Survivability Analysis of Next-Generation Passive Optical Networks and Fiber-Wireless Access Networks

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Abstract

Passive optical networks (PONs) are currently evolving into next-generation PONs (NG-PONs) which aim at achieving higher data rates, wavelength channel counts, number of optical network units (ONUs), and extended coverage than their conventional counterparts. Due to the increased number of stages and ONUs, NG-PONs face significant challenges to provide the same level of survivability like conventional PONs without exceeding the budget constraints of cost-sensitive access networks. Toward this end, partial optical protection in combination with interconnecting a subset of ONUs through a wireless mesh network (WMN) front-end are promising solutions to render NG-PONs survivable in a cost-effective manner. In this paper, we present a probabilistic analysis of the survivability of NG-PONs and hybrid fiber-wireless (FiWi) access networks taking both optical and wireless protection into account. In addition, we propose different selection schemes to wirelessly upgrade a subset of ONUs and investigate their performance for a wide range of fiber link failure scenarios and different NG-PON topologies.

Index Terms

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Fiber-wireless (FiWi) networks, FTTX, long-reach PON, next-generation PON (NG-PON), probabilistic analysis, protection, survivability, WDM, WMN.

ACRONYMS

AP	Access Point
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BPF	BandPass Filter
CO	Central Office
DBA	Dynamic Bandwidth Allocation
DOCSIS	Data Over Cable Service Interface Specification
EPON	Ethernet PON
FiWi	Fiber-Wireless
FTTB	Fiber-to-the-Business
FTTC	Fiber-to-the-Curb
FTTH	Fiber-to-the-Home
FTTx	Fiber-to-the-x
GEM	GPON Encapsulation Method
GPON	Gigabit PON
HDTV	High-Definition Television
LR-PON	Long-Reach PON
MIMO	Multiple-Input Multiple-Output
MP	Mesh Point
MPCP	MultiPoint Control Protocol
MPP	Mesh Portal Point
NG-PON	Next-Generation PON

OAMP	Operation, Administration, Maintenance, and Provisioning
OEO	Optical-Electrical-Optical
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
PHY	PHYsical
PON	Passive Optical Network
QoE	Quality-of-Experience
QoS	Quality-of-Service
R&F	Radio-and-Fiber
RAU	Remote Antenna Unit
RF	Radio Frequency
RoF	Radio-over-Fiber
RTT	Round-Trip Time
SIFS	Short InterFrame Space
SLA	Service Level Agreement
STA	wireless STAtion
SUCCESS-HPON	Stanford University aCCESS-Hybrid WDM/TDM PON
SUCCESS-PON	Stanford University aCCESS-PON
TDM	Time Division Multiplexing
VHT	Very High Throughput
VoD	Video on Demand
WDM	Wavelength Division Multiplexing
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network

NOTATION

d_i	Distance between ONU i and OLT
D	Number of failure-free connections between pairs of ONUs
$k(i,j)$	Last common splitter of ONUs i and j
m	Number of ONUs connected to splitter s_n of stage n
M	Number of ONU-MPPs (cardinality of $\mathcal{W}$)
n	Index of PON stage
N	Number of ONUs
$\mathcal{O}$	Subset of ONUs optically connected to the OLT after fiber link failure(s)
OP	Number of optically protected ONUs
p_e	Probability of incoming fiber link and outgoing fiber link failures of 1:1 splitter
p_{ij}	Probability that ONUs i and j are optically connected via OLT
p_n	Probability of fiber link failure in stage n
$p_{s_n i}$	Probability that ONU i is optically connected to splitter s_n of stage n
q_i	Probability that ONU i is optically connected to the OLT
r_i	Probability that ONU i is connected to the OLT after wireless upgrade
$\mathcal{W}$	Set of ONU-MPPs

I. INTRODUCTION

Fiber-to-the-home (FTTH) or close to it (FTTx) networks are poised to become the next major success story for optical fiber communications. Future FTTx access networks unleash the economic potential and societal benefit by opening up the first/last mile bandwidth bottleneck between bandwidth-hungry end users and high-speed backbone networks. Due to their longevity, low attenuation, and huge bandwidth, passive optical networks (PONs) are widely deployed to realize cost-effective FTTx access networks.

Fiber has been envisioned for delivering broadband services for over 30 years. However, many roadblocks related to component and installation costs have slowed down the progress toward FTTx since it was first proposed. Currently, FTTH is being installed in many countries, but it still represents only a fraction of all deployed broadband lines [1]. The two major state-of-the-art PON standards IEEE 802.3ah Ethernet PON (EPON) and ITU-T G.984 Gigabit PON (GPON) consist both of a single upstream wavelength channel and a separate single downstream wavelength channel, whereby both channels are operated using time division multiplexing (TDM). EPON and GPON are expected to coexist for the foreseeable future as they evolve into next-generation PONs (NG-PONs) [2], [3].

NG-PONs can be categorized into high-speed TDM PON, wavelength division multiplexing (WDM) PON, and long-reach PON (LR-PON) [4], [5]. While current PONs are able to provide service only for a maximum of 256 optical network units (ONUs) located at a range of 20 km from the optical line terminal (OLT), LR-PONs are designed for longer distances between the OLT and ONUs of up to 100 km as well as larger numbers of ONUs (2000 to 4000 ONUs) [6]. Due to the higher data rates, wavelength channel counts, number of ONUs, and coverage of NG-PONs, network survivability is becoming a key issue. While in conventional Gb/s PONs with typically 32-64 attached ONUs fiber link cuts only affect a relatively small number of subscribers, survivability of high-capacity NG-PONs with fibers carrying multiple wavelength channels in both upstream and downstream directions, each wavelength operating at 10 Gb/s, becomes increasingly important due to the fact that fiber link failures would result in the loss of significantly higher traffic volumes. NG-PONs such as high-speed 10 Gb/s PONs offer enough capacity not only for (best-effort) residential use but also for business applications, which require carrier-class survivability for business continuity [7].

The following techniques might be applied to resolve the survivability issues of NG-PONs:

1) **Full/partial PON duplication (optical protection):** With full PON duplication, a spare set of OLT and ONUs as well as optical fiber links and photonic network elements, e.g., splitters, is deployed to protect the primary optical infrastructure with a secondary backup [8]. While full PON duplication

techniques in most cases might be cost-prohibitive, partial PON protection seems more viable, where only a subset of fibers are protected through stand-by fibers.

2) **Wireless mesh network (WMN)-based fiber-wireless (FiWi) architecture (wireless protection):** Emerging FiWi broadband access networks combine the capacity of optical fiber networks with the ubiquity and mobility of wireless networks. FiWi networks aim at providing wired and wireless services over the same infrastructure simultaneously, thus potentially leading to major cost savings [9]. Recently, various FiWi network architectures have been investigated by integrating different optical and wireless technologies [10]. In a WMN-based FiWi network, a subset or all ONUs of an NG-PON network are equipped with wireless devices, referred to as mesh portal points (MPPs) in IEEE 802.11s. In the resultant WMN-based FiWi protection technique, an MPP forwards frames to another ONU via wireless links instead of going through the OLT. In an IEEE 802.11s based WMN, MPPs are able to send frames to each other directly (single-hop) or through intermediate wireless mesh points (MPs) by means of multi-hopping. We note that WMN can be deployed using any wireless local area network (WLAN) technologies, such as IEEE standards 802.11 a/b/g/n or the emerging very high throughput (VHT) WLAN, whereby the maximum distance between two adjacent WMN nodes (i.e., maximum length of one wireless hop) depends on the applied wireless technology. For instance, the maximum distance between two adjacent WMN nodes has to be less than 2.7 km (line-of-sight) in IEEE 802.11n for a slot size of 9 μs and short interframe space (SIFS) of 16 μs. Applying orthogonal frequency division multiplexing (OFDM) and multiple-input multiple-output (MIMO) antennas in the physical (PHY) layer of IEEE 802.11n WLANs provides various capabilities, such as antenna diversity (selection) and spatial multiplexing. The use of multiple antennas in next-generation WLAN-based WMNs provides multipath capability, which increases both throughput and transmission range. In a fading channel, multiple antennas can increase the system reliability through spatial diversity. It was shown in [11] that by transferring the same data across different paths, multiple independently faded data symbols can be successfully received at

the destination node and the transmission reliability is increased significantly. Furthermore, the enhanced PHY layer of next-generation WLANs applies two powerful adaptive coding schemes: space time block coding (STBC) and low density parity check coding (LDPC). According to [12], [13], the robustness and reliability of next-generation WLAN based networks can be improved significantly by using the two aforementioned coding schemes. In WMNs, multiple redundant paths exist throughout the network. Mesh nodes may re-route traffic along alternative paths. It was shown in [14] that adding redundant mesh points to WMNs improves the wireless link availability and reliability significantly. Due to the nature of WMNs, their channels are not error-free. WLAN-based WMNs apply a data link layer error control technique, known as automatic repeat request (ARQ), which uses acknowledgment messages and packet retransmissions to achieve reliable data transfer. To further improve the network reliability, error correction schemes such as forward error correction (FEC) can be used. Hybrid adaptive FEC and ARQ techniques were proposed in [15] to increase the reliability of WLAN-based networks. We note that current IEEE 802.3ah EPON and emerging IEEE 802.3av 10G-EPON provide 1 Gb/s and 10 Gb/s, respectively. On the other hand, next-generation WLAN-based WMN and emerging very high throughput (VHT) WLAN-based WMN technologies are able to provide raw data rates of 600 Mb/s and 1 Gb/s, respectively. It is important to note that the bandwidth of EPON and PONs in general is shared among all ONUs. That is, under the assumption of bandwidth fairness, the data rate available to a single EPON ONU is equal to 1/32 Gb/s $\approx$ 31 Mb/s for a typical scenario of 32 ONUs, which is below the data rate offered by an 802.11n WLAN access point (AP) possibly attached to the ONU. Also note that unlike EPON (and PONs in general) WMNs allow for spatial reuse of bandwidth, whereby a given channel can be used multiple times in different regions of the WMN that do not spectrally overlap. As a result, the aggregate capacity of a WMN is beyond that of a single WLAN link.

In this paper, we focus on the survivability analysis of optical NG-PONs and emerging bimodal FiWi access networks and examine the benefit of upgrading selected ONUs with wireless equipment in order to improve network survivability in a pay-as-you-grow manner. The contributions of this paper are threefold. First, we evaluate the survivability of NG-PONs and FiWi networks by means of probabilistic analysis taking both optical and wireless protection into account. Second, we propose and examine different ONU selection schemes to improve the survivability of NG-PONs by means of wireless extensions and partial optical protection. Third, in our numerical work we study the impact of different network topologies on the survivability of NG-PON and FiWi networks for a wide range of fiber link failure scenarios. To our best knowledge, this is the first paper that presents a thorough probabilistic analysis of the survivability of NG-PONs and emerging FiWi networks. Note that the maximum coverage and other technological constraints of emerging optical and wireless networks is an important factor which is outside the scope of this paper and is left for future research.

The remainder of the paper is structured as follows. Section II briefly reviews previously proposed PON protection techniques. Section III describes the salient features of PONs, NG-PONs, and FiWi networks. Section IV elaborates on the survivability analysis of NG-PONs and FiWi networks. Numerical results are presented in Section V. Section VI concludes the paper.

II. Related Work

Protection is an important issue to avoid service outage and improve PON survivability. The following four different PON network protection schemes are specified in ITU-T G.983.1 [8], [16]: (i) feeder fiber protection: This method protects the feeder fiber by means of a spare fiber between OLT and the passive optical splitter/combiner at the remote node, whereby the spare fiber is attached to the feeder fiber via optical switches; (ii) OLT & feeder fiber protection: In this scheme, an additional OLT is used to provide both OLT and feeder fiber protection; (iii) full duplication: This approach protects all ONUs as well as OLT and both feeder and distribution fibers; (iv) independent duplication of feeder and branch fibers: This method protects feeder and distribution fibers independently and provides OLT and ONU fault recovery. Two of the above mentioned ITU-T G983.1 protection techniques (i.e., OLT & feeder fiber protection and full duplication techniques) are considered in ITU-T G.983.5 for the delivery of highly reliable services

[17].

In [18], a 1:1 protection scheme was proposed to back up the distribution fibers of a WDM PON. In the proposed architecture, ONUs are equipped with optical switches and filters and a bidirectional connection between each pair of ONUs is provided by using additional optical fiber links. In [19], the survivability of a WDM PON was investigated and a new survivable architecture was proposed and experimentally examined. In the proposed optically 1:1 protected WDM PON, automatic protection switching with in-service fault localization was performed by the ONUs. A 1:W shared protection scheme (using W working and 1 protecting resources) was proposed and investigated for an arrayed waveguide grating (AWG)-based WDM PON [20]. The proposed architecture provides self-protection and automatic traffic restoration capability for a distribution fiber cut. In the Stanford University access (SUCCESS)-PON, multiple PONs are connected to the same central office (CO), whose transmitters might be shared for downstream transmission among all attached PONs [21]. To provide a smooth migration path from current TDM PONs to WDM PONs, the so-called SUCCESS-HPON (hybrid WDM/TDM PON) was proposed, where a fiber ring interconnects multiple PONs with the CO [22]. Although the above mentioned protection techniques provide protection for OLT and/or ONUs as well as feeder and/or distribution fibers, using full optical protection methods are cost-prohibitive for cost-sensitive access networks.

According to [23], the ITU-T G.983.5 protection techniques are more costly than unprotected network and the protection schemes proposed in [18], where ONUs are directly connected to each other. While the proposed protection scheme provides connection availability of 99.999 percent (5 nines), deploying and maintaining optical fiber links in the access area is costly. WMN-based FiWi network protection is an attractive technique which might be used to survive fiber cuts in a more cost-effective manner. Moreover, extending PONs with WLAN-based WMNs provides flexibility and mobility support for end users. The FiWi network proposed in [24] consists of an optical WDM backhaul ring with multiple single-channel or multichannel PONs attached to it which are protected using a WMN between them. In PON-based FiWi networks, the network performance heavily depends on the positioning of the ONUs. Different schemes, e.g., random and deterministic methods, were studied in [25] to find the optimal placement of ONUs in terms of processing time, complexity, and installation cost. The optimum real-estate cost deployment of ONUs in FiWi networks was studied in detail in [26] and [27].

III. PONs, NG-PONs, and FiWi Networks

In this section, we briefly review the salient features of current TDM PONs, NG-PONs, and FiWi networks.

A. PONs

Typically, PONs have a physical tree topology with the CO located at the root and the subscribers connected to the leaf nodes of the tree at a distance of up to 20 km. As illustrated in Fig. 1, at the root of the tree is an OLT which is the service provider equipment residing at the co-located central office. The PON connects the OLT to multiple ONUs (the customer premises equipment) through a 1:N optical splitter/combiner. An ONU can serve a single residential or business subscriber, referred to as FTTH and fiber-to-the-business (FTTB), or multiple subscribers, referred to as fiber-to-the-curb (FTTC). Each ONU buffers data received from the attached subscriber(s) in one or more priority queues. In general, the round-trip time (RTT) between OLT and each ONU may be different [28].

In current TDM PONs, the OLT broadcasts data to all ONUs in the downstream direction (point-to-multipoint). In the upstream direction, however, ONUs cannot communicate directly with one another. Instead, each ONU is able to send data only to the OLT (multipoint-to-point). TDM allows all ONUs to share the upstream and downstream wavelength channels without channel collisions. To facilitate dynamic bandwidth allocation (DBA) and arbitrate the upstream transmissions of multiple ONUs, the so-called multipoint control protocol (MPCP) specified in IEEE 802.3ah is deployed in EPON. In addition to auto-discovery and registration, MPCP uses two types of polling messages (i.e., REPORT and GATE) to facilitate arbitration. Each REPORT message is used by an ONU to report bandwidth requirements of up

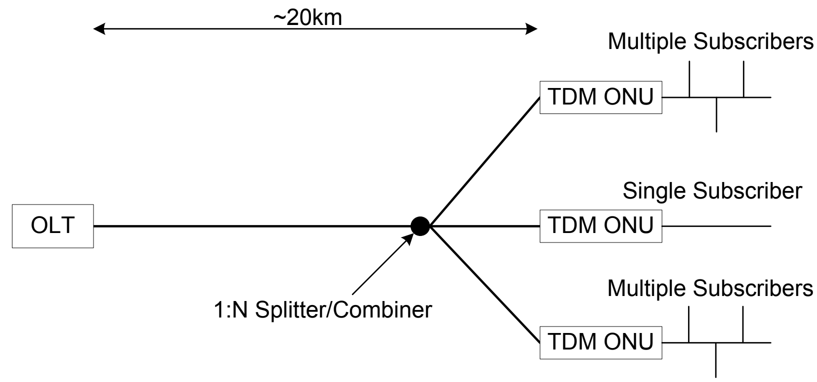


Fig. 1. Network architecture of a conventional TDM PON with one OLT and $N = 3$ ONUs.

to eight priority queues to the OLT. The GATE message is generated by the OLT and contains up to four transmission grants per ONU. Note that no specific DBA algorithm is specified in IEEE 802.3ah [29].

IEEE 802.3ah EPON with a symmetric line rate of 1.25 Gb/s and ITU-T G.984 GPON with an upstream line rate of 1.244 Gb/s and a downstream line rate of 2.488 Gb/s represent current state-of-the-art commercially available and widely deployed TDM PONs. Operation, administration, maintenance, and provisioning (OAMP) capabilities are provided by GPON. GPON applies GPON encapsulation method (GEM) to efficiently support traffic mixes consisting not only of ATM cells but also TDM (voice) and variable-size packets. On the other hand, EPON aims at converging the low-cost equipment and simplicity of Ethernet with the low-cost infrastructure of PONs. In EPON, security and OAMP may be implemented using the data over cable service interface specification (DOCSIS) OAMP service layer on top of the MAC and physical (PHY) layers of EPON.

B. NG-PONs

NG-PONs are PONs (either EPON or GPON) that provide higher data rates, larger counts of wavelength channels, longer fiber ranges, and/or higher splitting ratios, as well as broader functionalities than current PONs, as explained in the following.

1) High-speed TDM PON: For both EPON and GPON, standardization efforts have begun to specify symmetric or asymmetric data rates of up to 10 Gb/s [2]. Very recently, the IEEE standard 802.3av for 10

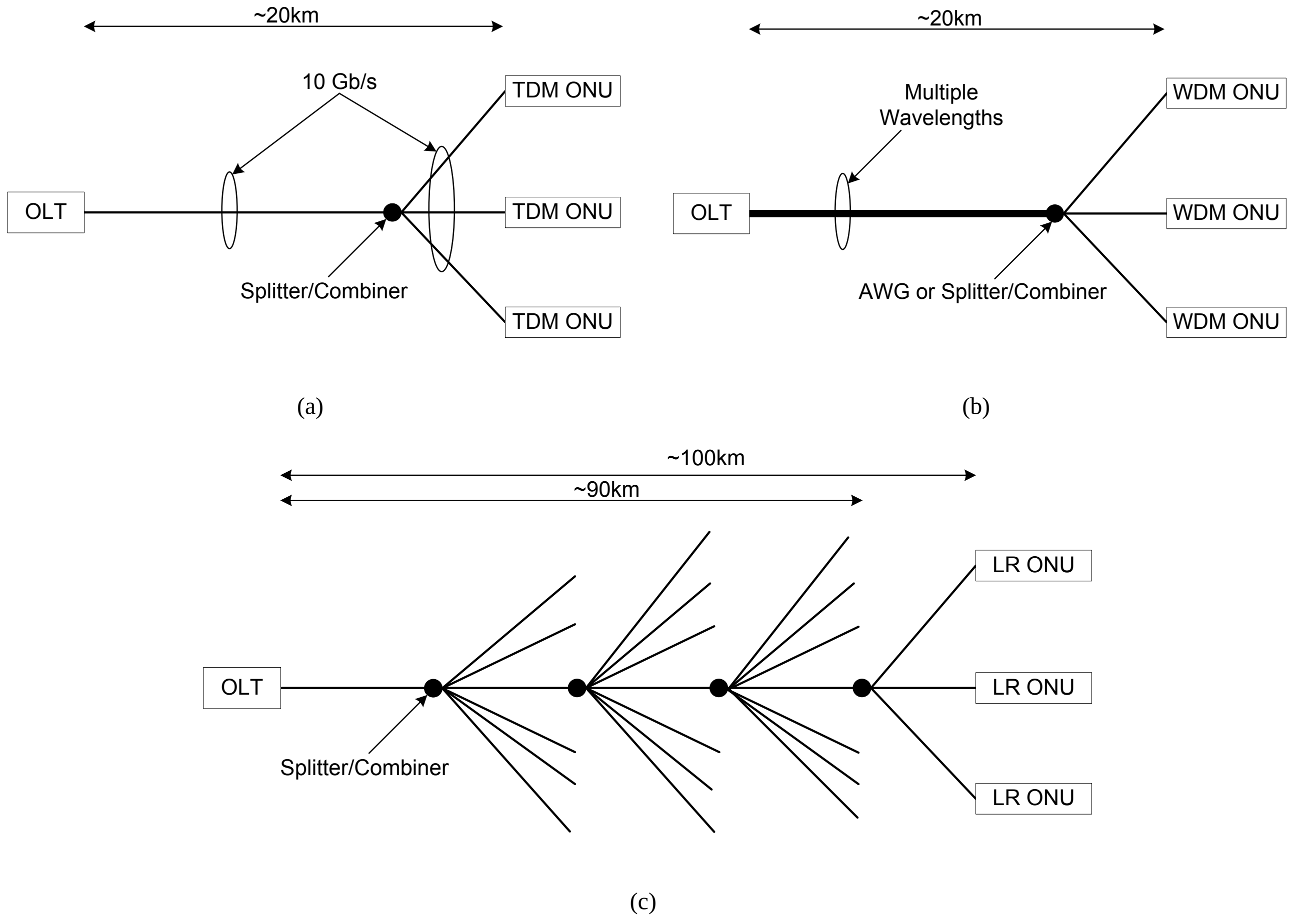


Fig. 2. Next-Generation Passive Optical Networks (NG-PONs): (a) high-speed TDM PON, (b) WDM PON, and (c) LR-PON.

Gb/s EPON has been approved to support emerging bandwidth-hungry applications, e.g., high-definition television (HDTV) and video on demand (VoD), and provide sufficient capacity as backhauls of wireless access networks [5]. According to [30], a few years may be required for high-speed TDM PONs such as the recently approved 10G-EPON to be technically and economically mature enough to launch into the access network market. It is important to note that additional equipment protection functionalities might be considered for high-speed TDM PON which are outside of IEEE 802.3av standard scope. Fig. 2(a) shows the network architecture of a high-speed TDM PON.

2) WDM PON: In [31], different types of WDM PON have been studied. In a wavelength-routing WDM PON, each ONU is assigned a dedicated pair of wavelength channels for upstream and downstream transmission, which brings some advantages, but requires replacing the power splitter in installed TDM PONs with a wavelength demultiplexer. According to [2], a more practical approach towards WDM

PONs is to leave the existing power-splitting PON infrastructure in place and select wavelengths at each ONU using a bandpass filter (BPF) with a small insertion loss of 1 dB. To ensure that WDM enhanced ONUs, operating on additional wavelengths, can be installed on legacy TDM PON infrastructures, the conventional TDM ONUs may be equipped with wavelength blocking filters which let only the legacy TDM wavelength pass. Fig. 2(b) shows a WDM PON network architecture.

3) LR-PON: As shown in Fig. 2(c), LR-PONs increase the range and splitting ratio of conventional TDM and WDM PONs significantly [32]. State-of-the-art LR-PONs are able to have a total length of 100 km potentially supporting 17 power-splitting TDM PONs, each operating at a different pair of upstream and downstream wavelength channels and serving up to 256 ONUs, translating into a total of 4352 ONUs [6]. Unlike TDM and WDM PONs, LR-PONs typically have a multi-stage tree-and-branch topology and allow for the integration of optical access and metro networks. The broadened LR-PON functionality offers major cost savings by reducing the number of required optical-electrical-optical (OEO) conversions, at the expense of optical amplifiers required to compensate for propagation and splitting losses [33].

C. FiWi Networks

Hybrid FiWi access networks aim at providing wired and wireless quad-play services (voice, video, data, and mobility) over the same infrastructure simultaneously [9]. Radio-over-fiber (RoF)-based FiWi networks have been widely studied as an approach to integrate optical fiber and wireless networks. In RoF-based FiWi networks, radio frequencies (RFs) are carried over optical fiber links between a CO and multiple low-cost remote antenna units (RAUs) in support of a variety of wireless technologies, such as microcellular radio systems [34]. The additional propagation delay of deploying optical fibers in RoF networks may exceed certain timeouts of wireless MAC protocols, resulting in a deteriorated throughput-delay performance. More precisely, MAC protocols based on centralized polling and scheduling, e.g., IEEE 802.16 WiMAX, are less affected by increased propagation delays due to their ability to take longer walk times between the CO and wireless stations (STAs) into account by means of interleaved polling and scheduling of upstream transmissions originating from different STAs. However, in distributed MAC

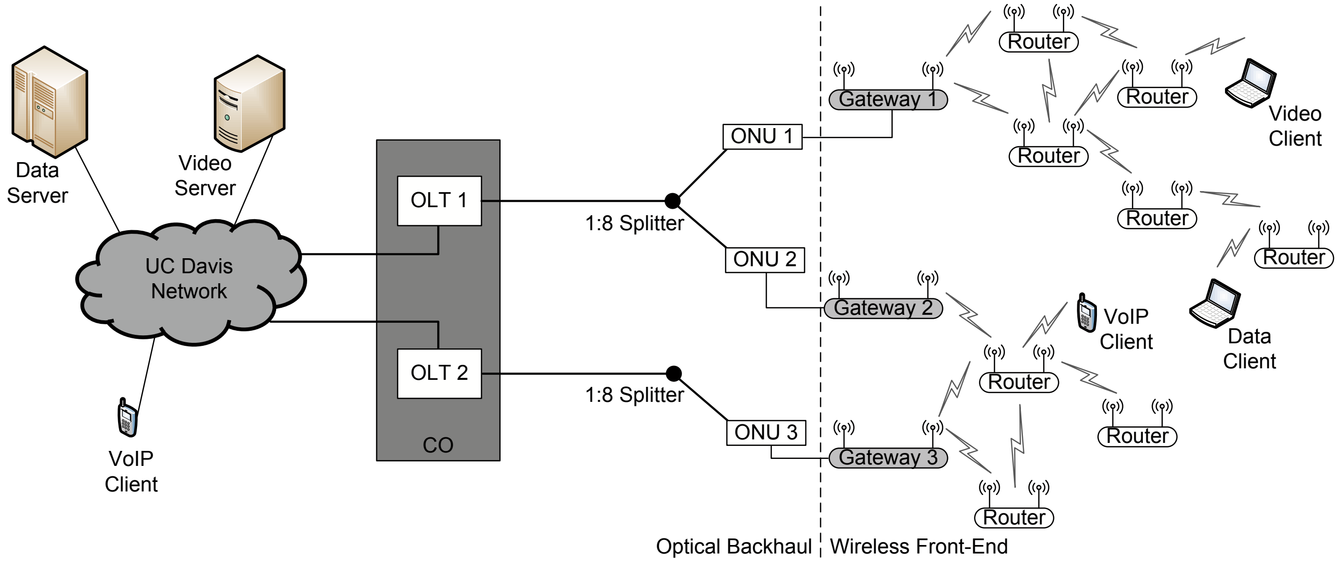


Fig. 3. R&F-based FiWi network: UC Davis R&F testbed integration of EPON and WMN [35].

protocols, e.g., the widely deployed DCF in IEEE 802.11a/b/g WLANs as well as EDCA in IEEE 802.11n based WMNs, the additional propagation delay between STAs (or MPs) and access point (AP), or MPP, poses severe challenges. The aforementioned limitations of WLAN-based RoF networks can be avoided in so-called radio-and-fiber (R&F) networks [9]. While RoF networks use optical fiber as an analog transmission medium between a CO and one or more RAUs with the CO being in charge of controlling access to both optical and wireless media, in R&F networks access to the optical and wireless media is controlled separately from each other by using different MAC protocols in the optical and wireless media, with protocol translation taking place at their interface. As a consequence, wireless MAC frames do not have to travel along the optical fiber to be processed at the CO, but simply traverse their associated AP and remain in the wireless network, thus avoiding the negative impact of fiber propagation delay on the network performance.

Fig. 3 shows a recently demonstrated R&F-based FiWi network architecture consisting of an integrated PON and WLAN-based WMN. In the University of California (UC) Davis testbed, there are two EPONs and an IEEE 802.11g WLAN-based WMN with a maximum transmission rate of 54 Mb/s [35]. In this figure, the gateways and routers denote MPPs and MPs as defined in IEEE 802.11s WMN, respectively.

Intermediate MPs are used by MPPs to extend the WMN signal range, whereby path selection in the WMN might be done based on the availability of the wireless channel and/or minimum number of hops. As shown in Fig. 3, optical protection is provided by using full PON duplication. We note that no survivability analysis has been provided for the optical nor wireless segments of the proposed FiWi network.

IV. SURVIVABILITY ANALYSIS

In this section, we analyze the survivability of NG-PONs and FiWi networks with and without partial optical protection. The considered LR-PON may be upgraded with WDM and/or high-speed transceivers to create WDM and/or high-speed TDM LR-PONs, respectively.

A. NG-PON without Protection

Let us first consider an LR-PON tree-and-branch topology without any protection and investigate its connectivity as a function of different fiber link failure probabilities. In a multi-stage tree-and-branch based LR-PON with N connected ONUs, we denote the probability that a given fiber link fails by p_n, where n is the index of the stage to which the fiber link belongs, as shown in Fig. 4. Note that the special case of only two stages $n = 0$ and $n = 1$ would correspond to conventional TDM/WDM PONs with a single splitter. Let p_0, p_1, $\ldots$ denote the fiber link failure probability of stage 0, 1, $\ldots$, respectively. We assume that fiber link failures occur independently from each other. Further, we define d_i as the distance (i.e., number of intermediate splitters) between a given ONU i and the OLT given by

$$d_i = distance(\text{ONU } i, \text{OLT}), i \in \{1, 2, \ldots, N\}. \tag{1}$$

Note that our model can be easily generalized by assuming different failure probabilities of fiber links belonging to the same stage (i.e., having the same distance to the OLT).

Let $k(i, j)$ be the distance of the last common splitter of ONUs i and j to the OLT (see Fig. 4 for illustration). The probability p_{ij} that ONUs i and j are connected via the OLT, which is equivalent to the

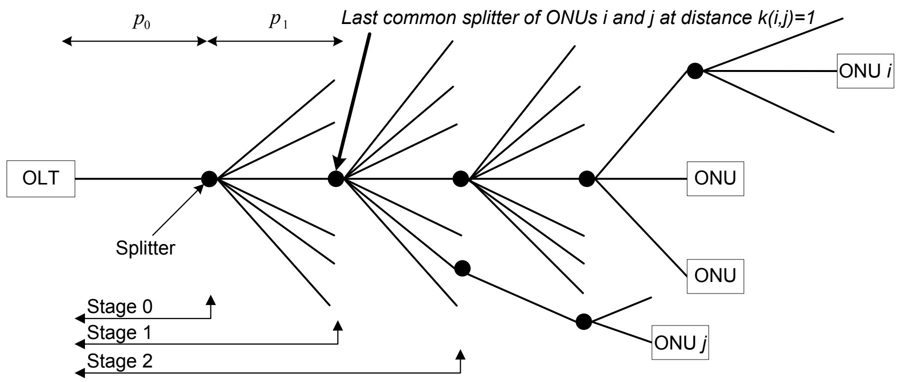


Fig. 4. LR-PON and last common splitter of ONU i and ONU j for $d_i = 5$, $d_j = 4$, and $k(i,j) = 1$.

probability that all fiber links from ONU i and ONU j to the OLT are intact, is given by

$$\begin{aligned} p_{ij} &= (1-p_0)\cdots(1-p_{k(i,j)}) \\ &\cdot(1-p_{k(i,j)+1})^2\cdots(1-p_{d_i\wedge d_j})^2 \\ &\cdot(1-p_{(d_i\wedge d_j)+1})\cdots(1-p_{d_i\vee d_j}), \end{aligned} \tag{2}$$

where $\wedge$ and $\vee$ denote the minimum and maximum values of two variables, respectively. In the first line of Equ. (2), the probability of all intact shared fiber links from the OLT to the last common splitter of the two ONUs is calculated (i.e., from p_0 to $p_{k(i,j)}$). In the second line of this equation, the probability of all intact fiber links from the last common splitter of the two ONUs to the ONU which has the minimum distance to the OLT (i.e., $d_i \wedge d_j$) is calculated. We note that in this calculation the ONUs apply different independent fiber links with the same failure probability which results in the squared probabilities. The probability of all intact fiber links from the ONU with minimum distance (i.e., $(d_i \wedge d_j) + 1$) to the ONU with maximum distance (i.e., $d_i \vee d_j$) is calculated in the third line of Equ. (2). Further, the probability that ONU i is connected to the OLT is given by

$$q_i = (1-p_0)\ldots(1-p_{d_i}). \tag{3}$$

B. FiWi: NG-PON with Wireless Protection

To provide survivability against fiber link failures, we have to find a set $\mathcal{W}$ of ONUs and equip each of them with an MPP such that they can communicate wirelessly even if the LR-PON fiber infrastructure fails completely. Generally speaking, $\mathcal{W}$ should be chosen as small as possible while at the same time guaranteeing a high degree of survivability. To allow for pay-as-you-grow wireless upgrades of LR-PONs and satisfy given cost constraints, in general only a subset of ONUs are equipped with an MPP, i.e., we fix the cardinality of $\mathcal{W}$ to $|\mathcal{W}| = M \leq N$.

In this paper, we propose the following selection schemes to identify the M ONUs and equip each of them with an MPP:

1) **Random selection:** In this scheme, M ONUs are randomly selected among the N ONUs.
2) **Uniform selection:** In this approach, the M selected ONUs include ONU 1 and ONU N. The other $M-2$ ONUs are uniformly selected among the remaining $N-2$ ONUs such that the index of two neighboring selected ONUs differs by $\lfloor N/(M-1) \rfloor$, i.e., $\mathcal{W} = \{$ONU i, $i = 1, 1 + \lfloor N/(M-1) \rfloor, \ldots, N\}$.
3) **Selection of weakest ONUs:** In this scheme, the M ONUs with the smallest probability q_i of being (optically) connected to the OLT are selected.
4) **Selection of strongest ONUs:** Conversely, this scheme selects the M ONUs with the largest probability q_i of being (optically) connected to the OLT.

Next, let $\mathcal{O}$ be the random subset of ONUs which are connected to the OLT optically after one or more fiber link failures have occurred. For a given set $\mathcal{W}$, the following two cases can happen:

- If $\mathcal{O} \cap \mathcal{W} = \phi$ (i.e., both sets are disjoint), then all ONUs in $\mathcal{O}$ and all ONUs in $\mathcal{W}$ can communicate among themselves, but no ONU in $\mathcal{O}$ can communicate with any ONU in $\mathcal{W}$.
- If $\mathcal{O} \cap \mathcal{W} \neq \phi$, then any pair of ONUs, say, ONUs i and j, in $\mathcal{O} \cup \mathcal{W}$ can communicate with each other even if ONU $i \in \mathcal{O}$ but $i \notin \mathcal{W}$ and ONU $j \in \mathcal{W}$ but $j \notin \mathcal{O}$, and vice versa.

For a given set $\mathcal{W}$, the expected number of ONUs, which are connected to the OLT is given by

$$\sum_{i=1}^{N} r_i, \tag{4}$$

where r_i is the probability that ONU i has a connection to the OLT, either directly optically or wirelessly-optically, after equipping the selected M ONUs with MPPs. In Equ. (4), r_i is given by

$$r_i = \begin{cases} \mathbb{P}(\mathcal{O} \cap \mathcal{W} \neq \phi), i \in \mathcal{W} \\ \mathbb{P}(i \in \mathcal{O}) = q_i, i \notin \mathcal{W}, \end{cases} \tag{5}$$

whereby $\mathbb{P}(\mathcal{O} \cap \mathcal{W} \neq \phi)$ is the probability that there exists at least one ONU in $\mathcal{W}$ which is also in $\mathcal{O}$, i.e., there is at least one wirelessly upgraded ONU that has a failure-free optical connection to the OLT. In the following, we describe the computer program we used to recursively calculate $\mathbb{P}(\mathcal{O} \cap \mathcal{W} \neq \phi)$ according to the four following steps:

1) First, we prune the LR-PON tree-and-branch topology by removing all ONUs that are not in $\mathcal{W}$ and the branches leading to them. The resultant pruned tree topology contains only the M selected ONUs in $\mathcal{W}$, including only the branches connecting them to the OLT.
2) In the pruned tree topology, splitters with one incoming fiber link of stage i and one outgoing fiber link of stage $i+1$ are replaced with a single fiber link whose assigned failure probability is equal to $p_e = 1 - (1 - p_i)(1 - p_{i+1})$. That is, 1:1 splitters together with their respective incoming fiber link and outgoing fiber link are replaced with a new fiber link of failure probability p_e.
3) Beginning at the leaves (i.e., M ONUs), we assign each of the splitters that are directly connected to the M ONUs the probability that it has at least one failure-free optical connection to one of its corresponding ONUs. For a given splitter s_n, n hops away from the OLT, this probability is given by

$$\mathbb{P}_{s_n} = 1 - \prod_{i=1}^{m} (1 - p_{s_n i}), \tag{6}$$

where m and $p_{s_n i}$ denote the number of ONUs connected to splitter s_n and the probability that ONU i is connected to splitter s_n, respectively. This step is repeated for all splitters of each stage of the pruned tree until we reach the first splitter s_1 next to the OLT.

4) Finally, we calculate the probability that the OLT has a failure-free optical connection to at least one of the M ONUs, which is given by

$$\mathbb{P}_{OLT} = (1 - p_0) \cdot \mathbb{P}_{s_1}. \tag{7}$$

Note that $\mathbb{P}_{OLT}$ is equivalent to probability r_i in Equ. (5) for $i \in \mathcal{W}$. Thus, we have $\mathbb{P}(\mathcal{O} \cap \mathcal{W} \neq \phi) = \mathbb{P}_{OLT}$ for ONU i, $i \in \mathcal{W}$.

C. FiWi: NG-PON with Both Wireless and Optical Protection

So far, we have assumed that the LR-PON under consideration has no optical protection. Recall from Section I, that partial optical protection is a viable solution to improve the survivability of LR-PONs by connecting one or more ONUs with additional back-up fiber links to the OLT. Now, if there exists an ONU, say, ONU 1, with a safe optical connection to the OLT (i.e., $q_1 = 1$) by means of optical protection and ONU $1 \in \mathcal{W}$, then $\mathbb{P}(\mathcal{O} \cap \mathcal{W} \neq \phi) = 1$ and $\sum_{i=1}^{N} r_i$ is maximal among all choices of $\mathcal{W}$ for a given $|\mathcal{W}| = M$, if we upgrade the $M - 1$ weakest ONUs (i.e., those ONUs with the lowest q_i) and ONU 1 with MPPs. Note that by maximizing $\sum_{i=1}^{N} r_i$ the mean number of ONUs connected to the OLT becomes maximal.

D. Failure-free Connections among ONUs

To evaluate and compare the aforementioned selection schemes, we compute the average number of failure-free connections among ONUs (i.e., pairs of ONUs connected by optical and/or wireless links). The average number D of failure-free connections among ONUs is given by

$$D := \mathbb{E}\left[|\mathcal{O} \cup \mathcal{W}| \cdot (|\mathcal{O} \cup \mathcal{W}| - 1)\right]. \tag{8}$$

To compute D, we can write

$$D = \mathbb{E}\left[\left(\sum_{i=1}^{N} \mathbb{1}_{\mathcal{O}\cup\mathcal{W}}(i)\right)\left(\left(\sum_{j=1}^{N} \mathbb{1}_{\mathcal{O}\cup\mathcal{W}}(j)\right) - 1\right)\right], \tag{9}$$

where $\mathbb{1}_{\mathcal{O}\cup\mathcal{W}}(i)$ denotes the indicator function of subset $\mathcal{O}\cup\mathcal{W}$ for a given ONU i and is given by

$$\mathbb{1}_{\mathcal{O}\cup\mathcal{W}}(i) = \begin{cases} 1, i \in (\mathcal{O}\cup\mathcal{W}) \\ 0, i \notin (\mathcal{O}\cup\mathcal{W}). \end{cases} \tag{10}$$

Using this definition of the indicator function, we can extend Equ. (9) to

$$D = \sum_{i=1}^{N}\sum_{j=1}^{N}\mathbb{P}(i \in (\mathcal{O}\cup\mathcal{W}), j \in (\mathcal{O}\cup\mathcal{W})) - \sum_{i=1}^{N}\mathbb{P}(i \in (\mathcal{O}\cup\mathcal{W})), \tag{11}$$

where the first term is computed by distinguishing the following cases

$$\mathbb{P}(i \in (\mathcal{O}\cup\mathcal{W}), j \in (\mathcal{O}\cup\mathcal{W})) = \begin{cases} 1, i \in \mathcal{W}, j \in \mathcal{W} \\ p_{ij}, i \notin \mathcal{W}, j \notin \mathcal{W} \\ q_j, i \in \mathcal{W}, j \notin \mathcal{W} \\ q_i, i \notin \mathcal{W}, j \in \mathcal{W} \end{cases} \tag{12}$$

and the second term is given by

$$\mathbb{P}(i \in (\mathcal{O}\cup\mathcal{W})) = \begin{cases} 1, i \in \mathcal{W} \\ q_i, i \notin \mathcal{W}. \end{cases} \tag{13}$$

V. Numerical Results

To facilitate a better understanding of survivability in NG-PONs, we first consider the impact of number of stages and number of ONUs on the optical fiber connection of ONUs to the OLT without taking the WMN into account. Let us start with a conventional 2-stage PON and consider a typical number of $N = 16$ ONUs connected to the OLT. We then increase the number of stages and number of ONUs to form NG-PONs. More specifically, we consider a binary tree based PON, where each additional stage increases the number of ONUs by a factor of 2. Toward this end, we replace the 1:16 splitter of the conventional PON with a 1:2 splitter and attach two 1:16 splitters to the leaves of the 1:2 splitter. As a result, the new PON has 3 stages and supports 32 ONUs at a distance of 2 from the OLT (i.e., $d_i = 2$). For each additional stage, we insert a 1:2 splitter next to the OLT and double the number of branches and attached ONUs until we reach the maximum number $N = 4096$ ONUs, which is close to the experimentally

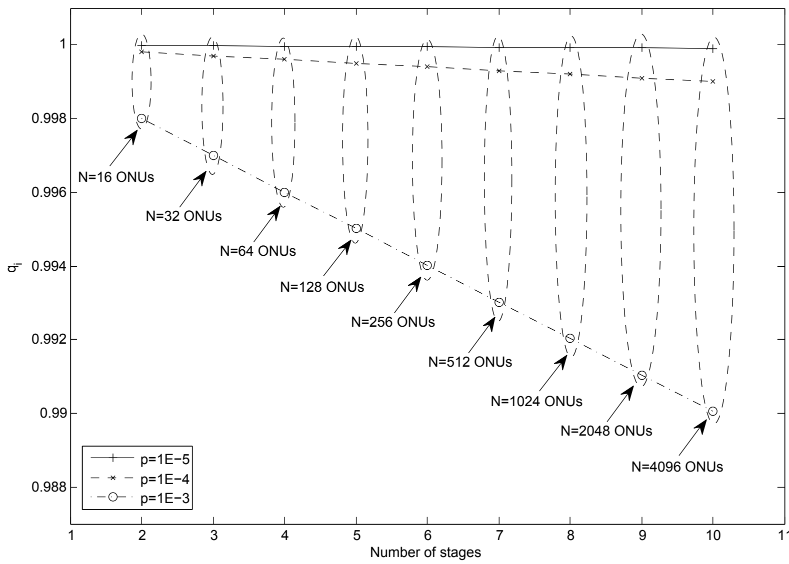


Fig. 5. Impact of number of stages and number of ONUs on the probability q_i of an intact optical connection of ONU i to the OLT.

demonstrated state-of-the-art LR-PON with a total of 4352 ONUs [6]. For now, we assume the same failure probability for the fiber links of different stages (i.e., $p_0 = p_1 = \cdots =: p$). Fig. 5 depicts the probability q_i that a given ONU i is connected to the OLT vs. the number of stages for different fiber link failure probability $p \in \{10^{-5}, 10^{-4}, 10^{-3}\}$. We observe that the probability of an intact optical connection to the OLT decreases for an increasing number of stages and ONUs, especially for $p = 10^{-3}$. This figure illustrates the importance of providing improved survivability in NG-PONs as their increased number of stages and ONUs result in a decreasing ONU connectivity probability q_i.

Next, we investigate the beneficial impact of interconnecting ONUs through a WMN. Fig. 6 depicts the average number D of failure-free connections among a fixed number of $N = 1024$ ONUs vs. fiber link failure probability p, which is assumed to be the same in all eight stages of the binary tree. For simplicity, we use the random selection scheme to choose $M \leq N = 1024$ ONUs, whereby $M \in \{0, 16, 32, 64, 128, 256, 512, 1024\}$. Except for $M = N$, we observe that the average number of failure-free connections decreases for an increasing fiber link failure probability and asymptotically approaches zero for $M \leq 64$. Increasing the number of wirelessly upgraded ONUs to $M = 128$ and higher increases the number of failure-free connections. The random selection of $M = 512$, i.e., randomly equipping 50%

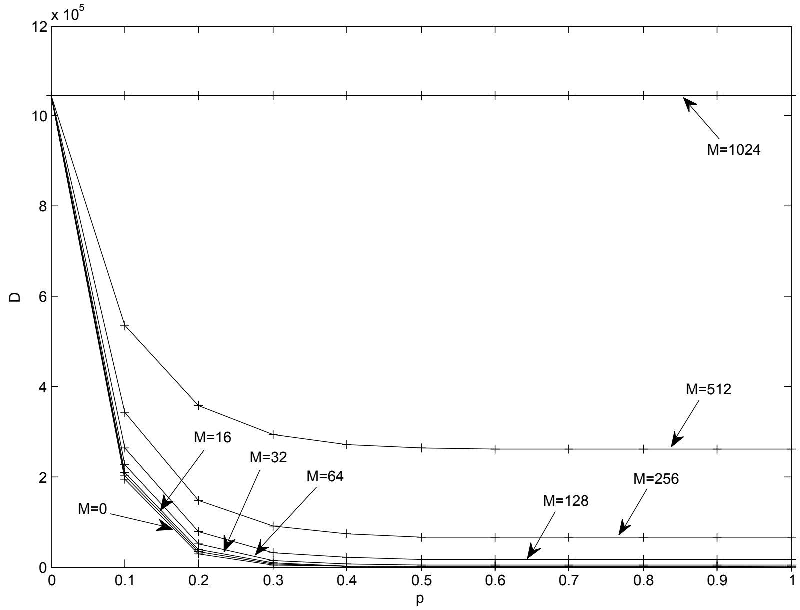
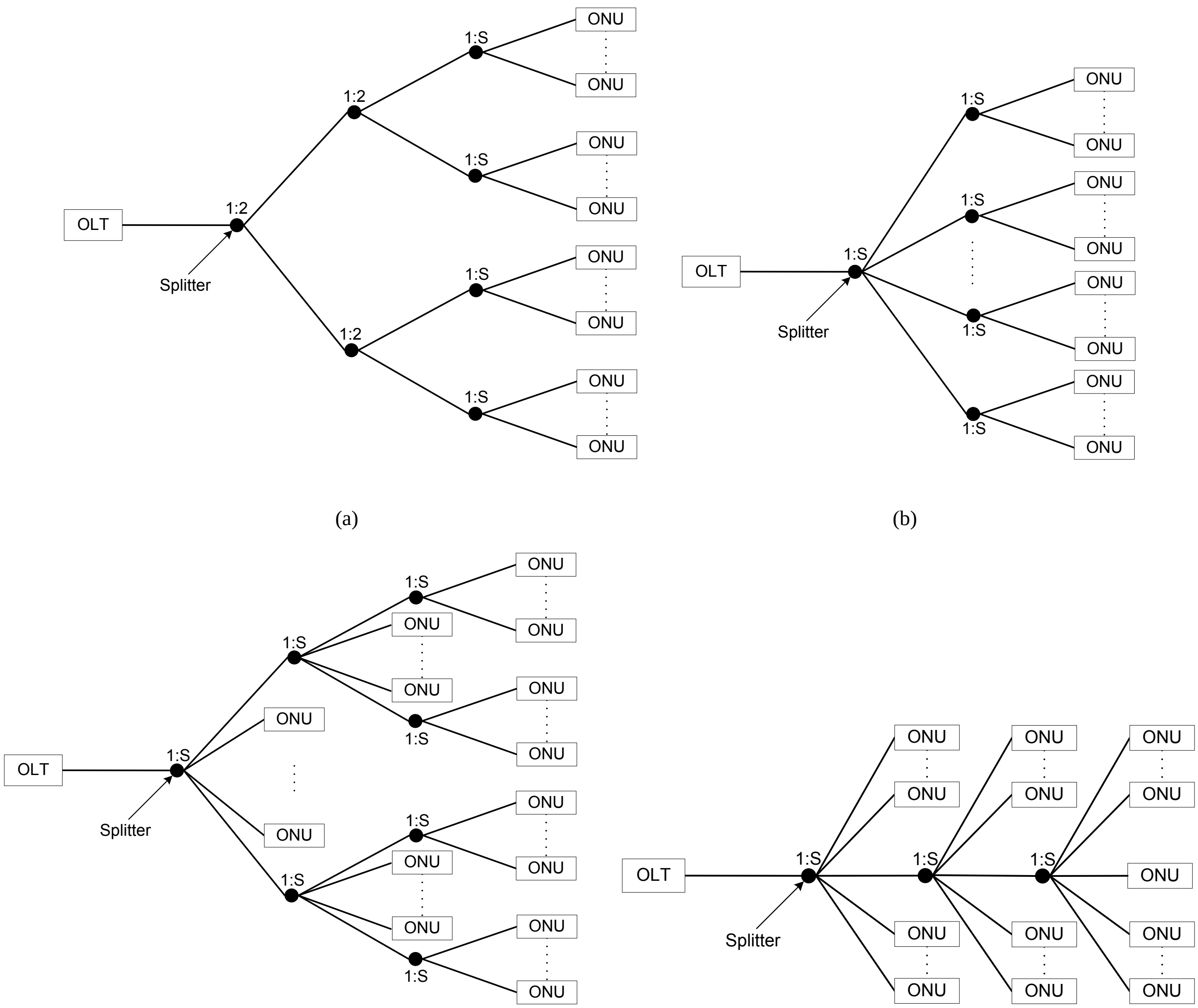


Fig. 6. Average number D of failure-free connections among $N = 1024$ ONUs vs. fiber link failure probability p (same for all stages).

of the ONUs with MPPs, helps maintain roughly 25% of all connections among ONUs for a medium and high fiber link failure probability p. Note that full connectivity among all ONUs can be achieved for any value of p by equipping all $N = 1024$ ONUs with an MPP.

In the following, we examine the benefits and limitations of equipping a subset of ONUs with MPPs in greater detail by taking a number of different NG-PON topologies into account and comparing them to the above binary tree topology. Fig. 7 shows the four different NG-PON topologies we consider for the performance evaluation of our proposed selection schemes:

- *Binary tree*: As mentioned above, the binary tree uses 1:2 splitters in all its stages except for the last one. The last stage uses 1:S splitters to connect the ONUs to the tree. Each additional stage increases the number of attached ONUs by a factor of 2. Note that in the binary tree all ONUs have the same distance to the OLT.
- *Full tree*: In the full tree, each stage deploys 1:S splitters. Similar to the binary tree, all ONUs have the same distance to the OLT. Clearly, for a given number of ONUs their distance is smaller in the full tree than in the binary tree.
- *Pyramid*: The pyramid uses only 1:S splitters, but ONUs are allowed to be located at different



(a) (b) (c) (d)

Fig. 7. NG-PON topologies: (a) binary tree, (b) full tree, (c) pyramid, and (d) cube.

distances from the OLT. In the pyramid, ONUs are connected not only to the splitters of the last stage but also to intermediate splitters. Specifically, each intermediate splitter connects to $S-2$ ONUs while the remaining 2 branches connect to the next stage. At the final stage, each splitter connects to S ONUs. Note that like the binary tree, each additional stage of the pyramid doubles the number of connected ONUs.

- *Cube*: Similar to the pyramid, the cube deploys only 1:S splitters and allows ONUs to have different distances to the OLT, whereby each stage increases the number of ONUs by $S-1$ ONUs. In the

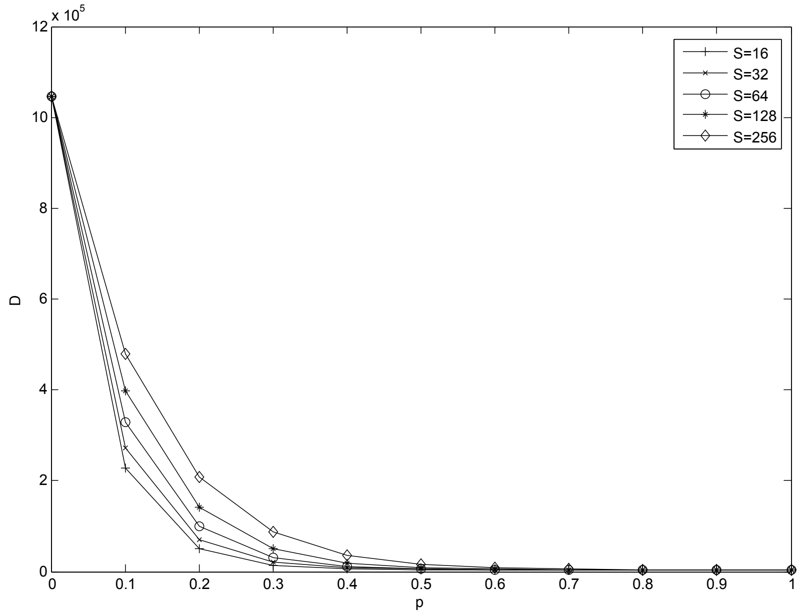


Fig. 8. Average number D of failure-free connections vs. fiber link failure probability p in binary tree with different splitting ratio S for $M = 64$ and $N = 1024$.

cube, each intermediate splitter connects to $S - 1$ ONUs while the remaining branch connects to the next stage. The final splitter has S ONUs attached to it.

Changing the splitting ratio S of the aforementioned topologies leads to different NG-PON configurations. Fig. 8 shows the impact of different $S \in \{16, 32, 64, 128, 256\}$ on the average number D of failure-free connections in a binary tree with $M = 64$ and $N = 1024$ vs. fiber link failure probability p (same for all stages). We observe from Fig. 8 that the average number of failure-free connections among ONUs increases for increasing splitting ratio S. This is due to the fact that a larger S implies that fewer stages are required to connect the 1024 ONUs to the OLT. The reduced number of required stages in addition to the fact that with an increased S there are more fiber links at the final stage, whose cuts affect only single ONUs, make the binary tree more robust against link failures, resulting in an increased number of failure-free connections and improved survivability. More importantly, note that the results shown in Fig. 8 are the same for all four different selection schemes. That is, in a binary tree we obtain the same value of D independent of the applied selection scheme. This is due to the fact that all ONUs have the same distance and are thus identical in terms of link failure probability and disconnection from the OLT.

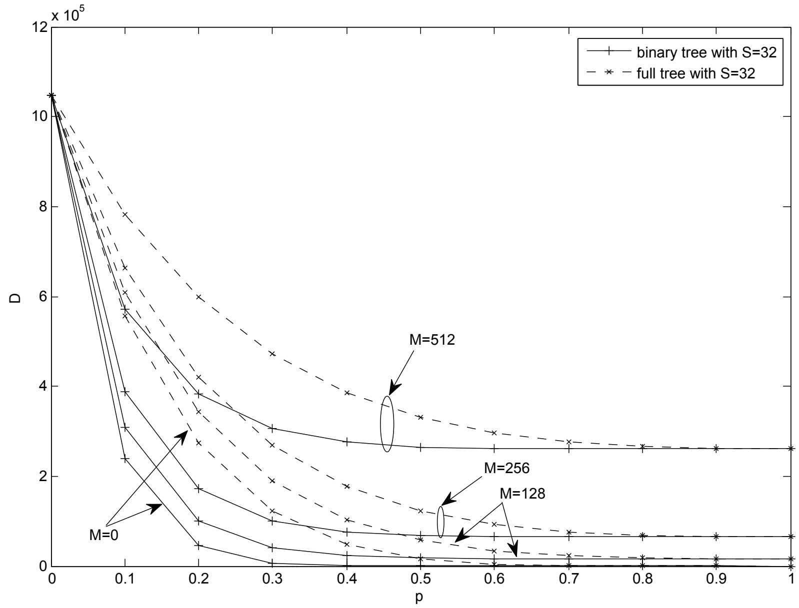
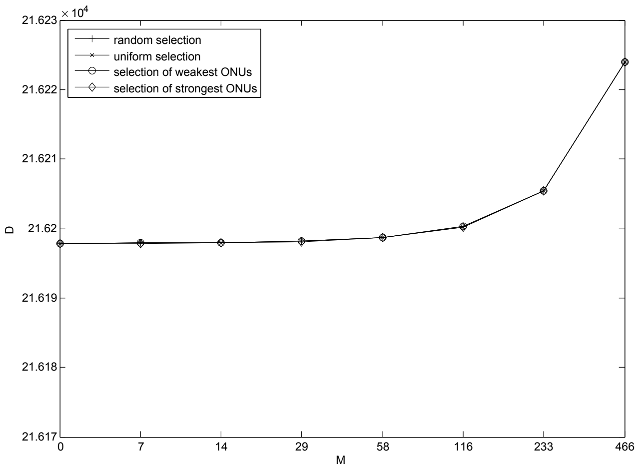


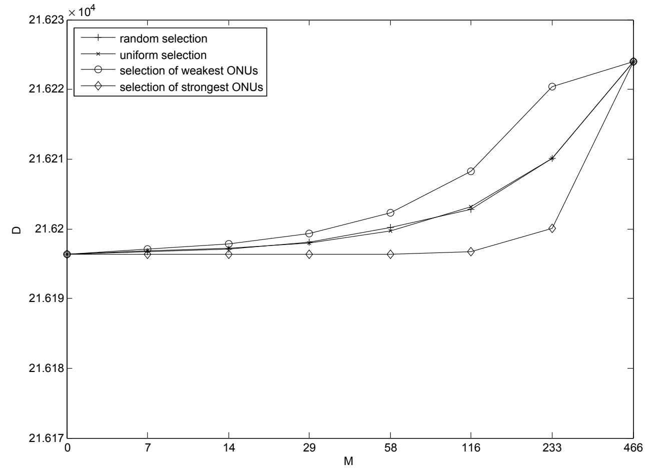
Fig. 9. Average number D of failure-free connections vs. fiber link failure probability p in binary tree and full tree with splitting ratio $S = 32$ for different M ($N = 1024$ fixed).

As a consequence, operators of a binary tree based NG-PON are free to choose any ONUs for a wireless upgrade in order to achieve the same level of survivability, thereby greatly simplifying network migration from NG-PON to FiWi networks. The selection of the M ONUs can be made based on the requirements of the available WMN. For instance, a network operator may select M ONUs that are close to each other in order to build a WMN with fewer or even no intermediate MPs and wireless links of shorter length. The same observations hold for our second NG-PON topology, the full tree. However, the full tree is able to achieve a significantly higher number D of failure-free connections than the binary tree, as shown in Fig. 9 for a fixed splitting ratio $S = 32$ and different $M \in \{0, 128, 256, 512\}$, whereby $N = 1024$.

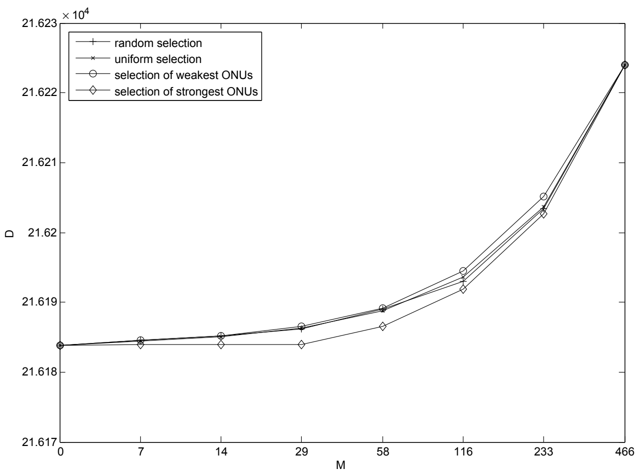
Next, we examine the pyramid NG-PON topology where ONUs don't have the same distance to the OLT. Fig 10 compares the performance of our different selection schemes for a 5-stage pyramid NG-PON topology with splitting ratio $S = 32$, which translates into a total number of $N = 466$ ONUs, in terms of average number D of failure-free connections vs. number M of ONU-MPPs. Furthermore, we allow each stage to have a different fiber link failure probability, i.e., $p_0 \neq p_1 \neq \cdots \neq p_4$. More specifically, we consider different scenarios where the fiber link failure probability per stage is descending, ascending,



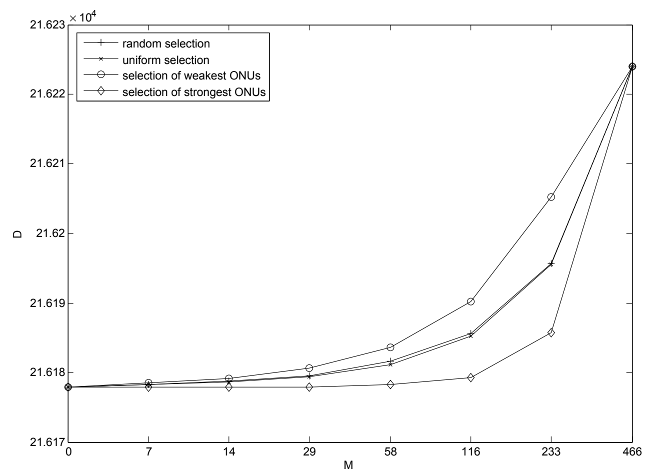
(a)



(b)



(c)



(d)

Fig. 10. Performance comparison of different selection schemes for a 5-stage pyramid NG-PON topology with splitting ratio $S = 32$ interconnecting $N = 466$ ONUs and various fiber link failure probability scenarios: (a) descending, (b) ascending, (c) ascending-descending, and (d) descending-ascending.

or a combination thereof for an increasing distance from the OLT. In the descending scenario, the fiber link failure probability per stage decreases for an increasing distance from the OLT. Conversely, for an increasing distance from the OLT the fiber link failure probability per stage increases in the ascending scenario. In the ascending-descending scenario, the fiber link failure probability per stage increases for an increasing distance from the OLT, with the middle fiber link having the highest link failure probability, and from that link for an increasing distance from the OLT the fiber link failure probability per stage decreases. Conversely, in the descending-ascending scenario, the fiber link failure probability per stage decreases for an increasing distance from the OLT, with the middle fiber link having the lowest link failure probability, and from that link for an increasing distance from the OLT the fiber link failure probability per stage increases. In Fig. 10(a), the fiber link failure probability per stage decreases by a factor of 10 for an increasing distance, whereby $p_0 = 10^{-4}$, $p_1 = 10^{-5}$, $p_2 = 10^{-6}$, $p_3 = 10^{-7}$, and $p_4 = 10^{-8}$. We observe that all four selection schemes essentially show the same performance since all ONUs, independent of their distance, are equally affected by the dominating fiber link probabilities p_0 and p_1 which are by one or more orders of magnitude larger than p_2, p_3, and p_4. In contrast, a significant difference between the selection schemes can be observed in the opposite case where the fiber link failure probability per stage increases by a factor of 10 for an increasing distance, as shown in Fig. 10(b) for $p_0 = 10^{-8}$, $p_1 = 10^{-7}$, $p_2 = 10^{-6}$, $p_3 = 10^{-5}$, and $p_4 = 10^{-4}$. While no significant difference between the uniform and random selection schemes can be observed, Fig. 10(b) demonstrates that the scheme of selecting the M weakest ONUs clearly outperforms the strongest ONU selection scheme. More precisely, with the strongest ONU selection scheme, the performance gain is negligible for up to $M = 116$, i.e., even upgrading 25% of the ONUs with MPPs does not achieve any sizable survivability improvement. Conversely, with the weakest ONU selection, the number D of failure-free connections grows exponentially for increasing M, reaching almost full connectivity already for $M = 233$, i.e., 50% of the ONUs are upgraded with an MPP. In Fig. 10(c), the central stage is assumed to suffer from the maximum fiber link failure probability while fiber links failures become less likely towards the OLT and far distant ONUs, i.e., we have $p_0 = 10^{-8}$, $p_1 = 10^{-6}$, $p_2 = 10^{-4}$, $p_3 = 10^{-6}$, and $p_4 = 10^{-8}$. As shown in Fig. 10(c), we observe that such a failure scenario makes the difference between the weakest and strongest ONU selection schemes less pronounced and makes them comparable to the random and uniform selection schemes, especially for small and large values of M. In the fourth and final failure scenario under consideration, the central stage is assumed to be less failure prone than the other stages by setting $p_0 = 10^{-4}$, $p_1 = 10^{-6}$, $p_2 = 10^{-8}$, $p_3 = 10^{-6}$, and $p_4 = 10^{-4}$, as depicted in Fig. 10(d). Similarly to Fig. 10(b), the weakest ONU selection scheme is again superior to the strongest ONU selection scheme. However, for all four selection schemes the number D

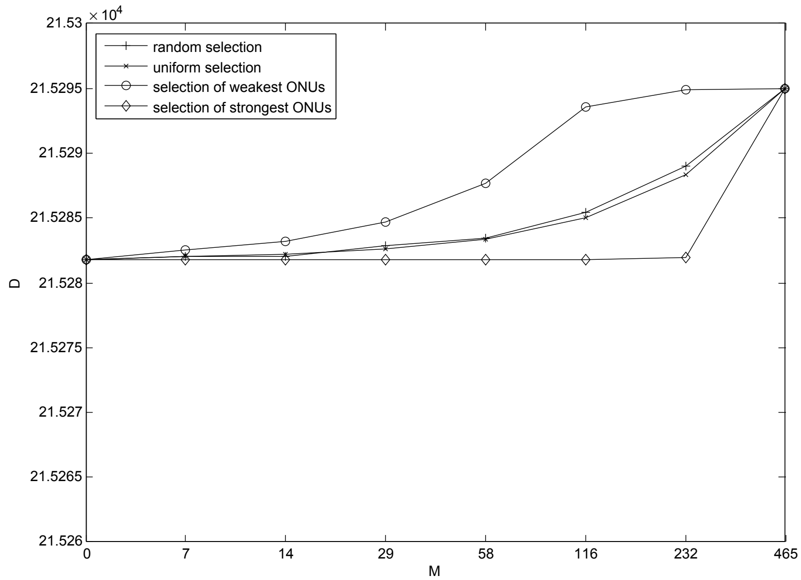


Fig. 11. Performance comparison of different selection schemes for a 5-stage cube NG-PON topology with splitting ratio $S = 117$ interconnecting $N = 465$ ONUs under the ascending fiber link failure probability scenario.

of failure-free connections is smaller in Fig. 10(d) than in Fig. 10(b) for $M < N$.

We have also studied the impact of the four aforementioned failure scenarios (descending, ascending, ascending-descending, descending-ascending) on the performance of the cube NG-PON topology. For a fair comparison with the above pyramid topology, we have considered a 5-stage cube that interconnects almost the same number of ONUs $N = 465$. Towards this end, we had to set the splitting ratio of the 5-stage cube to $S = 117$. Overall, we observed the same general behavior as in the pyramid with only a few subtle differences, as highlighted in Fig. 11 for the ascending failure probability scenario with $p_0 = 10^{-8}$, $p_1 = 10^{-7}$, $p_2 = 10^{-6}$, $p_3 = 10^{-5}$, and $p_4 = 10^{-4}$. Fig. 11 illustrates that the choice of the right selection scheme becomes even more important in the cube topology. While there is again no major difference between the random and uniform selection schemes, the superiority of the weakest ONU selection scheme over the strongest ONU selection scheme is more pronounced in Fig. 11 than in Fig. 10(b). The former one achieves a value of D close to the maximum for already $M = 116$, i.e., upgrading only 25% of the ONUs with an MPP, while no significant performance gain can be observed for the latter one, even by wirelessly upgrading $M = 232$, i.e., 50% of the ONUs, with an MPP. Thus,

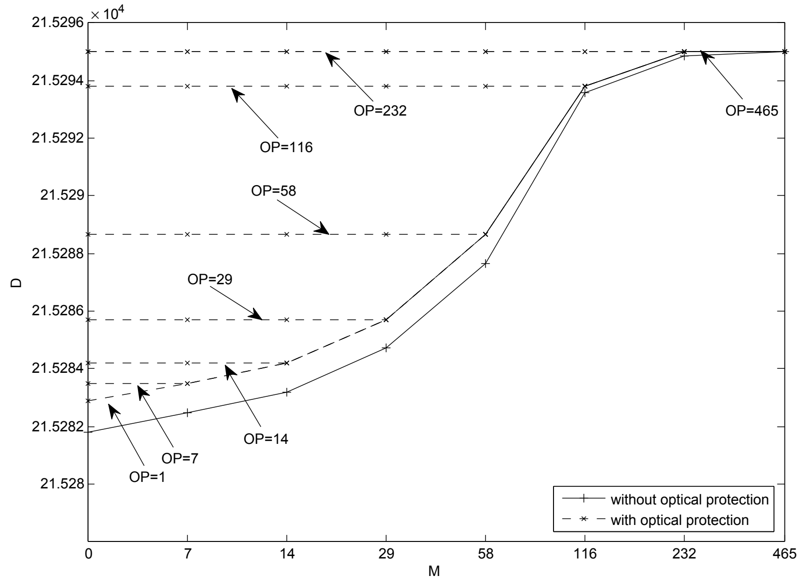


Fig. 12. Average number D of failure-free connections vs. number M of wirelessly upgraded ONUs for a 5-stage cube NG-PON topology ($S = 117$, $N = 465$) with and without optical protection.

it seems that that for an NG-PON topology with a high splitting ratio, such as our considered cube with $S = 117$, the survivability can be improved significantly (i.e., D close to maximum) by equipping only a relatively small subset of ONUs with an MPP. In other words, an NG-PON topology with a high splitting ratio has the potential to provide a good survivability performance-cost trade-off by deploying the right selection scheme.

So far, we have assumed that there is no optical protection. Fig. 12 depicts the beneficial impact of deploying optical protection in addition to interconnecting a subset of ONUs through a WMN for the aforementioned 5-stage cube topology with $S = 117$ and $N = 465$. The figure shows the average number D of failure-free connections vs. number M of wirelessly upgraded ONUs with and without optical protection using the weakest ONU selection. More precisely, without optical protection we select the M weakest ONUs and interconnect them through a WMN, as discussed above in Fig. 11. With optical protection, the wirelessly upgraded M ONUs are additionally optically protected by means of back-up fibers such that their optical connection to the OLT can be considered safe, i.e., $q_i = 1$. In Fig. 12, the number OP of optically protected ONUs is $OP \in \{1, 7, 14, 29, 58, 116, 232, 465\}$. Fig. 12 clearly demonstrates that deploying partial optical protection in combination with using a WMN front-end helps increase D significantly. Especially for small to medium M (and OP), partial optical protection is an effective yet cost-efficient means to improve the survivability of NG-PONs and FiWi networks considerably.

VI. Conclusions

Current TDM PONs are evolving into NG-PONs with the goal to achieve higher performance parameters, e.g., higher data rates, increased splitting ratios, and longer fiber reach than current state-of-the-art EPON/GPON architectures. In conventional PONs, protection may be considered cost-prohibitive due to the relatively small number of ONUs (typically in the range of 16 to 64). However, due to their significantly higher number of attached ONUs, data rates, wavelength channel counts, and extended coverage, network survivability is becoming a key issue in NG-PONs. In this paper, we have analyzed the survivability of NG-PONs and emerging hybrid FiWi networks in terms of failure-free connections, either only optical or mixed optical-wireless, among ONUs taking both optical and wireless partial/full protection into account. We have compared the performance of various schemes to select ONUs and interconnect them wirelessly through a WMN under the consideration of different network topologies and a wide range of fiber link failure scenarios. Our obtained results indicate that for a given number of ONUs NG-PON configurations with a higher splitting ratio are able to achieve a higher degree of survivability in terms of failure-free connections among ONUs. Furthermore, we have found that the choice of the right selection scheme has a significant impact on the survivability of NG-PONs and FiWi networks. In the example of the cube NG-PON topology, by using the weakest ONU selection scheme the number of failure-free connections among ONUs is almost maximized by wirelessly upgrading only 25% of the ONUs. Finally, we have seen that partial optical protection in combination with a WMN front-end is an effective and cost-efficient means to improve the survivability of NG-PONs and FiWi networks considerably, especially for small to moderate numbers of required ONU-MPPs. Note that our study focused on analyzing the impact of link and node failures on the connectivity of NG-PONs and FiWi access networks. An interesting future research avenue would be to take the different data rates of state-of-the-art optical and wireless access technologies into account in order to provide acceptable service continuity in the event of single or multiple network failures.

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