A Novel Design of Cost-Efficient Long-Reach Survivable Wireless-Optical Broadband Access Network

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***Abstract*—Wireless-optical broadband access networks (WOBANs) have gained extreme importance due to their ability to provide ubiquitous and high-speed Internet access. Since in long-reach WOBAN, wireless front-end is fed by a long-reach optical back-end, provisioning protection against failure of a WOBAN segment (due to failure of its feeder fiber and/or optical line terminal) is a primary concern. The failure causes simultaneous disconnection of a large number of users, resulting to poor connection availability and service dissatisfaction for users and high revenue loss for network operators. Focusing on the problem of a WOBAN segment failure, we propose a novel multi-cast multi-hop protection architecture (MCMHPA) to design a survivable WOBAN wherein traffic of a failed WOBAN segment is recovered by employing the residual bandwidth of other neighboring WOBAN segments. In MCMHPA, we provide a novel architecture of backup optical network units (optical devices used to transmit/receive traffic in condition of the segment failure) to implement multi-cast and multi-hop mechanisms. The proposed architecture offers multi-hop backup optical paths by using the minimum number of optical devices and fibers, thereby incurring low expenditure to design a survivable WOBAN.**

***Index Terms*—Wireless-opitcal, WOBAN, protection, survivability, multi-cast, multi-hop.**

I. Introduction

Importance of Internet in our day-to-day life is increasing rapidly due to the rapid emergence and wide acceptance of new bandwidth-intensive applications and services. Moreover, on-line access of existing services, such as shopping, banking, gaming etc. is being preferred over their off-line modes. As a result, traffic demand per user is expected to grow from Mbps to Gbps order in the next few years. To provide high bandwidth to users, optical networking technology-based solutions are being considered as the key solutions since the last two decades [1], [2]. Two single-wavelength based passive optical network (PON) standards, namely, Ethernet PON (EPON) and gigabit-capable PON (GPON) have been widely deployed in many countries in different forms, such as fiber-to-the-home (FTTH) networks, fiber-to-the-curb (FTTCurb) networks, fiber-to-the-office (FTTO) networks, fiber-to-the-cell (FTTCell) networks, etc. [3], [4]. These networks (EPON and GPON) have limited network reach of about 20 km. To increase network reach (from 20 km to 100 km or more) in order to serve distant users and avoid the cost of running multiple local exchanges, the ideas to develop long-reach PON (LR-PON) have been largely discussed [5], [6]. Even though at the beginning, demands for high bandwidth were only from business or industrial users, later high bandwidths are also being requested by residential users. The high bandwidth demands are primarily catered by setting up fiber-based wired connections [7], [8]. On the other hand, over the last few years, mobile/wireless traffic has also been growing rapidly due to rapid increase in the usage of smart-phones, tablets and laptops. Thus, in order to serve mobile/wireless users with high offered bandwidth, setting up access networks with wireless front-end and optical back-end gained momentum and several practical deployments of wireless-optical broadband access networks (WOBANs) have been demonstrated [9]–[12]. The deployments show that WOBAN is a favorable solution to provide high bandwidth to users in academic campuses, large industries and public places, such as railway stations, bus-stand, malls etc. Hereafter, in this paper, we refer the mobile/wireless users as only the users.

Fig. 1 illustrates a typical architecture of a long-reach WOBAN comprising of multiple WOBAN segments wherein each segment consists of an optical back-end and a wireless front-end. The optical back-end is setup by deploying an optical line terminal (OLT) in central office (CO), multiple optical network units (ONUs) and a passive splitter and combiner (PSC) in distribution section (that also includes the network users). The OLT acts as an interface between core network and the access network. A fiber, referred to as feeder fiber (FF) is setup between the OLT and PSC, whereas a dedicated fiber, referred to as distribution fiber (DF) is deployed between the PSC and an ONU. In long-reach WOBAN, FF length may be about 60 km and even may be extended to 100 km (or more) to penetrate into a large service region, whereas the DF length may be extended up to 10 km. One or more optical amplifiers (OAs) are also deployed to compensate high optical power loss that primarily occurs due to the large fiber attenuation loss (because of long network reach) and large insertion loss (because of using PSCs of high splitting ratios to serve a large number of users). The wireless front-end is

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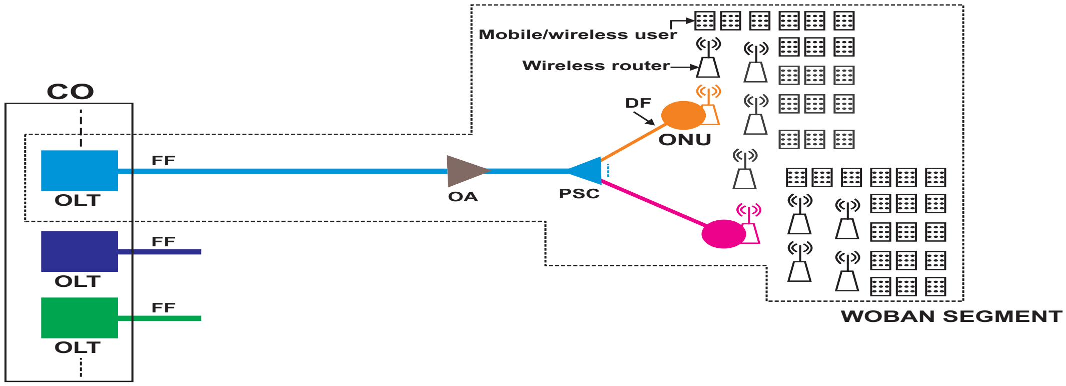

Fig. 1: Illustration of a typical architecture of long-reach WOBAN.

setup by integrating each ONU with a wireless router and deploying additional intermediate routers in the service area to form a mesh topology, which enables traffic transmission between ONUs and wireless routers through wireless links. Wireless routers located within the coverage reach of users allow downstream and upstream traffic flow to/from the users.

Providing high connection availability to users is also a primary concern besides providing high bandwidth to users. In WOBAN, several users may be simultaneously disconnected due to a device/fiber failure. Since WOBAN front-end design follows a mesh topology, the front-end is self-healing and it can recover traffic itself in case a failure occurs in the front-end. However, WOBAN back-end design follows a tree topology and thus, the back-end requires protection against any optical device and/or fiber failure. In [13]–[20], authors consider failure of DFs and propose methods to setup wireless multi-hop backup paths to send traffic of a disconnected ONU (the ONU gets disconnected due to its DF failure) to its neighboring ONUs (whose DFs are geographically disjoint with the DF of the disconnected ONU). These studies consider single DF failure only; the failure of FF and/or OLT (that leads to the failure of an entire WOBAN segment) is not considered. Traffic of multiple simultaneously disconnected ONUs (due to simultaneous failure of multiple DFs) cannot be sent to their neighboring ONUs through wireless links and thus, it is required to setup backup optical path(s).

A very few research studies, such as [21] and [22] raise and address the issue of failure of an entire WOBAN segment due to failure of its OLT and/or FF. Authors in [21] make a provision to exploit residual bandwidth of neighboring segments to recover traffic of all the users of a failed segment. In this respect, dedicated backup fibers are setup from the failed segment to its neighboring segments to utilize their residual bandwidth efficiently. This scheme provisions to setup a large number of backup fibers and incurs very high fiber deployment cost in areas without any existing fiber infrastructure. This study does not provide the protection architecture to transmit traffic from the failed segment to its neighboring segments. Liu *et al.* [22] propose a protection scheme that explores setting up of multi-hop backup optical paths from a failed segment to its neighboring segments so as to efficiently utilize the residual bandwidth of the neighboring segments. However, this scheme does not provide any architecture to develop multi-hop backup optical paths and transmit traffic from the failed segment to its neighboring segments. Since the above-mentioned protection schemes do not provide their protection architectures, it is difficult to implement them in practical scenarios and evaluate their performances in view of satisfying the power-budget and cost-budget requirements.

In this paper, we propose a novel protection architecture, referred to as multi-cast multi-hop protection architecture (MCMHPA) to provide protection against a WOBAN segment failure (due to the failure of its FF and/or OLT), wherein we provision to multi-cast the traffic of a failed segment to its neighboring segments to use their residual bandwidth. We also provision to setup multi-hop backup optical paths to send the traffic from the failed segment to its neighboring segments. Therefore in MCMHPA, we propose a novel architecture of backup ONUs (some specific ONUs that are optimally selected to transmit/receive traffic between the segments) to implement multi-cast and multi-hop mechanisms. This architecture provisions to use the minimum number of optical devices and/or fibers to provide protection for segments. To the best of our knowledge, this is the first study that provides an architecture to implement traffic multi-casting through multi-hop optical paths in the optical access networks with due consideration of stringent optical power budget. Moreover, this is the first physical implementation of a protection scheme for providing protection against failure of a WOBAN segment.

We organize the paper as follows. In Section 2, we present the proposed protection architecture (MCMHPA) and its implementation. In section 3, we provide a comparative analysis of MCMHPA. Section 4 accommodates simulation results. Finally, we conclude the paper in section 5.

II. Multi-cast Multi-hop Protection Architecture (MCMHPA)

In MCMHPA, we setup backup optical paths by deploying backup DFs among all WOBAN segments with an objective to recover their traffic in conditions of their failure that mainly occurs due to failure of their OLT and/or FF. When

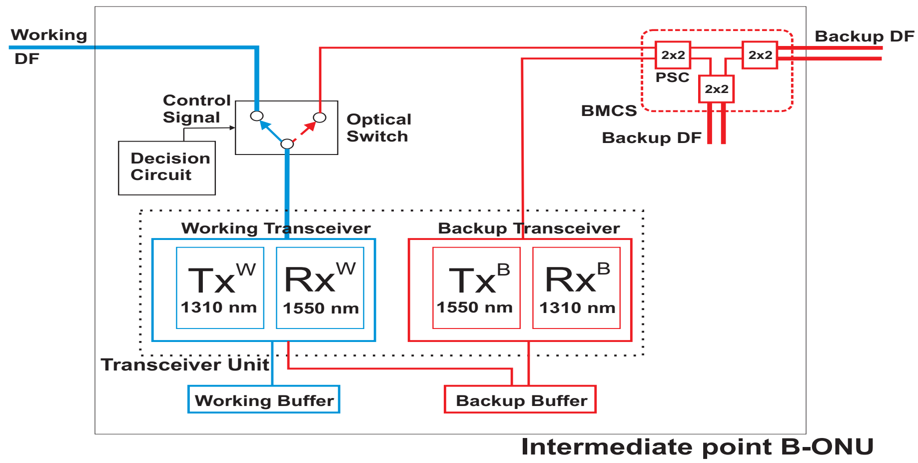

Fig. 2: Illustration of proposed intermediate point B-ONU architecture.

a segment fails, all ONUs of the segment are simultaneously disconnected from their OLT. In this respect, to recover traffic of the failed segment, we provision to utilize the residual bandwidth of its neighboring working segments. Traffic of the failed segment is multi-cast to its neighboring working segments through multi-hop backup optical paths. The traffic of the failed segment can also be sent to its neighboring working segments by setting up a dedicated backup optical connection/path (i.e., without traffic multi-casting and multi-hopping) between the failed segment and its each neighboring segment, but this approach requires dedicated backup optical transceiver and fiber for each dedicated backup optical connection. However, MCMHPA avoids the need of dedicated backup optical transceivers and fibers due to facilitating traffic multi-casting and multi-hopping, thereby resulting as a very cost-efficient approach to design a survivable WOBAN.

In each segment, we first select one specific ONU that can receive traffic from all the users of its segment (through wireless links) in conditions of its segment failure, by following the existing minimum cost recovery (MRC) method [22]. The MRC method optimally selects an ONU as specific ONU for which the total traffic delay from all the users is minimum. In this paper, we refer the specific ONU of each segment as backup ONU (B-ONU) and all other ONUs as normal ONUs (N-ONUs). After selecting B-ONU in each segment, we develop a backup fiber topology by connecting the B-ONUs of all segments, where B-ONUs located at intermediate point(s) and end point(s) of the topology are referred to as intermediate point B-ONUs and end point B-ONUs, respectively. When a segment fails (due to the failure of its OLT and/or FF), the B-ONU of the failed segment first receives the traffic from all the users of its segment through wireless links and thereafter, multi-cast the traffic (of its failed segment) to the B-ONUs of its neighboring working segments through multi-hop backup optical paths (forming the backup optical fiber topology). The B-ONU of a working segment first picks up only the traffic having its address (i.e., the address of B-ONU of the working segment) and thereafter, sends the traffic (of

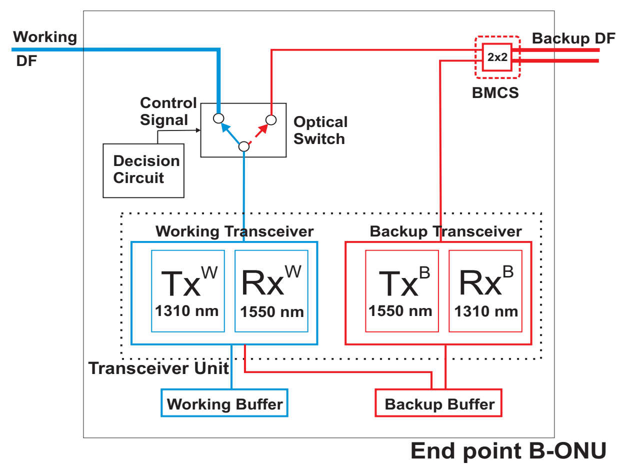

Fig. 3: Illustration of proposed end point B-ONU architecture.

the failed segment) to its OLT using the residual bandwidth of its segment. In MCMHPA, we propose novel architectures of intermediate point B-ONUs and end point B-ONUs to perform traffic multi-casting through traffic multi-hopping.

Architectures of intermediate point B-ONU and end point B-ONU are illustrated in Fig. 2 and Fig. 3, respectively. To design the B-ONUs (intermediate point as well as end point B-ONUs), we equip an N-ONU with one additional optical transceiver, referred to as backup transceiver (Tx^B/Rx^B) and one additional electronic buffer, referred to as backup buffer. Configuration of the backup transceiver is different from the working transceiver (Tx^W/Rx^W) since the working transceiver contains 1310 nm optical transmitter and 1550 nm optical receiver, whereas the backup transceiver contains 1550 nm optical transmitter and 1310 nm optical receiver. Working buffer is used only with working transceiver, whereas backup buffer is used with both the backup and working transceivers. The backup buffer of B-ONU of a working segment is used to store the upstream and downstream traffic of the failed segment. The optical transmitter (of the working transceiver) of

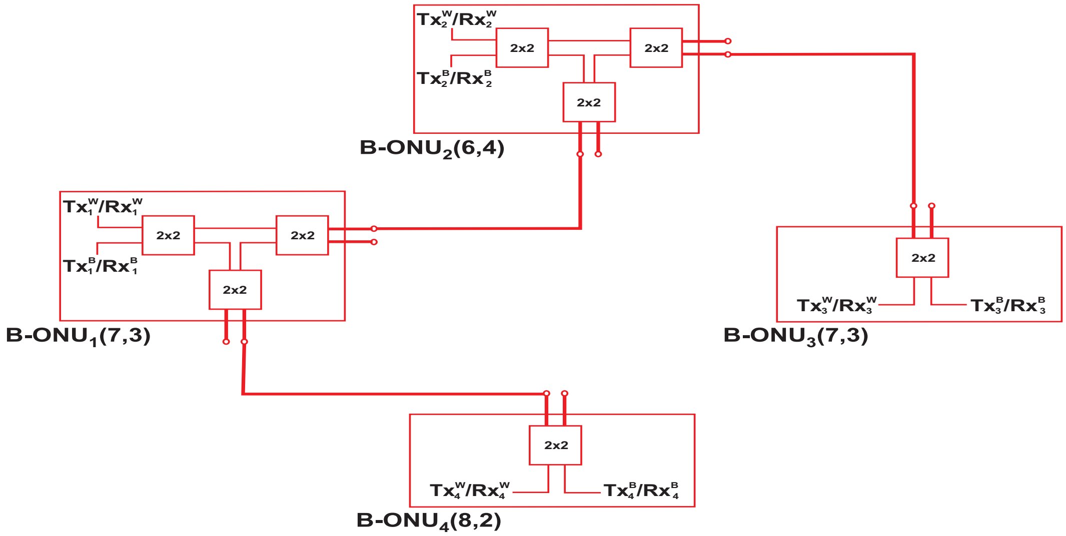

Fig. 4: Illustration of implementation of MCMHPA for an example WOBAN with four segments.

the B-ONU of the working segment acquires upstream traffic of the failed segment from the backup buffer and transmits to its OLT by employing the residual bandwidth of its segment, whereas the optical receiver (of the working transceiver) of the B-ONU (of the working segment) receives the downstream traffic of the failed segment from the OLT and stores in the backup buffer. On the other hand, the optical transmitter (of backup transceiver) sends the downstream traffic of the failed segment to the B-ONU of the failed segment from the backup buffer, whereas the optical receiver (of the backup transceiver) of the B-ONU (of the working segment) is used to receive upstream traffic of the failed segment from the B-ONU of the failed segment and stores the traffic in the backup buffer. We develop a PSC structure, referred to as backup multi-cast structure (BMCS) in each B-ONU and it is different for both intermediate point B-ONU and end point B-ONU. The BMCS of the intermediate point B-ONU is formed by using three 2x2 PSCs, whereas the BMCS of end point B-ONU is formed by using one 2x2 PSC. Both working and backup transceivers of a B-ONU are connected to its BMCS. BMCSs in the intermediate B-ONU and the end point B-ONU contain four backup outlet ports and two backup outlet ports, respectively; it implies that the maximum four and two backup paths may originate from the intermediate B-ONU and end point B-ONU respectively. However, lower/higher order structures can be developed, if required. We deploy an optical switch (OS) at each B-ONU to switch the working transceiver of the B-ONU of the failed segment to its BMCS in order to get connected to its backup DF(s). The OS is triggered by a decision circuit (an electronic circuit) that keeps the information of failure of the segment.

In Fig. 4, we present the implementation of MCMHPA by using an example WOBAN scenario comprising of four WOBAN segments, viz. SEG_1, SEG_2, SEG_3 and SEG_4. We refer the B-ONUs of the segments as $B\text{-}ONU_1$, $B\text{-}ONU_2$, $B\text{-}ONU_3$ and $B\text{-}ONU_4$, respectively. In this scenario, $B\text{-}ONU_1$ and $B\text{-}ONU_2$ are the intermediate point B-ONUs whereas $B\text{-}ONU_3$ and $B\text{-}ONU_4$ are the end point B-ONUs. For illustration, we consider that the total bandwidth of each segment is 10 units, whereas the traffic demands of SEG_1, SEG_2, SEG_3 and SEG_4 are 7 units, 6 units, 7 units and 8 units, respectively; thus the residual bandwidth of SEG_1, SEG_2, SEG_3 and SEG_4 are 3 units, 4 units, 3 units and 2 units, respectively. In this figure, we associate traffic demand and residual bandwidth of each segment to its B-ONU and show the B-ONUs (of different segments) as $B\text{-}ONU_1(7,3)$, $B\text{-}ONU_2(6,4)$, $B\text{-}ONU_3(7,3)$ and $B\text{-}ONU_4(8,2)$, respectively. We setup backup optical paths for each segment to recover its traffic during its failure conditions. To provide protection to SEG_1, we explore one (more) segment(s) with residual bandwidth of 7 units so that traffic demand of SEG_1 (i.e., 7 units) can be accommodated in its neighboring segments (viz. SEG_2 and SEG_3). We employ 4 units and 3 units of residual bandwidth of SEG_2 and SEG_3, respectively.

We setup and configure two backup optical paths by deploying new fibers: one single-hop backup path from $B\text{-}ONU_1(7,3)$ to $B\text{-}ONU_2(6,4)$ [$B\text{-}ONU_1(7,3)$ – $B\text{-}ONU_2(6,4)$] and another two-hop backup path from $B\text{-}ONU_1(7,3)$ to $B\text{-}ONU_3(7,3)$ [$B\text{-}ONU_1(7,3)$ – $B\text{-}ONU_2(6,4)$ – $B\text{-}ONU_3(7,3)$]. To provide protection to SEG_2, traffic demand of SEG_2 (6 units) may be accommodated using residual capacity (6 units) from its neighboring segments (viz. SEG_1 and SEG_3). In this case, we do not need to setup new backup optical paths as the backup optical paths have already been setup among these segments and we provision to use 4 units of residual bandwidth of SEG_1 and 2 units of residual bandwidth of SEG_3. Therefore, we configures two single-hop backup optical paths, viz. $B\text{-}ONU_2(6,4) - B\text{-}ONU_1(7,3)$ and $B\text{-}ONU_2(6,4) - B\text{-}ONU_3(7,3)$. To provide protection to SEG_3, we find the residual capacity of 7 units from its neighboring segments viz. SEG_1 and SEG_2. Also in this case, we do not need to setup new backup optical paths (as

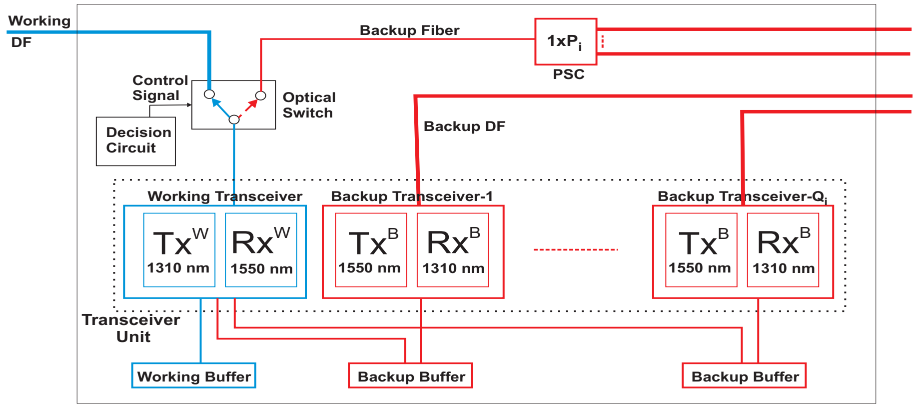

Fig. 5: Illustration of proposed potential architecture of B-ONU for existing protection scheme [21].

the backup optical paths have already setup among these segments). We provision to use 3 units of residual bandwidth of SEG_1 and 4 units of residual bandwidth of SEG_2. Therefore, we configure one single-hop backup optical path and one two-hop backup optical path viz. $B\text{-}ONU_3(7,3) - B\text{-}ONU_2(6,4)$ and $B\text{-}ONU_3(7,3) - B\text{-}ONU_2(6,4) - B\text{-}ONU_1(7,3)$, respectively. To provide protection to SEG_4, we find the residual capacity of 8 units from its neighboring segments viz. SEG_1, SEG_2 and SEG_3. In this case, we need to setup a new backup optical path from $B\text{-}ONU_4(8,2)$ to $B\text{-}ONU_1(7,3)$. We provision to use 3 units of residual bandwidth of SEG_1, 4 units of residual bandwidth of SEG_2 and 1 unit of residual bandwidth of SEG_3. Therefore, we configure three backup optical paths, one single-hop backup optical path viz. $B\text{-}ONU_4(8,2) - B\text{-}ONU_1(7,3)$, one two-hop backup optical path viz. $B\text{-}ONU_4(8,2) - B\text{-}ONU_1(7,3) - B\text{-}ONU_2(6,4)$ and one three-hop backup optical path viz. $B\text{-}ONU_4(8,2) - B\text{-}ONU_1(7,3) - B\text{-}ONU_2(6,4) - B\text{-}ONU_3(7,3)$. It is important to note that we presented the general architecture of B-ONUs and general implementation of MCMHPA. However, architectures of B-ONUs may be modified for a given WOBAN scenario to remove nonessential additionally deployed optical components viz. backup transceiver, backup buffer and BMCS. As for example, if a segment is not employed to allocate its residual bandwidth to its neighboring segments then there is no need to deploy backup transceiver and backup buffer in its B-ONU.

III. Comparative Analysis

In this section, we offer a comparative analysis of the proposed MCMHPA with reference to the existing protection scheme presented in Ref. [21]. Since authors in [21] do not provide any protection architecture to implement their protection scheme, we propose a novel and potential protection architecture to implement their protection scheme. The protection architecture for the existing protection scheme and its implementation are presented in Fig. 5 and Fig. 6, respectively. First, we discuss the protection architecture. From the Fig. 5, it can be clearly seen that each B-ONU in the existing protection scheme needs multiple backup transceivers in contrast to single backup transceiver in MCMHPA. Moreover, a dedicated backup DF is required to connect a backup transceiver of a B-ONU to the working transceiver of another B-ONU. A $1xP_i$ PSC is associated to the working transceiver of each i^{th} B-ONU to send the traffic to P_i number of other B-ONUs in case of the segment failure of the i^{th} B-ONU. Q_i represents the number of backup transceivers in i^{th} B-ONU and it is determined based on how many other B-ONUs are provisioned to send their traffic to the i^{th} B-ONU in conditions of their segment failure. Now, we discuss the implementation of the scheme with the help of the same example WOBAN scenario of four WOBAN segments presented in Fig. 4. The figure reveals that $B\text{-}ONU_1(7,3)$, $B\text{-}ONU_2(6,4)$ and $B\text{-}ONU_3(7,3)$ each is provisioned to support 3 other B-ONUs; therefore each of them is composed of three backup transceivers. Since $B\text{-}ONU_4(8,2)$ is not provisioned to support any other B-ONU, no backup transceiver is placed in it. Working transceiver of $B\text{-}ONU_1(7,3)$, $B\text{-}ONU_2(6,4)$, $B\text{-}ONU_3(7,3)$ and $B\text{-}ONU_4(8,2)$ are associated with 1x2 PSC, 1x2 PSC, 1x2 PSC and 1x3 PSC, respectively. Moreover, dedicated backup DFs are deployed to connect the working transceiver of a B-ONU to the backup transceivers of other B-ONUs. Thus, with this short example we show that existing schemes require highly costly and complicated protection architectures that may fail to yield interests in network operators to grasp them.

IV. Results

In this section, we provide a simulation study conducted to evaluate performance of the proposed architecture (MCMHPA) with reference to an example WOBAN scenario. We assess performance of MCMHPA in terms of the total number of hops required to send traffic from the failed segment to the working segments and incurred optical power loss in backup optical paths. It is notable that we do not compare the MCMHPA with the existing protection schemes as the existing protection schemes do not provide their protection architectures and thus, it is very difficult to evaluate their performances. For simplicity, we consider a WOBAN scenario with four segments (as presented in Fig.3). We also consider 16 ONUs in each WOBAN segment and the size (i.e., the

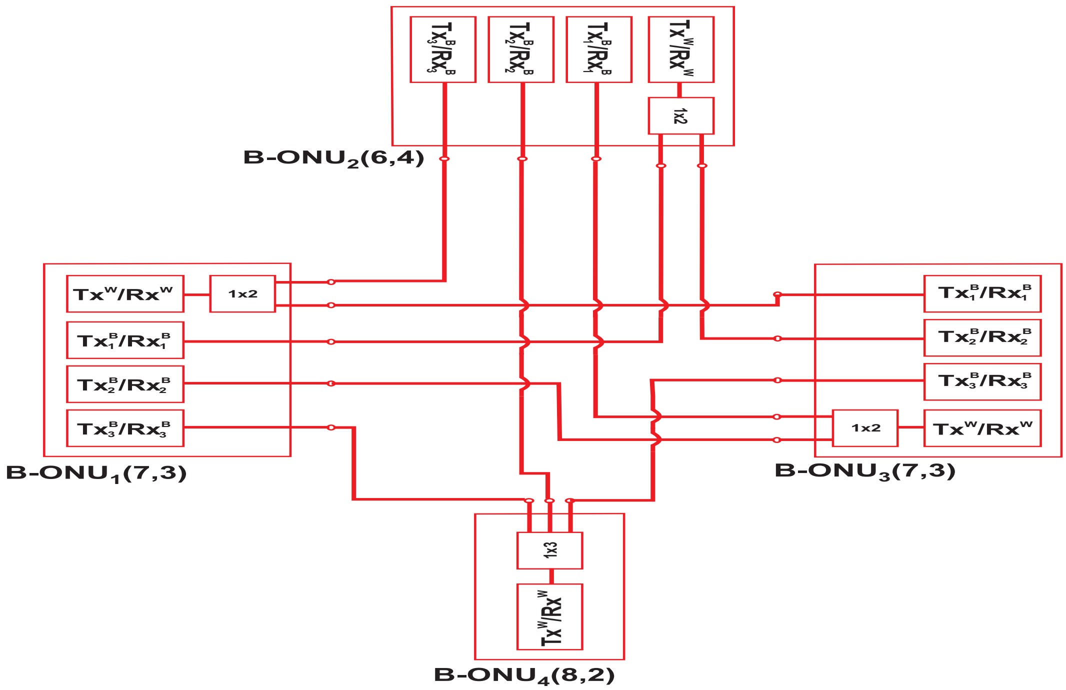

Fig. 6: Illustration of implementation of existing protection scheme [21] for an example WOBAN with four segments.

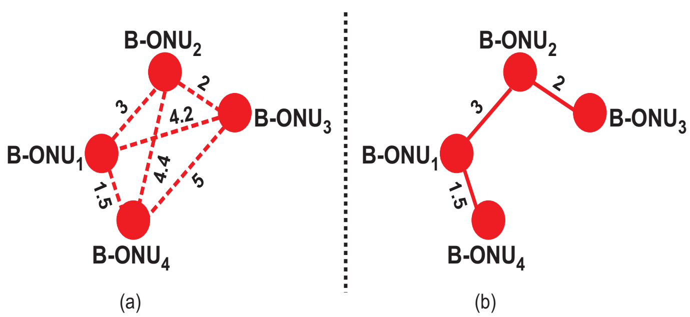

Fig. 7: (a): Illustration of physical distances (represented by link weights in km) between B-ONUs and (b): Illustration of the resultant backup fiber topology.

total number of inlet/outlet ports) of PSC in each segment is also 16. The FF and DF lengths of each segment are considered to be 60 km and 5 km, respectively. Geographical distance (Km) between two B-ONUs of any two segments (as presented in Fig. 5a) is obtained following an uniform random distribution with random numbers generated between 1 and 5. We employ the following costs for optical devices (unit element) - backup optical transceiver: \$1500, fiber/km: \$160, fiber deployment/km: \$7000, PSC/port: \$30 and OS: \$100. Fiber attenuation is considered to be 0.2 dB/km.

In Fig. 7(b), we show the resultant backup fiber topology designed with the objectives to minimize the expenditure (i.e., protection cost) of deployment of backup fiber keeping into consideration the cases without the existing fiber infrastructure and to minimize traffic delay even in the presence of fiber infrastructure. In Fig. 8, we illustrate the number of hops required on backup optical path for the traffic of each segment (viz. SEG_1, SEG_2, SEG_3 and SEG_4) to reach its neighboring segments. We present results for five different scenarios (viz. [6,5,7,6], [6,7,7,8], [7,8,8,7], [5,6,6,6] and [7,7,7,7]) where each scenario represents a set of traffic demands of segments/B-ONUs of the WOBAN. Results show that the B-ONU with higher traffic demand needs higher number of hops. Moreover, the traffic of end point B-ONUs (viz. $B\text{-}ONU_3$ and $B\text{-}ONU_4$) traverses more hops than the traffic of intermediate point B-ONUs (viz. $B\text{-}ONU_1$ and $B\text{-}ONU_2$) for the same traffic demand. For example, in the second scenario (viz., [6,7,7,8]), $B\text{-}ONU_2$ and $B\text{-}ONU_3$ have same traffic demand of 7 units but the required number of hops for the traffic of $B\text{-}ONU_2$ and $B\text{-}ONU_3$ are 7 and 11, respectively. This occurs since the intermediate point B-ONUs are directly (or in single-hop) connected to higher number of neighboring B-ONUs in comparison to end point B-ONUs.

In Fig. 9, we illustrate an optical power loss introduced to the traffic of each segment in its backup optical paths (that originate from the B-ONU of the segment and terminate to the OLT of the neighboring segments). We present results for five different scenarios (viz. [6,5,7,6], [6,7,7,8], [7,8,8,7], [5,6,6,6] and [7,7,7,7]). Results show that the segments/B-ONUs whose traffic traverses higher number of hops (Fig. 8 shows results for hops) suffers from higher optical power loss since insertion loss is introduced at each hop by BMCS of the intermediate point/end point B-ONU. The end point B-ONUs experience more optical power loss than intermediate point B-ONUs as the traffic of end point B-ONUs traverses more hops than intermediate point B-ONUs. For example, in the second scenario (viz. [6,7,7,8]), $B\text{-}ONU_2$ and $B\text{-}ONU_3$ have

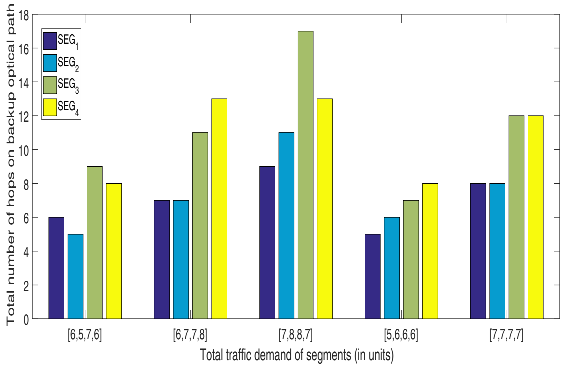

Fig. 8: Number of hops required on backup optical path for different segments in different traffic scenarios.

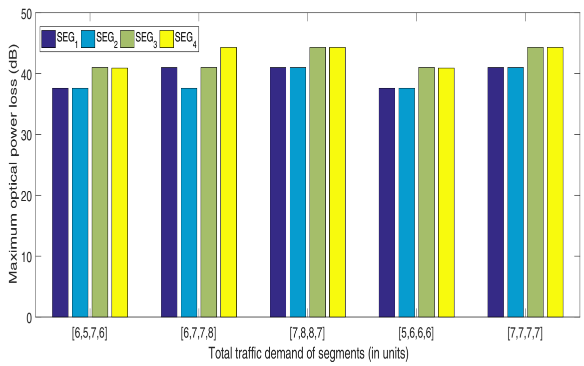

Fig. 9: Optical power loss (introduced in transmitting traffic of a failed segment) for different traffic scenarios.

same traffic demand of 7 units but the optical power loss for $B\text{-}ONU_2$ and $B\text{-}ONU_3$ are 37.6 dB and 41 dB, respectively. The largest value of the optical power loss is 44.3 dB for some B-ONUs in some scenarios (e.g., $B\text{-}ONU_3$ and $B\text{-}ONU_4$ in scenario-4 [7,7,7,7]) as shown in the figure. Practically, the receiver sensitivities of OLT and ONUs are typically about -28 dBm and -31.4 dBm, respectively, and gain of OA is about 27 dB; thus, it is easy to compensate the incurred optical power loss of about 44.3 dB (for an input optical power of 0 dBm). The incurred total protection cost for the considered WOBAN scenario is \$53420.

V. Conclusion

In this paper, we proposed a novel protection architecture, namely MCMHPA, to design a long-reach survivable WOBAN. In MCMHPA, we proposed a novel architecture of B-ONUs (accounted for transmitting and receiving traffic in condition of any segment failure) to implement multi-cast and multi-hop traffic transmission. We presented results in terms of the required number of hops and incurred optical power loss in backup optical paths for different traffic scenarios. Results show that MCMHPA offers delay- and power-efficient backup optical paths for each segment while incurring the minimum total protection cost. In future, we plan to formulate linear programming based optimization model and efficient heuristic scheme to implement MCMHPA for WOBANs with a large number of segments. We plan to show cost, power and availability analysis for a WOBAN deployed using the proposed architecture.

References

[1] G. Kramer, M. De Andrade, R. Roy and P. Chowdhury, "Evolution of optical access networks: architectures and capacity upgrades," in *Proceedings of the IEEE*, vol. 100, no. 5, pp. 1188-1196, May 2012.

[2] J. Segarra, V. Sales and J. Prat, "Access services availability and traffic forecast in PON deployment," in *Proc. ICTON*, pp. 1-6, 2011.

[3] D. Chitimalla et al., "QoE enhancement schemes for video in converged OFDMA wireless networks and EPONS," *IEEE/OSA J. of Opt. Comm. Netw.*, vol. 10, no. 3, pp. 229-239, March 2018.

[4] J. Elbers and K. Grobe, "Optical access solutions beyond 10G-EPON/XG-PON," in *Proc. OFC*, 2010.

[5] D. P. Shea and J. E. Mitchell, "A 10-Gb/s 1024-way-split 100-km long-reach optical-access network," *Journal of Lightwave Technology*, vol. 25, no. 3, pp. 685-693, March 2007.

[6] B. Skubic et al., "Dynamic bandwidth allocation for long-reach PON: overcoming performance degradation," *IEEE Communications Magazine*, vol. 48, pp. 100-108, Nov. 2010.

[7] F. Phillipson, C. Smit-Rietveld, and P. Verhagen, "Fourth generation broadband delivered by hybrid FTTH solution-A techno-economic study," *J. Opt. Commun. Netw.*, vol. 5, no. 11, pp. 1328-1342, 2013.

[8] M. V. derWee, K. Casier, A. Dixit, B. Lannoo, S. Verbrugge, D.Colle, and M. Pickavet, "Techno-economic evaluation of open access on FTTH networks," *J. Opt. Commun. Netw.*, vol. 7, no. 5, pp. 433–444, May 2015.

[9] N. Ghazisaidi et al., "Fiber-Wireless (FiWi) networks a comparative techno-economic analysis of EPON and WiMAX," in *Proc. IEEE GLOBECOM*, pp. 1-6, Nov. 2009.

[10] N. Ghazisaidi and M. Maier, "Fiber-wireless (FiWi) access networks:A survey," *IEEE Commun. Mag.*, vol. 47, no. 2, pp. 160-167, Feb. 2009.

[11] P. Chowdhury, B. Mukherjee, and S. Sarkar, "Hybrid wireless-optical broadband access network (WOBAN): prototype development and research challenges," *IEEE Netw.*, vol. 23, no. 3, pp. 41-48, May 2009.

[12] M. Agiwal, A. Roy and N. Saxena, "Next generation 5G wireless networks: a comprehensive survey," *IEEE Communications Surveys and Tutorials*, vol. 18, no. 3, pp. 1617-1655, 2016.

[13] N. Ghazisaidi, M. Scheutzow, and M. Maier, "Survivability analysis of next-generation passive optical networks and fiber-wireless access networks," *IEEE Trans. Reliab.*, vol. 60, no. 2, pp. 479-492, Jun. 2011.

[14] S. Sarkar et al., "RADAR: Risk-and-delay aware routing algorithm in a hybrid wireless-optical broadband access network (WOBAN)," in *Proc. OFC*, pp. 1-3, Mar. 2007.

[15] N. Correia, J. Coimbra, and G. Schutz, "Fault-tolerance planning in multi radio hybrid wireless-optical broadband access networks," *IEEE/OSA J. Opt. Commun.* Netw., vol. 1, no. 7, pp. 645-654, Dec. 2009.

[16] J. Gupta and A. Adhya, "Clustering-based multi-hop protection scheme for long-reach passive optical network against single shared-risk link group failure," *Springer Photon. Netw. Commun.*, pp. 1-14, 2016.

[17] J. Gupta and A. Adhya, "A novel fiber-constrained protection scheme for passive optical networks," in *Proc. ICACCI*, pp. 1358-1361, Sept. 2018.

[18] H. Zhang, R. Wang, H. Wang and G. Wu, "A new lossless fault-tolerance mechanism in hybrid wireless-optical broadband access network," in *IEEE Access*, vol. 6, pp. 19427-19440, 2018.

[19] H. Zhang, R. Wang, H. Wang and G. Wu, "A novel fault tolerance parallel routing mechanism with network coding in hybrid wireless-optical broadband access network," in *Proc. ICNC*, pp. 822-826, 2018.

[20] J. Chen and L. Wosinska, "Analysis of protection schemes in PON compatible with smooth migration from TDM-PON to hybrid WDM/TDM-PON," *OSA J. of Optical Net.*, vol. 6, no. 5, pp. 514-26, May. 2007.

[21] T. Feng and L. Ruan, "Design of a survivable hybrid wireless-optical broadband access network," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 3, no. 5, pp. 485-464, May 2011.

[22] Y. Liu, L. Guo, and X. Wei, "Optimizing backup optical-network-units selection and backup fibers deployment in survivable hybrid wireless-optical broadband access networks," *J. of Lightw. Technol.*, vol. 30, no. 10, pp. 1509-1523, May 2012.