Hybrid Fiber and Microwave Protection for Mobile Backhauling

Yanpeng Yang, Ki Won Sung, Lena Wosinska, and Jiajia Chen

***Abstract*—Several studies are showing that the optical fiber based backhauling offers a future proof solution to handle rapidly increasing traffic in wireless access networks and outperforms other existing backhauling technologies, such as microwave and copper, in terms of capacity, scalability and sustainability. However, the deployment cost of fiber infrastructure is relatively high and it may be difficult to provide a cost efficient and flexible protection strategy for the fiber backhauling network. Considering that protection is very important in order to avoid service interruption in high capacity mobile backhauling network, in this paper, we propose a hybrid fiber and microwave protection scheme for mobile backhauling based on passive optical network (PON). The proposed reliable architecture is compatible with any wavelength division multiplexing (WDM) based PON, e.g., pure WDM PON and a hybrid time and wavelength division multiplexing (TWDM) PON, offering high flexibility and relatively low deployment cost. The backup for feeder fiber is provided by dual homing while the protection of distribution section can be established via a microwave connection between two base stations in case a high reliability performance is required, e.g., for macro cells covering large service areas. We have carried out an extensive assessment of our approach in terms of connection availability, failure impact, complexity and flexibility in providing resiliency. We also show a comparison with other existing solutions. The evaluation results confirm that our scheme can achieve relatively high flexibility and reliability performance while maintaining low complexity compared with the existing approaches.**

***Index Terms*—Mobile backhauling; Hybrid Fiber and Microwave technology; Passive optical network (PON); Protection scheme.**

I. INTRODUCTION

The bandwidth demand required by 3/4G and the future 5G mobile services is expected to reach an astounding increase, i.e. in the magnitude of 1000-fold in the coming decade [1], which in turn will bring a number of challenges on backhauling networks.

Several backhauling alternatives for cellular networks are available, such as based on copper, fiber or microwave. Microwave approach is able to provide capacity up to several Gbps with a maximum reach of a few kilometers. A recent report in [2] estimates that microwave represents nearly 50% of global backhaul deployments. Copper networks, which make up for nearly 20% of all backhaul deployments, are likely to decrease due to their limited capacity and poor ability to scale in a cost efficient manner. Looking forward, fiber is expected to replace copper based wire-line connections, and increase its overall share. In contrast to the other two technologies, fiber connection can easily provide very high bandwidth (e.g. over 100Gbps) and long reach (i.e. in the magnitude of several tens of kilometers) while consuming less energy [3]. Therefore, fiber based approaches are promising for backhauling the future ultra-high capacity mobile networks. It has been found that passive optical network (PON) outperforms other fiber based network architectures in terms of cost and power efficiency [4]. Furthermore, network operators are advocating node consolidation, where several central offices can be merged and located in a single central access node, in order to reduce operational complexity and cost [5]. In this regard, long-reach PON (LR-PON) is considered as one of the best alternatives. In LR-PON the maximum reach can exceed 100 km [4], which makes it possible to combine the access and metro networks into one segment, and in this way simplify network operation and reduce the cost. Moreover, advances in wavelength division multiplexing (WDM) technology, make WDM based PONs to promising candidates, offering high data rate and large splitting ratio [4]. Therefore, in this paper we focus on WDM based LR-PON for mobile backhaul, where an optical line terminal (OLT) is located at the central office (also referred to as the metro/core node which is at the edge of the core network) while each optical network unit (ONU) is backhauling the traffic from one cell and is co-located with the associated base station (BS).

Meanwhile, the rapidly growing traffic demand increases importance of reliability performance of mobile backhauling [4], where the availability requirement of 4 or 5 nines (99.99% or 99.999%) needs to be satisfied. It has been proved [6] that without any protection in PON, connection availability of 4 nines cannot be achieved, in particular in long reach deployment scenarios. There are many resiliency schemes proposed for PON based fixed access network, most of which could be also applied for mobile backhauling applications, e.g., [7] [8] [9] [10] [11]. [7] and [8] both present restorable architectures for WDM-PONs, but the protection function of these two schemes covers only part of the fibers, i.e., either feeder fiber (FF) shared among all the ONUs [8] or distribution fiber (DF) which is dedicated to a specific ONU [7]. Full protection schemes based on duplicated fibers have also been investigated. For instance, two types of resilience schemes that can offer full protection capability have been standardized by ITU-T [9]. Obviously, they can offer very high reliability performance by duplicating all fiber segments and optical equipment. In [10], a reliable PON architecture utilizing multiple stages of wavelength MUX/DEMUXs (e.g., arrayed waveguide gratings (AWGs)) is proposed. In this case an ultra-high number of ONUs can be supported by a single PON. Paper [11] introduces a scalable mechanism which combines star and bus topologies. However, all of these schemes come at the expense of high investment cost, in particular for the civil work to deploy a geographically disjoint DFs dedicated to each ONU, which substantially increases the cost on a per-user/cell basis. In contrast, utilizing wireless technology for protection of mobile backhaul network allows for reusing the existing

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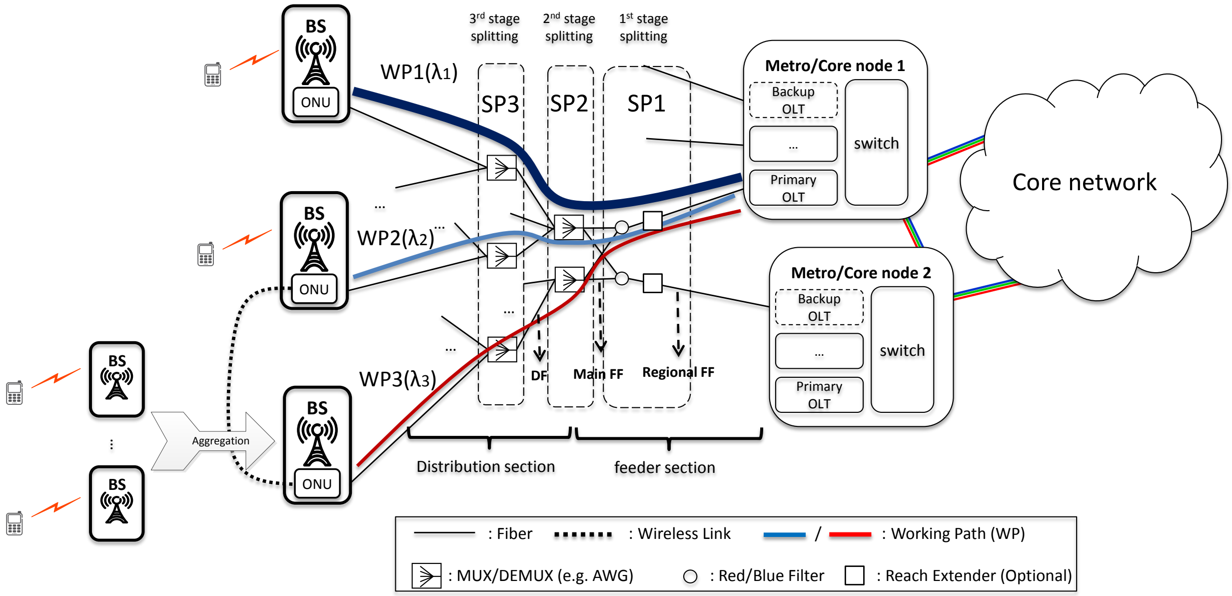


Fig. 1: Proposed protection scheme (λ_1 for WP1 and λ_2 for WP2 belong to blue band, while λ_3 for WP3 belongs to red band.)

infrastructure of the cells (e.g., BS tower) to accommodate extra antennas needed for the protection purposes, so that no big extra cost is needed apart from the wireless equipment. Meanwhile, establishing wireless connection for protection is obviously less cost- and time-consuming compared to the wired technology. Moreover, the wireless equipment used for protection could be switched off or put in low-power mode to save energy during the normal operation. Besides, most of the schemes mentioned above, e.g., [10] [11], consider protection of the fiber infrastructure while optical components are still unprotected. Recent studies [12] [13] point out that a single component failure (e.g., failure of OLT) may have a high impact and affect all the connections. In [14] and [15] survivable PON based wireless-optical access networks are proposed, where the protection is based on routing the signals through backup ONUs and wireless routers. However, these solutions still suffer from some disadvantages, i.e., 1) the backup segment requires extremely high spare capacity, particular for a potential failure occurring in feeder section, and 2) the transmission via wireless routers may cause severe delay if multiple hops are involved. It has been shown in [14] that even with the optimized algorithm the delay via the wireless routers could be more than 5ms when the traffic load is high. Furthermore, it could cause approximately 30% packet loss in case of failure occurred at the OLT. It might be acceptable for residential users, but for mobile backhauling it may become a serious issue, particularly for future *5G* mobile services.

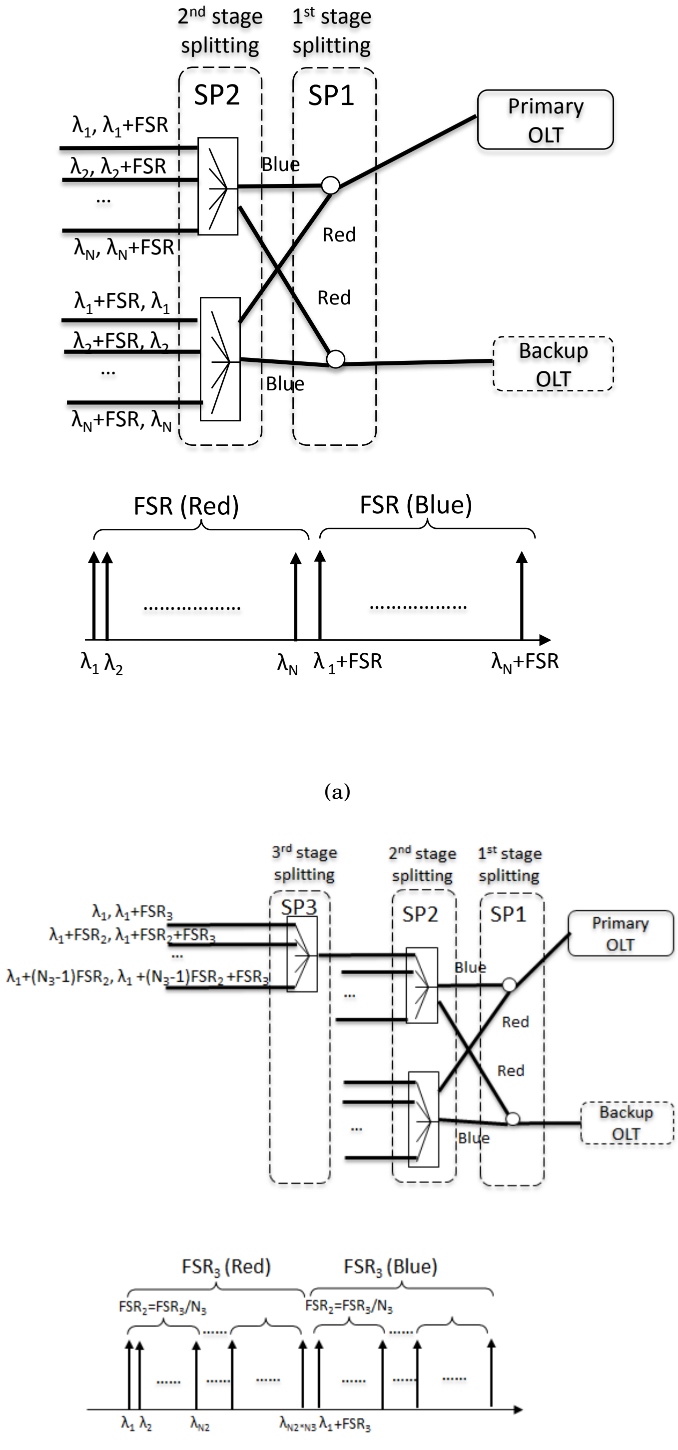
Considering the aforementioned aspects, in this paper we propose a hybrid fiber and microwave based protection scheme that offers resilience for mobile backhaul network. In addition, our approach can flexibly support different reliability requirements and provide either full protection, including fibers and optical devices, or only feeder section, i.e., FFs and OLT, which are shared by all ONUs. We evaluate our scheme in terms of reliability performance, complexity and flexibility in providing resiliency, and compare with some existing approaches. The results show that our architecture outperforms all the other considered schemes by offering higher connection availability and flexibility at potentially lower cost. Furthermore, we investigate the failure impact factor (FIF) of the unprotected part in all the considered architectures and verify the necessity to protect some high impact components.

The remainder of this paper is organized as follows. Section II describes the proposed protection scheme where dual-homed FFs are protecting the part shared by all the connected cells while a microwave connection is added to offer an end-to-end protection for the cells requesting high reliability. In Section III, we evaluate and compare the performance in terms of complexity, connection availability, failure impact and flexibility among all the considered protection schemes. Finally, the conclusions are drawn in Section IV.

II. PROTECTION SCHEME

A. Architecture

The proposed hybrid fiber and microwave self-protected PON architecture is illustrated in Fig. 1. The working paths (WPs), e.g., WP1, WP2, and WP3 shown in Fig.1, indicate the connection between the central node and base station under the normal operation where there is no fiber cut or any equipment failure. All the paths we considered here are for bidirectional communication. Either the same waveband or two separate ones are used for the upstream and downstream traffic. Two key features of our approach are: 1) dual-homed FFs for the protection in the feeder section shared by all the cells; and 2) an optional microwave connection in the distribution section (e.g., for a macro-cell that aggregates the traffic from multiple small BSs shown in Fig. 1), which is established between two neighboring ONUs having disjoint distribution fibers. In this way, a full protection, where all the components along the working path are protected, can be provided for some selected cells. In addition, the optional microwave connection offers high flexibility for implementing backup in the distribution part of the network, i.e., only where it is required.



(a)

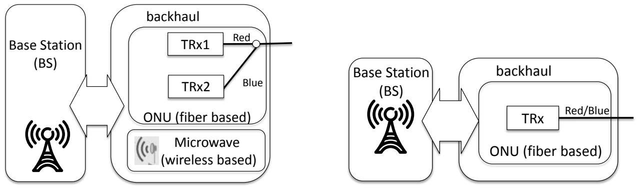
(b)

Fig. 2: Configuration of splitting stages: (a) 2-stage and (b) 3-stage

Two OLTs which are located at neighboring central offices at the edge of the core network protect each other. As shown in Fig.1, in our approach FF consists of two sections, namely main FF (MFF) and regional FF (RFF). Two disjoint RFFs are deployed between the OLTs and the first stage of splitting points (SPs), while MFFs connect the first and second stage of SPs. The proposed protection scheme can be applied to a general fiber layout deployment, which may have k ($k > 1$) stages of SPs (e.g., SP1, SP2, SP3, etc.). The fibers between SP2s and base stations are referred to as distribution fibers (DFs). Figure 2 shows the configuration of the case with two stages of SPs (i.e., $k = 2$). In the first stage, two waveband filters, e.g., red/blue filters, are placed to split all the wavelengths into two wavebands, while in the second stage two wavelength MUX/DEMUXs or power splitters are required. The ONUs connected to the first SP2 utilize blue waveband for working and red waveband for backup. On the other hand, the ONUs associated to the second SP2 (on the bottom) have red waveband for working and blue waveband for protection. In this way, the spectrum is fully utilized. Furthermore, by deploying splitting components, e.g., AWGs or power splitters in the second and/or further stages, the structure can support both pure WDM PON and TWDM PON. In case of pure WDM PON, a dedicated wavelength is assigned to each cell. For TWDM PON, at least one stage of SPs has to be splitters in order to enable several cells share the same wavelength. The consecutive SPs can be co-located at the same geographical place. For instance, all the SP1s and SP2s can be co-located, if the length of MFFs is very short (almost=0). Reach extender (RE) can be used to improve the optical power budget of the connections if needed.

In case where AWGs are employed in our scheme, several free spectral ranges (FSRs) are utilized. As illustrated in Fig. 2, N denotes the splitting ratio of the AWGs at the 2nd stage, where their FSR is equal to the red (R) or blue (B) band of the filters at SP1. The maximum number of connected BSs in this case is $2N$ and the channel spacing of AWGs is FSR/N. It can be further extended to be a more general case with more stages of splitting points (e.g., three-stage case shown in Fig. 2b). We use N_i ($1 \leq i \leq k$) to denote the maximum fan-out (i.e. the number of output ports) of the SP$_i$ and FSR$_i$ ($1 \leq i \leq k$) to represent the FSR of the AWGs in the SP$_i$. Then, the maximum number of BSs supported by the PON is $N_1 \times N_2 \times \cdots \times N_k$ and the wavelength channel spacing of the AWGs in the i-th stage of SPs (i>1) is FSR$_i$/N_i. It should be noted that N_1=2, which means the number of output ports for the band filters at the first stage of SPs is fixed and equal to two. FSR$_k$ corresponds to the size of the whole R or B band. The channel spacing of the AWGs in the SP$_i$ should be the same as the FSR$_i-1$, i.e. FSR$_i$/N_i=FSR$_i-1$ ($1 \leq i \leq k$). For the cases where power splitters are deployed in some SPs or replace all the AWGs in the aforementioned scenarios, e.g., if broadcast-and-select WDM PON or TWDM PON are considered, the configuration of the first stage of SPs (SP1) should not be changed. At the ONU side, a tunable filter may be required to select the assigned wavelength from the signals broadcasted by the splitters. Meanwhile, in all the cases the wavelength plan for each cell (or the cells in the same embedded TDM PON for TWDM PON case) can be exactly the same.

Figure 3 shows the configuration of the ONU. In Fig. 3(a), two optical and one microwave transceivers (TRXs) are



(a) (b)

Fig. 3: Configuration of ONU (a) with and (b) without protection for its neighbor

installed in the ONU offering end-to-end resiliency for its neighbor. For microwave technology, we consider a point-to-point link, which can be millimeter wave or licensed sharing access/authorized sharing access (LSA/ASA) bands. One optical TRX sends its own primary signal while the other two (i.e. one optical and one microwave TRXs) are for distribution section protection of its neighbor. Thanks to a proper configuration of SPs in our scheme, it is guaranteed that the optical TRXs for working and protection always use different wavebands (i.e., one for R band and one for B band). When the distribution section protection of its neighbor is not required, one optical TRX at the ONU is sufficient (see Fig. 3(b)).

B. Failure Recovery

Figure 4 illustrates the protection paths (e.g., PP1, PP2 and PP3) for the feeder section. When a failure occurs in the feeder section, all the signals are switched to the protection paths composed by the disjoint FF and the backup OLT (e.g., PP1, PP2 and PP3 in Fig. 4). For the dual-homing scheme, the signaling between the primary and backup OLTs is required through the core network to trigger the protection switching. It can be seen that the backup path in case of the feeder failure uses different waveband than its primary path. For instance, if the primary channel is in the R band, then its protection path uses the wavelength in the B band. For any type of WDM based PON the ONU is required to be colorless (i.e., ONU is able to transmit and receive any wavelength that is used in the PON [16]) in order to simplify the installation and maintenance process. Therefore, for the WDM based PONs offering colorless feature at ONUs, the change of the wavelength for the protection needed in our scheme would not introduce any significant extra cost.

Our resilience scheme for the distribution section is presented in Fig. 5. This function can be offered on request, and doesnt need to be provided to all the BSs from the very beginning. In some deployments, where small BSs (e.g. pico-cell, etc.) are backhauled by a fiber, protection of the distribution section of the fiber backhaul network is not required. The proposed protection can be easily offered on demand in the future, since it only needs setting up an extra wireless link. On the other hand, a macro-cell that aggregates the traffic from multiple small BSs cannot tolerate long connection interruption in its backhaul, because a large amount of traffic may be affected. The protection path for end-to-end resiliency of a certain ONU (e.g., the one at BS3 with WP3 as a primary path) is composed by two parts: 1) the protection path against the failure occurred at feeder section of its neighboring ONU with a complete disjoint distribution fiber segment (PP3.1 dashed line in Fig. 5); and 2) a microwave link starting from its neighbor (PP3.2 dotted line in Fig. 5). In the example shown in Fig. 5, backhauling for BS3 shows both distribution and feeder fiber protection. Its adjacent ONU at BS2 should be configured as the one shown in Fig. 3(a). In case the distribution fiber of working path is cut, then all the traffic will be shifted to the protection path (i.e. PP3.1+PP3.2). PP3.1, which connects backup OLT at MC2 and ONU at BS2, uses the same wavelength as WP3. Besides, if the bandwidth of the primary channel is not sufficient and there is no failure in the network, the end-to-end backup path can be used for some temporary low-priority traffic (e.g., best effort) which does not require high quality of service.

III. PERFORMANCE EVALUATION

In this section, we assess the performance of the proposed scheme with respect to complexity and flexibility in provisioning protection, connection availability, and failure impact. For simplicity, we consider our proposed architecture utilizing a pure WDM PON with two stages of SPs (i.e., k=2). For the comparative study we select three existing schemes where the similar number of ONUs per working FF is considered. The key findings from the comparison can be applied to a general case with more stages of SPs or to a TWDM PON. Hereafter, we refer to our approach as Scheme 1 and to the ones presented in [10], [11] and [15] as Schemes 2-4, respectively.

A. Complexity

Table I presents the number of network elements of each type needed to deploy the certain protection scheme. These figures are directly related to the system complexity and the deployment cost. In our scheme, we put one backup optical TRX and one wireless TRX at ONU side in order to provide end-to-end protection. In contrast, in Scheme 2 and 3, either optical switches (OSs) or more DFs are required, particularly for DF protection. Wireless connection proposed in our scheme makes the deployment for DF protection more flexible and less costly compared to Scheme 2 and 3, because much less civil work is needed to set up the wireless connection between ONUs than to put protection fiber in the ground. The average cost of deploying one kilometer fiber duct is $\$60000$ [12] while establishing a wireless connection is obviously much cheaper (around $\$150$ and its yearly spectrum leasing fee is approximately $\$200$ [17]). This huge difference in expense enables hybrid fiber and microwave scheme for protection in mobile backhauling to be significantly less costly than the pure fiber based schemes. Compared with Scheme 4 [15] which is also a hybrid fiber and wireless protection, our scheme requires neither dedicated backup ONUs (i.e., the extra ONU which is needed only for protection but not connected with any BS) nor interconnection fibers between two PONs. The wireless connections in Scheme 4 may suffer from multi-hop communication through wireless routers that will cause potential high delay. Besides, half of capacity in one PON should be reserved in order to guarantee FF protection of its neighboring PON. Meanwhile, when a potential failure occurs in the feeder section of PON, via wireless routers all the traffic will first need to congest in the ONU dedicated for backup purpose. We assume C is the bandwidth required for the connection between the OLT

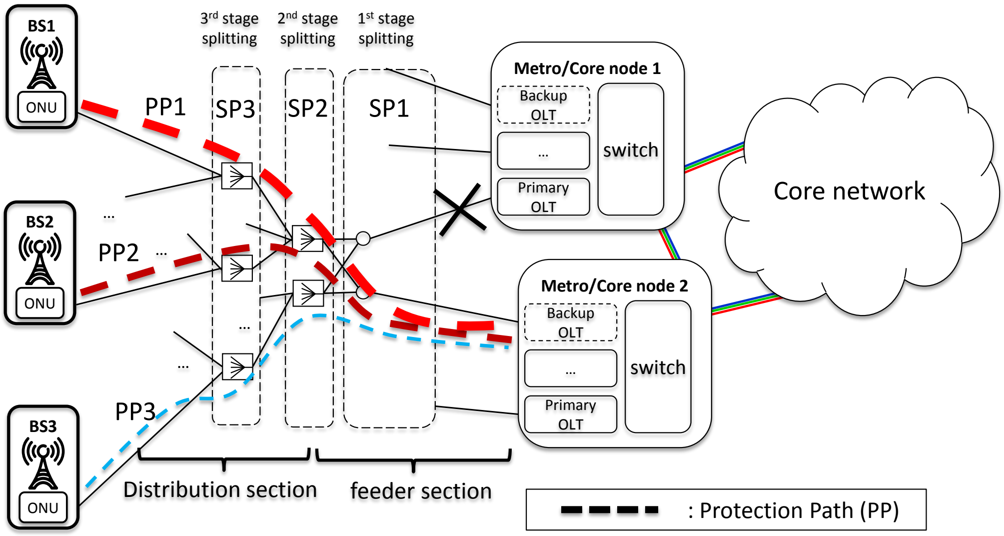


Fig. 4: Protection of feeder section

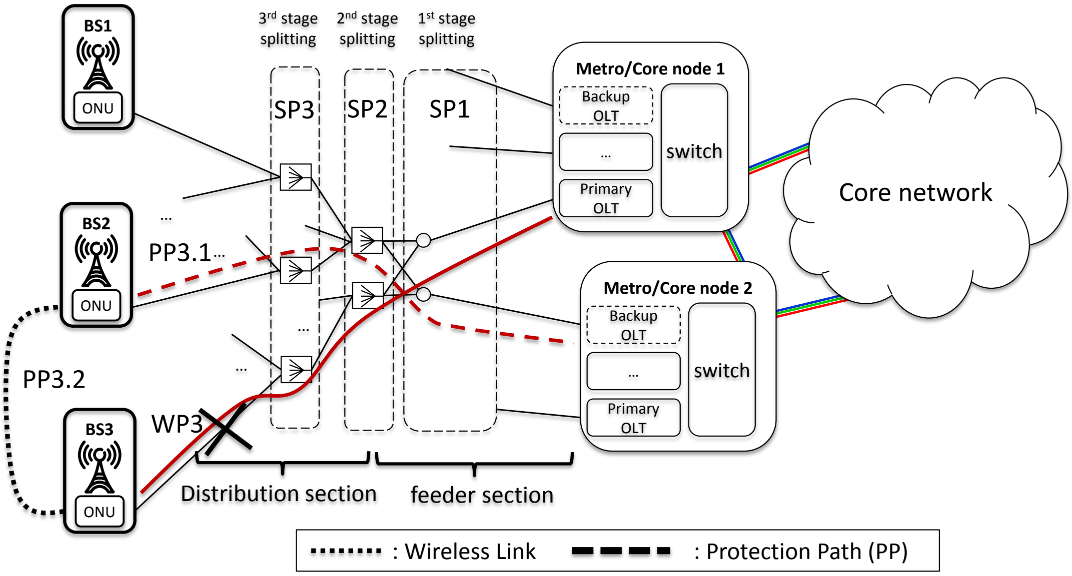


Fig. 5: A full protection with microwave connection for distribution section

and one ONU, and then the wireless segment in Scheme 4 should be able to handle the capacity up to $(M-1)\times C$. Considering $C = 100 Mbps$ and $M = 32$, it might be still feasible to have wireless routers to handle the capacity up to around 3Gbps. However, for future *5G* mobile service with the magnitude of 1000-fold capacity increase in the coming decade, using Scheme 4 for protection may cause a severe scalability problem.

At the OLT side, our scheme utilizes two separate OLTs with dual-homed FFs which protect each other by utilizing waveband efficiently. Scheme 3 [11] exploits shared TRX protection and puts m extra backup TRXs for M working ones ($m \leq M$) in the OLT which can only provide m:M shared TRX protection. However, OLT failures may be caused not only by a TRX fault but also by malfunctioning of other components (e.g. chassis including power supply, card board, etc.) [17]. Therefore, only TRX protection may not be sufficient. In summary, our scheme has relatively low complexity in offering protection and high efficiency of bandwidth utilization compared with the other considered approaches.

B. Connection Availability

To assess the reliability performance we derived connection availability models represented by the reliability block

TABLE I: Comparison of the Number of Network Elements in One PON

	Scheme 1	Scheme 2	Scheme 3	Scheme 4
No. of ONUs per working FF	M	M	M-1	M(One is dedicated to protection and M-1 are associated to BSs)
No. of working/backup optical TRXs at ONU side	1/1	1/0	1/0	1/0 (if working ONU) 0/N (if backup ONU)
No. of working/backup optical TRXs at OLT side	M/M	M/0	M/m (m backup TRXs should be tunable)	M/M
No. (and size) of AWGs in the field	2 (2xM/2)	1 (M×M) and M (1×M/2)	1 (M×M)	2 (1×M)
No. of optical switches per ONU	0	1	1/(M-1)	0
No. of disjoint FFs	2 RFFs and 4 MFFs	M	2	1(1 more interconnection fiber (IF) is required to connect two ONUs dedicated to protection)
No. of DFs normalized to one working FF	M	M (Another M interconnection fibers between two neighboring ONUs if DF protection is required.)	2M (in order to make a ring for distribution section protection)	M
Consisting of Wireless TRX or not	Yes	No	No	Yes
Total capacity required for protection carried out by wireless segment	C (assuming C is average bandwidth required for the connection between the OLT and one ONU)	Not applied	Not applied	Up to $(M-1)\times C$

diagrams (RBDs) for the considered protection schemes. The block diagrams are shown in Fig. 6. The connection is defined between OLT and ONU (located at BS).

The RBDs consist of blocks connected in series and in parallel. Each block in the diagram represents a device or a fiber/wireless link. A system represented by blocks in series is available when all blocks in the series are available, while a system represented by blocks in parallel is available when at least one of the blocks is available. The availabilities of fiber links are calculated by multiplying the availability of the fiber per km by L, where L denotes the length of the fiber link in km. Here, Scheme 1 represents the proposed approach with full protection while Scheme 1^* refers to the case with only feeder protection. The expressions of the connection availabilities in all the considered protection schemes are derived according to the RBDs shown in Fig. 6 and given by Equations 1-5. Definitions of the symbols and the related values are shown in Table II:

$$\begin{aligned}A_{\text{Scheme1}} = {} & A_{\text{X}_1} \times (1 - A_{\text{Y}_1}) \\ & \times [1 - (1 - A_{\text{MFF1}} \times A_{\text{X}_2}) \times (1 - A_{\text{MFF2}} \times A_{\text{Y}_2})] \\ & + (1 - A_{\text{X}_1}) \times A_{\text{Y}_1} \times A_{\text{Y}_2} \\ & + A_{\text{X}_1} \times A_{\text{Y}_1} \times (1 - A_{\text{MFF1}}) \times (1 - A_{\text{MFF2}}) \times A_{\text{Y}_2} \\ & + A_{\text{X}_1} \times A_{\text{Y}_1} \times [1 - (1 - A_{\text{MFF1}}) \times (1 - A_{\text{MFF2}})] \\ & \times [1 - (1 - A_{\text{X}_2}) \times (1 - A_{\text{Y}_2})]\end{aligned} \tag{1}$$

$$\begin{aligned}A_{\text{Scheme1}^*} = {} & A_{\text{X}_1} \times [1 - (1 - A_{\text{MFF1}} \times A_{\text{X}_2}) \\ & \times (1 - A_{\text{MFF2}} \times A_{\text{Y}_2})]\end{aligned} \tag{2}$$

$$\begin{aligned}A_{\text{Scheme2}} = {} & A_{\text{ONU}} \times A_{\text{OS}} \times [1 - (1 - A_{\text{MFF1}} \times A_{\text{X}_2})^2] \times A_{\text{AWG2}} \\ & \times [1 - (1 - A_{\text{FF1}}) \times (1 - A_{\text{FF2}})] \times A^2_{\text{Splitter}} \times A_{\text{OLT}}\end{aligned} \tag{3}$$

$$\begin{aligned}A_{\text{Scheme3}} = {} & A_{\text{ONU}} \times [1 - (1 - A_{\text{DF}})^2] \times A_{\text{AWG2}} \\ & \times [1 - (1 - A_{\text{FF1}}) \times (1 - A_{\text{FF2}})] \times A_{\text{OS}} \times A_{\text{AWG2}} \\ & \times [A_{\text{TRX}} + (1 - A_{\text{TRX}}) \times A^{\text{M}-1}_{\text{TRX}} \times A_{\text{PTRX}}] \\ & \times A_{\text{OLTChasis}}\end{aligned} \tag{4}$$

$$\begin{aligned}A_{\text{Scheme4}} = {} & 1 - (1 - A_{\text{ONU}} \times A_{\text{DF}} \times A_{\text{AWG2}} \times A_{\text{FF}} \times A_{\text{OLT}}) \\ & \times (1 - A^2_{\text{Wireless}} \times A^3_{\text{ONU}} \times A_{\text{IF}} \times A_{\text{DF}} \times A_{\text{AWG2}} \\ & \times A_{\text{FF}} \times A_{\text{OLT}})\end{aligned} \tag{5}$$

Connection availability in Equation 1 corresponds to the total probability that the connection is available and is a sum of 4 expressions representing the conditional probabilities that the connection is available. We look through the connection from the ONU towards the OLT. The first two elements correspond to the condition that either Link X_1 or Y_1 (see Fig. 6b) is available. The last two elements represent the conditions where both Link X_1 and Y_1 are available. If neither MFF1 nor MFF2 works, Y_2 has to be available. Otherwise, it is sufficient if either Link X_2 or Y_2 is available.

The unavailability values of devices and fibers are listed in Table II. We consider LR-PON scenario where approximately 80 central offices are replaced by a single one [19] [20]. The fiber lengths in different scenarios (i.e., dense urban,

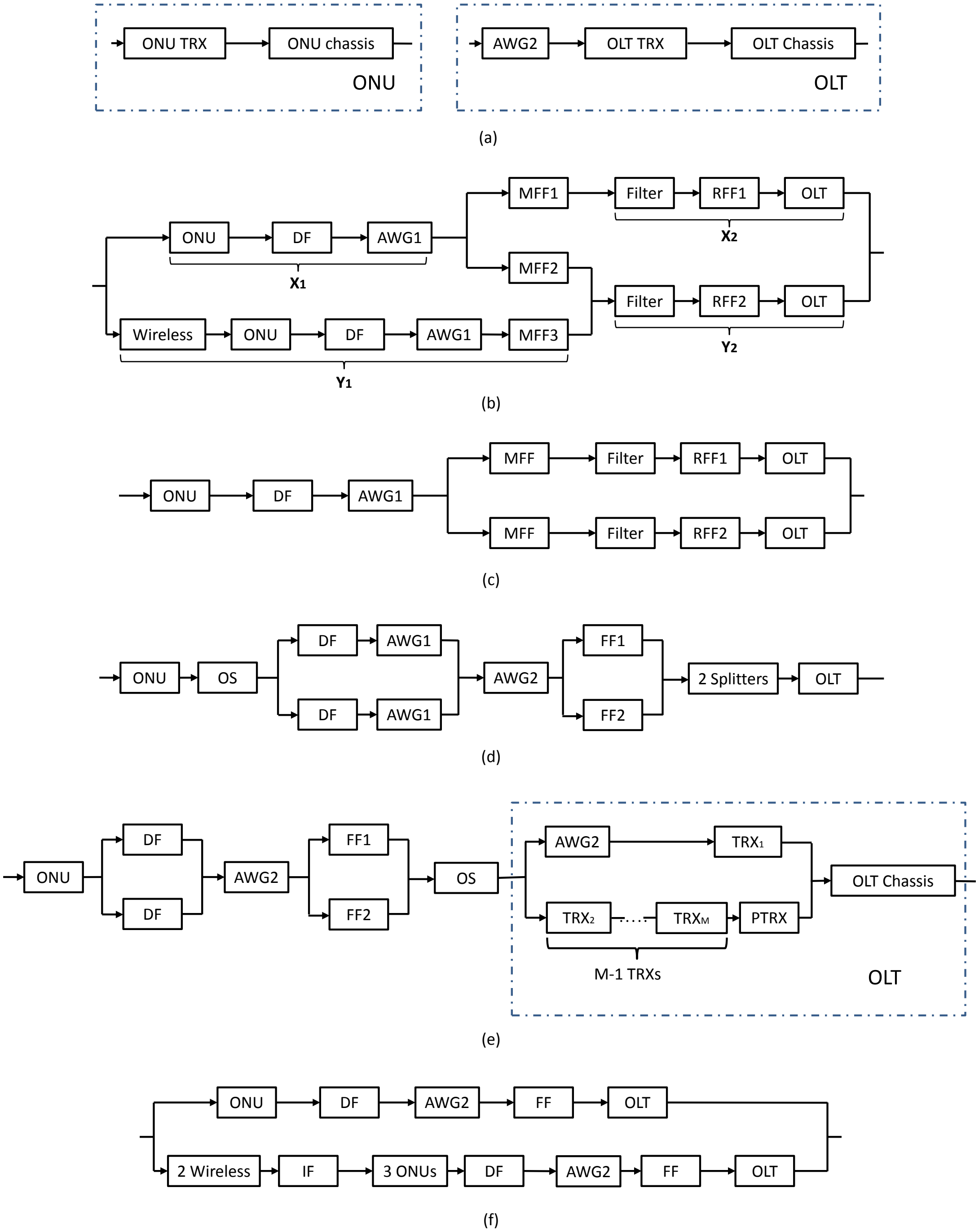


Fig. 6: Reliability block diagrams for (a) ONU and OLT (excluding the one in Scheme 3), (b) Scheme 1, (c) Scheme 1*, (d) Scheme 2, (e) Scheme 3 with 1:M sharing protection at OLT and (f) Scheme 4 with two hops for wireless connection. FF1 denotes working FF, FF2 represents protection FF.

TABLE II: Component/Fiber Unabailability Data and Symbols [17] [18]

Component	Symbol	Unavailability	Component	Symbol	Unavailability
Optical TRX	U_{TRX}=1-A_{TRX}	4×10^{-6}	Tunable Optical TRX	U_{PTRX}=1-A_{PTRX}	1.1×10^{-5}
Optical Switch	U_{OS}=1-A_{OS}	6×10^{-6}	Optical Filter	U_{Filter}=1-A_{Filter}	1.3×10^{-6}
Splitter	$U_{Splitter}$=1-$A_{Splitter}$	10^{-7}	OLT Chassis	$A_{OLTChassis}$	2.2×10^{-5}
Distribution Fiber	U_{DF}=1-A_{DF}	8×10^{-6}/km	Feeder Fiber	U_{FF_i}=1-A_{FF_i}	1.2×10^{-5}/km
AWG (80 channels)	U_{AWG1}=1-A_{AWG1}	6×10^{-6}	AWG (160 channels)	U_{AWG2}=1-A_{AWG2}	9×10^{-6}
Wireless link	$U_{Wireless}$=1-$A_{Wireless}$	3.3×10^{-5}	ONU Chassis	$A_{ONUChassis}$	2.55×10^{-5}
ONU	$A_{ONU}=A_{TRX}\times A_{ONUChassis}$		OLT	$A_{OLT}=A_{TRX}\times A_{AWG2}\times A_{OLTChassis}$	
Link X_1	$A_{X_1}=A_{ONU}\times A_{DF}\times A_{AWG1}$		Link X_2	$A_{X_2}=A_{Filter}\times A_{RFF1}\times A_{OLT}$	
Link Y_1	$A_{Y_1}=A_{Wireless}\times A_{ONU}\times A_{DF}\times A_{AWG1}\times A_{MFF3}$		Link Y_2	$A_{Y_2}=A_{Filter}\times A_{RFF2}\times A_{OLT}$	

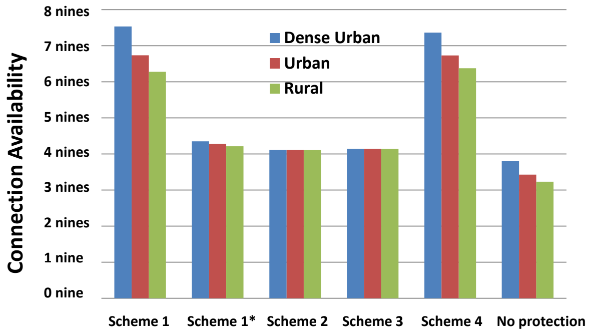


Fig. 7: Connection availability performance for all the considered schemes

urban and rural) are shown in Table III. The similar connection availability results can be obtained in the other LR-PON scenarios where a lower number of central offices are merged. Besides, we assume that each working FF carries 160 wavelengths. . Three different types of service areas are considered, i.e., dense urban, urban and rural, where the rural scenario corresponds to sparsely populated area and hence the fiber is in average longest compared to dense urban and urban scenarios. The results shown in Fig. 7 prove that our scheme with full protection offers the highest connection availability, over 7 nines (99.99999%) in the urban area. Even with only feeder section protected (i.e., Scheme 1^*), our approach still outperforms Scheme 2 and 3 which have protection for both FF and DF. The high availability results in our scheme are due to the protection of the entire OLT. Furthermore, the OLT failure can have an impact on the network reliability performance, which is assessed in the next section.

Moreover, it should be noted that in this paper we do not differentiate the fiber link availability in rural/urban areas while in practice the fiber link availability might be different. However, this difference would not change the general trend of reliability performance for different schemes as shown in Fig. 7.

C. Failure Impact Factor

Failure impact factor (FIF) [12] is a measure, which can reflect a risk that a large number of customers are affected by a single failure. For instance, all the connections in the PON would be down due to an OLT failure, while fault in an ONU would only affect one cell. Thus, by evaluating FIF of different components in PON we can identify the critical parts of the network that should be protected in the first place. The calculation of FIF takes two parameters into account, i.e., number of customers affected by a failure occurring in a certain component or a link (referred to as failure penetration ratio FPR) and its unavailability U, which equals to the probability that it is failed (shown in Table II)

FIF is expressed as:

$$FIF_{\text{component/link}} = FPR_{\text{component/link}} \times U_{\text{component/link}} \quad (6)$$

In general, the higher FIF the larger is impact of the failure. Furthermore, we define the FIF of a connection only considering components and links which are not protected (see Equation 7). It is because if a component or a link is protected, its failure wont affect any customers.

$$FIF_{\text{connection}} = \sum_{i \in unprotected} FIF_{\text{component}_i/\text{link}_i} \quad (7)$$

According to this definition, FIF of a connection in our scheme with full protection (i.e. in Scheme 1) and in Scheme 4 would be zero because there the entire paths are protected. For this reason, we only discuss FIF of a connection in Scheme 1^*, Scheme 2 and 3.

TABLE III: Fiber Length in Different Scenarios [19] [20]

	Fiber Length (km)		
	Working FF	Protection FF	DF
Dense Urban	6	11	1.5
Urban	23	38	2.5
Rural	40	72	3.5

TABLE IV: Comparison of Failure Impact Factor

Scheme 1*	FIF	Scheme 2	FIF	Scheme 3	FIF
ONU	2.55E-05	ONU	2.55E-05	ONU	2.55E-05
DF	2.80E-05	OS	0.60E-05	AWG	0.00144
AWG	0.00048	AWG (M×M)	0.11520	OS	0.00096
		Splitters	0,02560	OLT	0.00496
		OLT	0.44799		
SUM	0.00053	SUM	0.58882	SUM	0.00739

Table III shows the results obtained for rural scenario, i.e., where the FIF is highest among all the considered scenarios.

According to [12] [13], FIF<0.1 (which implies that less than 1000 users would be affected by any failure given that the connection availability is higher than 99.99%) would be an acceptable level from a network operator perspective. Our scheme with only FF protection has obviously lower FIF of connection than the other two considered schemes because the unprotected part is only belonging to one connection. In Scheme 2, FIFs of the OLT and AWG are extremely high because many connections are affected by failures of these components. In this case, a protection for OLT and AWG is recommended since the failure impact is high.

D. Flexibility of protection deployment

According to the FIF results, the impact of failures of ONU and DF is much lower than OLT and FF. Nevertheless, the protection of all ONUs and DFs requires deploying large amount of TRXs (wireless/optical) and fibers. Thus, the operators may prefer to offer ONU and DF protection only optionally to some important connections requiring very high reliability performance (e.g., Macro BSs covering the large areas) in order to avoid big investments, which may not pay off.

TABLE V: Comparison of Protection Capability

	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Protection of FF	Yes	Yes	Yes	Yes
Protection of DF	Optional	Optional	Mandatory	Mandatory
Protection of OLT	Yes	No	Only $m{:}M$ TRX protection	Yes (for feeder protection, half of total capacity should be reserved.)
Protection of SPs	SP1s are always protected, the others are protected if DF protection is offered.	M (1×M/2) AWGs are protected	No	Yes
Protection of ONU	Optional	No	No	Yes

The comparison of flexibility to offer protection capability is shown in Table IV. All the schemes can provide protection for FF and DF but protection of OLT or some components in SPs is not always available. Schemes 3 and 4 have to provide full protection (i.e., both DF and FF protection) to all the users. It means that either all the supported cells have full protection or no protection at all. Scheme 2 can be upgraded from only FF protection to FF+DF protection for some selected cells by adding extra OSs and fibers interconnecting two neighboring ONUs, which requires expensive civil work. However, in our scheme, we can flexibly offer protection either to the SP1s or all the way down to the cell, according to the reliability requirement of a certain connection. Besides, the operator may install the TRXs wherever and whenever ONU and DF protection is needed. As the BSs are already deployed, the extra cost for upgrading protection includes only the optical TRXs and wireless connection setup. It can be considered as an important advantage for our scheme since it enables operators to have a flexible solution to meet the diverse reliability requirements without need of paying high cost for the protection upgrade.

IV. CONCLUSION

In this paper, we propose a hybrid fiber and microwave protection scheme for PON-based mobile backhauling. The novel architecture employs microwave connection and dual-homed FF which are used for distribution and feeder section protection, respectively.

We analyzed the complexity, flexibility and reliability performance of the proposed approach and compared with several existing solutions. The results confirm that our scheme with full protection shows significantly higher reliability performance than Scheme 2 and 3 while achieving the similar connection availability as Scheme 4. Moreover, it is shown that our scheme with only protection of the feeder section can still maintain an acceptable level of connection availability. By calculating the FIF of unprotected parts of connections we also demonstrated that some optical devices that are shared among many cells (e.g., OLT and AWG) need protection to avoid a risk that many users will be affected by a single failure. It is commendable that our scheme can provide end-to-end protection with relatively low complexity compared to the other evaluated schemes. In addition, our scheme gives the operators the flexibility to install protection in the distribution section according to the various reliability performance requirements.

Therefore, our approach can be considered as a reliable and flexible solution, which is able to adapt to high capacity demand of future mobile backhauling.

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REFERENCES

[1] Qualcomm Incorporated (2013, June), The 1000x data challenge, available on http://www.qualcomm.com/1000x/.

[2] T. Naveh, Mobile backhaul: fiber vs. microwave: Case study analyzing various backhaul technology strategies, white paper, Ceragon Network Ltd., Oct. 2009.

[3] P. Monti, S. Tombaz, L. Wosinska, and J. Zander, Mobile backhaul in heterogeneous network deployments: Technology options and power consumption, *in 14th International Conference on Transparent Optical Networks (ICTON)*, July 2012.

[4] D. Breuer, F. Geilhardt, R. Hulsermann, M. Kind, C. Lange, T. Monath, E. Weis, "Opportunities for next-generation optical access," *IEEE Commun. Mag.*, vol.49, pp.s16-s24, Feb. 2011.

[5] D. P. Shea, and J. E. Mitchell, Long-reach optical access technologies, *IEEE Network*, vol. 21, no. 5, pp. 5-11, Sept. 2007.

[6] J. Chen, C. M. Machuca, L. Wosinska, and M. Jaeger, Cost vs. Reliability Performance Study of Fiber Access Network Architectures, *IEEE Commun. Mag.*, vol. 48, No. 2, pp.56-65, Feb. 2010.

[7] Z. X. Wang, X. F. Sun, C. L. Lin, C. K. Chan, and L. K. Chen, A novel centrally controlled protection scheme for traffic restoration in WDM passive optical networks, *IEEE Photon. Technol. Lett.*, vol. 17, no. 3, pp. 717719, Mar. 2005.

[8] K. Lee, S. B. Lee, J. H. Lee, Y. G. Han, S. G. Mun, S. M. Lee, and C. H. Lee, A self-restorable architecture for bidirectional wavelength-division-multiplexed passive optical network with colorless ONUs *Opt. Express*. vol. 15, no. 8, pp. 4863-4868, Apr. 2007.

[9] Broadband optical access systems based on Passive Optical Networks (PON), ITU-T Recommendation G983.1, 2005.

[10] J. Chen, L. Wosinska, M. N. Chughtai, and M. Forzati, Scalable passive optical network architecture for reliable service delivery, *J. Opt. Commun. Netw.*, vol. 3, no. 9, pp. 667673, Aug. 2011.

[11] H. Fan, J. Li, and X. Sun, Cost-effective scalable and robust star-cross-bus PON architecture using a centrally controlled hybrid restoration mechanism, *J. Opt. Commun. Netw.*, vol. 5, no. 7, pp. 730740, July 2013.

[12] M. Mahloo, A. Dixit, J. Chen, C. Carmen, M. Machuca, B. Lannoo, and L. Wosinska, Towards reliable hybrid WDM/TDM passive optical networks, *IEEE Commun. Mag.*, accepted.

[13] A. Dixit, B. Lannoo, D. Colle, M. Pickavet, J. Chen and M. Mahloo, Efficient protection schemes for hybrid WDM/TDM passive optical networks, *IEEE International Conference on Communications (ICC)*, Workshop on New Trends in Optical Networks Survivability, June 2012.

[14] S. Sarkar, H.-H. Yen, S. Dixit, and B. Mukherjee, RADAR: risk-and-delay aware routing algorithm in a hybrid wireless-optical broadband access network (WOBAN), *in Optical Fiber Communication Conf. and the Nat. Fiber Optc Engineers Conf. (OFC/NFOEC)*, 2007, OThM4.

[15] T. Feng, and L. Ruan, Design of a survivable hybrid wireless-optical broadband access network, *J. Opt. Commun. Netw.*, vol. 3, no. 5, pp. 458464, May. 2011.

[16] K. Iwatsuki, and J-i. Kani, Applications and Technical Issues of Wavelength-Division Multiplexing Passive Optical Networks With Colorless Optical Network Units, *J. Opt. Commun. Netw.*, vol. 1, no. 4, pp. C17C24, Sep. 2009.

[17] Private communication with industry partners in ICT-DISCUS project.

[18] J. Chen, Efficient Resiliency Mechanisms for Next Generation Passive Optical Networks, *in the 9th International Conference on Information, Communications and Signal Processing (ICICS)*, Dec. 2013.

[19] C. M. Machuca, K. Wang, M. Kind, and K. Casier, Total cost comparison of next generation optical access networks with node consolidation, *in the 17th European Conference on Networks and Optical Communications (NOC)*, June 2012.

[20] OASE deliverable D5.1: Overview of tools and methods, May 2011.