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A novel survivable architecture for hybrid WDM/TDM passive optical networks

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ABSTRACT

A novel tree–ring survivable architecture, which consists of an organization of a wavelength-division-multiplexing (WDM) tree from optical line terminal (OLT) to remote nodes (RNs) and a time division multiplexing (TDM) ring in each RN, is proposed for hybrid WDM/TDM passive optical networks. By utilizing the cyclic property of arrayed waveguide gratings (AWGs) and the single-ring topology among a group of optical network units (ONUs) in the remote node, not only the feeder and distribution fibers, but also any fiber failures in the RN rings are protected simultaneously. Five-Gbit/s transmissions under both normal working and protection modes were experimentally demonstrated and a traffic restoration time was successfully measured.

1. Introduction

The hybrid WDM/TDM passive optical network (PON) is considered a promising candidate solution to broadband access networks by enabling a delivery of high speed services to subscribers with a low unit cost, since it combines the high-speed transmission property of WDM technology and the low cost characteristics of TDM technology [1]. However, the conventional PON architecture can provide only limited protection feature [2], which may induce enormous data loss due to any fiber failure and thus greatly reduces the reliability of the whole network. Therefore, many schemes have been proposed to provide protection and restoration functions for PONs [3–15]. In [3–7], survivable WDM PONs with tree topology were realized either through the periodic wavelength routing properties of AWGs [3–5] or the self-protection between the grouped ONUs [6,7], which required optical switches at the ONUs. When a fiber failure happened, the transmission on the failed link could be rerouted to its protection link either via AWGs [3–5] or via the back-up ONUs [6,7]. Ring architectures have also been proposed to provide protection features for PONs, adopting either double-ring topology [8,9] or single-ring topology [10–12]. In such architectures, either the second fiber ring of the two fiber rings or the second transmission direction on the single fiber ring is utilized for the protection traffic. In [13], a star–ring architecture was proposed to provide survivability for a metro WDM network, in which a double-ring structure was used. However, most of the above mentioned schemes are specially designed for WDM PONs, which may exceed the budget constraints of cost-sensitive access networks with increased number of stages and ONUs. In [14,15], a cost effective survivable hybrid wireless-optical access network was proposed. By interconnecting a subset of ONUs through a wireless mesh network, the protection feature of PONs could be relieved, since the traffic restoration was partly done by wireless network. However, due to the complexity of a wireless network, a complicated algorithm may be needed to recover traffic. Besides, the wireless network may limit the traffic speed. Therefore, a survivable hybrid WDM/TDM PON, which can provide both high speed services with a low unit cost and also avoid enormous loss in data and business due to any possible fiber failure, is highly desirable [16]. Recently, several interesting schemes [17–23] have been proposed to provide survivability in hybrid WDM/TDM PONs. In [17], a hybrid WDM/TDM PON with tree architecture was proposed, in which an optical line terminal was located at the root of the tree and the ONUs at the leaves. By duplicating the link from the root to the leaves, failed traffic on the working path could be rerouted onto the duplicated protection link to recover the data. But in order to protect the whole network, a large amount of extra fiber links were needed. Another network accommodating both TDM PONs and WDM PONs in the same fiber infrastructure was proposed in [18]. Any failure in either feeder fiber or distribution fibers in this architecture could be protected, but the optical fibers and switches were doubled in order to provide a protection path for each service. A simpler passive protection structure in a ring-type hybrid WDM/TDM PON was proposed in [19]. Although much less

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duplicated fiber links or optical switches were needed, only feeder fibers were protected in the scheme. In [20,21], a ring–tree hybrid WDM/TDM PON was proposed. By using a ring topology to interconnect WDM-based OLTs and employing a tree topology to interconnect TDM-based ONUs, feeder fibers could be protected, but the distribution fibers from remote node (RN) to ONUs could not be cost-effectively protected. In order to realize the simultaneous protection for feeder and distribution fibers, architectures employing mutual protection between two adjacent ONUs were proposed in [22,23]. The architecture could reduce the protection cost by omitting some of the protection distribution fibers. However, some extra fibers were needed to interconnect adjacent ONUs.

In this paper, we propose and demonstrate a tree–ring survivable architecture for hybrid WDM/TDM PONs. Different from the WDM-ring based architecture proposed in [24], we reconstructed the ONUs when employing a single-ring topology among a group of them in the RN to realize a self-protection function for the whole network. Our proposed architecture can successfully not only protect a failure in either feeder or distribution fibers, but also protect any fiber failure in the RN rings. In addition, the single ring topology can reduce the number of protection fibers as well as the cost compared with [18]. We have experimentally demonstrated 5-Gbit/s transmissions both in normal working and protection modes and a fast traffic restoration has been achieved.

2. Proposed survivable architecture for WDM/TDM passive optical networks

Fig. 1(a) depicts the proposed survivable WDM/TDM hybrid PON with $N \times M$ ONUs, where N is the number of TDM RNs, and M is the number of ONUs a single TDM ring accommodates via a same pair of wavelengths at the TDM RN, say (λ_i, λ_i') used for the downstream and upstream transmissions, respectively, in the TDM ring at TDM RN #i. At the OLT, continuous wave light source λ_k (for $k=1,2,\ldots,N$) from the downstream transmitter #k is first fed into a Mach–Zehnder intensity modulator (IM) driven by the downstream data for TDM RN #k before combined with other modulated downstream wavelengths via a $N \times 1$ AWG. The combined downstream wavelengths are then delivered to the destined TDM RNs via a fiber feeder (either F1 or F2) after amplified by a bidirectional Erbium-doped fiber amplifier (EDFA), which can be constructed by two conventional EDFAs and two optical circulators. F1 and F2 are connected to the ith and $(N+i)$th input ports of a $2 \times 2N$ AWG respectively, whose ith and $(N+i)$th output ports are connected to TDM RN #i via a 2×2 optical coupler. Under the normal working mode, the downstream wavelengths will be delivered via the fiber feeder F1 and destined to the TDM RNs after demultiplexed via the $2 \times 2N$ AWG. If a fiber failure occurs at any point between OLT and the TDM RN, power loss can be detected by the monitoring unit (M_0), which triggers a 1×2 optical switch at the OLT and switches downstream wavelengths to F2, which is employed as the protection path. At the TDM RN, the downstream wavelength is fed into the TDM ring composed of M ONUs, and broadcast to all ONUs. An ONU, as shown in Fig. 1(b), is simply composed of a 2×2 optical switch, optical coupler, optical circulator, monitoring unit (M_1), receiver and transmitter. When the downstream wavelength is fed into an ONU via the input port, part of the downstream power is dropped by the coupler for receiving and detection, while the remaining power passes through the ONU and will be utilized by other ONUs. The upstream transmission from an ONU is added to the TDM ring via the optical circulator. In order to avoid collision in the upstream transmission, only one ONU in the ring can transmit upstream data in a single allocated time slot, which is typical in a TDM PON. Besides the protection provided against any fiber failure between the OLT and the TDM RN, the network can also provide protection against any fiber failure in the TDM ring at a TDM RN. In a TDM

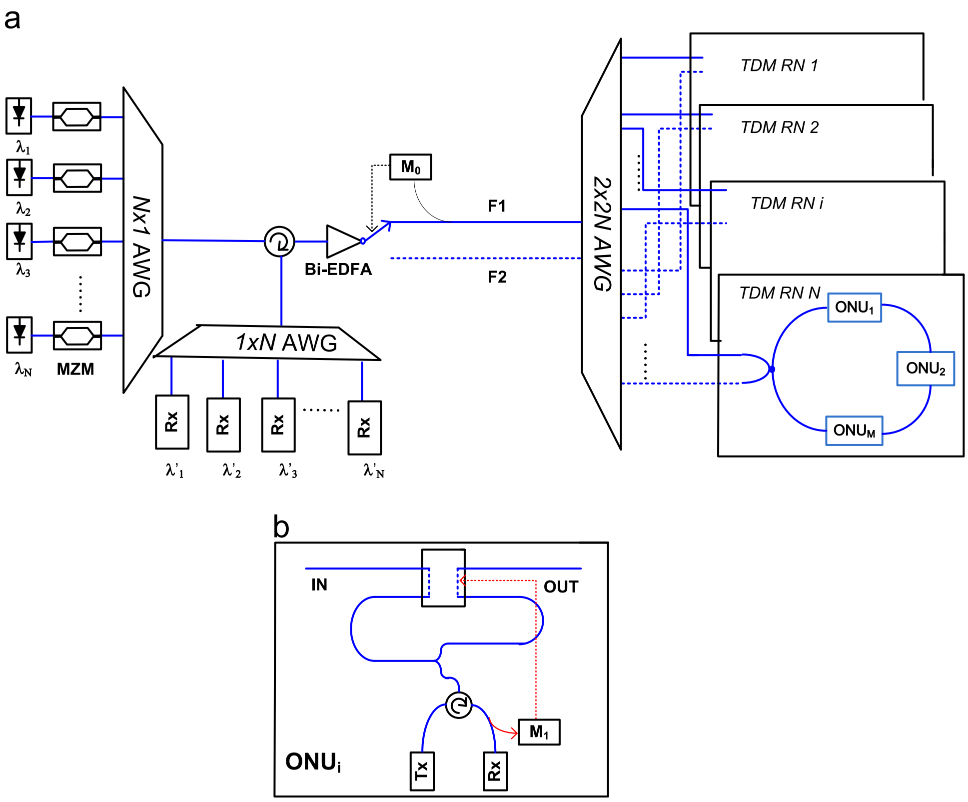

Fig. 1. Proposed survivable architecture for WDM/TDM passive optical networks. (a) Configuration of the proposed network and (b) schematic diagram of the ONU module. M: monitoring unit.

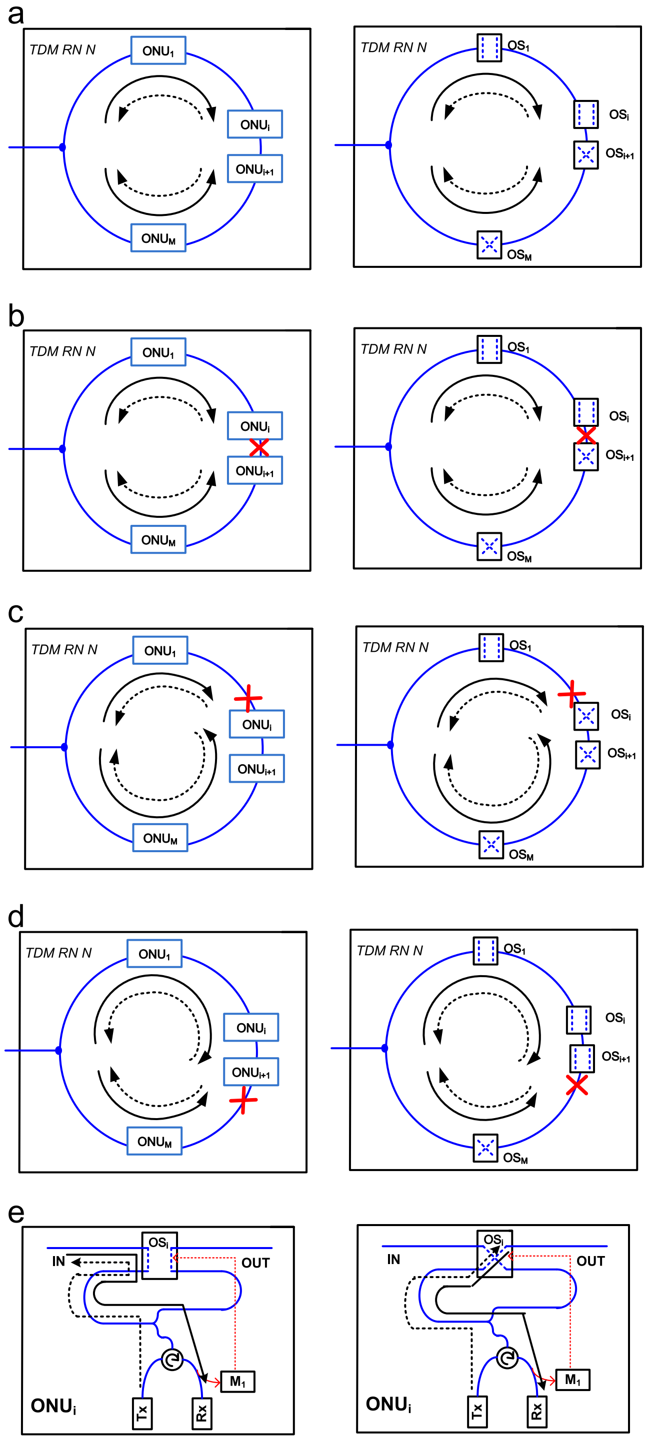

Fig. 2. Traffic in a TDM RN ring composed of M ONUs and the configuration of the OS in each ONU. (a) Traffic and the configuration of the OS in the corresponding ONUs under normal working mode. (b) Traffic and the configuration of OS in the corresponding ONUs when a fiber cut occurs between ONU_i and ONU_{i+1}. (c) Traffic and the configuration of OS in the corresponding ONUs when a fiber cut occurs between ONU_1 and ONU_i. (d) Traffic and the configuration of OS in the corresponding ONUs when a fiber cut occurs between ONU_{i+1} and ONU_M. (e) Routing paths of the downstream and upstream traffic in an ONU when its OS is in different states. OS: 2 × 2 optical switch. Solid and dashed arrows show the routing paths of the downstream and upstream traffic, respectively.

ring, ONUs are located one after another in clockwise (CW) direction, which means ONU_i (for $i=2,3,\ldots,M-1$) is connected with ONU_{i-1} via its input port, while it is connected with ONU_{i+1} via its output port as shown in Fig. 1(a).

Fig. 2 shows the traffic in a TDM RN ring composed of M ONUs and the configuration of the 2 × 2 optical switch (OS) in each ONU. In the ring, ONUs are first divided into two groups. The first group contains the ONUs from ONU_1 to ONU_i. The second group contains the remaining ONUs, from ONU_{i+1} to ONU_M. In the first ONU group, the OSs are set into bar state, while the OSs in the second group are set into cross state. Under normal working mode, as shown in Fig. 2(a), the downstream and upstream transmissions in the first ONU group propagate in CW and counterclockwise (CCW) directions, respectively, while the transmissions in the second group propagate in the opposite directions. When a fiber cut occurs between ONU_i and ONU_{i+1}, as shown in Fig. 2(b), no power loss will be detected by any ONU and the transmissions are kept unaffected. Therefore, no protection switching is triggered. When a fiber cut occurs in the first ONU group, say between ONU_{i-1} and ONU_i, as shown in Fig. 2(c), the OSs in the ONU group placed behind the failure point in CW direction are all changed from bar state to cross state while the OSs in the ONU group placed before the failure point in CW direction are kept in bar state. Thus, OS_j (for $j=1,2,\ldots,i-1$) are kept in bar state, while OS_j is changed into cross state. In this way, the traffic before the failure point remains unaffected, while the traffic behind the failure point changes its original transmission direction: downstream transmission propagates along CCW direction and upstream transmission along CW direction. When a fiber cut occurs in the second ONU group, say between ONU_{i+1} and ONU_{i+2}, as shown in Fig. 2(d), the OSs in the ONU group placed before the failure point in CW direction are all changed from cross state to bar state while the OSs in the ONU group placed behind the failure point in CW direction are kept in cross state. Thus, the OS_{i+1} is changed into bar state, while OS_j (for $j=\mathrm{i}+2,\mathrm{i}+3,\ldots,M$) are kept in cross state. In this way, the traffic behind the failure point remains unaffected, while the traffic before the failure point changes its original transmission direction: downstream transmission propagates along CW direction and upstream transmission along CCW direction. From the analysis above, the affected traffic due to the fiber cut is quickly recovered and the survivability of the whole network is assured.

3. Experimental demonstration

Fig. 3 shows the setup of our proof-of-concept experiment for the proposed WDM/TDM hybrid PON. A continuous wave light source at 1546.9 nm was intensity-modulated by a 5-Gbit/s $2^{31}-1$ pseudorandom binary sequence (PRBS) downstream data before fed into a 1 × 16 AWG, which was used to emulate a WDM channel for the TDM ring at the TDM RN. The downstream data were then amplified to about 6 dBm before fed into a 20 km dispersion shift fiber (DSF). DSF was employed to emulate a dispersion compensated transmission path. It could be replaced by a standard single-mode fiber with dispersion compensating module. The downstream data were delivered to the TDM ring either via DSF1 in the normal working mode or via DSF2 in case of a fiber cut in DSF1. The protection switching was realized by the 1 × 2 optical switch controlled by the monitoring unit M_0. At the TDM RN, the downstream data were fed into the TDM ring comprising two ONUs via a 2 × 2 optical coupler. OS_1 in the ONU_1 was set into bar state, while the OS_2 in the ONU_2 was set into cross state. In the normal working mode, the downstream data were passed to ONU_1 and ONU_2 along CW and CCW directions, respectively, while the upstream 5-Gbit/s $2^{31}-1$ PRBS data, which were intensity modulated onto the upstream continuous wave at 1559.7 nm via another IM at the transmitter module in each ONU, propagated in opposite direction. When a fiber cut occurred as shown in Fig. 3, the loss of downstream power in ONU_2 triggered the monitoring unit (M_1), which changed the 2 × 2 optical switch OS_2 into bar

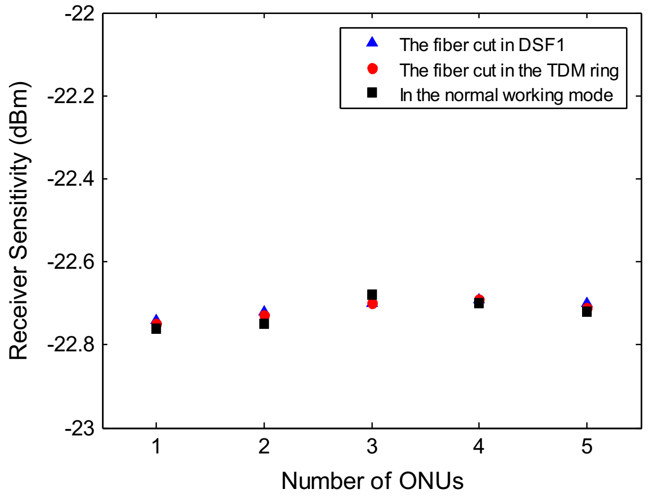

Fig. 7. Receiver sensitivity (at BER$=10^{-9}$) for ONU_2.

monitoring unit M_0, as shown in the inset of Fig. 6. The different switching time between M_0 and M_1 is mainly attributed to the different optical switches we used in the experiment. The similar BER performances observed in both normal working and protection modes imply negligible degradation caused by connection switching due to the abrupt fiber cut.

In our experiment, the power fed into transmission link was about 6 dBm, for downstream data. The losses caused by transmission, optical circulator, optical coupler (with the splitting ratio of 50:50) and optical switch were around 5 dB, 0.5 dB, 3 dB and 0.5 dB respectively. Thus the power for downstream data detection at ONU_2 was around -9 dBm, providing more than 13 dB system margin. By using an amplifier before a multiplexer, the system can provide enough power margin for the upstream transmission.

We have also investigated the receiver sensitivity of ONU_2, when more ONUs were located between ONU_1 and ONU_2 by simulation, as shown in Fig. 7. When the total number of ONUs is less than 5, the power budget is enough for every ONU either in normal working mode or in protection mode even for the worst case. The receiver sensitivity has negligible change with the increased number of ONUs, except less than 0.5 dB difference from that in the real experiment. However, with further increased number of ONUs, the BER performance will decrease, since there is not enough power fed into the receiver to reach the power for a required BER performance (e.g. BER$=10^{-9}$). By adjusting the splitting ratio of the 1×2 optical coupler placed in the ONUs, the number of ONUs with the required BER performance could be increased to 10 when the splitting ratio was set as 10:90. In addition, this number of ONUs with the required BER performance can be further increased by either inserting a preamplifier at the receiver side or increasing the power fed into the TDM ring.

4. Summary

We have proposed and experimentally investigated a novel survivable WDM/TDM PON architecture. By using TDM rings for ONUs in the RN, the survivable protection architecture can simultaneously protect against the distribution and feeder fiber failures as well as the fiber failures in the ring. Error-free transmissions at BER$=10^{-9}$ for downstream and upstream in either working or protection mode were successfully demonstrated.

References

[1] D. Shin, D. Jung, H. Shin, J. Kwon, S. Hwang, Y. Oh, C. Shim, IEEE/OSA Journal of Lightwave Technology 23 (1) (2005) 187.
[2] Broadband Optical Access Systems Based on Passive Optical Network (PON), ITU-T Recommendation G.983.1, 2005.
[3] E.S. Son, K.H. Han, J.H. Lee, Y.C. Chung, Survivable network architectures for WDM PON, in: Proceedings of the IEEE/OSA Optical Fiber Communication Conference/National Fiber Optic Engineers Conference (OFC/NFOEC), Paper OFI4, Anaheim, California, USA, 2005.
[4] Arshad Chowdhury, M.F. Huang, H.C. Chien, Georgios Ellinas, G.K. Chang, A self-survivable WDM-PON architecture with centralized wavelength monitoring, protection and restoration for both upstream and downstream links, in: Proceedings of the IEEE/OSA Optical Fiber Communication Conference/National Fiber Optic Engineers Conference (OFC/NFOEC), Paper JThA95, 2008.
[5] Arshad Chowdhury, Hung-Chang Chien, Shu-Hao Fan, Cheng Liu, Charles Su, Gee-Kung Chang, A survivable protection and restoration scheme using wavelength switching of integrated tunable optical transmitter for high throughput WDM-PON system, in: Proceedings of the IEEE/OSA Optical Fiber Communication Conference/National Fiber Optic Engineers Conference (OFC/NFOEC), Paper OThK6, 2011.
[6] T.J. Chan, C.K. Chan, L.K. Chen, F. Tong, IEEE Photonics Technology Letters 15 (11) (2003) 1660.
[7] X.F. Sun, C.K. Chan, L.K. Chen, IEEE Photonics Technology Letters 18 (4) (2006) 631.
[8] B. Glance, C.R. Doerr, I.P. Kaminow, R. Montagne, IEEE/OSA Journal of Lightwave Technology 14 (11) (1996) 2453.
[9] C.H. Kim, C.-H. Lee, Y.C. Chung, IEEE Photonics Technology Letters 10 (1998) 1340.
[10] Y.H. Joo, G.W. Lee, R.K. Kim, S.H. Park, K.W. Song, J. Koh, S.T. Hwang, Y. Oh, C. Shim, IEEE Photonics Technology Letters 16 (2004) 683.
[11] S.B. Park, C.H. Lee, S.G. Kang, S.B. Lee, IEEE Photonics Technology Letters 15 (2003) 1657.
[12] X.F. Sun, C.K. Chan, Z.X. Wang, C.L. Lin, L.K. Chen, IEEE Journal on Selected Areas in Communications 25 (4) (2007) 18.
[13] Martin Maier, Martin Reisslein, IEEE Communications Magazine 42 (11) (2004) s19.
[14] Taiming Feng, Lu Ruan, Journal of Optical Communications and Networking 3 (5) (2011) 458.
[15] Navid Ghazisaidi, Michael Scheutzow, Martin Maier, IEEE Transactions on Reliability 60 (2) (2011) 479.
[16] Jiajia Chen, Lena Wosinska, Carmen Mas Machuca, Monika Jaeger, IEEE Communications Magazine 48 (2) (2010) 56.
[17] Abhishek Dixit, Bart Lannoo, Didier Colle, Mario Pickavet, Jiajia Chen, Mozhgan Mahloo, Efficient protection schemes for hybrid WDM/TDM passive optical networks, in: Proceedings of the 2012 IEEE International Conference on Communications (ICC), June 2012, pp. 6220–6224.
[18] Jong Hoon Lee, Ki-Man Choi, Jung-Hyung Moon, Sil-Gu Mun, Jun-Young Hoon-Keun Lee, Kim, Chang-Hee Lee, IEEE/OSA Journal of Lightwave Technology 27 (19) (2009) 4311.
[19] Dong-Min Seol, Eui-Suk Jung, Byoung-Whi Kim, A simple passive protection structure in a ring-type hybrid WDM/TDM-PON, in: Proceedings of the 11th International Conference on Advanced Communication Technology, ICACT, 2009, pp. 447–449.
[20] Josep Prat, Jose Lazaro, Philippe Chanclou, Risto Soila, Pantelis Velanas, Antonio Teixeira, Giorgio Tosi Beleffi, Ioannis Tomkos, Dimitrios Klonidis, Hybrid ring–tree WDM/TDM-PON optical distribution network, in: Proceedings of the 11th International Conference on Transparent Optical Networks (ICTON), July 2009, Th.B3.1.
[21] Martin Maier, Martin Herzog, Martin Reisslein, IEEE Communications Magazine 45 (5) (2007) 50.
[22] Jiajia Chen, Lena Wosinska, Sailing He, IEEE Photonics Technology Letters 20 (6) (2008) 389.
[23] Jiajia Chen, Lena Wosinska, Performance analysis of protection schemes compatible with smooth migration from TDM-PON to hybrid WDM/TDM-PON, in: Proceedings of the IEEE Optical Fiber Communication Conference/National Fiber Optic Engineers Conference, 2007, JWA85.
[24] Kostas Ramantas, Kyriakos Vlachos, Georgios Ellinas, Antonis Hadjiantonis, Efficient resource management via dynamic bandwidth sharing in a WDM-PON ring-based architecture, in: Proceedings of the 14th International Conference on Transparent Optical Networks (ICTON),2012, Tu.C3.4.