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PROaccess: A Passive-Components-based Reconfigurable WDM-TDM Optical Access Network

Nguyen-cac TRAN[1], Eduward TANGDIONGGA[1], and Ton KOONEN[1]

[1]*Eindhoven University of Technology, Den Dolech 2, Eindhoven, 5600MB, The Netherlands
Tel: +31-40-247-5066, Fax: +31-40-245-5197, Email:c.tran.nguyen@tue.nl*

Abstract: The evolution of optical access networks have focused on improving their transmission capacity by increasing transmission bit rate per wavelength and number of wavelengths per fibre. However, the huge aggregated capacity is composed by separate bandwidth pools in which each wavelength channel is an independent pool. As a result, some wavelengths may be congested while others are underutilization. In order to allow the system capacity to be a single bandwidth pool, the wavelength reconfigurability is required in which an user can be relocated to another wavelength if the current wavelength is congested. Adding reconfigurable feature also adds complexity, hence CAPEX and OPEX to the networks. Therefore, networks operators up to now have been reluctant despite of benefits of the flexible bandwidth delivery. In this paper, we propose a cost-effective, reconfigurable optical access network by employing passive network components in the remote node and dual conventional optical transceivers in ONUs. The novel approach allows outside plant totally passive and ONUs without tunable filters and lasers. Despite of using only passive and non-tunable components, it still attains a superior flexibility. The architecture is demonstrated with the bidirectional transmission at 10 Gb/s symmetrically.

Keywords: Reconfigurable, WDM-TDM, Optical Access Networks

1. Introduction

Optical access networks are widely deploying to replace copper-based access networks. The fast-growing demand from the end-users is the driving force behind this wide scale replacement. The availability of high-speed connections to the end-users in turn inspires folks to come up with interesting, useful, and bandwidth-consuming applications, e.g., 3D YouTube, BitTorrent, and Immersive TV. This cycle forces optical access networks to further upgrade their capacity by increasing the transmission bit rate per wavelength and the number of wavelengths per fiber. However, the huge aggregated capacity of the system now raises an issue of network resource under utilization since user demands are highly fluctuating. Thus, intelligent features such as optical reconfigurability are introduced to efficiently utilize network resources [1]. By the optical reconfigurability, it means that an ONU can be reallocated to another wavelength channel in the system if required.

Figure 1 shows the system blocking probability for a static WDM access network and a fully flexible WDM access network. The fully flexibility means an ONU in such networks can be relocated to any other wavelength if the current wavelength is congested. Both networks have the same aggregated capacity, i.e., 16 wavelength channels, 1.25 Gbps per wavelength and 512 users. The upper bounds of system blocking probabilities are calculated for two types of user requests, i.e., 63Mbps/request and 125 Mbps/request and
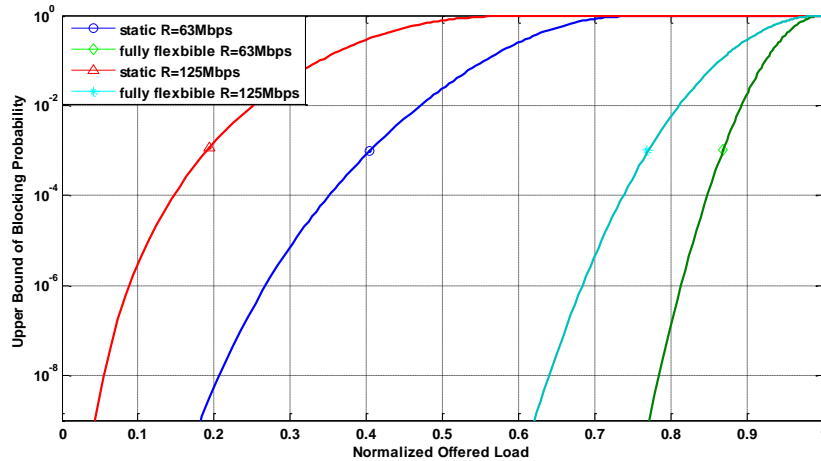
Figure 1: Blocking probability upper bound as a function of offered load normalized to aggregated system capacity for static and fully flexible system with 16 wavelength channels and 1.25 Gb/s per channel

the request birth and death rate follows Poisson stochastic process. The plots show that the fully flexible network significantly reduces blocking probability. If maximum acceptable blocking probability is 1 percent, the fully flexible network can accommodate much more loads, e.g., 2 to 3 times to the static one in this case. In the other word, it means that the network resource utilization is dramatically improved, hence the network operator revenue.

Reconfigurable optical access networks could be classified based on the location where network reconfigurability is handled: at the remote node (RN) by the wavelength routing [2][3][4] or at the optical network units (ONUs) by the wavelength selection [5]. In the wavelength routing option, optical active components are used in RN for routing wavelengths using ring resonators [3], or SOA-array [2]. The use of active components removes the passive merit of the optical distribution network (ODN). The active RN requires a power supply and a temperture control. The wavelength selection option, on the other hand, keeps ODN compartible with existing passive optical access networks (PONs). A strait forward method is using a passive power splitter in the RN to broadcast all wavelength channels to every ONU, then one of them is selected by a tunable filter and a tunable laser [5]. Passively broadcasting wavelengths requires extremely high power budget, which may lead to the use of an optical power amplifier, which is undesirable for a passive RN. Furthermore, the tunable filter and the tunable laser leading to an expensive and less reliable ONU. Therefore, despite the benefits of flexible bandwidth distribution, the reconfigurable optical access is not attractive yet for network operators.

In this paper, we propose a passive-components-based reconfigurable optical access network or PROaccess in which ONUs could be relocated in a subset of two wavelength channels (each channel contains a downstream and an upstream wavelength). However, these subsets overlap in order to enable flexible bandwidth rearrangement. By this rearrangement mechanism, PROaccess is able to achieve performance close to fully flexible networks where ONUs could be relocated to any wavelength in the system.

2. Passive-components-based Reconfigurable Architecture

Figure 2 shows the proposed architecture in which optical line terminal (OLT) transmits two wavelength bands. The lower band contains *M* continuous wave (CW) wavelengths for upstream (US) reflective modulation at the ONU side and the higher band contains *M* data-
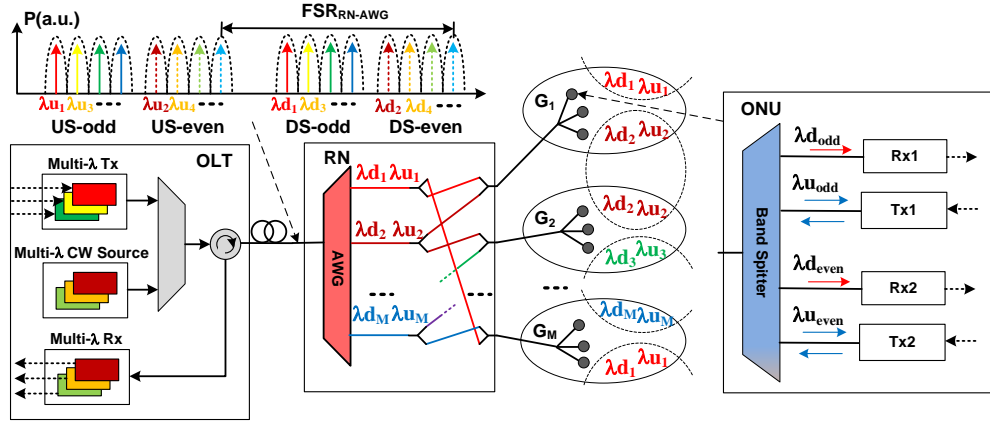
Figure 2: Representative cyclic reconfigurable optical access architecture in which wavelength pairs are demultiplexed and then cyclically combined at the remote node
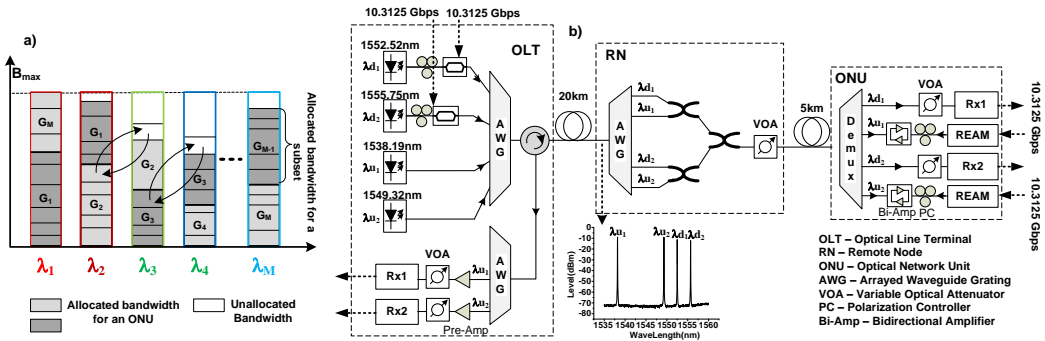

Figure 3: a) Concept of bandwidth rearrangement where unallocated bandwidths are shifted toward a hot spot, b) Experimental setup demonstrating cyclic reconfiguration, as a subset of the system described in Figure 2

modulated wavelengths for downstream (DS) transmission. Each US wavelength has a corresponding DS one where the spectral distance is one free spectral range (FSR) of the arrayed waveguide grating (AWG) in the RN. As a result, the wavelength pair appears at the same port of the AWG. An output of the AWG is split into two branches, one branch combines with previous-index wavelength pair and the other branch combines with next-index wavelength pair in an interleaving and cyclic manner. For example, wavelength pair $(\lambda d_1, \lambda u_1)$ is split and combined with wavelength pairs $(\lambda d_M, \lambda u_M)$ and $(\lambda d_2, \lambda u_2)$. The following pair $(\lambda d_2, \lambda u_2)$ is split and combined with $(\lambda d_1, \lambda u_1)$ and $(\lambda d_3, \lambda u_3)$ as depicted in Figure 2. Thus, each RN output port could serve one subgroup of ONUs with two wavelength pairs by employing a power splitter.

Since the US band is further divided into odd-index and even-index sub-bands and the same for the DS band, the band splitter at the ONU side is designed to demultiplex four sub-bands to separate ports. Therefore, an ONU is able to demultiplex four received wavelengths to the appropriate ports because no wavelength falls to the same sub-band. The ONU electrically selects to operate on one wavelength pair or even both of them. This configuration allows ONU to be wavelength-agnostic while avoiding the use of tunable filters and tunable lasers at the ONU which are less stable and more costly.

One of the advantages of this architecture is that the wavelength pairs are cyclically interleaved among ONU subgroups which allow system-wide allocated bandwidth rearrangement as visualized in Figure 4.a). For convenience in the figure, $(\lambda d_x, \lambda u_x)$ wavelength pair is denoted as λ_x. For example, subgroup G_1 demands more bandwidth
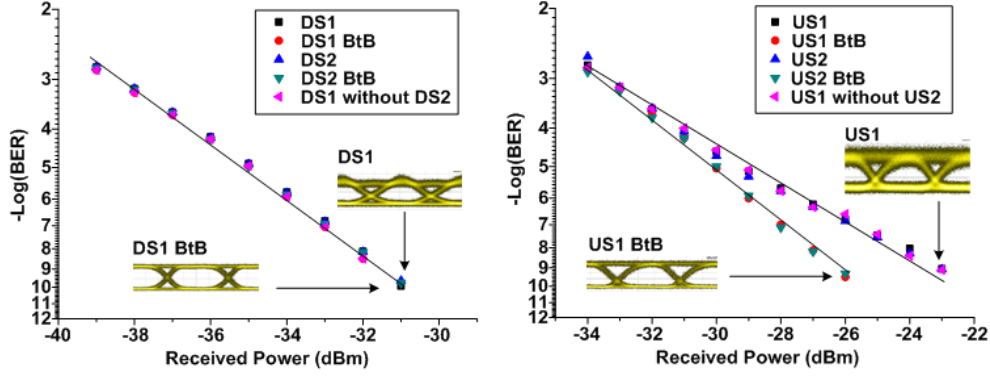
Figure 4: Receiver performance for downstream (left) and upstream (right) channels

which neither λ_1 nor λ_2 can provide. Thus, the system performs bandwidth rearrangement by relocating one or more ONUs in G_2 from λ_2 to λ_3, hence virtually the available (unallocated) bandwidth from λ_3 is shifted to λ_2 in order to provide to G_1. Available bandwidth from a wavelength can reach any other wavelength by several shifting steps because in general available bandwidth from a wavelength can be shifted to any adjacent wavelengths. Therefore, by rearranging feature the performance of PROaccess is close to that of fully reconfigurable networks where available bandwidth is shifted directly towards the hotspot wavelength.

In addition, the dual-transceiver allows the ONU to be relocated to a new wavelength in a make-before-break mechanism during rearranging process. Hence, interruption of on-going services is completely avoided. Consequently, network reconfiguration is transparent to upper layers.

3. Experimental Demonstration

The proof-of-concept experimental setup shown in Figure 3.b) consists of two wavelength pairs (λd_1, λu_1) and (λd_2, λu_2). The DS wavelengths λd_1 (1552.52 nm) and λd_2 (1555.75 nm) are externally modulated by 10.3125 Gb/s non-return-to-zero (NRZ) 2^{31}-1 pseudorandom bit sequence (PRBS) and multiplexed together with CW US seeding wavelengths λu_1 (1538.19 nm) and λu_2 (1549.32 nm). These wavelengths are specified by ITU-T 100GHz-spacing wavelength grid and selected from available DFB laser sources in our laboratory. The launched power towards the OLT-AWG is 0 and 3 dBm for DS wavelengths and US wavelengths, respectively. After transmission over 20km standard single mode fiber (SMF), they are demultiplexed at the RN by a commercial 32-port 100GHz-spaced C-band AWG with 2.5 dB insertion loss. Then λd_1 and λu_1 are combined using a 2x2 3dB coupler and the same for λd_2 and λu_2 to the emulate cyclic property of the proposed AWG. The two pairs are then combined again to be a RN output port. The variable optical attenuator (VOA) in the RN emulates the losses associated with a splitting ratio of 1:8. After further transmission over 5km from RN to ONU, the wavelengths are demultiplexed by a 16-port 200GHz-spaced C-band AWG in which two DS wavelengths are routed to the avalanche photodiode (APD) receivers and two US wavelengths are routed to the reflective electro-absorption modulators (REAM). US wavelengths are modulated by 10.3125 Gb/s NRZ 2^{23}-1 PRBS and propagate back to OLT. We use a bidirectional amplifier which provided a gain of 20dB for each direction before the REAM to compensate for 8-dB REAM insertion loss and transmission loss.
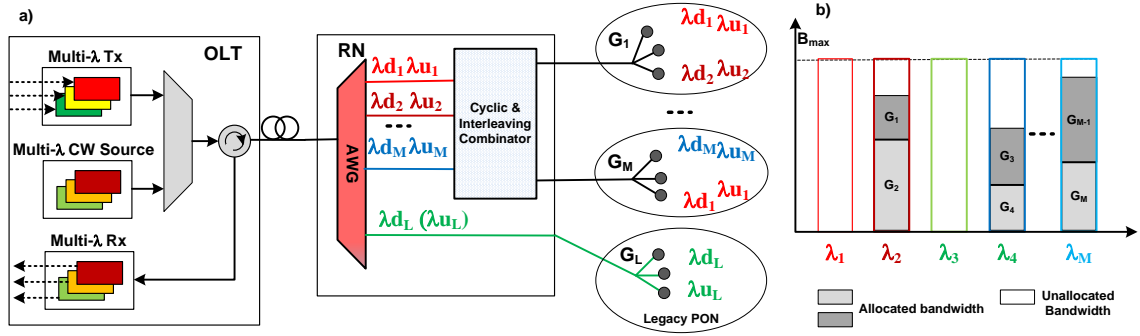
Figure 5: a) A Coexistent Scenario with a Legacy PON, b) ONUs concentration in even-index wavelengths in light-load hours to save power consumption

The total link loss for each direction is 30 dB while a total loss of 31 dB for downstream results in error-free transmission providing a margin of 1 dB. This margin could be improved by increasing the launched power however, the launched power for DS wavelengths is maintained at 0 dBm to avoid nonlinearities. In the upstream direction, the bidirectional amplifier is used since the REAM provided no gain but 8-dB insertion loss. However, the external amplifier could be removed if an REAM-SOA (semiconductor optical amplifier) reported in [6] is used instead of REAM. To achieve error-free transmission, a pre-amplifier has to be used in front of upstream receivers in OLT since without it the minimum achievable error rate is 10^{-7}.

Results in Figure 4 shows four measurement cases in each direction including the case when only channel 1 (λd_1, λu_1) is working. In all DS cases in Figure 4(left), the error performance is identical to the baseline optical back to back (BtB) performance. The performance of DS1 without DS2 is coincided due to good isolation in the passive components. For US performance shown in Figure 4(right), all transmission cases suffer a power penalty of 2.5 dB to get error-free performance which is due to backscattering and reflections from the seeding wavelength transmission.

In the proposed architecture, a DS wavelength should have a US wavelength spaced by one FSR to exploit the cyclic property of the AWG at RN. This requirement is somewhat restrictive in terms of wavelength planning especially when coexistence with traditional PONs is considered. This requirement could be relaxed in the proposed architecture if the 2x2 3dB couplers are used to combine the wavelength pairs as suggested in the experimental setup. As the coupler also acts as splitter to provide two branches for interleaving combination, no additional power loss is introduced.

4. Discussions on the Merits of PROaccess

PROaccess uses a novel approach, which employs only low-cost mutual-techology components. In fact, Those components are similar to the ones in legacy PONs (GPON, XGPON, EPON, 10G-EPON) and WDM PONs. The dual transceiver can be made from two discrete small form factor (SFP) transceivers and a Coarse-WDM (CWDM) can be used as the 1:4 bandspliter, which give 20 nm window for each sub-band. If the wavelength planning for 4 particular sub-bands does not fit with standard CWDMs, designing a dedicated 1:4 bandspiter is always possible. In the techno-economical perspective, it is ready for implementing PROaccess.

A smooth upgrade path from existing PONs also can be defined by appropriate modification of the RN as shown in Figure 5.a). For example, the wavelength channel, using by old ONUs in a legacy PON can bypass the interleaving combination part at the RN. The additional loss added by the AWG in the legacy PON link has to be compensated properly. From a specific scenario, the RN modification and wavelength planning can be concretely defined.

PROaccess is scalable since regardless of total number of ONUs, a wavelength channels is only split to serve two subgroup of ONUs. The power budget can be determined when the number of ONUs per subgroup is known. In broadcast-and-select architecture [5], this property can not be achieved because a wavelength is broadcasted to all ONUs in the system.

PROaccess can be seen as a green soluation since the system is able to concentrate ONUs to several wavelength channels and allow other channels (transceivers and related parts) going to standby mode to save the power in non-peak hours as depicted in Figure 5.b). The network aggregated capacity is usually planned for peak hours based on sevice level aggreements (SLA). However, the total of peak hours is usually not longer than 10 hours per day [7]. Enabling the network capacity as needed potentially save signifcant power consumption. Quantitavely evaluation of the power saving by PROaccess is one of our future works.

5. Conclusion

In this paper, we presented a passive-components-based reconfigurable WDM-TDM optical access network. The RN is designed to be completely passive and a tunable transceiver at the ONU side is avoided by using a band-splitter and a dual-transceiver. Although an ONU is allowed to be relocated between only two wavelength pairs, the system still attains superior flexibility by allocated bandwidth rearrangement mechanism. The architecture is demonstrated experimentally with error-free 10 Gbps bidirectional transmission. The physical performance was shown to be tolerable.

We continue to explore some aspects of the proposed architecture including wavelength planning, efficient integration of optical components at the ONU side, and implications on the MAC layer. We believe that the proposed concept is a feasible proposal for the optical access community which up to now has been reluctant to adopt reconfigurability because of its complexity and expensiveness.

Acknowledgments

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