 2, no. 1, pp. 28–37, January 2010.

[8] N. Ghazisaidi, M. Scheutzow, and M. Maier, "Survivability analysis of next-generation passive optical networks and fiber-wireless access networks," *IEEE Transactions on Reliability*, vol. 60, no. 2, pp. 479–492, June 2011.

[9] M. Mahloo, J. Chen, L. Wosinska, A. Dixit, B. Lannoo, D. Colle, and C. Machuca, "Toward reliable hybrid WDM/TDM passive optical networks," *IEEE Communications Magazine*, vol. 52, no. 2, pp. S14–S23, February 2014.

[10] L. Kazovsky, S.-W. Wong, T. Ayhan, K. Albeyoglu, M. R. N. Ribeiro, and A. Shastri, "Hybrid optical-wireless access networks," *Proceedings of the IEEE*, vol. 100, no. 5, pp. 1197–1225, May 2012.